12.4 IMPROVEMENT OF AEROSOL OPTICAL DEPTH DATA FOR LOCALIZED SOLAR FORECASTING

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1. Introduction

Solar generation is variable in nature; the amount of incoming solar radiation available for harvesting by solar panels is influenced by factors including the position of the sun, clouds, aerosol properties, ground albedo, ozone and water vapor in the atmosphere (Gueymard and George, 2005). It is well-known that atmospheric aerosols can attenuate solar insolation by scattering and absorption and therefore affect the solar radiation budget (Li et al., 2017). The National Solar Radiation Database (NSRDB) developed by the National Renewable Energy Laboratory (NREL), United States, is simulated by the Physical Solar Model (PSM) with the input information of surface reflectance, cloud and aerosol properties from satellite measurements and model reanalysis (Sengupta et al., 2018). The current aerosol optical depth (AOD) data used in PSM is from National Aeronautics and Space Administration's Modern Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) and is regridded from the resolution of $0.5^{o} \times 0.5^{o}$ to 4 km × 4 km using an elevation-based scaling. However, the elevation-based downscaled AOD data may not appropriately represent the spatial distribution of aerosol, especially over highly polluted area (e.g., due to wildfires, industrial and transportation emissions) where the gradient of AOD could be large and localized AOD profiles may vary considerably within the specified spatial resolution. The Moderate Resolution Imaging Spectroradiometer (MODIS) Multi-Angle Implementation of Atmospheric Correction (MAIAC) provides AOD product at 1 km resolution with high accuracy. Therefore, the goal of this analysis is to investigate whether using MODIS MAIAC AOD product with spatial resolution of 1 km may improve localized solar forecasting as compared to using the current 4-km elevation-based MERRA-2- AOD.

The first objective of this study is to verify if the 1-km MODIS MAIAC AOD can better represent the detailed spatial distribution of localized.

2. Data and method

In this study, we used the AOD data from MERRA-2 reanalysis, MODIS MAIAC, and AERONET.

Based on the assumption that the surface characteristics change relatively slowly in time, MODIS MAIAC focuses on characterizing surface reflectance by using a sliding window technique and improving pixel and image processing algorithm to retrieve AOD at 1 km resolution with high accuracy (Lyapustin et al., 2018). MODIS MAIAC provides variables including column water vapor (CWV), cloud mask, AOD, aerosol type (background/smoke/dust), and smoke injection height from 2000 to present. The temporal resolution of MAIAC product is daily.

MERRA-2 aerosol reanalysis product is simulated by Goddard Chemistry Aerosol Radiation and Transport (GOCART) coupled with the Goddard Earth Observing System atmospheric model from 1980. The AOD product is assimilated with AOD measurements from MODIS Terra and Aqua, Advanced Very High Resolution Radiometer (AVHRR) instruments, Multiangle Imaging SpectroRadiometer (MISR) and ground-based AERNONET (Molod et al., 2015, Randles et al., 2016). MERRA-2 AOD is further downscaled from 0.5o to 4 km based on elevation and the temporal resolution is linearly downscaled to 5 minutes (Sengupta et al., 2018).

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The AERONET project is a ground-based remote sensing network for observation of aerosol (Holben et al., 1998). The daily-averaged level-1.5 (cloud-screened and quality controlled) and level-2.0 (quality assured) AOD are used in this study. AOD at 550 nm is calculated by using $\mathring{A}ngstr\ddot{o}m$ exponent in the two neighboring bands at 440(or 500) and 675 nm.

In order to verify if the 1-km MAIAC AOD can better represent the detailed spatial distribution of localized aerosols, we first explore the MAIAC AOD and MERRA-2 AOD in areas known to have relatively high levels of air pollution and with Both AOD and DNI measurements are needed to conduct an evaluation. Therefore, we focused on the areas including California State and New York City, U.S as shown in Fig. 1. The AOD data from MAIAC, MERRA-2, and AERONET from 2018 to 2019 are used in this study. The AERONET AOD are used as true values of AOD to evaluate the accuracy of the MODIS MAIAC AOD and MERRA-2 AOD and the statistical analysis were calculated.

