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# ANALYSIS OF THE INFLUENCE OF THE METROPOLITAN AREA OF BELO HORIZONTE ON LOCAL METEOROLOGY USING WUDAPT – URBAN WRF MODEL

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## 1. INTRODUCTION

In 2016, an estimated 54.5% of the world's population lived in urban settlements (UN, 2016). Urbanized regions support the development of many and diverse activities that have the potential to modify, locally or regionally, the natural composition of the air as well as the balance of energy flow between the surface and the boundary layer by the land use changes (Oke *et al*., 2017). The temperature and composition of the air of the so called Urban Canopy Layer (UCL) are the results of the fluxes of mass, energy and momentum exchanged by the air of the planetary boundary layer (PBL) above, with the city structure, being affected by the arrangement of buildings, presence of vegetation and human activities (Martilli, 2014). Capturing these effects on local meteorology using numerical models has been a growing area of study.

Mesoscale models such as WRF (Weather Research and Forecasting) have been updated to be able to account for new factors that can influence on local climate. The Urban Canopy Models (UCM) are used to represent the urban areas for more accurate estimation of 2-m air temperature, 10-m wind speed, 2-m relative humidity, precipitation, surface temperature and other parameters (Jandaghian *et al*., 2017). Developed by Martilli et al. (2002), the module BEP (Building Effect Parameterization) is a multi-layer UCM that represents the most sophisticated urban modeling. BEP recognizes the three-dimensional nature of urban surfaces and the fact that buildings vertically distribute heat, moisture and momentum through the whole urban canopy layer, which allows for additional interaction of buildings (both the vertical and horizontal surfaces) with winds, temperature, turbulent kinetic energy (TKE), as well as the absorption, reflection, emission by building walls and roads (Chen *et al*., 2011).

As the cities are very heterogeneous, their features need to be simplified and divided into classes. The urban module requires as input data, to each class, radiative and thermal properties, besides morphological parameters (building height distribution and street orientation). One of the available classification to urban meteorological studies are the Local Climate Zones (LCZ). The Local Climate Zones (LCZ) represent a generic description of land use and occupation, free of cultural factors and easy to understand. There are seventeen LCZ types, including ten constructed types (LCZ 1-10) and seven land cover types (LCZ A-G)(Figure 1). To each LCZ is known data regarding surface properties, which can be used as input to BEP's urban canopy parameters (UCP).

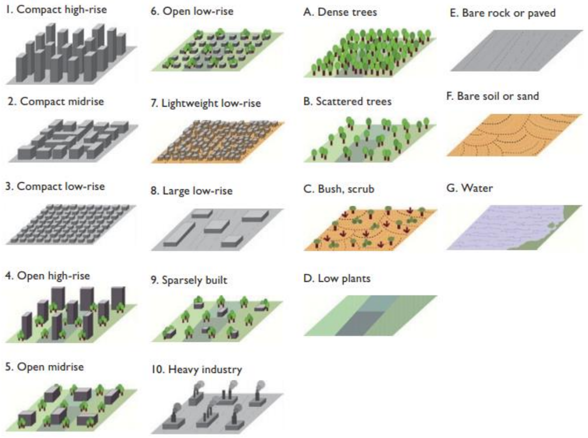

Fig. 1. Local Climate Zones classes (Stewart and Oke, 2012).

To evaluate the improvement on meteorological parameters prediction by the urbanized WRF (uWRF) version when compared to the default model, and to investigate the impact of a future scenario of urban growth on local meteorology, this study considered for testing, the

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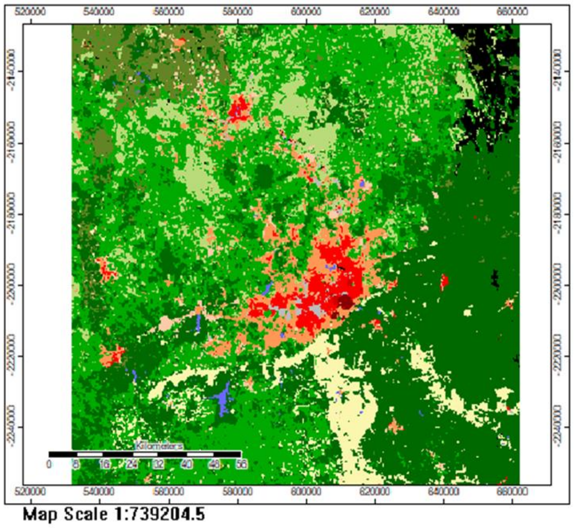
Metropolitan Area of Belo Horizonte/Brazil. Such area is the seventh most populated metropolis in South America with 5.3 million inhabitants, and for which temperature increases have been verified through the years, being, possibly, related to the changes on land cover.

