Study of urban heat islands using different urban canopy models and identification methods

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Introduction:

The urban heat island (UHI) effect can be described as a positive thermal anomaly in urban areas with respect to their rural surroundings. UHIs can be influenced by:

• Urban features such as, buildings' geometry, roads width, lack of vegetated surfaces, and the distinctive urban materials radiative, thermodynamic, and aerodynamic properties;

• Local physiographic features, such as proximity of water bodies, altitude, and topography;

• Anthropogenic heat release (e.g., air conditioning, traffic, human metabolism).

UHIs and heatwaves can interact synergistically. This is particularly worrying since future climate projections show an aggravation of heat-related risks resulting from UHIs during heatwave events, due to the increase in future heatwaves intensity, frequency, and duration. Hence, the accurate modelling and measuring of UHIs during extreme HW events is critical. In this study, the Weather Research and Forecasting (WRF) model version 3.9 [1] is coupled with two different urban canopy models (UCMs) to estimate the intensity and distribution of the near-surface UHI in the Lisbon metropolitan area, during the record-breaking August 2003 European heatwave event.

Objectives:

Compare the performance of the single-(SLUCM) [2] and multilayer (BEP-Building effect parameterization) [3] UCMs coupled with WRF, along with the application of two UHI identification methods (i.e., classic method and local method).

1. Model setup

Forcing data: ERA-Interim reanalysis (res.: 0.75°×0.75°) [4]

Simulation period: July 28th to August 2nd, 2003 (+24h spinup)
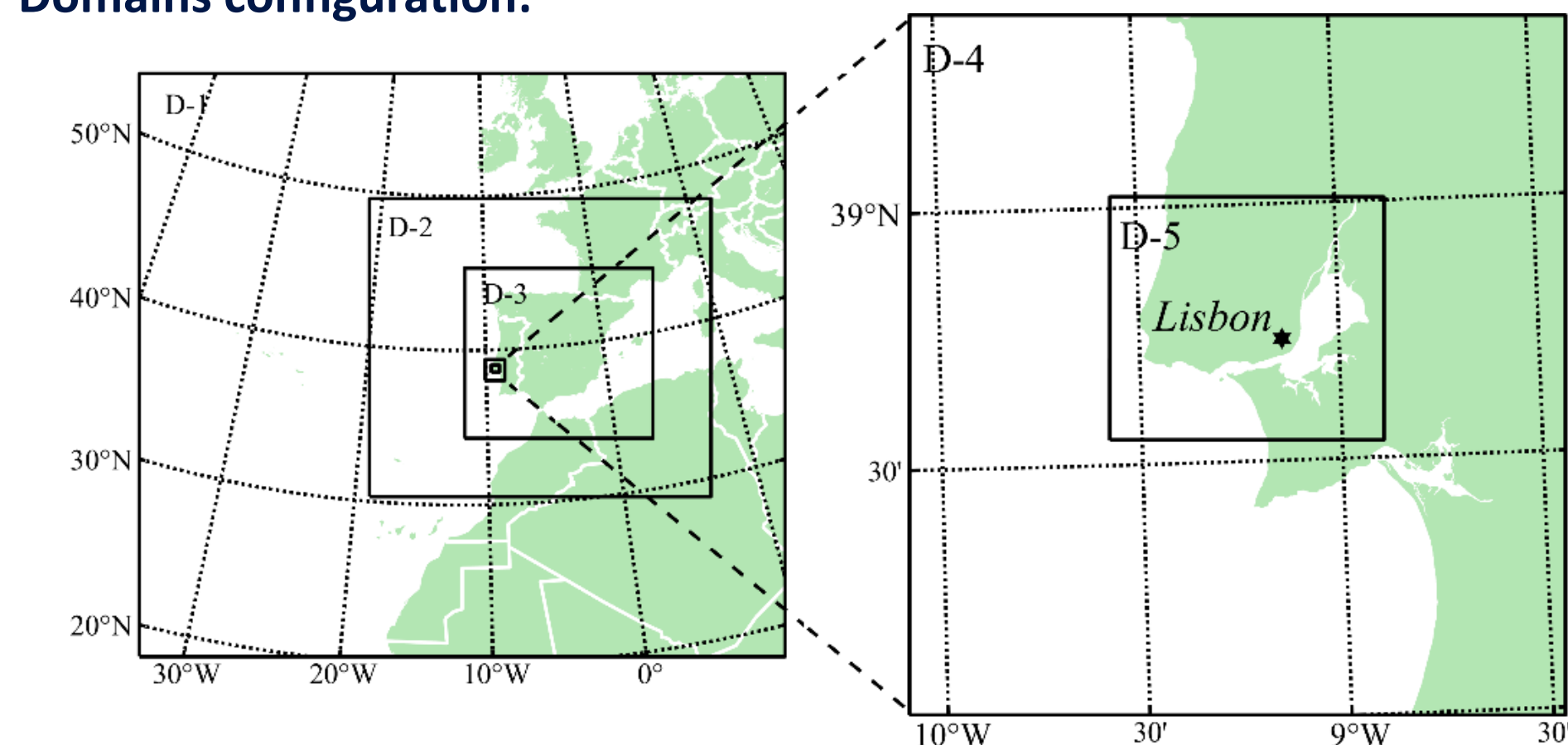
Domains configuration:

