COMPARING PERFORMANCE OF SOLARGIS AND SUNY SATELLITE MODELS USING MONTHLY AND DAILY AEROSOL DATA

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1. Introduction

Monthly data of Aerosol Optical Depth (AOD) or Linke turbidity are used in the satellite-based solar radiation models until recently, which is given by the limited availability of the atmospheric information. The European consortium working within the project MACC (Monitoring Atmospheric Composition & Climate) and lead by ECMWF (European Centre for Medium Range Weather Forecast) introduced a new version of the aerosol database, which replaces the prototype called GEMS (Morcrette et al. 2009).

The MACC database, operationally calculated within the Integrated Forecast System by ECMWF, provides several atmospheric parameters with a spatial resolution of 1.15 arc-degree (≈125 km at the equator) and a time step of 6 hours. It represents the period from year 2003 to the present time. The time step of 6 hours shows high fluctuation of AOD, and given the uncertainty and low spatial resolution we found it as a good compromise to use the daily averages for adequate representation of the spatial and time dynamics of aerosols in solar modelling.

AOD is a parameter with highest uncertainty in the solar radiation computational chain (Cebecauer et al., 2011), and the MACC AOD data have capacity to substantially improve calculation of solar radiation, the first results being presented by Cebecauer and Suri (2010). The development is ongoing, and reduction of the uncertainty can be further achieved by improving the chemical transportation models governing the interaction of aerosols in the atmosphere, calculation of AOD at several wavelengths and increasing the spatial resolution.

In this paper we further analyze benefits of MACC AOD operational calculations on an example of SUNY and SolarGIS solar radiation models, which process Meteosat and GOES satellite data. Both models use the same clear-sky model - simplified SOLIS (Ineichen, 2008) and they apply multispectral satellite data for cloud index calculation (Cebecauer et al. 2010, Perez et al. 2010). The effects of daily and monthly averaged AOD values are shown on the calculation of GHI (Global Horizontal Irradiance) and DNI (Direct Normal Irradiance). The selected sites provide a good representation of different climate zones (Tab. 1). Difficult sites were intentionally chosen, with complex geography and in high turbidity regions, to demonstrate the advantages and limits of analyzed AOD data.

Tab. 1: Validation stations. At sites marked by an asterisk (*) winter data are excluded from the analysis

Site name	Country	Network	Model	Latit.	Longit.	Year
Bondville*	USA, IL	BSRN/SURFRAD	SUNY	40.07	-88.37	2010
Boulder	USA, CO	BSRN/SURFRAD	SUNY	40.13	-105.24	2010
Desert Rock	USA, NV	BSRN/SURFRAD	SUNY	36.63	-116.02	2010
Fort Peck*	USA, MT	BSRN/SURFRAD	SUNY	48.32	-105.10	2010
Goodwin Creek	USA, MS	BSRN/SURFRAD	SUNY	34.25	-89.87	2010
Penn State*	USA, PA	SURFRAD	SUNY	40.72	-77.93	2010
Sioux falls*	USA, SD	BSRN/SURFRAD	SUNY	43.73	-96.62	2010
Carpentras	France	BSRN	SolarGIS	44.08	5.06	2004/03-2009/11
Sede Boqer	Israel	BSRN	SolarGIS	30.91	34.78	2004/03-2006/06
Solar Village	Saudi Arabia	BSRN	SolarGIS	24.91	46.41	2000/01-2001/12
Tamanrasset	Algeria	BSRN	SolarGIS	22.78	5.51	2004/03-2006/12
Ilorin	Nigeria	BSRN	SolarGIS	8.53	4.57	2004/03-2005/07
Upington	South Africa	ESKOM	SolarGIS	-28.45	21.24	2007/07-2009/12

All stations belong to the BSRN/SURFRAD radiometric network with high standards for measurements; meteo station in Upington is operated by Eskom, South Africa. To eliminate possible interference of snow on the accuracy of solar irradiance modeling for the sites in US, the winter data were not assumed. In the data quality checking, it has been identified that data for Ilorin do not have the expected quality.

