Highly resolved WRF-BEP/BEM simulations over Barcelona urban area with LCZ

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A B S T R A C T

This study evaluates the performance of urban schemes integrated in the Weather Research and Forecasting model (WRF) using Local Climate Zones (LCZ) as land use classification. We applied two multi-layer urban schemes: 1) Building Effect Parameterization (BEP) and 2) Building Energy Model coupled with BEP (BEP + BEM), over the Metropolitan Area of Barcelona (MAB) at $1km^2$ horizontal resolution for July 2016. These two simulations were compared with observations and a standard WRF simulation (BULK approach). Corine Land Cover 2012 provides background information for the entire simulation domain, while the LCZ covers MAB classifying the land cover into 10 classes according to urban morphology and thermal properties.

BULK and multi-layer urban scheme experiments present a similar general error trend: overestimation of relative humidity and planetary boundary layer height and underestimation of temperature. Although BEP has the best correlation with observations, this is the scheme with the highest value of bias and RMSE for temperature and relative humidity, in particular during the night/morning. On the other hand, BEP + BEM performed with the minimum RMSE associated for temperature and relative humidity in the entire domain. BEP + BEM has shown to be more sensitive than the other schemes over locations where the land use in the model grid differs to the real one, which is a common consequent limitation of horizontal model resolution. This study also suggests that depending on the synoptic condition the scheme accuracy on determining PBLH might change considerably.

1. Introduction

In the last few decades, humanity has seen a substantial shift in the distribution of people. Not only does the global population continue to grow at a significant pace, as this pace is faster in urban areas. Currently, 54% of the world population is living in urban areas and it is expected to increase to 66% by 2050 (WHO, 2016). Furthermore, cities consume about 75% of global primary energy and emit between 50 and 60% of the world's total greenhouse gases. This figure rises to approximately 80% when the indirect emissions generated by urban inhabitants are included (URL1, 2020). As a consequence, urban areas are responsible for a disproportionately large contribution to a wide range of environmental problems, from global (climate change) to local (air pollution and thermal stress). This has resulted in the importance of urban planning to mitigate the impact of cities on its inhabitants from

social, environmental and health perspectives (de la Paz et al., 2016; Li et al., 2018; Rafael et al., 2017; Salamanca et al., 2012).

The urban atmosphere is strongly modified by anthropogenic activities (industry, traffic, domestic heating/cooling, etc.), as well as by surface materials that retain more energy than in rural areas. Meteorological features at different scales also play an important role in determining the general air circulation in the city (mesoscale phenomena) while local meteorological features take place near the surface where the general air circulation might be influenced by urban morphology (Middel et al., 2014; Santiago and Martilli, 2010; Xu et al., 2017). Atmospheric models have been used to better understand the dynamics of the urban atmosphere and to test the best urban planning strategies in order to improve thermal human comfort, wind flow at the street level and the influence on atmospheric pollutants dispersion, as the UrbanSIS project (Gidhagen et al., 2020) and others have shown.

Usually, these strategies include studying the effect of building height, street directions, implementation of trees in the streets, parks or green roof tops and strategies for the abatement of anthropogenic air pollutant concentrations (Amorim et al., 2013; Morini et al., 2017; Rafael et al., 2018; Vos et al., 2013).

The urban schemes developed and integrated in the Weather Research and Forecasting model (WRF, Skamarock et al., 2008) are: Single Layer Urban Canopy Model (SLUCM - Kusaka et al., 2001), Building Effect Parameterization (BEP, Martilli et al., 2002) and BEP coupled to the Building Energy Model (BEP + BEM, Salamanca and Martilli, 2010). They have been proved to be appropriate tools for studying the urban heat island in different European cities such as: Madrid (de la Paz et al., 2016; Salamanca et al., 2012), Vienna (Hammerberg et al., 2018), Berlin (Kuik et al., 2016), Athens (Giannaros et al., 2018), Rome (Morini et al., 2017) and Budapest (Göndöcs et al., 2017).

Additional input data related to the urban morphology and surface thermal characteristics are needed so that the effects of buildings are simulated as well as the urban heat fluxes. Thus, Local Climate Zones (LCZ, Stewart and Oke, 2012) database developed by Gilabert et al. (2018) for the MAB region is used to characterize urban areas into 10 classes. Non-urban land covers are then characterized by Corine Land Cover 2012 (CLC12), used as background information. The most important difference between CLC12 and LCZ is that the first considers only the land cover and human activity, while the last results from a combination of those with urban morphology and building thermal properties, making it an important base for urban climate studies.

The goal of this study is to evaluate the performance of WRF and its multi-layer urban schemes (BEP and BEP + BEM) having the Metropolitan Area of Barcelona as case study. One of the novelties of this study resides in the use of the LCZ map to define urban land covers. This approach, fostered by the WUDAPT project, is becoming more and more popular and it has already been used for Madrid (Brousse et al., 2016), Vienna (Hammerberg et al., 2018) and Bologna (Zonato, 2016) in Europe. However, this study is the first that uses this approach for a coastal Mediterranean city, increasing the body of knowledge about the importance and applicability of this methodology for different city typologies.

A detailed description of the modelling set up, simulation domains and input data used to perform this study are described in section 2, followed by the analysis and discussion of results (section 3) and lastly the conclusions (section 4).

2. Data and methods

2.1. Modelling system

The Weather Research Forecasting (WRFV3.9.1) model (Skamarock et al., 2008) is a numerical weather prediction and atmospheric simulation system designed for both research and operational applications. Its dynamics solver integrates compressible and non-hydrostatic Euler equations with several physical and dynamic options designed to phenomena at regional scale. However, motivated by the increasing interest on simulating the urban atmosphere and also due to its complex dynamics, developments have been integrated into the main WRF parameterizations (Salamanca et al., 2018). The bulk scheme (hereafter denoted as BULK), included in the Noah Surface Model is one example of this (de la Paz et al., 2016; Liu et al., 2006), through the modification of some parameters to better represent urban areas in what wind-speed and heat storage capacity concerns. More recently, urban canopy schemes were developed and included into WRF, as physics options. These more advanced urban schemes were specifically designed to represent city morphology (e.g. building and street canyon geometry) and surface characteristics (e.g. albedo, heat capacity, emissivity, urban/ vegetation fraction). The currently available urban canopy schemes are:

- Single Layer Urban Canopy Model (SLUCM - Kusaka et al., 2001);
- Building Effect Parameterization (BEP, Martilli et al., 2002): a multi-layer layer scheme;
- BEP coupled to the Building Energy Model (BEP + BEM, Martilli et al., 2002; Salamanca and Martilli, 2010): second generation of BEP that considers energy consumption in buildings (heating/ cooling) for a more accurate effect on urban heat budget.

SLUCM and BEP compute the thermal and momentum interactions between the atmosphere and the city in a single- and multi-layer model grid, respectively. SLUCM has a simple 2D geometry, symmetrical street canyons with infinite length, canyon orientation and diurnal variation of solar azimuth angle. Thus, the radiation treatment is three-dimensional (3D) (Kusaka et al., 2001). On the other hand, BEP parameterizes a 3D urban morphology in a multi-layer model grid, and it is capable to estimate the heat fluxes from roofs, ground and walls, individually (Martilli et al., 2002). This way, BEP scheme computes the impact of buildings on the airflow and turbulence (term included in the conservation equation for the Turbulent Kinetic Energy – TKE), as well as the source/sinks of heat by solving the energy budget for each surface (de la Paz et al., 2016; Martilli et al., 2002). Unlike BEP that keeps the indoor temperature constant, BEP + BEM calculates the anthropogenic heat generated by air conditioning systems, as well as the heat exchanges between the interior of building and outer atmosphere (Brousse et al., 2016; Göndöcs et al., 2017; Salamanca and Martilli, 2010). In this study, BULK, BEP and BEP + BEM options are tested to conclude about the performance of such schemes in Barcelona urban region.

As indicated in Table 1, the vertical turbulent transport is parametrized using the Bougeault and Lacarrere (1989) turbulent scheme. This scheme has a prognostic equation for the TKE and includes a nonlocal term during convective conditions. It has been chosen because it is among the best for the coastal area (Banks et al., 2016), and it is the PBL scheme that has been tested most extensively coupled with BEP and BEP-BEM.

