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ASSESSMENT OF DAILY ATMOSPHERIC TURBIDITY DATABASES USING AEROSOL OPTICAL DEPTH AND DIRECT NORMAL IRRADIANCE MEASUREMENTS

Luis Martin-Pomares[1], Jesus Polo[2], Daniel Perez-Astudillo[1] and Dunia A. Bachour[1]

[1] Qatar Environment and Energy Research Institute (QEERI), HBKU, Qatar Foundation, Doha, Qatar

[2] Energy Department, CIEMAT, Madrid, 28040, Spain

Abstract

This study presents the validation of atmospheric turbidity databases. It is divided into two parts. The first part shows the validation of three Aerosol Optical Depth (AOD) databases with worldwide coverage. AOD at 550nm estimates from MISR, MODIS-L3 satellites and MACC model and water vapour from NCEP are compared against measurements from 865 AERONET stations as ground-truth data for more than one year in each location.

The second part addresses the limitation that ground measurements of AOD are not always available. An alternative methodology is presented here to evaluate the AOD databases. It consists of comparing the daily Linke Turbidity Index (TL) obtained from the databases to the corresponding TL derived from DNI measurements.

All databases show a significant overestimation of AOD and errors in terms of rRMSD are between 85 and 118% in total for the AERONET stations validated.

Keywords: *Atmospheric aerosols, turbidity, solar radiation, AOD, TL*

1. Introduction

Aerosol Optical Depth (AOD) is the degree to which aerosols prevent the transmission of light by absorption or scattering of light and is defined as the integrated extinction coefficient over a vertical column of the unit cross-section (Albrecht, 1989).

AOD is a fundamental parameter for the modelling of solar radiation. It is mainly needed for clear sky models (Gueymard, 2008; Ineichen, 2008; Rigollier, Bauer, & Wald, 2000).The clear sky models are an essential component of many methods of solar radiation estimation from satellite images (Polo, Antonanzas-Torres, Vindel, & Ramirez, 2014; Rigollier & Wald, 1999). The measurements of AOD are scarce in the world due to the high cost of installing and running a station to measure this variable. Because of this scarcity, AOD estimated from satellite images or chemical transport models are widely used.

Another index to quantify turbidity is the Linke Turbidity (TL) index (Ineichen & Perez, 2002; Kasten, 1996; Linke, 1922) which establishes a relationship between the real and theoretical optical depth of the atmosphere and represents the degree of transparency of the atmosphere. It is an adequate approximation when quantifying the effects of absorption and dispersion of solar radiation when traversing the atmosphere. TL can be obtained directly from solar radiation ground measurements; however, due to the unavailability of ground data, it is derived from empirical adjustments (Kasten, 1980).

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Several validations of AOD databases in a regional scale have been presented previously (Antonanzas-Torres et al., 2014; Eissa et al., 2015; Ruiz-Arias, Dudhia, Gueymard, & Pozo-Vázquez, 2013; Zhong & Kleissl, 2015), but a global validation has not been done yet. In this study, we present first results of a comprehensive validation of three AOD databases (MODIS, MACC and MISR).

Besides, as in most of the locations, AOD measurements are not available, we present a methodology to estimate turbidity from solar radiation measurements. The turbidity of two sites obtained using Linke TL from Direct Normal Irradiance (DNI) ground measurements is presented to show the capabilities of this methodology.

2. Experimental Datasets

In this section, we present the experimental data used in this study.

2.1 Aeronet ground measurements

Field measurements from the NASA AERONET (AErosol RObotic NETwork) program are available all around the Globe. We have used in this study 865 stations from the AERONET network. The measurements were collected during different periods. For each AERONET station, the measurements of the CIMEL CE-318 Sun photometer were converted into aerosol optical properties and are available for public access (http://aeronet.gsfc.nasa.gov). The data sets include the aerosol optical depth (AOD) at eight different wavelengths, as well as the solar zenith angle and the total column content in water vapour (PW). The AERONET Level 2.0 products (cloud-screened and quality assured) are compared in Section 4 to the daily AOD at 550 nm from MODIS, MISR and MACC. Daily PW is compared with NCEP model.

