Sensitivity of WRF/Urban Simulations to Urban Morphology Parameters: A Case Study in the City of Bolzano

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Abstract

The recent progress in numerical weather prediction modelling, and in particular the possibility to reach increasingly finer spatial resolutions, allowed researchers to reproduce building-atmosphere interactions in a more accurate and realistic way, especially in urban areas.

The present work aims at evaluating the impact of high-resolution gridded datasets of urban morphology parameters on the results of numerical simulations of atmospheric processes performed with the WRF/Urban suite in the city of Bolzano (Italy), and to analyze how they affect near-ground temperature fields.

A sensitivity test was carried out, combining the WRF model with the Building Effect Parameterization (BEP) scheme to simulate two typical clear-sky summer days, respectively with and without the input gridded data of urban morphology. The structure and the morphology of the city of Bolzano were carefully reproduced through several fine-scale morphometric parameters from surface and terrain models (0.5 m resolution).

The results highlight that urban morphological parameters display a high spatial variability, moderately affecting the distribution of the temperature field near the ground.

High-resolution meteorological fields inside urban areas can be valuable information for building energy simulations. Accordingly, a scheme of model chain coupling WRF and TRNSYS codes is proposed, in order to enhance the future assessment of urbanization effects and in the same way to provide more realistic and accurate building energy simulations.

1. Introduction

In densely urbanised areas, buildings are among the most important factors controlling energy, mass and momentum exchanges between the earth surface and the atmosphere. This interaction has close influence on the Urban Heat Island (UHI) phenomenon, which consists in a significant increase of air temperature in the city center compared to the surrounding areas. Nowadays, recent progress in numerical weather prediction modelling, along with increasing availability of high-power computational resources, allow for reaching much higher spatial resolutions, even in operational model runs for routine weather forecasting. Accordingly, a more detailed parameterisation of these processes can be included, reproducing building-atmosphere interactions in a more precise and realistic way, especially in urban areas. Numerical models involve different spatial scales. In particular, two main models can be distinguished: mesoscale models (representing the atmospheric structures and working at horizontal resolutions of 1–10 km) and microscale models (e. g. Computational Fluid-Dynamics (CFD) models, Building Energy Simulations, working at much finer resolutions). Focusing on urban areas, microscale models require detailed information about buildings structure, while meso-scale models need a parameterization of averaged urban morphology features. In this context, mesoscale meteorological models, estimating the mean thermal and dynamical effects of the cities on the atmosphere have been increasingly applied to urban areas (Salamanca et al., 2011). Indeed, implementing urban schemes with detailed urban morphological parameters can provide better tools for evaluating the urban morphology impacts on the urban microclimate and the surrounding buildings. For this reason, the National Urban Database and Access Portal Tool (NUDAPT) was designed to

provide gridded datasets of urban canopy parameters for 44 US cities. Many recent studies highlighted the importance of using fine-resolution input datasets of urban morphology parameters to keep pace with the increasingly high resolution of operational model runs, in order to improve the accuracy of the results (Solazzo et al., 2010; Salamanca et al., 2011; Giovannini et al, 2014). The Weather Research and Forecasting (WRF) model can be coupled either with a single-layer urban canopy model (Kusaka et al., 2001) or with a multilayer canopy model (Martilli et al., 2002), providing a valuable approach to represent the heterogeneities of urban morphology, considering three different urban surfaces (walls, roofs, and roads) and infinitely long street canyons (cf. Giovannini et al., 2013). Moreover, the BEP scheme can be coupled with a simple Building Energy Model (BEP+BEM), which provides a multilayer urban parameterization that takes into account the exchanges of energy between building and atmosphere (Salamanca and Martilli, 2010). The embedded building energy module estimates the heat diffusion through building envelopes and the radiation exchange between indoor surfaces, the heat generation of occupants and equipment, the energy consumption of air conditioning systems and natural ventilation.

