SPATIAL ANALYSIS AND CHARACTERIZATION OF DUST PARTICLES USING REMOTELY-SENSED DATA AND ITS EFFECTS ON SOLAR PV POWER PRODUCTION: CASE OF THE PHILIPPINES

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ABSTRACT: As solar radiation penetrates the atmosphere, a significant amount of energy is lost due to its interaction with atmospheric constituents including absorption and reflection by water vapor and air molecules. The said attenuation of energy impacts electric power production from solar photovoltaic (PV) systems. Solar PV systems have become one of the widely used alternatives for electricity generation due to their advantages on scalability and promising solar cell conversion efficiency. However, these systems can be significantly affected by environmental factors including dust accumulation which decreases the amount of energy produced. This study aims to characterize dust particles in the Philippines in terms of particle size and amount of aerosols using remotely-sensed data estimated using daytime aerosol property data on Aerosol Optical Thickness (AOT) and Angstrom Exponent (AE), respectively, derived from Advanced Himawari Imager 8/9 (AHI-8/9) satellite data. Trend analysis was done to the mean AOT and AE for each month and for the whole timeline (2017-2021), decomposed using the AirRGB method. AHI-8/9 products were then compared to the retrieved Aerosol Optical Depth (AOD) and Angstrom Exponent (α) from MODIS Terra satellite data. Results show that areas with relatively high estimated dust deposition ($0.218 \leq \text{AOT} \leq 0.230$) can be found in Eastern Visayas, Eastern Mindanao, and Western Luzon. Meanwhile, fine aerosol particles ($0.80 \leq \text{AE} \leq 0.93$) are dominant in Northern Luzon and Palawan while coarse aerosol particles ($0.68 \leq \text{AE} \leq 0.70$) are dominant in Mindanao. Lastly, the decrease in solar PV power output due to dust deposition was estimated at 20-30%. Results from this study can be a useful input in the development of a forecasting model for solar PV output power since dust accumulation on modules must be quantified and considered for its impact on the system's output power. This study demonstrates the novelty of using AHI-8/9 aerosol property product as input to the AirRGB model instead of MODIS data, and its application to the estimation of the combined effects of dust and precipitation on solar PV production. For future work, analyzing the correlation between the RGB scenarios from AirRGB decomposition and socio-economic development can be considered.

1. INTRODUCTION

Solar PV systems have become one of the widely used alternatives for electricity generation due to their advantages on scalability and promising solar cell conversion efficiency. However, these systems can be significantly affected by environmental factors including dust accumulation which decreases the amount of energy produced (Yang et al., 2016). The accumulation of dust on solar panels reduces the irradiance received by a PV system, effectively decreasing its efficiency (Principe and Takeuchi, 2019b). This is highly apparent in regions with high rates of dust soiling and low frequency and intensity of rain (Zorrilla-Casanova et al., 2011). Accumulated dust causes a screening effect on the solar panel which lowers the performance of solar cells over time (Zorrilla-Casanova et al., 2011). The study aims to assess the impact of dust on solar PV power production using satellite-derived aerosol properties data.

Aerosols are tiny solid and liquid suspended particles in the atmosphere, excluding clouds and precipitation. These may include dust, sea salts, smoke from wildfire, pollution, and even volcanic ash (Fu, 2015). Cloud, aerosol, and other atmospheric particles contribute to the attenuation of incoming solar radiation. In the absence of clouds, dust and aerosol particles are the main source of attenuation of the surface solar radiation.

Aerosol Optical Thickness (τ) is a dimensionless quantitative measurement of solar radiation extinction by scattering and absorption. It exhibits the amount of aerosol in the vertical column of atmosphere over the observed area. Fig. 1 shows a sample AOD generated from MODIS 1-Month aerosol optical thickness using the Terra satellite. Clear sky ($\tau < 0.2$) is visualized as pale yellow whereas reddish brown indicates hazy conditions ($\tau > 0.2$) (NASA Earth Observations, 2021).

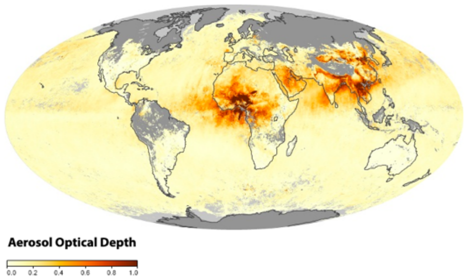

Figure 1. March 2021 Aerosol Optical Depth (© NASA Copyright 2021)

Angstrom coefficient (α) is a qualitative measure of aerosol particle size (Angstrom, 1929). The angstrom coefficient exhibits an inverse proportionality with the particle size. Values of $\alpha < 1.0$ indicate coarse mode aerosols of radii $\gtrsim 0.5\mu m$ such as dust and sea salt. Aerosols with $\alpha > 1.0$ indicate fine mode aerosols of radii $\lesssim 0.5\ \mu m$ and are usually associated with haze, pollution and biomass burning (Schuster, et al., 2006).