## 2. METHODS

### *2.1 Land Use (LU) Classification – WUDAPT Methodology – Current and Future Scenario of Urbanization*

MABH LCZ classification followed the procedures established by the WUDAPT (*World Urban Database and Access Portal Tools*) website for level 0 (less detailed). Methodology proposed by the project is based on the supervised classification technique, from the Remote Sensing field of study. Selected training areas on the Google Earth along with Landsat 8 images (acquisition date: 18 Sep. 2016) were imported to SAGA software for supervised classification of the current MABH land use. Results can be seen at Figure 2a.

To check the effect of urban expansion on the local meteorology, a scenario of future urbanization was also proposed. Local climate zones from the current situation were converted into more urbanized areas, as the following criteria: LCZ 3 were converted into 1, LCZ 6 and 9 into LCZ 3, LCZ B and C into LCZ 9 and LCZ D into LCZ 6. To classes not mentioned, current land use was maintained. In Figure 2b, it is possible to check the expansion of the urban sprawl and in Table 1, area percentages of each LCZ on the current LU and on future scenario.



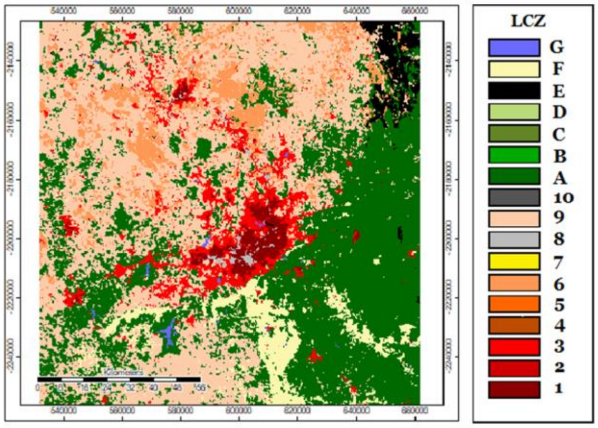


Fig. 2. (a) Current Local Climate Zone Classification of the Metropolitan Area of Belo Horizonte and (b) future urbanization scenario.

Table. 1. % of area occupied for each LCZ on MABH current and future urbanization scenario.

| LCZ | 1 | 3 | 6 | 8 | 9 |
|---|---|---|---|---|---|
| Current LU | 0.14% | 1.88% | 4.83% | 0.45% | 1.65% |
| Future LU | 2.06% | 6.46% | 8.23% | 0.45% | 38.56% |

### *2.2 Weather Research and Forecasting Setup – Default and Urban*

Were performed three simulations: a) WRF default with no LU update (MODIS); b) WRF coupled with BEP (uWRF) with the current LU; c) uWRF with future urbanization scenario. Items (a) and (b) had as objective to check if there would be any improvement on meteorological predictions variables by coupling the urban module, while (c) intends to foresee how the local meteorology would be affected if the region presented a moderate scenario of urban growth.

The meteorological simulations were performed for 10 days of September of 2017, during a dry season, by the non-hydrostatic, mesoscale Weather Research and Forecasting model, version 3.9.1. Three nested domains, centered at the same coordinate, have been set up: a larger domain on 25 km spatial resolution, the second domain on 5 km resolution and the innermost domain on 1 km resolution. The initial and boundary conditions were provided by the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) final analysis data on a 0,25 x 0,25° horizontal resolution. A warm-up of 24 h was applied in the simulations to minimize the impacts of trading conditions. It was considered two urban surface parameterizations in the simulations: default and multi-layer Building Effect Parameterization.

The inclusion of the LCZ classes on WRF code were performed according to the instructions in Martilli et al. (2016) which provided the information to enable BEP running by using the accompanying form and function data tables of WUDAPT Level 0 based on the LCZ classification scheme. Although classification was performed using all the 17 classes, only the urban classes were inserted on the code. The various urban canopy parameters (UCP) required by BEP initialization, such as heat capacity, thermal conductivity and surface albedo of ground, wall and roof, were adopted from Stewart and Oke (2012), Stewart *et al*. (2014) and Hammerberg *et al*. (2018).