2.2. Experiment set up

This study focuses on the Metropolitan Area of Barcelona (MAB) and its surrounding, located at 41°26′24″N, 2°6′18″E. To simulate the target region, two two-way nested domains were defined. The parent domain (CAT), covering the whole Catalonia region (WE: 278 km, NS: 270 km), has a horizontal resolution of 3 km × 3 km. CAT domain is followed by a finer domain comprehending the Metropolitan Area of Barcelona (MAB) at 1 km × 1 km horizontal resolution (WE: 78 km; NS: 78 km) (Fig. 1). The domain geometry is based on previous studies conducted by the meteorological services of Catalonia over the MAB (MeteoCat, personal communication in March 2018). Vertically, both domains are described by 45 layers (model top pressure: 100 hPa), being the urban canopy described by four layers about 10 m thick each. Finally, 0.25° global tropospheric analysis on a 6 h-basis (NCEP/NOAA, 2015) provide initial and boundary meteorological conditions to the mother domain.

Table 1
Parameterizations used for each experiment.

|	BULK	BEP	BEP + BEM
Urban scheme	Included in the Noah Land Surface Model	BEP	BEP + BEM
Land surface model	Noah Land Surface Model (Liu et al., 2006)		
PBL scheme	Bougeault-Lacarrère PBL (BouLac), designed to use with urban schemes (Bougeault and Lacarrere, 1989)		
Microphysics	WRF Single Moment 6-class scheme		
Long- and short-wave radiation	Rapid Radiative Transfer Model for General circulation models (RRTMG) scheme		
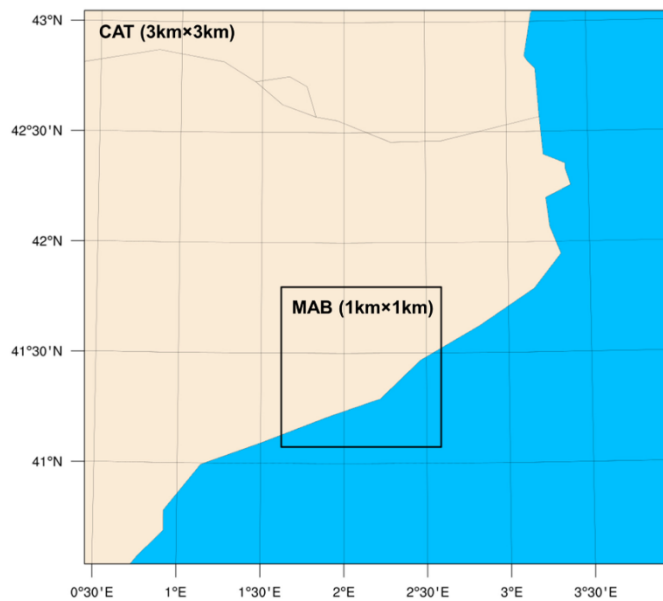
Fig. 1. Simulation domains: Catalonia domain (CAT) and the Metropolitan Area of Barcelona (MAB) with 3 km × 3 km and 1 km × 1 km horizontal resolution, respectively.

Three experiments are performed to figure out what is the best urban scheme to simulate meteorological fields in MAB during typical summer conditions. For this reason the whole month of July 2016 was simulated. The spin up period comprehends five days (1–5 July 2016). Table 1 presents the main model parameterizations used within this work for both domains.

2.2.1. Case study and land use

In both domains, the background land use is represented by Corine Land Cover 2012 (CLC12) while urban areas in MAB are represented by the Local Climate Zone (LCZ) (Brousse et al., 2016) (Fig. 2).

CLC12, originally at 100 m resolution, consists of 44 land use classes. In order to be incorporated into the WRF model, CLC12 classes have been remapped to the 20 MODIS land use classes following Pineda et al. (2004), to allow the compatibility with the Noah LSM. Furthermore, CLC12 have been interpolated at each model domain resolution, choosing the most present value for each cell.

The LCZ is a product of the level 0 methodology proposed by the World Urban Database Access Portal Tool (WUDAPT) consisting on classifying urban and rural lands with similar climatic characteristics, form and function (Brousse et al., 2016; Stewart and Oke, 2012; Zonato et al., 2020). In total, the LCZ comprises 17 land use classes, of which 10 are dedicated to urban areas. The WRFV3.9.1 used in this study includes appropriate adaptations to the code (Brousse et al., 2016) based on the instructions by Martilli et al. (2016). in this way, the 10 urban classes (from LCZ) plus the "Bare rock or paved" (considered as asphalt, class E in Stewart and Oke, 2012) are taken by the model with specific thermal and geometric parameters. Thus, BEP and BEP + BEM consider 11 urban classes (Figure 2, LCZ: 1–10 and E) instead of the traditional three assumed within WRF (1. Low density residential, 2. High density residential and 3. Commercial).

The LCZ map of Barcelona is created using the WUDAPT method at Level 0 (see www.wudapt.org), with a resolution of 100 m. It consists of a supervised classification of Landsat images using a Random Forest Classification algorithm (Breiman, 2001).The method requires first to draw polygons of uniform land cover in Google Earth (training areas, TA). Then the algorithm combines spectral bands with the TA defined before to obtain the LCZ classification to be used as input for WRF. In this case, Landsat images from different days (18/03/2013, 16/07/2013 and 10/06/2014) are used. TA are then modified to obtain a satisfactory definition of LCZ comparing with the real morphology of the city.

Once the LCZ classification is produced, it is incorporated within the WRF model choosing the most present value for each cell in the innermost domain. In order to implement the modified urban land mask in WRF, original 33 land use classes have been extended to 41 to allow the code to read the LCZ classification.

MAB is the second largest Spanish metropolitan area and it is the sixth in Europe. Within the boundaries of Barcelona city, the most prominent LCZ class is Compact midrise, covering 31.7% of the city and hosting 75.8% of its dwellers (Table 2). Thus, this is the most densely populated area in the city (18,678 people·km^2).

The Barcelona city centre, mainly classified as Compact midrise (LCZ 2), is known by its two distinct urban geometries: 1) L'Eixample district characterized by regular blocks crossed by wide and straight avenues (75% is LCZ 2). In spite of its regular geometry, 20% of L'Eixample is classified as LCZ 1. Other land use classes represent ~5% of the area of this district and 2) three neighborhoods of the old city (Gràcia, Raval and Gótico) have with narrow streets and an unregularly pattern. Here, ~4% is LCZ 1, ~50% is LCZ 2, ~10% is LCZ 3 and ~ 20% is non-urban. The second largest LCZ is Dense trees (14.6% of Barcelona area), mainly occupied by the Collserola Park (~512 m above sea level) which is the most important green area of the city. The urbanized suburbs, where 17.2% of the MAB population lives, are mainly classified as Compact midrise.

Each urban LCZ is characterized by typical geometrical parameters and thermal properties of building materials. The parameters used in this study are shown in the supporting material. Geometrical parameters are set to typical values for each LCZ, as suggested in Stewart and Oke (2012) to evaluate the capability of LCZ classification to be adopted for most of the cities in the world. On the other hand, building thermal properties are the same for LCZ 2,3,5 and 9, whose walls are supposed to be built with solid brick, while roofs with tiles of the same materials. LCZ 8, that describes industrial areas, is supposed to be built with concrete, and its thermal properties are assumed both for walls and roofs. Finally, LCZ 1 and 4 are composed of modern buildings, so their respective thermal properties are used. For all classes, the physical properties of asphalt have been set for the ground. Concerning the parameters for the rooms in buildings, air conditioning systems are supposed to be turned on all day, with a target temperature of 25 °C, for all LCZ, with a comfort range of 0.5 °C. Moreover, equipment inside each room produce a peak heat of 20 W/m^2 for all LCZ, apart for LCZ 1, 4 and 8, that are supposed to produce a peak heat of 36 W/m^2, due to higher density of people in LCZ 1 and 4 and higher density of equipment for industrial purposes in LCZ 8.

