Sensitivity Analysis of SEBE Model Using Different Meteorological Input: A Case Study in Bolzano, Italy

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Abstract

In the present study, a sensitivity analysis was carried out in order to evaluate the performance of the Solar Energy on Building Envelopes (SEBE) model to different meteorological input data. The model was applied on a six-months period from July to December 2018. Geostationary satellite data provided by Meteosat MSG was first validated against measurements from permanent weather stations located both in the urban area of Bolzano and in the surrounding countryside. Subsequently, several SEBE sim ulations were performed in order to compare the outcomes obtained from satellite data against simulations fed by meteo-radiometric measurements. The validation of satellite data shows that global shortwave irradiance data provided by the Meteosat are representative of the solar radiation fluxes, even in a complex terrain. SEBE simulations fed by different meteorological input performed well at different comparison locations although showing slightly broad errors using satellite data as input.

1. Introduction

The importance of a reliable assessment of solar radiation in urban environment modelling is growing together with the spatial resolutions of models. Monitored meteorological parameters are essential to provide accurate boundary conditions as input for the models. Indeed, a growing number of weather stations are available in the complex urban environment, but each one provides data representative of a specific site morphology, encouraging their use for a limited area. Providing proper boundary conditions for urban modelling remains a difficult task, as they are usually derived from observations limited at a single-point, which negatively affects model reliability, especially in complex terrains (Pappaccogli et al., 2018).

In this work, a case study for the urban area of Bolzano, Italy, was proposed in order to study the applicability of satellite data as available meteorological input for urban modelling in complex terrain. Furthermore, possible advantages led by satellite input data over weather stations were discussed as well, such as: (a) a better representation of shortwave flux in a 4-5-kilometer modelled grid; (b) the absence of potential biases due to the position of the weather station; (c) the availability of a regular pattern of input data at a global scale, which allows modelling where ground recordings are scarce.

As a first step, the images from Meteosat Second Generation (MSG) satellite were analysed to obtain hourly Surface Solar Irradiance (expressed as watts per square meter), which was first validated against global horizontal irradiance measurements from a network of ground weather stations located both in the urban and in the surrounding rural areas of Bolzano. Several simulations were then performed with the Solar Energy on the Building Envelopes (SEBE) model, in order to compare the outcomes obtained from satellite data against simulations fed by meteo-radiometric measurements. Finally, in order to test the performance of the SEBE model on different urban surfaces, such as roofs and walls, a validation was carried out on three different sites located in the urban area of Bolzano.

This work is organized as follows. The second section introduces the Meteosat satellite data and the spatial input used in the SEBE model, providing detailed information regarding the datasets and the methodologies used in this work, respectively. The

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third section describes first the validation of the Meteosat satellite data by means of a comparison with data from a network of ground weather stations, and then the sensitivity analysis carried out to assess the impact of different input data on SEBE model results. Finally, the fourth section contains the discussion and conclusions.

2. Methods

2.1 Satellite Data

The hourly solar surface irradiance (SSI) data (Fig. 1) were derived from images obtained by geostationary Meteosat Second Generation (MSG) class meteorological satellites, operated by EUMETSAT. The images were obtained using the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on-board instrument. The Meteosat satellites were placed in two geostationary locations: Meteosat-8 over Indian Ocean and Meteosat-11 in latitude-longitude 0°. The satellite data was remapped onto a 0.05° regular grid and expressed in watt per square meter. In particular, at the Bolzano latitude (i.e., 46.50 °N), the horizontal spatial resolution of each pixel is about 25 km².