The present work adopts the most advanced urban parameterization scheme coupled with the WRF model, i.e. the Building Effect Parameterization (BEP) (Martilli et al., 2002), in order to evaluate climatic conditions in the city of Bolzano. The city is located in the northeastern Italian Alps, in a basin where three valleys join (Fig. 1). Climatic conditions in the city are tightly connected with the complex topography of the surrounding area that influences in particular the flow field, mainly characterized by daily-periodic up- and down-valley winds from tributary valleys, especially in the warm season. Many studies investigated the interaction between urban area and these phenomena, emphasizing the important influence of local winds on the urban environment (Kuttler et al., 1996; Piringer and Baumann, 1999; Giovannini et al., 2011).

The objective of the present work is to develop a complete dataset of fine-scale urban canopy parameters (UCPs) in Bolzano, in order to assess their impact in WRF-urban canopy models. This methodology, besides providing an accurate description of the temperature field in the urban area, can be used also to evaluate the effects of particular urban heat island mitigation strategies, or to assess the energy consumption in buildings.

This work is organized as follows. The datasets and the methodologies used to obtain urban canopy parameters are described in detail in section 2. Section 3 describes the results of sensitivity tests performed by means of the WRF/urban scheme. Finally, section 4 presents some conclusions and the proposal of a model chain including the mesoscale model (nested WRF-urban from 10.8 to 0.4 km resolution) and the well-known building energy simulation code TRNSYS.

2. Input Datasets and Modelling Setup

2.1 Input Datasets – UCPs

As reported in the study of Giovannini et al. (2014), high-resolution meteorological simulations in complex terrain require a high-resolution topography dataset. For this reason, here the topographical data obtained from the Viewfinder Panoramas (original horizontal spatial resolution ~30 m) were used. Fig. 1 (right) shows the topography of the inner domain, highlighting the urban area of Bolzano. The dataset Corine was used for the land cover parameters, reclassifying the 44 Corine categories into the 20 (+3 special classes for urban land use) Modis categories, in order to fit the WRF look-up tables.

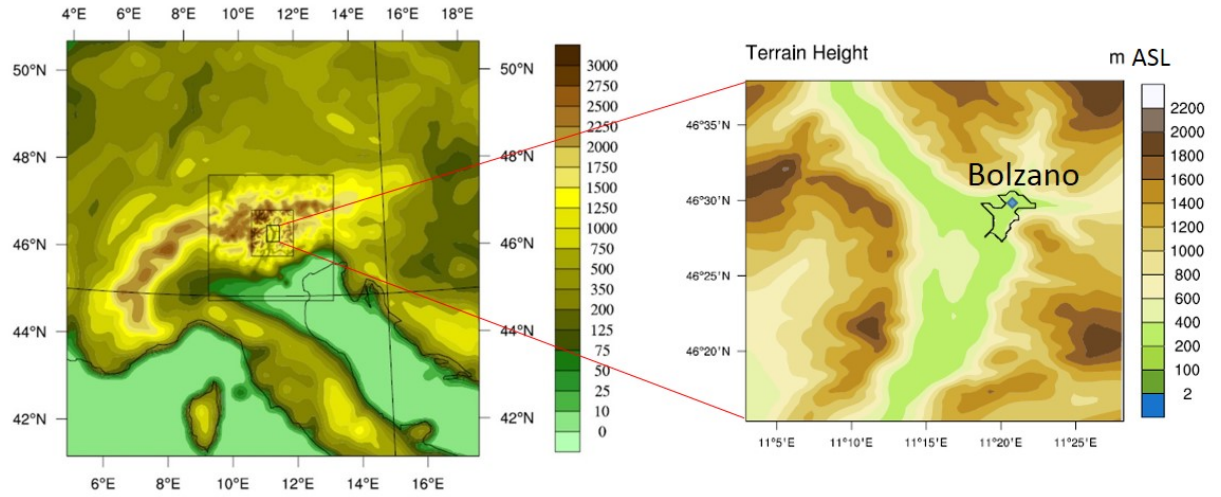

Fig. 1 – The four nested domains used for the numerical simulations (left). The zoomed-in area (right) represents the inner domain and the black line contours the urban area of the city of Bolzano