2.3. Observations

The observed data used to evaluate the WRF output are provided by the Meteorological Service of Catalunya (MeteoCat). As the LCZ information is not available for the whole simulation domain, only those stations placed within the area with LCZ information were selected (Fig. 3) for the evaluation performance of WRF modelling system. Table 3 compiles information on meteorological stations, namely coordinates, variables measured, sensor height above the ground as well as the land use class in the LCZ database at 100 m × 100 m horizontal resolution and in the model cell (1000 m × 1000 m) corresponding to each station. Due to the re-gridding from LCZ database to model grid, some information is diluted which leads to a potential mismatch of the land use class. An example of this is the group of sites classified as "Low plants". Their majority are placed on lawns and surrounded by building at a distance larger enough to not be present in the 100 m × 100 m cell of the original land use database but at less than 1000 m distance. Another example is the Zoo station, located in a city-park (the Parc de la Ciutadella) that is classified as "Low plants" in the 100mx100m LCZ database. This park is surrounded by "Compact midrise" areas. After the
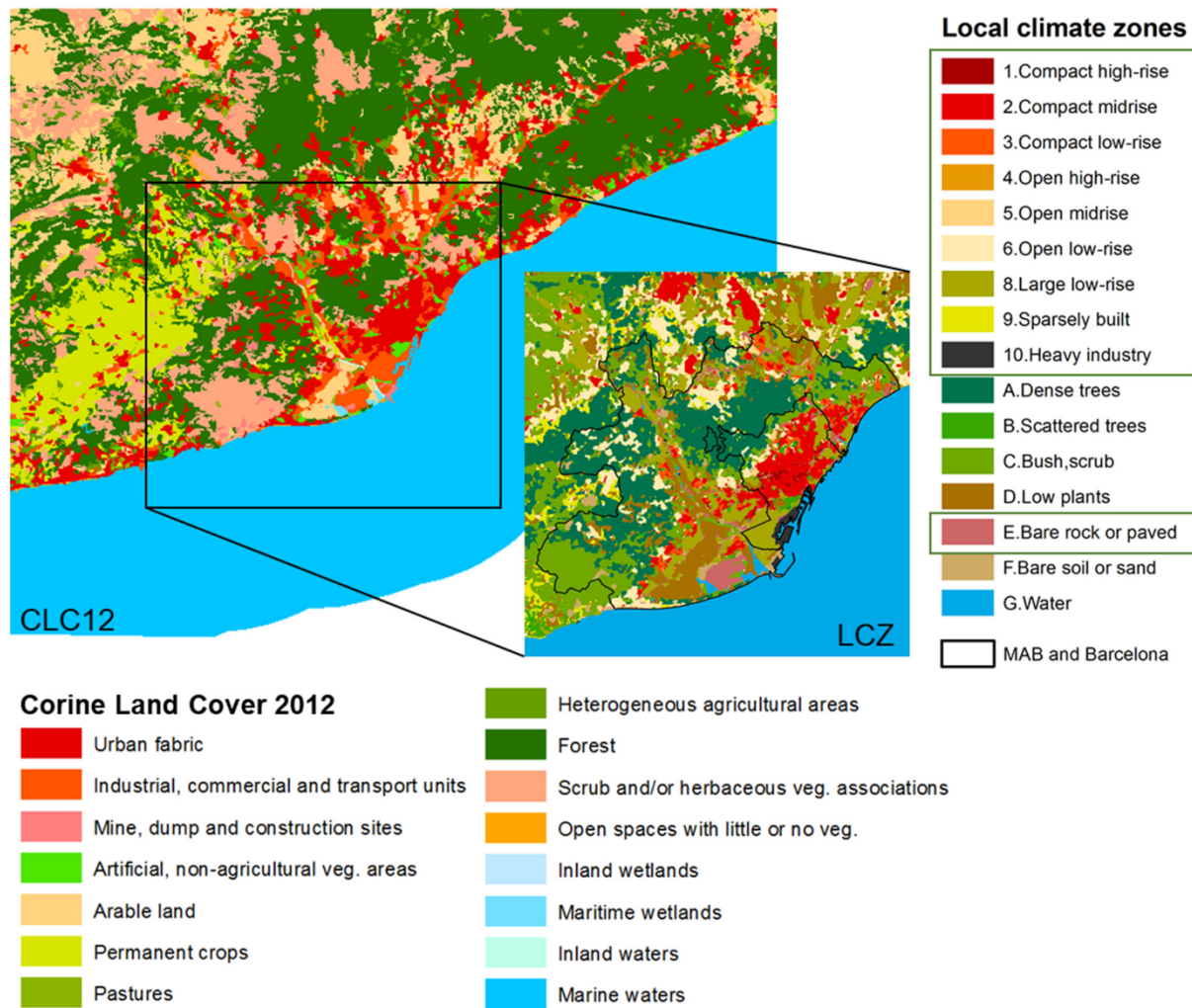
Fig. 2. Land use in MAB domain: Corine Land Cover 2012 (CLC12, left panel) and Local Climate Zones (LCZ, right panel). Urban classes are inside the right rectangles (LCZ: 1–10 and E). MAB and Barcelona limits are marked as solid black lines in LCZ map. CLC12 is aggregated into its level 2 of classes (x.x – i.e. Urban fabric is 1.1 in CLC12 and it includes all subclasses 1.1.x).

Table 2
Area and population of MAB and Barcelona city.

LCZ class	MAB			BCN		
	Area (km^2)	Area (%)	Population (%)	Area (km^2)	Area (%)	Population (%)
1.Compact high-rise	4.82	0.76	4.77	4.08	4.03	8.02
2.Compact midrise	57.94	9.09	64.14	32.17	31.74	75.80
3.Compact low-rise	18.84	2.96	9.57	2.50	2.47	3.52
4.Open high-rise	0.13	0.02	0.03	0.11	0.11	0.05
5.Open midrise	3.93	0.62	1.60	1.72	1.70	1.46
6.Open low-rise	42.82	6.72	5.34	4.03	3.98	1.42
8.Large low-rise	72.97	11.45	6.10	17.35	17.12	4.14
9.Sparsely built	3.28	0.51	0.17	0.19	0.19	0.02
10.Heavy industry	6.22	0.98	0.08	5.56	5.48	0.16
E.Bare rock or paved	25.46	3.99	2.82	3.77	3.72	2.59
No urban	401.04	62.91	5.39	29.86	29.47	2.83
Total	637.45			101.35		

re-gridding, the park area is split into four model cells what makes "Compact midrise" class taking over park-related classes. As a consequence, the Zoo site is classified as "Compact midrise" instead of "Low Plants".

The radiosonding measurements launched by MeteoCat and placed in the Physics Faculty of University of Barcelona (blue dot in Fig. 3) are used to determine boundary layer height (PBLH) for further comparison with modelled data. The use of radiosounding data for this purpose is an accepted reference approach in the scientific community (Seibert et al., 2000). According to Stull (2000) and Seibert et al. (2000), the top of the boundary layer is defined as the minimum high where the virtual potential temperature (θ_v) equals the surface value. The same approach is used to determine PBLH by the BouLac parameterization within the WRF model. Thus, vertical measurements of temperature (°C), barometric pressure (hPa), relative humidity (%), and dew point temperature (°C) were taken into consideration to calculate θ_v for different altitudes under non-cloudy conditions, so that PBLH is inferred.

3. Results

3.1. Statistical analysis

The statistical analysis of the simulation performances is presented in Fig. 4, through the correlation factor (R), the systematic error (bias) and the root mean square error (RMSE). Here, the observation towers are aggregated in accordance to the land use classes assumed by WRF (see Table 3). All the experiments present the same error trend: overestimation of relative humidity (bias > 0) and underestimation of temperature (bias < 0). In average, the highest correlations with observations for relative humidity and temperature, respectively, are
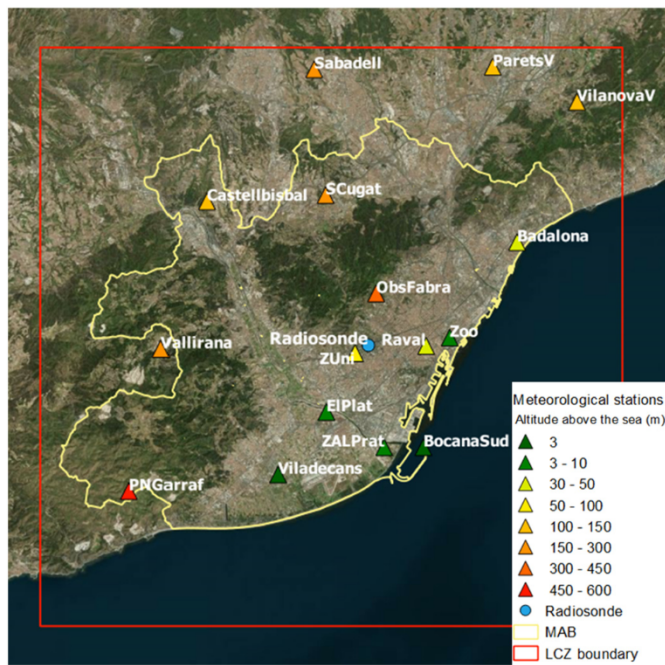
Fig. 3. Detail of the MAB domain: location and altitude above the sea (m) of the meteorological stations used for the evaluation performance of WRF modelling system; MAB and LCZ boundaries.

given by BEP (0.71, 0.92), followed by BEP + BEM (0.68, 0.91) and BULK (0.66, 0.89) (Fig. 4). Nevertheless, BEP is the scheme with the highest RMSE and bias, mainly during the night (from 19 h to 06 h UTC, Fig. 5). BEP predicts, thus, colder and moister atmosphere during night time than BULK and BEP + BEM in the entire domain.

