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Improvement of Aerosol Optical Depth Data for Localized Solar Forecasting

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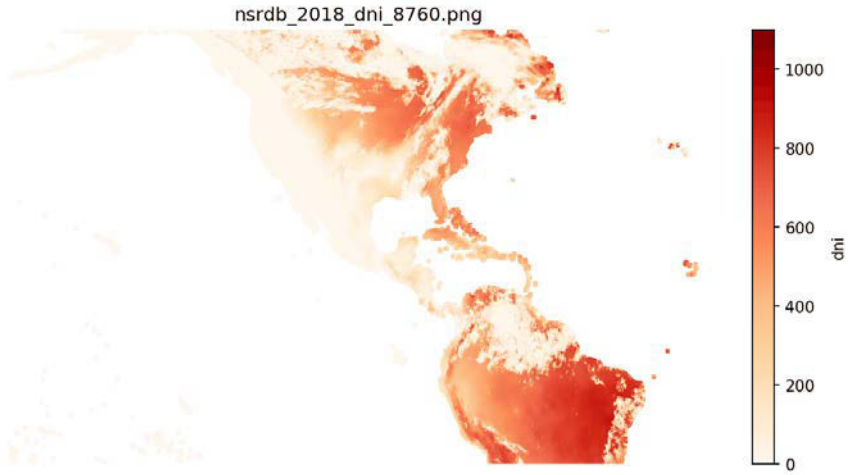
100th AMS Annual Meeting 2020
Boston, Massachusetts
January 12–16, 2020

Solar Resource Information

- Solar resource information is important for solar photovoltaic (PV) plant developers and investors to estimate the solar yield and return on investment.
- Because long-term, high-quality solar measurements are expensive and not readily available, solar radiation maps from modeling are the most commonly used data sets for the PV community.
- The National Solar Radiation Database (NSRDB) from the National Renewable Energy Laboratory is a popular source of satellite-based solar radiation data.



Geostationary Operational Environmental Satellite-(GOES-) based direct normal irradiance (DNI) from the NSRDB: https://nsrdb.nrel.gov

Impact of Air Pollution on Solar Irradiance

- Mapping solar radiation requires high-quality data with sufficient spatial resolution for key parameters, including cloudiness, site pressure, water vapor, ground albedo, ozone, and aerosol optical depth (AOD) (Gueymard and George 2005).
- Because of various limitations, AOD still lacks accurate, spatially dense determination among these parameters.
- Solar output can be reduced by more than 20% in highly polluted locations (Li et al. 2017).

The NSRDB is simulated by the Physical Solar Model (PSM) with a 4-km elevation-scaled Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) AOD; however, the 4-km MERRA-2 AOD might not appropriately represent the spatial distribution of aerosol loading, especially over highly polluted areas with large gradients of AOD.

Gueymard, C.A., and R. George. 2005. "Gridded Aerosol Optical Depth Climatological Datasets Over Continents for Solar Radiation Modeling." In *Proceedings of the Solar World Congress, International Solar Energy*, Orlando, FL.

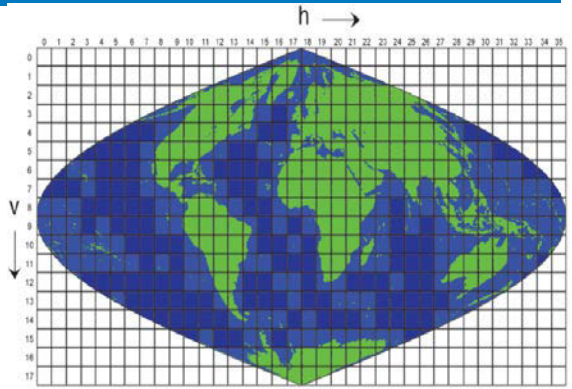
Li, X., F. Wagner, W. Peng, J. Yang, and D.L. Mauzerall. 2017. "Air Pollution Reduction of Solar Resource in China." In *Proceedings of the National Academy of Sciences* 114 (45): 11867–11872. https://doi.org/10.1073/pnas.1711462114.

