
Integration of ground measurements to model-derived data

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Summary

Bankable data for solar energy projects needs to ensure as much as possible the accuracy and general quality of solar radiation data to be used in the solar resource assessment studies for any site of interest in a project development. The term “site adaptation” is being used in the framework of solar energy projects to refer to the improvement that can be achieved in satellite-derived (or more generally model-derived) solar irradiance when short-term local ground measurements are used to correct systematic errors and bias of the original dataset. This document presents a review of different techniques for correcting long-term satellite-derived solar radiation data by using short-term ground measurements. The collaborative work has been done within the framework of Task 46 “Solar Resource Assessment and Forecasting” of the International Energy Agency’s Solar Heating and Cooling Programme. Different approaches whose use depends on the origin and characteristics of the uncertainties of the modelled data are presented. Recommendations to the use of ground measurements and the results of several approaches to improve satellite-derived data are shown through this report highlighting the importance of using site adaptation and the different degree of improvement that can be achieved depending on the climatological characteristics of the site.

1. Introduction and objectives

The successful utilization of solar energy systems requires a good knowledge of the solar radiation components' magnitude during the design and deployment phases. Concentrating Solar Power (CSP) projects, for instance, require reliable and accurate data on the direct normal irradiance (DNI) reaching their collectors. Similarly, solar projects using flat-plate collectors (PV or thermal) rely on good predictions of the incident global horizontal irradiance (GHI) or, even better, the tilted irradiance (GTI), also referred to as "plane of array" (POA). From the initial site selection stage to the plant's design and financing the solar resource assessment plays a major role in the success of the project whenever monthly or annual plant predictions are needed (Sengupta et al., 2015; Stoffel et al., 2010). Routine solar resource measurements are usually scarce and not usually available, or not accurate enough, at the selected site to properly evaluate the resource over the long-term, and consequently to secure the acceptance of the project. In addition, the inter-annual variability of solar radiation components has an important impact when determining the uncertainty associated with the energy yield prediction of solar plants over their lifecycle. Consequently, long-term solar radiation time series are required to derive a stable climatological mean and the associated standard deviation (Meyer et al., 2006; Sengupta et al., 2015; Stoffel et al., 2010). Because multi-decade measurements are hardly available at any potential solar power plant site, long-term time series of solar resource data must generally be derived from modelled data, typically using satellites to detect the strong influence of clouds on solar radiation. A variety of such model-derived data sets is currently available from different providers for almost every possible location worldwide, and for periods covering at least 10 years.

Based on the few existing comparative studies between satellite-derived solar radiation estimates and ground measurements (e.g., Gueymard, 2011; Ineichen, 2014), it is apparent that significant differences exist. For sound solar resource assessments, all model-derived estimates must be qualified as much as possible using locally available ground measurements. Moreover, all large solar power projects must respond to stringent bankability criteria, following the regular practice of financial institutions. From this standpoint, the detailed knowledge of the seasonal and inter-annual variability in the solar resource (DNI for projects using concentrating collectors; or GTI for PV projects) is of critical importance. Therefore, bankable energy production scenarios must be based on a statistical analysis of long time series. Since a large inter-annual variability of the solar resource means a larger risk, this variability must be studied. Current studies demonstrate that the inter-annual variability in DNI is significantly larger than that in GTI, itself larger than that in global horizontal irradiance (GHI) (Gueymard, 2012; Gueymard and Wilcox, 2011).

Different methodologies are currently being proposed to estimate the solar radiation components, but those based on meteorological satellite imagery are the most widely used, especially for the applications under study here, which require long-term solar irradiance time series (Hammer et al., 2003; Janjai et al., 2005; Perez et al., 2013; Perez et al., 2002; Polo J. et al., 2008; Rigollier et al., 2004). A thorough validation exercise of most of the current satellite-based databases has been performed within the Task 46 SHC-IEA activities (Ineichen, 2014).

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Satellite-derived irradiance data have the potential to accurately provide long-term hourly (sometimes sub-hourly) time series of solar radiation components; however, they are also subject to several sources of error, whose complex causes typically affect GHI, GTI and DNI differently (Cebecauer et al., 2011). For instance, satellite-derived methods usually require external atmospheric information on the most important attenuating components under cloudless conditions, namely aerosols and precipitable water vapor, with an important impact on the final uncertainty (Gueymard, 2012; Gueymard, 2014; Gueymard and Thevenard, 2009). Therefore, proper evaluation and characterization of the uncertainty sources of satellite-derived data constitute a crucial step towards the bankability of solar resource assessments for solar power plants. For instance, the correct identification and correction of systematic errors or bias in satellite-derived data by comparison with quality ground data can result in an important reduction of uncertainty. More precisely, if the satellite-derived estimates for a specific site can be calibrated against a short-term local measurement campaign, which is normally required by financial institutions, and typically starts a few months after the beginning of the project, the long-term solar resource accuracy can be substantially improved. This process of calibration or correction of modeled data is similar to what had been developed for the wind industry in the past (Eichelberger et al., 2011; Potter et al. 2008). Similarly to the case of wind energy resource assessment, different methods may be used, which are discussed in the sections below. Whereas the purpose of these methods is clearly defined, the terminology varies depending on the method's proponent. For instance, these methods may be referred to as "site adaptation" (Perez et al., 2013; Suri and Cebecauer, 2011), "dataset merging" (Thuman et al., 2012), or "measured record extension" (Bender et al., 2011; Gueymard et al., 2012). For clarity and conciseness, all these methods will be collectively referred to as "site adaptation" in what follows. In summary, all the various statistical methods that have been developed to decrease the uncertainty in the local solar resource try to improve satellite-derived irradiance data (by lowering their random errors, and most importantly their bias) using characteristics of corresponding ground observations during overlapping time periods.

Within Task 46 Solar Resource Assessment and Forecasting of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme an important effort is being made on improving the bankability of solar radiation datasets by developing procedures and methods designed to increase the quality of both ground measurements and modeled data, and to combine them efficiently as well. This report is intended to review the state of the art on the latter issue, which has become critical to improve bankability.

2. Ground measurement requirements

Before the integration of ground measurements into model-derived data can be performed with reasonable accuracy, the quality of the measurements has to be assured. The following steps should be fulfilled in order to obtain measurements of sufficient quality:

1. Proper design of the ground stations characteristics according to the intended aim of the data.

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2. Selection of radiometers having low uncertainty for the requested solar component
3. Proper installation of structures, sensors, instruments, power supply, and ancillary equipment.
4. State-of-the-art calibration of the radiometers with an adequate schedule of future calibrations.
5. Regular maintenance of the station – mainly cleaning of sensor heads and verification of alignment and level.
6. Commissioning and regular check of the station by qualified experts including proper documentation of all quality-related aspects
7. Extensive quality control of the recorded data to assess their effective accuracy, flag dubious data, and apply corrections (only where advisable).

Only measurements fulfilling all these requirements are regarded as valid and should be used for fusion with model-derived datasets. Otherwise, the model-derived datasets could be worsened by measured data of insufficient quality, due to, e.g., significant bias. Next, the requirements for ground measurements are summarized. This summary is partly contained in (Wilbert et al., 2015) which is based on (Sengupta et al., 2015; WMO, 2008)

2.1 Instrumentation

The decision on selecting the proper instrumentation depends on the possible frequency of maintenance visits and the qualification of the maintenance personnel. First, GHI measurements are discussed, followed by DNI measurements.

For sites that have daily maintenance by qualified personnel, the first choice for obtaining the highest possible quality in GHI measurement is to use the “component-sum” method that combines direct and diffuse (DIF) measurements from precision thermopile instruments. This method uses a pyranometer qualified as ‘secondary standard’ according ISO 9060 (1990) for measurement of DIF (using a tracking shading disk or shading ball to block the sun) and an ISO secondary standard pyrliometer to measure DNI. Since (i) the magnitude of DNI is usually much larger than that of DIF; and (ii) the experimental uncertainty of such a pyrliometer is significantly lower than that of unshaded pyranometers measuring GHI, the ‘total irradiance’ measured with the component-sum method is of higher quality than derived from the best thermopile pyranometers (Michalsky et al., 1999)—assuming that the sun tracker works continuously and is correctly aligned to the solar disk.

If daily cleaning cannot be provided or if a solar tracker station is either not available or if the readings of DNI and/or DIF appear erroneous GHI should be obtained from an unshaded pyranometer.

GHI measurements should be collected with ISO ‘first-class’ or WMO ‘high-quality’ pyranometers. Alternatively, the use of photodiode sensors is permitted, only if the instrument has been properly corrected and calibrated (Geuder et al., 2011). Such photodiode pyranometers with diffusor disks can even be preferable if the sensors cannot be cleaned daily

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as these sensor are affected less by soiling than instruments with clear optics (Maxwell et al., 1999; Pape et al., 2009). Further, all data from photodiodes must be sufficiently corrected for the influences of (a) the sensor head temperature on instrument sensitivity, (b) the increasing spectral shift at decreasing sun elevation angles (sometimes called 'air mass correction') and (c) the deviations in sensitivity, which affect many photodiode sensors at low sun elevation (so-called 'cosine error'). If the effects at low sun elevation are not properly corrected, the corresponding data must be flagged and eliminated from the data fusion process.

For DNI measurements, a similar recommendation applies. At sites where is weekly or daily maintenance by well qualified personnel, an ISO first class or a WMO good quality pyrhelimeter should be used. Alternatively, a Rotating Shadowband Irradiometer (RSI) may be used if it is thoroughly calibrated and if correction functions for systematic errors have been applied (see also text above for GHI). As mentioned above for the GHI the application of an RSI can be of advantage for sites where no weekly or daily maintenance by well trained personnel is available.

2.2 Installation

The installation of the radiometric station should follow the best practices manual (Sengupta et al., 2015). Selection of a good site that is representative of the surrounding environment is critical in order to obtain valuable and accurate meteorological measurement data. In general, the site should be representative of the meteorological conditions in the whole area of interest and should not be affected by obstructions like close hills, buildings, structures, or trees. Guidelines for site selection are described for each measurement variable in the WMO Guide to Instruments and Measurements (WMO, 2008) .