The land cover dataset is shown in Fig. 2. As the goal of this research concerns the urban environment, detailed maps of urban morphology were developed. Using digital surface and terrain models (0.5 m resolution) from the GeoCatalogo of the Autonomous Province of Bolzano (http://geocatalogo.retecivica.bz.it/geokatalog), fine resolution maps of urban morphology parameters were calculated by means of the QGIS + Urban Multi-scale Environmental Predictor (UMEP) and Matlab© software. Collected data and maps were processed in order to obtain gridded urban canopy parameters (UCPs) with a horizontal spatial resolution of 100 m, directly used as input for the BEP scheme. The structure of the city of Bolzano was carefully reproduced using a set of seven morphometric parameters: the average and standard deviation height of the buildings named respectively h_m and h_s, the building plan area fraction $\lambda_p = A_p/A_{tot}$ (where A_p is the plan area of buildings and A_{tot} is the total area of the cell) and plan-area-weighted mean building height $h_{aw} = (A_p * h_m)/A_p$; the building envelope area to plan area ratio $\lambda_b = (A_p + A_w)/A_{tot}$ (where A_w is the wall surface area); the frontal area index $\lambda_f = A_{proj}/A_{tot}$ (where A_{proj} is the total area of buildings projected into the plane normal to the approaching wind direction at 0°-45°-90°-135°), the urban fraction λ_u (percentage of the cell covered by urban land use). Finally, the distribution of building heights h_i (that corresponds to the plan area fraction of the buildings every five meters in each computational cell) at 5 m vertical intervals was calculated on fifteen vertical urban levels. The methodology used to calculate the main urban morphological parameters is reported in Burian et al. (2008). Fig. 3 shows respectively the distribution of λ_p (a), λ_b (b), h_m (c) and λ_u (d), on a 100 m grid resolution. The same parameters have been used as input for the BEP scheme in the WRF model, averaging those previously calculated in order to adapt them to the 400 m WRF resolution. Results are shown in Fig. 4. Fig. 3 and 4a, 4b, and 4c highlight, as expected, that the highest values of these urban morphology parameters are mainly located in the central part of the city, which is characterized by a typical South Tyrolean architectural design, consisting of 4-5-storey historic buildings flanking narrow (often arcaded) street canyons. In particular, the highest values of λ_p and λ_b occur in this area, which underlines the high density of the urban area. Furthermore, high values occur also in the southern area of the city, which is the industrial and commercial areas, and in the northwestern part of the residential area, where high residential buildings are present (Fig. 4c). Finally, in order to check the consistency of the gridded morphology data, they were overlaid on Google Earth maps.

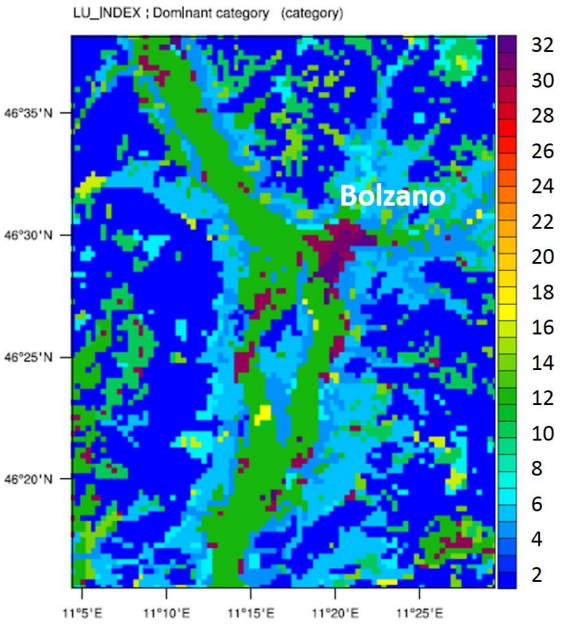

Fig. 2 – Modis land use categories in the inner model domain. Categories 31-33 indicate urban land use, namely 31: Low intensity residential, 32: High intensity residential, 33: Industrial or commercial