Figure 1. Domains' configuration used in the WRF model simulations. Model domains with D-1 (81 km), D-2 (27 km), D-3 (9 km), D-4 (1 km), D-5 (333 m).

Model land use: CORINE land cover [5] with ~100 m resolution, reclassified to the United States Geological Survey land use classification system with 33 categories (Figure 2)
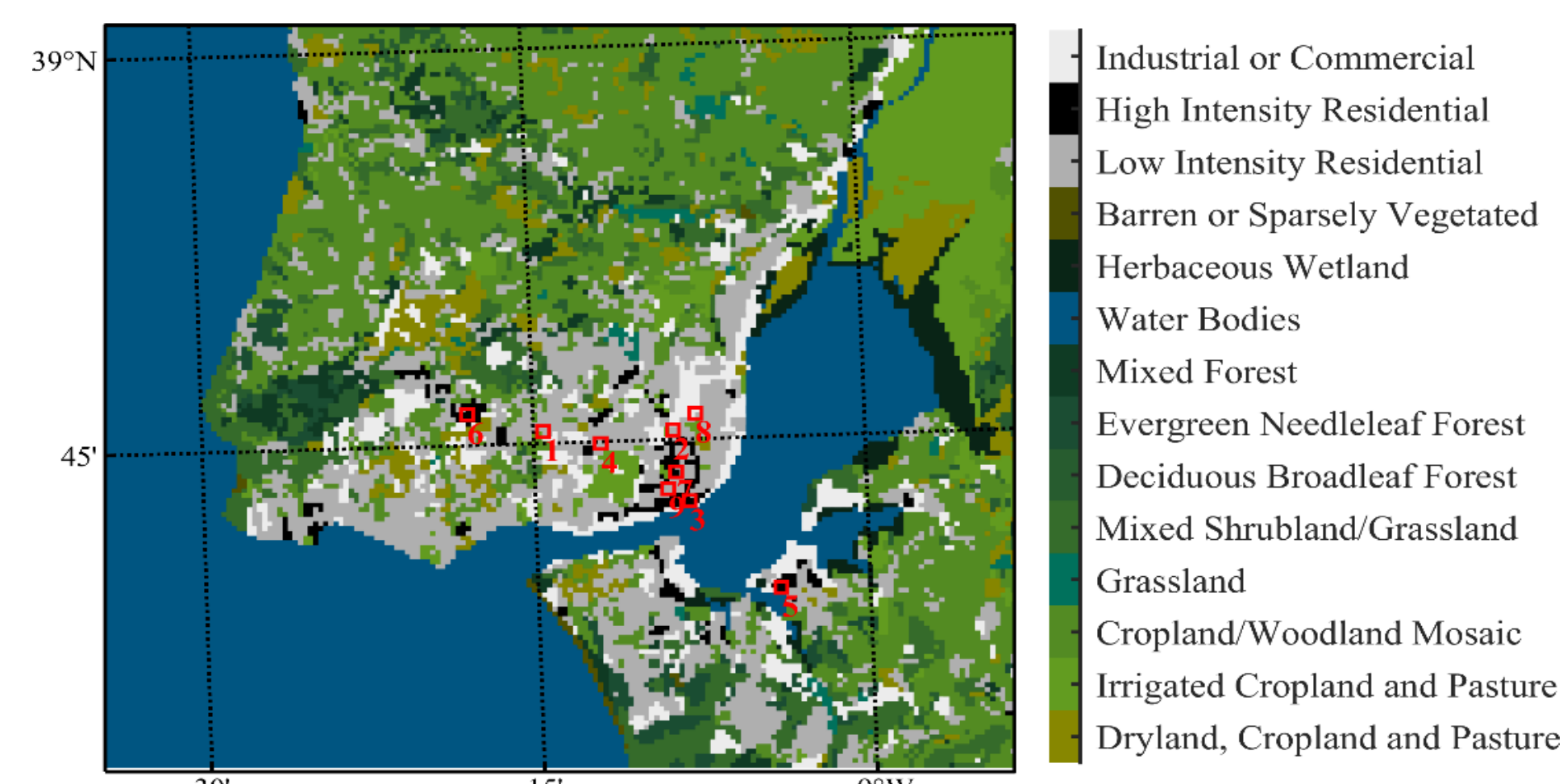