2.3 Calibration

All radiometers should be properly calibrated at accredited laboratories, following state-of-the-art procedures (Geuder et al., 2011; Sengupta et al., 2015). Well calibrated thermopile radiometers can in turn be used to transfer their calibration to photodiode sensors at the site, as described in the literature (Geuder et al., 2011).

The correction functions required to make the reading of photodiode sensor comparable to that of reference thermopile radiometers can be thought of as an essential part of their calibration process. Not all manufacturers or installers provide this service, however.

2.4 Maintenance

All radiometers should be well maintained and, most importantly, cleaned regularly. The minimum requirement for pyrhelimeter cleaning is every 3rd day, but a daily frequency is

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recommended (WMO, 2008), particularly in coastal, dusty or polluted areas.. Weekly or even monthly cleaning in clean areas could be sufficient for sensors with diffusor disks instead of clear optics, because they are much less prone to detrimental soiling effects than thermopiles (Maxwell et al., 1999; Pape et al., 2009).

To avoid systematic errors due to low cleaning frequency a posterior soiling correction procedure described in the literature should be applied (Wolfertstetter et al., 2014). This is especially important in case of dirty environments and sparse or long cleaning intervals. Irradiance measurements impacted by soiling tend to be low, thus creating a systematic or variable bias, which should be imperatively avoided.

For an effective utilization of ground irradiance measurements for improving satellite-derived estimates, the quality of the measurements must be assured as high as possible. Trying to apply site adaptation methods using low-quality (thus biased) ground observations can result in a degradation of accuracy and bankability rather than the desired improvement. All instruments should be properly calibrated, operated and well maintained, including regular and frequent cleaning. The measurement protocol should be rigorous and follow the best practices and available standards (Sengupta et al., 2015; Stoffel et al., 2010). In addition, the derived time series should be thoroughly quality controlled, and should be as continuous as possible. Large data gaps (e.g., 1 month) significantly increase the uncertainty in the solar resource assessment. Small data gaps (e.g., 1 hour during a day) can be filled in various ways. Quality check methods such as BSRN recommendations (McArthur, 1998), SERI-QC (NREL, 1993) or those delivered in the MeSOR (Management and Exploitation of the Solar Resource) project (Hoyer-Klick et al., 2009) should be used to detect either values beyond physical limits or incoherent values as a consequence of errors in solar tracking systems. The use of such methods requires the availability of the three essential solar irradiance components (GHI, DNI, and DIF).

2.5 Commissioning

The commissioning, operation and maintenance of ground stations able for producing high quality data should follow these general guidelines:

General requirements:

- Dimensions for the selected measurement site should be at least 10×10 m², with a recommended area free of obstructions of 25×25 m²
- Slopes should be avoided, a horizontal ground is desirable
- Motor vehicle access should be possible in order to facilitate transportation, installation and O&M activities, while public access should be restricted or avoided. Preferably, a security fence should be constructed around the site, but should avoid interference with the normal operation of the sensors.
- Remote data transmission via mobile phone network, phone landline, Ethernet or even radio frequency should be possible. Operators should check the communications

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options and in particular mobile phone network signal strength and integrity before final site selection. Where no other communication means are available, satellite data transfer might also be considered.

- Avoid power lines crossing the site, either underground or above ground. Other than to minimize the influence of shadows, this is for safety reasons in order to avoid electric shocks in case of touching the power lines, while it is also important to eliminate the influence of electric fields from alternating current power lines that might disturb the measurements by inducing noise signals in the cabling of the station. Contact local utilities for the location of buried utility lines

Additional requirements for measurement of solar radiation:

- The distance between radiation sensors and any obstacle should be at least 10 times the difference in height between the sensor and the obstacle.
- No obstruction should be within the azimuthal range of sunrise and sunset above the plane of sensing throughout the year; any obstruction above the horizon affects the measurements and leads to errors. On sites where it is not possible to avoid obstructions, the complete details of the horizon and any obstructions should be included in the description of the station to facilitate a subsequent assessment of their impact.
- No direct shade, artificial light or reflections from reflective surfaces should inflict the sensor at any time of the day and year.
- Construction features that may attract roosting or nesting birds should be avoided; otherwise the use of spike strips or other measures is recommended.

The operator is finally responsible for the selection of an adequate location for installing measurement stations. Even as the conditions of each prospective site are particular, some general recommendations for sites to avoid is provided here, although the list is not exhaustive:

- Low places where water might accumulate after rainfall or floods
- Erosion prone areas
- Large industrial areas
- Proximity to any sources of dust, aerosols, soot or other particle emissions
- Steep slopes
- Sheltered hollows
- Existing high vegetation or places with fast growing seasonal vegetation
- Shaded areas
- Swamps
- Areas with snow drifts
- Dry and dusty areas with a nearby dirt road
- Irrigated agricultural land

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To avoid theft or damage of equipment, the station should be properly monitored and protected with a security fence as described below:

- The fence should be of enough height to avoid or discourage people and animals from climbing over.
- The fence perimeter must be at a distance of at least twice the difference between instrument height and fence height with the sensor located at a higher level.
- It is recommended to secure a location within private property or property of public institutions.
- For security and surveillance reasons it is recommended to have local staff near the station that can monitor the station at regular intervals and can report possible vandalism, lightning damage, malfunction, etc. These intervals should be determined based on O&M needs, accessibility, funding, and other factors.

2.6 Measurement station installation recommendations

Sensors and installations for other relevant meteorological parameters for solar resource assessments at large-scale solar plants are usually installed in a combined measurement station. These are usually air temperature and relative humidity, wind speed and direction, barometric pressure and often precipitation sensors. In addition, atmospheric visibility is sometimes measured, and other devices can be utilized such as mirror exposure frames for mirror soiling rate assessment, dust samplers for dust load measurement, or construction material samples for corrosion rate determination.

All peripheral auxiliary equipment necessary for proper operation of the meteorological station should be stored safely in a weatherproof box, which should be easily accessible for maintenance and inspection purposes. The measurement equipment should be properly selected in order to satisfy the required accuracy for each parameter to be measured.

The measurement data sampling rate should be 1 Hz. A data logger should control and store the measurements for retrieval during a period of at least one year. A temporal resolution of at least 10 minutes is the minimum acceptable, although it is recommended to store data at 1 minute intervals, with the datalogger system recording and storing average, maximum, minimum, and standard deviations in the selected period. The means for collecting the data daily or in comparably short intervals (software for data collection and monitoring access) should be provided along with the equipment, as well as remote communications and monitoring devices.

For unattended remote sites, automatic weather stations must provide their own power source through a solar photovoltaic panel and a backup battery of proper capacity. The backup battery must be specified to supply at least the amount of energy needed by the system to ensure proper operation during the time that the maintenance team requires detecting and correcting the power supply failure, which should normally not exceed one week.

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The equipment should be properly grounded to prevent lightning damage, and also shielded to prevent radio frequency interferences.

The following documentation should be included with the measurement equipment:

- Layout diagram for the whole station area (within the fence)
- Drawings of required foundations, grounding poles and all other necessary civil works on the measurement site
- Installation and operation manuals for each device or sensor
- Maintenance instructions for high-quality data acquisition and transmission.
- Indication of basic emergency procedures and operator contact data to facilitate local staff reporting of any anomalous situation.

Thorough and regular maintenance of the equipment assures its proper functioning, reduces the effects of possible malfunctions thanks to early detection, and avoids or reduces the number and duration of data gaps.

The maintenance personnel should keep a logbook in which normal and unusual events are described. The technician attending the station must be trained to fill the logbook properly during each visit. Detailed information recorded in the logbook can be of the highest value if data quality issues arise. Events to be noted in the logbook are e.g. occurrence of insects, nesting birds or animals at short distance, occurrences of localized dust clouds (such as caused by traffic on a dusty road), and episodes of haze or fog. Any abnormal events, the condition of the instruments, infrastructure and environment should be documented on any occasion when such observations have been made. Pictures with date/time stamps are useful for this purpose and provide a valuable visible insight on the conditions of instruments. The horizontal level of the instruments should be checked each time, particularly if their pedestal or the ground around it shows signs of alteration or erosion.

Instrument maintenance and operation should only be performed by qualified, trained personnel. The frequency and extent of maintenance visits also depends on the instrumentation and site characteristics, and requires careful consideration during the planning stage of the measurement campaign. The cost of maintenance during a long-term measurement campaign can easily exceed the initial cost of the instrumentation. The planned cost of operation and maintenance has to be considered in the budgetary framework, and additional provisions should be made in order to face any unexpected malfunction.

The equipment should be protected from power outage by providing an uninterruptable power supply (UPS), which also needs regular check-up. It should send an alarm when the UPS starts providing backup power, so that the operation and maintenance personnel can react within the duration time of the battery. Since the efficiency of UPS batteries tends to degrade over time and under severe environmental conditions, they must be tested at regular intervals (e.g., every 6 months or even shorter intervals) and replaced if necessary.

RSI instruments are not as prone to soiling effects as other radiation sensors such as pyrhemometers. Nevertheless, they require regular cleaning. The cleaning interval should be defined at the beginning of the measurement period by analysing the immediate effect of

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cleaning on the measurement signal. Depending on how the noted period after which the sensor soiling remarkably influences the measurement, the cleaning interval should be adjusted in a way that soiling effects are never bigger than to cause a 1-2% degradation in sensor accuracy. Each cleaning and the state of the sensors should be documented and the measurement values should be checked to evaluate the effect of cleaning on the recorded values. Taking photographic records of the sensor with time/date stamps before and after the cleaning events is recommended.

Pyranometers and photodiodes measuring global and diffuse radiation must be perfectly levelled. Any misalignment needs to be rapidly detected, corrected and documented. Accurate alignment of sensors should be checked regularly using a spirit level with at least 35 arc seconds sensitivity. Bubble levels present in some sensors are a quick indicator of inclination but do not provide accurate sensitivity.

