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On the improvement of MACC aerosol spatial resolution for irradiance estimation in the United Arab Emirates

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Abstract

In desert regions, dust is the most critical atmospheric parameter for irradiance assessment and solar resource conversion. Nowadays, atmospheric communities – chemical transport and re-analysis models – provide aerosols information, including dust, but with a spatial resolution greater than 100 km. This low spatial resolution makes the prediction of aerosol loads in a small scale very difficult, considering the possible high spatial variability of this aerosol loads in such desert regions. It has been indeed established in the United Arab Emirates that the variation of aerosol optical depth (AOD) within 100 km can lead to 18% deviation on Direct Normal Irradiance (DNI) estimations. Therefore, the MACC AOD, which is provided at a spatial resolution of 125 km, has to be corrected before being used for DNI estimation, as well as any other publicly available AOD database. In this work, images from the High Resolution Visible channel data of the SEVIRI instrument on board Meteosat Second Generation satellite are used to downscale the MACC AOD. The first results of the downscaling approach are tested with one year datasets of AOD from two AERONET ground stations showing that this downscaling leads to a decrease of the mean absolute error on AOD and on the corresponding estimated DNIs.

Selection and/or peer-review under responsibility of ISES

Keywords: irradiance estimation, aerosol optical depth, dust, UAE

1. Introduction

In desert regions such as the United Arab Emirates (UAE), the bulk of sunlight attenuation is due to aerosols. In the UAE, dust represents more than 60% of aerosols and is responsible for the high aerosol

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optical depth (AOD) observed. This combined with low cloud occurrences makes aerosols the most critical factor for irradiance assessment, and notably for the direct component.

In the framework of Predisol project lead by Total, the EU-funded MACC (Monitoring Atmosphere Composition and Climate) aerosols has been identified as the most suitable publicly available source of AOD for irradiance calculations. It has been shown that MACC AOD product overestimates the AOD measured in the Aerosol Robotic Network (AERONET) by 26% in the UAE [1]. The standard deviation (STD) amounts to 42%. These deviations lead to 3% and 12% biases and 4% and 16% STD in the estimation of global horizontal (GHI) and direct normal (DNI) irradiances respectively. Besides, analyses of time series of irradiance measurements from pyranometric ground stations and AERONET-derived irradiances show that the differences between them increase with the distance, due to the modification of aerosol loads. When the AERONET and irradiance stations are 100 km apart, the STD reaches 7% for GHI and 18% for DNI. This illustrates the spatial variability of the aerosol loads in this area is significant over distances lower than 100 km. Since the spatial resolution of MACC is approximately 125 km in UAE, a downscaling of the MACC AOD should be made to expect better accuracy in irradiance estimation.

In this work, the overall accuracy of MACC AOD, and the variation of accuracy of the derived irradiance with distance from the aerosol data source, are first presented. Then, to increase the spatial resolution of the estimated AOD, two fusion techniques to merge low resolution (125 km) MACC AOD and high resolution (3 km) MSG (Meteosat Second Generation) HRV (High Resolution Visible) reflectance are explored. The main goal is to be able to inject the high resolution spatial structure of HRV in the MACC AOD map. The preliminary fused product MACC+HRV AOD is then validated against AERONET AOD measurements at two stations. Finally, a cross-comparison is made between irradiances estimated from the three AOD datasets.

2. Aerosol datasets

2.1. AOD from MACC re-analysis model

The MACC project funded by the European Commission in the framework of its FP7 program, is notably preparing the operational provision of global aerosol properties forecasts together with physically consistent total column content in water vapor and ozone. Such information hasn’t been available so far from any operational Numerical Weather Prediction (NWP) centres. The MACC reanalysis delivers AOD values at 550 nm and 1240 nm, from which the Angstrom coefficient is derived. It also delivers partial optical depths at 550 nm for dust, organic, sea salt, sulphate, and black carbon aerosol species [2] [3]. In this work, we only use MACC AOD data at 550 nm. According to the ECMWF (European Centre for Medium-Range Weather Forecasts) mission statement, all NWP forecasts are provided at 3-hourly temporal resolution. The MACC AOD predictions are obtained on a global grid at reduced Gaussian Grid resolution from equator to pole with a resolution of 1.125° along the latitudes and from 1° to 20° along the longitudes. In the UAE, the spatial resolution of MACC AOD datasets is approximately 125 km.

