Assessing Solar Radiation in the Urban Area of Bolzano, Italy, by Means of SEBE Simulations

Gianluca Pappaccogli – Free University of Bozen-Bolzano, Italy – gianluca.pappaccogli@unibz.it
Giovanni Pernigotto – Free University of Bozen-Bolzano, Italy – giovanni.pernigotto@unibz.it
Alessandro Prada – University of Trento, Italy – alessandro.prada@unitn.it
Andrea Gasparella– Free University of Bozen-Bolzano, Italy – andrea.gasparella@unibz.it

Abstract

Downward shortwave incoming irradiance plays a key role in urban areas, especially in those located in complex terrains. Accurate modelling of this weather variable is crucial for the characterization of physical processes, and in particular heat exchanges, occurring between buildings and the urban atmosphere. In this framework, the present research evaluated the capabilities of the Solar Energy on Building Envelopes (SEBE) model, which can be used to describe the urban geometry through 2D high-resolution DSMs and simulate total irradiation on buildings' façades. Specifically, this work focused on the urban area of Bolzano, a city located in the north-eastern Italian Alps in a basin where three valleys join, and assessed the SEBE output by comparison with the total daily irradiation on a vertical building façade for a six-month period (i.e. July-December 2018). Meteorological forcing for simulations was provided by the observed hourly data of shortwave radiation (i.e. global GHI and diffuse DHI horizontal, and direct normal DNI irradiance), collected at rooftop level in the urban area of Bolzano. The overall performance of the model was found to be accurate, both for different analysed periods and for daily climatic classification.

1. Introduction

The constant increase in energy demand has brought increasing attention to solar energy as an energy source which is available worldwide, especially in urban areas where other renewable energies are generally not present. Moreover, in a context of continuous urbanization, the study of solar radiation in the complex urban environment is becoming crucial in order to provide building simulation codes with robust and adequate inputs. Indeed, the shaded/sunlit urban surface portions represent the dominant component of shortwave energy input in urban areas, especially during clear-sky conditions. However, the complex shadowing patterns led by different building distributions represent the main challenge in terms of computational effort needed to create urban models.

For this purpose, simplifying the assumptions of the three-dimensional geometry of urban fabric is required in agreement with the represented level. Accordingly, several urban parametrization schemes have been developed since the 2000s, with different levels of detail, such as the *slab* (Liu et al., 2006), *single-layer* (Kusaka et al., 2001) and *multi-layer* (Martilli et al., 2002; Masson et al., 2000) models, representing respectively 2D or 3D regular building volume arrays. In these schemes, the distribution and intensity of solar radiation reaching the different urban surfaces are computed by a simple shadow-casting algorithm in conjunction with a rotating, infinitely-long street canyon scheme (Lindberg et al., 2015a).

In recent years, several GIS-based tools have been developed using high-resolution digital surface models (DSMs) derived from LiDAR data, in order to estimate solar radiation for extensive urban areas, such as the Solar Energy on Building Envelopes – SEBE (Lindberg et al., 2015b). Accordingly, 3D geographical data of urban fabric make it possible to derive very high-resolution information about building structures, which are typically used in micro- to local scale modelling, providing realistic representations of specific building stocks.

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). (2020). Building simulation applications BSA 2019. bu,press. https://doi.org/10.13124/9788860461766

