Advantages of using a fast urban canopy model as compared to a full mesoscale model to simulate the urban heat island of Barcelona

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Abstract. As most of the population lives in urban environments, the simulation of the urban climate has become a key problem in the framework of the climate change impact assessment. However, the high computational power required by these simulations is a severe limitation. Here we present a study on the performance of a Urban Climate Model (UrbClim), designed to be several orders of
5 magnitude faster than a full-fledge mesoscale model. The simulations are validated with station data and with land surface temperature observations retrieved by satellites. To explore the advantages of using a simple model like UrbClim, the results are compared with a simulation carried out with a state-of-the-art mesoscale model, the Weather Research and Forecasting model, using an Urban Canopy model. The effect of using different driving data is explored too, by using both relatively low
10 resolution reanalysis data (70 km) and a higher resolution forecast model (15 km). The results show that, generally, the performance of the simple model is comparable to or better than the mesoscale model. The exception are the winds and the day-to-day correlation in the reanalysis driven run, but these problems disappear when taking the boundary conditions from the higher resolution forecast model.

15 1 Introduction

According to the United Nations, more than 50% of the world population lives in cities, and this percentage is expected to increase in the coming decades. The urban environment is known to modify the local climate in several different ways. The main one is the so-called Urban Heat Island (UHI) effect, that consists on temperatures being several degrees higher over the urban area with respect to
20 its rural surroundings. Due to anthropogenic climate change, the frequency of heat waves is expected to undergo a widespread increase (Meehl and Tebaldi, 2004) in the following decades. This raises concerns about the vulnerability of people living in urban areas.

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Although the magnitude of the UHI effect does not necessarily increase due to global warming (Lauwaet et al., 2015), it has been shown to be large enough to pose significant impacts. The most

25   important ones are human health, through heat stress (Gabriel and Endlicher, 2011; Dousset et al., 2011) and energy consumption (Kikegawa et al., 2006; Kolokotroni et al., 2012).

The physical causes of the UHI effect were enumerated by Oke (1982), but the relative contribution of each one is still discussed. Zhao et al. (2014) used satellite observations and a model simulation to calculate the relative contribution of the different causes of the Urban Heat Island in

30   65 cities of North America. They considered contributions from modifications in the radiative balance, evaporation, convection efficiency, heat storage and anthropogenic heat sources. They found that the relative contribution of these factors depends on the local background climate of the city, and on the time of the day. In general, during daytime, convection efficiency and evapotranspiration are the main drivers of the UHI, while heat storage is the most relevant during the night. How-

35   ever, other authors (Arnfield, 2003), highlight the complexity of the problem, that is very related to the difficulty of getting observations of the urban climate with enough detail and reliability. Zhao et al. (2014) used satellite retrieved land surface temperatures, but these can defer from screen level temperatures. Furthermore, the complexity of the urban surface, featuring anisotropy, and vertical surfaces, makes it complicated to sample by satellites (Voogt and Oke, 1998). These difficulties with

40   the observations increase the value of numerical simulations, that can produce fields which are not observable but, obviously, hamper the validation of the models.

Recently, Urban Canopy models or parameterizations have been included in many Regional Climate Models (RCMs) (see. for example Huszar et al. (2014) and Ching (2013)). The RCMs are limited area models which are used to downscale the climate change projections from the coarse

45   resolution Global Circulation Models. Nevertheless, computational power limitations do not allow RCMs to reach the level of resolution that is required to resolve most of the cities. Here we show how, by using a simplified model, it is possible to reach resolutions of 250m with affordable computational resources. This model, called UrbClim, has been developed by De Ridder et al. (2015), and is described in section 2.3. UrbClim has been already validated in a few European cities (De Ridder

50   et al., 2015; Zhou et al., 2015; Lauwaet et al., 2016) and used to generate Climate Change projections (Lauwaet et al., 2015). In the present paper, we validate UrbClim over the city of Barcelona, and compare it with a standard mesoscale model, the Weather Research and Forecast model (WRF), using a Urban Canopy parameterization. This parameterization was developed by (Chen et al., 2011) and has been verified in several studies (Lee et al., 2011).

55   Barcelona is located in the Euro-Mediterranean area. This area has been defined as a primary climate change hot spot (Giorgi, 2006), as it emerges as an especially responsive area to climate change, with more frequent, longer and harsher summer heat waves (Meehl and Tebaldi, 2004; Ballester et al., 2009, 2010a, b). In addition to the larger magnitude of the projected temperature increase, the Mediterranean countries are already now more vulnerable to environmental summer conditions. For

60 example, the negative effects of the record-breaking 2003 heat wave in central and southern Europe were particularly damaging in the Euro-Mediterranean arch (Robine et al., 2008). The seasonal mortality excesses were indeed similar in Spain (13,7%), France (11,8%) and Italy (11,6%), although temperature anomalies were at least twice as large in France than in the southern countries (Ballester et al., 2011). This larger sensitivity to environmental conditions is exacerbated by urban pollution

65 in old people living in cities with pre-existing or chronic cardiovascular and respiratory diseases (McMichael et al., 2006).

