ASSESSMENT OF SATELLITE AEROSOL OPTICAL DEPTH TO ESTIMATE PARTICULATE MATTER DISTRIBUTION IN VALENCIA CITY

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ABSTRACT

The estimation of exposure to PM_{10} and $PM_{2.5}$ requires the knowledge of surface concentration at high temporal and spatial resolutions. In this paper, the relation between PM10 and $PM_{2.5}$ ground data and MODIS AOD satellite data has been evaluated to determine the concentration of particulate matter in Valencia, Spain. This was done using data from the Valencian Network of Surveillance and Control of Air Pollution and the scientific data set "Optical Depth Land and Ocean" from MODIS Terra and Aqua with 3km of spatial resolution. The linear regression model for PM_{10} provided a regression slope of 25.99 $\mu g.m^{-3}$ and an interception of 12.07 $\mu g.m^{-3}$ (RMSE = 8.61 $\mu g.m^{-3}$), while for $PM_{2.5}$ the slope and interception were 26.87 $\mu g.m^{-3}$ and 5.98 $\mu g.m^{-3}$ (RMSE = 5.5 $\mu g.m^{-3}$).

Index Terms— *AOD, particulate matter, MODIS, air quality, Valencia*

1. INTRODUCTION

Outdoor air pollution is a serious environmental health problem worldwide. Long-term exposure to particulate matter (PM), a mixture of solid and liquid particles smaller than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$) suspended in the air, is related with a number of adverse health effects, including cardiovascular and respiratory diseases, in addition to some cancers [1]. Furthermore, recent studies associate PM with climate change [2].

A major problem in epidemiological studies of health effects is the limited geospatial information on particulate air pollution [3]. Stationary environment monitors leave large uncovered areas which require to be completed with other sources of information [4]. As a result of this need, numerous studies incorporate satellite imagery in the assessment of atmospheric pollutants [5].

The aerosol optical depth (AOD) is the key parameter for measuring the aerosol load in atmospheric column. In order to estimate the surface PM values from space, it is possible to analyze the correlations between the AOD obtained by MODIS and the PM measured at surface [5, 6]. In this work, the relationships between PM_{10} and $PM_{2.5}$ registered in situ and satellite AOD data has been evaluated to determine the concentration of particular matter in Valencia, Spain.

2. MATERIALS AND METHODS

2.1. Study area description

The city of Valencia lies along the Spanish Mediterranean coast on a small alluvial plain, corresponding to a subarid Mediterranean climate. The area is occasionally affected by mineral dust events from Sahara region and biomass burning smoke [7]. Because the spread of the city over the surrounding small towns near it, the urban area has a population of nearly two million, from which only 786,000 live in Valencia [8]. Previous studies in Valencia show a relationship between an increase in black smoke and an increase in the number of emergency admissions for heart disease [9].

Figure 1. Map of Valencia city. The red circles indicate the land monitoring station with their respective names, while the green square indicates the Burjassot AERONET station.

2.2. Monitoring data

Data for hourly PM_{10} and $PM_{2.5}$ concentration was downloaded from the Valencian Network of Surveillance and Control of Air Pollution (http://www.agroambient.gva.es/web/calidad-ambiental). The city of Valencia has 5 monitoring stations, whose distribution is displayed in Figure 1. In order to relate the surface hourly concentrations with the satellite measurements, the closest measured value at the overpassing time of Aqua and Terra satellites was taken, with a maximum difference of 30 minutes. The study period is from 1 January 2008 to 31 December 2016.

2.3. MODIS 3km AOD products and calibration

MODIS products used in this study come from both Terra (MOD04_3k) and Aqua (MYD04_3k) satellites (Level 2, collection 6) with daily global coverage and 3km spatial resolution [10]. MODIS products were obtained from the "Level 1 and Atmosphere Archive and Distribution System" at NASA (https://ladsweb.modaps.eosdis.nasa.gov).