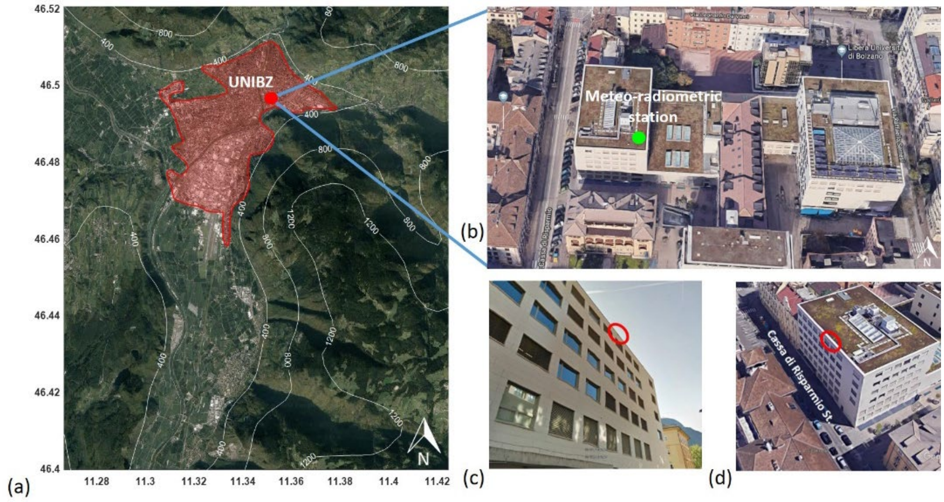

Fig. 1 – (a) The urban area of Bolzano (area shaded in red). Height contours (above sea level) are also presented, (b) The zoomed-in area represents the position of the meteo-radiometric station located on the rooftop of the Free University of Bozen-Bolzano, (c,d) Position of SPN1 sunshine pyranometer fixed on the vertical façade exposed to west at 25 a.g.l.

In this work, Solar Energy on Building Envelopes (SEBE) was used to estimate the shortwave irradiance on the ground, roofs and building walls throughout the urban core of the medium-sized (approximately 100,000 inhabitants) city of Bolzano. The city is located in a basin where three valleys in the north-eastern Italian Alps join (Fig. 1a). The climatic conditions in the city are closely related to the complex topography of the surrounding area, which influences in particular the flow field and solar radiation (Pappaccogli et al., 2018). It is therefore crucial to take into account the interactions between the surrounding orography, which generates a shadowing effect, and geometry of the urban fabric, which modifies the radiative balance within the urban environment (i.e., the share of direct and diffuse shortwave radiation). In the current research, observed horizontal solar radiation data were used as meteorological input for SEBE, and the computed solar radiation on a vertical building surface compared with measurements collected in a six-month period (i.e., July–December 2018).

2. Methods

2.1 Model Structure

SEBE uses digital surface models (DSMs) to calculate solar radiation, which consist of building and ground heights. In addition, two optional DSMs of the same resolution and extent as the ground and building DSM can be used to represent 3D vegetation of trees and bushes (which are not considered in this case study). Specifically, the SEBE model computes the 'shadow volumes' by sequentially moving the raster DSM at the azimuth angle of the sun, reducing the height at each iteration based on the elevation angle of the sun (Ratti and Richens, 1999). For a detailed description of the shadow casting algorithm, see Ratti and Richens (2004), and Lindberg and Grimmond (2010).

Based on observed hourly meteorological data as input, the SEBE model uses the unobstructed three components of shortwave radiation: direct radiation perpendicular to the sun (DNI), horizontal diffuse (DHI) and global (GHI). As these variables are not commonly available (especially DNI and DHI), the model allows the calculation of the diffuse component from the global through the statistical model presented in Reindl et al. (1990), which can take into account the ambient air temperature (T_a) and relative humidity (RH) to improve the accuracy of the calculation. Accordingly, the direct shortwave radiation component (DNI) on a surface perpendicular to the sun rays is then estimated from DHI using the following equation:

$$I = (G - D) / \sin \eta \qquad (1)$$

where η is the sun's altitude.

In order to avoid the hourly time step iteration, the meteorological data are pre-processed and redistributed into 145 patches of similar solid angles throughout the sky vault according to the well-known approach presented by Tregenza and Sharples (1993). The diffuse radiation component is redistributed for the patches based on the all-weather model of sky luminance developed by Perez et al. (1993).
The output of the SEBE model consists of the total irradiance for a roof pixel (*R*) on a DSM by summing the direct, diffuse and reflected radiation as follows

$$R = \sum_{i=1}^{p} [(I\omega S + DS + G(1 - S)\alpha)]_i \quad (2)$$

where *p* is the number of patches on the hemisphere, *I* is the incidence direct radiation, *D* is diffuse radiation, *G* is the global radiation originating from the i^{th} patch, α is the surface albedo and ω is the sun incidence angle. The first and second terms represent the direct and diffuse irradiance respectively, whereas the third term accounts for reflected irradiance (Lindberg et al., 2015b). S represents the shadow computed at each pixel:

$$S = S_b - (1 - S_v)(1 - \tau) \quad (3)$$

where S_b and S_v are respectively shadows from buildings and vegetation, and τ is the transmissivity of shortwave radiation through vegetation.
Finally, the reflection term at the wall pixels is only considered for half of the hemisphere, with the reflected part originating from the ground calculated as follows:

$$\mathrm{Ground}_{\mathrm{reflected}} = (G\alpha)/2 \quad (4)$$

For tilted roofs, the reflection from the ground is not considered, as it is negligible due to the small view factor from the tilted roofs to the ground (Lindberg et al., 2015b).

