First Steps in the Cross-Comparison of Solar Resource Spatial Products in Europe

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First Steps in the Cross-Comparison of Solar Resource Spatial Products in Europe

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Abstract

Yearly sum of global irradiation is compared from six spatial (map) databases: ESRA, PVGIS, Meteonorm, Satel-Light, HelioCliom-2, and NASA SSE. This study does not identify the best database, but in a relative cross-comparison it points out to the areas of higher variability of outputs. Two maps are calculated to show an average of the yearly irradiation for horizontal surface together with the standard deviation that illustrates the combined effect of differences between the databases at the regional level. Differences at the local level are analysed on a set of 37 randomly selected points: global irradiation is calculated from subset of databases for southwards inclined (at 34°) and 2-axis tracking surfaces. Differences at the regional level indicate that within 90% of the study area the uncertainty of yearly global irradiation estimates (expressed by standard deviation) does not exceed 7% for horizontal surface, 8.3% for surface inclined at 34°, and 10% for 2-axis tracking surface. Higher differences in the outputs from the studied databases are found in complex climate conditions of mountains, along some coastal zones and in areas where solar radiation modelling cannot rely on sufficient density and quality of input data.

Keywords: solar radiation database, maps, benchmarking

1. Introduction

Solar energy technologies and energy simulation of buildings need high quality climatic data in the phase of localisation (siting), design, financing, and system operation and management. The choice of the best technological option depends among other things on the geographic region, as the performance of solar energy systems is influenced by solar resource and other climate parameters.

Several spatial databases of solar resource information are now available as a result of European and national projects. They have been developed from various data inputs, covering different time periods, where diverse approaches have been applied. Although quality assessments of the individual databases have been performed, no inter-comparison of the outputs was performed. When comparing various data sources, differences show up which is confusing, especially to users who are not fully aware of the uncertainties and the limits of data application. Therefore, better understanding of the geographic distribution and variability of solar resource in Europe is needed.

In this contribution we open a complex issue of benchmarking the solar radiation databases and underlying models for deriving information relevant to energy technology. We focus on a comparison of six spatial databases and integrated systems that offer solar resource and climate data and energy-related services for Europe: Meteonorm [1], ESRA [2], Satel-Light [3], NASA SSE/RETScreen [4], HelioClim/SoDa [5], and PVGIS [6]. This list is not exhaustive, and in future also other databases may be considered, including those that cover smaller regions. We compare *yearly sum of global irradiation* as obtained by querying each database. Map analysis compares horizontal irradiation, while on a set of 37 randomly selected points we compare irradiation received by inclined and 2-axis tracking surfaces.

2. Specifications of the solar radiation databases and underlying methods

2.1. General specifications

Spatially-distributed (map) solar radiation databases are classified according to several factors:

- *Input data* from which they have been created: (a) observations from the meteorological stations (global, diffuse and direct irradiances, and other relevant climate data), (b) digital satellite images or (c) combination of both; here also ancillary atmospheric data used in the models are considered, such as water vapour, ozone and aerosols;
- *Period of time* (typically a number of years) which is represented by the input data;
- *Spatial resolution*, i.e geographical distribution of the meteorological sites, grid resolution of the satellite data and resulting outputs;
- *Time resolution*, which characterises periodicity of the measurement of the input data and of the resulting parameters. Thus a primary database may include time series with periodicity of a few minutes up to hourly and daily averages (sums), or it may contain only monthly and long-term averages.
- *Methodical approach* used for computation of the primary database: typically solar radiation models combined with interpolation methods (e.g. geostatistical methods or splines, in case that ground observations are used) or algorithms for satellite data processing (e.g. Heliosat). Primary database typically consists of global, direct normal or diffuse irradiances (irradiation in case of time-integrated products) and also some auxiliary parameters such as clear-sky index.
- *Simulation models* used for calculation of derived parameters, such as global irradiance for inclined and sun-tracking surface, spectral products (e.g., illuminances, UV and PV-related irradiances), estimation of terrain effects, derived statistical products (e.g. synthetic time series).