To take full advantage of the urban parameterizations, a vertical resolution of 44 eta levels was used, with the first 18 levels located below 1.5 km height. The parameterizations chosen to simulate the meteorological conditions of the MABH were based on the best result obtained after twenty-two simulations. Physical schemes used were: WSM6 (microphysics), rrtmg (longwave radiation), Dudhia (shortwave radiation), Revised MM5 Monin-Obukhov (surface layer), Noah land-surface model (land surface), Mellor-Yamada-Janjic TKE scheme (planetary boundary layer) and Betts-Miller-Janjic (cumulus).

### *2.3 Simulations Validation*

Simulation results were analyzed according to the statistical indexes and benchmarks (Column 3-Table 2) suggested by Emery et al. (2001). The statistical indexes are: Mean Bias (MB), Mean Absolute Gross Error (MAGE), Root Mean Square Error (RMSE) and Index of Agreement (IOA). The evaluated variables were: air temperature, specific humidity and vector wind. Observed meteorological data were acquired from the automatic surface station Pampulha, operated by the National Institute of Meteorology (INMET).

## 3. RESULTS AND DISCUSSION

### *3.1 WRF Default and Urban – Performance Evaluation*

Data obtained from the simulation as well as the data observed on the Pampulha station were used to calculate the statistical indexes, summarized in Table 2. Values that did not meet the benchmarks intervals are marked in red.

Table. 2. WRF simulation performance using statistical indexes for the MABH.

| Meteorological parameter | Index | Benchmark | Default | Urban |
|---|---|---|---|---|
| Temperature (2 m) | MB (K) | ≤± 0.50 | -0.34 | -1.37 |
| | MAGE (K) | ≤ 2.00 | 1.00 | 1.56 |
| | IOA | ≥ 0.80 | 0.98 | 0.95 |
| Wind speed (10 m) | MB (m.s$^{-1}$) | ≤± 0.50 | 2.40 | -0.64 |
| | RMSE (m.s$^{-1}$) | ≤ 2.00 | 2.67 | 1.09 |
| Wind direction (10 m) | MB (°) | ≤± 10.00 | -1.09 | 6.32 |
| | MAGE (°) | ≤ 30.00 | 18.61 | 20.49 |

For temperature, the mean bias indicates that both configurations are underestimating the observed data from the Pampulha station, being this more significant for the urbanized version. Evaluating the historical series, it is possible to verify that default WRF tends to overestimate peaks of maximum temperatures while uWRF follows them more accurately. Both models, however, perform poorly when estimating minimum temperatures. Tendency is stronger on uWRF simulation, presenting faster and more drastic cooling during the nighttime than default version, what contributes to a more negative mean bias. Such findings were also verified by other authors, as Salamanca *et al.* (2011) and Gutiérrez *et al*. (2015).

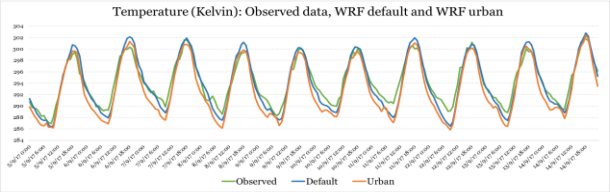


Fig. 3. Temperature (at 2m) time series with data observed at the Pampulha meteorological station and simulated by both WRF versions.

Wind speed for both simulations presented opposite behaviors. Results generated for default version, as expected, overestimated velocities while uWRF was not only capable of reducing bias but also the associated error. It is also known that WRF has limitations in predicting wind direction when terrain is complex (Reboredo *et al*., 2015), as in this case, where station is in a green region surrounded by urbanized areas, but observing the statistical indexes and the wind rose plot (Figure 4) is possible to notice that both version reproduced wind direction satisfactorily.

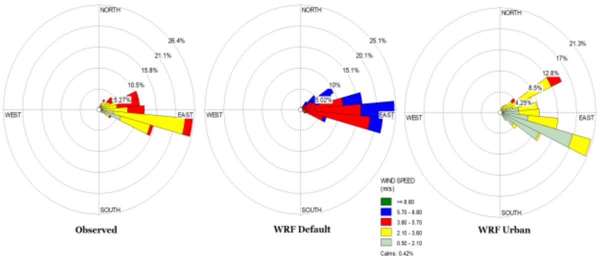


Fig. 4. Wind rose for observed data at the Pampulha meteorological station and simulated by both WRF versions.