2.2 Model Setup

The SEBE model was evaluated by comparing simulated and observed vertical shortwave radiation data on the building façade exposed to west and located in the core area of Bolzano, Italy (Fig. 1). The assessment was performed by considering a daily time step. Surface albedo was set to 0.15, which represents the typical value for urban surfaces (Oke, 1989).

2.3 Simulated Domain and Meteorological Input Data

A regular domain of approximately a 1 km^2 horizontal dimension with spatial resolution of 1 m (Fig. 2) was derived by the spatial average of digital surface models with 0.5 m resolution from the GeoCatalogo of the Autonomous Province of Bozen-Bolzano (http://geocatalogo.retecivica.bz.it/geokatalog). The fine resolution of DSM was able to represent different heights and orientations of the walls, and to take into account the slope of the roofs, when different building architypes are analysed. Fig. 2 shows the building height distribution across the model domain, displaying input building information used in the SEBE model.
The observed solar radiation data provided by the meteorological station located at the Free University of Bozen-Bolzano on the flat rooftop of the E-building were used as input and boundary conditions for SEBE simulations (Fig. 1b).This station was installed at the Free University of Bozen-Bolzano in 2017, on the rooftop of the building of the University, in a position relatively free from external obstructions (above the rooftop level of the city). The measurements site is located in the city centre (Lat. +46°29.89' N; Lon. +11°20.98' E), which is representative of the climatic conditions of the basin, located away from the slopes of the surrounding mountains. Specifically, the measurements of the direct normal and diffuse horizontal solar radiation are carried out respectively by means of an EKO MS-56/pyrheliometer and a MS-802/pyranometer, fixed on a STR-22G EKO sun-tracker station, both for six months (i.e. from July to December 2018).
In this study, vegetation is excluded in the DSMs, as it is not present in the analysed street canyon.

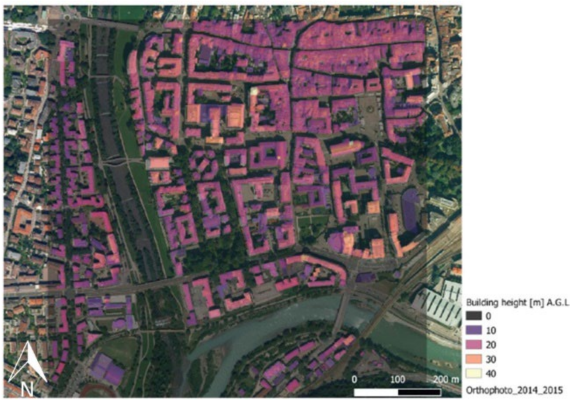

Fig. 2 – The study area in Bolzano (Italy), used for model evaluation, showing building height provided by *DSMs* (spatial resolution 1 m).

2.4 Field Observations

The SEBE model was evaluated for one point location placed on the building façade of the Free University of Bolzano, located in the urban core of the city (Fig. 1c, d). The façade borders a regular street canyon with an aspect ratio *H*/*W*~1.3 (where *H* is the average building height and *W* is the average width of the street), which is delimited by multi-storey buildings with tilted rooftops.

In particular, a SPN1 pyranometer was installed on the external façade of the E-building of the Free University of Bozen-Bolzano at a height of 25 m a.g.l. (Fig. 1c, d). The façade is exposed to the west (azimuth angle =270°) according to a surface analysis based on the DSM model. Data were collected between 5 July 2018 and 31 December 2018. Solar radiation on this vertical surface was saved at the acquisition sampling frequency of 1 minute, and later recalculated into hourly integrals by means of MATLAB® software, in order to match the time resolution needed for input data in the SEBE model. A total of 179 daily data points were used in the evaluation analysis.