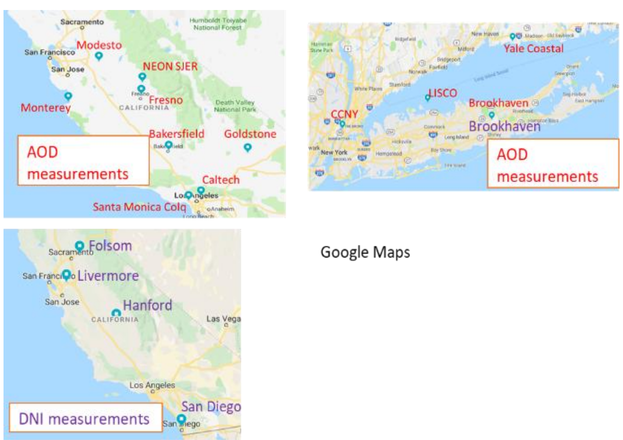

Figure 1. The map of California State and New York City, US, with the location of AOD and DNI measurements from Google Maps.

3. Result

3.1 Comparison of spatial distribution and time series of MAIAC AOD and MERRA-2 AOD

The results of the spatial distribution of topography, monthly-mean 1-km MAIAC AOD, and monthly-mean 4-km MERRA-2 AOD over New York City, NY, San Joaquin Valley, CA, and Los Angeles (LA), CA are shown in Fig. 2. The 1-km MAIAC AOD can represent more detailed spatial distribution of AOD and larger variation of magnitude of AOD over NYC and San Joaquin valley, especially over the coastal area of Long Island. However, for LA, the value of MERRA-2 AOD is generally higher than MAIAC AOD.

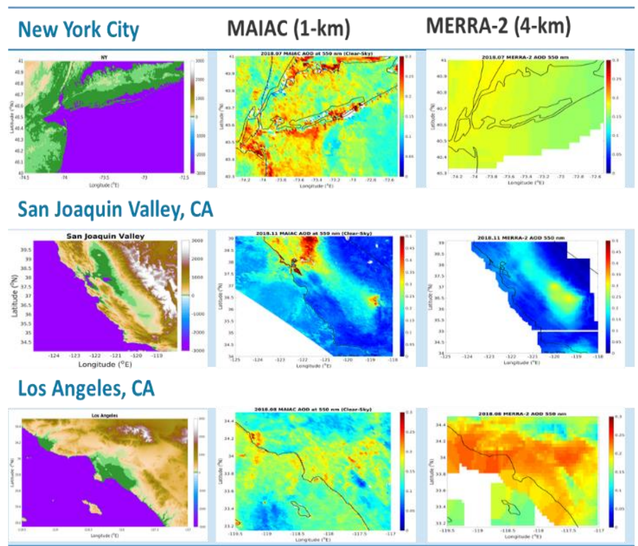

Figure 2. Spatial distribution of topography (left column), monthly-mean MAIAC AOD (middle column), and monthly-mean MERRA-2 AOD (right column) over New York City, NY, on July 2018, San Joaquin Valley, CA, on November 2018, and Los Angeles, CA, on August 2018.

We further compared these two products in the same resolution (4-km) and calculate the difference between MAIAC AOD and MERRA-2 AOD as shown in Fig. 3. The difference shows the MAIAC AOD is higher around the Long Island on July 2018 and around San Francisco on November 2018, which could be due to the transport of smoke to San Francisco. For LA, MAIAC AOD is lower than MERRA-2 AOD on Aug. 2018. Generally, these two AOD products are quite different in spatial and need further evaluation with AERONET AOD.

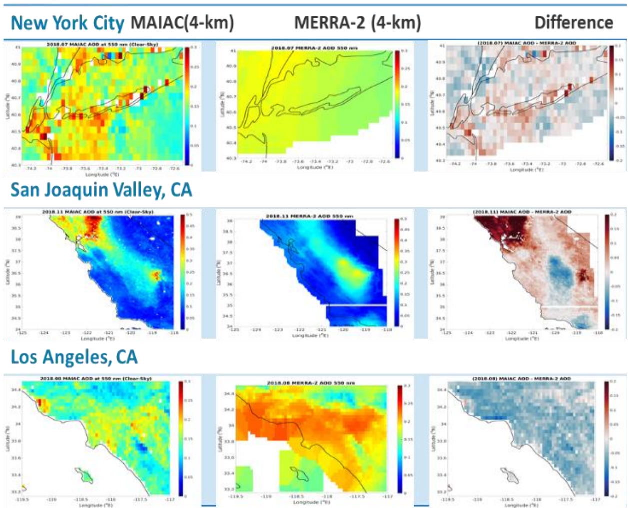

Figure 3. Spatial distribution of 4-km monthly-mean MAIAC AOD (left column), 4-km monthly-mean MAIAC AOD (middle column), and the difference between MAIAC and MERRA-2 2 AOD (right column) over New York City, NY, San Joaquin Valley, CA, and Los Angeles, CA.