In a study by Principe and Takeuchi (2019b), pixels with an aerosol optical depth of $\alpha > 0.2$ are considered as affected by dust and will therefore cause a decrease in the output solar PV power production. Dust particles are then categorized into fine particles where $\alpha \geq 1$ and coarse particles where $\alpha < 1.0$ using the Angstrom coefficient. The decrease in PV power output (ΔPPV) due to dust accumulation can be computed using Eq. (1):

$$\Delta PPV = A_{cell}\eta R'\Delta\eta_d \tag{1}$$

where A_{cell} is the total aggregated pixel area for the solar PV installation, η is the conversion efficiency, R' is the adjusted solar radiation data, and η_d is described in Eq. (2) (Principe and Takeuchi, 2019b).

$$\overline{\Delta\eta_d} = 0.3\frac{\sum_{i=1}^{n} x_{d_i} x_{r_i}}{n} \quad where \quad x_{di} = \begin{cases} 0, & if\ AOD \leq 0.2 \\ R_{RGB} & otherwise. \end{cases} \quad x_{ri} = \begin{cases} 0, & if\ pcp\_rate > 20mm/day \\ 1 & otherwise. \end{cases} \tag{2}$$

Advanced Himawari Imager-8/9 Aerosol Property and MODIS Aerosol Optical Depth products were compared to select the best satellite data relevant to this study.

Characterization of dust particles in the Philippines in terms of particle size and amount of aerosols using remotely-sensed data is done using daytime Aerosol Optical Thickness (AOT) and Angstrom Exponent (AE), respectively, derived from Advanced Himawari Imager 8/9 (AHI-8/9) satellite data.

2. MATERIALS AND METHODS

2.1 Himawari-8/9 Aerosol Property Product

The Japan Aerospace Exploration Agency (JAXA) P-Tree system (www.eorc.jaxa.jp/ptree) provides access to multi-satellite products such as the Himawari Standard Data (HSD) by the Japan Meteorological Agency (JMA), Himawari L1 data, as well as some geophysical parameters already produced by JAXA using the HSD which includes aerosol property, cloud property, sea surface temperature, short wave radiation / photosynthetically active radiation, chlorophyll-a, and wildfire. The P-Tree system also supplies model products such as aerosol properties by MRI/JMA and sea surface temperature by JAXA and JAMSTEC (Japan Aerospace Exploration Agency, 2021).

In this study, the Angstrom Exponent and Aerosol Optical Thickness at 500 nm wavelength values were extracted from the daytime Aerosol Property product to map the distribution of aerosols in the Philippines from 2017 to 2021. The full-disk NetCDF product has a spatial resolution of 5 km. The Level 3 product which provides monthly temporal resolution data was used in this study for map generation and as input to AirRGB decomposition method Meanwhile, the hourly temporal resolution data was used for data comparison between the aerosol property products of Himawari-8/9 and MODIS. The monthly Level 3 product is also a result of averaging the 10-min Level 2 product.

A common algorithm was used by Yoshida et al. (2018) for the retrieval of aerosol properties from AHI and MODIS Aqua. Their results showed that AOT values estimated from AHI were generally consistent with those from MODIS. Furthermore, the AHI aerosol property retrieval algorithm was improved by investigating the causes of the differences in AOT values among sensors such as variations in scattering angle (Yoshida et al., 2018).

2.2 MODIS Aerosol Property Product

The Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol product monitors the ambient aerosol optical thickness. MODIS on NASA Terra satellite generates AOD using measurement of atmospheric reflection and absorption of visible and infrared light. Daily Level 2 (MOD04_L2) with a spatial resolution of 10x10 km was gathered for the quantification of dust accumulation effects on solar PV potential.

The comparison of MODIS aerosol data with AERONET ground-based observations yields a linear regression slope of 1.06 and negligible intercept, demonstrating consistency between values (Jiang et al., 2019). While several studies observed the differences in AOT values of MODIS and AHI, revealing an underestimation of AHI AOT aerosol property retrievals in the morning and overestimation in the afternoon (Gao et al., 2021; Jiang et al., 2019), their spatial distribution is still comparatively similar. Furthermore, a moderate agreement was observed between AHI AOT and AERONET measurements, and the Mann-Whitney-Wilcoxon test revealed that there is no significant difference between their measurements (Jiang et al., 2019).

In this study, Himawari-8/9 aerosol property is used because of its advantage in spatial and temporal resolution which will be useful in the development of a forecasting model for solar PV output power since dust accumulation on modules must be quantified and considered for its impact on the system's output power.

2.3 AirRGB Decomposition

A novel decomposition scheme for characterizing urban air quality was developed by Misra et al (2017) using Aerosol Optical Depth (AOD) and Angstrom Exponent (AE) values from MODIS Terra three distinct scenarios: 'R' for high AE and high AOD; 'G' for high AE and low AOD; and 'B' for low AE and low AOD. A triangular color scale (red for R scenario, green for G scenario, and blue for B scenario) is used to visualize and easily segregate regions having high industrial aerosols from only natural aerosols. A scatterplot containing the average of monthly AOD and AE values for each city location on the x- and the y-axis, respectively, considers an arbitrary bounding triangle RGB such that the coordinates lie within the triangle as much as possible and its vertices correspond to: a) high AE and high AOD, b) high AE and low AOD, and c) low AE and low AOD, labeled as R, G, and B, respectively. Each coordinate inside triangle RGB is decomposed into a 3-band RGB-scale by computing its distance from each vertex as l_R, l_G, and l_B. A distance vector l is derived in Eqs. (3) and (4) by normalizing each distance metric by the side opposite to the corresponding vertex.