2. Monthly and daily aerosol data

Aerosols are, after clouds, the second most important factor determining DNI, and to a lesser extent, GHI. Under clear skies, aerosols are the main source of attenuation for DNI. The Aerosol Optical Depth (AOD) parameter is used to characterize the overall radiative effect of aerosols. Aerosols have a high spatial and temporal variability in both composition and quantity. Up to very recently, only monthly-average AOD data were used in solar radiation modeling. This simplification artificially removes the high frequency aerosol fluctuations, thus resulting in skewed frequency distribution of DNI (and GHI) and in failure to represent extreme events (Fig. 1).

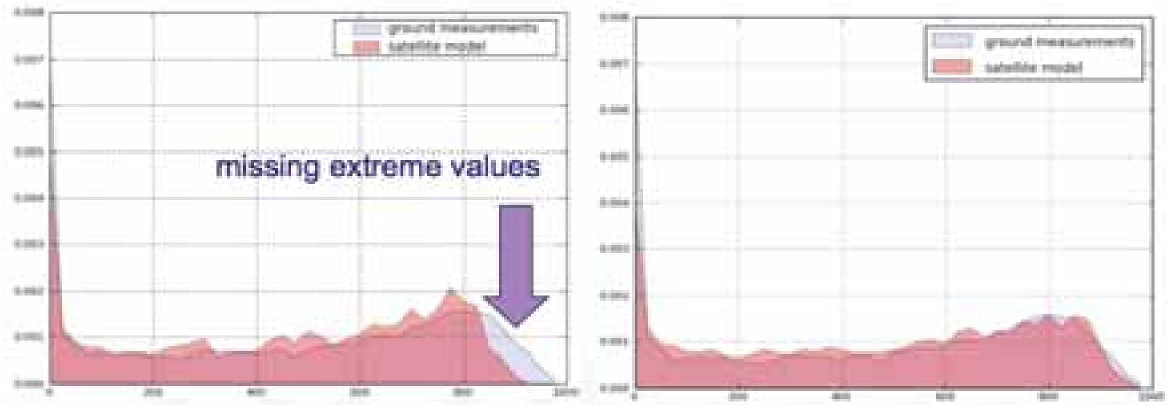

Fig. 1: Distribution of hourly DNI values for the Tamanrasset – red: modeled data, blue: ground observations. Left: data calculated using long-term monthly AOD averages, right: data calculated in operational SolarGIS using daily values. The left graph demonstrates the skewed representation of values in the range from 750 to 950 W/m^2.

Use of monthly averages of AOD in the satellite model results in a uniform monthly clear-sky radiation values omitting any information about day-by-day variation. The effect of such clear-sky model parameterization is a distorted distribution of the DNI values with erroneous representation of extreme events such as very high or very low aerosol loads (Fig. 2).

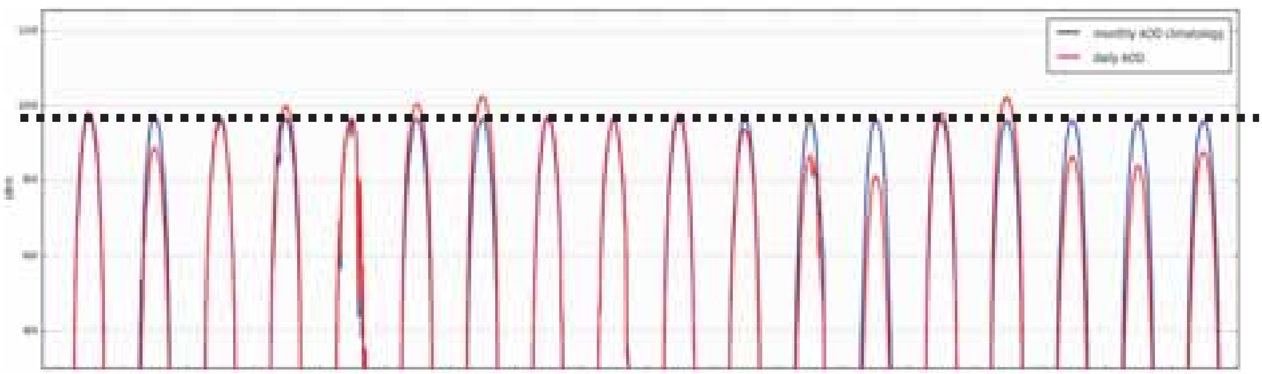

Fig. 2: 15-minute DNI profiles for 18 days, at the Upington site. Blue: DNI calculated using long-term monthly averages; red: DNI calculated in operational SolarGIS using daily values. The red profiles demonstrate how daily variability of aerosols (AOD) strongly affects the accuracy of the estimates.

