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A solar atlas for the Trentino region in the Alps: quality control of surface radiation data

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Abstract

The accurate measurement and assessment of the solar radiation available at the Earth's surface are important for a wide range of energy-related applications. They are particularly challenging in mountainous areas, where orographic effects greatly increase spatial and temporal variability of radiation. In this contribution criteria and outcomes from the quality control of a set of hourly global irradiation observations, collected at the radiometric stations of the Trentino region (Italian Alps) during the years 1987-2012, are presented. The validated dataset will provide the basis for a high-resolution solar atlas of Trentino.

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Keywords: solar radiation; ground observations; quality control; complex terrain; Alpine region.

1. Introduction

The accurate assessment of the solar radiation available at the Earth's surface is essential to a wide number of energy-related applications, such as planning and sizing of photovoltaic plants [1] and other solar energy systems, or design of energy-efficient buildings. A good knowledge of the solar radiation climatology is also relevant to a variety of scientific and technical fields, such as meteorology, hydrology, ecology, forestry, agriculture and health studies. The characterization of solar radiation from observations is particularly challenging in mountainous regions,

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for its temporal and spatial variability are higher than over flat terrain [2]. This mainly depends on orography-related effects, like shadowing by surrounding orography, variation of the terrain elevation (i.e. atmosphere thickness) and reduction of the sky-view factor. Also typical weather phenomena, like summer convection over mountain tops due to air mass convergence driven by diurnal local winds [3], may play a role.

In general solar radiation ground-based observations are prone to multiple types of error. They may be caused by the failure of the sensor or of the data logger, by the wrong installation or calibration of the instrument, as well as by external factors, like the soiling of the pyranometer's dome by dust, ice or snow, or its shadowing by some obstacle (e.g. a tree or a building) [4]. As a consequence, a strict quality control (QC) of radiation data is mandatory in order to exclude erroneous and/or suspicious data, and obtain accurate estimates of the available solar resource [5]. QC of radiation data is even more important in mountainous regions, where frequent inspections of stations are not feasible due to accessibility issues and costs, and operational conditions are typically rather harsh. For example, the snow-cover persistence at elevated sites may cause large records of data to be rejected, if pyranometers are not cleaned regularly. QC procedures for radiation data usually include tests based on lower and/or upper threshold values, within which valid data are expected to fall. Thresholds can be inferred either from solar radiation models, to identify physically impossible values, or from the data themselves (i.e. from long-term data statistics or from data collected at neighboring stations), to detect implausible values [6]. The reader is referred to Younes et al. [4], Journée and Bertrand [6], Geiger et al. [7] and Muneer and Fairooz [8] for an exhaustive review of QC criteria commonly applied to radiometric observations.

In this paper preliminary results from a high-resolution solar atlas of Trentino, a small mountainous region in the Italian Alps, are reported. The atlas will be primarily based on the interpolation of ground-based observations, but it will also benefit from the integration of satellite-based radiation fields. In particular, the criteria adopted for the QC of horizontal global irradiation (G) hourly data, collected at the local radiometric stations during the years 1987-2012, are presented here. The quality tests are chosen among those widely used in QC procedures for solar radiation data. In some cases they are slightly modified in order to meet the nature of observations taken over complex terrain. Selected results from the dataset validation are shown.

The paper is organized as follows. Section 2 presents the study area, the radiometric network and the analyzed dataset, while Sect. 3 lists the QC tests applied to the data, as well as the coding system adopted. Results of the validation of radiation data are shown in Sect. 4. Finally, Sect. 5 provides a brief summary of the work and conclusions, together with an outlook on future work.

2. The dataset

2.1. The study area

The study area is the territory of the Autonomous Province of Trento – usually referred to as Trentino – in north-eastern Italy. The Trentino region is located on the southern slope of the Alps, immediately north of the Po Valley. The region (surface area: 6212 km^2) is almost entirely mountainous, with terrain elevations ranging from 65 to 3764 m m.s.l., and displays a very heterogeneous morphology (see Fig. 1). Indeed, it is characterized by the presence of many mountain chains and uplands, as well as by some major Alpine valleys and several smaller side-valleys. As a consequence, the local climate is also very heterogeneous. It varies from the typical Alpine climate characterizing the most elevated areas, to the sub-continental climate of the minor valleys, to the sub-Mediterranean conditions found in the southernmost part of the region, due to the mitigating effect of Lake Garda. Such a great variability over such a small region implies that a large number of observational sites are ideally needed for an adequate characterization of the climatology of solar radiation, as well as of other meteorological variables.