Quality of an individual data set is assessed for a set of locations by comparing them to ground measurements, where the first order statistics is calculated (bias, root mean square deviation, standard deviation, the correlation coefficient) and the frequency distribution is analysed. In this work we focus on the relative map-based cross comparison of several solar radiation products. Such comparison provides means for improved understanding of regional distribution of the uncertainty by combining all existing resources (calculating the average of all) and quantifying their mutual agreement by the means of standard deviation.

2.2. Analysed databases and integrated systems

Each of the databases analysed here is integrated within a system (software setup) that provides additional tools for search, query, maps display, and calculation of derived parameters. *PVGIS* (the European section), includes solar radiation database developed by combination of solar radiation model and interpolated ground observations. The datasets *Satel-Light* and *HelioClim-2* (accessible through the SoDa web portal) are built from Meteosat and MSG satellite images, respectively. *NASA SSE release 6* (accessible also through RETScreen software) combines results from ISCCP satellite project with NCAR reanalysis products. Primary data incorporated in *Meteonorm version 6.1* and *ESRA* are developed by interpolation of ground observed data with support of satellite images (MSG and SRB, respectively).

Table 1. Technical parameters of the solar radiation databases.

Database & availability	**Data inputs**	**Period**	**Time resolution**	**Spatial resolution (in study region)**	**RMSD/ MBD (%)**
PVGIS Europe *(internet)*	~560 meteo stations	1981-1990	Monthly averages	1 km x 1 km + on-fly disaggreg. by 100 m DEM	4.7/-0.5 [6]
Meteonorm 6.1 *(CDROM and internet)*	Meteo stations + satellite data	1981-2000	Monthly averages	Interpol. (on-fly)+ satellite; disaggreg. by 100 m DEM	6.2/0 [7]
ESRA *(CDROM)*	~560 meteo stations + SRB satel. data	1981-1990	Monthly averages	5 arc-minute x 5 arc-minute	~7.5/- [8]
Satel-Light *(internet)*	Meteosat 5, 6, 7	1996-2000	30-minute	4.6-6.2 km x 6.1-14.2 km	21.0/-0.6 [9]
HelioClim-2 *(internet)*	Meteosat 8 and 9 (MSG)	2004 - 2007	15-min	3.1-4.2 km x 4.1-9.6 km	25.3/2.2 [9]
NASA SSE 6 *(internet)*	GEWEX/SRB 3 + ISCCP satel. clouds + NCAR reanalysis	1983-2005	3-hourly	1 arc-degree x 1 arc-degree	8.7/0.3 [4]

Table 2. Methods used in calculation of primary and derived parameters.

Database/ system	**Global horizontal radiation**	**Diffuse fraction**	**Inclined surface (diffuse model)**	**Simulation of time series**	**Derived parameters**
Satel-Light	Heliosat 1 (Dumortier diffuse clear sky model)	Skartveit et al. 1998	Skartveit & Olseth 1986	Real 30-minute data	G, B, D, illuminances, ext. statistics
Meteonorm ver. 6.1	3D inverse distance interpol. by Zelenka et al 1992 and Wald & Lefevre 2001; Heliosat 1 for sat. data	Perez et al. 1991	Perez et al. 1987	Synthetic time series from monthly averages by Aguiar et al 1988, and Aguiar & Collares-Pereira 1992	G, D, B, terrain shadowing (beam and diffuse)
PVGIS Europe	3D spline Interpol. of ground data + model r.sun: Suri & Hofierka 2004	Measured at 63 stations, the rest estim. by Czeplak 1996	Muneer 1990	Simulation of daily profile from monthly averages by Suri & Hofierka 2004	G, D, terrain shadowing (beam only)
ESRA	Interpol. of ground data by co-krigging: Beyer et al. 1997	Measured at 63 stations, the rest estimated by Czeplak 1996	Muneer 1990	Simulation of daily average profile by Collares-Pereira & Rabl 1979, and Liu & Jordan 1960	G, D,B, clearness, zones
NASA SSE rel. 6	Satellite model by Pinker & Laszlo 1992	Erbs et al. 1982	Retscreen method by Duffie & Beckman 1991	Simulation of daily average profile by Collares-Pereira & Rabl 1979, and Liu & Jordan 1960	G, B, D, extended number of parameters & statistics
HelioClim ver. 2	Heliosat-2 (Rigollier et al. 2004)	N/A	N/A	Real 15-minute data	G

In Tabs. 1 and 2 we summarise the main characteristics of the databases/systems including the quality indicators Root Mean Square Difference (RMSD) and Mean Bias Deviation (MBD). While NASA, Satel-Light, PVGIS, and partially also Meteonorm systems are available for free, the ESRA, HelioClim-2 and full version of Meteonorm are to be purchased.