The operational version of SolarGIS (http://solargis.info) uses daily AOD values. At present, the daily MACC AOD data exist only since 2003. For the older period, SolarGIS still uses only monthly long-term averages (Fig. 3).

Fig. 3: MACC AOD data for the Upington site. Daily values are available only for the era from 2003 onwards. For the older period, long-term monthly average values are used in SolarGIS

The current MACC data correctly represent the magnitude of the aerosol variability over both time and space (Cebecauer, 2011), however some bias has been identified in regions with high aerosol loads known also by an extreme daily and seasonal dynamics (see an example of Nigeria and Saudi Arabia (Fig. 4). The reported issues will be dealt with in the next version (MACC II) of the aerosol chemical-transport model.

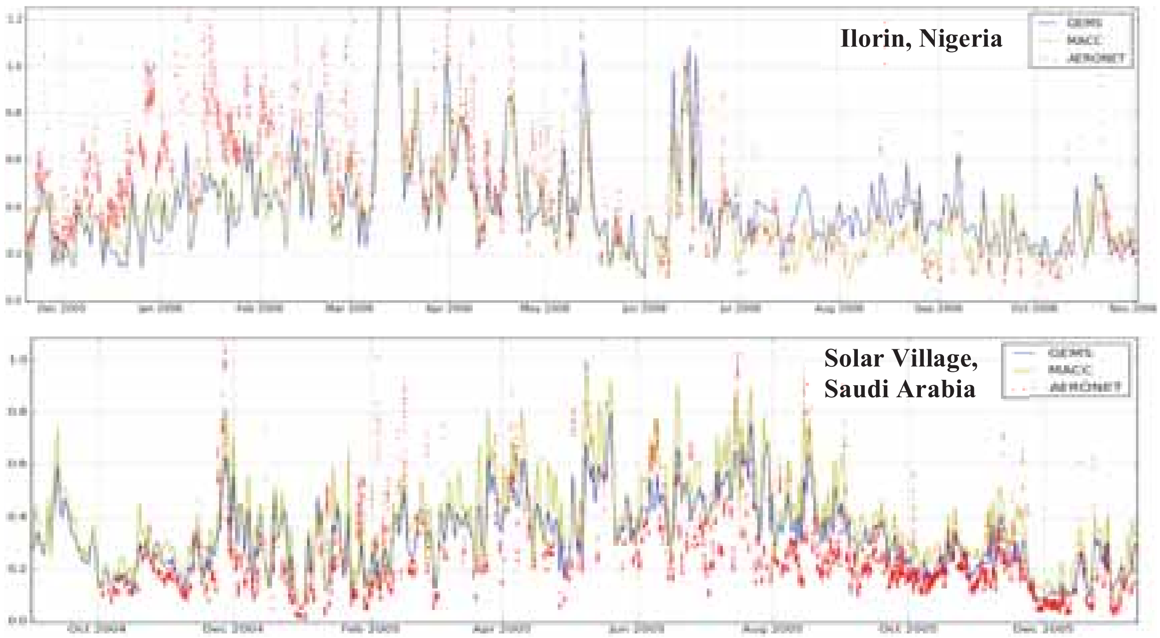

Fig. 4: Comparison of AERONET ground measurements with AOD data as calculated by MACC, showing the performance of the current MACC model in "difficult" regions known by extreme dynamics of aerosols. The data profile from the older prototype GEMS are also shown for comparison. Daily MACC values are operationally used in SolarGIS

3. Method

Three options are compared, while approaches for SUNY and SolarGIS models differ:

1. Monthly AOD: In the SUNY model, ASRC monthly AOD values are used as they are currently implemented in the operational model. For SolarGIS, long-term monthly AOD values are calculated by averaging of daily data. Therefore the approach differs for SUNY and SolarGIS;
2. MACC daily AOD: the original MACC daily-averaged AOD data are used in the calculations;
3. Calibrated MACC daily AOD: Due to bias identified for some sites, the daily AOD data are calibrated as follows:
   a. In SUNY model, the daily data are calibrated so as to match ASRC monthly AOD averages, developed previously, and operationally used for North America in SolarAnywhere (http://www.solaranywhere.com);
   b. In SolarGIS, the daily MACC data are calibrated using AERONET aerosol measurements. Details of this calibration is explained in the following paragraphs.