For high quality and reliable measurements it is recommended to ensure automatic data collection through a suitable communications system, and also perform regular (e.g. daily) screening for measurement failures and evaluation of data quality. Rapid detection of measurement problems can be achieved with visual quality assessment tools (Wilcox, 1996). If developing such capabilities is beyond the reach of the analyst in charge of using the data, specialized data acquisition and quality management software should be obtained from commercial sources, or else specialized service providers should be contracted. A procedure for analysis and correction of soiling effects should be included in the analysis software.

2.7 Measurement uncertainty

Measurements have to be accompanied with uncertainty information. If no detailed individual derivation of the uncertainty is given, overall uncertainty may be estimated. In this case uncertainty estimation must be more conservative than the derivation of individual uncertainty values, which takes into account the time-specific conditions of each instrument. As temporal averaging reduces the uncertainty values, such error estimates always must be given related to the specific integration interval.

2.8 Spatial resolution

In general it must be recognized that measurements of solar radiation data refer to a point while model-derived solar radiation data refer to an area of large extent. Today the typical size of satellite-derived solar radiation values is in the range of 10 km² to 100 km², which corresponds with satellite pixel sizes of about 3 km to 10 km or approximately 0.1°. Best achievable cloud information from geostationary satellites is in the range of 1 km, which is also utilized by several satellite retrievals. Some solar resource data providers even claim to reach down to around 250 m spatial resolution by spatial disaggregation techniques using digital elevation models of higher resolution. However, even these algorithms still use data sets of

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much coarser resolution in the order of $0.5^\circ \times 0.5^\circ$, which relates to about 2 000 km² to 3 000 km² large boxes, for consideration of aerosol or water vapor data. Further, none of the satellite-derived products is mapping the clouds well, which leads to a parallax effect. Thus, the given specification of satellite-derived spatial resolution must be treated carefully and even the highest resolved data rather tend to be related to an area of around 100 km². For this reason usually the best fit of satellite-derived to ground-measured data occurs if both are averaged over about 60 min. Then due to cloud movement and changes in cloud cover the spatial averaging effect of the satellite observation and the temporal averaging effect of the ground-based measurements lead to the best agreement.

2.9 Temporal resolution

Based on these spatial-temporal averaging effects a 60-min temporal resolution is recommended. Ideally the 60 min averages are calculated from measurements logged in 1 min intervals and sampled in 1 second resolution as discussed above. Such 1 min data allow for much better quality checks than, e.g. 10 min data.

In general, best results in later adaption processes are achieved with a maximum of temporal overlap of ground measurements and satellite-derived data. Therefore, the measured time series should cover as long a time period as possible. However, at a minimum an entire year is recommended as all azimuth angles are covered seasonal variability are covered (Schumann et al., 2011).

2.10 Data gaps

Different methods also exist to aggregate data points at their nominal time step (e.g., 1-min or 10-min) and derive the necessary temporal averages (e.g., monthly and annual). To minimize the impact of data gaps, the recommended practice should be followed (Roesch et al., 2011).

For missing values various gap-filling methods exist such as described by Schwandt et al. (2014) should be used. Filling of measurement gaps helps to lengthen the amount of data available for data integration. However, gap filling represents a synthesis of values, using temporal or spatial interpolation. Thus, gap filled data sets shall not be applied for validation or data fusion with modeled data sets. The only exception is for very short gaps in high resolution measurement series within the averaging period. Up to a maximum of 25% of the data may be missing in an averaging interval. For example, if up to a total of 15 min of the measured data are flagged as erroneous due to obstructions the hourly value still may be taken as a valid measurement, if properly averaged by completion through gap filling or alternatively simply be averaging over the full 60 min considering the gap as “not a number” (NaN) values.

3. Review of existing site adaptation methods

Site adaptation methods are closely dependent on the type of model used to estimate the solar irradiance components and obtain their long-term time series. The first subsection below provides an overview of these satellite methods.

3.1 Solar radiation modeling

Satellite-based methods for estimating solar radiation components at the earth surface have become a de facto standard in current solar resource assessment studies. The underlying methodologies have been evolving during the last 30 years, following advances in remote sensing and other techniques. The literature documents this trend from the first simple methods (Cano et al., 1986; Gautier et al., 1980; Moser and Raschke, 1983) until the more intricate methods in current use (Mueller et al., 2004; Perez et al., 2002; Rigollier et al., 2004; Schillings et al., 2004). For solar applications, most developments followed an empirical or semi-empirical approach, also referred to as the cloud-index method. In parallel, applications in meteorology and climatology rather followed a truly physical approach, which however could not provide reasonable estimates of DNI. In recent years, a convergence between these two different approaches has started to manifest. Physical methods (using retrievals of cloud optical properties from satellite observations) can now provide appropriate datasets for solar applications (Sengupta et al., 2014).

Time series derived from geostationary satellite observations offer the advantage of providing global (world) coverage (at least between latitudes of 60°S and 60°N), and long periods of data (up to ≈20 years currently, for geographic areas covered by the oldest satellites with appropriate sensor). The current fleet of geostationary satellites is judiciously positioned to continuously sense the radiance from the atmosphere at hourly or sub-hourly time steps. The nominal spatial resolution of the satellite-derived irradiance data is ~1 km for the visible channel and ~3-4 km for the infrared channels. The large geographical coverage of these methods means they are able to supply solar irradiance information for almost every site of the earth. However, shortcomings do exist because satellite-based methods cannot always model all possible local effects or specific features of a target site. Indeed, complex terrain with highly variable elevation, coastal areas, areas or periods with unusual or rapidly changing cloud conditions, highly reflective albedo (typical of sand or salt deserts and snow-covered areas), and inaccuracies in local atmospheric constituents information (mostly aerosol optical depth and water vapor), are examples of the possible features that might substantially affect

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the final uncertainty, and hence the bankability of solar energy projects (Cebecauer and Suri, 2010; Cebecauer and Suri, 2012; Cebecauer et al., 2011).

Solar radiation estimation methods based on Numerical Weather Prediction (NWP) models have started to surface as an alternative to satellite-based methods. However, their performance is still far behind of what can be achieved with satellite-based methods (Boilley and Wald, 2015; Jia et al., 2013; Kennedy et al., 2011). A major advantage of NWP models is that they can provide up to 30-year historical series of solar radiation at virtually every site on Earth (even at high latitudes). As the quality and amount of observations provided by the constellation of weather satellites increases, the quality of NWP-based solar radiation estimates is also expected to increase.

Additionally, time series can be generated from data fusion, methods for combining two or more data sets in order to obtain a synthesized data set with better properties than the original ones (Blanc et al., 2012; Meyer et al., 2008). The specific procedures and methods for this purpose are highly dependent on the input data sets characteristics.

The recent boom of the solar energy industry, and particularly the increase in new deployments of solar systems using concentrating collectors over many different climatic zones around the world, has encouraged studies to improve the accuracy of satellite estimations of DNI. This is understandable because DNI is much more sensitive to atmospheric conditions (particularly cloudiness and aerosols) than GHI or GTI. Therefore, the risk of error in DNI is significantly larger than in GHI or GTI. In any case, the correction techniques reviewed below would also be beneficial to PV applications, by improving GHI and GTI estimates.

The adaptation techniques described below demonstrate how the incorporation of short-term ground measurements of solar irradiance and/or the use of accurate local atmospheric data can result in a significant improvement in the accuracy and reliability of satellite-derived solar resource data.

3.2 Physically based methods for site adaptation

One approach of correcting model-derived solar radiation data consists in adjusting the atmospheric input data so that the new results better match the ground-based observations. In principle, this approach might lead to a modification of any input, such as cloud properties, but in most cases today the main target is aerosol turbidity.

3.2.1 Adaption of aerosol optical properties

Many satellite derived hourly time series of DNI are affected by significant monthly and annual bias over regions where high aerosol loads are frequent (Cebecauer et al., 2011; Gueymard, 2011). Therefore, to obtain high accuracy and low bias in solar irradiance estimates (particularly DNI), the aerosol optical depth (AOD) used as input in satellite-based methods must have the lowest bias possible.

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Gueymard et al. (2012) proposed a correction method based on ground observations of AOD and predictions with the REST2 model. However, due to the scarcity of ground AOD observations the correction method was generalized to the use of large-scale AOD datasets. The methodology involves comparing hourly DNI and GHI outputs of the REST2 model with DNI and GHI derived from the satellite model for clear-sky conditions. A correction factor can be obtained,

$$R_c = \frac{I_{REST2}}{I_{satellite}} \quad (1)$$

This factor can then be used to correct the original all-sky irradiances derived from the satellite-based model.

Suri and Cebecauer (2011) proposed a similar method where the aerosol dataset is adapted to match the output of the clear-sky model to the measured irradiance during clear-sky days.

The generation of new and more accurate global aerosol datasets is also an ongoing issue, to which important efforts are being devoted. For instance, Gueymard proposed a global aerosol dataset of 0.5°x0.5° spatial resolution using monthly averages from MODIS retrievals, MATCH reanalysis and AERONET measurements, also introducing an altitude correction on AOD based on a Digital Elevation Model (DEM), to reduce systematic errors (Gueymard and Thevenard, 2009). This effort is being improved by the addition of other sources of data, such as MISR satellite retrievals and gridded climatologies (Gueymard and Sengupta, 2013).

Similarly, a reported method proposed a data fusion approach of daily AOD MODIS estimates and daily AOD AERONET observations based on *kriging* and optimal interpolations (Ruiz-Arias et al., 2013a). In this method, the existing gaps in the satellite AOD estimates over cloudy areas are first removed, then the whole grid is debiased and, finally, locally adjusted to match the AERONET observations better. Therefore, the method proposes an *end-to-end* approach that removes data gaps in the satellite retrievals, and debiases the AOD estimates successively at large and local scales. In contrast with previous methods, the local adjustment does not just correct the satellite estimates where a collocated AERONET sunphotometer exists, but also considers the AOD spatial covariance structure so that the information on the AOD satellite error at AERONET stations is spread over neighboring areas, thus increasing the area of influence of the ground AOD observations. Fig. 1 shows a case study for a single day, 17 June 2009, over the contiguous USA. Fig. 1 (a) shows the original daily AOD MODIS retrievals, which contain many data gaps and probable AOD over-predictions due to cloud contamination or high surface albedo. If a regular interpolation method were used to fill up these data gaps, as shown in Fig. 1 (b), the high AOD values would spread over the whole area, resulting in a suspicious AOD map. To solve this issue, Ruiz-Arias et al. (2013a) propose to use previous knowledge of the AOD error within the kriging interpolation procedure. Thereby, all potentially too high AOD values are filtered out and, after data gaps filling, the resulting map is much more credible (Fig. 1 (c)). A final local adjustment is added to achieve a better match between ground observations and satellite estimates, as shown in Fig. 1 (d).