Figure 2. Model land use representation in D-5 with the location of the nine meteorological stations (numbers from 1 to 9) used to validate the WRF model simulations. (see Silva et al. 2021 [6] for further details).

Table 1. *Percentage of urban and green fraction used for each urban class.*

Urban Class	Green fraction (%)	Urban fraction (%)
Industrial or comercial	5	95
High intensity residential	10	90
Low intensity residential	50	50

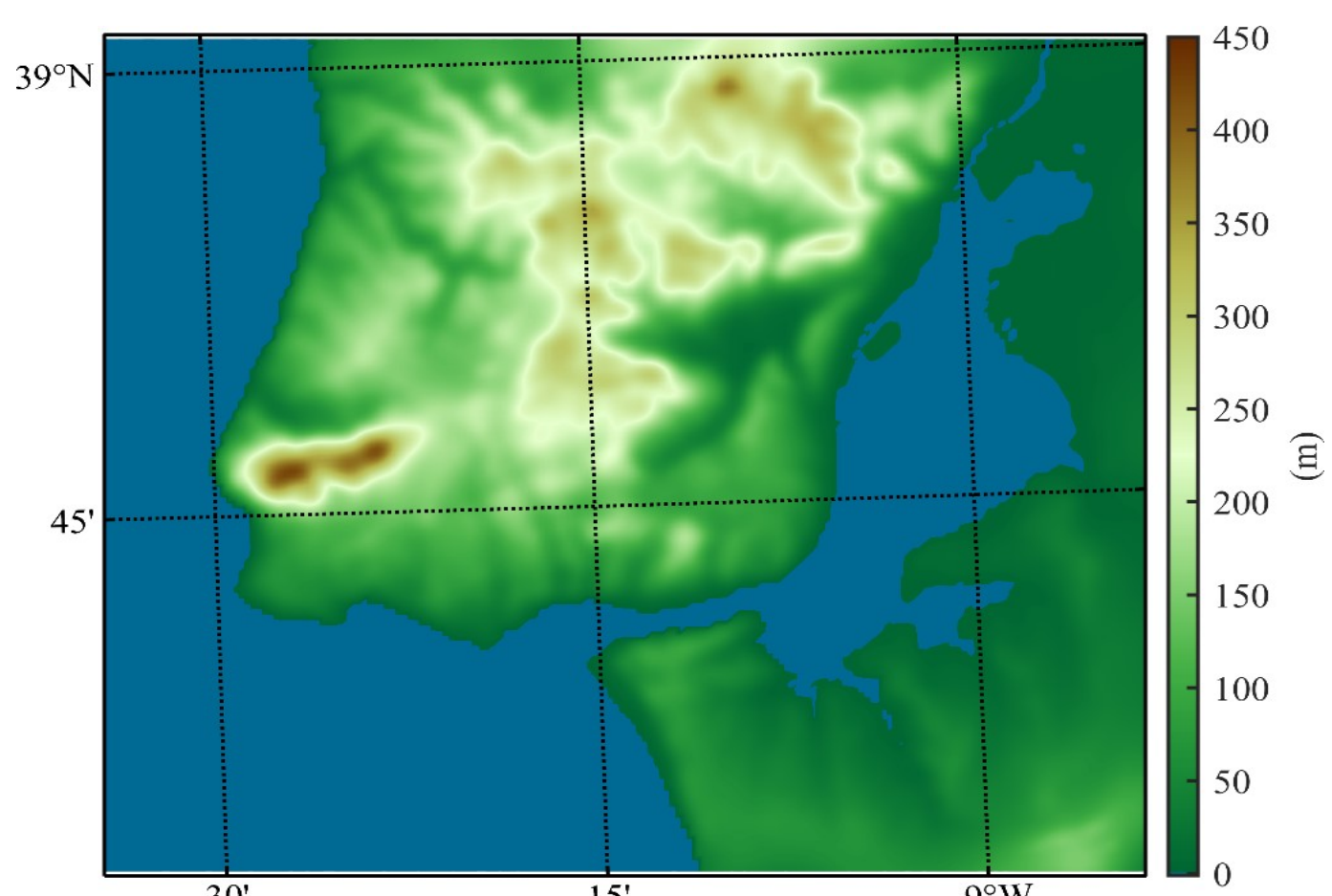**Model Topography:** NASA's Shuttle Radar Topographic Mission (SRTM) [7] with ~90 m resolution (Figure 3)

Figure 3. Representation of WRF model topography in domain D-5.