Figure 4 shows the time series of the daily-mean MAIAC AOD, MERRA-2 AOD, and AERONER AOD for four AERONET sites (Fresno in San Joaquin Valley, CA, Santa Monica College in LA, CA, Brookhaven in Long Island, NY, and Mexico City, Mexico) during 2018. For the sites in CA State, the AOD values from all three products are usually higher in summer, which is possibly due to more wildfire activities in summer. As to the Brookhaven site, the number of MAIAC AOD measurements is less than that in CA and Mexico City, which could be due to more cloudy days in New York. This may affect the statistical analysis shown in Sect. 3.3. For Mexico City site, the AOD value is much higher than other sites with the value usually above 0.3 in spring and summer, indicating air pollution is more severe in Mexico than in US. Besides, the AERONET AOD is mostly higher than both MAIAC AOD and MERRA-2 AOD in spring in Mexico City site.

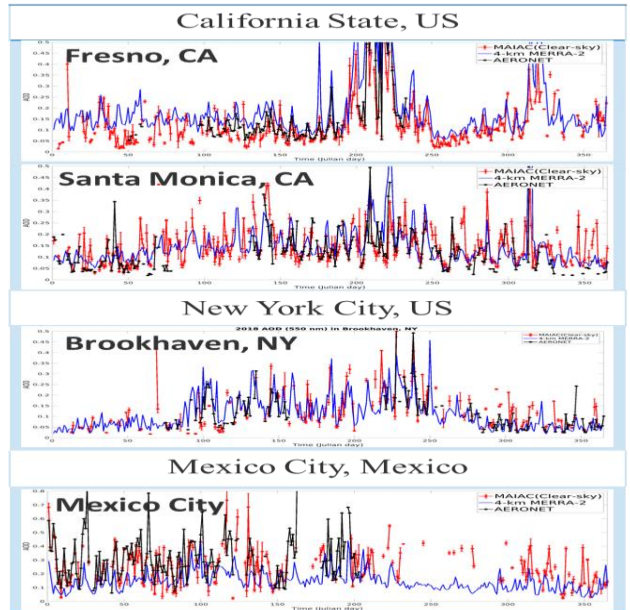

Figure 4. Time series of daily-mean MAIAC AOD (red line), MERRA-2 AOD (blue line), and AERONER AOD (black line) for four AERONET sites (Fresno, Santa Monica, Brookhaven, and Mexico City) during 2018.

3.2 Statistical analysis

Lastly, the statistical results are calculated including Root mean square error (RMSE), mean bias error (MBE), and correlation coefficient (R) for the MAIAC AOD and MERRA-2 for each AERONET sites in California Sate, New York City, and Mexico City as shown in Table 1. It should be noted that we do the calculation only when MAIAC AOD, MERRA-2 AOD, AERONET AOD data are all available. For the sites in CA, the results show the MAIAC AOD performs better than MERRA-2 AOD for over half of the sites with smaller RMSE and MBE and higher R. For the sites in NYC, MERRA2 AOD performs better than MAIAC AOD except Yale Coastal sites. This is possibly because MERRA-2 AOD is reanalysis product and has more and continuous data, while there is no MAIAC AOD data when it is cloudy.

And for the site in Mexico City, MAIAC AOD performs better with smaller RMSE and MSE and with high R. The MSE of MAIAC AOD is less than that of MERRA-2 AOD by an order and the R of MAIAC is triple as that of MERRA-2 AOD.

Table 1. Summary of the statistical analysis including Root mean square error (RMSE), mean bias error (MBE), and correlation coefficient (R) for the MAIAC AOD and MERRA-2 for each AERONET sites in California Sate, New York City, and Mexico City. The product which performs better is highlighted by green color.