2.2 WRF Numerical Simulation

In order to assess the impact of the urban canopy parameters on the WRF simulation output, the non-hydrostatic version of the WRF model (version 3.8) coupled with Building Effect Parameterization BEP scheme (Martilli et al., 2002) was used (Skamarock et al., 2016). The 54-h WRF-urban simulations started at 1800 UTC (LST=UTC+1 h) 19 July 2015 and ended at 0000 UTC 21 July 2015. Simulations were carried out using four two-way nested domains (nesting ratio=3) with the grid resolution for the inner domain of 400m×400m (Fig. 1 and Tables 1 and 2 show details about domains dimension and resolution). Initial and boundary conditions derive from the National Center for Environmental Prediction (NCEP), where meteorological data have 1-deg grid resolution (about 120 km) and 6 h time resolution. 30 eta levels (terrain-following hydrostatic-pressure vertical coordinate) are used in the vertical. The simulations were run with the Bougeault and Lacarrère (1989) scheme for the Planetary Boundary Layer (PBL) parameterization, while the Noah land surface model (Chen and Dudhia, 2001) for the land surface processes parameterization.

Table 1 – Details of resolution of nested WRF domains

Domain	n.points_we	n.points_sn	dx(m)	dy(m)
d01	100	100	10800	110800
d02	91	91	3600	3600
d03	91	100	1200	1200
d04	82	106	400	400

3. Sensitivity Test

In order to analyze in detail the impacts of the gridded datasets of the urban morphology parameters, sensitivity simulations were performed with and without these input data. The simulation considering urban morphology parameters is referred to as BEP_PAR, while the one using only standard input for the BEP scheme (i.e. without the gridded datasets of urban morphology) is referred to as BEP_NOPAR. In this case, since the grid data of urban morphology are absent, the three urban classes describe the urban settlements (Fig. 2), i.e. the ancient and high-intensity residential class (class number 31), the recent high- or low-intensity residential class (class number 32), and the industrial and commercial class (class number 33), from which the urban scheme looks up the morphology parameters.

The simulation results show that the strongest temperature differences between the two simulations occur in the central part of the city, where the influence of the morphology parameters on the performance of the urban scheme is higher. At night temperatures are slightly higher (~ 0.5 - 1 °C) in BEP_PAR than in BEP_NOPAR, especially in the central part of the urban area, while in the central hours of the day the opposite occurs, mainly in the downtown area, which is characterized by densely packed buildings and narrow street canyons.

These results (obtained from BEP_PAR) are in reasonable agreement with observations performed in Trento (Giovannini et al., 2011), showing a quite strong nocturnal urban heat island (UHI), especially under low wind speed and clear sky conditions, whereas an urban cool island is likely to develop in the morning.