2.2 Radiometric measurements

The radiometric data used in this study for the validation is located in China and South of Spain. DNI is measured with first class pyrheliometer. Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI) were also available from secondary standard pyranometers. Both stations have solar trackers and shading ball for DHI. Data is registered every 10 minutes in both stations, and hourly averages were calculated. BSRN quality checks (Long & Dutton, 2002) are applied to remove suspicious wrong data.

2.3 Aerosol and Atmospheric databases

The atmospheric and aerosol datasets, compared in this study, come from different sources. Daily values of AOD at 550nm from satellite and models are the following:

- MODIS-L3: daily values of AOD with a spatial resolution of 1ºx1º for the period from the year 2004 to the present.
- MACC (Monitoring Atmospheric Composition & Climate from ECMWF): daily values of AOD with a spatial resolution of 1.125ºx1.125º for the period from 2003 to the present.
- MISR (Multi-angle Imaging SpectroRadiometer): daily values of AOD with a spatial resolution of 0.5ºx0.5º for the period from 2001 to the present.

Daily PW from AERONET stations is validated with NCEP (National Centers for Environmental Prediction) for the temporal period coincident. The spatial resolution of NCEP data is 1ºx1º.

3. Methodology

The parameters to validate daily AOD at 550 nm and PW from different databases with AERNET stations are mean bias deviation (MBD), root mean squared deviation (RMSD) and its relative value as rMBD and rRMSD. The relative expressions are obtained using the following equations:

$$\mathrm{rMBD} = \frac{1}{N}\sum_{i=1}^{N}\left(\hat{x}_i - x_i\right) \qquad \text{(eq. 1)}$$

$$\text{rRMSD} = \frac{\sqrt{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2 / n}}{\overline{x}} \qquad \text{(eq. 2)}$$

where N is the population size, x is the observed value, $\overline{x}$ is the mean of observed values, and $\hat{x}$ is the predicted value.

The following parameters have also been calculated (Espinar et al., 2009). The correlation coefficient (R), Kolmogorov–Smirnov test Integral (KSI), and its relative magnitude (KSI (%)), the critical limit from the original Kolmogorov–Smirnov test (Over), and its relative (Over(%)), the evaluation parameter based on KSI and Over (KSE) and RIO, combination of the three most representative parameters: OVER (%), KSI (%), and RMSD (%).

3.1 Turbidity from DNI measurements

Besides, when AOD measurements are not available, we have used DNI measurements to validate the satellite and model estimates. We have extracted turbidity from DNI measurements after identifying clear sky conditions which can be done automatically or manually by visual inspection. We have used the last option. The values of TL are obtained using the inverse of a clear sky model for clear sky days at solar noon (Ineichen & Perez, 2002).

AOD at 550 nm from MODIS, MISR and MACC are converted to TL values using Ineichen correlation (Pierre, 2008) and daily PW from NCEP.

4. Results

In this section, we present the primary results.

4.1 Validation of Aerosol Optical Depth (AOD) from satellite and models

The next tables show the results for MBD, RMSD, rMBD, rRMSD, R, KSI, KSI (%), Over, Over(%), and RIO, (Espinar et al., 2009) for daily PW from NCEP model compared with AERONET measurements:

Tab. 1: Statistical errors of daily water vapour column from NCEP model compared with AERONET stations

MODEL	MBD	RMSD	rMBD (%)	rRMSD (%)	R
NCEP	0.17	0.65	16.87	42.66	0.72

Tab. 2: Errors for daily water vapour column from NCEP model compared with AERONET stations

MODEL	IKS	IKS %	Over	Over %	KSE	RIO
NCEP	0.27	94.03	0.11	47.25	141.28	91.89

As we can see from the results, NCEP database presents a considerable overestimation and rRMSD is considerably high.

