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Spatio-Temporal Variations in the Associations between Hourly $PM_{2.5}$ and Aerosol Optical Depth (AOD) from MODIS Sensors on Terra and Aqua*

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Abstract

Recent studies have explored the relationship between aerosol optical depth (AOD) measurements by satellite sensors and concentrations of particulate matter with aerodynamic diameters less than 2.5 μm ($PM_{2.5}$). However, relatively little is known about spatial and temporal patterns in this relationship across the contiguous United States. In this study, we investigated the relationship between US Environmental Protection Agency estimates of $PM_{2.5}$ concentrations and Moderate Resolution Imaging Spectroradiometer (MODIS) AOD measurements provided by two NASA satellites (Terra and Aqua) across the contiguous United States during 2005. We found that the combined use of both satellite sensors provided more AOD coverage than the use of either satellite sensor alone, that the correlation between AOD measurements and $PM_{2.5}$ concentrations varied substantially by geographic location, and that this correlation was stronger in the summer and fall than that in the winter and spring.

Keywords

Aerosol Optical Depth; Moderate Resolution Imaging Spectroradiometer; Terra; Aqua; $PM_{2.5}$; Contiguous United States

1. introduction

Particulate matter less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) is a category of air pollutant that consists of solid particles and liquid droplets in organic and inorganic substances. The major components of $PM_{2.5}$ are sulfate, nitrates, ammonia, sodium chloride, carbon, mineral dust, and water [1]. According to the US Environmental Protection Agency

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(EPA) [2], the major components of $PM_{2.5}$ in the eastern United States are sulfate, organic carbon, and ammonia; in the western United States, organic carbon, nitrate, elemental carbon, and sulfate constitute approximately 70 % of $PM_{2.5}$. $PM_{2.5}$ can be emitted as the result of natural processes such as forest fires as well as from anthropogenic sources such as power plants, factories, and vehicles.

$PM_{2.5}$ is small enough to be inhaled through the throat and nose, and exposure to $PM_{2.5}$ has been associated with increased risk for respiratory and cardiovascular diseases and death [3-6]. Because of these adverse health effects, federal, state, and local government agencies across the continental United States have established a ground-level $PM_{2.5}$ monitoring network with approximately 1500 sampling sites. However, because the distance between many monitoring sites makes it difficult to construct a continuous map of $PM_{2.5}$ concentrations for the entire country [7,8], aerosol optical depth (AOD) measurements by remote sensing satellites have been used to supplement $PM_{2.5}$ data [9,10].

In recent years, AOD data from Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard two satellites (Terra and Aqua) operated by the US National Aeronautics and Space Administration (NASA) have been used to estimate the relationship between AOD and $PM_{2.5}$ concentrations [11]. Although researchers have explored the relationship between ground-measured $PM_{2.5}$ concentrations and MODIS AOD data, few have compared estimates of this relationship based on combined data from both satellites with estimates based on data from each satellite alone. In this study, we report the spatial coverage and AOD-$PM_{2.5}$ association of two different approaches in conjunction with ground-based monitoring stations, which may provide insights for national research into the effects of fine particulate matter on human health.

2. methods

2.1. Description of Data

We analyzed daily MODIS AOD data collected by the Terra and Aqua satellites during 2005 because that was the year with the highest average data coverage per day (27%). The Level 2 MODIS science data include many parameters associated with location and time, solar and viewing geometry, science, cloud mask and quality assurance [12]. Optical Depth Land and Ocean (ODLO) is a science parameter that includes AOD values at 0.55 μm for both ocean and land.

We downloaded Terra and Aqua daily ODLO measurements for 2005 (Collection 5.1) from NASA's Level 1 and Atmospheric Archive and Distribution System (LAADS) as Level-2 AOD data sets [12]. The MOD04 is the first data set to monitor global AOD over land [13]. The Level-2 AOD data are derived from Level-1 products at a $10 \times 10\ km^2$ nominal spatial resolution. The AOD values of the ODLO parameter are stored as 2-byte integers, which require a conversion procedure to obtain real physical AOD values using the equation with a scale factor (a) and offset value (b).

Physical AOD values of ODLO parameter = $a \times (\text{integer value} - b)$ where a is equal to 0.001 and b is equal to 0 (personal communication with Bill Ridgway in NASA, August 19, 2009). AOD values generally range from 0 to 5, with values greater than 1 being associated with heavy haze [7, 13].