In a DNI sensitivity analysis conducted by Ruiz-Arias et al. (2013b) under clear-sky conditions, it is shown that, using the original AOD retrievals interpolated as in Fig. 1 (b) to remove all AOD

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data gaps, the resulting DNI estimates are positively biased by more than 5%, and including a significant uncertainty. If, in contrast, corrected AOD values are used (following the methodology behind Fig. 1 (d)), the DNI bias vanishes and 90% of the DNI estimates have a low (<5%) uncertainty for AOD below 0.2. These results pertain only to the specific case of the North American continent, where AOD is generally low to moderate. Much larger aerosol loads are frequent over many regions of the world, where similar studies would thus be necessary.

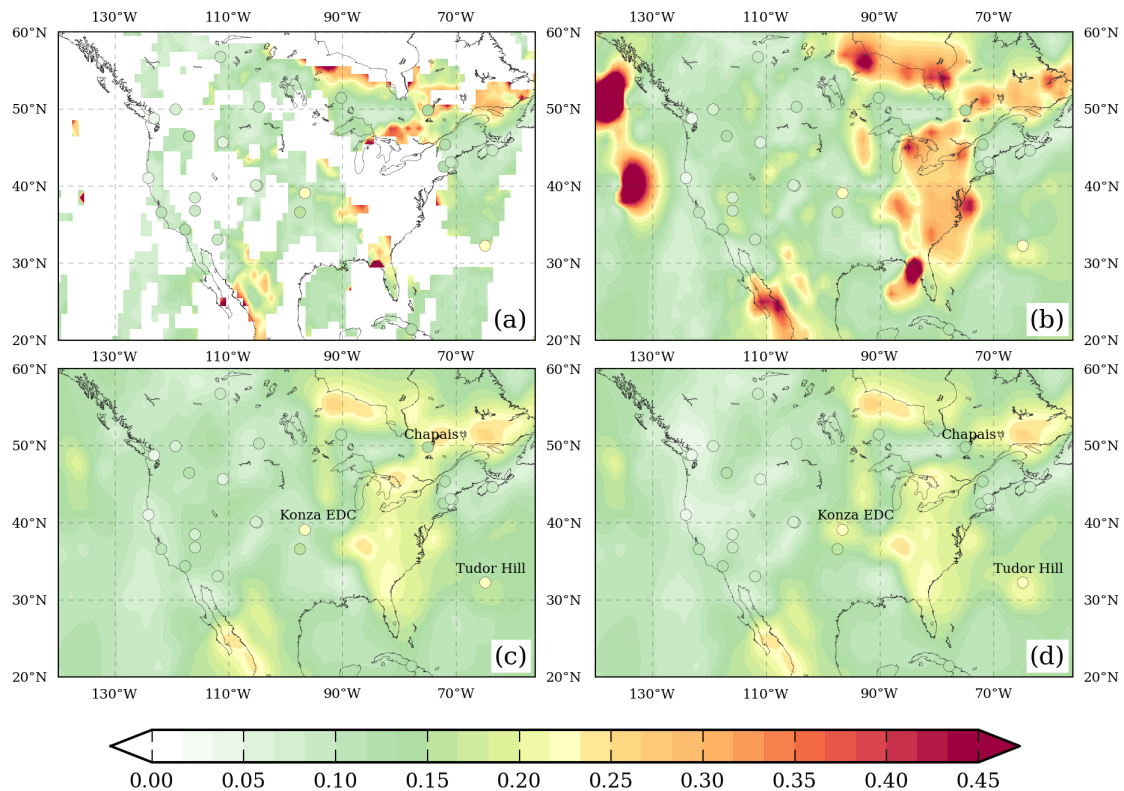


Fig. 1 Intermediate results for 17 June 2009 of the AOD correction method proposed by Ruiz-Arias et al. (2013a). (a) Original daily AOD MODIS retrievals; (b) Results obtained with a regular ordinary kriging interpolation procedure to fill the gaps in (a); (c) Results obtained with an ordinary kriging interpolation procedure in which the expected error in the AOD MODIS is considered; (d) Results obtained after final local adjustment using AERONET observations of AOD and an optimal interpolation procedure to correct the AOD grid shown in (c).

3.3 Statistical methods for site adaptation

Statistical adaptation of model-derived results also known as model output statistics (MOS) frequently is used in various fields of applied meteorology. Rain rates could be corrected to better reflect local conditions. Wind speeds are commonly adapted to local measurements for wind resource analysis. Similar approaches can be used to adjust model/satellite-derived solar radiation values to local measurements. Various such approaches are used today, which are described in this section.

3.3.1 BIAS removal by linear adaptation

Satellite-based methods for deriving solar radiation components may exhibit systematic errors that could yield to a general overestimation or underestimation trend, referred to as bias and characterized by the mean bias (MB) statistics. Bias between the predicted and measured irradiance may result from systematic features of the radiative model or from regional inconsistencies in the external input data (mostly aerosols or water vapor).

When short-term high quality ground DNI and GHI measurements are available the bias in satellite irradiance estimations can be reduced by correlating them together to find a correction factor (Carow, 2008; Cebecauer and Suri, 2010; Harmsen et al., 2014; Vindel et al., 2013).

The simplest method is just to estimate the Mean Bias Deviation (MBD) and remove it from the whole dataset. As an example let's consider a satellite estimation of DNI for one year that has a clear trend to overestimate the ground data, showing a MBD value of -18.52 W m^{-2} and a RMSD (root mean square deviation) of 159 W m^{-2} . The application of this simple method consists of subtracting 18.52 from all the estimated DNI values and thus the resulting estimations will be unbiased. Fig. 2 shows the scatter plot of the initial and corrected DNI estimates. The corrected estimates exhibit a better correlation coefficient with the ground data, although the RMSD (with a value of 158 W m^{-2}) remains practically constant.

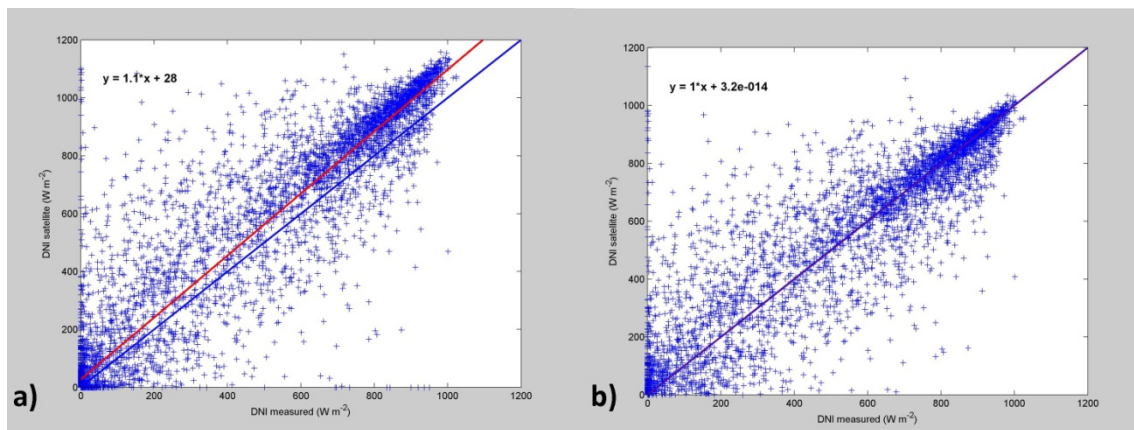


Fig. 2 Example of BIAS removal from satellite-derived DNI by subtracting the MBE. a) scatter plot of the uncorrected estimates. b) scatter plot of the corrected estimates

Bias removal can also result from linear fitting of the points in a scatter plot and subtracting the diagonal line. The following example shows daily global (GHI) irradiation derived from satellite exhibiting a clear overestimation of the ground values (MBD= $-373 \text{ Wh m}^{-2} \text{ day}^{-1}$ and RMSD= $572 \text{ Wh m}^{-2} \text{ day}^{-1}$). The subtraction of the fitted line ($y_{sat} = a x_{ground} + b$) and the diagonal ($y = x$) produces new estimations with negligible bias and lower root mean square deviation (MBD= $-2 \text{ Wh m}^{-2} \text{ day}^{-1}$ and RMSD= $452 \text{ Wh m}^{-2} \text{ day}^{-1}$).