Model Physics options:

Table 2. *Physics options used in the UHI simulations.*

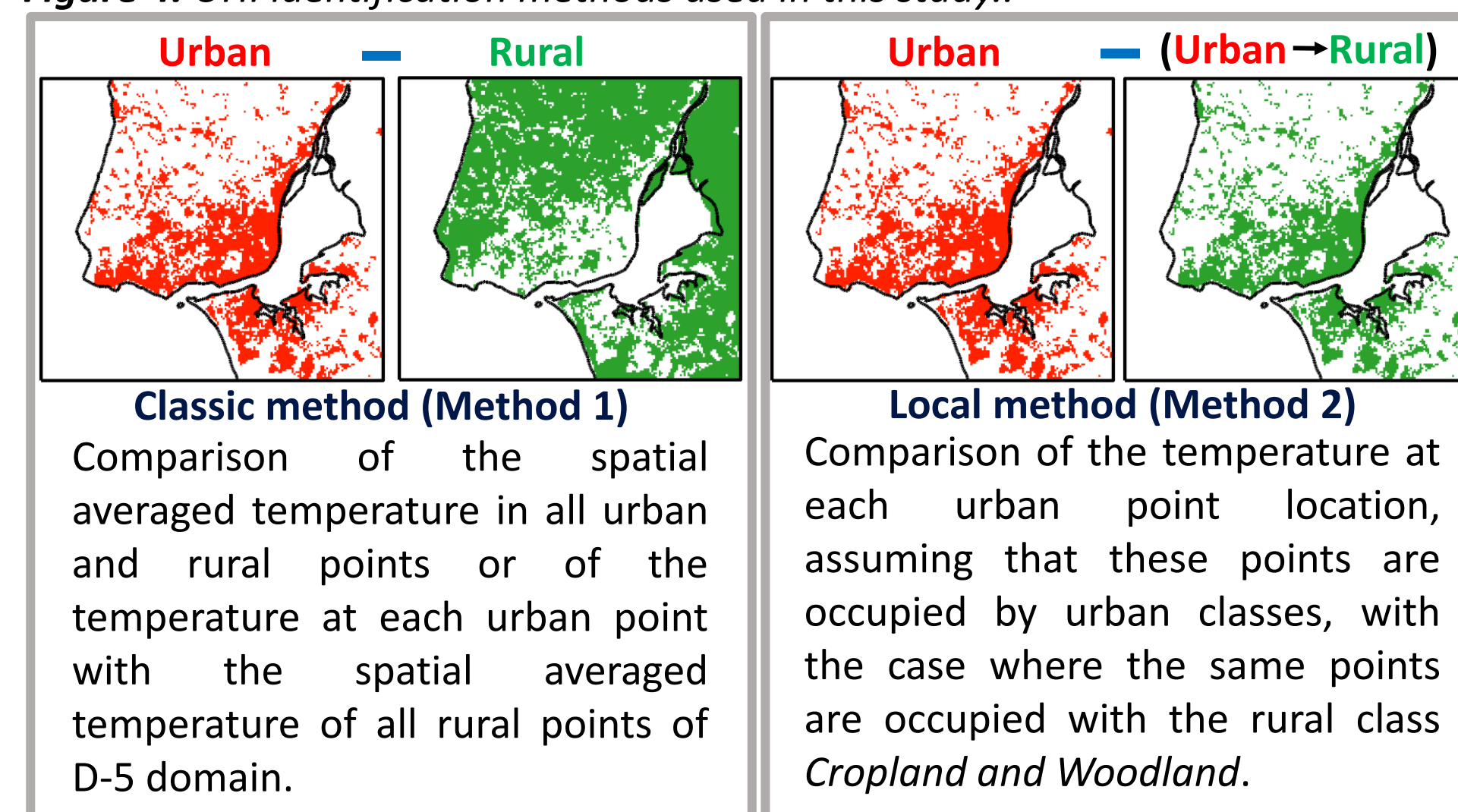| Model Physics	Scheme
Microphysics	WSM6
Shortwave radiation	Dudhia
Longwave radiation	RRTM
Surface layer	Revise MM5
Land surface	Noah LSM
Planetary Boundary Layer	BouLac PBL
Cumulus	Grell-Freitas (turned off in D-4 and D-5)
Urban physics	Noah bulk/SLUCM/BEP

2. Methodology

• Simulations with and without urban classes using SLUCM and BEP UCMs;

• When SLUCM and BEP are deactivated, artificial surfaces are treated by a bulk scheme (Noah bulk scheme);

• No anthropogenic heat in all simulations;

• Simulations with BEP have three levels whithin the urban canopy layer;

• Top of the urban canopy layer is defined at same height for SLUCM and BEP.