2.2. The radiometric network

Trentino benefits from a very dense network of radiometric stations (cf. Fig. 1). Indeed, a total number of 104 stations were active at the end of 2012. These stations are managed by three different institutions: the meteorological office of the Autonomous Province of Trento (Meteotrentino; 26 stations), the Edmund Mach Foundation (FEM; 77 stations) and the University of Trento (UniTN; 1 station). Either 15-min (Meteotrentino) or 1-h values (FEM) of global irradiation (units: MJ m^{-2}) are measured at most stations, while 10-min observations of global irradiance (units: W m^{-2}) are collected at UniTN station. First-class Kipp & Zonen CM6B thermopile pyranometers are installed at first-level FEM stations, while second-class Davis and MTX silicon cell pyranometers are installed at second-level and forestry FEM stations respectively. Meteotrentino stations are provided with second-class silicon cell pyranometers produced by Metex, while UniTN station is also equipped with a Kipp & Zonen CM6B.

Although the average distance to the nearest station is rather low (about 3 km; see Fig. 2a), the spatial distribution of the stations is not very homogeneous. Indeed, observational sites are preferentially situated at the floor of the largest valleys and in the most populated areas, while the most elevated areas are not very densely instrumented or even completely lack stations (cf. Figs. 1 and 2b). This is partially ascribable to the higher costs and the greater difficulties associated with the instrumentation maintenance in elevated, not easily accessible sites. Apart from technical issues, the greater density of stations on the valley floors also reflects the agro-meteorological nature of the FEM network.

2.3. The data

The dataset is composed of hourly observations of *G*, which were retrieved by cumulating sub-hourly data in case of higher original resolution (i.e. for data from Meteotrentino and UniTN stations). Data were stored using a “backward” convention for timestamps, e.g. the “01:00 LST” label corresponds to measurements collected between 00:01 and 01:00 LST (UTC+1).