Project Objectives

1. To verify if the 1-km MODerate Resolution Imaging Spectroradiometer (MODIS) Multi-Angle Implementation of Atmospheric Correction (MAIAC) AOD can better represent the detailed spatial distribution of localized aerosols:
   - We explore the MAIAC AOD and MERRA-2 AOD in areas in the United States and Mexico known to have relatively high levels of air pollution, and we evaluate their accuracy with the ground-truth AOD measurements from the AErosol ROBotic NETwork (AERONET).
2. To investigate whether the high-resolution AOD data can improve the NSRDB:
   - The 1-km gridded MAIAC AOD data will be used as input for the PSM to simulate DNI. The accuracy of the simulation results will be evaluated with DNI measurements and compared with the current NSRDB.

MODIS MAIAC

- Based on the assumption that the surface characteristics change relatively slowly in time, MODIS MAIAC focuses on characterizing surface reflectance.
- Uses a sliding window technique and improved pixel and image processing algorithms to retrieve AOD at a 1-km resolution with high accuracy from 2000 to present
- Variables: column water vapor, cloud mask, **AOD** and aerosol type (background/smoke/dust), smoke injection height.
- Period of evaluation: 01/01/2018–12/31/2018
- Temporal resolution: daily.



MODIS sinusoidal tiles

MAIAC AOD (20191108, NASA WorldView)

Modern Era Retrospective Analysis for Research and Applications, Version 2

- The MERRA-2 aerosol reanalysis product is simulated by Goddard Chemistry Aerosol Radiation and Transport (GOCART) coupled with the Goddard Earth Observing System, Version 5 (GEOS-5) atmospheric general circulation model (Molod et al. 2015; Gelaro et al. 2017; Randles et al. 2016).
- AOD from MODIS Terra and Aqua, advanced very high-resolution radiometer instruments, multi-angle imaging spectroradiometer, and ground-based AERNONET are assimilated into GEOS-5.
- MERRA-2 AOD are further downscaled from 0.5^{o} to 4 km based on elevation, and the temporal resolution is linearly downscaled to 5 minutes (Sengupta et al. 2018) from hourly data.

Molod, A., L. Takacs, M. Suarez, and J. Bacmeister. 2015. "Development of the GEOS-5 Atmospheric General Circulation Model: Evolution from MERRA to MERRA2." *Geoscientific Model Development* 8: 1339–1356. https://doi.org/10.5194/gmd-8-1339-2015.

Gelaro, R., et al. 2017. "The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)." *Journal of Climate*. https://doi.org/10.1175/JCLI-D-16-0758.1.

Randles, C.A., et al. 2016. *The MERRA-2 Aerosol Assimilation* (NASA/TM–2016-104606), Volume 45.

Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby. 2018. "The National Solar Radiation Data Base (NSRDB)." *Renewable and Sustainable Energy Reviews* 89: 51–60. https://doi.org/10.1016/j.rser.2018.03.003.

AErosol ROBotic NETwork Aerosol Optical Depth

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

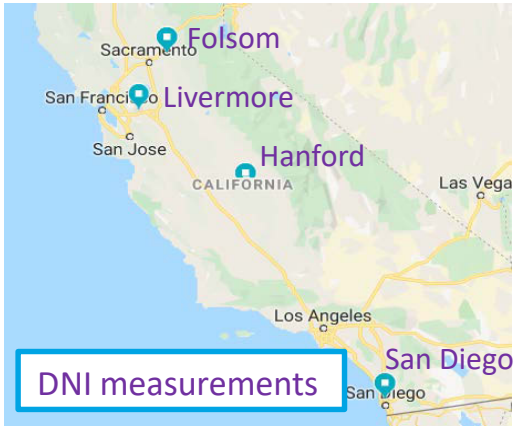
Holben, B.N., et al. 1998. “AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization.” *Remote Sensing of the Environment* 66 (1): 1–16.

Study Areas: New York and California

Global horizonal irradiance = Direct normal irradiance x cosθ + Diffuse horizontal irradiance

DNI is more sensitive to AOD.