Geographical extension of the spatial products differs: from global (NASA and Meteonorm) to cross-continental (HelioClim-2 covering Europe, Africa and Southwest Asia) and European (ESRA, PVGIS and Satel-Light). Here we focus on the subsection of the European continent (Fig. 1) where all the data sources overlap.

3. Method

3.1. Map comparison

Map-based comparison as performed here is a type of relative benchmarking of solar databases. It does not point to the "best" database, but it gives an indication of the *user's uncertainty at any location within the region*. As the existing spatial products cover different periods of time, this comparison introduces also uncertainty resulting from the interannual variability of solar radiation. Here we perform a cross-comparison of maps of *long-term average of yearly sum of global horizontal irradiation*.

The maps from all data providers are harmonised and integrated into a geographical information system (GIS) with latitude/longitude spatial reference. The grid resolution of 5 arc minutes is chosen to provide a representative outlook at the regional (rather than local) differences within the continent. Choosing such a resolution, more detailed features that are present in the databases of HelioClim-2, Satel-Light, PVGIS and Meteonorm are suppressed (smoothed out), but the regional features are well pronounced. Integration of 6 data sources of yearly sums of global horizontal irradiation provides three results:

- *Map of overall average* gives the user an indication of spatial distribution of solar resource estimated by the simple averaging of the 6 datasets;
- *Map of standard deviation* provides information on magnitude of differences between the combined data sources, i.e. user's uncertainty. If we assume that the estimates are normally distributed, from standard deviation a confidence interval can be calculated in which the value falls corresponding to a given probability. For example, a multiple of 1.95996 would give a range where the value from the average map falls with 95% probability.
- *Maps of differences* between individual databases and the overall average indicate deviation of the values in the particular dataset from the overall average.

3.2. Point analysis

The maps give good insight into regional differences, however due to the coarse grid resolution (5 arc minutes) they smooth out local effects. Some of the integrated systems incorporate specific algorithms, such as an application of high-resolution Digital Elevation Model (DEM), which may increase the difference between results for a given site. Thus, for a set of 37 randomly selected points we analyse the values and resulting differences that a user obtains for a particular site when consulting directly each data source/system. In areas with higher agreement of all 6 databases (standard deviation lower than 4%) we selected 15 points, and in areas with higher disagreement (standard deviation between 5% and 11%) another 22 points.

For each point we calculated the yearly sum of global irradiation for (1) south-oriented surface inclined at 34 degrees (close to the typical optimum angle for PV systems in Europe), and (2) for 2-axis sun-tracking systems.

4. Results

While the map of yearly sum of global horizontal irradiation (Fig. 1) shows the average of 6 databases, the map of standard deviation (Fig. 2) indicates how much the datasets differ in various regions. Higher disagreement between the databases can be found not only in higher mountains (the Alps, Pyrenees, Carpathians, etc.), but also along some coastal zones and in flat regions, e.g. around the Baltic and North Seas. Higher standard deviation in Bulgaria and Romania, in South Scandinavia, and Po plain relates to uneven distribution of the input ground data and questionable quality of the older ground measurements that are used in ESRA and PVGIS. However, cumulative distribution of the map values (Fig. 4 right) shows that standard deviation does not exceed 6% in 78% of the study region, and only in rare (extreme) cases is it higher than 12%.

The analysis on 37 selected points shows some cases with higher differences (some of them are not present in the coarse-resolution maps) with average standard deviation 5.6%. Mean bias difference (see yellow box in the Fig. 3) indicates that satellite databases (Satel-Light and HelioClim-2) show generally higher values compared to the products relying on ground measurements (ESRA, Meteonorm and PVGIS). This difference may be partially explained by the time period of data covered. While Satel-Light and HelioClim-2 represent last 10 years, ESRA and PVGIS are based on one decade of data (1980s), and Meteonorm represents two decades (1980s and 1990s). The NASA SSE product partially spans both periods and also generally gives results that are intermediate between the two groups.