3. Results

Using the meteorological data collected at the university building rooftop as input for SEBE, the observed and simulated daily vertical total irradiation were compared for the analysed period of July to December 2018.

In order to obtain a representative sky-type classification, the clearness index was computed using the Surface Solar Irradiance (SSI) provided by MSG Meteosat satellite data normalized by the corresponding extra-atmospheric irradiance according to Ineichen et al. (2009), as ground measurements in complex terrain are affected by the shadowing effect of surrounding orography. Accordingly, the average daily values of the clearness index are used to classify different weather conditions. To quantitatively validate the results of the model, the mean error (BIAS), the root-mean-square error (RMSE) and the coefficient of determination (R^2) were evaluated, quantifying the difference between the simulated and observed daily total irradiation on the building façade.

Fig. 3 reports the comparison between observed and simulated total daily irradiation (expressed as watthours per square meter) on the vertical surface, which are respectively correlated with the clearness index and daily climatic classification. As shown in Fig. 3a, the SEBE model performs well at the analysed location during different climatic conditions (R^2 = 0.952), showing a good estimation of the shortwave fluxes on the vertical wall in the street canyon. As can be noted, a slight overestimation of the modelled shortwave fluxes at the wall location occurs, with a BIAS of 31.83 Wh m^{-2}.

Focusing on the different climatic classes, no specific pattern can be observed. Specifically, an overestimation of the simulated total daily irradiation occurs during overcast sky conditions (BIAS = 134.4 W m^{-2}), which decreases during intermediate (BIAS = 125.4 W m^{-2}) and clear-sky (BIAS = 31.8 W m^{-2}) conditions. However, several significant underestimations occur during clear-sky conditions, which lead to an increase in RMSE (246.3 Wh m^{-2}), while no significant outliers are observed for intermediate and clear-sky conditions.

These errors are linked to the inexact partition between the global and diffuse radiation components during clear-sky conditions.

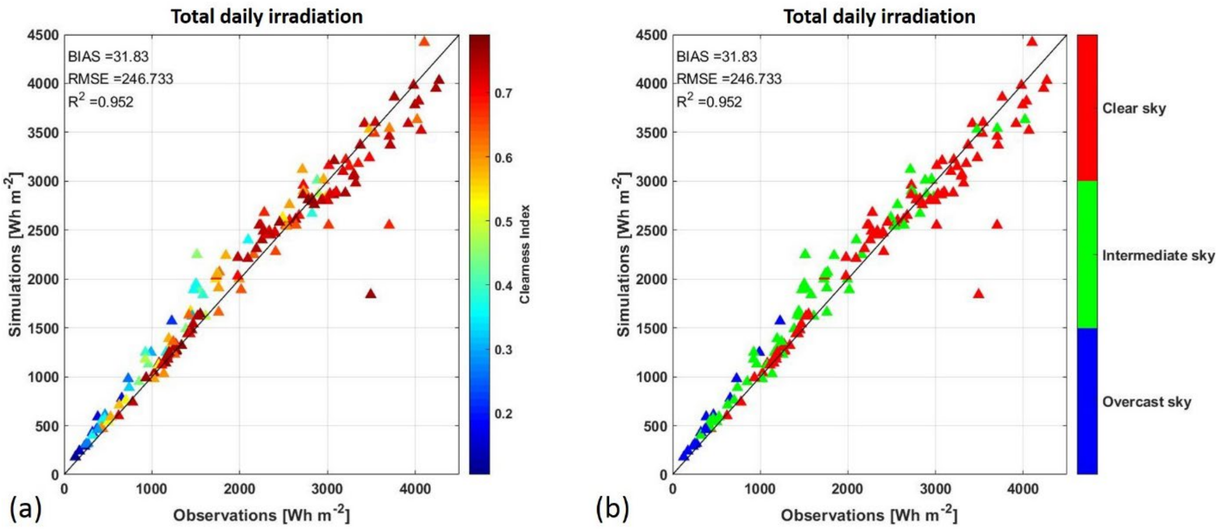

Fig. 3 – Scatter plots of observed and simulated total daily irradiation correlated to (a) clearness index, (b) daily sky-types classification, during the analyzed period (i.e., July–December 2018)

Finally, it should be remembered that the university building is located in the historical city centre, which is characterized by complex envelope structures (e.g., historical towers, balconies etc.), probably not perfectly described by the 1 m digital surface model.