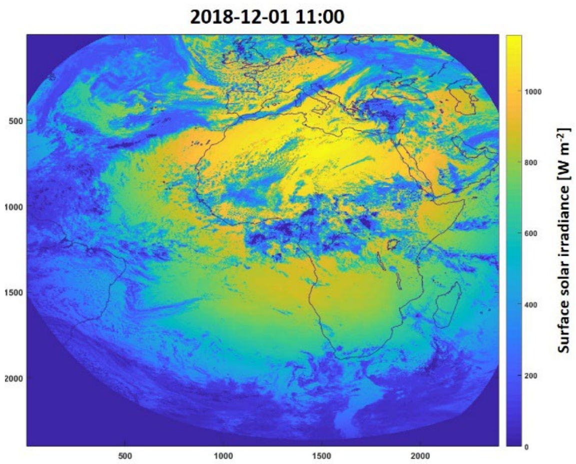

Fig. 1 – Example of Surface Solar Irradiance (SSI) from the Meteosat satellite data. The slot shown is 01 December 2018 at 11:00 UTM

In order to test the quality of the satellite data, Meteosat images were validated by a comparison with ground measurements, through an analysis of the hourly irradiance values. Specifically, the satellite global horizontal irradiation GHI was compared against ground measurements at five convectional weather stations during a six-month period (i.e. July to December 2018), being representative of the annual declination variation. These meteorological stations provide measurements in both urban and rural areas, and belong to the network of conventional weather stations operated by the Provincial Agency for Environmental Protection (APPA), the Autonomous Province of Bolzano, as well as the meteo-radiometric station installed on the rooftop of the E-building of the Free University of Bozen-Bolzano. An overview of the weather stations selected for the aforementioned analysis is reported in Table 1.

Table 1 - List of selected weather stations for radiation measurements located close to the urban area of Bolzano used in the validation of the satellite-based radiation estimates.

ID Station	Position (°N, °E)	Altitude (m)	Location
AMBA	46.4993/11.3420	286	Rooftop/Urban
BOL	46.4977/11.3128	254	Suburban
BRO	46.4065/11.3111	226	Rural
SGEN	46.5304/11.3319	970	Rural
UNI	46.4981/11.3495	292	Rooftop/Urban

The validation results are reported in Section 3.1. Specifically, the hourly GHI estimates from MSG and the pyranometers at the five selected weather stations are compared, referring to all sky conditions that occurred during the entire 6-month dataset (i.e. July to December 2018). In order to quantitatively validate satellite data, the root-mean-square error (RMSE), mean error (BIAS) and the coefficient of determination (R^2) were evaluated, quantifying the difference between ground measured and satellite GHI. However, only values for a solar elevation > 10° were used in the analysis, as recommended by Ineichen et al. (2009).

Furthermore, a clearness-index was obtained using the solar radiation data provided by satellite images as they are not affected by the shadowing effect of surrounding orography in complex terrain measurements. Specifically, the Surface Solar Irradiance (SSI) provided by MSG Meteosat satellite data

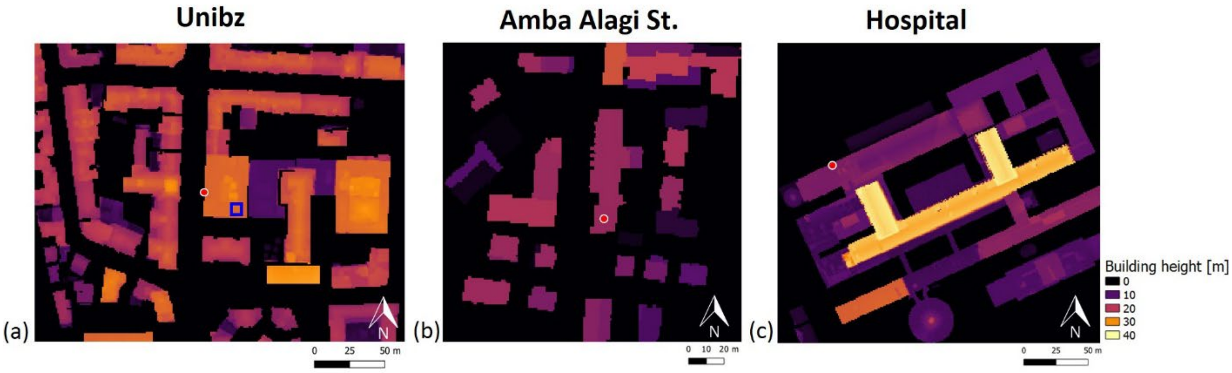

Fig. 2 - Digital surface model DSM with 1 m spatial horizontal resolution representing building heights at (a) university building ("Uni"); (b) Amba Alagi St. ("Amba") and (c) hospital ("Osp"). Observation points (red dots) and meteo-radiometric station ("UNI", blue square) are also shown