MODIS provides retrievals products of aerosol and cloud properties through a dark target algorithm that makes use of surface reflectance in different wavelength channels over land and over ocean. For this study, the scientific data set (SDS) "Optical Depth Land and Ocean" that combine the algorithm for both surfaces were used [10]. Furthermore, MODIS AOD values with a highest quality assurance (QA = 3) and cloud coverage less than 30% have been used in this work.

In order to validate the AOD obtained by satellite, ground AOD measurements of a sunphotometer from the Aerosol Robotic Network (AERONET) were used. The CIMEL CE318 is a solar photometer that measures direct solar radiation in various spectral channels located at Burjassot (Figure 1). According to the processing level the data is classified into different ranges. In this work, AERONET level 2.0 data was used, which corresponds to data with guaranteed quality, where pre and post-calibrations are taken into account.

For the calibration of MODIS values with AERONET point measurement, a 3.25 km buffer centered on the AERONET site was chosen to coincide with a half-hour AERONET data segment in the time of the satellite overpass [11]. To be comparable with the spectrum setting of MODIS, AERONET AOD records at 500nm were interpolated at 550nm using the equation:

$$\tau_\lambda = \beta\lambda^{-\alpha} \quad (1)$$

where τ_λ is the AOD at the wavelength λ, β is the turbidity coefficient (approximated AOD at a wavelength of 1 μm), and α is the Angstrom exponent. The interpolation was performed using quadratic interpolation in log/log space of the measured AOD at 440, 500, 675, 870 and 1020 nm [11].

2.4. PM-AOD relationship

As a first approach, the correlation of the data series for AOD MODIS and $PM_{2.5}$ and PM_{10} from each land monitoring station was analyzed in detail. The sites that did not show significant Pearson correlation were then discarded and a linear regression model was applied to the AOD and PM_{10} and $PM_{2.5}$ datasets.

All mathematical, graphical and modeling analyses were performed using the statistical software R, while QGIS was used for the maps.

3. RESULTS AND DISCUSSION

3.1. Calibration

The results from the calibration of "Optical Depth Land and Ocean" SDS for MODIS Terra and Aqua suggest that MODIS AOD measurements at the Burjassot site show a congruent relation (Figure 2). The Pearson correlation factors for Terra (0.79, p<0.001) and Aqua (0.84, p<0.001) are consistent to those obtained for the SDS "Optical Depth Land" and "Optical Depth Ocean" with a spatial resolution of 10 km for the same site over a similar period [12].

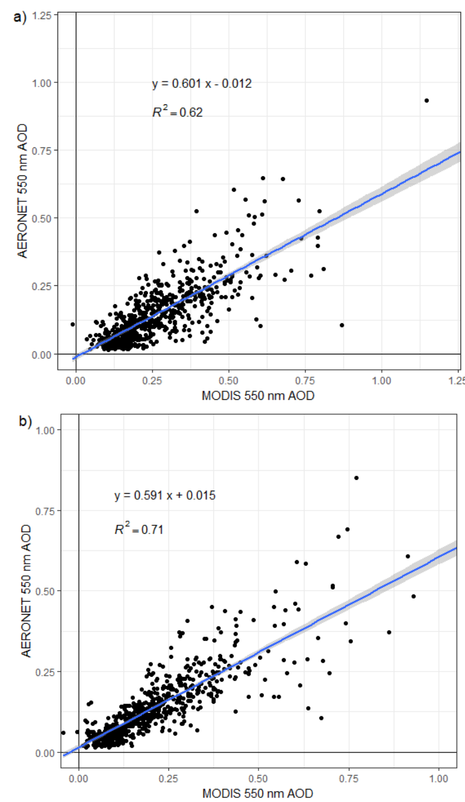

Figure 2. Straight calibration lines for "Optical depth land and ocean" SDS for a- MOD04_3k and b - MYD04_3k. The solid blue line is the result of the linear fitting of the data and the grey area the 95% confidence level interval for predictions.

3.2. Descriptive statistics

A total of 4558 MODIS images were used in this study, 2288 of them belonged to the Terra satellite and 2270 to the Aqua satellite. The descriptive statistics for the fitted models variables are listed in Table 1.