The next tables show MBD, RMSD, rMBD, rRMSD, R, IKS, IKS(%), Over, Over(%), KSE and RIO for AOD at 550 nm for MODIS and MISR satellites and MACC model:

Tab. 3: Statistical errors of daily Aerosols Optical Depth (AOD) at 550 nm from MODIS and MISR satellite and MACC model compared with AERONET stations

SATELLITE/MODEL	MBD	RMSD	rMBD (%)	rRMSD (%)	R
MODIS	0.03	0.20	40.58	118.10	0.48
MISR	-0.02	0.17	6.66	85.60	0.29
MACC	0.02	0.18	32.07	101.86	0.33

Tab. 4: Errors for daily Aerosols Optical Depth (AOD) at 550 nm from MODIS and MISR satellite and MACC model compared with AERONET stations

SATELLITE MODEL	IKS	IKS %	Over	Over %	KSE	RIO
MODIS	0.06	56.77	0.02	25.25	82.02	99.46
MISR	0.05	96.66	0.02	46.69	143.35	114.52
MACC	0.06	87.38	0.02	46.28	133.66	117.75

All databases show overestimation which is considerably high in the case of MODIS and MACC. It has a direct effect on clear sky models output and solar radiation derived satellite from a satellite which will be underestimated in the case of using raw AOD values from these databases. MISR satellite presents better results globally in terms of rMBD and rRMSD, maybe due to its higher spatial resolution.

4.2 Validation of Aerosol Optical Depth (AOD)

The hourly values of DNI for a clear sky day selected manually for a location in Spain are shown in the next figures for several days. In the plots, measured clear sky DNI (blue), modelled clear-sky DNI (green), DNI estimated from satellite MODIS TL and DirIndex model (pink) and DNI estimated from satellite MODIS TL and Louche model (red). In the figure, we also show the values of daily TL estimated from MODIS satellite and calculated from measurements for all hourly values and two hours during the day at noon time (11:00 and 12:00 UTC). The values of TL are calculated from measurement at noon hours because there are some days which have clear sky conditions in most of the times of the day but not in all.

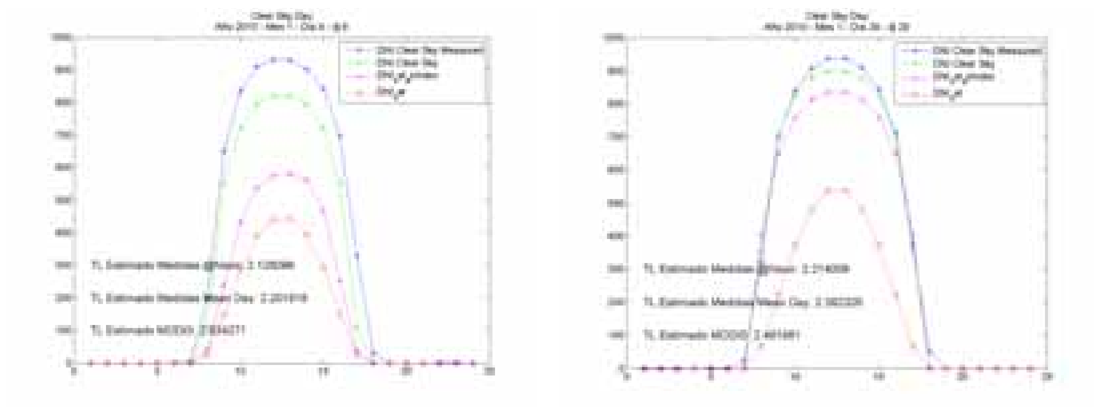

Fig. 1: TL estimated from MODIS and measurements of DNI for a clear sky day. 09/01/2010 and 29/01/2010 in Spain.

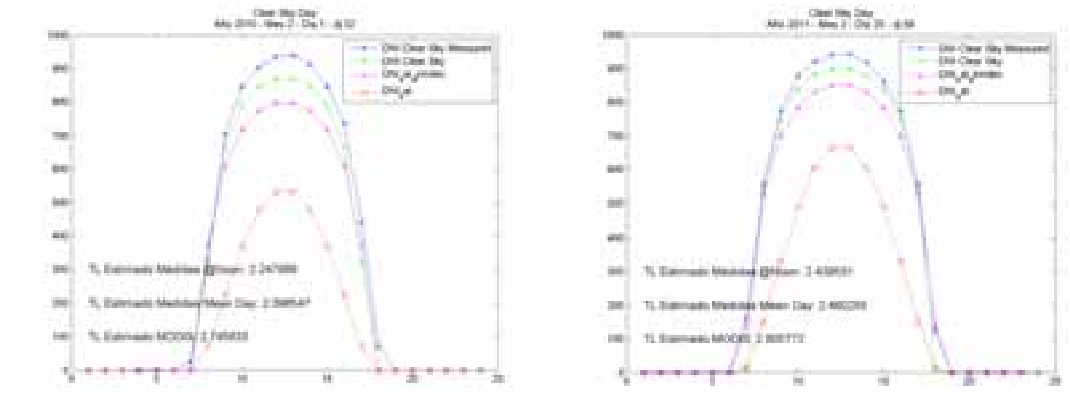

Fig. 2: TL estimated from MODIS and measurements of DNI for a clear sky day. 01/02/2010 and 25/02/2011 in Spain.