Taking into account all these considerations, the city of Barcelona emerges as a particularly vulnerable area within the continent. Barcelona is located in northeastern Spain, surrounded by the Mediterranean Sea in the south and east, a small 500m mountain range in the northwest, and two

70 rivers in the southwest and northeast (figure 1). Its Mediterranean climate (Csa in the Köppen classification) is shaped in summer by the local wind breeze regime, whose diurnal evolution exhibits a clockwise rotation from southerlies in the morning to winds blowing roughly parallel to the southwest-northeast shoreline in the late afternoon (Redaño et al., 1991).

The main goals of the paper are:

75 – Evaluation of a simulation of the urban climate of the city of Barcelona with the UrbClim model, by comparing it with station and satellite data.

– Analysis of the sensitivity of the simulation to the boundary conditions, comparing two simulations nested in global datasets with different horizontal resolution (70 km and 15 km).

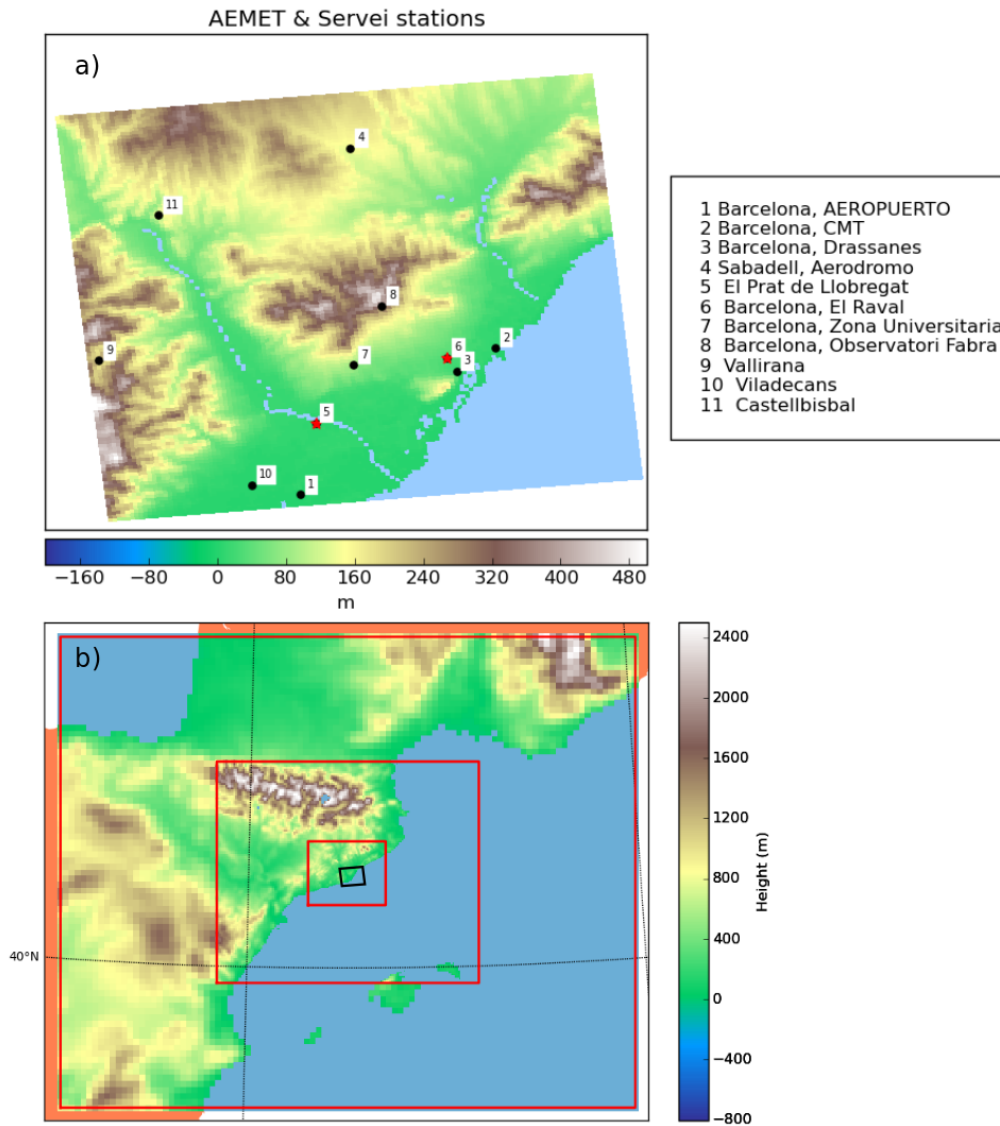
– Comparison of the UrbClim simulations with a benchmark simulation carried out with a state-
80 of-the art mesoscale model, focusing both on model skill and computational resources demanded.