2.2. AOD from AERONET network

The NASA-operated international network, AERONET provides ground-based sun photometer measurements of local AOD. The NASA-operated AERONET program gathers aerosol information and provides reference data that can be used for satellite-based retrievals of aerosol optical properties. Datasets are available online (http://aeronet.gsfc.nasa.gov) and contain AOD measurements at 16 different wavelengths as well as total water vapor column measurements and several variability related coefficients used for automatic cloud screening procedure. AERONET AOD datasets are considered as reference: their accuracy values are ± 0.01 for wavelengths down to 440 nm and ± 0.02 for higher wavelengths [4]. For comparison against MACC AOD, the AOD at 550 nm ($AOD_{\lambda=550nm}$) is needed. This specific AOD is computed from AODs at 440 nm and 870 nm using the following equation:

$$AOD_{\lambda} = AOD_{\lambda 0} (\lambda / \lambda_0)^{-\alpha} , \quad (1)$$

where α is the Angstrom coefficient calculated from $AOD_{\lambda=440nm}$ and $AOD_{\lambda=870nm}$, and λ_0 and λ are the wavelengths.

Since measurements at some AERONET stations correspond to campaigns and were performed over short a period, there are only a few stations available for MACC AOD validations. The Fig. 1 depicts the AERONET stations – and their locations – having at least 6 months of measurements in UAE. It is to be noted that only two AERONET stations are currently operational: these two stations are located in Mezaira and Masdar Institute (see Fig. 1).