Table 3. *WRF simulation experiments performed in this study..*

Simulation Name	Nº of Vertical Levels	Urban Parameterization	Urban Land Use Categories
SLUCM		Yes	Yes
NO_SLUCM	46	Noah bulk	Yes
NURB_SLUCM		Yes	No
BEP		Yes	Yes
NO_BEP	49	Noah bulk	Yes
NURB_BEP		Yes	No

• Two UHI identification methods were applied using the different simulations (see Figure 4);

• Local method (or Method 1) removes local physiographic influences and only accounts for urban effects on UHI;

• Classic method (or Method 2) accounts for both urban and local physiographic effects.

Figure 4. *UHI identification methods used in this study..*

Classic method (Method 1) Comparison of the spatial averaged temperature in all urban and rural points or of the temperature at each urban point with the spatial averaged temperature of all rural points of D-5 domain.

Local method (Method 2) Comparison of the temperature at each urban point location, assuming that these points are occupied by urban classes, with the case where the same points are occupied with the rural class *Cropland and Woodland*.

3. Results and discussion

How does Method 1 and Method 2 compare?

• The nighttime UHI intensity using Method 1 is about double of Method 2 for both UCMs during the heatwave period (see Figure 5);

• An urban cold Island (UCI) occurred during daytime, except for BEP using Method 2.
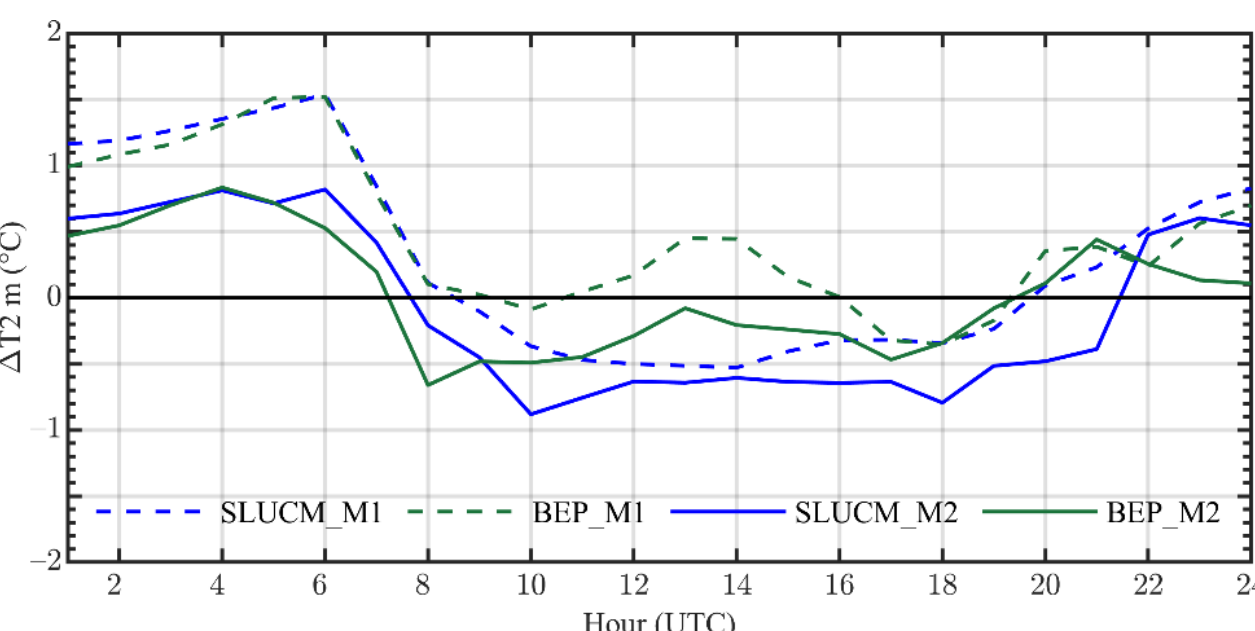

Figure 5. Heatwave averaged mean diurnal cycle of the Lisbon near-surface UHI: using Method 1 (M1—dashed lines) and Method 2 (M2—solid lines), for SLUCM (blue lines) and BEP (green lines) UCMs.