Table 1. Descriptive statistics of PM_{10} and $PM_{2.5}$ concentration ($\mu g.m^{-3}$) and AOD by MODIS Terra and Aqua for the period 2008-2016.

Var.	Min	SD	Max	Mean	Median
PM_{10}	2.00	16.80	239.00	21.07	17.00
$PM_{2.5}$	< LD	9.89	97.00	11.99	10.00
AOD	0.002	0.106	1.103	0.196	0.178

Figure 3 shows the evolution of PM_{10} and $PM_{2.5}$ concentration for the period 2008-2016. Extremely high values can be explained by atypical meteorological conditions, which have a significant effect on air quality. Since the main interest of this work is focused on studying frequent concentrations, the atypical data of concentrations measured for PM_{10} and $PM_{2.5}$ were removed: 52 values of $PM_{10} > 50$ $\mu g.m^{-3}$ and 23 data of $PM_{2.5} > 30$ $\mu g.m^{-3}$.

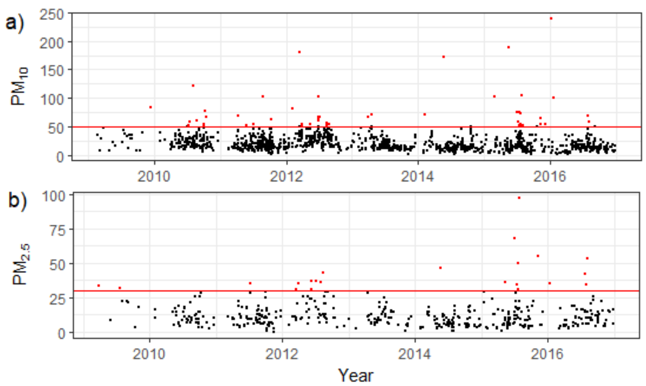

Figure 3. a) PM_{10} and b) $PM_{2.5}$ concentration for the period 2008-2016. Atypical values can be observed on the red line.

The correlation of the data series for PM_{10} and $PM_{2.5}$ with AOD from MODIS Terra and Aqua was 0.25 ($p < 0.001$, n=525) and 0.28 ($p < 0.05$, n=152) for Terra and 0.19 ($p<0.001$, n=753) and 0.36 ($p < 0.001$, n=272) for Aqua. In order to obtain a greater amount of data to validate the linear model, we worked with the measurements of both satellites together where the correlation was 0.22 ($p<0.001$, n=1278) for PM_{10} and 0.30 ($p<0.001$, n=424) for $PM_{2.5}$.

Differences were observed by analyzing the correlation of the data series for AOD MODIS and PM_{10} and $PM_{2.5}$ from each land monitoring station, which are summarized in Table 2. Since the values collected by the satellite are areal and the surface data are at ground level for a point, it is possible to attribute this variance to the influence of fixed sources on monitoring stations, such as the dust of a construction or a street canyon effect.

Discarding Pista de Silla, Vivers and Avd. Francia ground stations, a Pearson correlation was obtained for both satellites of 0.29 ($p<0.001$, n = 763) for PM_{10} and 0.40 ($p<0.001$, n = 297) for $PM_{2.5}$. These values are consistent with the literature on the subject [10]. The correlation coefficients in coastal areas cannot be as high, which seems to be related to the ocean surface wind speed and cloud cover [13]

Table 2. Pearson correlation factor table of AOD MODIS with PM_{10} and $PM_{2.5}$ from each land monitoring station. * $p<0.01$, ** $p < 0.001$, ns = non-significant.