$$l = \left[\frac{l_R}{L_R}, \frac{l_G}{L_G}, \frac{l_B}{L_B}\right], \tag{3}$$

where

$$\begin{aligned} l_R &= |(y_B - y_G) \times (x_C - x_B) + (y_B - y_C) \times (x_B - x_G)|, \\ l_G &= |(y_R - y_B) \times (x_C - x_R) + (y_R - y_C) \times (x_R - x_B)|, \\ l_B &= |(y_G - y_R) \times (x_C - x_G) + (y_G - y_C) \times (x_G - x_R)|. \end{aligned} \tag{4}$$

Values for channel R, G, B are normalized by the maximum possible distance vector and multiplied by 100 shown in Eq. (5).

$$[R, G, B] = l \cdot \frac{100}{\frac{l_R}{L_R} + \frac{l_G}{L_G} + \frac{l_B}{L_B}}, \tag{5}$$

A study on global urban air quality analysis showed a sharp divide exists between North American and European cities and Asian cities in terms of baseline pollution and slopes of R and G trends (Misra et al., 2017). Furthermore, pollution continues to increase in South Asia and Southeast Asia (Misra et al., 2017). In a similar study done over the Asia Pacific region, almost all countries in the region suffer from the effects of dust, particularly severe in East

Asia, except in Japan and Korea, during the June-July-August season (Principe and Takeuchi, 2019a).

3. RESULTS AND DISCUSSION

3.1 Comparison of Himawari-8/9 with MODIS Aerosol Data

The point of interest was identified to be PAGASA, Quezon City which is the nearest weather station to the actual experiment set-up being conducted at UP Diliman, Quezon City for further studies.

Himawari uses 24-hour period values while MODIS uses spot data only. MODIS satellite data for the Philippines were taken at a daily interval between 1:00 AM to 4:00 AM UTC. Hourly AHI-8 data Aerosol Property was downloaded from JAXA Himawari. Instead of comparing the daily products directly, 1:00 AM to 4:00 AM UTC Himawari data were extracted from the hourly readings of Himawari to get an accurate comparison. Data filtering was done as a pre-processing technique by removing samples with “No Data” and extreme data values.

As shown in Fig. 2A and Fig. 2B, R-squared values of 76.4% and 84.6% were observed from the linear regression of the AOT and AE values, respectively. The fitted line plots show that MODIS and Himawari data exhibit a strong correlation.

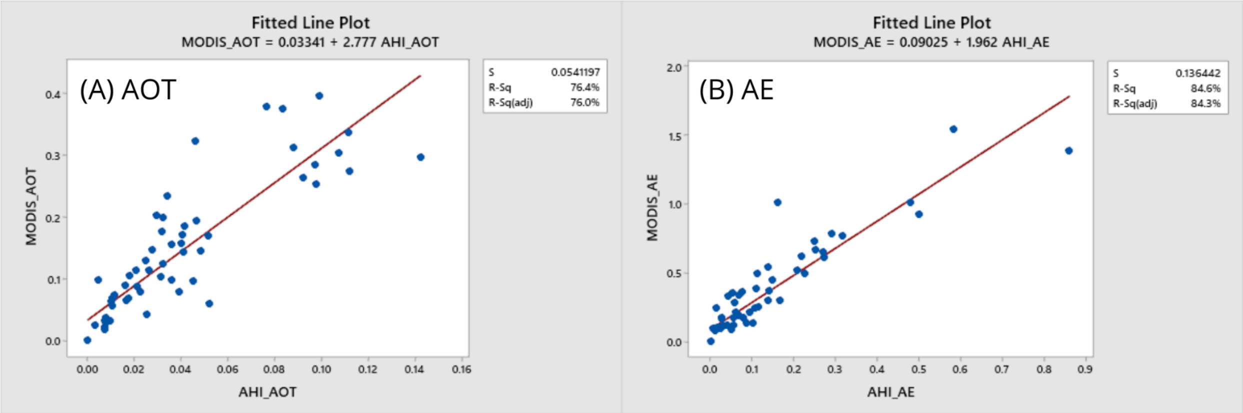

Figure 2. Linear Regression of Monthly Averaged a) Aerosol Optical Thickness and b) Angstrom Exponent

Hourly AHI-8 data and daily MODIS data were resampled into monthly temporal resolution as shown in Fig. 3A and Fig. 3B. Underestimation of AHI-8 aerosol properties can be observed for both the aerosol optical thickness and angstrom exponent parameters. This implies that the actual vertical thickness and particle size of the aerosol may be larger and finer than recorded satellite values.