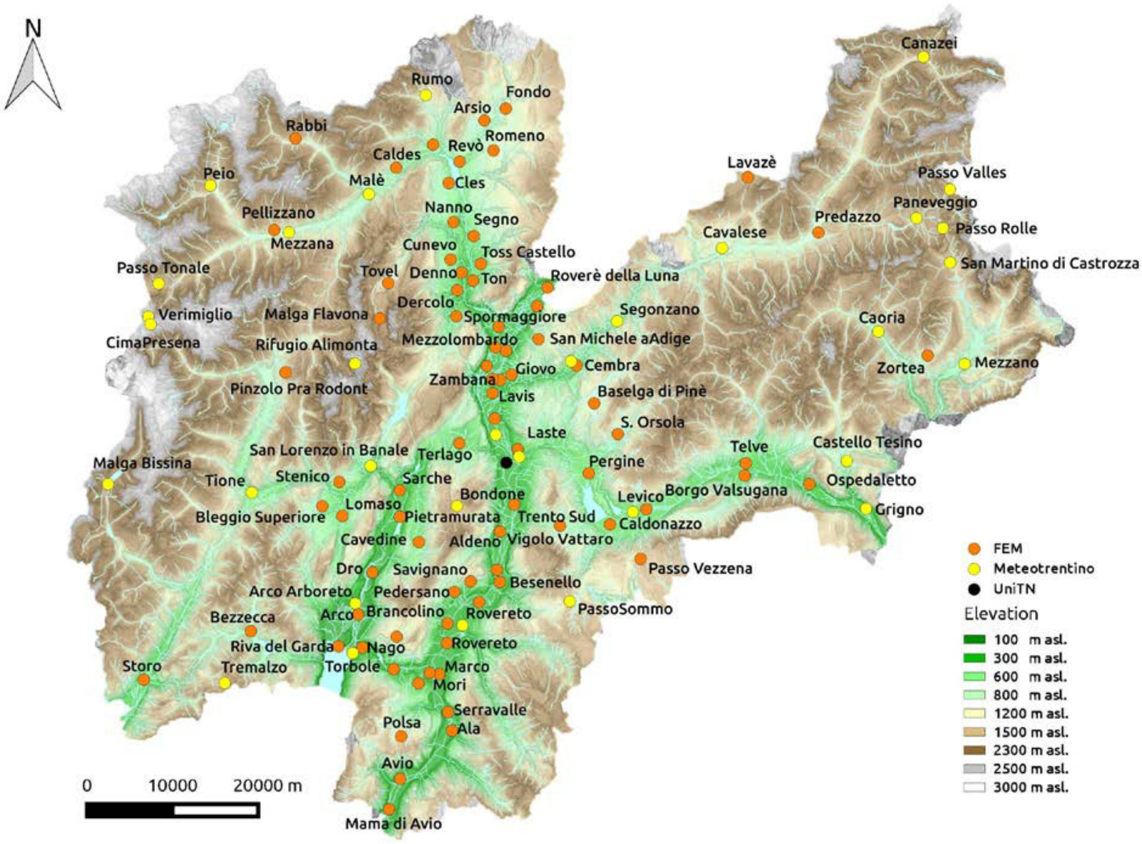

Fig. 1. Map of terrain elevation for the Trentino region. The stations of the local radiometric network are indicated by dots, whose colors identify the managing institution (see legend).

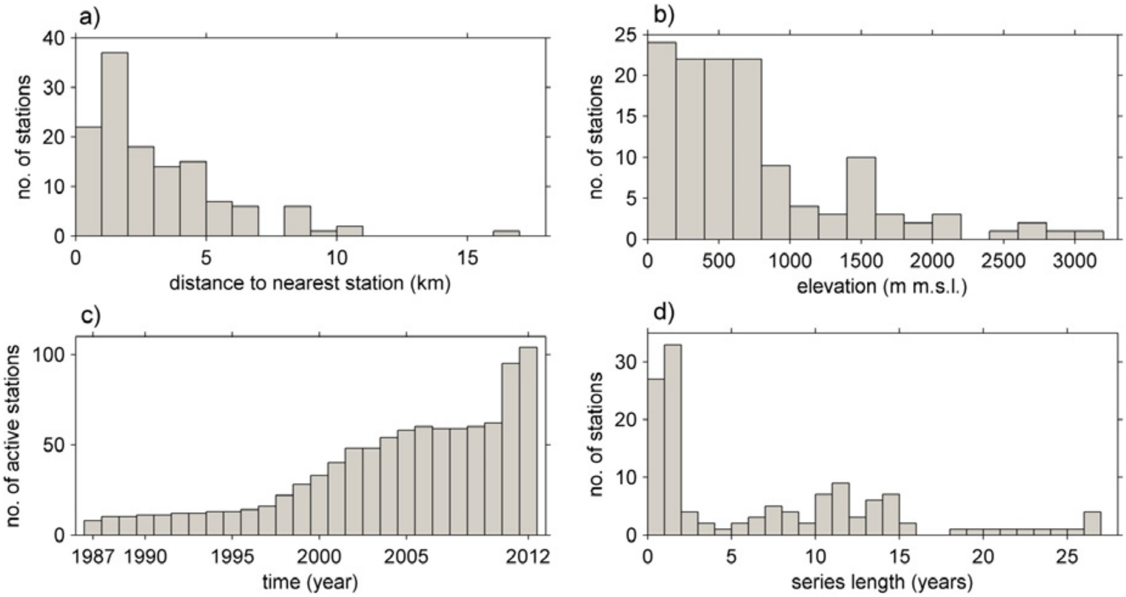

Fig. 2. Radiometric stations of Trentino: histograms of a) distance to the nearest station, b) elevation, c) number of active stations per year and d) length of time series.

The first observations included in the analysis date back to the year 1987, while the most recent were collected on 31-12-2012. However, the overall temporal coverage of the dataset is not homogeneous, for the number of stations considerably grew along the years, especially starting from 1998 and 2010, as can be seen in Fig. 2c. Accordingly, a large number of time series displays lengths of less than 5 years, and only 12 long-term records (i.e. 20 years or more), suitable for the detection of possible climatological trends, are available (cf. Fig. 2d).

3. The quality control procedure

3.1. Quality control criteria

In general, QC criteria for radiation data take into account the physics of solar radiation processes, the temporal variability of observations and their statistics, and the spatial correlation of simultaneous observations from neighbouring sites. The criteria implemented for the automatic QC procedure, taken from Journée and Bertrand [6], are reported below. Notice that, due to the complex orography of Trentino, some tests from the literature were modified to properly take into account orography-related effects, especially for early-morning and evening hours.