## 3.2 Urban Expansion and Local Meteorology

The current land use of MABH was modified to represent a fictional scenario of urban growth. Influence on local meteorology were mainly evaluated from the perspective of thermal impact of the land cover substitution. Situation considered was the conversion of an urban cell located at the city center of Belo Horizonte previously classified as LCZ3 (current land use – LU) converted into LCZ 1 (future LU). Therefore, the following urban canopy parameters were altered: impervious fraction; height distribution; heat capacity, thermal conductivity and surface albedo of ground, wall and roof. In Figure 5 is possible to verify temperature differences between them. Time is expressed on GMT (Local time: -3h). In general, the future land use (LU) proposed can contribute to temperature (at 2m) elevation (up to 3°C). It was identified a tendency of higher temperatures during the nighttime and lower temperatures during the day period on the future scenario when compared to the current land use. One of the hypotheses that help to explain such findings is the radiation trapping effect and shadowing accounted for BEP. When a LCZ 3 urban cell is converted into a LCZ 1, shadowing from higher buildings contribute to attenuate diurnal temperatures while the same buildings impede longwave radiation to escape from urban canyons during the nighttime, increasing temperature.

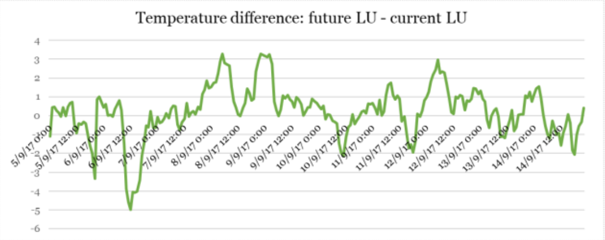


Fig. 5. Temperature (at 2m) difference between an urban cell classified as LCZ 1 (on a future scenario of urban growth) and LCZ 3 (current situation).

As temperature can be influenced by other aspects, latent and ground heat flux were also evaluated. Positive fluxes indicate that heat is being emitted from the surface to the atmosphere, while negative fluxes mean surface is absorbing it. In Figure 6 (a) latent heat flux time series was plotted and in (b) ground heat flux.

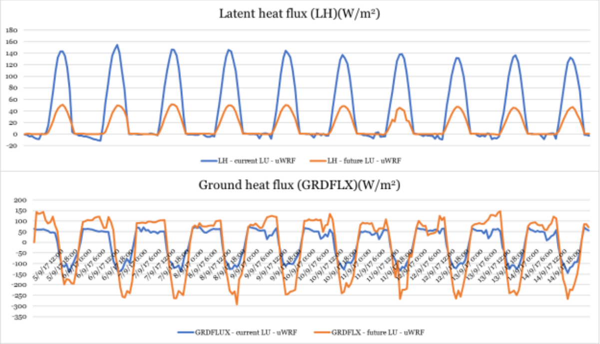


Fig. 6. (a) Latent heat flux and (b) ground heat flux from current and future scenario of urbanization.

Due to the increase of the urban fraction on the transformation of LCZ 3 areas into LCZ 1, latent heat flux (LH) was significant reduced on the future scenario of urbanization. It can also be noted that there is an increase of the parcel absorbed by the ground (GRDFLX) during daytime and increase of the parcel dissipated during nighttime. Such findings both support the results obtained on Figure 5 (of temperature increase), as corroborate the analysis made for the diurnal and nocturnal cycle.

Upward sensible heat flux was also evaluated but no significant difference was verified, indicating land use changes were not drastic enough to cause it any alteration.

## 4. CONCLUSIONS

After model validation, was noted that Urban WRF was capable of, considerably, reducing wind speed mean bias and error. For temperature, it was proven to be more accurate in predicting maximum peaks while lower temperatures were underestimated, what contributed to a negative bias. In this way, to improve uWRF performance, the urban canopy parameters introduced on BEP should be replaced, when available, by observed data. For this study, except for building heights, all the UCP were adopted from the literature.

From the proposed scenario of urban expansion was verified a possible increase on temperature for areas converted into more impervious and verticalized zones, with a difference of up to 3 °C. Increase on temperature can be partially explained by the reduction of the parcel dissipated as latent heat due to the increase of the urban fraction; and by the increase of the heat parcel absorbed during the daytime, consequently increasing the amount of heat that is dissipated during nighttime. In regarding the urban module BEP, it is important to emphasize that it was able to recognize two different land uses, simulate the main urban effects and to produce coherent results. The impacts of urbanization on other meteorological variables will be analyzed to future studies along with their vertical profiles.

## 5. ACKNOWLEDGEMENTS

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