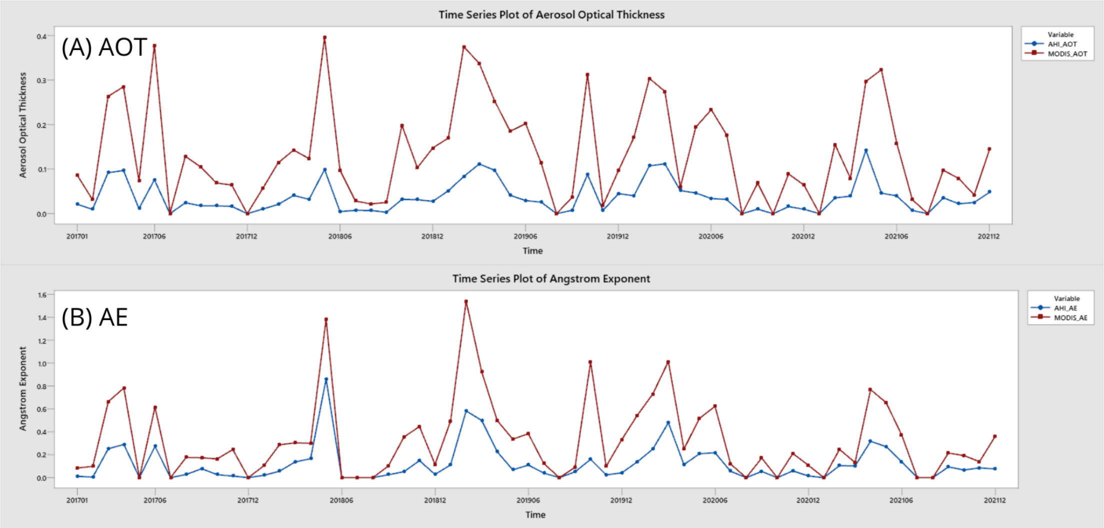

Figure 3. Time Series Plot of Monthly Averaged (A) Aerosol Optical Thickness and (B) Angstrom Exponent

3.2 Aerosol Optical Thickness and Angstrom Exponent from 2017 to 2021 in the Philippines

AOT data may also be used as a reasonable proxy measurement for surface particulate matter, PM 2.5 (Chudnovsky et al., 2013). Hence, the 0.2 threshold was used to determine which areas with more or less amount of dust deposition (Principe and Takeuchi, 2019a & 2019b). In solar PV installations, the decrease in solar PV power potential due to dust depends on the intensity of rainfall which can impede or promote the accumulation of dust on a PV module (Principe and Takeuchi, 2019a). Fig. 4 shows the annual mean AOT from 2017 to 2021. It can be observed that among the years on the study's timeline, year 2019 generally consists of AOT greater than 0.2 in most of the areas. The hotspot analysis of the AOT dataset generally characterizes the regions in Luzon and Mindanao islands as having lesser AOT, and Visayas as having more AOT for the whole timeline as shown in Fig. 4. Results show that areas with relatively high estimated dust deposition (0.218 ≤ AOT ≤ 0.230) can be found in Eastern Visayas, Eastern Mindanao, and Western Luzon.

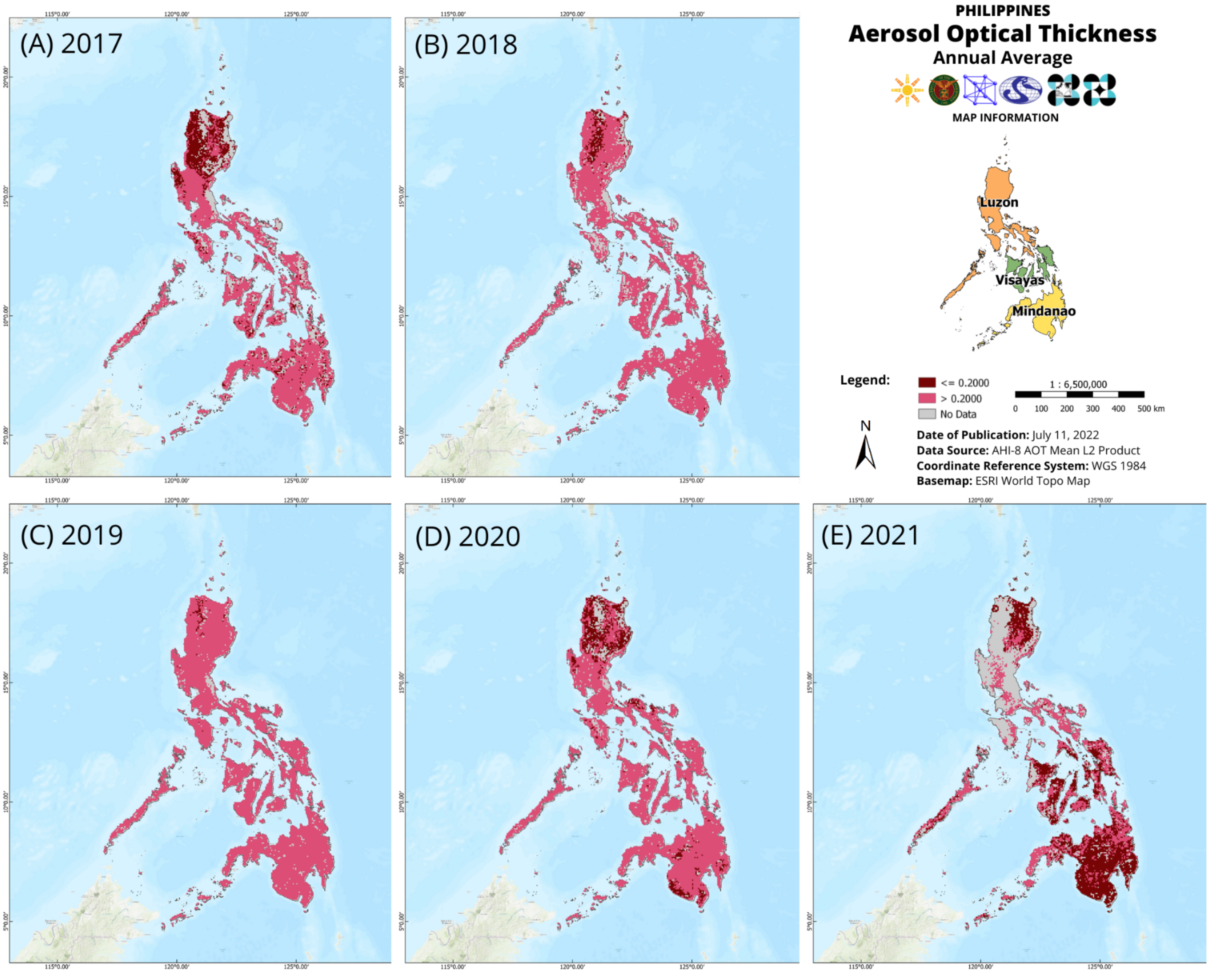

Figure 4. Mean annual average aerosol optical thickness for the Philippines for years (A) 2017, (B) 2018, (C) 2019, (D) 2020, and (E) 2021