2 Data and Methodology

2.1 Surface stations

As a first approach in the evaluation of the model performance, we have used data from a set of
85 meteorological stations, 4 of them belonging to the Spanish Meteorological Agency (AEMET) and 7 to the Catalan Meteorological Service (SMC). All are well maintained automatic stations, that deliver meteorological data with 10 or 20 min frequency. In the present work, only hourly data were used. The locations of these stations, as well as their names, are displayed in figure 1a, together with the topography.

90 Station number 5 (El Prat de Llobregat) is chosen to be representative of a rural location near the city. This station is located in the middle of cereal fields, 300 m from the Llobregat river and 650 m from the closest urban area. Station number 6 (el Raval) is instead chosen as the reference urban station. This station is located on the roof of a building, at the city centre of the city, 8.5 Km away

Figure 1. a) Topography of the UrbClim domain and locations of the meteorological stations used. The two stations used as references to compute the Urban-Rural difference are highlighted with red stars. b) Three WRF domain edges (red squares) and UrbClim domain edges (black contour), together with the topography of the WRF domains with 10, 3.3 and 1.1 km resolution.

from the rural station. These two points are almost the closest possible rural-urban points located at
95   a similar height. The rural station is at 8 m above sea level, while the urban station is at 33 m, which can account for a difference of 0.15-0.25 °C difference in a standard atmospheric profile. The rural station is located in a delta, and therefore the surrounding topography is flat, which does not favour

temperature inversions during night time hours. Thus, the differences between these two stations are considered to be representative of the UHI effect in the city of Barcelona.

100   2.2   Satellite data

The spatial pattern of the simulations is evaluated through data from the MODerate Resolution Imaging Spectoradiometer (MODIS) of the National Aeronautics and Space Administration (NASA) of the United States. Following previous works (Schwarz et al., 2011; Zhou et al., 2015), MODIS datasets MOD11A2 and MYD11A2 (version 5) were downloaded and processed. These correspond

105   to the Terra and Aqua satellites respectively, and are 8-day aggregations of the daily MOD11A1 and MYD11A1 datasets, using only the clear-sky days. The variable considered is Land Surface Temperature (LST), which is derived from the infrared radiance and emissivity estimated from land cover types. A more detailed description of the algorithms is available in Wan (2008).

The LST data were processed considering only the data flagged as "good quality, not necessary

110   to examine more detailed QA" in the Quality Flag provided with the data, and with no cloudy days during the 8 day period. MODIS and UrbClim LST data were interpolated to a 0.01 deg. regular grid for direct comparison. Finally, only the images with less than 14% missing values were used (this does not include the data over the sea which are always missing). This process left a total of 15 values for most gridpoints (supplementary figure 1) over the whole period.

115   2.3   The UrbClim model

The UrbClim model is designed to reproduce the main features of the urban climate requiring the minimum amount of computational power, so that it is possible to perform long runs at a resolution of hundreds of meters. A detailed description of the model is available in De Ridder et al. (2015).

UrbClim models the lower 3 km of the atmosphere, and consists of a 3-D boundary layer model

120   and land-surface scheme with urban physics. The boundary data needs to be read from a lower resolution model. Given that UrbClim generates very small internal variability, the stability of the simulation is not compromised by the difference in the resolutions of the UrbClim and driving models, as it normally occurs with conventional mesoscale models. Nonetheless, this resolution jump can sometimes affect the quality of the simulation if the driving model does not accurately reproduce the

125   local climate.

The land use data, that are needed to represent the surface properties, are taken from the CORINE dataset (http://www.eea.europa.eu/publications/COR0-landcover). This dataset is publicly available online, and was produced by the European Environmental Agency at a resolution of 100 m.

The land-surface scheme is a standard soil-vegetation-atmosphere model based on De Ridder et al.

130   (1997) with some extensions. In the original scheme, the urban canopy was represented as a simple impermeable slab. In the updated version, described in detail in (De Ridder et al., 2015), this is extended in many ways. However, it can still be considered a simple urban canopy model compared

with other existing approaches. The 3D boundary layer model represents a simplified atmosphere by using the conservation equations for the horizontal momentum, potential temperature, specific
135 humidity and mass. The turbulent vertical diffusion is represented following Hong and Pan (1996).