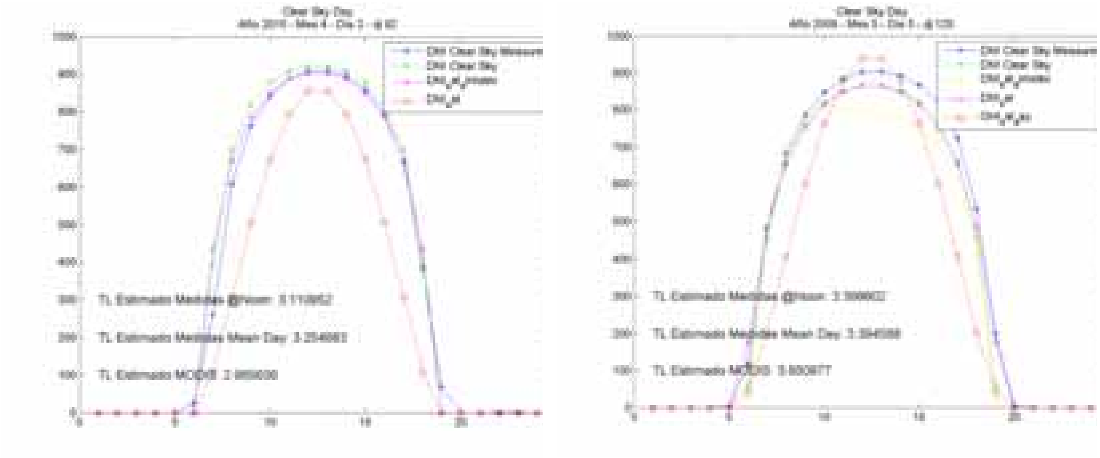

Fig. 3: TL estimated from MODIS and measurements of DNI for a clear sky day. 02/04/2010 and 05/05/2009 in Spain.

The next figures represent the same information as in the last ones but for cloudy conditions.

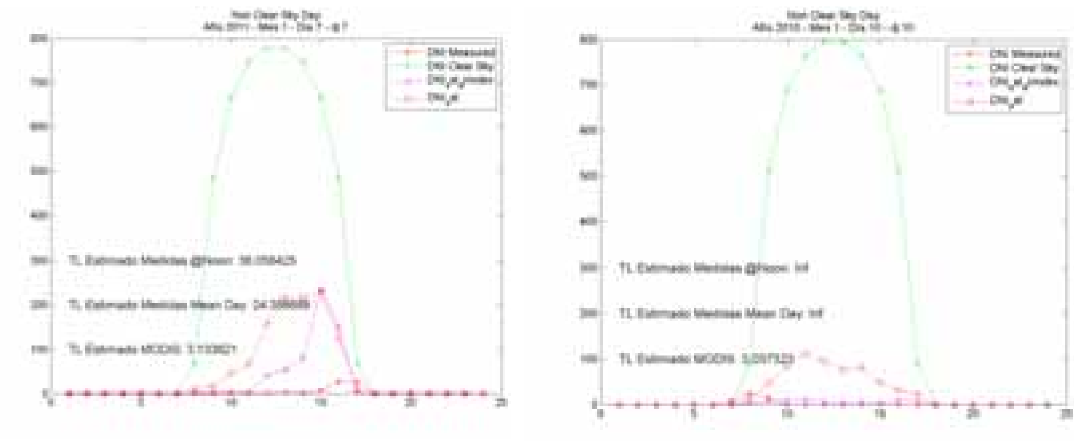

Fig. 4: TL estimated from MODIS and measurements of DNI for a cloudy sky day. 07/01/2011. 10/01/2010 in Spain.