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$$y_{new} = y_{sat} - [(a - 1)x_{ground} + b] \quad (2)$$

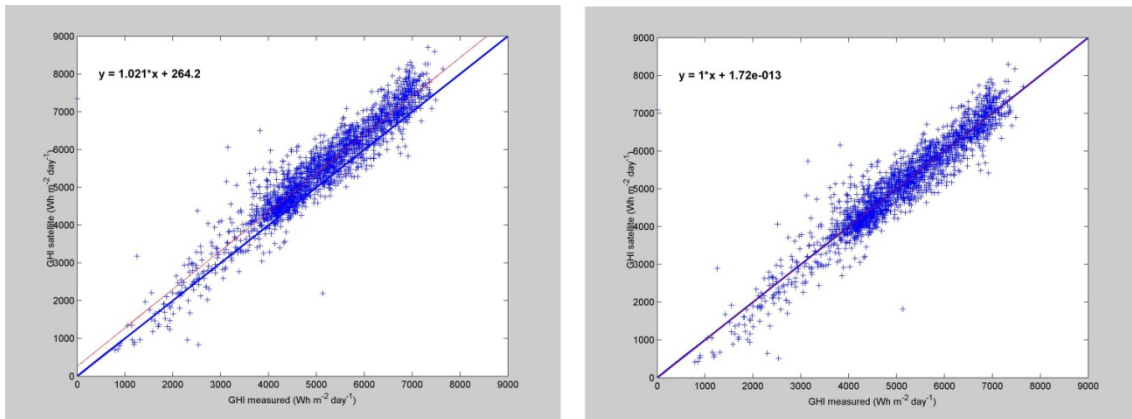


Fig. 3 Example of bias removal by subtracting the fitted line and the diagonal of a scatter plot of GHI values. Initial estimations on the left and corrected values on the right

Depending on the specific characteristics of the deviations from the ground data linear fit corrections can be applied to a subset of derived data instead of to the whole dataset. The following example shows the daily DNI derived from satellite imagery for a site in Northwest India during 2011 compared to the ground data (Fig. 4). Satellite estimations showed a MBD of 70 W m^{-2} and RMSD of 200 W m^{-2} , which provides evidence of a trend to underestimate the hourly measured DNI. A noticeable underestimation of DNI can be observed for the dryer seasons (days 1-150 and 250-365) and overestimation is observed during the monsoon season (Polo et al., 2015).

Under the hypothesis that underestimation in dryer seasons could be attributed to an overestimation of the aerosol loads a subset of the derived data is extracted by selecting hourly DNI estimates that fulfill the following conditions:

- Direct normal irradiance above 50 W m^{-2}
- Conditions close to clear sky days
- Days belonging to the dryer seasons (i.e. excluding the monsoon)

The conditions close to clear sky days have been selected by computing the daily clearness index (KTD, the ratio of the daily global irradiation to the daily extraterrestrial) and assuming that $KTD > 0.5$ represents days with mostly clear sky conditions. Regarding the first condition, the lower bound imposed on DNI (higher than 50 W m^{-2}) improves the goodness of fit in the range that most contributes to energy production. Thus, using the expression (2) a new DNI dataset for the year 2011 can be built by merging the new selected and transformed data with the unselected data from the original satellite estimations. The new dataset of DNI estimates for 2011 shows a MBD= -0.6 W m^{-2} and a RMSD= 166 W m^{-2} . Therefore, the satellite-derived data have been adapted to the specific conditions observed in the ground data to an unbiased new dataset with smaller dispersion. Fig. 5 shows the daily values of the adapted DNI dataset for 2011 compared to the ground measurements. A much better agreement can be observed

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now with the adapted dataset, particularly in winter and summer seasons; in addition the cumulative distribution function of the corrected dataset agrees with the experimental one.

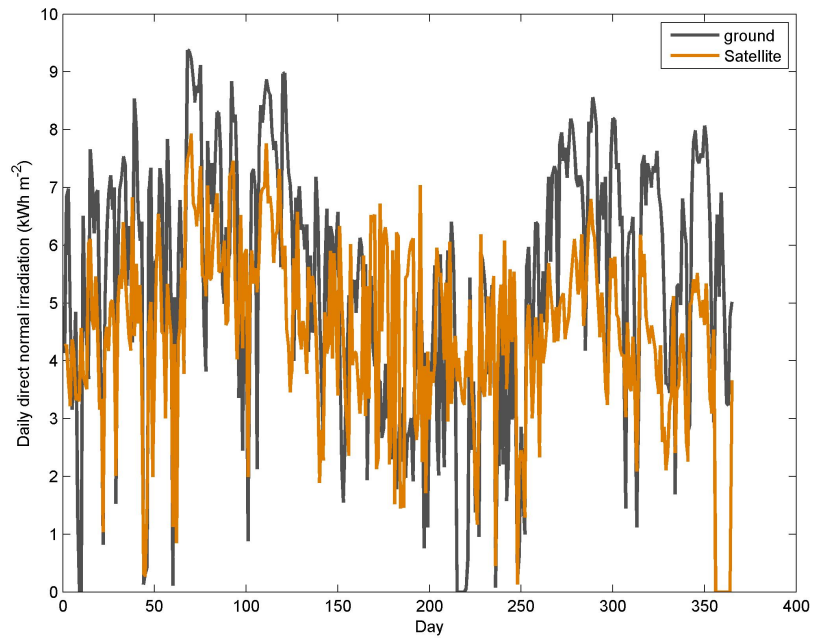


Fig. 4 Daily DNI estimates compared with ground data in Northwest India (Polo et al., 2015)

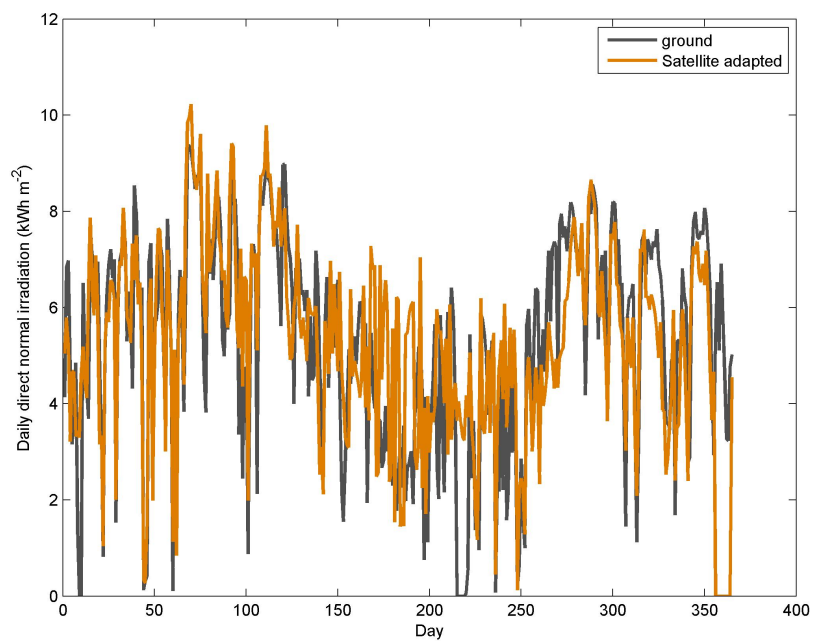


Fig. 5 Daily DNI corrected estimates compared with ground data in Northwest India (Polo et al., 2015)

Within the ENDORSE (Energy DOWNstReam SERVICES project the linear bias correction method of Carrow was explored by dividing the data set in different bins of the solar angle, clear sky index and irradiance (Blanc et al., 2012). The method was evaluated for a SOLEMI dataset (Schillings et al., 2004) using ground data from 10 Baseline Surface Radiation Network (BSRN) stations. In all cases the bias of the original data was improved but no general improvement was observed in other statistical parameters like RMSE or Kolmogorov-Smirnov Integrals (KSI). These authors also suggested that there was a threshold in the uncertainty of satellite-derived data that limits the application of correction methods. According to the findings of the ENDORSE project satellite-derived data with RMSE of less than 20% and 2 in relative KSI should not be further corrected in order to avoid artificial effects that the correction methods could induce.

3.3.2 Non-linear methods for site adaptation

Several more elaborate methods for site adaptation of satellite derived data with short-term ground measurements have been presented recently.

Carow introduced a parameter dependent modification as well as a so called feature transformation modification (Carow, 2008). The first method uses a defined combination of parameters, e.g. clear sky index and sun elevation angle and modifies additively or multiplicatively the original satellite time series. The additive modification efficiently reduces MBD and the RMSD on average. The second method, feature transformation, uses properties of the cumulative distribution function of high quality ground measurements and transfers those via look-up tables to the satellite-derived time series. The modification causes the distribution functions to move closer together. (Schumann et al., 2011) additionally show that improvements made by feature transformation strongly depend on the length of the overlap of satellite-derived irradiance data and ground-based measurements. It is recommended to take at least a whole year of measurements to develop the adaptation algorithm.

Mieslinger presents another method based on minimizing the following cost function (Mieslinger et al., 2013),

$$J = \frac{1}{2N} \sum_{i=1}^N (y_{sat} - y_{ground})^2 \quad (4)$$

The method is based upon the assumption that lower irradiances are often overestimated with simultaneous underestimation of high irradiance levels so that a third degree polynomial is assumed for the data. Minimizing the cost function with additional conditions to the polynomial results in a biasfree adaptation algorithm. The adaptation yields to a better match of satellite-derived and ground measured irradiance data in terms of RMSD as well as better statistics of adapted values concerning the Kolmogorov-Smirnov test. Due to an additional

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weighting function, strong deviations in the range of high irradiance values can be reduced significantly.

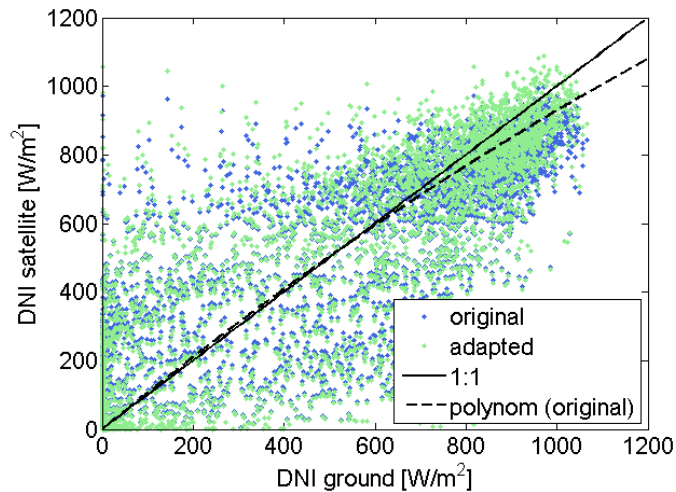


Fig. 6 Scatter plot of ground measured and satellite-derived DNI values from EHF (Department of Energy and Semiconductor Research from Univ. of Oldenburg) in blue and after applying the adaptation algorithm in green. The dashed line displays the polynomial applied to the satellite-derived data. (Mieslinger et al. 2014)

Another method for combining short-term ground measurements with longer-term satellite data is model output statistics (MOS) (Bender et al., 2011). MOS is a multi-variate linear regression analysis between a prescribed set of predictors (satellite derived data or estimations from numerical weather prediction models, for instance) and the surface observational data. The objective is to develop a multi-linear regression equation to correct the estimated values removing the bias and adjusting the variance. An example of MOS correction, applied here to DNI data from Tamanrasset, Algeria, is shown in Fig. 7 (Gueymard et al., 2012). The study evaluated the impact of varying overlapping periods of measured and modeled data, from 0 to 12 months in 3-month increments. An example of bias reduction as a function of time is provided in Table 1.