2.4 Experimental setup

UrbClim

The UrbClim simulations cover the five warmest months of year 2011, i.e. from May to September. The domain is represented by a horizontal grid with 121x121 points at a resolution of 250 m, with
140 19 vertical levels up to 3000 m (figure 1a). The driving model data is updated every 3 hours. Two simulations have been studied, labeled as UC-ERA and UC-FC. The former is driven by the ERA-Interim reanalyses (Dee et al., 2011), while the latter is driven by the Integrated Forecast System (IFS) version 37r2 global forecast model of the European Centre for Medium-Range Weather Forecasts (ECMWF). In 2011, this model ran with a spectral resolution of T1279 ($\simeq$15 km), in contrast
145 with the T255($\simeq$70 km) of ERA-Interim. Thus, it is able to provide more local details, which can be important give the aforementioned mesoscale-driven weather of Barcelona.

WRF

The Weather Research and Forecast model is an open-source, non-hydrostatic limited area model (Skamarock et al., 2008). Thanks to its availability, it has a large community of users. These con-
150 tribute to the development of WRF, which is leaded by the National Center for Atmospheric Research (NCAR). One particularity of this model is that a large amount of parameterization schemes, dynamical options, and sub-modules, available to the user to choose among them. These options are set up in a namelist file that must be edited for each simulation. The version of WRF used is the 3.6.1.

In the present work, WRF was configured to run in three nested domains 1b, with horizontal reso-
155 lutions of 9, 3 and 1 km and 40 vertical levels. The 250m of UrbClim were not reached because the computational cost was not affordable. However, the simulations were carefully configured to make them comparable with UrbClim: They were nested in the same dataset (ERA-Interim) and used the same land use (CORINE). WRF land use is by default taken from the United States Geological Survey (USGS) dataset. Thus, the CORINE land classes were mapped to the USGS 33 classes following
160 table 7.1 of Chrysoulakis et al. (2014).

Despite being nested in a reanalysis, the regional models tend to generate their own internal variability. There are two approaches to solve this: using nudging, or restarting the model frequently. In this case, based on the experience of previous works (Menendez et al., 2014; García-Díez et al., 2015), daily 36 hours simulations have been carried out and concatenated leaving 12 hours as spin-
165 up. These simulations cover the same time span as UrbClim, May to September 2011. Thus, 153

Table 1. Scores of daily mean 2 meter temperature for the UC-ERA, UC-FC and WRF simulations and the 11 stations.

Station	Bias (C°)			RMSE (C°)			Variance ratio		
	UC-ERA	UC-FC	WRF	UC-ERA	UC-FC	WRF	UC-ERA	UC-FC	WRF
1	1.4	0.1	-0.5	2.0	0.9	0.9	1.1	0.8	0.7
2	2.0	0.7	-0.8	1.9	0.8	0.7	1.6	1.1	0.9
3	1.6	0.3	-0.8	1.9	0.8	0.7	1.5	1.1	0.9
4	2.1	1.1	1.1	2.1	1.2	1.1	1.4	1.0	1.0
5	1.1	0.2	-0.3	1.7	0.6	0.7	1.3	1.1	0.9
6	1.2	0.1	-1.0	1.8	0.7	0.6	1.5	1.1	0.9
7	1.8	0.5	0.6	1.8	0.7	0.8	1.4	1.0	0.9
8	0.6	-0.7	0.6	1.8	1.1	0.9	1.1	0.8	0.8
9	0.5	-0.3	-0.2	1.6	0.7	0.7	1.1	0.9	0.9
10	1.2	-0.2	0.3	1.7	0.6	0.7	1.4	1.0	0.9
11	0.3	-0.5	-0.0	1.7	0.8	0.8	1.2	0.9	0.9

individual simulations have been carried out. To handle them, the WRF4G framework (Fernández-Quiruelas et al., 2015) has been used.

3 Results

3.1 Time series

170 Table 1 shows the standard scores of daily mean 2 meter temperature for the UC-ERA, UC-FC and WRF simulations and the 11 stations. The largest errors are found in UC-ERA, which generally overestimates daily temperatures by up to +2°C in some stations. This overestimation is associated with the misrepresentation of the sea breeze, which has larger effect on maximum temperatures (see below).

175 UC-ERA also overestimates the day-to-day variability, having higher Root Mean Square Error (RMSE) than the other runs. Instead, UC-FC and WRF show similar, smaller scores, which indicate the good performance of these simulations.

As UrbClim is hardly able to generate internal variability, these results can be interpreted as a comparison between Urban Canopy+PBL models driven by ERA-Interim (70 km), ECMWF forecast (16 180 km) and WRF (1 km). Thus, differences in the results show the added value of the higher resolution in the ECMWF forecast model and WRF. However, note that the extra resolution of WRF (about 15 times higher than ECMWF) is not clearly improving the results. This is consistent with previous studies suggesting diminishing returns for added value in this resolution ranges (García-Díez et al., 2015).