We obtained hourly ground-level $PM_{2.5}$ concentrations across the contiguous US states from EPA's Air Quality System (AQS), which collects ambient air quality data from state, local, and tribal agencies [14]. All AQS $PM_{2.5}$ data are collected in accordance with EPA-approved reference and equivalent sampling methods, and all monitors in the contiguous US are included in the AQS.

We also obtained monitor site information from the AQS, including the category of land use near the sites (agricultural, commercial, industrial, residential, or other), the population density category of site areas (rural, suburban, or urban), and the latitude and longitude of the sites. We adopted an exact pixel-to-point match procedure to extract AOD values. All the points, representing each ground-level station, were overlaid on the MODIS ODLO parameter imagery to derive an AOD value for each pixel where a monitoring station is located by its latitude and longitude. The linked data set with both daily AOD and hourly $PM_{2.5}$ has 66,768 records (36,587 for Terra and 30,181 for Aqua). The monthly- and seasonal-average AOD values of individual ground stations were derived from the daily AOD data set.

2.2. Statistical Analyses

We used a linear mixed model with a site-level random effect to evaluate the correlation between AOD measurements and hourly $PM_{2.5}$ measurements in the District of Columbia and all contiguous states except Vermont, Wisconsin, and West Virginia (which had no matched AOD and $PM_{2.5}$ site-level data). Among states included in our study, the sample sizes of $PM_{2.5}$ measurement sites for which matching AOD data were available ranged from 116 in Wyoming to 7232 in California. For each state, the model had the following form:

Hourly $PM_{2.5} \sim$ Land Use + Site Setting + Season + AOD + Site (random effect).

Land use categories were agriculture, commercial, industrial, residential (reference) and “other”; site setting (*i.e.*, population density) categories were rural, suburban, and urban (reference); season categories were spring, summer, fall, and winter (reference). All models also adjusted for site-level random effects of unobserved or unmeasured factors associated with $PM_{2.5}$ measurements. We used regression coefficients associated with AOD to evaluate the direction and magnitude of the association between AOD and $PM_{2.5}$ and considered p-values <0.05 to be indicative of a statistically significant association between AOD and $PM_{2.5}$ concentrations. All the models were implemented in SAS 9.3 using Proc MIXED.

3. Results

3.1. AOD Coverage

We found that the mean number of days with valid AOD data was higher with use of the combined Terra and Aqua datasets (117) than with use of either the Terra dataset (91) or the Aqua dataset (78) alone (Figure 1). Terra and Aqua provided similar AOD coverage in the western and central regions of country; however, Terra provided better coverage in the eastern region. We also found that the use of data from both satellites generally resulted in more valid observations than the use of data from either satellite alone (Figure 2), although the overall increase in spatial coverage with both satellites was primarily attributable to greater coverage during winter. During the other three seasons, the use of data from both satellites resulted in coverage little different from that with each satellite alone (Figure 2(b)).

As shown in Figures 3(a) and (b), more sufficient number of valid-AOD days at each monitoring station was generally obtained with both Terra and Aqua, compared with their individual AODs. We also observed that integrated AODs with Terra and Aqua provide more sufficient observations with valid monthly-average AODs across all ground monitoring stations, as depicted in Figures 3(c) and (d).

3.2. Relationship between AOD Measurements and PM2.5 Concentrations

Overall, we found that AOD measurements were significantly associated with $PM_{2.5}$, concentrations in all states except Colorado, although the strength of this association varied substantially by state, and the association was generally stronger in eastern states than in western states (Table 1 and Figure 4). State-level regression coefficients for AOD ranged from 1.93 in Colorado to 46.0 in Nebraska.

We also found a significantly greater correlation between AOD measurements and $PM_{2.5}$ concentrations during the summer and fall than during the winter and spring in all states except Montana, Nebraska, and Wyoming. The reason we found no significant seasonal effects in these three states was largely because of a lack of data for the winter and spring: Montana had only 6 records for the spring and winter, Nebraska had only 4, and Wyoming had only 2.