The calibration of MACC data for the SolarGIS region (Europe, Africa and Asia) is based on the point AOD measurements from the AERONET network. The quality level 2 AERONET measurements (http://aeronet.gsfc.nasa.gov/) were integrated on the daily basis and compared to the MACC daily AOD values. The difference was analyzed for each month individually and the calibration was applied only for months where number of valid AERONET-MACC values exceeded the limit of 30 pairs. For Europe, Africa and Asia a total of 76 stations with sufficient number of valid data pairs were selected.

As the influence of the AOD on the modeled DNI and GHI is non-linear, the calibration of AOD must resemble the distribution of the AEORONET values. This is important especially for very low AOD values where even slight change of AOD results in significant change of DNI. For this reason the AERONET-MACC difference was analyzed for 5th and 50th percentiles separately. Subsequently these differences were used for piecewise calibration of MACC AOD database.

The specific issue is extrapolation of the calibration factor identified for individual data points to the surrounding area. The spatial distribution of aerosols is controlled by specific geographical conditions, therefore several criteria were used to define region of influence: distance from the points, geographical barriers, similarity of AOD in region to point AOD (given by the monthly average and variability values). By combination of these criteria, regions of correction influence and weights were defined for each AERONET site.

It is to be stressed that SolarGIS approach does not aim at full matching of MACC data with AERONET values, rather the objective is to identify significant geographical patterns for potential temporary correction of the existing MACC data until the release of the MACC II version.

An example of spatial distribution of the calibration coefficients for the SolarGIS model is shown in Fig. 5.

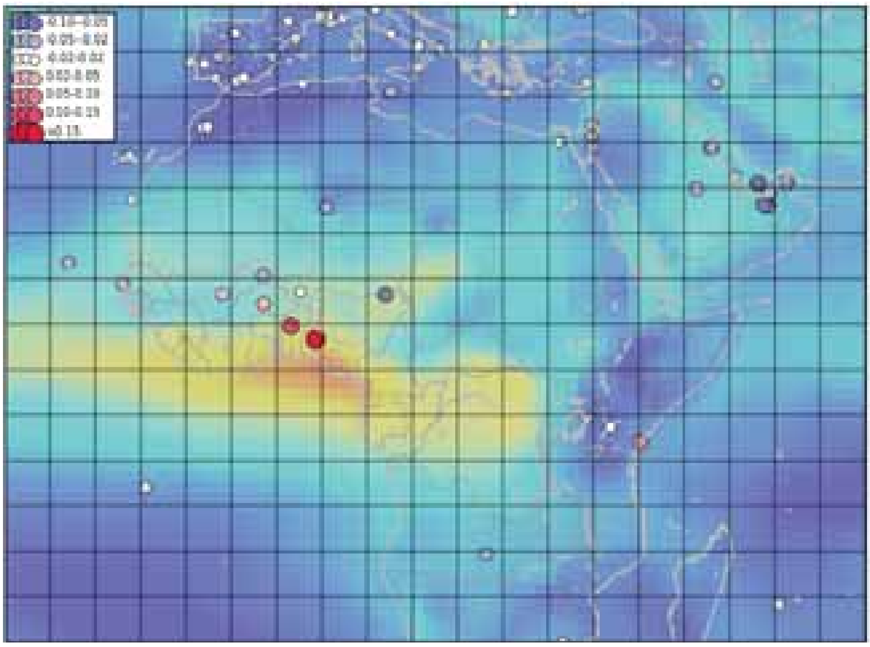

Fig. 5: Example of difference of 5th percentile between GEMS/MACC data and AERONET in January for AOD sites in Southern Europa, Middle East and Africa for valid AERONET sites. Information in the background: monthly AOD average calculated from the MACC daily data.