Figure 2. Average daily temperature cycle in the urban (left) and rural (middle) stations. The difference urban - rural is shown in the panel on the right.

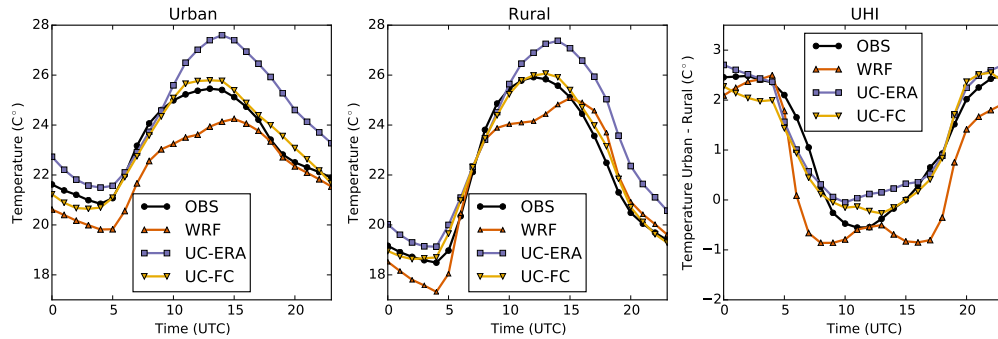
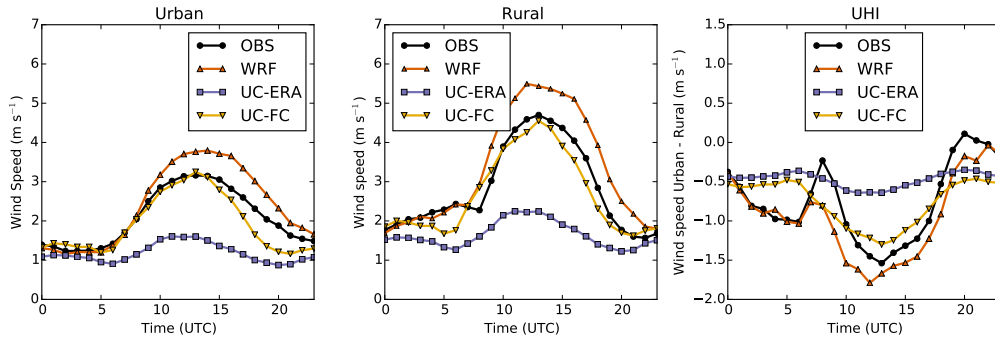



Figure 2 shows the average daily cycles for the urban and rural stations, as well as their difference. The average magnitude of the UHI during the night is found to be 2.5°, which is large enough to have direct impacts on human health during heat wave episodes (Ye et al., 2012). During daytime hours, the UHI is found to decrease down to -0.5°. Note that this is in very close agreement with the values derived from observational data in (Moreno-garcia, 1994), despite it used two different reference points. The measurement of the UHI with only two points has some limitations, as it may be sensitive to very local features such as the land use in the vicinity of the stations. However, the representativeness of these points has been carefully checked with high resolution satellite images. In addition, the agreement with previous studies increases our confidence in the results here presented.

UC-ERA tends to overestimate temperatures in both stations after 10 UTC and particularly during daytime hours, but errors in both stations cancel each other, and therefore the UHI magnitude is generally well represented with biases smaller than 0.5°. The UHI average daily cycle is similar in UC-FC and UC-ERA, but UC-FC does not show any warm bias, and accurately reproduces the observed temperatures of the individual stations.

In the case of WRF, we initially considered the nearest gridpoint to the rural and urban stations, and biases in the three panels were found to be clearly larger than those in UrbClim (not shown). This problem was found to be related to the land use of the gridpoints, which were not representative of the land use of the stations. Indeed, the gridpoint representing the rural station was found to be classified as urban in the land cover map used by WRF. In order to address this problem, we considered a more representative, adjacent gridpoint to represent the rural station, which is used throughout the paper.