• Spatial patterns of the heatwave averaged UHI using Method 1 show a dipole structure due to the sheltering effect of the high topography in the north-western part of the Lisbon metropolitan area, that blocks the prevailing northern winds during the heatwave, and enhibits the advective cooling in the south-western part (Figure 2 and Figure 6);

• The sheltering effect results in an intensification of the UHI south of the high topography region and a reduction over it;

• The daytime and nighttime UHI spatial patterns using Method 2 show respectively an overall cooling effect and an overall warming effect due to urban fabric across the whole domain.
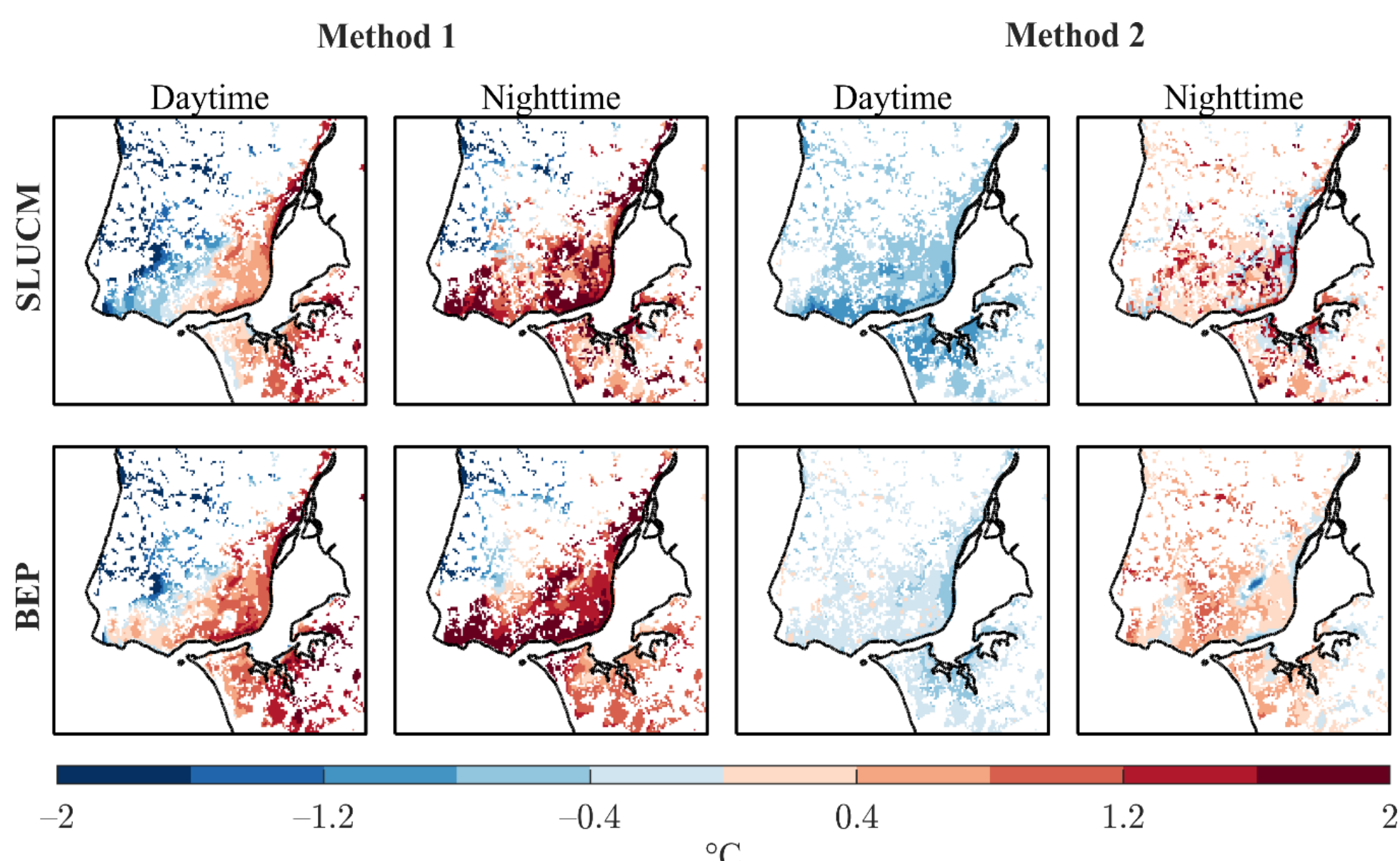

Figure 6. Heatwave averaged daytime and nighttime fields of the near-surface UHI identified using Method 1 and Method 2 and for SLUCM and BEP urban canopy models.