4. Results

In general, the use of daily aerosols shows improvements in ability of both models to represent hourly values of DNI and GHI as an effect of aerosol dynamics. From the viewpoint of running the operational model, the new atmospheric dataset better captures daily variability, especially events with extreme atmospheric load of aerosols. Thus it reduces uncertainty of instantaneous DNI and GHI estimates (Figs 6 to 9).

The main accuracy improvements are achieved in reduction of Root Mean Square Deviation (RMSD) and improved distribution function of especially DNI. The bias for daily values indicates a need for systematic correction of the MACC calculation scheme in some regions, especially in those with high concentration and dynamics of aerosols.

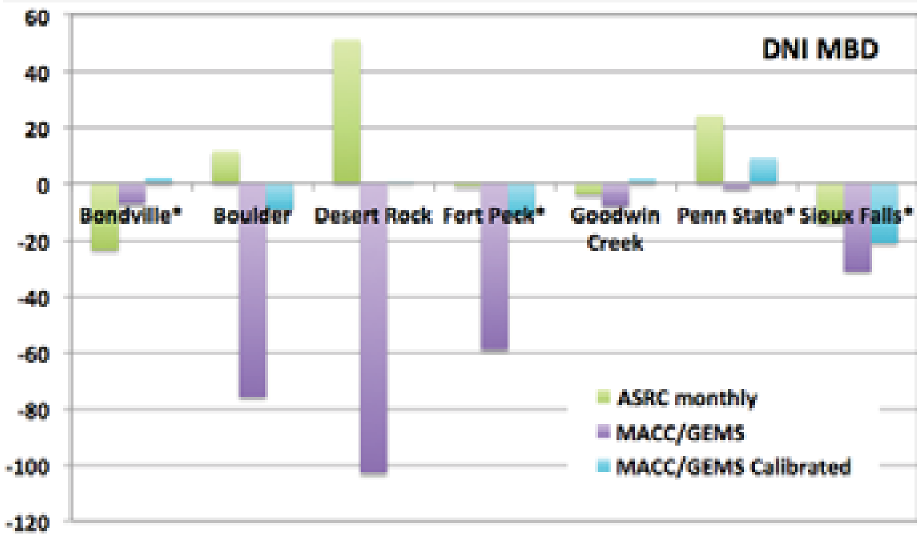

Fig. 6: Mean Bias Deviation for hourly DNI values related to SUNY model

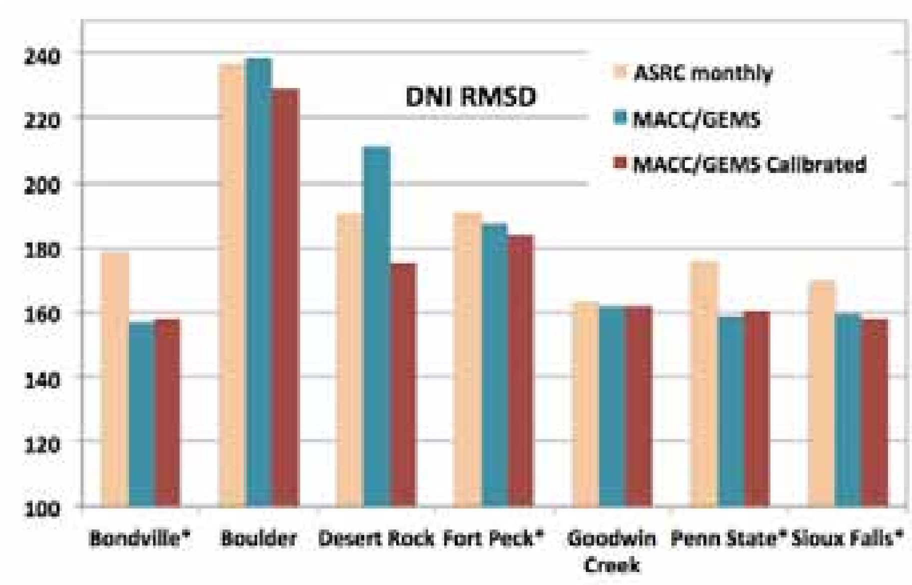

Fig. 7: Root Mean Square Deviation for hourly DNI values related to SUNY model

Use of monthly AOD data in satellite-based solar radiation models does not allow for representing high irradiance values (Figs. 9a, 10a). The use of daily data improves representation of hourly values (Figs. 9b, 10b), however due to bias in AOD, correction is needed in some regions. Calibration is based on the regional analysis of ASRC monthly values (for SUNY model) and on AERONET measurements (for SolarGIS model), see Figs. 9c, 10c.