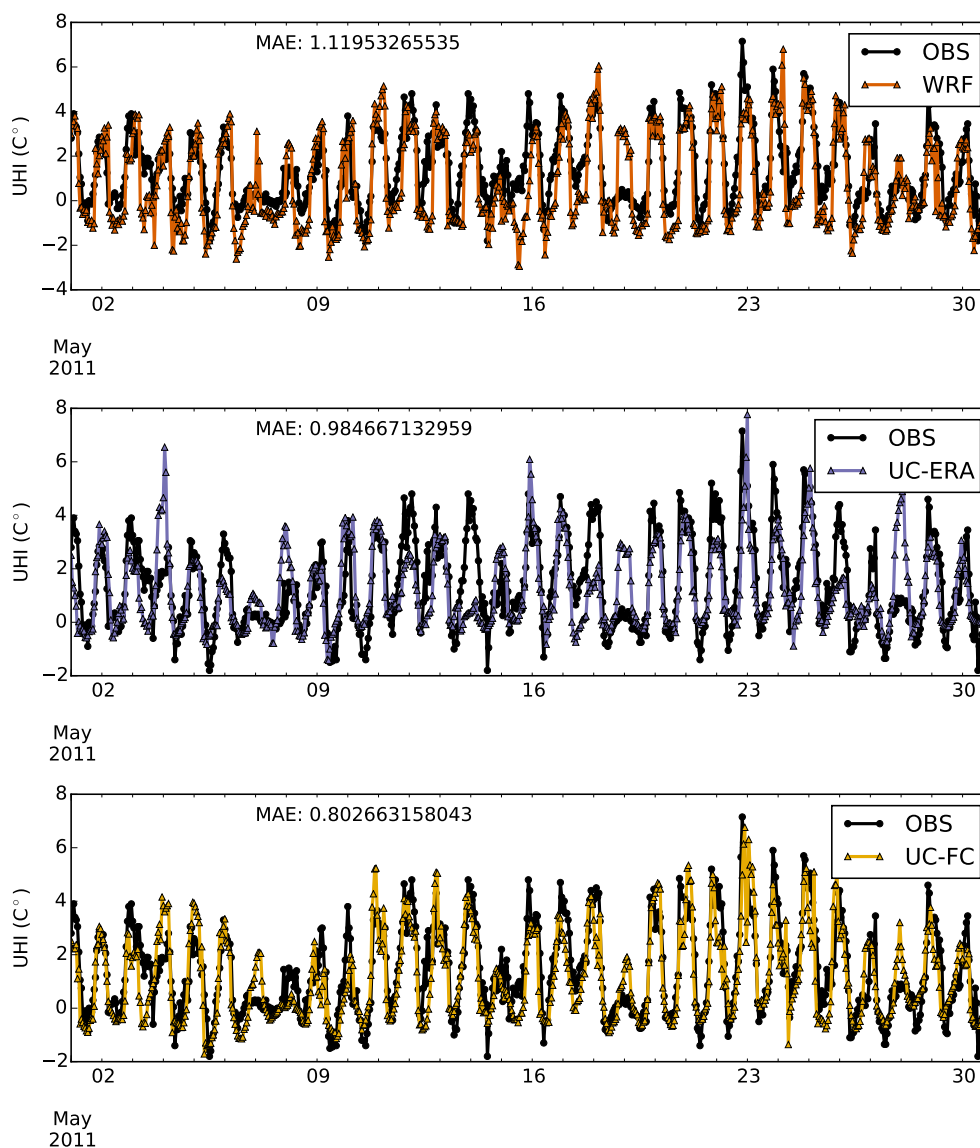
Results show that biases in WRF for the individual stations are large and negative during the morning hours, before 15 UTC, but comparable in magnitude to those in UC-ERA. In addition, although the UHI at noon is correctly reproduced by WRF, it exhibits large bias maxima of -1.5° and -1° at 7 and 17 UTC, respectively.

Figure 3. Same as figure 2, but for wind speed.

Regarding the wind speed (figure 3), the intensity of the sea breeze is clearly underestimated in the run driven by the ERA-Interim reanalysis, with a bias of up to -2.5 m s^{-1} at noon in the rural station. This problem is likely to be related with the coarse resolution of the ERA-Interim driving run, which is not able to resolve the sharp daytime, thermally-driven pressure gradient between the continent and the sea. The lack of sea breeze in turn explains the nearly constant daily cycle of the rural minus urban difference in wind speed in UC-ERA. The wind regime is clearly better reproduced in the other simulations. UC-FC accurately reproduces the daily wind cycle in both the urban and rural stations, while WRF overestimates the wind speed by up to 1 m s^{-1} during daytime hours. Regarding the urban minus rural difference, WRF is the model that better captures the hourly evolution of the wind speed. UC-FC does catch well the overall magnitude of the difference, but without reproducing the secondary minima and maxima of 6 and 8 UTC.

It is interesting to highlight the day-to-day variability of the observed and simulated times series, which are here depicted in figure 4 for the month of May. The whole period is not shown for clarity, but the same conclusions are applicable for the other months. The daily evolution in the UHI is well represented in UC-FC and WRF, while biases of the order of up to $4°C$ at noon are found in UC-ERA for some specific days. However, the largest Mean Absolute Error (MAE) is found for WRF ($1.11°C$), due to the systematic underestimation of the UHI during daytime hours (figure 2). The best MAE score is found in UC-FC ($0.80°C$), which shows regular skill with almost no large errors in specific days.