As expected, a longer overlapping period translates into a lower uncertainty. However, an interesting result is that, for some of the five sites tested (which encompassed very low and stable to very high and variable AOD conditions), the improvement in modeled irradiance bias becomes modest for overlapping DNI observation periods longer than about 9 months, particularly if an uncertainty of 5% is considered sufficient. This seems to indicate that the method is very efficient and converges rapidly. A short overlapping period is obviously desirable since it accelerates the final steps of the solar project preparation.

Like all other adaptation methods availability of quality ground data is crucial to the MOS success, since the observations have a direct impact on how well the statistical model corrects for local conditions.

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Table 1: Modeled data error for DNI at Tamanrasset as percent of the mean for the training year (2005) and one additional year outside of the training period (2007). Table excerpted from (Gueymard et al., 2012).

Period of Observations	Training Year Uncertainty	Blind Comparison Uncertainty
0 month	9.0	9.0
3 months	7.0	7.2
6 months	5.1	5.9
9 months	3.0	4.2
12 months	1.0	2.6

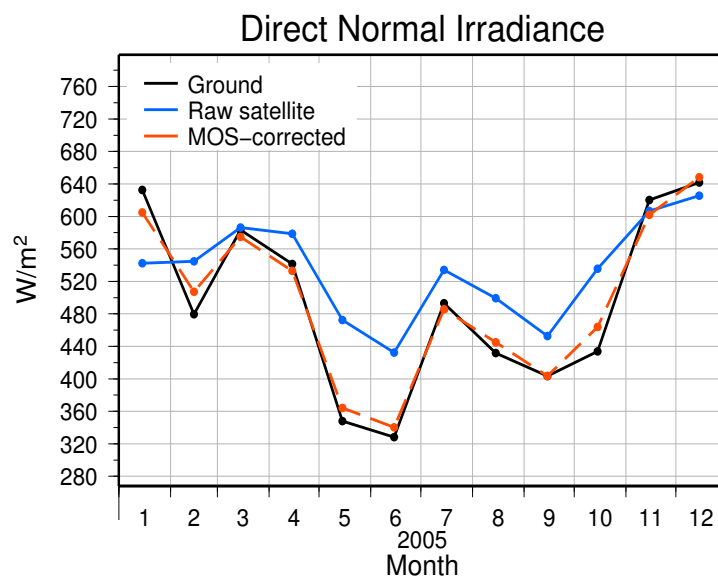


Fig. 7 Application of the MOS method to correct raw satellite-derived DNI values using ground measurements from Tamanrasset, Algeria. Results are shown for the training year 2005 (Gueymard et al., 2012).

A method similar to MOS, known as Measure-Correlate-Predict (MCP), is described by Thuman et al. (2012).

A novel method based on the Fourier decomposition is proposed by Armines MINES ParisTech for calibrating the daily global irradiation estimated by HelioClim-3 database (Vernay et al., 2013). The method consists of performing a Fourier transform on the clearness index errors and developing a regression for correcting the daily clearness index,

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$$KT_{HC3}^* = \alpha_{ST} + \delta_{ST} KT_{HC3} + \beta_{ST} \cos(2\pi F d_j) + \gamma_{ST} \sin(2\pi F d_j) \quad (5)$$

Where KT denotes the daily clearness index, F is the frequency ($1/365 \text{ days}^{-1}$) and d_j is the Julian day.

This methodology allows for the calibration of satellite-derived daily global irradiation by using 1-year of measuring campaign; however, the authors have extended the method for using shorter measuring campaigns. Thus, in southeast France (Provenze-Alpes-Cote d’Azur region) they conclude that a campaign of 9 months starting between January and May gives good accuracy.

The authors have extended the study of calibration of HeliClim-3 data to other European and African sites using mainly BSRN stations with good results (Vernay et al., 2012). Figure 8 shows the performances of the regression defined by eq. (5) at four sites along with the overall performances of the PACA region showing similar performances.

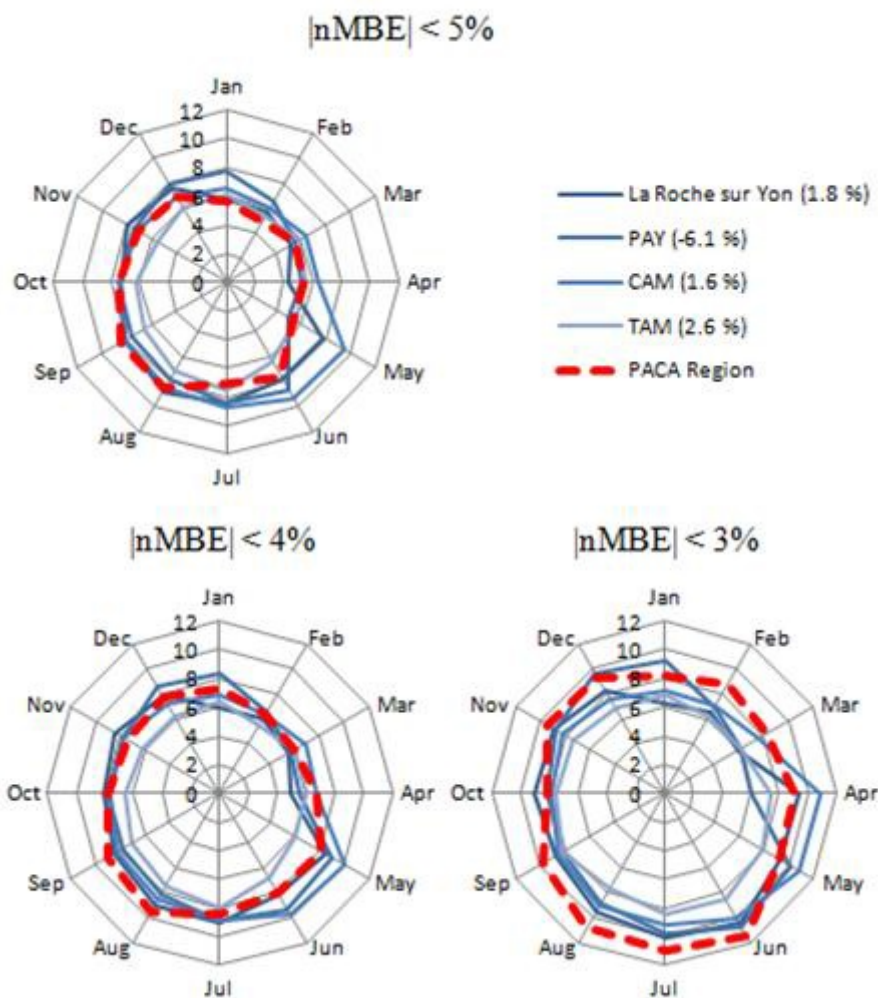


Fig. 8 P95 performance of regression equation (5) for four stations (Vernay et al., 2012).

3.3.3 Regional site adaptation

In the site adaptation methods presented so far, a correction model, which is generally a function of the satellite-based solar radiation estimates, is fitted against *concurrent* ground-based observations. Then, it is applied to *non-overlapping* periods of modelled and ground data to correct the former. Hence, the application of this methodology is possible only if overlapping modelled data and ground-based observations exist. Therefore, the correction step has to be typically postponed while an observing period of, ideally, at least one year, is completed. In addition, the likely decrease in temporal auto-correlation as the time lag between the model's training and correction periods increases is not generally considered, which can result in over- or under-corrections. This fact is particularly critical for DNI, in which inter-annual variability is usually much higher than for GHI (Gueymard et al., 2012; Lohmann et al., 2006; Pozo-Vázquez et al., 2011). Alternatively, irradiance observations obtained close to the location of interest can be used as long as the spatial covariance structure of the modelled data errors and ground observation errors is considered, in a similar way as in, e.g., the study by (Ruiz-Arias et al., 2013b) mentioned in Section 3.2.1 for the fusion of daily MODIS and AERONET AOD data.

In recent years, regional fusion methods for model-derived solar radiation data and ground-based observations have started to surface (Journée et al., 2012; Skamarock et al., 2008; Wald et al., 2003). Very recently, other authors have proposed an advanced regional fusion method (Ruiz-Arias et al., 2015). It consists of a numerical process by which the modelled solar radiation data, obtained typically from satellite-based techniques or NWP models, and provided as two-dimensional geo-referenced grids, are objectively adjusted at each model grid cell as a function of the reliability of the modelled solar radiation value at that grid cell with respect to the reliability of the nearby ground observations casted onto that grid cell. The feasibility of the method is demonstrated using monthly-averaged values of daily GHI and daily DNI obtained with the Weather Research and Forecasting (WRF) NWP model (Skamarock et al., 2008). Although the correction method is demonstrated only for NWP-based solar radiation estimates, it is equally applicable to satellite-derived solar radiation gridded datasets and other time scales. Fig. 9 shows a comparison of model-uncorrected and model-corrected DNI data against the respective DNI ground-based observations.