was normalized by the corresponding extra-atmospheric irradiance, as reported by Ineichen et al. (2009), as follows:

$$K_t = (SSI)/(SSI_{TOA}) \quad (1)$$

where SSI_{TOA} is the extra-atmospheric irradiance. In order to use the clearness index as a reliable sky condition descriptor, Perez et al. (1990) introduced a method to make the index independent of solar radiation angle:

$$K'_t = \frac{K_t}{\left\{1.031\, exp\left[\frac{-1.4}{(0.9+9.4/M)}\right]+0.1\right\}} \quad (2)$$

where K'_t is the modified global or solar surface irradiance clearness index, M is the optical air mass as defined by Kasten (1980) and h is the solar elevation angle above the horizon expressed in degrees:

$$M = [\sin h + 0.15\,(h + 3.885)^{-1.253}]^{-1} \quad (3)$$

Since the modified clearness index is relatively independent of the solar elevation angle, the three intervals were defined to characterize the three sky-types:

Clear sky conditions:	$0.65 < K'_t \leq 1.00$
Intermediate sky conditions:	$0.30 < K'_t \leq 0.65$
Overcast sky conditions:	$0.00 < K'_t \leq 0.30$

The sky-types classification is applied at the correlation analysis during the six-month analyzed period, which is reported in detail in Section 3.2.

2.2 Spatial Input Data

Three different locations were selected in order to validate the simulated SEBE output with radiometric ground observations. Specifically, Fig. 2a-c shows elements of the input surface information, such as the ground and building DSM, derived by the Geo-Catalogo of the Autonomous Province of Bolzano (http://geocatalogo.retecivica.bz.it/geokatalog). Two sets of data were used to derive the DSM: the LiDAR dataset was used to derive ground heights, whereas a high-detail 3D vector layer was used to define roof structures. As can be noted, only the area surrounding the comparison stations, which directly influences the measurements, has been modelled in order to reduce the computational effort of SEBE simulations.

The dimensions of the model domains are about one or two hundred meters on each side, with a horizontal spatial resolution of 1 m. The two weather stations referred to as Amba Alagi St., "Amba" and Hospital, "Osp", are both located on the building rooftops (Fig. 2b,c), characterized by a height of 17 m and 14 m, respectively, and record horizontal solar irradiation. By contrast, the University observation point ("Uni" in Fig. 2a) is located on the vertical façade of the E-building of the University Campus, at 25 m, and records vertical solar irradiation. Specifically, the validation instrument at the university site is a sunshine pyranometer SPN1, installed on a west-exposed vertical façade (Pappaccogli et al., 2019). "Uni" and "Amba" points are both located in the core of the city of Bolzano, in the dense neighbourhood of the city center, mainly characterized by midrise buildings (average heights of 13.6 m and 12.9 m, respectively), separated by non-extensive and scattered green areas (urban fraction ~70 %). The station named "Osp", instead, is located in the western part of the city in suburban area, where apple orchards and vineyards are contiguous to the urban area and fragmented only by sparse single-low buildings (Pappaccogli et al., 2018).

2.3 SEBE Simulations

As many simulations are involved in this work, each one adopting different sources and solar radiation components as meteorological input, a general overview of the SEBE simulations carried out is now presented. Since the analysis of the model results focuses on the comparison between observed and simulated daily solar irradiation at both wall and roof surfaces, for the purpose of readability, the names of the SEBE simulation report both the location used for comparison ("Uni, "Amba" or "Osp") and the source of meteorological input (Table 2). In particular, the source of meteorological input re indicated as "a" when the global horizontal irradiation GHI, the direct normal irradiation DNI, and the diffuse horizontal irradiation DHI measured by the meteo-radiometric station on the university E-building rooftop (referred to as "UNI") are used; "b" when only the UNI GHI is employed; and "c" when the GHI provided by Meteosat satellite is considered.