4. Discussion

Our results showed that the combined use of Terra and Aqua AOD data resulted in more days with valid AOD data than the use of AOD data from either satellite alone. Paciorek and Liu (2009) had argued that a lack of AOD data would be a major problem if AOD data from satellites were used as a proxy for $PM_{2.5}$ concentrations [8]. Our results indicated that this problem could at least be reduced with the use of data from multiple satellites.

We also found that the linear mixed model fully controlled for site-specific effects and seasonal influences on the relationship between AOD measurements and $PM_{2.5}$ concentrations. Our findings confirmed a significant linear association between AOD measurements and $PM_{2.5}$ concentrations, although the magnitude of this association was substantially weaker in the western region of the country than that in the eastern region. The relatively weak association in the west may be attributable to less accurate AOD measurements caused by high surface reflectance from rocky and desert areas [15].

Despite these inaccuracies, we anticipate that MODIS AOD data can be used as a surrogate for ground-level $PM_{2.5}$ concentrations in research requiring estimates of $PM_{2.5}$ exposure and that AOD data will be especially useful in studies of chronic disease outcomes during summer and fall and in geographic areas where the correlation between MODIS AOD data and $PM_{2.5}$ concentrations is particularly high [3-6]. Because of this potential usefulness of AOD data in public health studies, attempts should be made to provide more comprehensive AOD coverage. Until such comprehensive coverage is available, the use of models, such as the Land Use Regression and Community Multiscale Air Quality model, in conjunction with AOD data, may be one way to overcome a lack of AOD coverage and ensure adequate spatial continuity of AOD estimates for use in public health research [16, 17]. In a follow-up study, we plan to explore the relationship between ground-measured $PM_{2.5}$ concentrations and AOD values at US County or ZIP Code levels because many nationwide health surveys have used these levels as geographic units of analysis.

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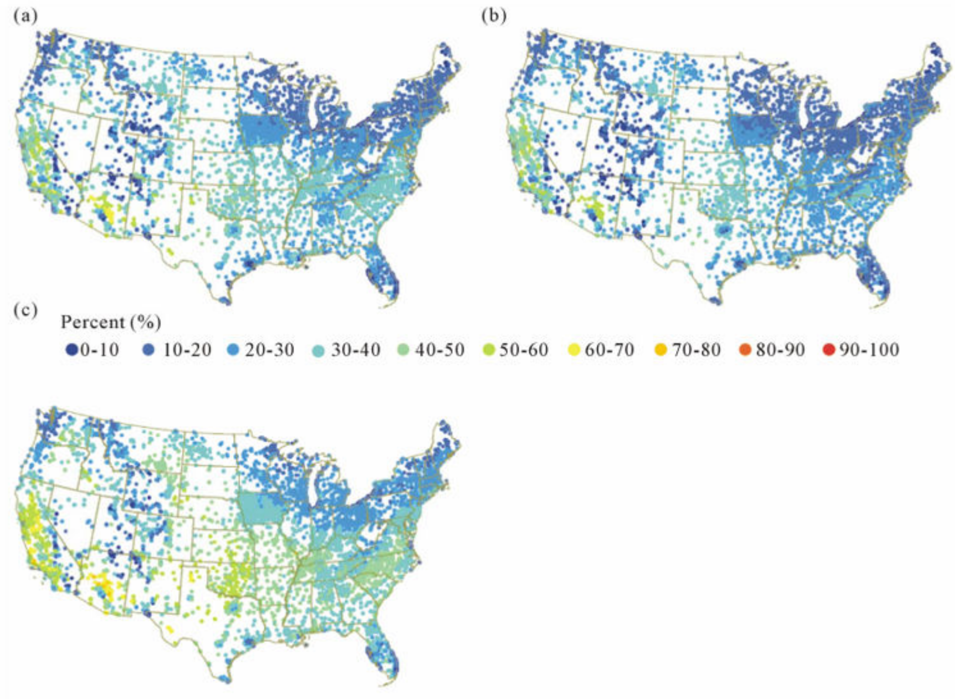

Figure 1.
Map showing percentage of days in which valid AOD data were collected at $PM_{2.5}$ monitoring sites by (a) Terra only, (b) Aqua only, and (c) Terra and Aqua.