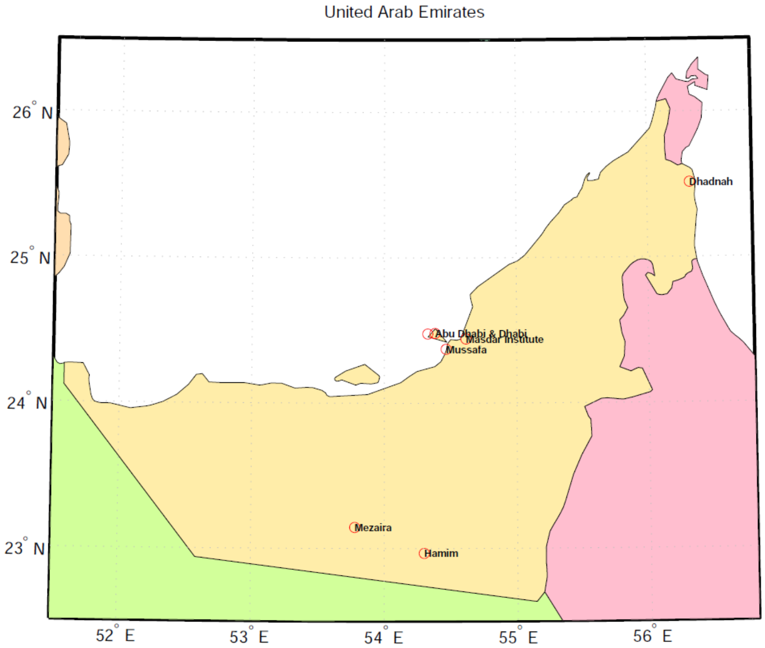

Fig. 1. AERONET stations in UAE having at least 6 months of measurements

3. Accuracy of MACC AOD

The comparison based on 14377 AERONET AOD data from all the AERONET stations in the UAE shows that the MACC AOD product overestimates the AOD by 26% in the UAE. The relative standard deviation (STD) on the estimated AOD reaches 42%, but the correlation coefficient around 0.8 showing that MACC reproduces the temporal variability of AOD in the region relatively well. No daily variation of deviation is observed, though the deviation significantly changes with month (see Fig. 2). The highest bias is reached in July (bias is 0.16), corresponding to the highest mean AOD and the lowest is obtained in November (bias is 0.04). Overall, the accuracy of MACC decreases when the AOD increases. These deviations lead to significant error in the estimation of irradiances. Over all the AERONET stations, the deviation – by the means of root mean square error (RMSE) – between irradiances estimated (using the radiative transfer model libRadtran [5] – see §4) with MACC aerosols and irradiances estimated with AERONET is 5% for GHI and 20% for DNI. The general overestimation of AOD leads to underestimation of GHI and DNI.

Nevertheless, Fig. 2 also shows that the correlation coefficient between MACC AOD and AERONET AOD is always greater than 0.5 and that the daily and seasonal variation of AOD is well modeled by MACC. A correction of MACC AOD with a linear function or with a constant value can be considered.

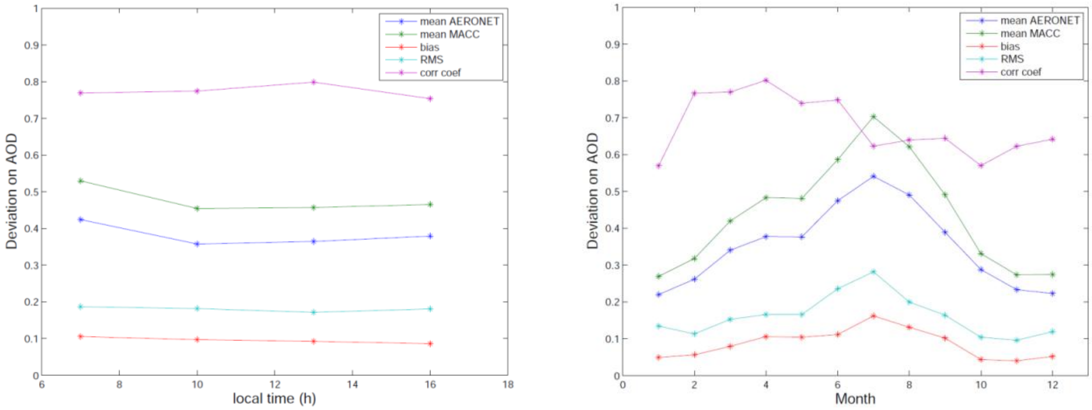

Fig. 2. Intra-day and monthly variation of the deviations between MACC AOD and AERONET AOD

4. Irradiance calculation using a radiative transfer model and influence of the location of aerosol data

4.1. The radiative transfer model libRadtran

Numerical radiative transfer models (RTMs) simulate the propagation of radiation through the atmosphere: they model the various processes occurring in the path of the sunlight from the top of the atmosphere towards the ground. RTMs are used to calculate the surface solar irradiance (SSI) (e.g. the GHI or the DNI) for given atmospheric and surface conditions. Under concern in this study is the SSI integrated over the whole spectrum, i.e. between 0.3 µm and 4 µm, called total or broadband SSI. The libRadtran RTM version 1.7[†], was applied. LibRadtran uses input data of the atmosphere, such as AOD, and surface properties. When not available, data have been replaced by standard assumptions. In this work, libRadtran is used in the same way as in [6]. When comparing irradiances from MACC to irradiances from AERONET, the only input that changes is the AOD i.e., MACC AOD and AERONET AOD respectively.

4.2. Influence of the distance to the aerosol grid point on the irradiance estimation

The comparison between irradiances estimated from AERONET using libRadtran and irradiances measured at the same location at Masdar Institute is presented in Figure 3. LibRadtran is run under cloudless sky conditions, in accordance with the Level 2 AERONET data used, which are cloud-screened.