Table 2 – Overview of the SEBE simulations with the respective analyzed building surface (left) and the meteorological input (top)

Daily global irradiation [Wh m^{-2}]	Source UNI **a**	 **b**	 Meteosat **c**
Variables	GHI/DHI/DNI	GHI	GHI
Wall	Uni-a	Uni-b	Uni-c
Roof	Amba-a Osp-a	Amba-b Osp-b	Amba-c Osp-c

As reported by Lindberg et al. (2015), GHI, DNI and DHI are preferable to run SEBE but they are rarely available since conventional weather stations usually provide only GHI measurements. In this case, SEBE computes the diffuse component through the statistical model by Reindl et al. (1990), which considers air temperature and relative humidity to improve the accuracy of the calculations.

3. Results

3.1 Satellite Validation

Fig. 3 shows the scatter-plot for the hourly GHI estimates from MSG and the pyranometers at the five selected weather station reported in Table 1. The dots refer to all sky conditions which occurred during the entire 6-month dataset (i.e. July to December 2018). The two regression lines (red lines) represent the confidence intervals of 2*RMSE.
As can be seen in Fig. 3, the satellite data compares well to ground observations throughout the analysed period (i.e. July to December 2018) and different weather conditions, which is confirmed by the correlation coefficient (R^2 = 0.93). No significant trend deviation can be observed, with a BIAS of about 9 W m^{-2}, and small relative errors (RMSE= 66.4 W m^{-2}). However, the satellite data tend to overestimate and underestimate solar irradiance peaks, respectively, during summertime and wintertime, especially under clear-sky conditions. As expected, some errors occur during evening and morning transition periods, due to the coarse spatial resolution of the satellite data, which is stressed by the complex orography of the terrain. It is worth noting that the larger spread of the points placed below the value of around 400 W m^{-2} represents the GHI values both during the winter and overcast days, when the performance of satellite images is lower compared to clear-sky conditions. Moreover, it is worth highlighting that both errors and analysis results are similar to the findings of several studies in the literature (Federico et al., 2009; Kosmopoulos et al., 2015; Gomez et al., 2016).

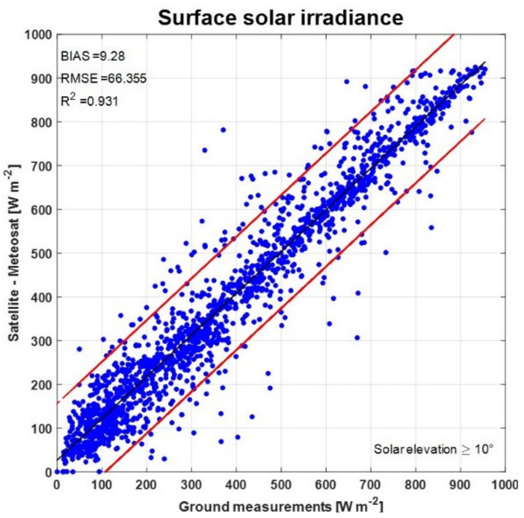

Fig. 3 – Satellite estimate of ground based measurement comparison for global horizontal irradiance (GHI) for all analyzed months (i.e. from July to December). Simple linear regression (black line), and confidence intervals of 2*RMSE (red lines)