Areas in the Philippines with consistent coarse aerosols can be found significantly in La Paz Tarlac; Parang, Maguindanao; and Tupi, South Cotabato (Fig. 6); while consistent fine aerosols can be found significantly in Laguna de Bay and in the series of mountains in Bicol namely Mt. Cabanbanan, Mt. Pulog, and Mt. Mymecodia (Fig. 7). Results show that fine aerosol particles (0.80 ≤ AE ≤ 0.93) are dominant in Northern Luzon and Palawan while coarse aerosol particles (0.68 ≤ AE ≤ 0.70) are dominant in Mindanao. In solar PV installations, even the size of dust particles affects the PV output such that dust of finer particles is distributed in a more uniform manner than that of coarser particles, minimizing the voids between particles which light can pass (Principe and Takeuchi, 2019a; El-Shohokshy and Hussein, 1993). The hotspot analysis of the AE dataset generally characterizes Luzon and Mindanao as having coarser aerosols and Visayas as having finer aerosols for the whole timeline as shown in Fig. 8.

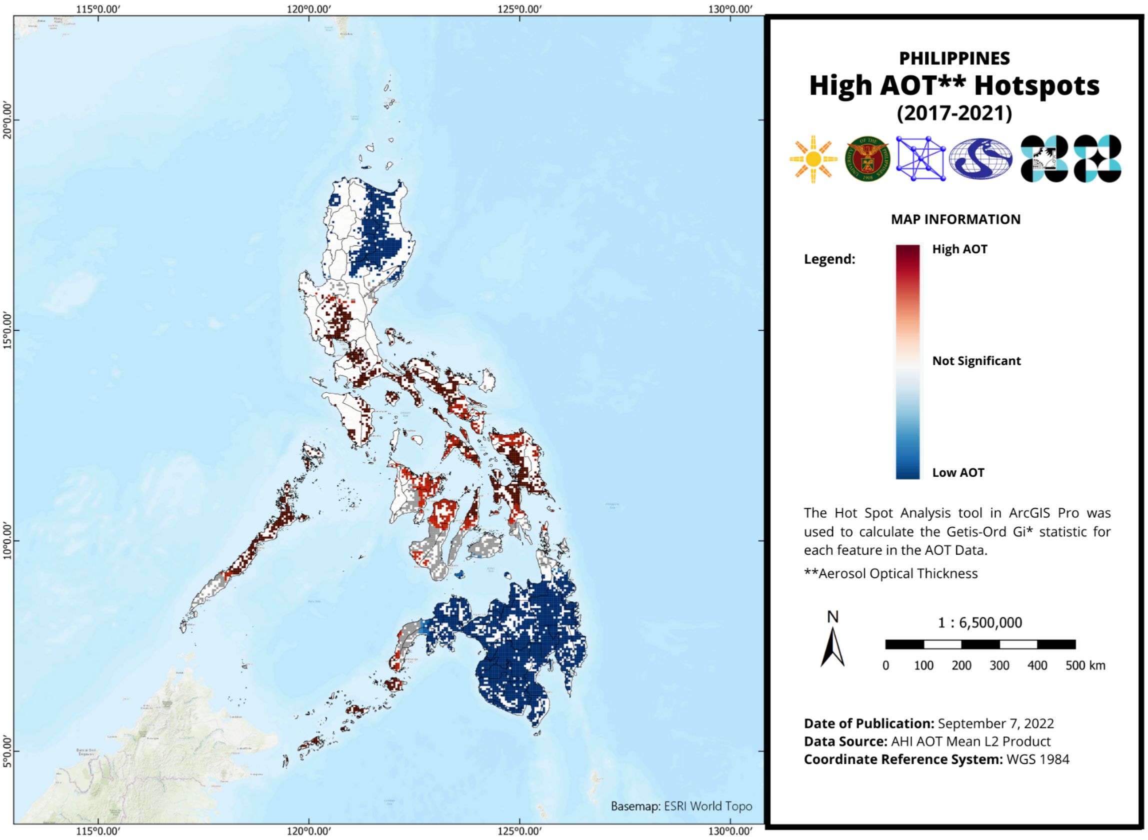

Figure 5. High aerosol optical thickness hotspots in the Philippines (2017-2021)