With the values calculated from the daily selection, we have obtained daily time series of TL. The next figures show some examples of the relationship between daily Linke Turbidity (TL) estimated from MODIS satellite (red line) and estimated from measurements (blue line) with clear sky days for several months in the location in Spain. TL is obtained from several years of measurements:

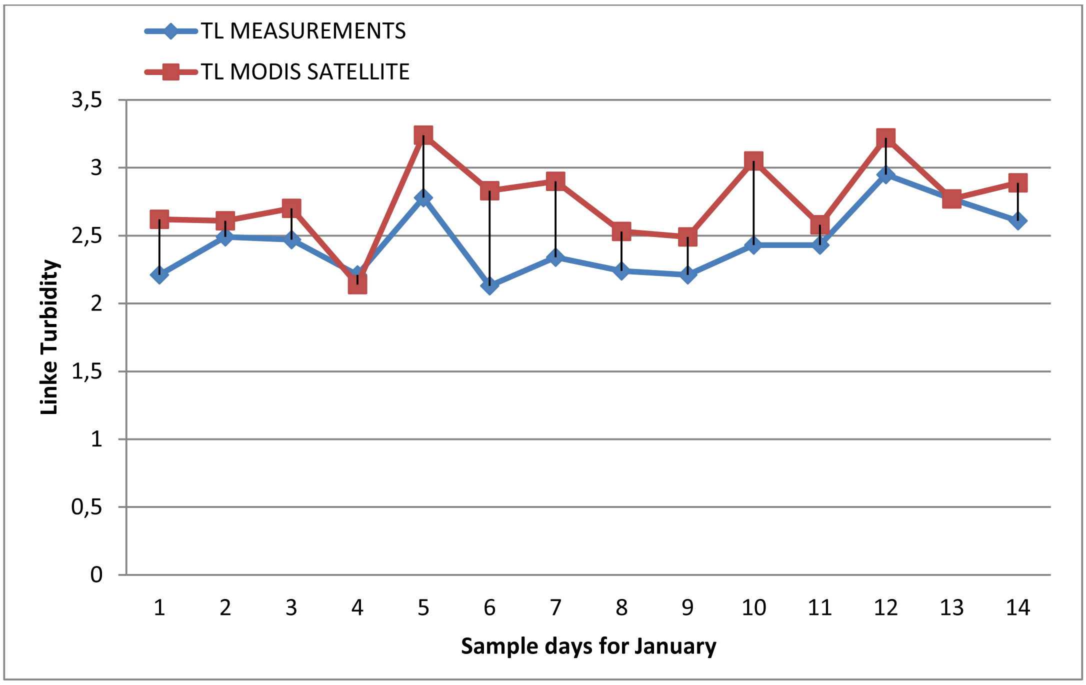

Fig. 5: Daily values of TL estimated from MODIS and measurements with clear sky days in January