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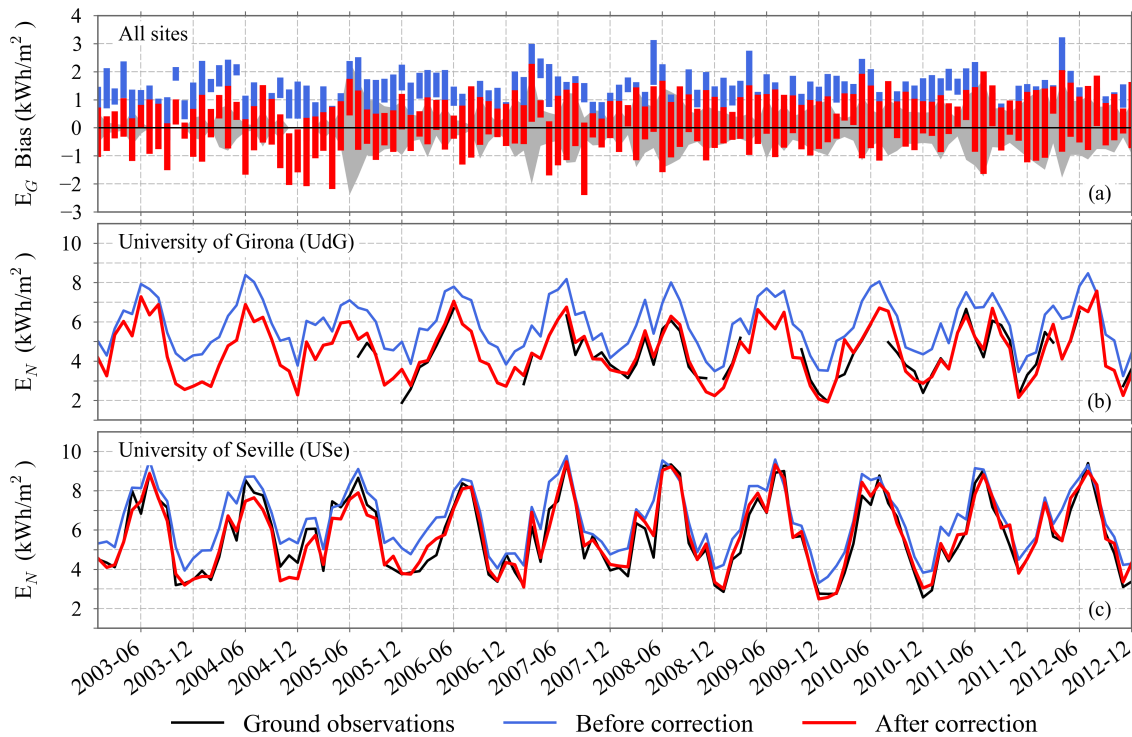


Fig. 9 Model-uncorrected (blue) and model-corrected (red) DNI (E_N) datasets compared to the ground-based validation observations. (a) All validation sites combined; (b) University of Girona (northeastern Spain); and (c) University of Seville (southwestern Spain). Bars in panel (a) extend from the mean bias error value ± 1 standard deviation of E_N . The gray shaded area encompasses ± 1 standard deviation of the observed E_N at the validation sites. Figure taken from Ruiz-Arias et al. (2015).

3.3.4 Site adaptation based on improving the cumulative distribution function

Correcting methods focused on fitting and improving the cumulative distribution function (CDF) of satellite-derived data compared to the CDF of ground data have been also proposed recently (Cebecauer and Suri, 2012). Also, the ENDORSE project investigated also the application of a feature transformation using the difference of data sets in cumulative distribution functions (Blanc et al., 2012). The feature transformation is based on the adaptation of the frequency distribution of the modeled data to the one of the ground data by using information of the relative distortion of the distribution of the satellite data from parallel sets (Carow, 2008; Schumann et al., 2011). The correction for a given satellite irradiance value was defined as the difference between the ground measured irradiance with the same CDF as the satellite irradiance and the satellite irradiance. The objective of the method was to approach the CDF of satellite-derived dataset to the ground data CDF (Figure 10). However, according to the ENDORSE project results this method did not result in significant improvement of the satellite-derived data.

The impact of the length of the overlap with measurements in the improvement of satellite-derived data was also studied with the feature transformation method (Schumann et al., 2011). In some cases they found that three continuous months of ground data could largely

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improve the modeled dataset. However, they noted that in order to take into account different seasonal characteristics at least one year of ground data would be needed.

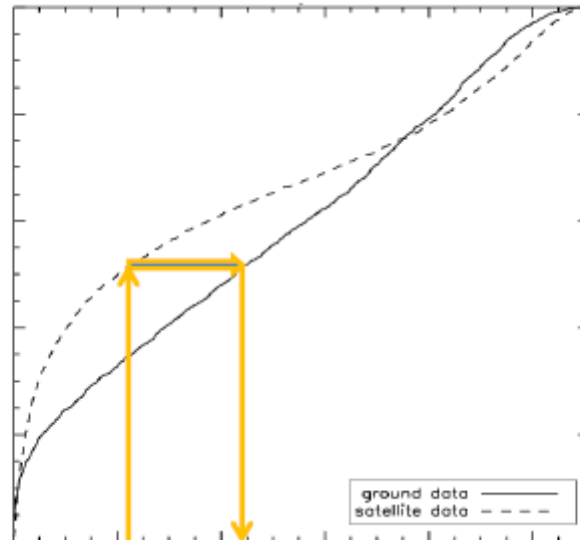


Fig. 10 Schematic of the feature transformation method based on the CDF (Blanc et al., 2012).

Nevertheless, by selecting specific subsets of satellite-derived data, according to the comparison with ground data, and applying linear correction factors can also result in an improvement of the cumulative distribution function (Polo et al., 2015).

3.3.5 BIAS removal by simple method based on satellite and re-analysis data

Satellite and especially re-analysis datasets are often biased. Within the framework of IEA SHC Task 46 a simple method to correct the bias of such data has been tested. The following measure-correlate-predict (MCP) method is applied to yearly averages, assuming that the relation between a shorter time period and a longer time period stays constant between the different datasets or nearby stations or grid points:

$$G_{y,l} = \frac{G_{x,l}}{G_{x,s}} \cdot G_{y,s} \quad (6)$$

Where $G_{y,l}$ is the long term average at location y , $G_{x,s}$ is the short term (one year) average at location x , $G_{x,l}$ is the long term average at location x and $G_{y,s}$ is the short term (one year) average at location y . This method is also used in wind energy.

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We applied this method to the following three long term datasets:

- NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA), re-analysis, resolution : 0.67x0.67° (<http://gmao.gsfc.nasa.gov/research/merra/>)
- NOAA NCEP, re-analysis, resolution: 1.5x1.5° (<http://www.ncep.noaa.gov/>)
- ECMWF ERA-INTERIM, re-analysis, resolution: 0.75x0.75° (http://apps.ecmwf.int/datasets/data/interim_full_daily/).
- Helioclim3.0 (HC) dataset (Version 5), satellite data, resolution approx. 5x5 km (http://www.soda-i-s.com/eng/helioclim/helioclim3_versions.html)

For ground truth we used data from the BSRN (Tamanrasset and Carpentras), MeteoSwiss (Bern/Zollikofen, Locarno/Magadino and Zürich/Fluntern) and 22 sites of Global Energy Balance Archive (GEBA) (Table 3). For BSRN and MeteoSwiss the 10 yearly averages of 2005-2014 are used; for GEBA the periods of 1981-2010 were mostly used.

Additionally long term trends of MERRA, ERA and GEBA ground measurements have been compared at 22 sites including the following tests:

- comparison of linear long term trends
- significance of trends (95% levels)
- relative standard deviation of yearly averages (12 monthly moving averages)

As shown in previous studies the bias of re-analysis data is high and is especially much higher than for satellite data (Boilley and Wald, 2015). For this reason re-analysis data should not be used without corrections. The results of the original RMSE values and the results based on MCP are listed in Table 2.

Table 2: Relative RMSE of the estimation of the long term averages for the 2 BSRN and 3 MeteoSwiss sites. The last row shows the variability of yearly averages of ground data as a benchmark.

Type	Original RMSE [%]	MCP RMSE [%]
Re-analysis NCEP	20.3	6.8
Re-analysis MERRA	16.3	3.3
Re-analysis ERA	11.2	3.4
Satellite (Helioclim)	3.8	3.0
Year to year var.	3.9	

The simple MCP method enhances the quality of re-analysis data by 60-70% and for satellite data by 20%. MCP with satellite data leads to the best results (RMSE = 3.0%). MCP with re-analysis data shows somewhat higher uncertainties (3.3% for MERRA and 3.4% for ERA). Only the uncertainty of MCP based on NCEP re-analysis is clearly higher as the year to year variability – which is the RMSE in the case of a one year measurement campaign. This shows that even when re-analysis data have high uncertainties in solar radiation values, they are useful for long-term approximations.

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The time series for two stations Potsdam (Fig. 11) and Beijing (Fig. 12) are shown below. In Potsdam the smoothed time series (5 years moving averages) of MERRA, ERA and GEBA are much in parallel. However during some periods (e.g. around 1986 or 2008) there are significant deviations. The trends are both positive; however the trend of GEBA is much stronger (3.2%/decade compared to 1.1-1.2%/decade). ERA and MERRA are very similar.

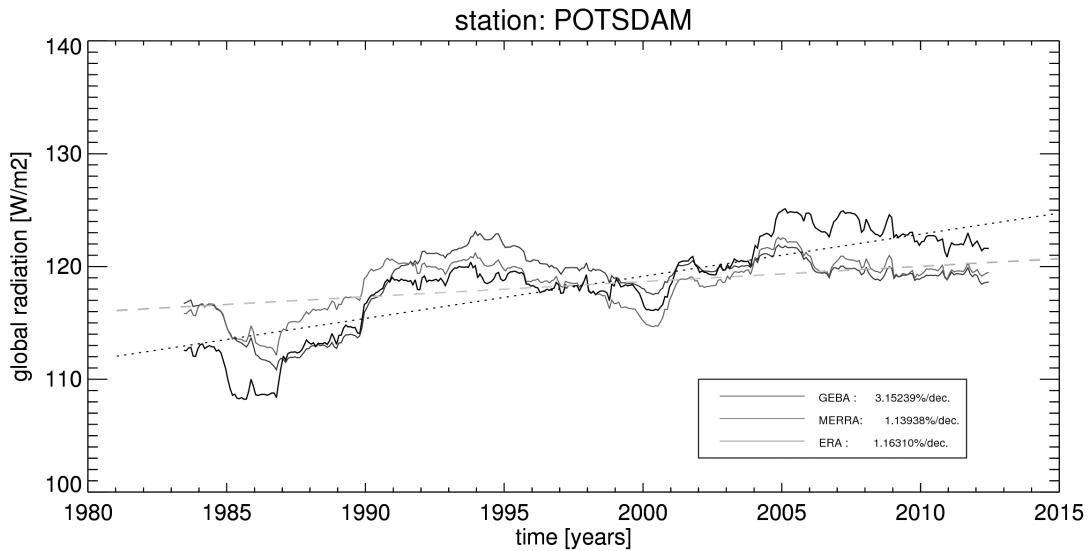


Fig. 11: Time series of 5 years moving averages of GHI of GEBA, MERRA and ERA for Potsdam (Germany) as well as the linear trends of the three data sources.