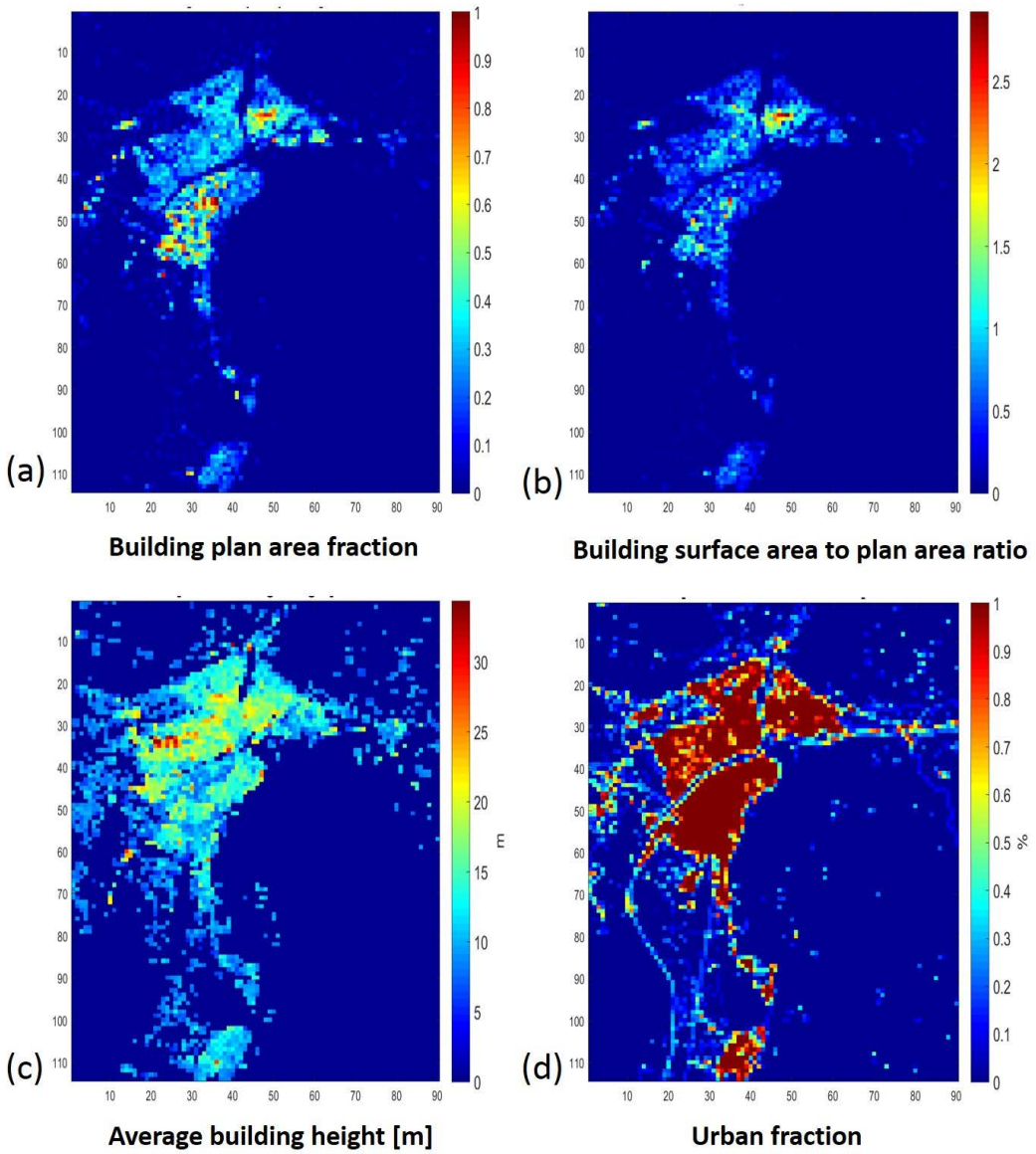

Fig. 3 – Urban morphology parameters calculated by means of MATLAB-QGIS software from digital surfaces and terrain model for the urban area of Bolzano (fine resolution-100 m). (a) Building plan area fraction λ_p, (b) building surface area to plan area ratio λ_b, (c) average building height h_m, (d) urban fraction λ_u.

Focusing on Fig. 5a, referring to nighttime (2315 UTC), the highest differences occur in the central part of the urban area, in accordance with the average values of the UCPs used in BEP_PAR, which, unlike the default urban classes, well capture the detail of the denser morphology and greater height of the buildings in that area. On the contrary, negative differences occur during daytime (Fig. 5b), especially in the morning, due to the density of urbanization which prevents solar radiation to penetrate inside narrow street canyons. However, this difference decreases until the central hours of the day, when the temperature differences between the two schemes are less than 0.5 °C. Summing up, as can be seen in Fig. 5a and 5b, areas with low positive and negative differences are present throughout the urban area, depending closely on the local values of the gridded morphology parameters. The maximum differences between the two simulations (i.e. BEP_PAR-BEP_NOPAR) are more than 1 °C, both during the day and the night, when negative and positive differences occur respectively.