California		RMSE	MBE	R
Fresno	MAIAC	0.0653	-0.0264	0.8316
	MERRA2	0.1193	0.0681	0.4371
Bakersfield	MAIAC	0.0724	0.0074	0.3273
	MERRA2	0.0622	-0.0052	0.1793
Modesto	MAIAC	0.0794	0.0087	0.9062
	MERRA2	0.1061	0.0190	0.7966
Monterey	MAIAC	0.0690	0.0255	0.7190
	MERRA2	0.0618	0.0106	0.7512
UCSB	MAIAC	0.0947	0.0455	0.3400
	MERRA2	0.0738	0.0144	0.5153
Caltech	MAIAC	0.0922	0.0019	0.6843
	MERRA2	0.0606	0.0140	0.9165
Santa Monica Colq	MAIAC	0.0705	0.0207	0.7044
	MERRA2	0.0745	0.0267	0.7347
New York City		RMSE	MBE	R
LISCO	MAIAC	0.1346	0.0977	0.6350
	MERRA2	0.0540	0.0075	0.7995
Brookhaven	MAIAC	0.0592	0.0171	0.8345
	MERRA2	0.0495	-0.0078	0.8759
CCNY	MAIAC	0.0724	0.0233	0.6503
	MERRA2	0.0389	2.95e-4	0.8855
Yale Coastal	MAIAC	0.0470	0.0201	0.9613
	MERRA2	0.0838	-0.0464	0.9388
Mexico				
Mexico City	MAIAC	0.1027	-0.0151	0.6998
	MERRA2	0.1635	-0.1061	0.2394

Then, the MAIAC AOD and MERRA-2 AOD data are further grouped into two groups according to the mean value of AOD for each region and the statistical results are shown in Table 2. For California State, the results show MAIAC AOD performs better than MERRA-2 AOD with smaller RMSE and higher R when the AOD value is greater than 0.1. However, MERRA2 AOD performs better than MAIAC AOD when the AOD value is less than 0.1. For New York City, the performances of MAIAC AOD and MERRA-2 AOD are similar when the AOD value is greater than 0.1. On the other hand, MERRA-2 AOD performs much better than MAIAC AOD in the condition of low AOD value. For Mexico City, MAIAC AOD performs slightly better than MERRA-2 when AOD value is less than 0.25 but performs much better when AOD value is higher than 0.25. Overall, the sensitivity test of MAIAC AOD and MERRA-2 AOD product to AOD value shows MAIAC AOD has better performance when the AOD value is higher in California State and Mexico City.

Table 2. Summary of the statistical analysis including Root mean square error (RMSE), mean bias error (MBE), and correlation coefficient (R) for the MAIAC AOD and MERRA-2 for each region (California Sate, New York City, and Mexico City). The product which performs better is highlighted by green color. The yearly-mean AOD values for CA, NYC, and Mexico City are 0.11, 0.12, and 0.31, respectively.

California		RMSE	MBE	R
AOD > 0.1	MAIAC	0.0990	-0.0170	0.7933
	MERRA2	0.1207	6.1e-4	0.6962
AOD ≤ 0.1	MAIAC	0.0673	0.0428	0.1990
	MERRA2	0.0465	0.0289	0.5056
New York City				
AOD > 0.1	MAIAC	0.0772	0.0113	0.7457
	MERRA2	0.0726	-0.0284	0.7869
AOD ≤ 0.1	MAIAC	0.0855	0.0492	0.2963
	MERRA2	0.0310	0.0085	0.5868
Mexico				
AOD > 0.25	MAIAC	0.1167	-0.0224	0.4501
	MERRA2	0.2049	-0.1742	0.0904
AOD ≤ 0.25	MAIAC	0.0812	-0.0056	0.3682
	MERRA2	0.0847	-0.0187	0.0722

4. Summary and future work

This study explored both 1-km MAIAC AOD and 4-km MERRA-2 AOD products and evaluated these two products with the ground-truth AERONET AOD over California State and New York City in US and Mexico City in Mexico. The results pointed out that 1-km MAIAC AOD can provide improved information of aerosol loading over areas with high level of AOD. The MAIAC AOD performs better in the AERONET sites in San Joaquin Valley, CA, US, and Mexico City, Mexico with smaller RMSE, smaller MBE, and higher correlation coefficient than MERRA-2 AOD. However, for AERONET sites in New York City, MERRA-2 AOD has smaller RMSE, smaller MBE, and higher correlation, which is possibly due to fewer measurements of MAIAC AOD than MERRA-2 AOD. Evaluation using AOD loading thresholds shows that MAIAC AOD performs better in CA and Mexico City for high AOD, while MERRA-2 AOD performs better in CA and New York City for low AOD.

In the next step, we will investigate whether the high resolution AOD data can improved the NSRDB, the 1-km gridded MAIAC AOD data will be used as input for the PSM to simulate global horizontal irradiance (GHI) and direct normal irradiance (DNI). The accuracy of simulation results will be evaluated by the GHI and DNI measurements from the Surface Radiation Budget Network (SURFRAD) and the magnitude of uncertainty of GHI and DNI will be compared with that from the current NSRDB.

5. Reference

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