In Beijing some time periods are also in parallel (e.g. around 2003). However the deviations are much bigger (e.g. 1985 or after 2005). ERA and MERRA are also very similar in this location. The linear trend is positive for MERRA and ERA, but negative for GEBA (MERRA and GEBA trends are significant, ERA not).

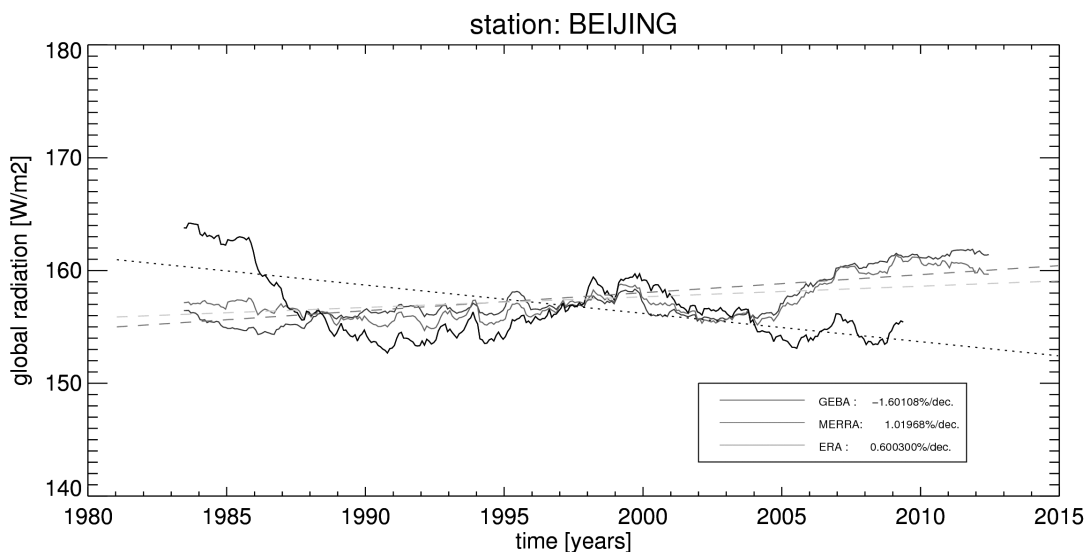


Fig. 12: Time series of 5 years moving averages of GHI of GEBA, MERRA and ERA for Beijing (China) as well as the linear trends of the three data sources.

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In Table 3 the trends for measured (GEBA), MERRA and ERA are listed for the 22 locations. Generally the trends for measured data are clearly higher and more often significant.

[Table 3: Trends in percent per decade of measured \(GEBA\) and modelled datasets for 12 months moving averages between 1981 and 2010/14; significance of trends \(in bracket if below 0.95 level.](#)

Sites for long term estimations	Trend measured [%/dec.]	Trend MERRA [%/dec.]	Trend ERA [%/dec.]
Hamburg, DE	3.6	2.0	1.1
Trier, DE	2.2	1.1	(0.8)
Braunschweig, DE	1.9	2.0	1.3
Würzburg, DE	2.2	1.4	1.4
Potsdam, DE	3.2	1.1	(1.2)
Salzburg, AT	4.7	(0.1)	(-0.1)
Locarno-Monti, CH	3.7	(-0.2)	(0.0)
Davos, CH	1.9	(0.3)	(0.7)
London, UK	5.3	-1.0	(-0.4)
Aberporth, UK	1.9	-1.5	(-0.4)
Eskdalemuir, UK	(1.8)	-2.0	(0.0)
Lerwick, UK	2.0	-1.5	(1.1)
Stockholm, SW	3.4	(0.1)	(-0.2)
Edmonton, CA	(-0.5)	(-0.2)	(-0.2)
Akita, JP	1.6	-0.9	(-0.4)
Sapporo, JP	2.0	-1.5	(0.0)
Fukuoka, JP	1.9	(-0.1)	(0.6)
Kagoshima, JP	3.4	(-0.2)	(-0.1)
Beijing, CN	-1.6	1.0	(0.6)
Poona, IN	-1.2	-2.0	-0.9
Ahmadabad, IN	-2.9	-1.2	-0.6
Madras, IN	-2.2	-1.7	-0.7

For MERRA 8 of 22 sites have the same signs and are significant. At 4 sites the trends have a different sign and at 8 sites the trends of one of the datasets are not significant. For ERA 6 of 22 sites have the same signs and are significant. At 16 sites the trends of one of the datasets are not significant. For Germany and India the trends are apparent with MERRA and ERA. For UK and Japan the trends have different signs.

The standard deviation of year to year averages of the 22 ground measurements is 4.7%, for MERRA 2.8% and for ERA 2.7%. Both re-analysis data underestimate the year to year variability clearly (with a factor of 1.8) at most sites. There is no clear correlation between the geographical features of the locations and the error of the variability estimation.

In addition the MCP adaptation method has been applied for GEBA locations (for estimation of 10 year averages). For MERRA (based on 12 months of measurements) the error comes to 3.1% and for ERA 2.9%, which is clearly lower than the year to year variations of the measurements, which shows that the MCP correction are useful. Only in Lerwick the year to year variability is lower than the MCP error. The results for the 22 locations are slightly lower

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as for the results shown in Table 2 (3.4% for ERA and 3.3% for MERRA), which is induced most presumably by the different set of locations.

Using only 6 months of measurements for the MCP method for both MERRA and ERA leads to 40% higher uncertainty levels, which are near the year to year variability. Using 18 months the MCP error is 20% lower than using 12 months. The duration of 12 months seems therefore to be a good trade-off between uncertainty and measurement effort.

Overall the analysis shows a diverse picture. MERRA gives somewhat more realistic trends than ERA (where most trends are not significant). ERA shows a little bit lower deviations of the monthly values and about the same uncertainty levels for MCP. For some areas the trends and fluctuations seem to be given well by MERRA and ERA, for some not. The deviations could be based on changing aerosol loads, which are not correctly included in the re-analysis datasets. However more work is needed to find the reason for this.

For this dataset the conclusions can also be drawn that MCP based on re-analysis data is useful, although variability and trends are not well represented.

4. Conclusions and outlook

Adjustment of model-derived solar radiation data to ground-based measurements is an established technique. Usually such methods are applied in advanced solar resource assessments, when a solar energy project site needs to be qualified for financing of large scale multi-MW-sized projects. For this purpose solar radiation measurements at the project site or in the near vicinity should be taken.

Great care must be taken to select only valid ground-based measurements. This requires selection of good instruments, proper calibration, installation and maintenance. Before application thorough quality checks of the measured data are required to ensure as much as possible the quality of the ground data.

The adjustment process either can be done by adapting the input data into the model to better fit the local measurements or by empirical adjustment of the model output data to the measurements (known as site adaptation). Some of the empirical models only modify the bias, while others also adjust the frequency distribution of irradiance values. The latter sort of adjustment processes are preferred so that the frequency distribution of adjusted solar irradiance data set is more realistic, which is important to receive reliable yield output, if applied in performance simulation tools. In some situations, correcting the bias and reducing the dispersion of satellite-derived data result in improvement of the cumulative distribution function. There is no unique method that covers all the situations and that can be successfully applied to the whole dataset, so that each site would require a specific initial study to identify the sources of discrepancies and then a proper method could be used for adapting the data.

The influence of the length of time of ground data overlapping with modelled data has not been completely studied yet. Even though Schumann et al. showed how the length of the

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overlap influences accuracy of the long-term average, this needs to be studied more in depth, covering the different correction methods and several sites of different climate.

The uncertainty of the long-term average of solar irradiance is a dominating parameter in risk analysis of solar power projects. The calculation of this uncertainty needs to take into account the different uncertainties associated with the model for generating the dataset and with the ground measurements used to validate and correct the modelled data. Therefore, a systematic deviation of the uncertainty of measurement-adjusted modeled data is strongly needed for bankable solar resource assessments. Such studies should derive how well various algorithms perform depending on overlap duration in various regions. Since the performance of the adjustment also depends on the quality of the satellite/model-derived data set, it is necessary to do such investigations for various data sets and sites.

In many cases there are no measurements available directly at the project site. Assuming that systematic errors of model-derived solar radiation data are similar at neighboring sites, an adjustment configured at a nearby measurement location may be transferred to the project site. Such an extrapolation likely works well, if local conditions such as albedo, elevation and shading conditions are similar. The distance between the measurement site and the project site may be evaluated systematically. The goal should be to get an error estimate depending on the distance, which in addition might also depend on quantifying elevation difference and other geographic parameters.

In conclusion, the solar radiation derived from models shows high accuracy and reliability in many current situations. Site adaptation techniques applied to the model-derived datasets improve significantly their quality by removing the bias and lowering the uncertainty. However, the sources of uncertainty are multiple and some climatic conditions have not yet been thoroughly studied, often due to the lack of quality and long-term ground measurements. Therefore, there is a need to put additional effort in the investigation of correction methods and in their applicability to different climatic conditions. Finally, all the adapted modelled data for any solar project must be supplied with the corresponding uncertainty for making it bankable.

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