Comparing BEP + BEM and BULK, the first presents, in general: 1) similar, yet slightly higher correlation for relative humidity and temperature, 2) lower RMSE for temperature and 3) similar RMSE for relative humidity (Fig. 4). The daily profiles of the systematic error, depicted in Fig. 5, reveal that the main differences between these two schemes, still on temperature and relative humidity, occur during sunlight period, when sea breeze takes place. During this time period BEP + BEM bias is closer to 0 than BULK. Out of that time range, both schemes present similar bias trends and magnitudes in all the stations analysed. As BULK accounts with less anthropogenic heat fluxes, the Mediterranean air mass that crosses the city is exposed to lower

anthropogenic heat fluxes. Thus, it reaches Sabadell station and the entire Valley region with slightly higher relative humidity and lower temperature than the other urban schemes (see also Fig. 7).

The Zoo station is presented here (Fig. 6) as an example of how an unreal input information can affect the analysis of results when comparing with observations. Due to the mismatch of the land use class (see section 2.3), the Zoo station, presents a different behaviour in comparison to other stations under "Compact midrise", namely Raval (Fig. 4). Here, the absence of vegetation in this model cell leads towards underestimation of relative humidity and overestimation of temperature, especially by the BEP and BEP + BEM schemes. The flawed behaviour of this station exacerbates the statistical analysis of "Compact midrise".

In what wind speed concerns, the statistical analysis (Fig. 4) suggests that the correlation between model results and observations is higher for BEP ($R = 0.74$) and BEP + BEM ($R = 0.73$) than for BULK ($R = 0.62$). On the other hand, BEP + BEM presents the highest RMSE and bias values for all land use classes analysed excepting to Compact midrise (C. mid) and Open midrise (O. mid), to which bias values are close to 0 m/s and RMSE is reduced to 48% (C. mid) and 26% (O. mid) in comparison to BULK. On the remaining locations, BEP is the scheme with lower RMSE for wind speed. All schemes underestimate wind speed in C. mid, O. mid and CLC12 (no urban classes) while they overestimate in the other locations.

Unlike for temperature and relative humidity, it is during the sunlight period (from 10 h to 18 h) that wind speed in BEP + BEM presents a different magnitude of the bias in comparison to the other schemes. At the Raval station, located on building rooftop, in a compact midrise urban structure, about 2 km away from the sea, BEP + BEM keeps wind speed bias closer to 0 during all day while BEP and BULK overestimate wind speed up to 2 m/s in sunlight period. An opposite effect is observed in ZUni, classified in the model grid as cropland in spite of its location is an urbanized area within the city of Barcelona. In ZUni, BEP + BEM underestimates wind speed mainly during sunlight while the other two schemes present a bias curve closer to 0 yet on the positive side. Sabadell station is located in a model grid cell classified as Open low-rise. Nevertheless it is originally classified as Low plants, located next to the Sabadell urban fabric. Here, BEP + BEM predicts weaker winds than the other schemes during the whole period, especially from 11 h to 19 h. This might be related to the influence of the sea breeze together to the air warming up by the city, more intense within the BEP + BEM scheme due to its accounting of anthropogenic heat fluxes released by building cooling. Inconsistencies between land use classification in the model grid and the real one (Table 3) might also

Table 3
Meteorological stations: measured parameters (Temperature (T), relative humidity (RH), and wind speed and direction (W)), altitude above the ground (m), land use class from LCZ database (at 100 m × 100 m) and in the model grid (at 1000 m × 1000 m) and coordinates.

| Station acronym	Measurement	Altitude above the ground (m)	Land use (*non-urban class)		Latitude	Longitude
			LCZ	Model		
Badalona	T, RH	50	Compact midrise	Compact midrise	41.452	2.248
Raval	T, RH, W	40	Compact midrise	Compact midrise	41.384	2.168
Zoo	T, RH	2	Low plants*	Compact midrise	41.389	2.188
Vallirana	T, RH, W	10	Open low-rise	Open low-rise	41.382	1.936
Castellbisbal	T, RH, W	10	Bush, scrub*	Open low-rise	41.479	1.975
Sabadell	T, RH, W	10	Low plants*	Open low-rise	41.566	2.070
ParetsV	T, RH, W	40	Open midrise	Open midrise	41.567	2.226
ElPlat	T, RH, W	10	Low plants*	Large low-rise	41.340	2.080
SCugat	T, RH, W	10	Low plants*	Large low-rise	41.483	2.080
ZALPrat	T, RH, W	10	Low plants*	Large low-rise	41.317	2.131
VilanovaV	T, RH	10	Bush, scrub*	Sparsely built	41.544	2.300
Zuni	T, RH, W	10	Low plants*	Crop./natural veg. Mosaic*	41.379	2.105
Viladecans	T, RH	2	Bush, scrub*	Croplands*	41.299	2.038
ObsFabra	T, RH, W	10	Dense trees*	Evergreen*Needleleaf Forest*	41.418	2.124
PNGarraf	T, RH	2	Bush, scrub*	Open Shrublands*	41.288	1.908
BocanaSud	W	10	Water*	Water *	41.317	2.165
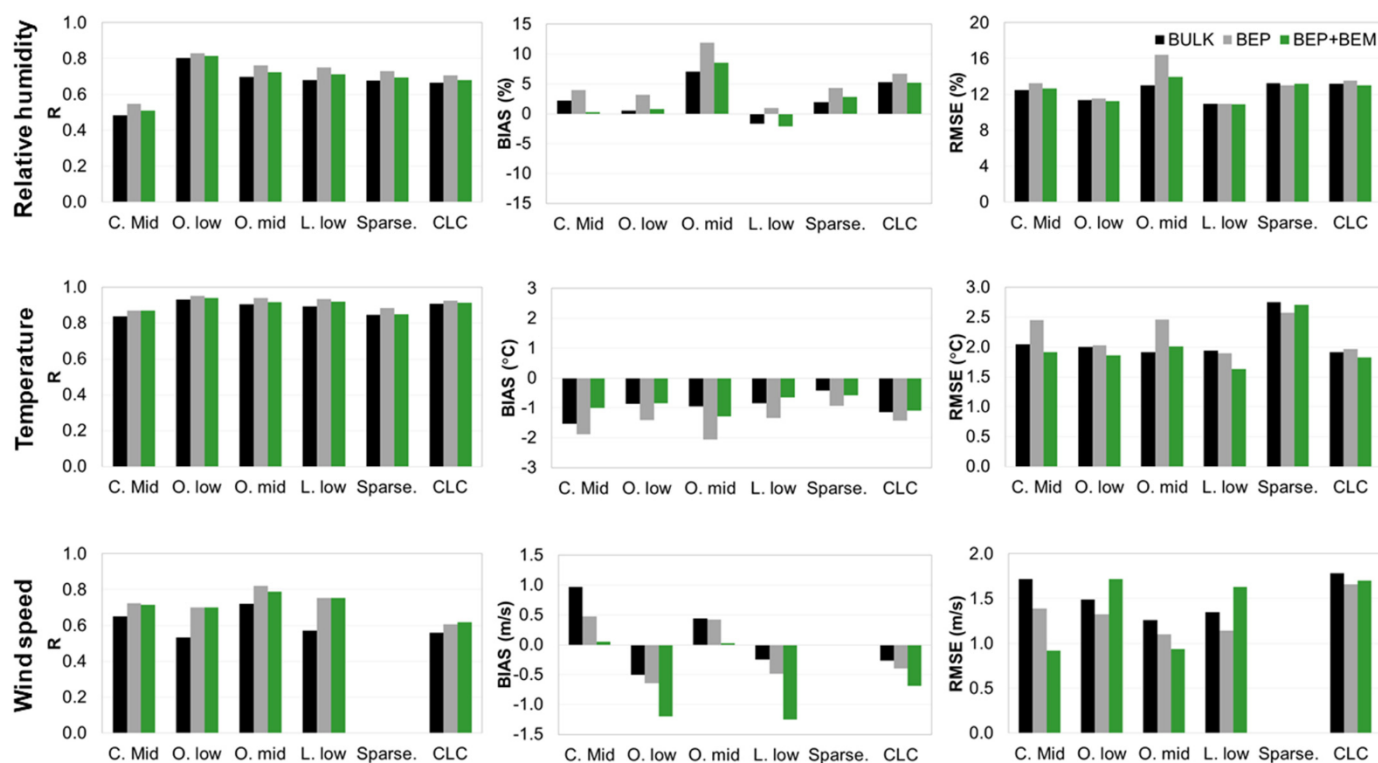
Fig. 4. Statistical analysis (R, bias and RMSE – columns) of BULK (black), BEP (grey) and BEP + BEP (green) performance concerning relative humidity, temperature and wind speed (rows).
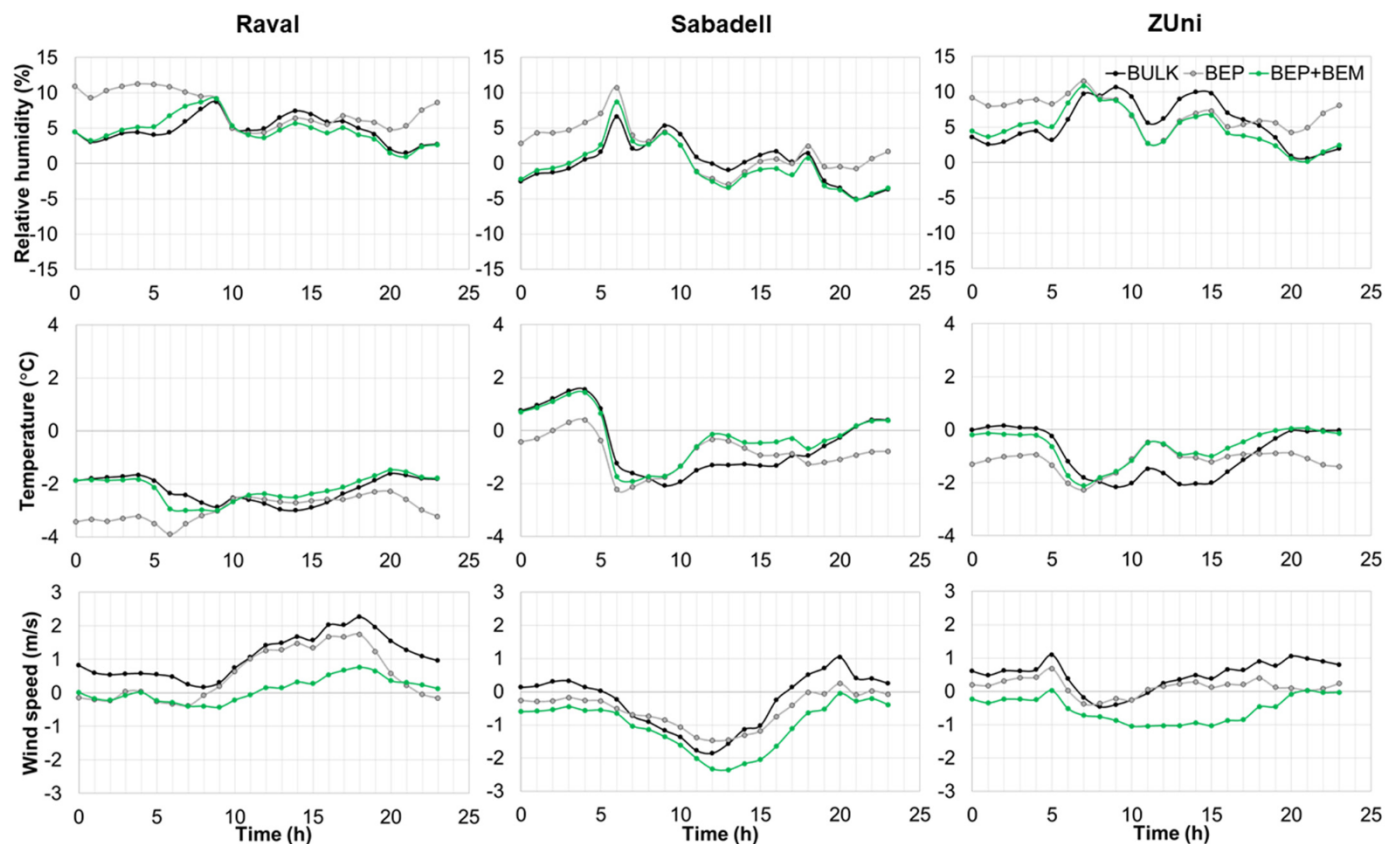