Physical threshold tests. The following physical thresholds were applied to diurnal observations (defined as hourly observations including at least 15 min of non-null extra-terrestrial irradiance, i.e. observations whose timestamps exceed sunrise and sunset times by more than 15 and less than 45 min respectively):

$$0.03 \cdot G_e \leq G < G_e \tag{1}$$

$$G < 1.1 \cdot G_c \tag{2}$$

The European Solar Radiation Atlas model (ESRA) [9,10] was used for the computation of hourly-cumulated values of G_e (horizontal extra-terrestrial irradiation) and G_c (horizontal clear-sky global irradiation), adopting a time step of 15 min and a Linke turbidity coefficient [11] of 2 (corresponding to very clear atmosphere and low-turbidity conditions). Astronomical sunrise and sunset times were also computed by means of the ESRA model. On the other hand, "orographic" sunrise and sunset times (i.e. the times of start and cessation of direct radiation, as determined by local orography) were retrieved thanks to the *r.horizon* module of GRASS GIS [12], on the basis of a 30-m resolution terrain elevation model [13]. An azimuthal angle step of 0.1° and a maximum distance of 200 km were adopted for the calculations. For observations collected between astronomical and orographic sunrise (sunset) times, when only diffuse radiation is measured, different limits were set:

$$0 \text{ MJ m}^{-2} < G \leq 0.76 \text{ MJ m}^{-2} \tag{3}$$

corresponding to a maximum (diffuse) irradiance of 210 W m^{-2} [5].

Step test. The test aims at identifying unphysical jumps between consecutive observations, corresponding to erroneous spikes or dips in the time series. Following recommendations by Journée and Bertrand [6], Eq. 4 was applied to pairs of consecutive observations taken at (*i*) and (*i*–1) hours:

$$\left| \frac{G^{(i)}}{G_e} - \frac{G^{(i-1)}}{G_e} \right| < 0.75 \tag{4}$$

Persistence test. The test checks the temporal variability of observations on daily basis, in terms of statistical parameters. In particular, both low and high inter-hour variability might correspond to instrumental failure. For daily mean (μ) and standard deviation (σ) of diurnal observations the following expression holds:

$$\frac{1}{8} \cdot \mu\left(\frac{G}{G_e}\right) \leq \sigma\left(\frac{G}{G_e}\right) \leq 0.35 \tag{5}$$

This test was performed only for days with at least three (if $N \leq 6$ h) or $N/2$ (if $N > 6$ h) hourly observations available (notice that N is the number of hours between "orographic" sunrise and sunset times).

Spatial consistency test. The test was applied to daily totals of global irradiation (G_d), to avoid "false" test failures caused by short-range and short-term variability of solar radiation on cloudy days. For each station *i*, $G_{d,i}$ was estimated by inverse-distance interpolation of observations from *n* neighboring stations (characterized by similar elevation and exposure). Then upper limits were applied to the difference between measured ($G_{d,i}$) and estimated ($G^*_{d,i}$) values:

$$\left| G_{d,i} - G^*_{d,i} \right| \leq C \cdot \frac{1}{n} \sum_{j=1}^{n} \left| G_{d,j} - G^*_{d,i} \right| \tag{6}$$

defined as fixed proportions of the mean bias over the stations involved in the interpolation, i.e. 50, 100 or 200%, corresponding to C = 1.5, 2 and 3 respectively. Journée and Bertrand [6] recommend C = 1.5, while here different thresholds were considered to account for the greater spatial variability of solar radiation induced by the complex orography.

3.2. Quality control codes

Associated with the tests described in Sect. 3.1, specific QC codes were assigned either to single hourly records or the 24 hourly records forming each controlled day, depending on the type of test. The coding system is summarized in Table 1, where also the final quality codes are reported, namely: 0 = valid data, 1 = suspicious data, 2 = erroneous data.

Table 1. Scheme of QC codes and associated final quality codes.