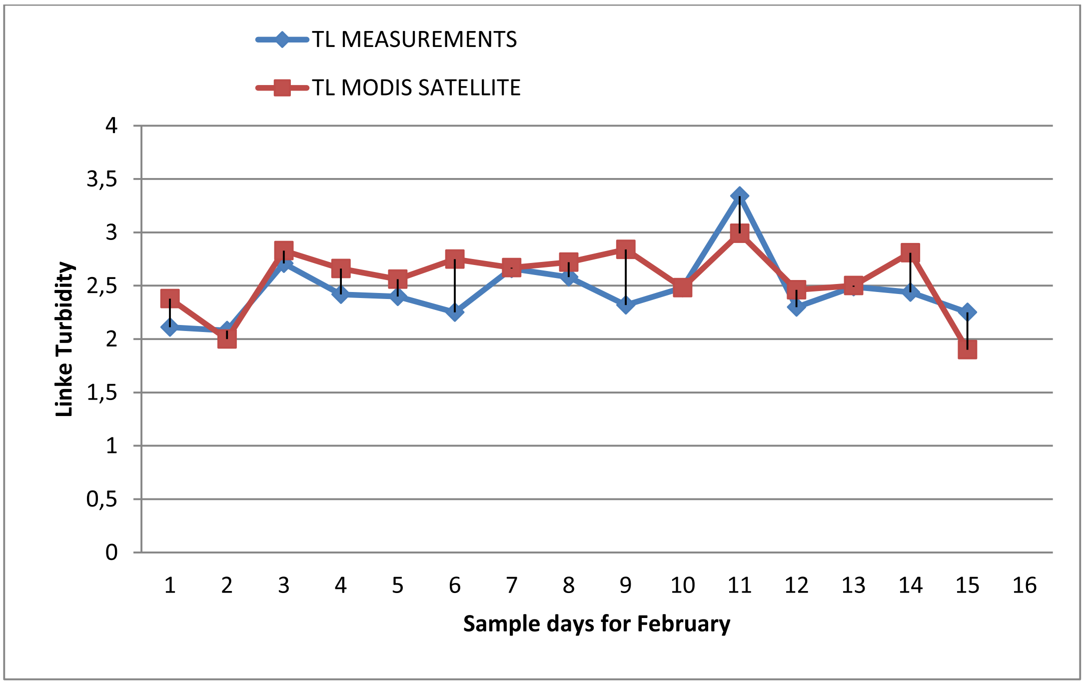

Fig. 6: Daily values of TL estimated from MODIS and measurements with clear sky days in February

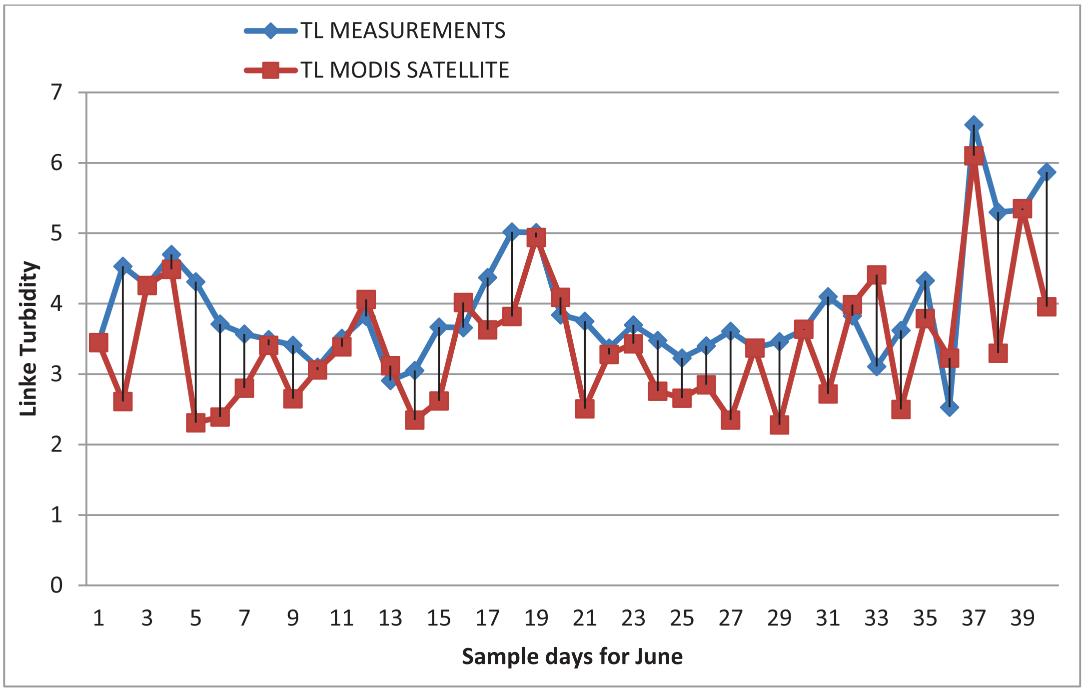

Fig. 7: Daily values of TL estimated from MODIS and measurements with clear sky days in June