3.2 SEBE Analysis

The analysis presented in this section (Fig.s 4 and 5) aims to evaluate the impact of the different meteorological input (i.e. three and one solar radiation components), provided by different sources (i.e., meteo-radiometric station and satellite), on the simulated daily surface irradiation on different building surfaces (i.e. roofs and walls). As in the satellite analysis, root-mean-square error (RMSE), mean error (BIAS) and the coefficient of determination (R^2) were evaluated (Table 3). Several scatter plots report the comparison between observed and simulated daily solar irradiation (expressed in watthours per square meter), distinguished respectively by the clearness-index (Fig. 4a-i) and sky-types classification (Fig. 5a-i).
Fig. 4a-c shows the comparison at the "Uni" site. The highest accuracy was found for simulations fed by "a" (UNI GHI/DNI/DHI) and "b" (UNI GHI) meteo-radiometric inputs, with a correlation coefficient R^2 of 0.95 and 0.96, respectively, while slightly lower accuracy was encountered in the case of "c" (Meteosat GHI) input (R^2= 0.88). For the Amba Alagi St. site (Fig. 4d-f), very good agreement was registered for all simulations (R^2 = 0.97-0.99), although a slight spread was detected for Amba-c simulation. Finally, the hospital site (Fig. 4g-i) displayed similar results for all different simulations (R^2 = 0.96). As can be noted, in the last site a slight overestimation occurred, especially during the summer period, as confirmed by a BIAS of 385-490 Wh m^{-2}. These larger errors are probably due to the critical position of the weather station, installed close to small obstacles (such as the HVAC system cooling towers), which are not properly described by the 1 m DSMs. Furthermore, it is worth noting that the slight differences between Osp-c and other simulations (i.e., Osp-a and, Osp-b) are most likely related to the greater distance between the hospital site and the UNI meteo-radiometric station, which represents the source of meteorological input.

Table 3 – Mean errors (BIAS), root-mean-square errors (RMSE) and coefficient of determination (R^2) for daily solar irradiation compared with measurements at the three sites

	BIAS (Wh m^{-2})	RMSE	R^2
Uni-a	43.11	248.44	0.95
Uni-b	17.18	208.20	0.96
Uni-c	56.67	388.54	0.87
Amba-a	121.44	302.40	0.99
Amba-b	99.19	260.77	0.99
Amba-c	28.38	374.80	0.97
Osp-a	490.8	728.43	0.97
Osp-b	479.46	706.15	0.97
Osp-c	385.97	608.02	0.97

In order to evaluate the performance of the model during different types of sky conditions, similar analyses were carried out for the selected weather stations (Fig. 5a-i). Overall, a strong correlation between observed and simulated daily irradiation was registered for the three different sky-type classes in all sites. However, clear-sky conditions were characterized by wider spreads in all sites, while lower values were observed under overcast conditions.