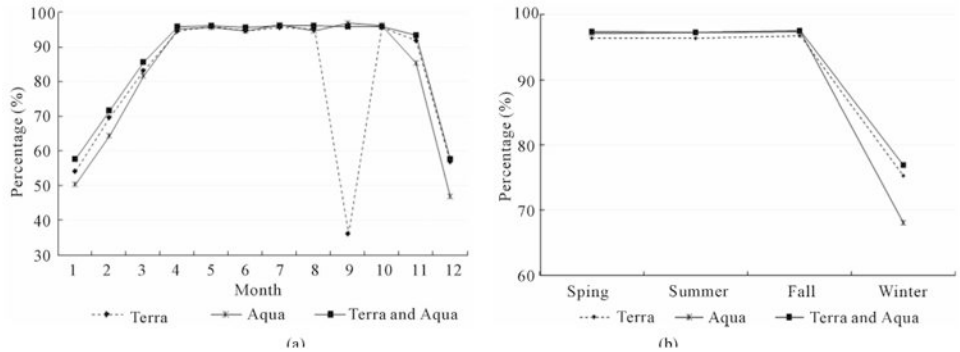

Figure 2.
Percentages of valid AODs for Terra only, Aqua only, and Terra and Aqua: (a) monthly AODs and (b) seasonal AODs.

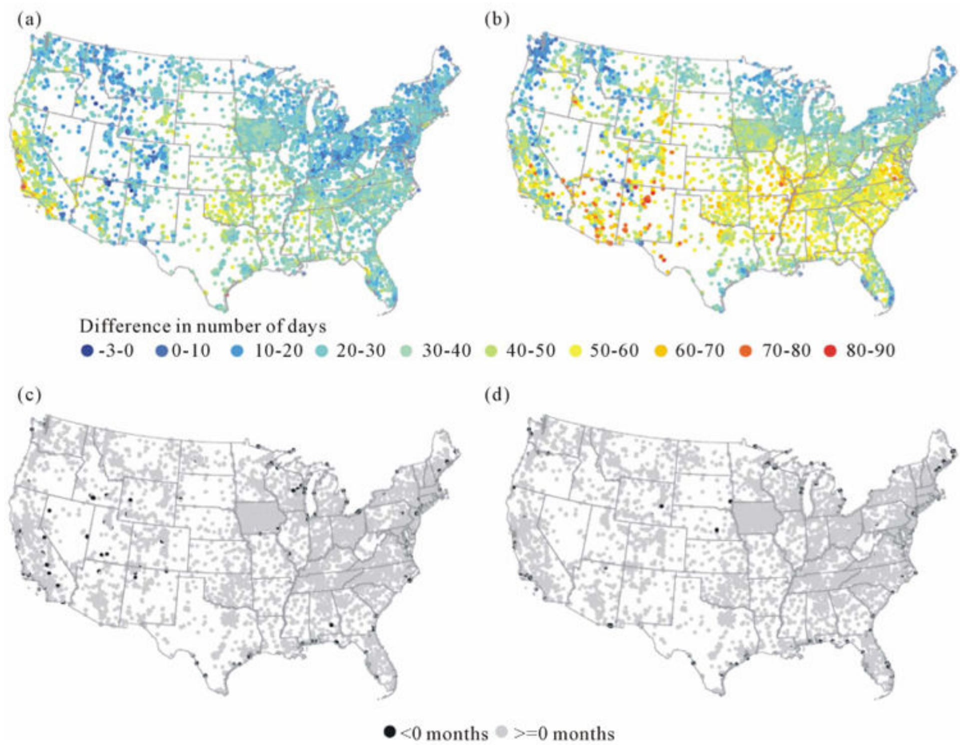

Figure 3.
Spatial distribution of differences in days and months with valid AODs at each station: (a) difference in number of days between combined Terra with Aqua and Terra alone, (b) difference in number of days between combined Terra with Aqua and only Aqua alone, (c) difference in number of months between combined Terra with Aqua and Terra alone, and (d) difference in number of months between combined Terra with Aqua and only Aqua alone.