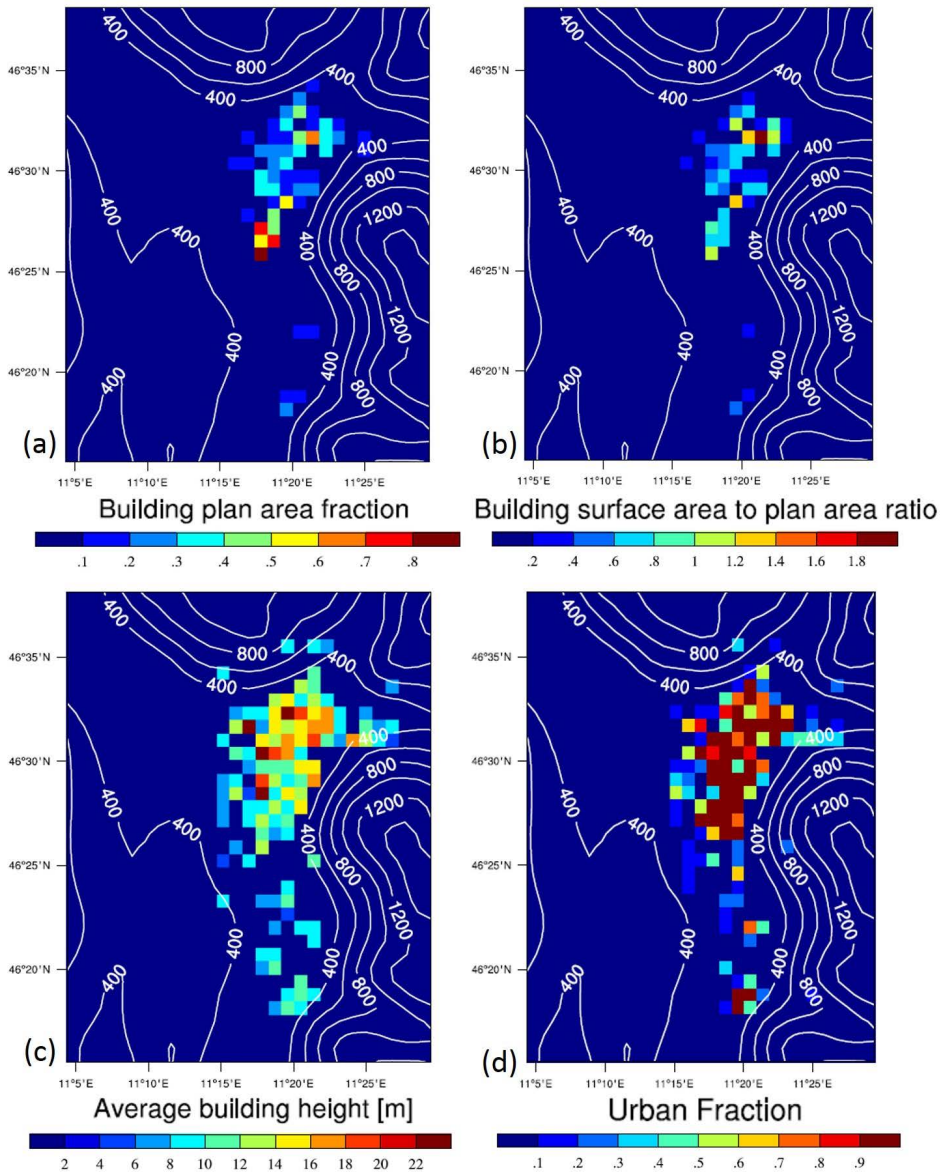

Fig. 4 – Urban morphology parameters averaging the finer-resolution previously calculated in Fig.3 and used in the BEP scheme. (a) Building plan area fraction λ_p, (b) building surface area to plan area ratio λ_b, (c) average building height h_m, (d) urban fraction λ_u. Detailed explanations of the parameters are given in section 2.1. Height contours are in above sea level (ASL)

4. Discussion and Conclusion

The WRF/BEP coupled model was applied, with and without urban morphology parameters, to simulate the atmospheric processes in the city of Bolzano during the hottest days in the summer 2015. A sensitivity test was performed to assess the impact of the gridded datasets of the urban morphology in the BEP scheme. The results show that the detailed urban parameters influence significantly the spatial and temporal variability of the urban temperatures throughout the day. In particular, the BEP_PAR simulation shows higher temperature than BEP_NOPAR in the historical city center already in the first nocturnal hours. On the contrary, the temperature in the downtown area tends to remain lower in BEP_PAR than in BEP_NOPAR throughout the morning (~1 °C), due to a cool island effect.