4. Conclusions

A six-month daily simulation was carried out by means of the Solar Energy on Building Envelopes (SEBE) model, in order to study the distribution of solar radiation on roofs and building walls through the core area of the city of Bolzano, Italy. The urban geometry was accurately described using high-resolution 2D raster DSM, which makes it possible to compute 3D surface irradiation information through an extensive area up the city-centre scale. Observed hourly data on shortwave radiation provided by a meteorological station installed on a university building were used as hourly input data for SEBE simulations. The model was evaluated for a vertical façade exposed to west, in a street canyon of Bolzano.

The results highlight that the SEBE model accurately reproduces the downward shortwave fluxes for the different simulated periods (i.e. from July to December) and for daily classifications of sky types. Further developments are planned in order to test the sensitivity of the SEBE model on different urban surfaces (such as tilted and flat roofs), using different meteorological input data (i.e. using only global horizontal radiation components provided by conventional weather stations or from satellites).

Acknowledgement

This study has been funded by the project "Klimahouse and Energy Production" in the framework of the programmatic-financial agreement with the Autonomous Province of Bozen-Bolzano of Research Capacity Building and by the internal project "Bolzano Solar Irradiance Monitoring Network-SOMNE" of the Free University of Bozen-Bolzano.

References

Ineichen, P., Barroso, C. S., Geiger, B., Hollmann, R., A. Marsouin, and R. Mueller. 2009. "Satellite Application Facilities irradiance products: hourly time step comparison and validation over Europe." *International Journal of Remote Sensing* Vol. 30, No. 21, 10, 5549-5571.

Kusaka, H., Kondo, H., Y. Kikegawa, and F. Kimura. 2001. "A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models". *Boundary-Layer Meteorology* 101(3): 329-358.

Lindberg, F., and C.S.B. Grimmond. 2010. “Continuous sky view factor maps from high resolution urban digital elevation models.” *Climate Research*. 42, 177–183.

Lindberg, F., C.S.B. Grimmond, and A. Martilli. 2015a. “Sunlit fractions on urban facets – Impact of spatial resolution and approach.” *Urban Climate* 12: 65-84.

Lindberg, F., Jonsson, P., T. Honjo, and D. Wästberg. 2015b. “Solar energy on building envelopes- 3d modelling in a 2d environment.” *Solar Energy* 115: 369-378.

Liu, Y., Chen, F., T. Warner, and J. Basara. 2006. “Verification of a mesoscale data-assimilation and forecasting system for the Oklahoma city area during the joint urban 2003 field project.” *Journal of Applied Meteorology and Climatology* 45(7): 912-929.

Martilli, A., A. Clappier, and M. W. Rotach. 2002. “An urban surface exchange parameterization for mesoscale models.” *Boundary-Layer Meteorology* 104(2): 261-304.

Masson, V. 2000. “A physically-based scheme for the urban energy budget in atmospheric models.” *Boundary-Layer Meteorology* 94(3): 357-397.

Oke, T. R., 1989. *Boundary Layer Climates*, second ed., Routledge London.

Pappaccogli, G., Giovannini, L., F. Cappelletti, and D. Zardi. 2018. “Challenges in the application of a WRF/Urban–TRNSYS model chain for estimating the cooling demand of buildings: A case study in Bolzano (Italy).” *Science and Technology for the Built Environment* 24:529–544.

Perez, R., R. Seals, and J. Michalsky. 1993. “All-weather model for sky luminance distribution—preliminary configuration and validation.” *Solar Energy* 50, 235–245.

Ratti, C.F. and P. Richens. 1999. “*Urban texture analysis with image processing techniques*.” In: Proc CAADFutures99, Atlanta, GA.

Ratti, C.F. and P. Richens. 2004. “Raster analysis of urban form.” *Environment and Planning B-Plann. Des*. 31, 297–309.

Reindl, D.T., Beckman, W.A., and J.A. Duffie. 1990. “Diffuse fraction correlation.” *Solar Energy* 45, 1–7.

Tregenza, P., and S. Sharples. 1993. “Daylighting Algorithms.” ETSUS, UK, 1350–1993.