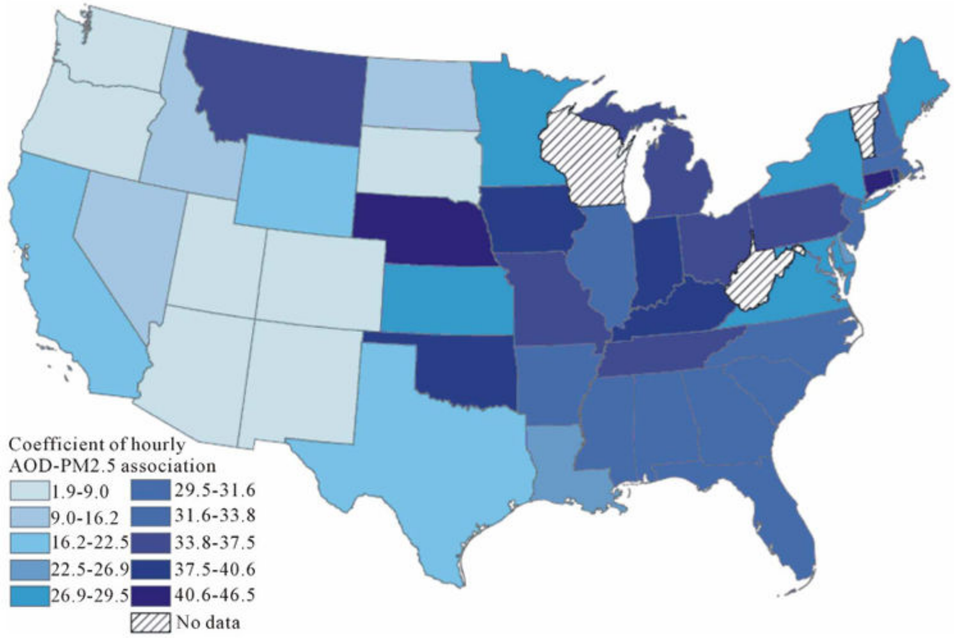

Figure 4.

Coefficients of hourly AOD-PM2.5 association by state.

Table 1

State-specific regression coefficients associated with satellite measurements of AOD.

State	Co-efficient	SE	*P* value	Sample Size (N)	State	Co-efficient	SE	*P* value	Sample Size (N)
AL	32.7	0.9	<0.0001	1975	NE	46.5	4.9	<0.0001	126
AZ	6.1	1.2	<0.0001	1103	NV	14.4	1.6	<0.0001	543
AR	31.3	1.4	<0.0001	847	NH	31.6	2.0	<0.0001	314
CA	20.7	1.0	<0.0001	7232	NJ	31.9	1.8	<0.0001	593
CO	1.9	1.8	0.2873	454	NM	8.0	1.3	<0.0001	1803
CT	42.9	1.8	<0.0001	743	NY	29.0	0.7	<0.0001	2924
DE	26.9	1.9	<0.0001	309	NC	32.2	0.8	<0.0001	3057
DC	29.0	2.6	<0.0001	171	ND	16.2	1.1	<0.0001	1423
FL	31.3	1.1	<0.0001	1654	OH	35.6	1.2	<0.0001	1307
GA	33.8	1.1	<0.0001	2354	OK	38.3	2.9	<0.0001	240
ID	16.0	1.3	<0.0001	4005	OR	5.9	0.7	<0.0001	5447
IL	30.3	1.1	<0.0001	1331	PA	37.5	1.6	<0.0001	939
IN	40.6	1.6	<0.0001	1075	RI	38.6	1.6	<0.0001	575
IA	39.6	1.4	<0.0001	978	SC	30.5	1.3	<0.0001	2038
KS	28.0	2.3	<0.0001	439	SD	9.0	2.2	<0.0001	589
KY	40.3	1.7	<0.0001	735	TN	36.1	1.0	<0.0001	2295
LA	25.2	1.5	<0.0001	1377	TX	22.5	0.5	<0.0001	6131
ME	28.2	1.7	<0.0001	448	UT	6.2	2.4	0.0104	369
MD	29.5	1.9	<0.0001	380	VA	29.1	1.3	<0.0001	795
MA	31.9	1.2	<0.0001	985	WA	8.3	0.5	<0.0001	5596
MI	35.0	2.6	<0.0001	210	WY	22.4	4.0	<0.0001	116
MN	28.3	1.2	<0.0001	1737					
MS	31.3	1.3	<0.0001	837					
MO	36.9	2.6	<0.0001	180					
MT	36.2	4.2	<0.0001	197	US	24.2	0.15	<0.0001	66,768