Further analyses are ongoing in order to investigate the model sensitivity with respect to fluxes and other micrometeorological variables. Based on the results of this paper, on the ongoing research activities, and on the continuous improvement of numerical capabilities at all scales, modelling building elements in more detail seems the further effort in

order to represent in a more accurate way the interaction between buildings and the urban atmosphere. To this regard there are some issues to overcome. On one hand the resolution typically used in mesoscale model simulations is not enough to provide details about the single building in the urban context. On the other hand, building energy simulations (BES) often focus on the single building without considering the urban context and the surrounding building effect on radiative and convective surface exchanges on the external envelope. Furthermore, providing proper initial conditions for these models remains a difficult task, as they are usually derived from observations (mostly taken within rural environment) limited to a single-point, which negatively affect model reliability. These criticalities pose a challenge when it comes to coupling these models with mesoscale models, especially when the impact of urbanization effects (UHI) on building energy performance is investigated.

In this context, WRF/Urban output can provide information that are not typically available from conventional climate data, e.g. Typical Meteorological Year, leading to a more robust source (spatially averaged) for initial conditions as compared to local observations. The possible advantages arising from the use of WRF/Urban output in building energy simulation may be shortly recalled in the following list:

1) Better knowledge of micrometeorological conditions representative of specific urban areas free from potential bias due to instrument location;

2) a more precise evaluation of temperatures on impervious urban surfaces, upper soil layers and overlying urban canopy layers;

3) a better prediction of future scenarios by assessing the feedback between buildings and the surrounding microclimate, which are directly affected by climate change mitigation strategies (e.g. green roofs, trees and vegetation).

A challenging opportunity that may be pursued in future developments of this research is the coupling of WRF/Urban with models dynamically reproducing building energetics (e.g. TRNSYS).

Table 2 Main features of the simulations in this paper

Schemes	BEP_PAR	BEP_NOPAR
Urban land use	Yes	Yes
Urban scheme	BEP	BEP
Gridded dataset of urban morphology	Yes	No

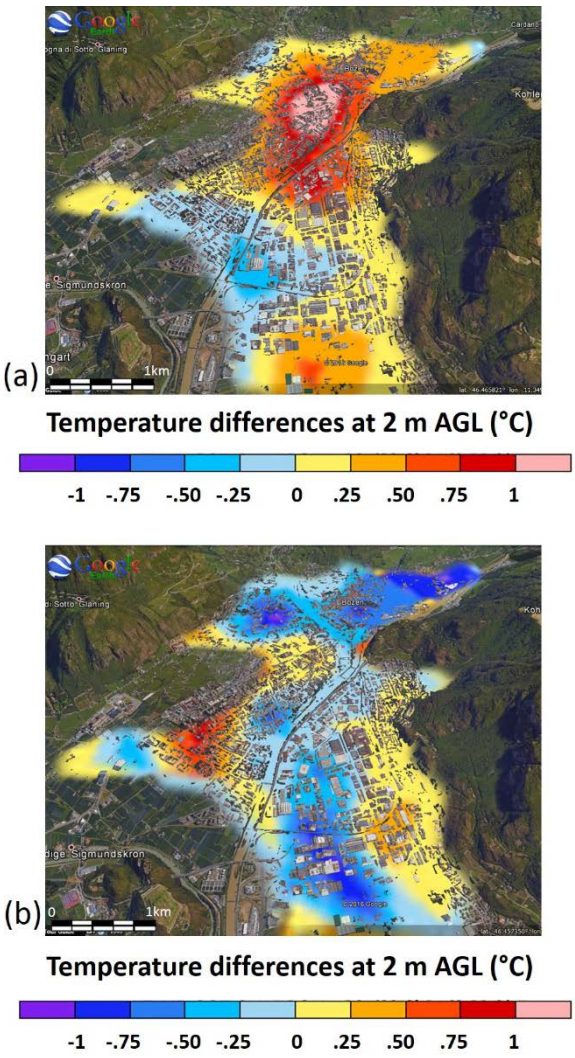

Fig. 5 – Temperature differences at 2 m AGL in the urban area of Bolzano at (a) 2315-nighttime, (b) 1200–daytime UTC respectively 19 and 20 July 2015

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