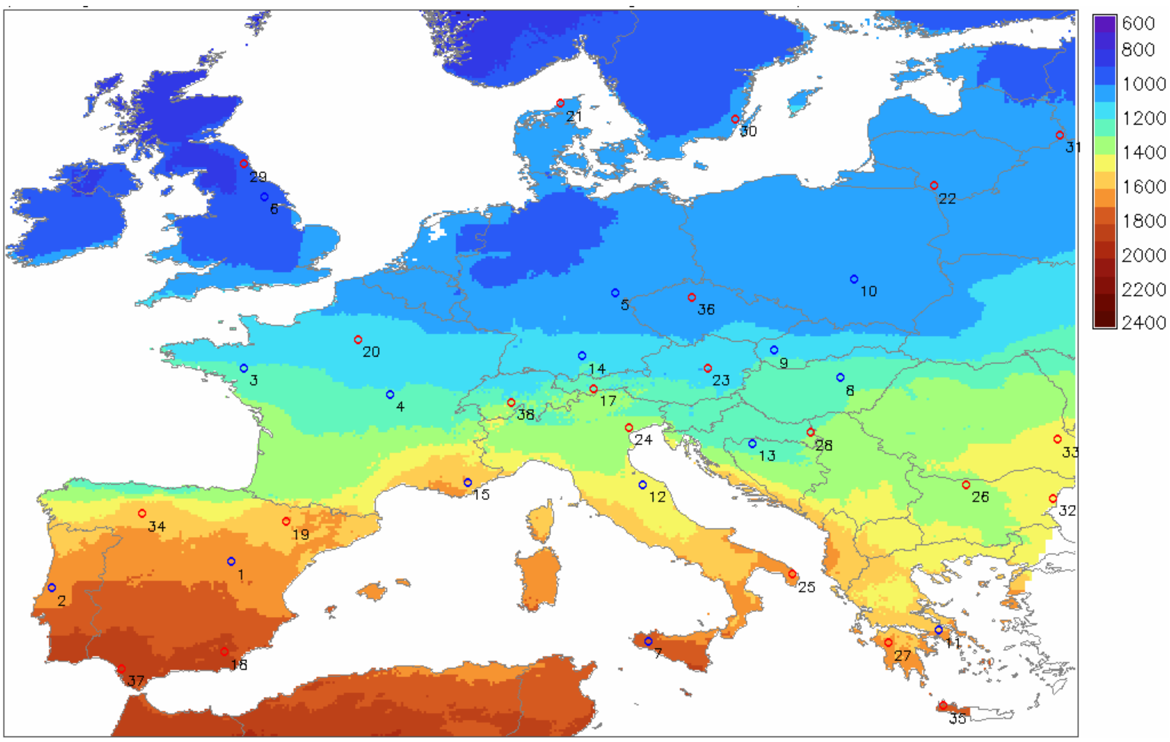

Fig. 1. Yearly sum of global irradiation on horizontal surface – average of 6 databases: Meteonorm v.6, ESRA, PVGIS, NASA SSE v.6, Satel-Light and HelioClim-2 [kWh/m^2]. Results for 37 randomly selected sites are shown in Fig. 3.