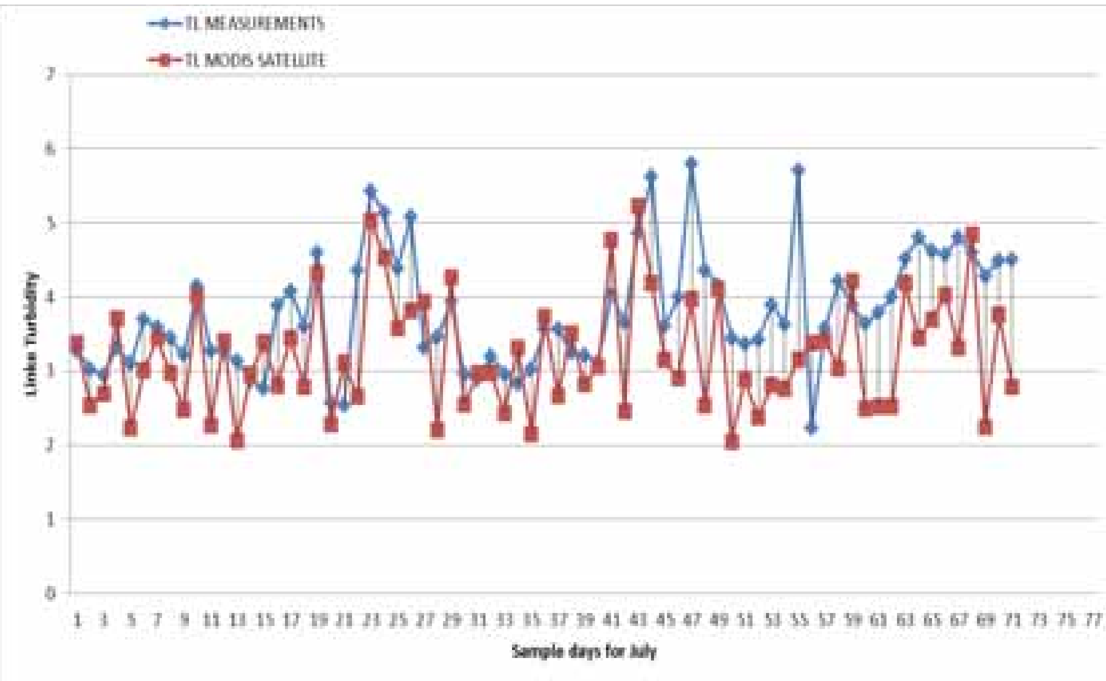

Fig. 8: Daily values of TL estimated from MODIS and measurements with clear sky days in July

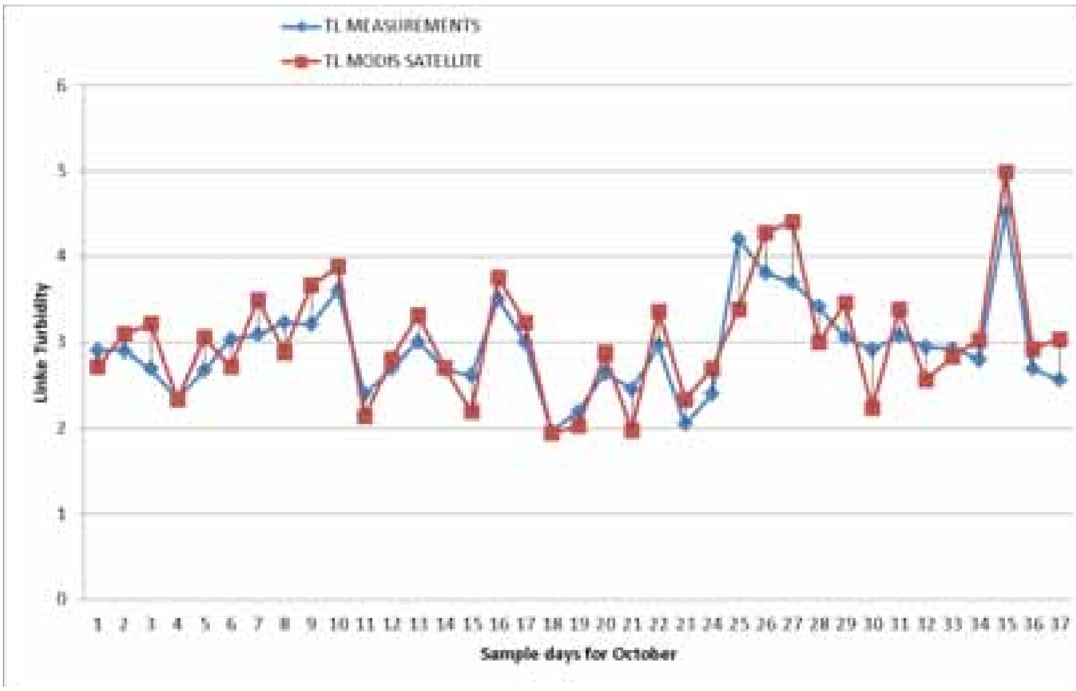

Fig. 9: Daily values of TL estimated from MODIS and measurements with clear sky days in October

As can be seen from last figures, MODIS database represents well turbidity for this location in Spain. The different observed between MODIS and TL derived from DNI measurement are due to deviations of clear sky models and raw spatial resolution of MODIS data.