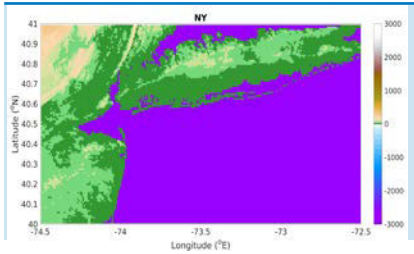
- Both AOD and DNI measurements are needed to conduct an evaluation.
- Areas with relatively high aerosol loading
- Areas with relatively large numbers of PV panels.



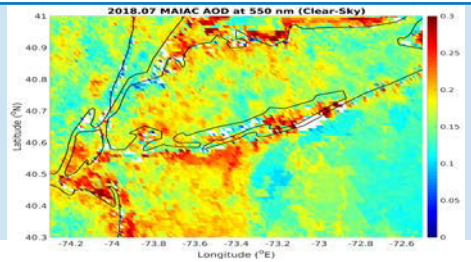
Google Maps

Result: Spatial Distribution of Monthly Mean Aerosol Optical Depth

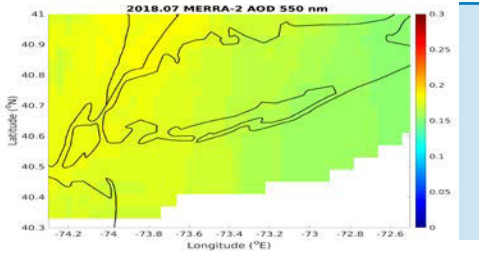
New York City



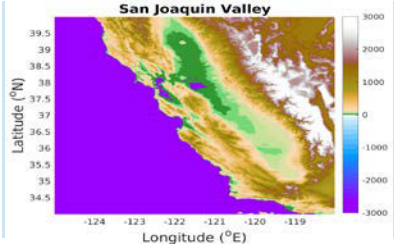
MAIAC (1-km)

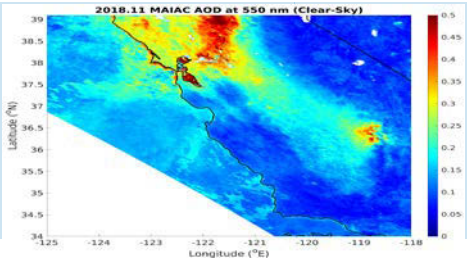


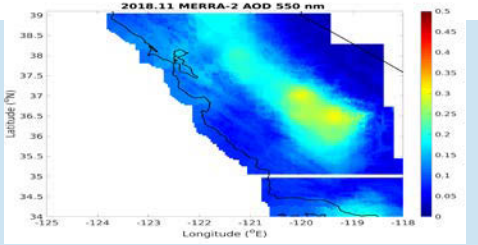
MERRA-2 (4-km)