[†] libRadtran (www.libradtran.org) [5] is freely available under GNU General Public License

The DNI modeled here is the sum of the DNI at the center of the sun disc and circumsolar normal irradiance (CSNI) in accordance with the aperture angle of ground sensor. 4% underestimation is obtained when CSNI is not taken into account. For the bias and the RMSE the reduction is less than 3% and 5% respectively, and the correlation coefficient is greater than 0.994. It can be concluded that the estimation of irradiances from AERONET measurements using the RTM libRadtran is highly accurate. The accuracy is close to that obtained with a well-maintained irradiance station in cloudless skies. It also means that an AERONET station can be considered as a source of ground based irradiance data for clear-sky instances[6].

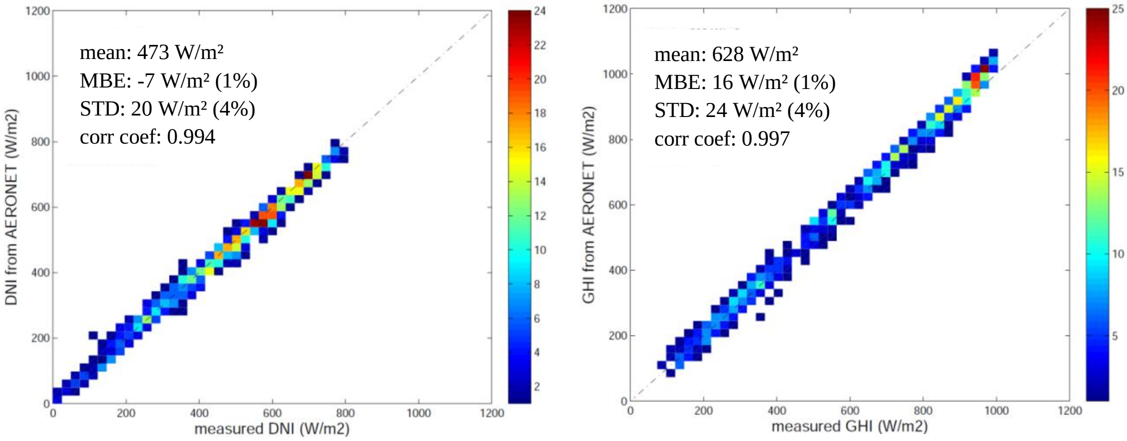

Figure 3. Comparison between the direct normal and the global horizontal irradiances estimated with libRadtran and AERONET and the corresponding ground-based irradiances measured at Masdar Institute, from June to November 2012.

The same types of comparisons were carried out between AERONET stations and the pyranometric stations located at different places in the UAE. As illustrated in the Fig. 4, a significant decrease in accuracy is observed when the distance between the AERONET and pyranometric stations is increasing.

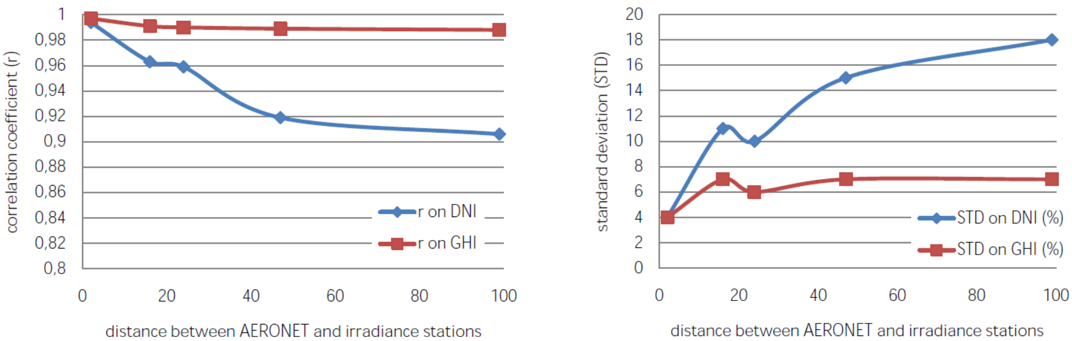

Figure 4. Variation of standard deviation and correlation coefficient with distance (in km) between the AERONET and the irradiance stations

The differences between measured and AERONET derived irradiances notably increases with the distance, due to the modification of aerosol loading. More precisely, when the AERONET and pyranometric stations are 100 km away, the standard deviation reaches 7% for GHI and 18% for DNI. This gives important information about the spatial variability of AOD in the UAE region, and shows the limitation of using aerosol properties that are measured (or estimated) on locations or grid cells that are more than 100 km away.