	Pista de Silla	Vivers	Politècnic	Avd. Francia	Molí del Sol
PM_{10}	ns n=376	ns n=76	0.22* n= 183	ns n=63	0.31** n =580
$PM_{2.5}$	ns n=66	ns n =34	0.40** n=83	ns n=27	0.40** n=214

3.3 Surface PM estimated from MODIS AOD

In order to elaborate a linear regression model, 75% of the data used to construct the linear model was randomly selected. Values with an absolute standard error greater than 3 were excluded. The linear regression model for PM_{10} provided a regression slope of 25.99 ± 3.57 $\mu g.m^{-3}$ and an interception of 12.07 ± 0.75 $\mu g.m^{-3}$, while for $PM_{2.5}$ the slope and interception were 26.87 ± 0.89 $\mu g.m^{-3}$ and 5.98 ± 4.49 $\mu g.m^{-3}$ (Figure 4). With the test data set the RMSE calculated for the models developed, were 8.61 $\mu g.m^{-3}$ and 5.5 $\mu g.m^{-3}$ for PM_{10} and $PM_{2.5}$ respectively.

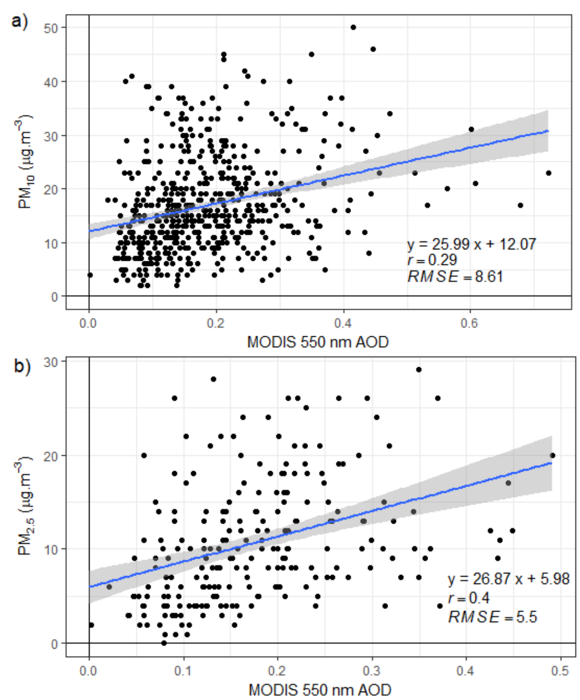

Figure 4. Comparison between AOD from MODIS 3km (MOD04_3k + MYD04_3k) and a) PM_{10} b) $PM_{2.5}$

Bearing in mind that the model fits best for $PM_{2.5}$, it was decided to use this variable for the elaboration of a daily average map for the city of Valencia. The modeled values can be seen in Figure 5. The highest concentrations are found in the central and southeastern part of the study area. It would be interesting to better understand this phenomenon, analyze the temporal behavior of the monitoring stations discarded in this study.

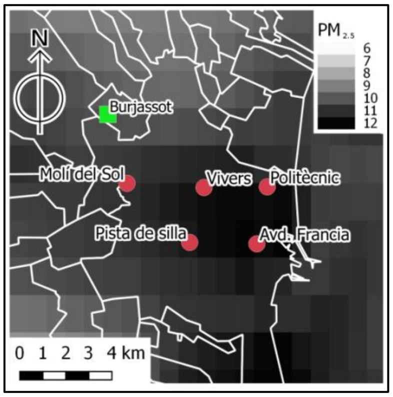

Figure 5. Mean daily $PM_{2.5}$ concentration map in Valencia, Spain, for the period 2008-2016. Units: $\mu g.m^{-3}$

4. CONCLUSION

The mean daily PM concentration of soil in Valencia, Spain, for the period 2008-2016 was estimated using satellite remote sensing data. For this purpose, a linear model was built with the AOD measurements of the MODIS sensor on board Aqua and Terra satellites. The calibration of the SDS "Optical Depth Land and Ocean" for both satellites was considered acceptable in the study area, and equally consistent than reported in the literature for other SDSs [10].

Assessing the linear regression model between AOD and PM, a low adjustment was observed. Limited variability of the measured PM concentrations in a small study area is one possible explanation. As a next step, it remains to study the incorporation of other descriptive variables to improve the results, looking at the possibility of working with multivariable models and incorporating random effects in mixed models.