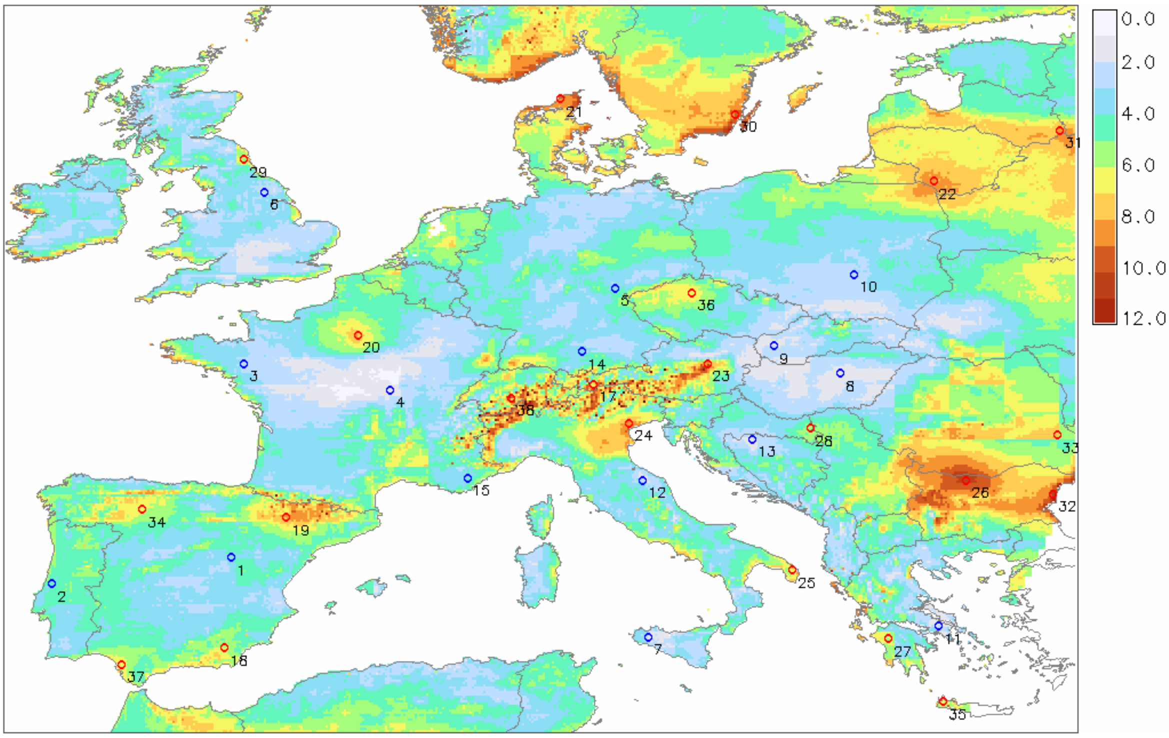

Fig. 2. Yearly sum of global horizontal irradiation –standard deviation of the values from 6 databases relative to the overall average shown in Fig. 1 [%]. Results for 37 randomly selected sites are shown in Fig. 3.

Part of the contribution from higher values obtained from HelioClim-2 database can be probably explained by Mean Bias Deviation calculated by comparison with data from 11 high-quality BSRN stations ([9] see Tab. 1).

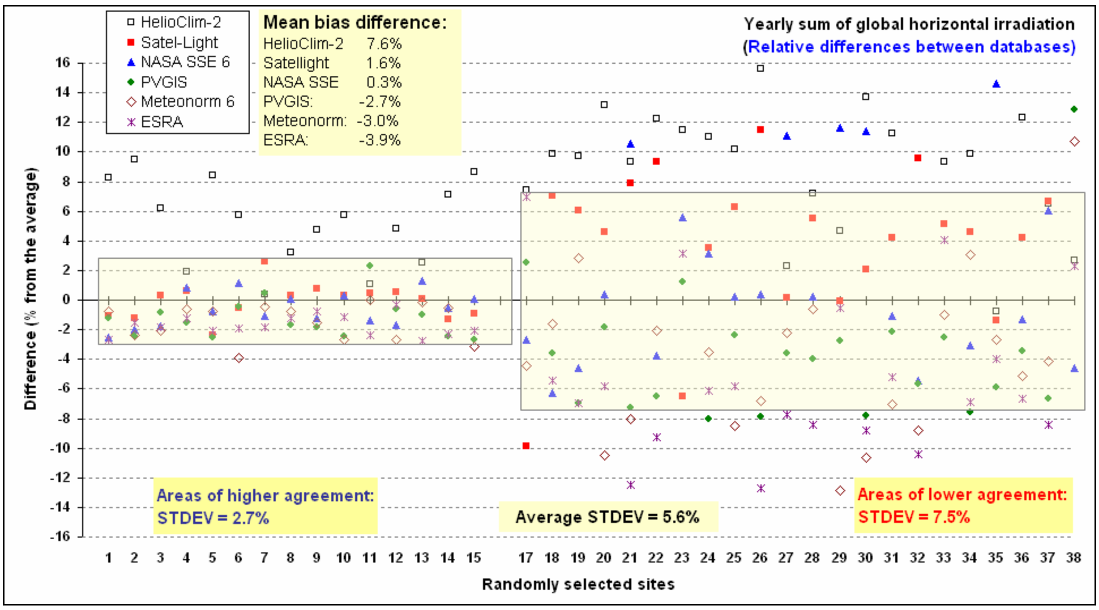

Fig. 3. Yearly sum of global horizontal irradiation – differences of the values from 6 databases relative to the overall average. First 15 points represent areas with higher agreement between databases; the other 22 points are randomly selected in areas where the difference between the databases is higher.