Fig. 5. Daily profile of the bias between observations and BULK (black), BEP (grey) and BEP + BEP (green) for relative humidity, temperature and wind U and V coordinates at Raval, Sabadell and ZUni.
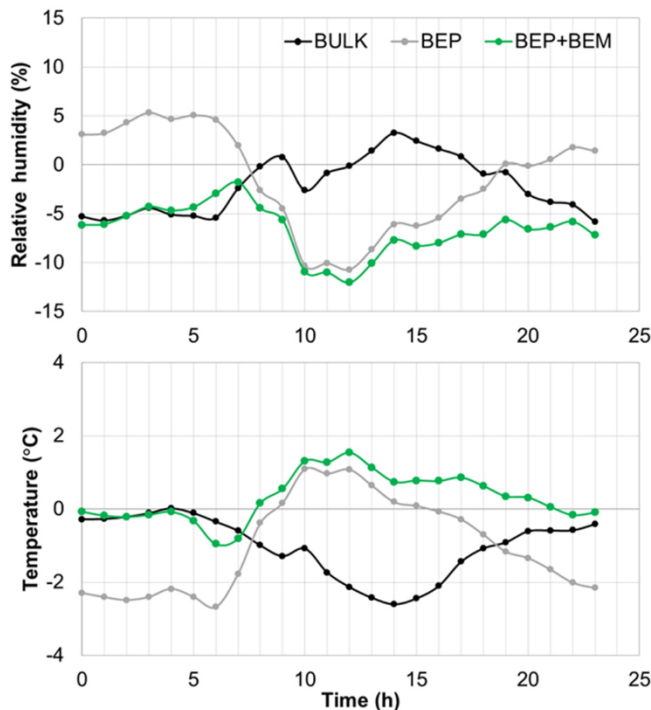
Fig. 6. Daily profile of the bias between observations and BULK (black), BEP (grey) and BEP + BEM (green) for relative humidity and temperature at Zoo.

justify such differences. In fact, BEP + BEM simulates the wind speed more accurately in Raval, ParetsV and Vallirana (not shown in this paper) than in other locations where, due to the conversion from 100 m to 1000 m, a different land class than the real one is assumed by the model. On the other hand, "Large low-rise" (L. low) group of stations presents, in general, low error values associated despite the mismatch of land use class due to the re-gridding process. This happen because "Large low-rise" are areas generally characterized by low vegetation, with sparse trees and sparsely build, which is not very different to "Low plants". The impact of mismatch is most notorious when the station gets a non-representative classification of the reality as in Zoo, classified as compact midrise.

3.2. Special and in situ analysis

3.2.1. Temperature and wind speed

Fig. 7 presents the averaged wind at 10 m (wind speed and direction) and surface temperature at 2 m (T2m) fields over July 2016 at 05 h, 12 h and 19 h UTC, obtained by BULK, BEP and BEP + BEM experiments.

During the day, BULK predicts wind and surface temperature patterns in a more homogeneous way across the domain than the other schemes here used, to which the compact urbanized areas are hot spots with higher T2m (Fig. 7). This is mainly because BULK does not allow the discretization of urban areas in different land use and physical property classes, while BEP and BEP + BEM consider 11 classes with specific physical characteristics (e.g. heat capacity, thermal conductivity, albedo, among many others). Moreover, BEP and BEP + BEM consider building structures and street canyons as well aiming a more realistic simulation of air flows and heat fluxes within the urban area, which are more intense during the day.

According to the results, the Valley region, north of Barcelona (comprehending Sabadell and Sant Cugat del Vallés cities) presents higher temperatures than in Barcelona due to the direct influence of the sea that cools down the air temperature in Barcelona (Figs. 7, 12 h UTC). The Mediterranean air mass transported towards the Valley is

warmed up while passing over Barcelona. This is evident in the three schemes, although in BEP and BEP + BEM the wind at 10 m slows down in the city due to urban drag effect. It is interesting to see that, in spite of BEP and BEP + BEM are schemes physically closer to each other, BEP + BEM presents similar T2m patterns to BULK than to BEP in the morning and evening. As expected, both urban canopy schemes provide a more evident urban heat island feature during day than BULK does. However, BEP simulation results suggest that heat is lost more quickly as the solar intensity decreases. In fact, T2m by BEP are the lowest in the morning and evening in comparison to the other two schemes under study, but higher than BULK at noon. The same behaviour is also visible in PBLH (Fig. 8) and sensible heat fluxes (Fig. 9) (discussed below) that may support the underestimation of temperature and overestimation of relative humidity in the morning and evening (Fig. 5).