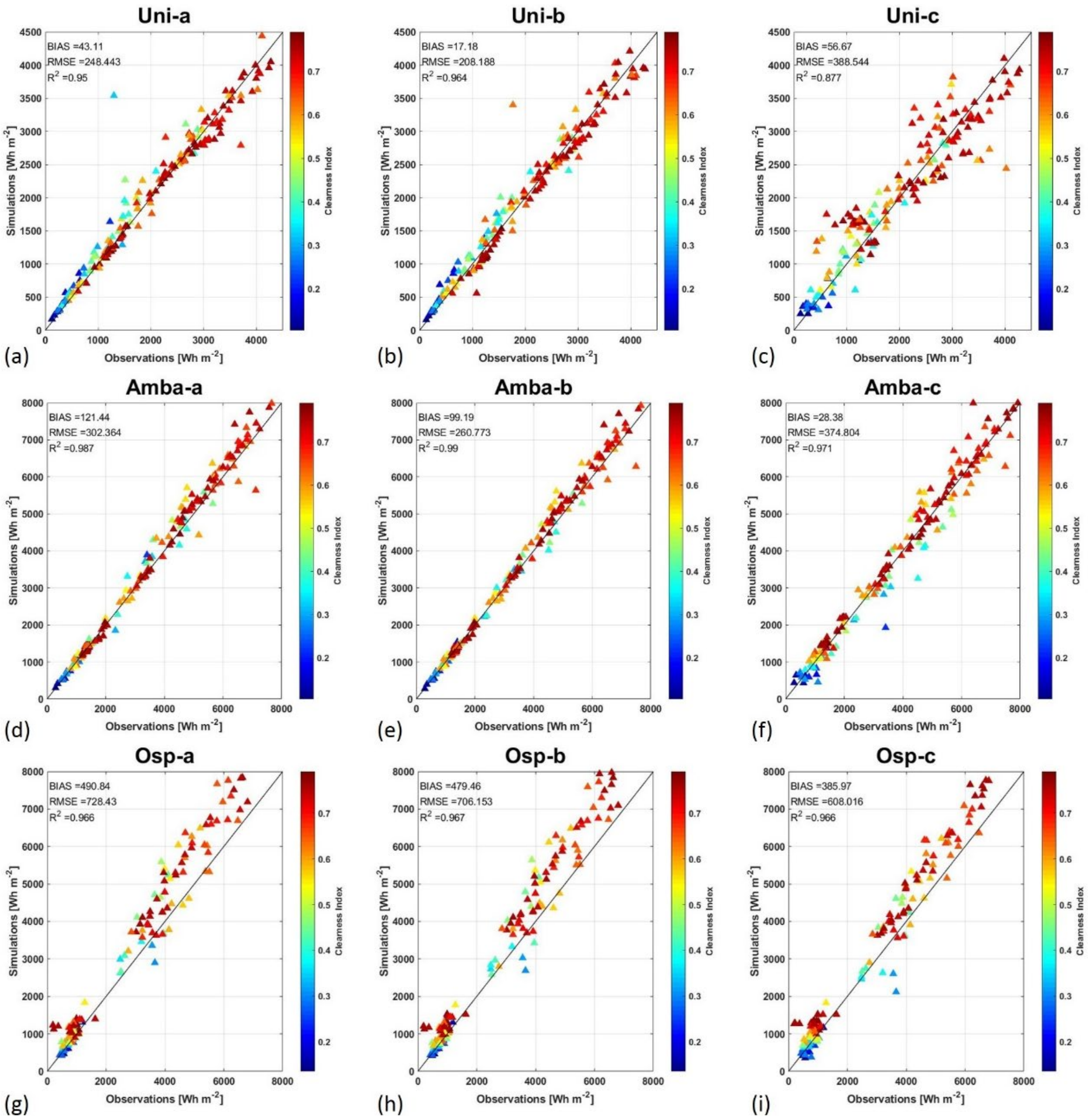

Fig. 4 – Scatter plot of observed and simulated total daily irradiation (Wh m^{-2}) correlated to clearness index during the analyzed period (i.e., July-December 2018) at (a-c) University; (d-f) Amba Alagi St., (g-i) Hospital location

4. Discussion and Conclusion

The results described in previous sections show that Meteosat satellite data, which provide the hourly Surface Solar Irradiance, are representative of the shortwave flux at urban scale, providing a regular input for modelled area even in a complex terrain. Indeed, the data used as boundary conditions in the SEBE model are able to describe the shortwave flux in a 4-5-kilometer grid, without affecting negatively the model reliability. However, ground measurements are still necessary in order to validate the relative satellite data according to weather station position.

In this respect, the global horizontal irradiance provided by Meteosat satellite images was compared with the ground measurements from a network of weather stations located close to the urban area of Bolzano. The satellite data were found in good agreement with the ground observations (R^2 > 0.93), throughout the analysed period (i.e. July to December 2018) and in different weather conditions. Nevertheless, satellite data tended to overestimate / underestimate solar irradiance peaks during summertime and wintertime, respectively, and especially under clear-sky conditions. Furthermore, some errors occurred during evening and morning transition periods, due to the coarse spatial resolution of satellite data.