For the same 37 points, global irradiation has been calculated for a south-oriented surface inclined at an angle of 34 degrees. Results from five systems are available (all except HelioClim-2). From linear fit of the values on the scattergram (Fig. 4 left) one can see that the standard deviation of estimations for an inclined surface increases in average by 21% compared to the horizontal irradiation (correlation coefficient 0.98). The differences between values for 2-axis tracking surface are calculated only for 3 systems: Meteonorm, NASA SSE/RETScreen and PVGIS. Here the standard deviation increases by 36% compared to the estimates for horizontal surface (correlation coefficient 0.97). Both simulations show a good agreement in the implementation of the underlying algorithms in the compared software.

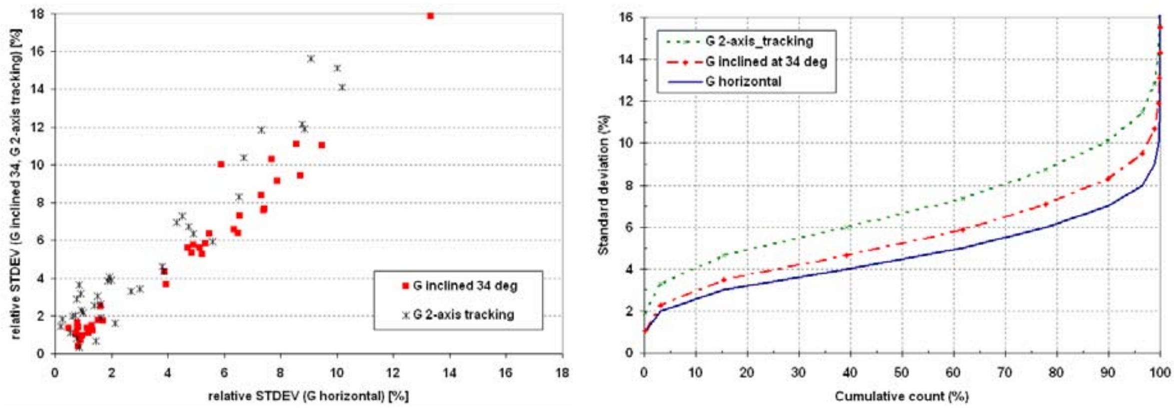

Fig. 4. Estimates of yearly sum of global irradiation. Left: Scattergram of 37 points showing relation between relative standard deviation calculated for horizontal surface and those calculated for 34° inclined and 2-axis tracking system [%]; Right: Cumulative distribution of relative standard deviation [%] for global horizontal irradiation summarised from the map and the standard deviation estimated for inclined, and 2-axis tracking surface by linear fit of points from the left.

By integration of findings from the map and point analyses (Figs. 2 and 4 left) we can estimate uncertainty for any point on the map for yearly values for horizontal, inclined and 2-axis tracking surfaces. Thus the cumulative distribution of user's uncertainty can be calculated from the map data for the whole study region. Fig. 4 (right) shows that for 90% of the study region the uncertainty of estimates of yearly global irradiation (expressed by standard deviation) is lower than 7% for a horizontal surface, 8.3% for a south-facing surface inclined at 34°, and 10% for a 2-axis tracking surface.

5. Discussion

Differences in the estimates using several solar radiation databases relate to a number of factors.

Analysis of interannual variability for 70 meteorological stations over Europe having data for at least 10 years shows that the standard deviation from the long-term average ranges typically between 3% and 6%. To capture this variability, a database should include data for at least 5 to 10 years depending on the climate region.

There is an inherent difference between in situ (ground) and satellite observations, and the methods how these data are processed. Databases relying on the interpolation of ground observations (Meteonorm, ESRA, and PVGIS Europe) are sensitive to the quality of measurements and density of the measuring stations (which is not satisfactory in many regions), and they typically represent only statistical values. The satellite-derived databases (e.g. HelioClim, NASA SSE, and Satellight) are more affected by higher uncertainty of the cloud cover assessment when the ground is covered by snow and ice and for low sun angles, but they offer time series with high time resolution (e.g. hourly data) and provide spatially-continuous coverage.