3.2.2. PBLH and sensible heat flux

The three experiments present significant differences on PBLH as shown in Fig. 8. In general, BULK predicts lower PBLH than the other urban schemes throughout the study area by mid-day, while at night it is typically higher than BEP and lower than BEP + BEM (Fig. 8 and Fig. 9). During the sunlight period (08 h–17 h UTC), both urban canopy schemes predicted similar behaviour on PBLH development. On the other hand, at night, the PBLH by BEP decay significantly in comparison to BEP + BEM. This might be caused by less heat released by the urban surfaces to the atmosphere during evening/night, predicted by BEP that, unlike BEP + BEM, does not take into account the extra energy for indoor cooling.

Locations not classified as urban, such as Viladecans, PNGarraf, ObsFabra, ZUni and BocadaSud (only ZUni is shown in Fig. 8), are not treated through urban schemes. All these stations, excepting ZUni, present very similar PBLH daily profiles for all the three experiments and lower PBLH heights that those found in urban areas. Unlike the other stations that are surrounded by forest or agricultural areas, ZUni is itself within the urbanized area of Barcelona. It may suggest that, in Zuni, most of the parameters analysed are affected by the city fluxes, occurring in the surroundings, via advection. In this case, the PBLH predicted by BEP and BEP + BEM is somewhat higher than the BULK one.

The sensible heat flux is negative in the night for BEP in Raval and Sabadell and for all schemes in Zuni, indicating the occurrence of radiative cooling which is potentiated by high levels of humanity. In fact relative humidity is typically overestimated by BEP at night (Fig. 5).

The time series of modelled PBLH and the one observed from radiosonde measurements at 12 UTC in Barcelona (Physics Faculty) is presented in Fig. 10. From this plot, it is notable that BULK prediction is the closest one to the observed values. This might be due to too high heat fluxes predicted by the urban scheme, however, having more measurements to estimate PBLH on other periods of the day, namely by the sunrise and sunset would be crucial to better analyse the real/model PBLH development. Nevertheless, BULK also overestimates PBLH in about half of the days. This made us to suspect that the performance of the three schemes under study might be influenced by different synoptic conditions, as the vertical profiles of T, θ and θᵥ (Fig. 11) suggest.

The analysis performed highlights that WRF model, namely BULK scheme, provide a good prediction of PBLH under high pressure system condition, as observed on July 30 (Fig. 10 and Fig. 11a) as well as in the day before and the following day. The synoptic condition on these days is considered most common in the Iberian (IP) during summertime (Valverde et al., 2015), characterized by the presence of a high pressure system over Azores islands and a low pressure system over Scandinavia. This situation is well captured by BULK. However, BEP and BEP + BEM overestimate the PBLH, which might be related to a higher surface sensible heat flux then BULK.

From 10 to 12 July (10 July is depicted as an example in Fig. 11b), the three schemes significantly overestimate PBLH (bias > 0). During
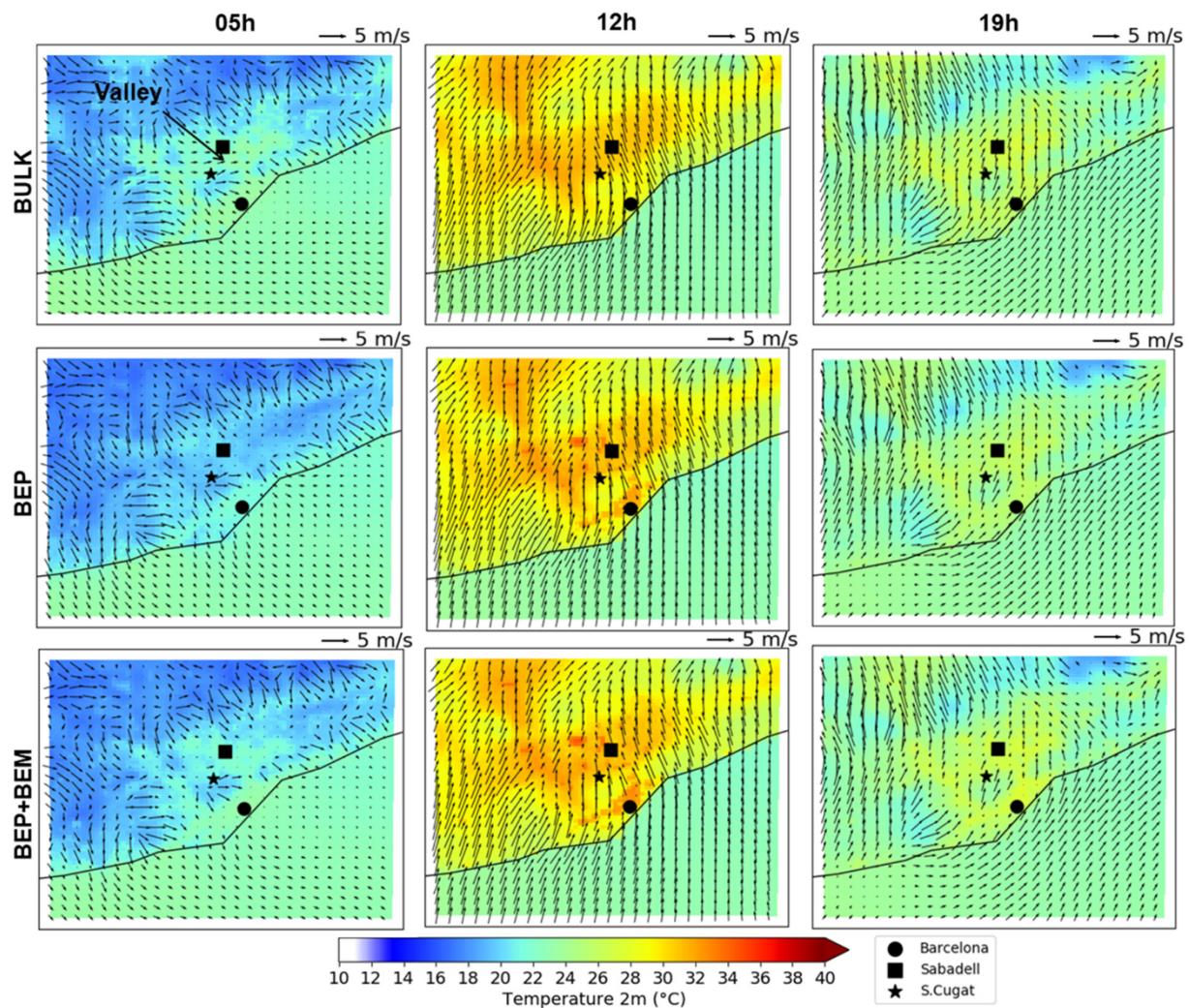
Fig. 7. Averaged wind fields (10 m) and T2m at 05 h, 12 h and 19 h (UTC) regarding the month of July 2016: BULK (top panel), BEP (central panel) and BEP + BEM (bottom panel). The black marks place Barcelona city (circle), Sabadell (square) and S. Cugat del Vallès (star).

these days, the high pressure system is over the Azores islands and, at 500 hPa, there is a well-defined anticyclone ridge over the Iberian Peninsula (IP), which makes the atmosphere highly stable above the boundary layer. Moreover, the solar radiation in the IP boosts the formation of a low thermal system (Millán et al., 1991). However, this low pressure is not strong enough to face the high pressure system above (Fig. 11b).

A low pressure system placed over the Atlantic, in between Great Britain and Greenland, invades southwards to IP latitudes provoking North Atlantic advection to Western of IP, bringing saturated air (from 18th to 20th). On 21st, the low pressure system dissipates and the moisture air warms up leading to atmospheric unstable conditions (Fig. 11c). In fact, according to the meteorological stations in Barcelona, the relative humidity is roughly 20% higher than the monthly average. In this case, WRF underpredicted PBLH (bias < 0). Nevertheless, both BEP and BEP + BEM present a better performance as a consequence of their overprediction trend.

The synoptic analysis was based in the Global Forecast System (GFS) analysed fields in the Wetterzentrale archive (www.wetterzentrale.de).

4. Summary and conclusions

High quality input data and parameterizations are crucial to obtain accurate modelling results. Within this work, the two multi-layer urban canopy schemes available in the WRF model, BEP and BEP + BEM,

were applied over the Metropolitan Area of Barcelona at high resolution using detailed urban land use from the Local Climate Zone (LCZ) of the MAB. The results were then analysed and compared with a default WRF setup (BULK) and observations from local meteorological towers and radiosonde. The analysis performed was based on temperature, relative humidity and wind (U and V components) for the entire month of July 2016, as well as on boundary layer height and heat fluxes.