Since the spatial resolution of aerosol databases is greater than 100 km (1.125° for the reanalysis model MACC, 1.9° for the chemical transport model MATCH [8]), they are not able to properly "represent" this actual spatial variability of the AOD. In this work, we propose to perform a downscaling processing of MACC AOD product using higher resolution – correlated – information derived from MSG in order to retrieve AOD higher spatial resolution to be most likely to describe the actual spatial variability of the AOD in the UAE.

5. Correction of MACC AOD for the UAE

Based on the assumption that in desert regions with rare cloud coverage, changes in signal received by SEVIRI are strongly related to changes in aerosol properties, we use the SEVIRI data to improve the spatial resolution of MACC AOD. The spatial and temporal resolutions of SEVIRI are 3 km and 15 minutes respectively. The first step was to find the spectral bands that have a high correlation with AOD.

The correlation coefficient between the reflectance from different MSG spectral bands and the MACC AOD at 500 nm at a given point is computed at each channel where a correlation is expected. The highest correlation coefficients are obtained with the HRV and the VIS 0.6 that corresponds to the central wavelength 0.6 µm. The HRV channel is chosen in this work because of its availability. The year chosen for this preliminary experiment is 2010. The AERONET stations used for validation are Mezaira and Mussafa, because they both provide enough AOD measurements and represent the two major types of climates in the region: desert and coastal. The correlation coefficient under all-sky condition between the HRV reflectance and the MACC AOD is generally between 0.4 and 0.6. This correlation coefficient is similar to that obtained between the AOD estimated with state-of-the-art hourly-resolved global models and the AERONET measurements [8].

5.1. Fusion processing of HRV data

For this first experiment, the HRV reflectance images are initially provided at the spatial resolution of approximately 2.5 km resolution upscaled with *ad hoc* low-pass filtering and bilinear interpolation to 10 km, and then 100 km resolution. In parallel, the MACC AOD at 125 km resolution was slightly downscaled up to 100 km. In the temporal domain, the 15-min HRV were aggregated to 3-hour HRV data to fit the time sampling of the MACC AOD product. A linear regression is made between AOD and HRV reflectance ρ, at the coarse resolution as follows:

$$a * \rho_{HRV,100km} + b = AOD_{MACC,100km} \qquad (2)$$

where a and b are the regression coefficients. The fused MACC AOD with the spatial resolution of 10 km is then simply derived as:

$$AOD_{MACC,10km} = AOD_{MACC,100km} + a * (\rho_{HRV,10km} - \rho_{HRV,100km}) \qquad (3)$$

As an example, a native downscaled AOD map is shown in the Fig. 5. It depicts more spatial features than the original map: the sea is differentiated from the land. Lower AODs are observed over the sea than over the land, as expected. Qatar is distinguished in the MACC+HRV map, while it is not in the original MACC AOD.

Comparisons between MACC AOD (1), MACC+HRV AOD (2), and AERONET AOD at Mezaira and Mussafa show only a little improvement on the bias of the AOD due to downscaling (Table 1). The standard deviation and the correlation coefficient (CC) do not change. It is expected to have better improvement if the cloud instants are filtered out.