QC code	corresponds to		quality code	applied to
0	valid record		0	hour
1	missing record		2	hour
2/1	physical threshold test (Eq. 1, lower boundary)	not passed	2	hour
2/2	physical threshold test (Eq. 1, upper boundary)	not passed	2	hour
3	physical threshold test (Eq. 2)	not passed	2	hour
4	step test (Eq. 4)	not passed	2	hour
5	persistency test (Eq. 5)	not passed	2	day
6	persistency test (Eq. 5)	not performed	1	day
7	physical threshold test (Eq. 3)	passed	0	hour
8	physical threshold test (Eq. 3)	not passed	2	hour
9	negative record		2	hour
-9	non-null nocturnal record		2	hour
0*	spatial consistency test (Eq. 6, C = 1.5)	passed	0	day
1*	spatial consistency test (Eq. 6, C = 1.5)	not passed	1	day
2*	spatial consistency test (Eq. 6, C = 2)	not passed	1	day
3*	spatial consistency test (Eq. 6, C = 3)	not passed	2	day

4. The quality control results

For a few stations the number of available data was considerably reduced after the QC, finally causing entire time series to be rejected. This indicates that difficulties and costs associated with the maintenance of a dense radiometric network, combined with the particularly harsh operational conditions typical of many mountain sites, may sometimes lead to observations of inadequate quality.

In Fig. 3 hourly frequencies of QC codes are shown as an example for Tovel station, which is greatly affected by orographic shadowing effects. The modification of the physical threshold tests (Eq. 3) allows the “rehabilitation” of many data (otherwise flagged as erroneous), especially for the hours between astronomical and orographic sunrise/sunset times (QC code combinations: 7 2/1, 7 2/2 3, 7 3). In particular, Eq. 1 sets a lower threshold which results too high in case of orographic shadowing and clear-sky conditions (7 2/1). Moreover, also the upper threshold values (2/2 3 and 3) may be subject to problems associated with possible clear-sky model inaccuracies, especially at low solar elevations. In this case, a careful visual inspection of data is required to determine whether the data should be rejected or not.

With regard to the spatial consistency test, the morphological complexity of the territory sometimes hinders the possibility of finding neighboring stations characterized by elevation and exposure conditions similar to those of the analyzed station. For example, in winter months Telve station exhibits a high number of suspicious and invalid data (QC codes: 1*,2*,3*), for in that months G_d estimates are systematically lower than observations (see Fig. 4). This is due to the influence of data from Borgo Valsugana station, lying only ~1.5 km away, at the same altitude but on the opposite side of the same W-E oriented valley. Due to its location Borgo Valsugana suffers from significant shadowing effects by surrounding reliefs. This causes the test (when applied to both stations) to return unreliable results, especially during the winter season. Unfortunately, the second closest station to Telve with a comparably long time series lies more than 20 km away at 1370 m m.s.l., i.e. almost at crest level, and hence exhibits a rather different radiation climatology. The spatial consistency test is sometimes affected also by inhomogeneities in the time series, which might lead to wrong G_d estimates and test results. Accordingly, poor-quality (fractions of) time series must be manually removed from the interpolation. On the other hand, the results of this test might turn out to be useful for later homogeneity analyses (cf. the construction of reference time series in Alexandersson [14]).