As expected, significant differences were found among BULK and both multi-layer urban canopy scheme simulations. The use of such schemes and LCZ made the study area warmer during the daytime while in the evening the heat over urbanized areas is more quickly dissipated than in BULK simulations. This is associated to the overall more detailed representation of the urban canopy, in particular the thermal properties of the urban surfaces. Additionally, the air conditioning (A/C) systems for house cooling considered in the BEP + BEM scheme induce more heat released to the atmosphere than in both BEP and BULK, making the urbanized areas warmer in BEP + BEM experiment than in BULK and BEP, not only during sunlight but also in the night.

The boundary layer heights predicted by both multi-layer urban canopy schemes are typically higher than those by BULK and the ones derived by measurements. Nevertheless, BULK, BEP and BEP + BEM presented the same bias signal. During July 2016, three synoptic conditions with different behaviours on PBLH calculation were identified: 1) Good prediction by BULK and overestimation by the BEP and BEP + BEM when the high pressure system over the Azores islands and
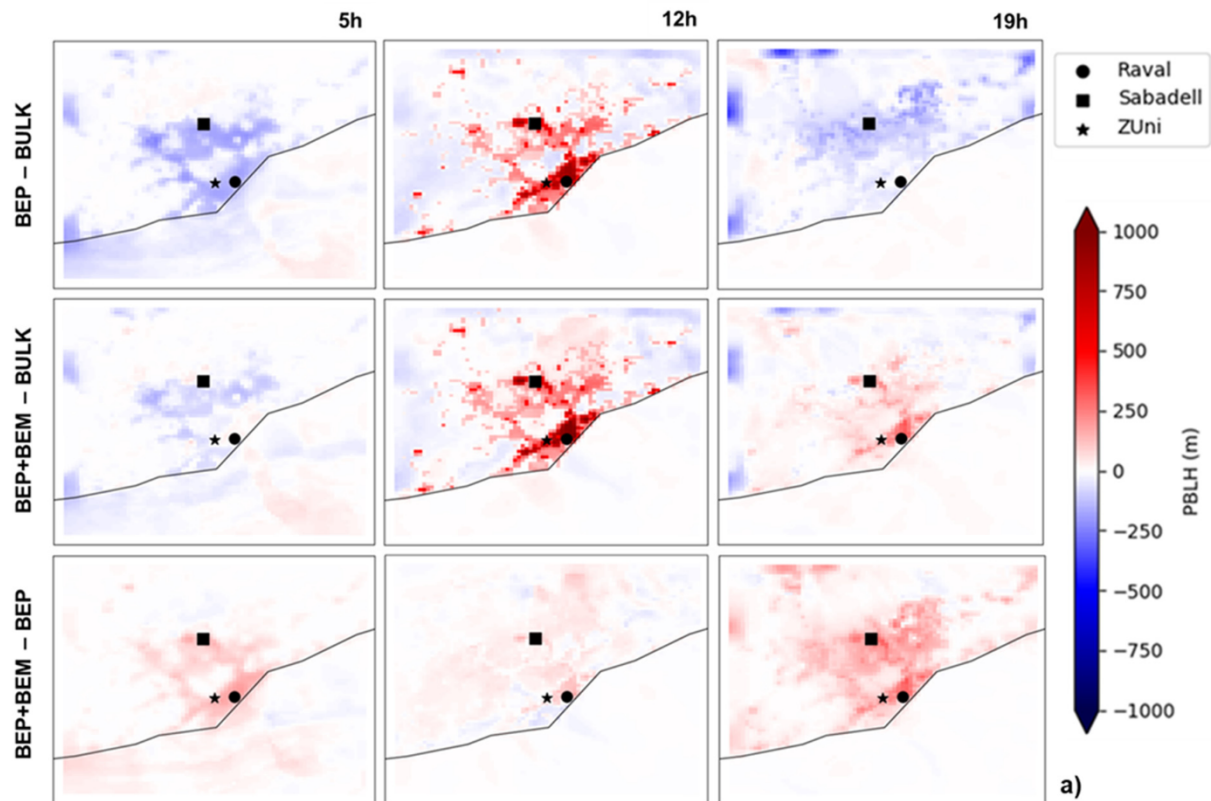
Fig. 8. Averaged differences in PBLH height: BEP – BULK (top panel), BEP + BEM – BULK (central panel) and BEP + BEM – BEP (bottom panel) over 05 h, 12 h and 19 h of July 2016. The black marks locate Raval, Sabadell and ZUni meteorological stations.
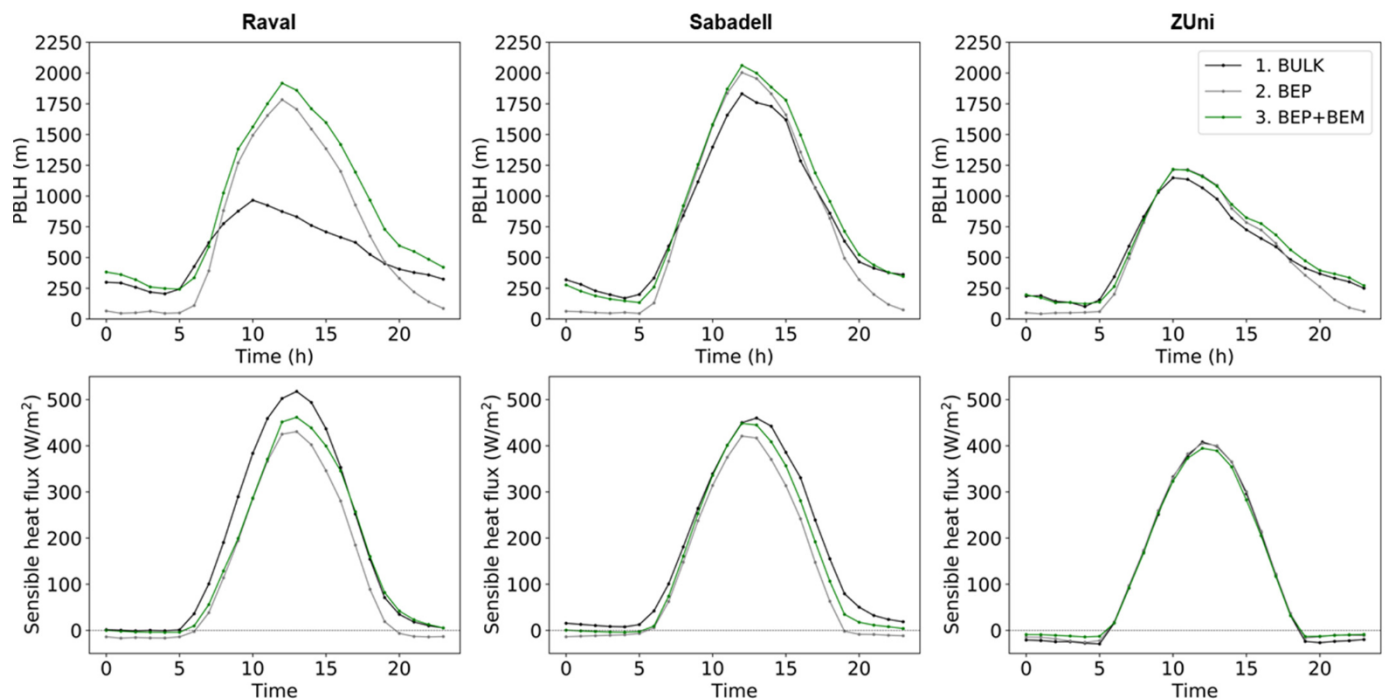

Fig. 9. Daily profile of PBL height (m) and the sensible heat flux (W/m^2) in: Raval, Sabadell and ZUni meteorological stations.

a low pressure system over Scandinavia; 2) Strong overestimation of PBLH for all the simulations under a well-defined anticyclone ridge over the IP and low thermal at surface; 3) Underestimation under unstable atmospheric conditions promoted by a North Atlantic advection that brought saturated air towards IP. The multi-layer urban schemes

predicted PBLH more accurately than BULK for the situation 3), mainly due to their overestimation tendency.