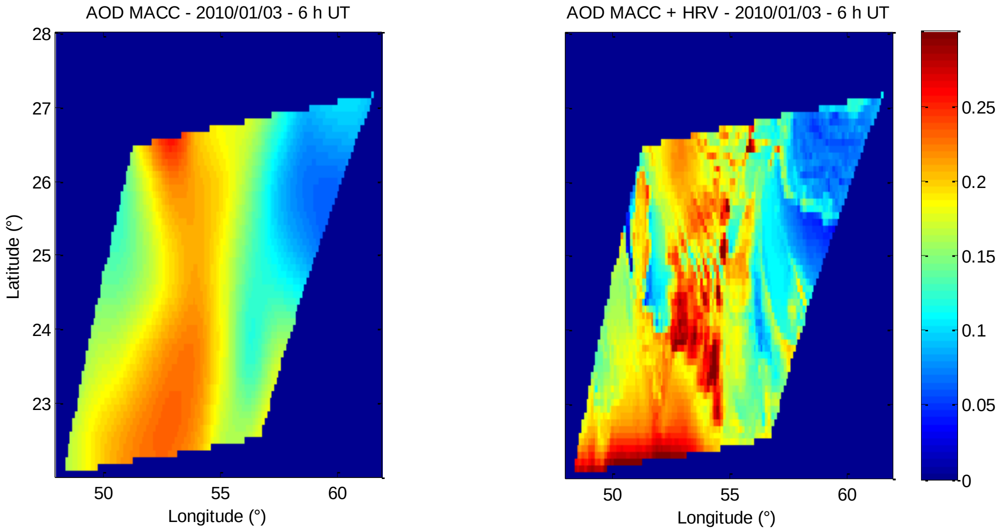

Figure 5. Native MACC AOD (125 km resolution) and the fused MACC+HRV AOD (10 km resolution) at the arbitrary date of 20100103T0600Z

Table 1. Validation of MACC AOD (100 km resolution, 1) and MACC+HRV AOD (10 km resolution, 2)

Station	Bias1 (%)	Bais2 (%)	STD1 (%)	STD2 (%)	CC1	CC2
Mussafa	21.2	20.7	34.2	34.5	0.838	0.837
Mezaira	34.6	31.1	44.9	44.7	0.769	0.769

This first experiment of a fusion processing between HRV reflectance images and MACC AOD product is not really encouraging but the comparison based on only two AERONET ground stations is not really conclusive. It is expected to have better improvement from the fusion processing with a specific of HRV reflectance images to detect and remove cloudy pixels.

5.2. Linear regression of MACC data

This section describes the second approach where the assumption is that the sky is often dusty in the region, and therefore, the variation of the signal received by the satellite should be linked to the variation of the amount of dust in the atmosphere. In this approach, it is assumed that the relationship between the HRV data at two locations is the same for AOD.

For the overall time series, the maximum and minimum reflectance (ρ) are found at each hour. Then a normalised reflectance is derived (see Eq. 2) [7]. Only solar elevation angles greater than 10° are considered.

$$n_{HRV} = (\rho - \rho_{min})/(\rho_{max} - \rho_{min}) \quad (4)$$

The correlation coefficient between n_{HRV} and MACC AOD is 0.52 for Mezaira and 0.47 for Mussafa. Considering the Figure 6, if the regression between $n_{HRV,red}$ and $n_{HRV,blue}$ give Eq. 5, then Eq. 6 holds:

$$n_{HRV,red} = a * n_{HRV,blue} + b \quad (6)$$

$$AOD_2 = a * AOD_{MACC} + b \quad (7)$$

where a and b and regression coefficients between the HRV pixels. Thus, the resolution of the obtained AOD is that of HRV. The HRV data we receive are resampled to 3 km resolution.

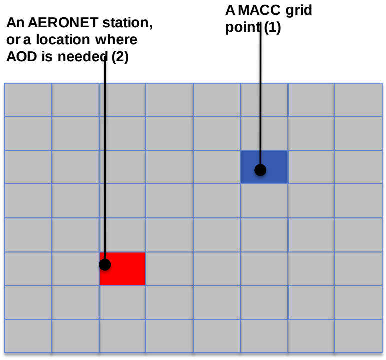

Figure 6. Representation of HRV pixels with a MACC and AERONET points

The following equations are obtained at Mezaira and Mussafa:

$AOD_{MACC\text{-}HRV} = 0.5055*AOD_{MACC} + 0.1285$ (for Mussafa)

$AOD_{MACC\text{-}HRV} = 0.6729*AOD_{MACC} + 0.0359$ (for Mezaira)