Figure 10 presents the results of applying the same methodology to a location in south-west China at an altitude of 3000 meters. Monthly TL derived from DNI measurements (purple line) is compared with TL from MISR (red line), MACC (blue line) and Meteotest databases (red line). MODIS values have not been included in this graphic as the database only had values from June to September for this location. Most probably because MODIS have difficulties estimating AOD over high reflectivity land surfaces and in winter months, due to the altitude of the site, most likely this site is entirely covered by snow. It works better over the ocean/sea.

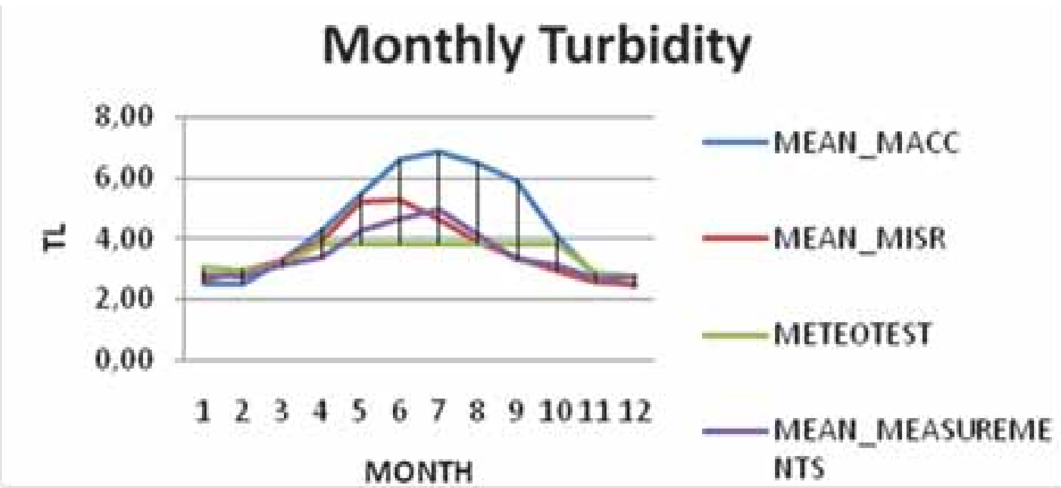

Fig. 10: Mean monthly Linke Turbidity values from DNI measurements, MACC, MISR and Meteotest database for a location in south-west of China

In this location, as can be seen in the last graphic, MACC presents a big overestimation. This resulted in obtaining yearly DNI estimations from satellite images around 30% less than ground measurements. MISR TL (AOD 550nm) estimations are the nearest to TL obtained from DNI measurements. Meteotest values don't follow the monthly dynamic of the turbidity.

The deviations between TL from databases (MODIS, MISR and MACC) and TL derived from DNI measurements can be corrected using different statistical methods (linear/non-linear). This process can be done to improve the calculations of clear sky models before the estimation/processing of solar radiation from satellite images

5. Conclusion

MODIS, MISR and MACC daily AOD at 550nm and daily PW from NCEP were compared against AERONET measurements for 865 locations. All databases show overestimation which is considerably high in the case of MODIS and MACC. This has a direct effect on clear sky models output and solar radiation derived satellite from a satellite which will be underestimated in case raw AOD values from these databases is used. MISR satellite presents better results globally in terms of rMBD and rRMSD, maybe due to its higher spatial resolution. Additionally, the difference in the quality between MISR and MODIS may also be induced by the different algorithms used to estimate the aerosols (not only the resolution). A methodology to estimate TL from DNI measurements was introduced. This can be used to correct turbidity in the databases before using it in models to derive solar radiation from satellite images.

In future works, we will create global uncertainty maps and a fusion daily AOD at 550nm and PW database combining AERONET data and corrected MODIS, MISR and MACC data using kriging techniques.

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