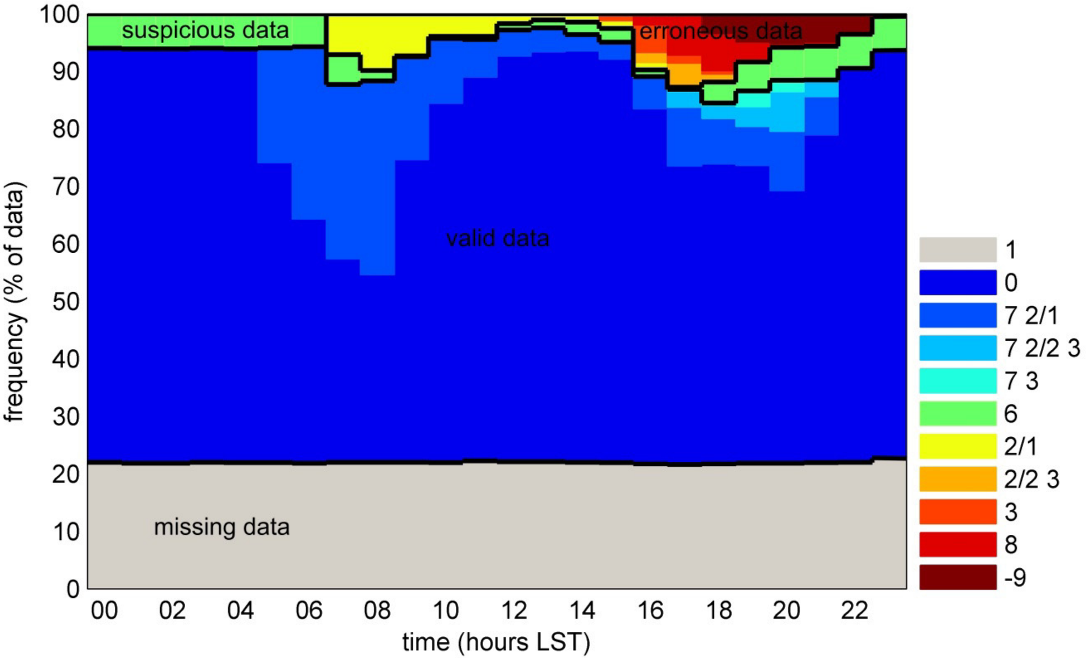

Fig. 3. Hourly frequencies of QC codes (cf. Table 1) for Tovel station (activity period: 17-05-2010 to 31-12-2012).

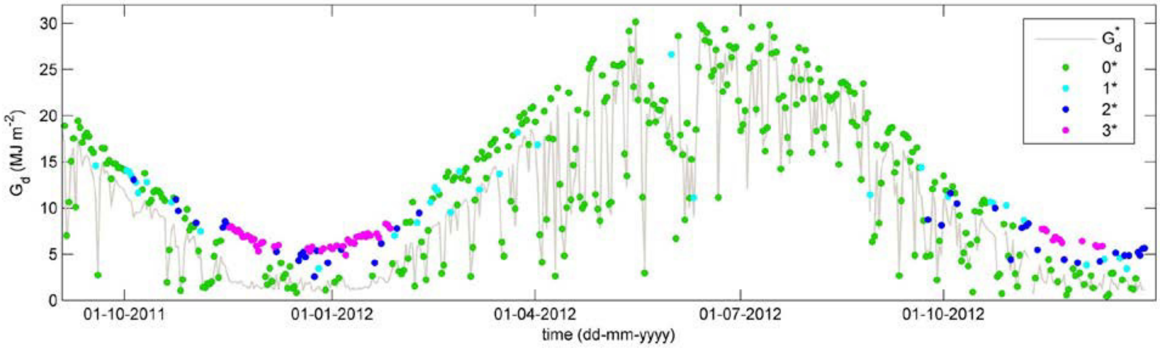

Fig. 4. Spatial consistency test results for Telve station: G_d observations (dots) compared with G_d estimates (line) from surrounding stations. See Table 1 for QC codes.

5. Conclusions and outlook

The paper presented criteria and results of the QC of hourly global irradiation data, collected in the mountainous region of Trentino in the north-eastern Italian Alps. After the description of the study area and of the local radiometric network, the QC tests applied to the dataset were described. They were chosen among widely adopted quality criteria, and partially modified to meet specific characteristics of the analyzed dataset.

The outcomes of the QC procedure highlighted that some time series are not of good quality, due to the additional difficulties and costs associated with the maintenance of meteorological stations in mountainous areas, and therefore need to be rejected. The results of the dataset validation also revealed the importance of a data-specific tuning of the thresholds values from the literature, in order to properly account for local orography-driven effects (like orographic shadowing) in complex-terrain regions. To this purpose clear-sky models based on GIS tools are extremely useful, as they are able to model the above-cited processes at very high resolutions. Moreover, the QC results also indicated that in mountainous regions the spatial consistency test is not always feasible, due to the wider range of elevation and exposure conditions of stations than in less heterogeneous areas.

The validated solar radiation dataset presented here will be the basis for the realization of a high-resolution solar atlas of Trentino. This will consist in monthly solar irradiation maps produced by interpolation of clear-sky index values (G to G_c ratio) retrieved from ground-based observations and GIS-based clear-sky model outputs. Geostatistical techniques, like residual kriging [15,16] or kriging with external drift [15], will be used (similarly to what done by Ruiz-Arias et al. [17]), and satellite-based measurements will be possibly integrated as in D'Agostino and Zelenka [18] and Journée and Bertrand [19], to take advantage of their continuous spatial coverage.

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