Results for GHI and DNI are shown also in Tabs. 2 and 3. It has been found that GHI data for Ilorin site have suspicious quality, therefore represented in Tab. 2 in Italics.

For the CSP and CPV projects, typically measured and satellite-based DNI data are correlated to reduce systematic deviation in the satellite data set, thus adapting them for local geographic conditions. In site adaptation the calibration procedure (as referred to in this paper) is performed.

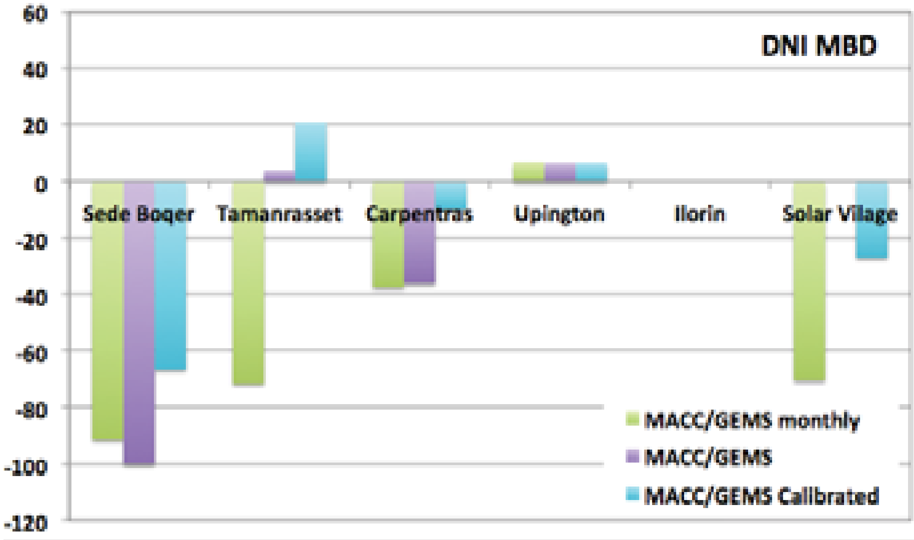

Fig. 8: Mean Bias Deviation for hourly DNI values related to SolarGIS model

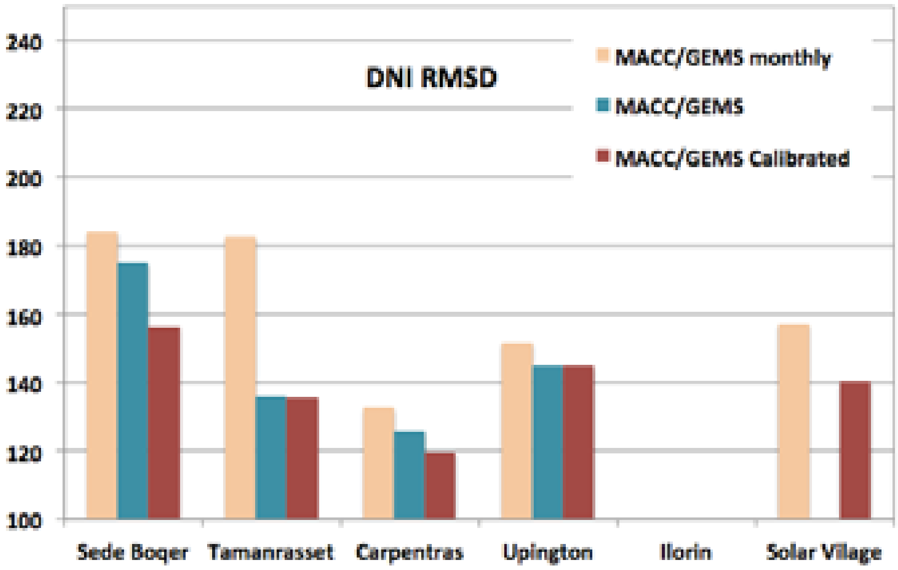

Fig. 9: Root Mean Square Deviation for hourly DNI values related to SolarGIS model