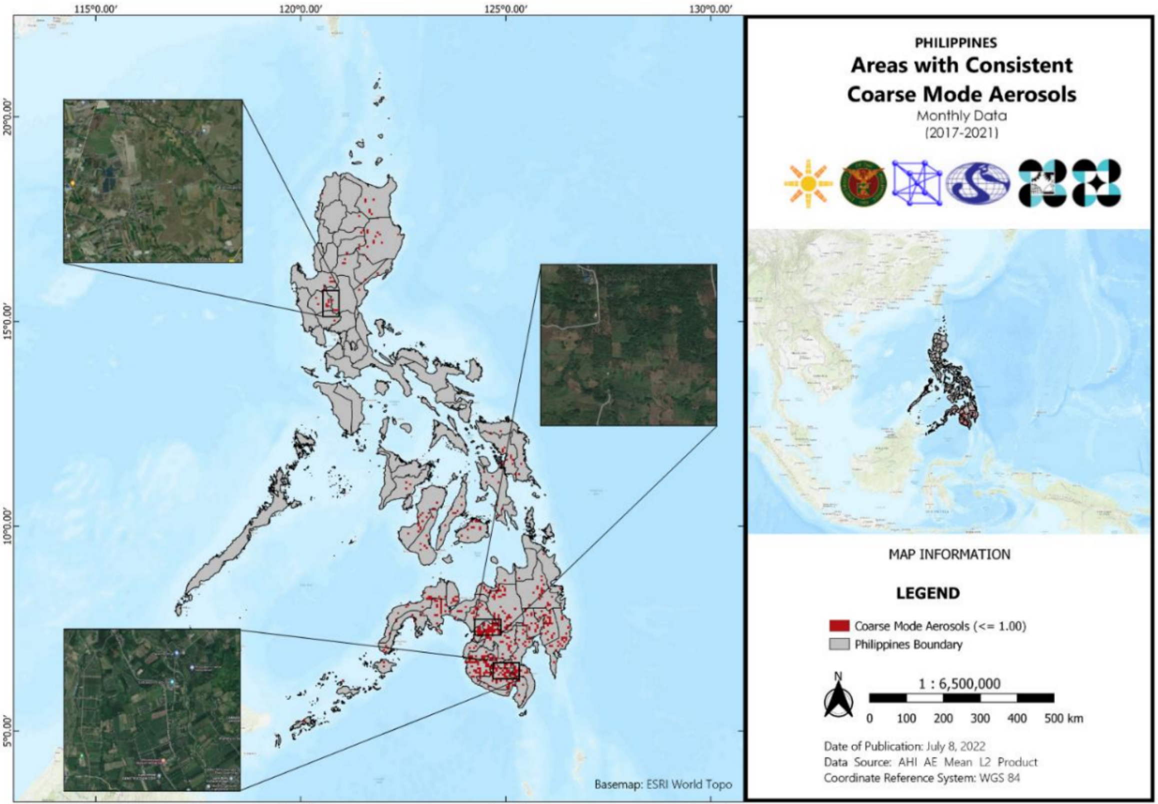

Figure 6. Areas with consistent coarse mode aerosols in the Philippines from 2017 to 2021.

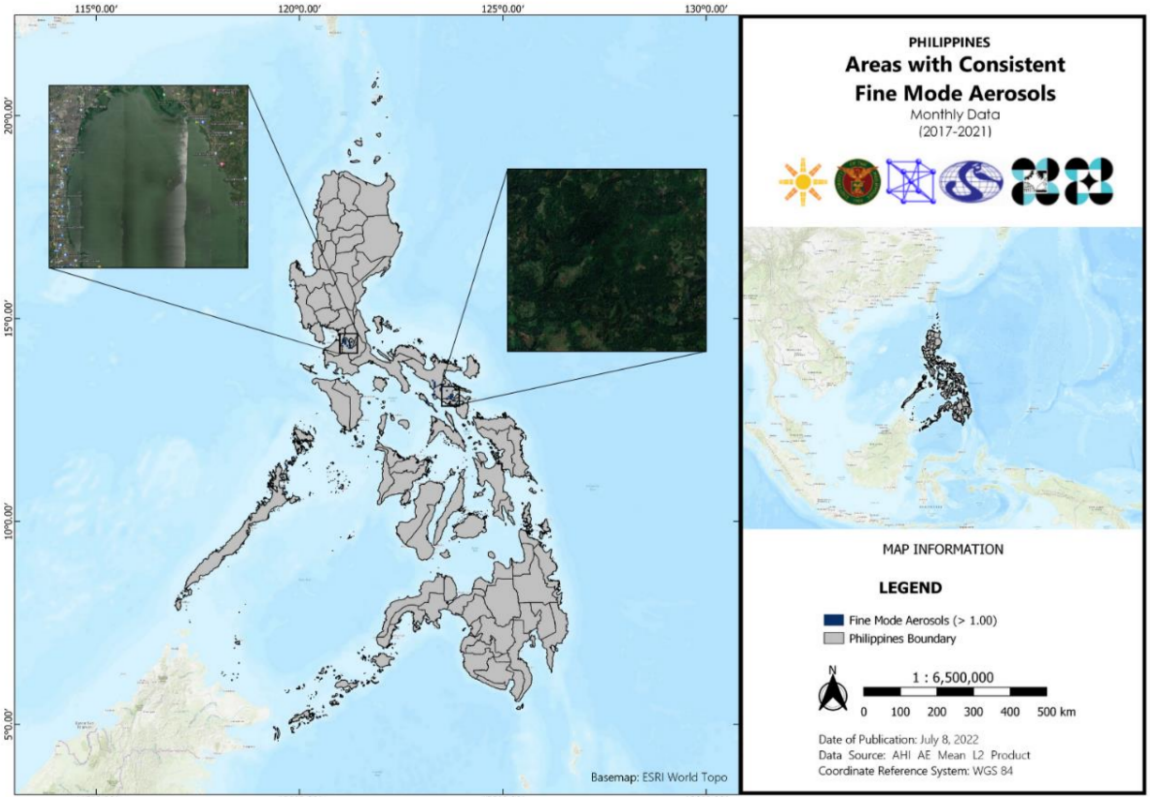

Figure 7. Areas with consistent fine mode aerosols in the Philippines from 2017 to 2021