How does SLUCM and BEP compare?

• BEP produces much larger turbulent kinetic energy (TKE) in the lower planetary bouday layer, especially during nighttime (Figure 7);

• This results in higher planetary boundary layer high (PBLH) in BEP (not shown);

• Both SLUCM and BEP models overestimate PBLH compared with radiosondes, but BEP more;

• Surface sensible heat fluxes over urban surfaces are negative in BEP during most of the day as consequence of the higher TKE produced by BEP (not shown), meaning that the surface is receiving heat from the atmosphere.
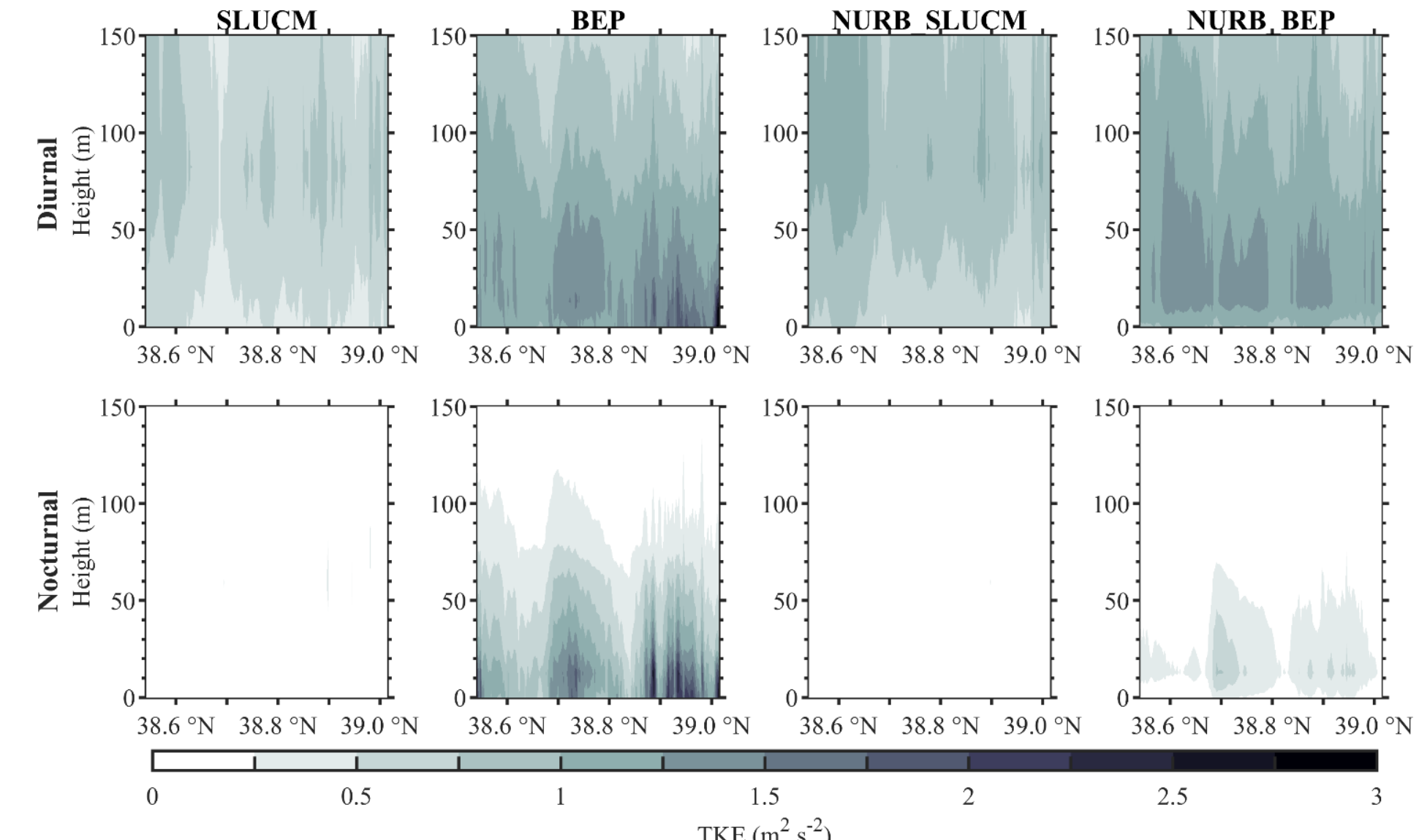

Figure 7. Heatwave averaged daytime and nighttime zonal means of the parameterized TKE in urban grid points (first 150 m of the PBL), for SLUCM and NURB_SLUCM (left column); BEP and NURB_BEP (right column) simulations.