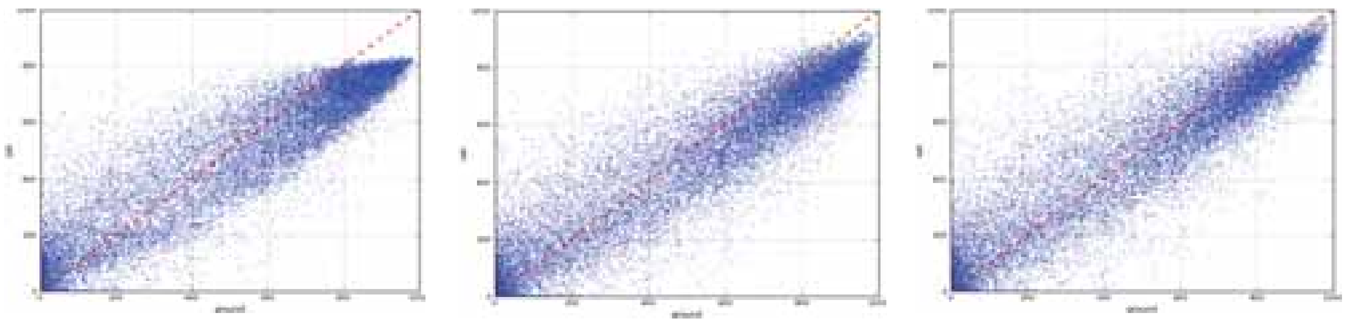

Fig. 10 Ground vs. modeled hourly values for Carpentras - Left: Monthly averaged AOD; Center: Daily AOD used in the operational SolarGIS; Right: daily calibrated

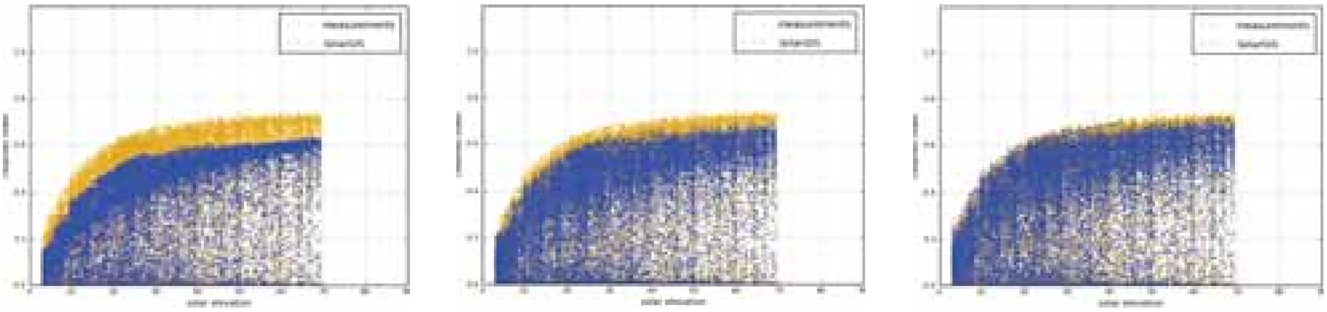

Fig. 11 Clearness DNI index versus sun elevation (hourly values) for Carpentras - Left: Monthly averaged AOD; Center: Daily AOD used in the operational SolarGIS; Right: daily calibrated

Tab. 2: Results for GHI values. The data for Ilorin are of suspicious quality, therefore shown in Italics.

GHI [W/m^2]		ASRC Monthly	Daily	Daily calibr.	ASRC Monthly	Daily	Daily calibr.
	Mean	MBD			RMSD		
Bondville*	366	-6	0	0	87	84	85
Boulder	392	-9	-6	-4	111	113	111
Desert Rock	456	7	0	3	76	76	75
Fort Peck*	379	-1	0	0	94	93	94
Goodwin Creek	410	-4	2	2	89	89	89
Penn State*	382	-1	0	0	99	98	98
Sioux Falls*	398	-3	0	0	77	76	76

GHI [W/m^2]		Monthly	Daily	Daily calibr.	Monthly	Daily	Daily calibr.
	Mean	MBD			RMSD		
Sede Boqer	543	3	-1	5	56	55	55
Tamanrasset	614	-17	-2	1	58	51	52
Carpentras	365	5	3	7	48	48	48
Upington							
Ilorin	*422*	*64*	*58*	*55*	*114*	*108*	*106*
Solar Vilage	535	-9		0	51		51