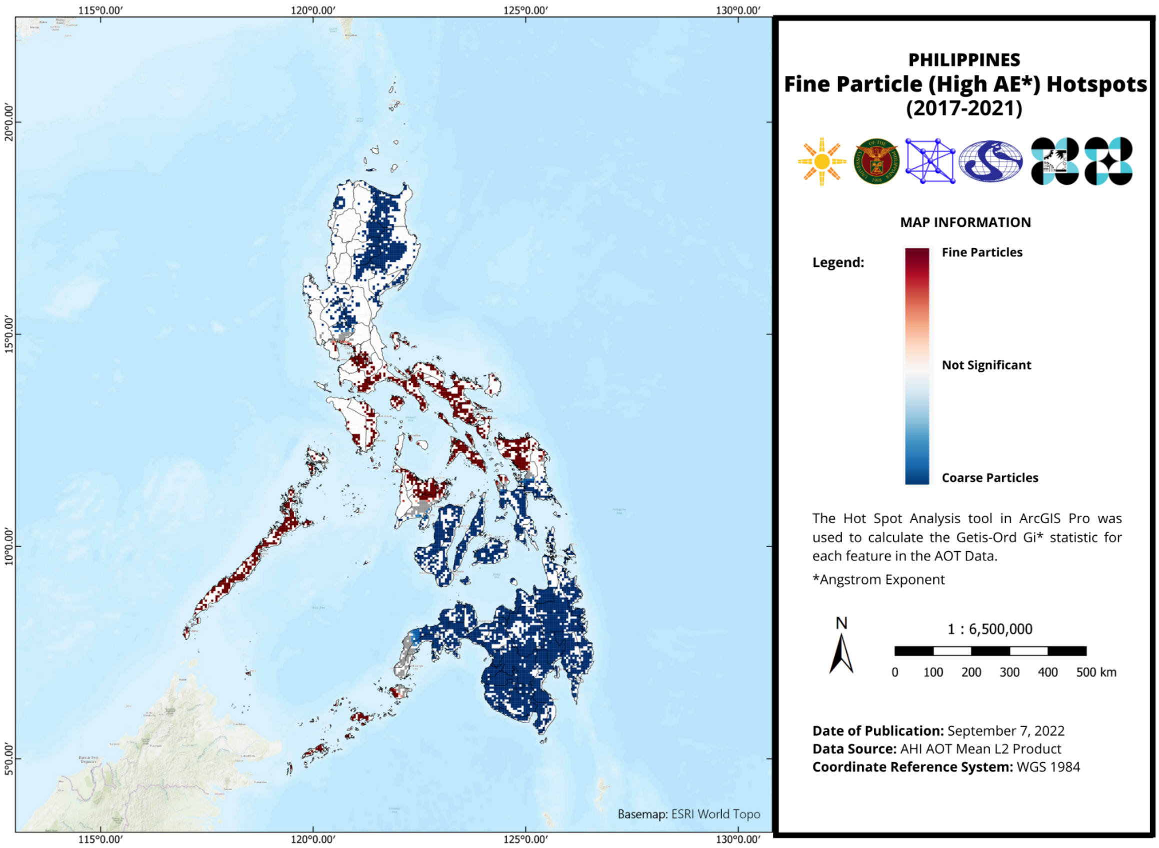

Figure 8. Fine particles (high angstrom exponent) hotspots in the Philippines (2017-2021)

3.3 Mean R_{rgb} Component in the Philippines

AOT and AE values from Himawari-8/9 Aerosol Property data were extracted on selected sites which are evenly distributed across the country. These sites were selected based on the availability of solar irradiation data from existing weather stations both at the solar power plants of the Philippine Department of Energy (DOE) and SolarEdge, and the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) stations. Additionally, other locations were also selected from the centroid of each province to add more data and improve the scatterplot. A five-year timeline from 2017 to 2021 was considered to visualize the distribution of AE and AOT values in the Philippines. This distribution will be the basis for the delineation of the bounding triangle from the AirRGB decomposition method which encloses the aerosol property data points.

While a 10-min temporal resolution of the aerosol property data was initially considered, only the average of the 10-min values was practically needed to visualize the distribution, hence, monthly data was sufficient for calculating the mean of all data from 2017 to 2021. It can be observed from Fig. 9 that AOT and AE (values scaled by 100) values fall within the range of 0 to 2. However, upon computing the average of the dataset, it can be further noticed that the data values are clustered within less than 1 for AE and less than 0.3 for AOT, and mean values of AE and AOT are 0.76 and 0.2, respectively.

From the scatterplot created, the bounding triangle from the AirRGB decomposition method was sketched by following the criteria of the corresponding arbitrary vertices: vertex R for high AE and high AOT, vertex G for high AE and low AOT, and vertex B for low AE and low AOT. The coordinates of these vertices were used in the equation to perform the AirRGB decomposition. The bounding triangle for the dataset considered is shown in Fig. 9.

While each R, G, and B value is needed in the AirRGB decomposition method, this study focuses more on the analysis of the first component (i.e., R_{rgb}) values since the R component is a parameter in the proposed equation for quantifying the combined effects of dust and precipitation on solar PV potential. R component demonstrates scenario of finer dust particle sizes and thicker amount of dust. Fig. 10 shows the range of R_{rgb} values calculated for the Philippines.