• Figure 8 shows a large difference in temperature between the surface (TSK) and the lower atmosphere (T2) using BEP, with the surface temperature beeing much lower than both soil and near-surface temperatures, which indicates that the surface is cooling;

• The difference is larger between the surface and near-surface temperatures in BEP;

• The surface cooling is compensated by the heat accumulated in the ground during the day, and later converted into sensible heat (at night), which is immediately transported by the large tubulent heat fluxes found in BEP.
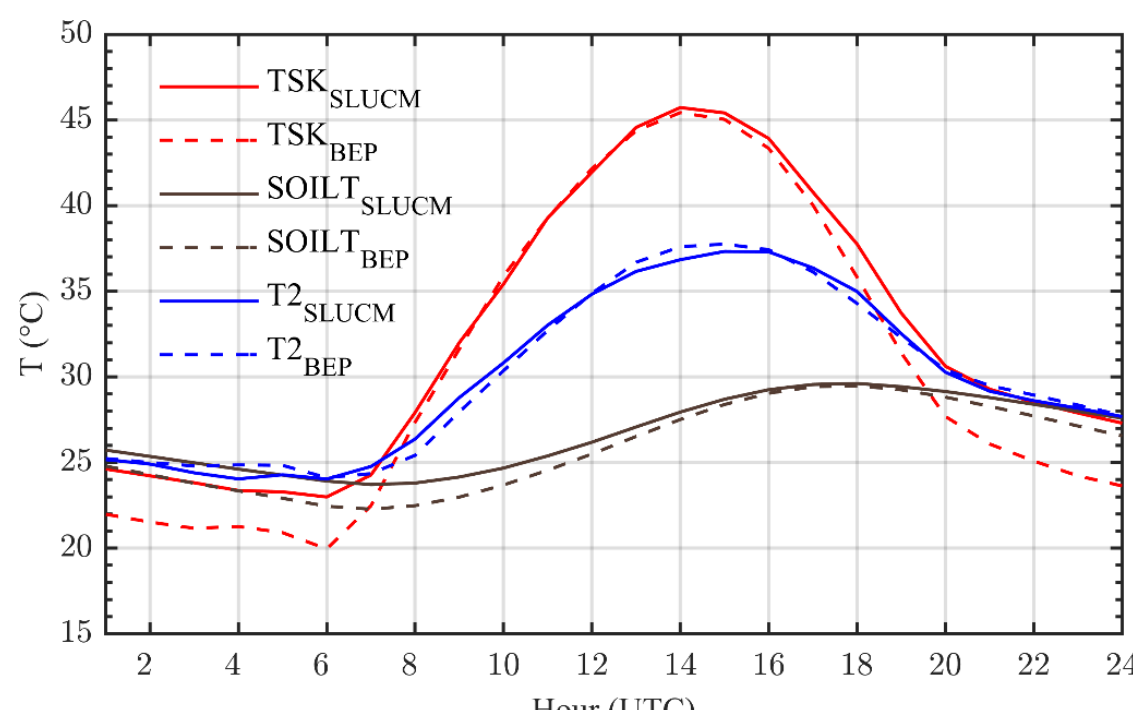

Figure 8. Heatwave averaged diurnal cicle of skin temperature (TSK), first layer soil temperature (SOILT), and two-meter temperature (T2), averaged over urban grid points.

4. Conclusions

• There are significant improvements in modeled near-surface temperature when using WRF coupled with SLUCM and BEP, but better with SLUCM for minimum and mean temperature and BEP for maximum temperature;

• The application of Method 2 results in higher UHI intensity due to the topographic sheltering effect of the high topography in the northern-western part of the Lisbon metropolitan area that blocks the northern winds and enhances the UHI at south of this high topography region;

• BEP significantly overestimates PBLH due to higher near-surface TKE production, which leads to excessive surface cooling;

• Comparison with previous studies indicates that BEP performance is very sensitive to the number and distribution of the model vertical levels within the urban canopy;

• Method 2 is the best option to develop UHI mitigation methods, despite its limitations in the application to other cities, particularly the type of land use that replaces the urban fabric (this is especially true for cities with more heterogeneous natural land use).

5. References

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