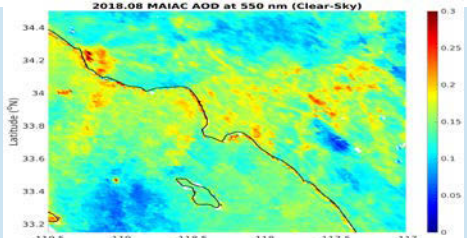
San Joaquin Valley, CA

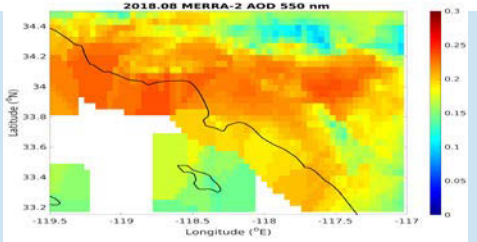




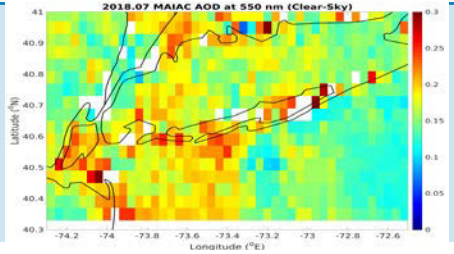
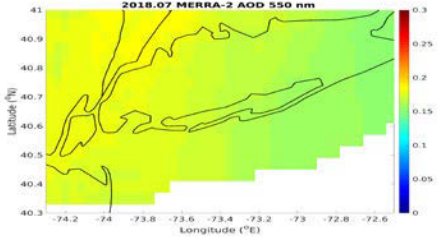
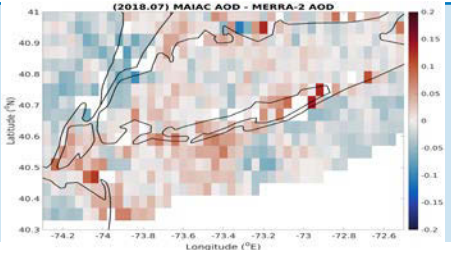
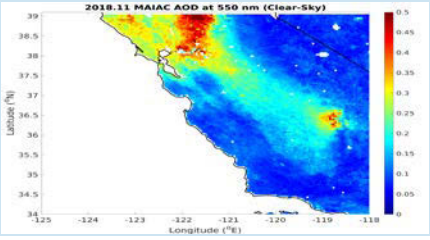
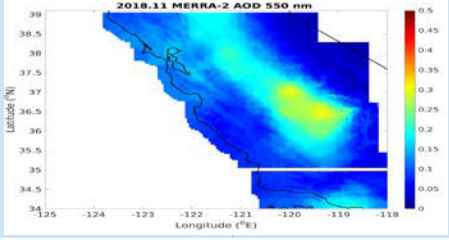
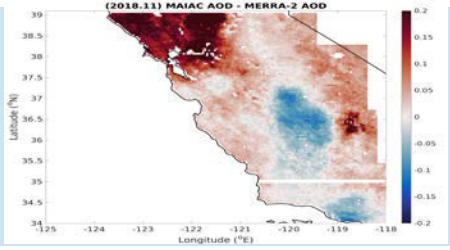
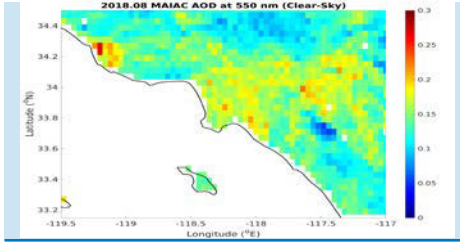
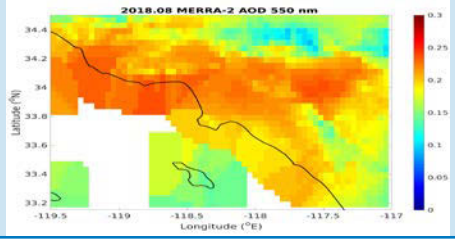
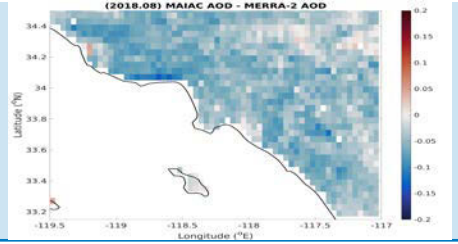


Los Angeles, CA





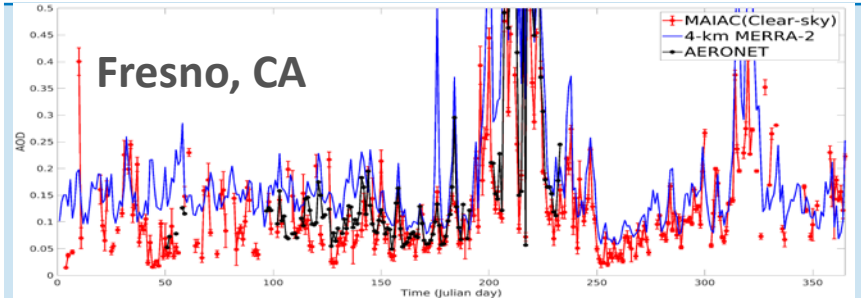
Result: Spatial Distribution of Monthly Mean Aerosol Optical Depth