Quality and the spatial detail of spatial database is determined by input data used in the models, mainly parameters describing the optical state of the atmosphere (such as Linke atmospheric turbidity, ozone, water vapour, aerosol optical depth), and Digital Elevation Models. The community of data developers lacks high quality aerosol data. High-resolution DEM is presently considered only in Meteonorm and PVGIS. Databases with coarser spatial resolution (e.g. NASA SSE) provide good regional estimates, however for studies at local level they may show deviations as they ignore local climate and terrain features.

The cross-comparison approach presented in this study assumes that each database has equal weight. Uncertainty can be reduced by weighting each contribution that is based on indicators of quality, number of data-years included, spatial resolution and incorporation of terrain effects. Including another two European satellite-derived databases, those owned by German Aerospace Center (DLR) and University of Oldenburg (both in Germany), and application of weighting will provide more complete picture of the uncertainty in the solar resource assessment.

6. Conclusion

This study provides a first insight into spatial distribution of uncertainty of solar radiation estimates by relative cross comparison of six data sources. In this stage only the yearly sum of global irradiation is considered, and all databases are assumed to give an equal contribution to the overall average. The map of standard deviation from the average indicates combined effect of differences between the databases, and in this study it is used as an indicator of the user's uncertainty.

Differences at the regional level indicate that within 90% of the study region the uncertainty of yearly global irradiation estimates expressed by standard deviation does not exceed 7% for horizontal surface, 8.3% for surface inclined at 34°, and 10% for 2-axis tracking surface. A user has to expect higher differences in the outputs from the studied databases in complex climate conditions of mountains, some coastal zones and in areas where solar radiation modelling cannot rely on sufficient density and quality of input data.

References

[1] J. Remund, S. Kunz, C. Schilter, Handbook of METEONORM Version 6.0, Part II: theory. Meteotest, 2007, http://www.meteonorm.com/.

[2] J. Greif, K. Scharmer, Eds., European Solar Radiation Atlas (ESRA), 4th edition. Scientific advisors: R. Dogniaux, and J. Page; Authors: L. Wald, M. Albuisson, G. Czeplak, B. Bourges, R. Aguiar, H. Lund, A. Joukoff, U. Terzenbach, H.-G. Beyer, and E. P. Borisenko, Paris: Presses de l'Ecole des Mines de Paris, 2000.

[3] D. Dumortier, M. Fontoynont, D. Heinemann, A. Hammer, J.A. Olseth, A. Skartveit, P. Ineichen, C. Reise. Satel-Light, a www server which provides high quality daylight and solar radiation data for Western and Central Europe. CIE 24th Session, Warsaw, pp. 277-281, 1999. http://www.satellight.com/core.htm.

[4] Surface meteorology and Solar Energy (SSE) Release 6.0 Methodology, draft version 1.005, 2008, http://eosweb.larc.nasa.gov/sse/. Accessible also through RETScreen software http://www.retscreen.net/.

[5] C. Rigollier, M. Lefevre, L. Wald, The method Heliosat-2 for deriving shortwave solar radiation from satellite images, Solar Energy, 77 (2004) 159-169, http://www.helioclim.org/radiation/. Accessible also through SoDa portal http://www.soda-is.com/.

[6] M. Šúri, T. Huld, T. Cebecauer, E.D. Dunlop, Geographic Aspects of Photovoltaics in Europe: Contribution of the PVGIS Web Site. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 1 (2008), in press, http://re.jrc.ec.europa.eu/pvgis/.

[7] J. Remund, Quality of Meteonorm Version 6.0. Proceedings of 10th World Renewable Energy Conference, 19-25th July 1008, Glasgow. (2008).

[8] H.-G. Beyer, G. Czeplak, U. Terzenbach, L. Wald, Assessment of the method used to construct clearness index maps for the new European Solar Radiation Atlas (ESRA), Solar Energy, 61 (1997) 389-397.

[9] P. Inneichen, Irradiance products validation and comparison against 13 ground stations, Working document of the MESoR project, 2008, http://www.mesor.net/.