Regarding the statistical analysis of the three simulations performance over Barcelona urban area during July 2016, BEP has the best correlation with observations. On the other hand, this is the scheme
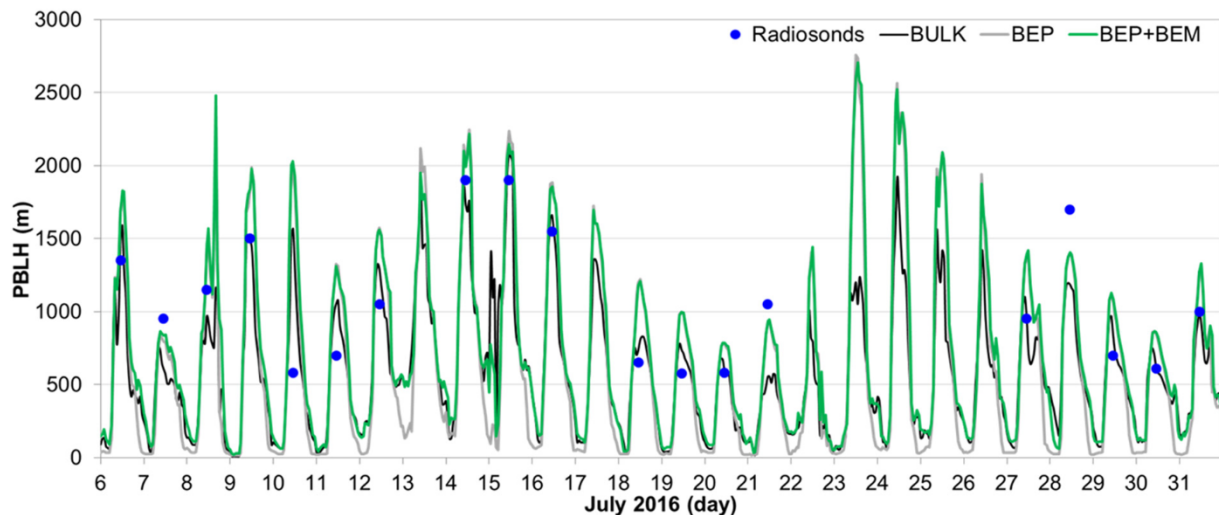
Fig. 10. PBLH measured at 12 h UTC (black dots) and hourly-based time series predicted by BULK (blue line), BEP (magenta line) and BEP + BEP (green line) at Physics Faculty.

with the highest value of bias and RMSE for most of the variables and urban classes, in particular during the night: overestimation of relative humidity and underestimation of air temperature. This phenomenon is also verified on daily profiles of PBLH and sensible heat fluxes, which is likely related to the sea-land-mountain breezes developed within the study region. BEP bias and RMSE are more prominent than other schemes. In fact, BEP has lower sensible heat fluxes mainly because it neglects anthropogenic heat and probably because the indoor temperature assumed is too cold, which may induce most of the difference in temperature. In addition, due to the higher overestimation of relative humidity by BEP at night, the radiative cooling effect might be stronger than in the other schemes, contributing to the reduction of the air temperature and then the underestimation of this physical property.

BEP + BEM performed with the lower RMSE associated for relative humidity and temperature all over the domain, as well as for wind speed at compact midrise (main LCZ class in Barcelona city) and open midrise urban structures – locations where the LCZ in the grid model at 1 km × 1 km is in accordance to the original LCZ database at

100 m × 100 m. It is, thus, a limitation imposed in part by the model resolution. Hereupon, further studies involving high quality input data: detailed land cover classification (e.g. LCZ), more accurate information on urban canopy structure and on urban surfaces physical/thermal characteristics; as well as higher horizontal model resolution are strongly recommended to perform urban simulations.

Author statement

Term	Definition
Conceptualization	This work was part of the 1st year of the Post-doc research grant of Isabel Ribeiro, entitled "Quantifying the impact of green infrastructures on (peri-) urban atmospheres (GUrbs)" that took place at the Autonomous University of Barcelona and was founded by P-SPHERE project under Marie Skłodowska-Curie program. Supervised by Gara Villalba. The main goal of this work is to evaluate the performance of the urban schemes in WRF over Barcelona.
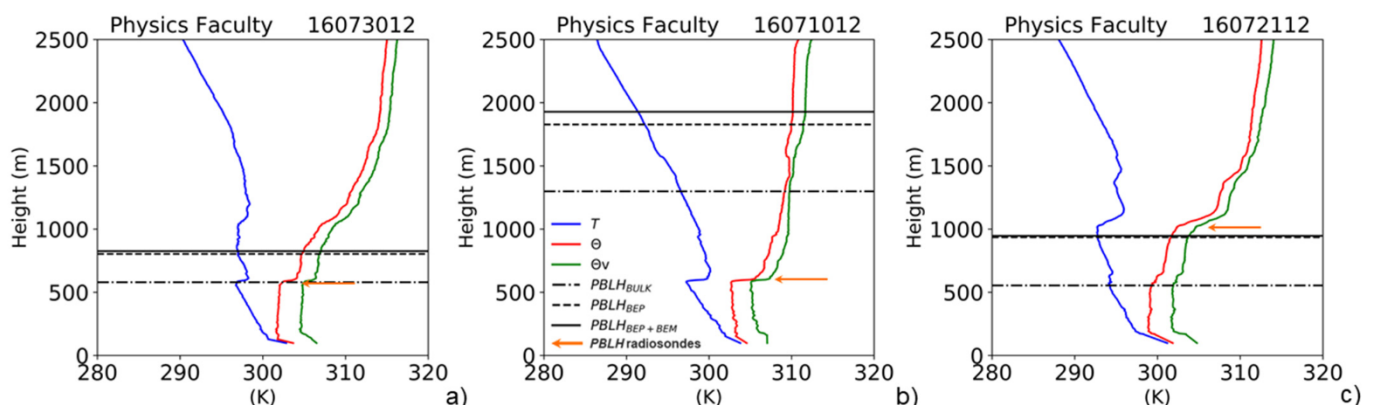
Bias [model – observations] (m)			
BULK	3	987	-494
BEP	239	1411	-119
BEP+BEM	248	1451	-116

Fig. 11. Vertical profiles of temperature (T), potential temperature (θ) and virtual potential temperature (θ$_v$) from radiosonding measurements, as well as the PBLH predicted by BULK (dotdashed line), BEP (dashed line) and BEP + BEP (solid line) at Physics Faculty, on a) 30th, b) 10th and c) 21st of July 2016 at 12 h UTC. Systematic error (bias, model-observation) concerning the days and hour of each vertical profile.

Methodology	The urban land use of the Metropolitan area of Barcelona was improved through the use of LCZ and CLC databases. The performance of the BULK and two multi-layer urban schemes in WRF (BEP and BEP + BEM) were assessed using observed data.
	The methodology was designed by Isabel Ribeiro, Alberto Martilli, Andrea Zonato and Gara Villalba
Software	WRF V3.9.1 (code adaptation by Andrea Zonato; simulations by Isabel Ribeiro)
	Phython scripts developed specifically for this work (Isabel Ribeiro and Marcus Falls)
	QGIS 3.3 (Andrea Zonato)
Validation	Some simulations and the analysis of the results were replicated within the producing phase of the work to make sure the results presented are correct.
	Isabel Ribeiro and Alberto Martilli made sure all the results present are correct.
Formal analysis	The analysis and discussion of the results were mainly performed by Isabel Ribeiro with important contributions by Alberto Martilli.
Investigation	The research involved was conducted by Isabel Ribeiro with contributions by Alberto Martilli and Andrea Zonato. Isabel Ribeiro also performed all the experiments, prepared the observed/modelled for analysis and the analysis/discussion itself.
Resources	The simulations and post-processing was done in the computational cluster "Port d'Informació Científica" (PIC) https://www.pic.es/
	Computational resources were paid by the URBANCO2FLUX grant (Marie Skłodowska-Curie) (Gara Villalba)
Data Curation	Isabel Ribeiro made sure that the model setup and source code, as well as pre- and post-processing are available to be used by the students and researchers currently involved in the on-going research activities at ICTA-UAB under the purview of Gara Villalba
Writing - Original Draft	The paper was mainly written by Isabel Ribeiro that counted to the scientific and grammar revision by Alberto Martilli and Gara Villalba.
Writing - Review & Editing	The paper was written by Isabel Ribeiro that counted to the scientific and grammar revision by Alberto Martilli and Gara Villalba.
	The reply to reviewers was also mainly performed by Isabel Ribeiro with contributions by Alberto Martilli.
Visualization	All work involved in post-processing of data, data visualization and presentations were done by Isabel Ribeiro.
Supervision	The scientific leadership is by Isabel Ribeiro with a strong contribution by Alberto Martilli
	Oversight by Gara Villalba since the work was part of her main projects.
Project administration	The management and coordination of responsibility for the research activity planning and execution was done by Isabel Ribeiro and Gara Villalba
Funding acquisition	Acquisition of the financial support for the project leading to this publication by Gara Villalba

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Competing Interest

None.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2020.105220.

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