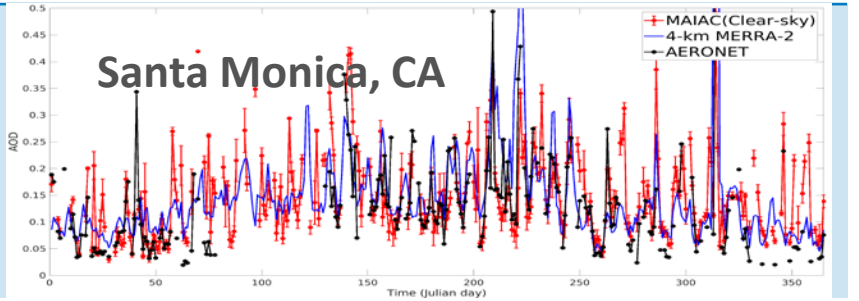
	MAIAC (4-km)	MERRA-2 (4-km)	Difference
New York City			
San Joaquin Valley, CA			
Los Angeles, CA			

Time Series of Daily Aerosol Optical Depth During 2018

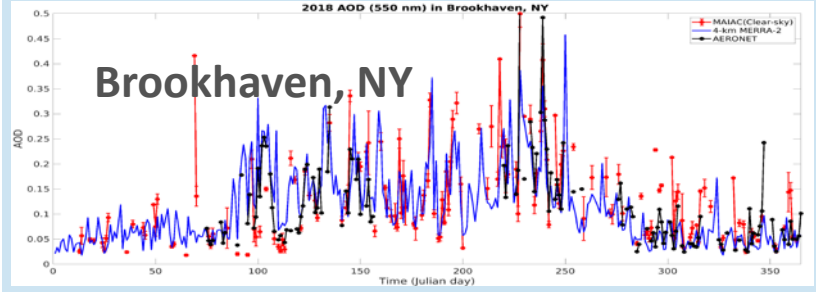
- Higher levels of AOD in California in summer and November because of wildfires
- Fewer MAIAC AOD measurements in New York possibly because of more cloudy days.

California, United States

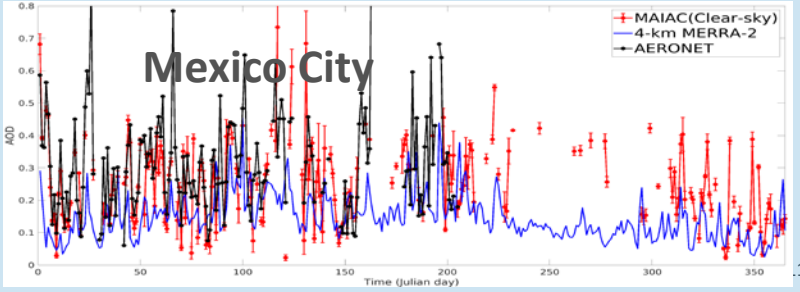




New York City, United States



Mexico City, Mexico



Comparison With AERONET Observations

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

Regional Comparison with AERONET Observations

- MAIAC AOD performs better in California when AOD > 0.1.
- MERRA-2 AOD performs better in New York, especially when AOD < 0.1.
- MAIAC AOD performs better in Mexico City.

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

Mexico		RMSE	MBE	R
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

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

- $\overline{AOD}_{AERINET}$ (California): 0.11
- $\overline{AOD}_{AERINET}$ (New York City): 0.12
- $\overline{AOD}_{AERINET}$ (Mexico City): 0.31

Summary

- 1-km MAIAC AOD can provide improved information of aerosol loading over areas with high levels of AOD.
- The MAIAC AOD performs better in the AERONET sites in San Joaquin Valley and Mexico City with smaller root mean square error (RMSE), smaller mean bias error (MBE), and higher correlation than MERRA-2 AOD.
- For AERONET sites in New York City, however, MERRA-2 AOD has smaller RMSE, smaller MBE, and higher correlation, which is possibly because of fewer measurements of MAIAC AOD.
- Evaluation using AOD loading thresholds shows that MAIAC AOD performs better in California and Mexico City for high AOD, whereas MERRA-2 AOD performs better in California and New York City for low AOD.

Future Work

The MAIAC AOD will be used as the AOD input for the PSM to simulate DNI and compare the with the NSRDB to see if the improved aerosol information can also improve solar irradiance estimates.

Because GOES-16 and GOES-17 have similar channels to MODIS, will it be possible to use the geostationary satellites to improve AOD for solar forecasting?

Thank You

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NREL/PR-5D00-75816

This work was authored in part by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the Laboratory Directed Research and Development (LDRD) Program at NREL. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.