Tab. 3: Results for DNI values

DNI [W/m^2]		ASRC Monthly	Daily	Daily calibr.	ASRC Monthly	Daily	Daily calibr.
	Mean	MBD			RMSD		
Bondville*	377	-23	-7	2	179	157	158
Boulder	465	11	-76	-9	237	239	229
Desert Rock	605	51	-103	0	190	211	175
Fort Peck*	421	-1	-59	-11	191	187	184
Goodwin Creek	432	-4	-8	2	164	162	162
Penn State*	358	24	-2	9	176	159	161
Sioux Falls*	432	-14	-31	-21	170	159	158

DNI [W/m^2]		Monthly	Daily	Daily calibr.	Monthly	Daily	Daily calibr.
	Mean	MBD			RMSD		
Sede Boqer	621	-91	-100	-66	184	175	156
Tamanrasset	629	-71	4	21	183	136	136
Carpentras	496	-37	-36	-10	133	126	120
Upington	651	7	6	6	152	145	145
Ilorin							
Solar Vilage	550	-70		-27	157		140

5. Conclusion

The new AOD data set from the MACC project and run by ECMWF gives the solar industry higher confidence in satellite-derived solar data products and their ability to represent different climates of the world.

The MACC project brings to the solar modeling community high resolution and high frequency data set available globally for the period of last nine years. The daily variability follows very well the magnitude and daily dynamics of aerosols, even in areas with extreme geographic and climate complexity, such as West Africa, Middle East and North India.

The availability of AOD daily values make it possible to identify unresolved issues in modeling the extremely complex chemical interactions of aerosols in the atmosphere, thus enabling for the first time to quantify the resulting uncertainty. Thus the uncertainty estimation is possible not only for a limited number of sites with high quality ground DNI or with aerosol measurements (as used to be a practice until very recently) but also in a wider spatial context - based on the understanding of the geography and seasonal changes of the climate.

This is for the first time when high frequency global AOD data have been analyzed in a large geographical context. It has been demonstrated that the implementation of daily AOD data from MACC project reduces RMSD and dramatically improves distribution of high frequency (e.g. hourly) DNI values. Some bias issues have been identified, especially in high turbidity areas and this knowledge helps at identifying the pathways of further development for aerosol modeling community to adapt the operational data products for the needs of solar energy.

Improvements in operational atmospheric calculations are ongoing and the reported deviations will be considered. The continuity of the calculation is secured by the new project MACC II, where substantial improvements of AOD database are planned.

6. References

Cebecauer T., 2011. MACC aerosols in solar radiation modeling for energy applications. Presentation. MACC Conference on Monitoring and Forecasting Atmospheric Composition, May 2011, Utrecht, Netherlands.

Cebecauer T., Suri M., 2010. Accuracy Improvements of Satellite-Derived Solar Resource Based on Gems Re-analysis Aerosols. Conference SolarPACES 2010, September 2010, Perpignan, France.

Cebecauer T., Suri M. and Gueymard C., 2011, Uncertainty sources in satellite-derived direct normal irradiance: how can prediction accuracy be improved globally? Proceedings of SolarPACES Conference, Granada, Spain.

Cebecauer T., Suri M., Perez R., 2010, ASES National Solar Conference 2010, Phoenix (AZ), USA.

Ineichen, P. 2008. A broadband simplified version of the Solis clear sky model, Solar Energy, 82.

Morcrette J., Boucher O., Jones L., Salmond D., Bechtold P., Beljaars A., Benedetti A., Bonet A., Kaiser J.W., Razinger M., Schulz M., Serrar S., Simmons A.J., Sofiev M., Suttie M., Tompkins A., Uncht A., 2009. GEMS-AER team. Aerosol analysis and forecast in the ECMWF Integrated Forecast System. Part I: Forward modelling. Journal of Geophysical Research, 114.

Perez R., P. Ineichen, K. Moore, M. Kmiecik, C. Chain, R. George and F. Vignola, 2002. A New Operational Satellite-to-Irradiance Model. Solar Energy 73, 5, 307-317P.