3.2 Spatial pattern

The evaluation of the spatial variability simulated by the urban climate model is a challenging issue due to the lack of reliable, high-resolution observations. Figure5 shows the average daily minimum temperatures for the UC-FC and WRF, for the 5 months considered. Although both models are able to resolve the main features of the UHI of Barcelona, the surrounding cities and the airport,

Figure 4. Hourly time series of the difference urban minus rural for May 2011.

the UrbClim run at a resolution of 250m provides much more detailed information, e.g. a clear

235 representation of the hill to the southwest of the city centre.

Unfortunately, the scarcity of surface observations did not allow us to evaluate the spatial patterns at the screen level, and therefore we evaluated the spatial variability of the model by analysing the MODIS satellite LST, as described in section 2.2.

During the night, both UrbClim and WRF have been found to overestimate LST over urban areas

240 and, thus, the LST UHI (figure 6). This is surprising, given the small error found in the validation

Figure 5. Daily minimum temperature averaged over the period May-September 2011 in UC-FC (left) and WRF (right).

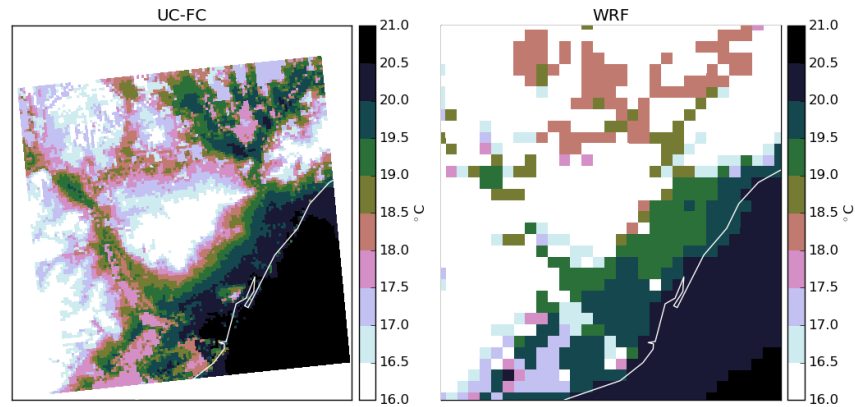
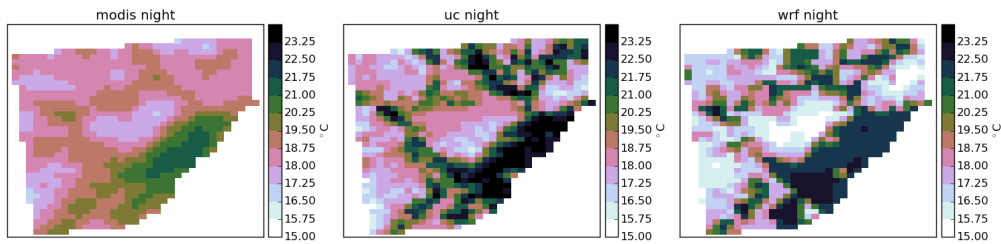



Figure 6. Land surface temperature averaged during nighttime hours over the period May-September 2011 in MODIS (left), UC-FC (center) and WRF (right).

of the screen level UHI. Other studies (Zhou et al., 2015) also found small errors when comparing MODIS and UrbClim LST in and around the city of London.advectionAs mentioned in the introduction, measuring LST over urbanised areas is challenging, due to the uncertainties associated with the measurement of both the radiation and the emissivity. The bias outside the urban areas is found to be small (figure 6), and the spatial patterns are reasonably similar. Determination of emissivity over urban areas is notoriously difficult and subject to a large uncertainty, which could explain at least part of model deviation for LST. The spatial Pearson correlations between the observed and simulated fields are 0.74±0.06 for UC-FC and 0.69±0.07 for WRF, where the confidence bounds were computed with bootstrapping (1000 samples). Thus, UrbClim correlation is higher, but the difference is not statistically significant, as the confidence bounds overlap. It is worth mentioning that the MODIS LST appears to have an effective resolution coarser than 1 km, given that the spatial patterns are smooth and do not resolve many detailed features.

3.3 Computational resources

In this section, the computational resources consumed by UrbClim and WRF are compared. The
comparison is not fully trivial because UrbClim does not currently support running in parallel. This
can be seen as an important drawback. However, UrbClim does not require a long spin-up, and
therefore the simulations can be parallelised just by splitting the time period in subperiods and run
the corresponding simulations simultaneously in different machines or nodes.