For the validation, at each hour in a given day where there are at least 4 AOD data measurements both in AERONET and in MACC, a linear interpolation at a 10-minutes time step is made from the first to the last AERONET measurement in that day. These 10-minutes resolution AOD data are used for validation and for irradiance calculations. Comparisons between MACC AOD (1), MACC+HRV AOD (2), and AERONET AOD at Mezaira and Mussafa show a significant improvement in the bias of the AOD with the downscaling (Table 2). The standard deviation slightly decreases. The correlation coefficient does not change because the native and the fused AOD are linked with a linear relationship. Overall, Tables 1 and 2 show that the accuracy of AOD increases with its resolution.

Table 2. Validation of MACC AOD (125 km resolution) (1) and MACC+HRV AOD (3 km resolution) (2)

Station	Bias1 (%)	Bais2 (%)	STD1 (%)	STD2 (%)	CC1	CC2
Mussafa	22.6	-9.3	36.6	34.8	0.793	0.793
Mezaira	36.6	1.4	44.4	35.6	0.799	0.799

These AODs are used as inputs to libRadtran for irradiance computations. The DNI and GHI calculated with MACC AOD (and MACC+HRV) are validated against those calculated with AERONET AOD. The scatter-plots and deviations obtained are presented in the Figs 7 and 8 respectively for Mussafa and Mezaira. As expected, the improvement on irradiances is similar to that the AOD. At the two stations, the biases on GHI and DNI significantly decrease.

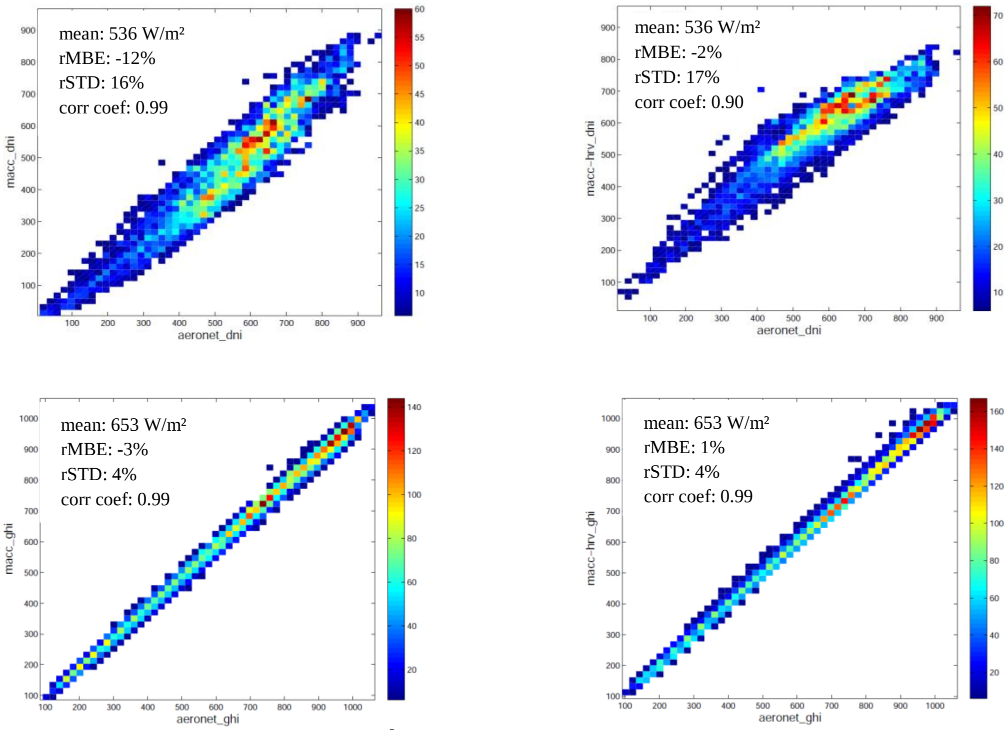

Fig. 7. Comparison of irradiances (in W/m^2) from MACC, and MACC+HRV AOD to those from AERONET AOD, at Mussafa