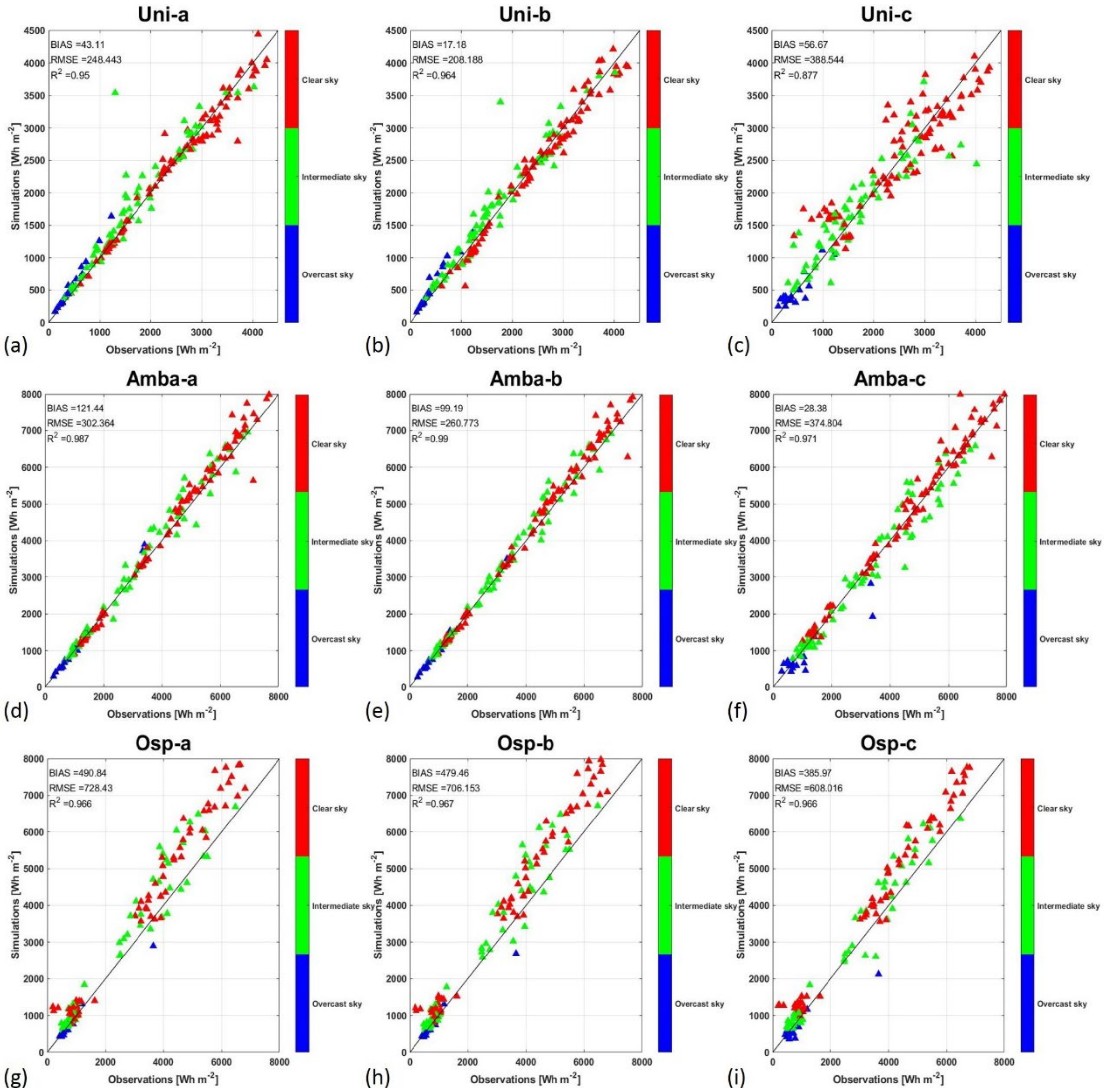

Fig. 5 – Scatter plot of observed and simulated total daily irradiation (Wh m^{-2}) correlated to sky-types climatic classification during the analyzed period (i.e. July-December 2018) at (a-c) University; (d-f) Amba Alagi St., (g-i) Hospital location

As a whole, only a very slight overestimation occurred in the analysed six-months period, showing a BIAS and RMSE of 9 and 66.3 Wh m^{-2} , respectively. In terms of simulations, the sensitivity analysis highlighted that the different meteorological inputs have a small impact on the performance of the SEBE model. Indeed, good results were obtained for all studied sites, on both vertical and horizontal urban surfaces, with a correlation coefficient in the range of 0.88-0.99. In particular, the best approximation was obtained with the model fed by the global horizontal irradiation only, using the statistical model by Reindl et al. (1990) to calculate the diffuse radiation component.

Referring to the future developments, the assessment of the impact of input weather data will be further investigated by the coupling of SEBE output with Building Energy Simulation models.

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