For a direct comparison, both models were run in the local cluster of the Institut Català de Ciències
del Clima (IC3), while the main UrbClim runs used in the paper were carried out in the VITO cluster.
The IC3 cluster is made of 48 homogeneous server blades, having each of them two "quad core"
processors, 48GB of memory, 146GB of disk space and fast network interconnect (Infiniband). The
blade model is Sun Blade X6270 (see http://www.oracle.com/us/products/servers-storage/servers/
blades/sun-blade-x6270-m2-ds-080923.pdf for a full description) equipped with Xeon (Nehalem)
X5570 processors. With this settings, a WRF simulation of 36 hours took 2.5 hours to finish (using
an average of 10 simulations), including the preprocess carried out with the WRF preprocessor
(WPS). This preprocess was run in serial, in 1 core, while WRF was run in 16 cores, this is, two
blades. Thus, the total serial equivalent wall-time was 40 hours, assuming perfect scaling (the real
value will be somewhat below). WRF was compiled using the Intel fortran compiler version 14.0.1
with the Intel MPI Library for Linux OS, Version 4.1 Update 3.

Regarding UrbClim, for this test, it has been compiled with the same compiler and run in the same
cluster. A 36-hours simulation with UrbClim took 0.3 hours to finish (average of 10 simulations)
running in one core. Thus, UrbClim running at 250 m resolution is found to be 133 times faster
than WRF at 1 km resolution. This enables downscaling large climate change ensembles for a big
collection of cities.

4 Conclusions

In the present work, we have evaluated the performance of a boundary-layer urban climate model
(UrbClim) for the warm season in the city of Barcelona. We were particularly interested in the study
of the urban heat island (UHI) effect, given that it represents a major source of health problems
in summer for vulnerable people living in urban environments (e.g. heat stress, temperature-related
mortality, pollution, vector-borne diseases). We have analysed the effect of the model resolution
in the driving simulation (UC-ERA and UC-FC), and compared these runs with the output of a
regional climate model (WRF). All these simulation have been evaluated against observations from
meteorological stations and satellite data (MODIS), in order to analyse the temporal and spatial
variability of the UHI effect, respectively.

The main conclusions of our work can be summarised as follows:

- The UHI in the city of Barcelona reaches $2.5°C$ at night.

This is relevant for the study of climate impacts, given that it increases the stress to the vulnerable population and for the health care systems under extreme conditions.

290   – UrbClim correctly reproduces the UHI of Barcelona when it is nested to the coarse dataset of ERA-Interim, with some systematic biases. When it is nested to a higher resolution model (ECMWF IFS), UrbClim additionally reproduces well the temperature evolution of the individual rural and urban stations used for the calculation of the UHI.

      – WRF reproduces the UHI intensity nearly as well as UrbClim, but it provides less detailed
295   spatial information consuming much larger computational resources.

      – The realism of the spatial pattern of LST is similar in UrbClim and WRF, when it is validated against MODIS data, even though significant biases are found in both models.

In conclusion, the choice between UrbClim and WRF for the simulation of the urban environment largely depends on the type of variable and process that is analysed. WRF has the advantage of
300   providing a more detailed and complete description of atmospheric winds and rainfall, which may be required in some applications (e.g. pollutant dispersion). Apart from this, UrbClim has been found to be an optimal tool for the numerical description of the UHI of Barcelona, providing an accurate description of the temperature field that is generally better than that in WRF. However, it must be taken into account that, if nesting UrbClim in a low resolution model, there will be inaccuracies
305   caused by the misrepresentation of the wind, specifically the sea breeze daily cycle. The sea breeze is important for reproducing the climate of Barcelona in summer, where the influence of mesoscale processes is strong. Note that this problem is a particularity of Barcelona, as it has not been found in other European cities where UrbClim nested in ERA-Interim has been successfully tested (De Ridder et al., 2015; Lauwaet et al., 2016; Zhou et al., 2015).
310   From these results, it is reasonable to infer that the skill of UrbClim, and probably of other similar urban climate models, is constrained by the performance of the driving model, and particularly for variables that are important for the UHI, this is, wind speed and cloudiness.

Code and data availability

The Urbclim source code is not publicly available. In order to access it, a specific agreement needs
315   to be signed with VITO. Please contact koen.deridder@vito.be for more details. The WRF model is an open source model, and its code is freely available upon registration in http://www2.mmm. ucar.edu/wrf/users/download/get_source.html. Weather station data from the Catalan and Spanish meteorological agencies is available for research purposes upon request in dades@meteo.cat and https://sede.aemet.gob.es/AEMET/es/GestionPeticiones/home respectively. MODIS data was down-
320   loaded from the "Reverb" NASA tool http://reverb.echo.nasa.gov, where it is freely available upon

registration. The CORINE land cover is available in the EEA website http://www.eea.europa.eu/
publications/COR0-landcover free of charge for both commercial and non-commercial purposes.

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