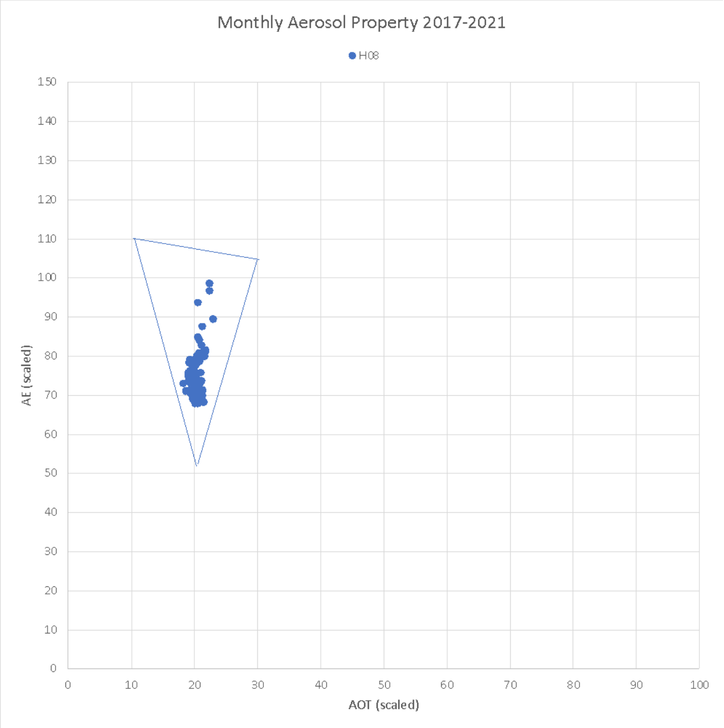

Figure 9. Scatterplot of mean of all monthly AHI-8/9 aerosol property data in the Philippines from 2017 to 2021

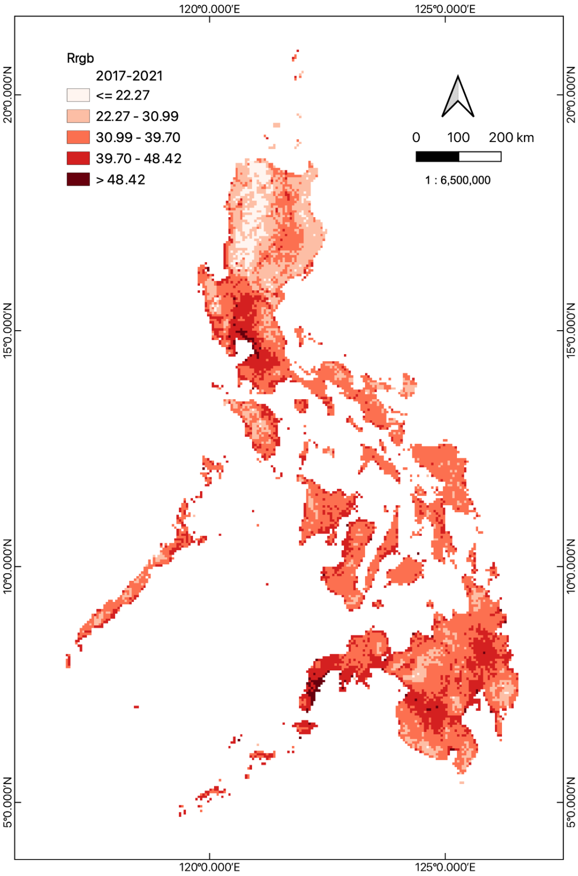

Figure 10. Range of R_{rgb} values in the Philippines considering AHI-8/9 monthly aerosol property data in the AirRGB decomposition method

In solar PV installations, the decrease in solar PV power output (PPV) efficiency due to dust accumulation can be up to 30% (Sayigh, 1978). Assuming no or little precipitation is available as a natural cleaning agent, high R values could indicate high dust deposition values. That is, solar PV systems installed in areas with high R values may be significantly affected by dust.

4. CONCLUSION

This study characterized dust particles in the Philippines in terms of particle size and amount of aerosols using remotely-sensed data estimated using daytime AE and AOT, respectively, derived from AHI-8/9 satellite data. Trend analysis was done on the mean AOT and AE for each month and for the whole timeline (2017-2021), and decomposed using the AirRGB method. Results show that areas with relatively high estimated dust deposition ($0.218 \leq \text{AOT} \leq 0.230$) can be found in Eastern Visayas, Eastern Mindanao, and Western Luzon. Meanwhile, fine aerosol particles ($0.80 \leq \text{AE} \leq 0.93$) are dominant in Northern Luzon and Palawan while coarse aerosol particles ($0.68 \leq \text{AE} \leq 0.70$) are dominant in Mindanao. Moreover, areas in the Philippines that may experience a decrease in solar PV power production due to dust deposition were determined due to high R_{RGB} values. Results from this study can be a useful input in the development of a forecasting model for solar PV output power since dust accumulation on modules must be quantified and considered for its impact on the system's output power. This study demonstrated the novelty of using AHI-8/9 aerosol property product as input to the AirRGB model instead of MODIS data, and its application to the estimation of the combined effects of dust and precipitation on solar PV production. For future work, analyzing the correlation between the RGB scenarios from AirRGB decomposition and socio-economic development can be considered.

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