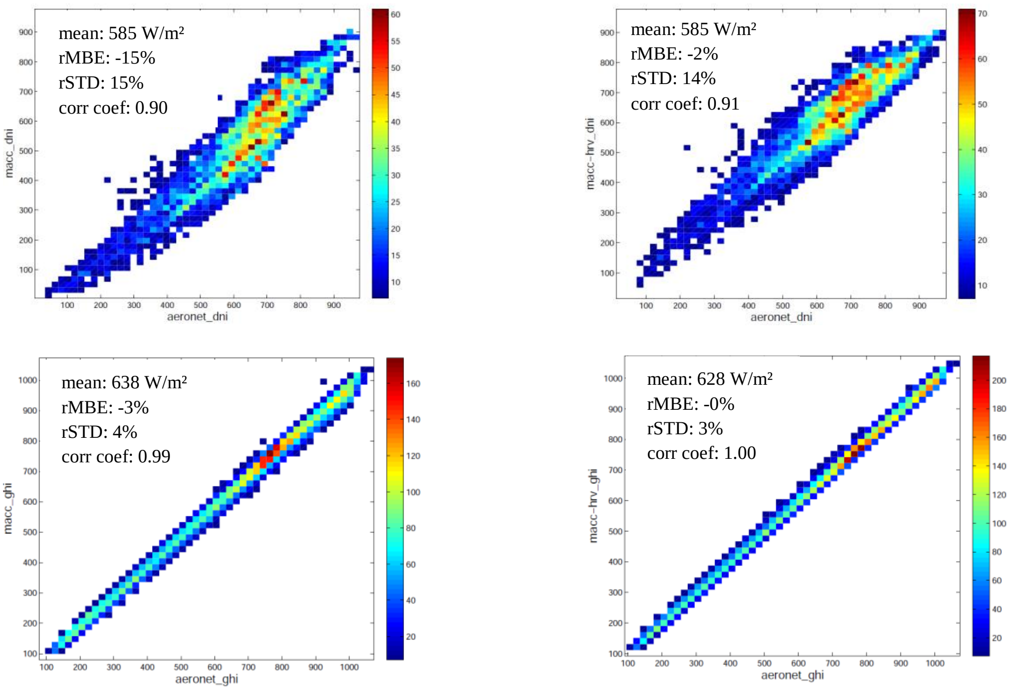

Fig. 8. Same as Fig. 7, but for Mezaira.

6. Conclusion

In the UAE region, AOD is one of the main atmospheric parameters for the prediction of the surface solar irradiance and more particularly the direct normal irradiance. Unfortunately, the low spatial resolution of publicly available global aerosol databases such as MACC AOD products and the lack of ground stations for AOD measurements make difficult and even impossible to account for the high spatial variability of the aerosol loads observed in the region.

In this work, preliminary experiments have been carried out with two approaches to enhance the spatial resolution of the MACC AOD product by the means of the HRV channel of SEVIRI instrument onboard the MSG geostationary satellite. The main assumption made is that, in desert regions, changes in signal received by SEVIRI are strongly related to changes in aerosol properties for at the pixel. This is partly confirmed with the correlation coefficients between the AODs and HRV ranging between 0.4 and 0.6. A linear regression is made between a reference HRV pixel and each HRV pixel inside the MACC pixel to reproduce the structure of the HRV image “inside” a MACC pixel. This correction significantly decreases the bias in the estimation of GHI and DNI without damaging the correlation coefficient and the standard deviation. The bias in the estimation of DNI decreases from 12% (and 14%) to 2%, and decreases from 2% (and 3%) to 1% (and 0%) for GHI.

This experiment is not fully conclusive due to a lack of ground-based dataset from different locations. But the presented idea of spatial resolution enhancement of MACC AOD product with high resolution reflectance of MSG shows potential improvements. It is expected that a good filtering of cloudy instants on MSG data before applying the downscaling method (regression or data fusion method) will lead to a decrease of standard deviation additionally.

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