5. REFERENCES

[1] World Health Organization, Ambient air pollution: A global assessment of exposure and burden of disease. ISBN: 9789241511353. (2016).

[2] Tai, A., PK, L. J. Mickley, and D. J. Jacob. "Correlations between fine particulate matter ($PM_{2.5}$) and meteorological variables in the United States: Implications for the sensitivity of $PM_{2.5}$ to climate change." *Atmospheric Environment* 44.32 (2010): 3976-3984.

[3] Just, AC., R. O. Wright, J. Schwartz, B. A. Coull, A. A. Baccarelli, M. M. Tellez-Rojo, E. Moody, Y. Wang, A. Lyapustin and I. Klooget. "Using high-resolution satellite aerosol optical depth to estimate daily $PM_{2.5}$ geographical distribution in Mexico City." *Environmental science & technology* 49.14 (2015): 8576-8584.

[4] Hu, X., Waller, L. A., Lyapustin, A., Wang, Y., and Liu, Y. "10-year spatial and temporal trends of $PM_{2.5}$ concentrations in the southeastern US estimated using high-resolution satellite data." *Atmospheric Chemistry and Physics* 14.12 (2014): 6301-6314.

[5] Duncan, B. N., A. I. Prados, L. N. Lamsal, Y. Liu, D. G. Streets, P. Gupta, E. Hilsenrath, R. A. Kahn, J. E. Nielsen, A. J. Beyersdorf, S. P. Burton, A. M. Fiore, J. Fishman, D. K. Henze, C. A. Hostetler, N. A. Krotkov, P. Lee, M. Lin, S. Pawson, G. Pfister, K. E. Pickering, R. B. Pierce, Y. Yoshida and L. D. Ziemba. "Satellite data of atmospheric pollution for US air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid." *Atmospheric environment* 94 (2014): 647-662.

[6] Van Donkelaar, A., Martin, R. V., Brauer, M., and Boys, B. L. "Use of satellite observations for long-term exposure assessment of global concentrations of fine particulate matter." *Environmental health perspectives* 123.2 (2015): 135.

[7] Díaz, J., Linares, C., Carmona, R., Russo, A., Ortiz, C., Salvador, P., and Trigo, R. M. "Saharan dust intrusions in Spain: Health impacts and associated synoptic conditions." *Environmental Research* 156 (2017): 455-467.

[8] Segura, S., Estellés, V., Utrillas, M. P., and Martínez-Lozano, J. A. "Long term analysis of the columnar and surface aerosol relationship at an urban European coastal site." *Atmospheric Environment* 167 (2017): 309-322.

[9] Ballester, F., J. M. Tenias, and S. Perez-Hoyos. "Air pollution and emergency hospital admissions for cardiovascular diseases in Valencia, Spain." *Journal of Epidemiology & Community Health* 55.1 (2001): 57-65.

[10] Remer, L. A., Mattoo, S., Levy, R. C., and Munchak, L. A. "MODIS 3km aerosol product: algorithm and global perspective." *Atmospheric Measurement Techniques* 6.7 (2013): 1829.

[11] Levy, R, and C. Hsu. "MODIS Atmosphere L2 Aerosol Product, NASA MODIS Adaptive Processing System." *Goddard Space Flight Center, USA, doi* 10 (2015).

[12] Segura, S., Estellés, V., Esteve, A. R., Tena, F., Utrillas, M. P., and Martínez-Lozano, J. A. "Assessment and application of MODIS ocean and land algorithms for the characterization of aerosol properties over a Mediterranean coastal site." *Atmospheric Research* 157 (2015): 66-73.

[13] Guo, J., F. Xia, Y. Zhang, H. Liu, J. Li, M. Lou, J. He, Y. Yan, F. Wang, M. Min and P. Zhai. "Impact of diurnal variability and meteorological factors on the $PM_{2.5}$-AOD relationship: Implications for $PM_{2.5}$ remote sensing." *Environmental Pollution* 221 (2017): 94-104.