Intercomparison between Satellite-Derived Aerosol Optical Thickness and $PM_{2.5}$ Mass.

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Abstract

We explore the relationship between column aerosol optical thickness (AOT) derived from the Moderate Resolution Imaging SpectroRadiometer (MODIS) on the Terra/Aqua satellites and hourly fine particulate mass ($PM_{2.5}$) measured at the surface at seven locations in Jefferson county, Alabama for 2002. Although the MODIS AOT is a column value and the $PM_{2.5}$ mass is representative of near-surface conditions, results indicate that there is a good correlation between the satellite-derived AOT and $PM_{2.5}$ (linear correlation coefficient, R=0.7) indicating that most of the aerosols are in the lower boundary layer. The maximum $PM_{2.5}$ and AOT values occur during the summer months due to enhanced photolysis, while the $PM_{2.5}$ has a distinct diurnal signature with maxima in the early morning (6:00~8:00AM) due to increased traffic flow and restricted mixing depths during these hours. Using simple empirical linear relationships derived between the MODIS AOT and 24hr mean $PM_{2.5}$ we show that the MODIS AOT can be used quantitatively to estimate air quality categories (e.g., good, moderate, unhealthy for special groups, unhealthy and hazardous) as defined by the U.S. Environmental Protection Agency (EPA) with an accuracy of more than 90% in cloud-free conditions for large spatial scales. Vertical profiles of aerosol concentration from current ground-based or future space-borne lidars such as the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and aerosol hygroscopiscity measurements will further enhance our capability to effectively use satellite data for air quality studies. A concerted effort is also needed to create a data base of high temporal resolution $PM_{2.5}$ data sets to further explore these relationships.

1. Introduction

Particular matter (PM), or aerosol, is the general term used for a mixture of solid particles and liquid droplets found in the atmosphere. Monitoring natural (dust and volcanic ash) and anthropogenic aerosols (biomass burning smoke, industrial pollution) has gained renewed attention because they influence cloud properties, alter the radiation budget of the earth-atmosphere system, affect atmospheric circulation patterns and cause changes in surface temperature and precipitation [see *Kaufman et al., 2002* and references there in]. Aerosols also reduce visibility and induce respiratory diseases when sub-micron sized aerosols penetrate the lungs thereby affecting air quality and health [*Krewski et al.,* 2000]. Increased exposure to particular matter with aerodynamic diameters[1] less than 2.5μm ($PM_{2.5}$) can cause lung and respiratory diseases and even premature death [*Wilson and Spengler* ,1996].

The Environment Protection Agency (EPA) evaluates air quality by comparing 24-hour averages of the measured dry particulate mass with the National Ambient Air Quality Standard (NAAQS). The ratio of particulate mass between the measured and NAAQS (expressed as a percent of NAAQS) is called air quality index (AQI) and can range from nearly zero in a very clean atmosphere to about 500 in very hazy conditions. The EPA further classifies air quality into five broad categories based on the computed AQI values [good (AQI<50; corresponding 24hourly mean $PM_{2.5}$ 0~15.4μgm^{-3}), moderate (AQI:51~100; $PM_{2.5}$:15.5~40.4μgm^{-3}), unhealthy for certain groups such as children or people with asthma (AQI 101~150; $PM_{2.5}$:40.5~65.4μgm^{-3}), unhealthy (AQI 151~200; $PM_{2.5}$:65.5~150.4μgm^{-3}), very unhealthy (201-300; $PM_{2.5}$:150.5~250.4μgm^{-3}), and hazardous (AQI:301-500; $PM_{2.5}$:250.5~350.4μgm^{-3} for AQI 301~400; $PM_{2.5}$ 350.5~500.4μgm^{-3} for AQI 401~500). Also, for healthy conditions, the 24-hour averaged $PM_{2.5}$ concentration must be less than 65.5μgm^{-3}

Several ground measurement networks are currently in operation to monitor aerosols for different purposes including the Aerosol Robotic Network (AERONET) [*Holben et al.*, 2001], the Interagency Monitoring of Protected Visual Environment (IMPROVE) network [*Malm et al.*, 1994], and about 4000

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[1] Aerodynamic diameter (d_a) is the diameter of a unit-density sphere having the same gravitational settling velocity as the particle (with diameter d_p) being measured. Approximately, $d_a \cong (\rho_p)^{0.5} d_p$, where ρ_p is the density of the particle.

observation sites that forms the EPA's State and Local Air Monitoring Stations (SLAMS). Although these point measurements are well calibrated, and have tremendous potential for examining aerosol-related climate and air quality issues, they are limited in space, and are inadequate to provide health alerts on large spatial scales, especially when the pollution comes from sources outside United States. Examples of transported aerosols include smoke from Central American biomass burning fires to southern U. S. [*Peppler et al., 2000*] and dust aerosols from the Saharan desert to eastern U.S. [*Propero*, 1999]. These episodic events could also transport disease-causing organisms with serious ecological consequences [*Shinn*, 2000].

Compared to ground measurements, satellite imagery, due to their large spatial coverage and reliable repeated measurements, provide another important tool to monitor aerosols and their transport patterns. Most aerosols in the atmosphere, due to their submicron sizes (except large dust and sea salt particles), are very efficient at scattering solar radiation and therefore, the visible portion of the electromagnetic spectrum is often used to retrieve aerosol information from satellite sensors [*Kaufman et al.*, 2002]. One important and common parameter that is retrieved from satellite sensors is aerosol optical thickness (AOT), which is a measure of aerosol extinction of atmospheric radiative transfer. *Kaufman and Fraser* [1983] expressed AOT (also denoted by τ) as:

$$\tau = \int_0^{TOA} \beta_{ext}(z)dz = \beta_{ext}(0) \times H_{eff} = f(rh) \times \mathrm{Q}_{\mathrm{dext}}(0) \times \mathrm{m}_{\mathrm{daer}}(0) \times \mathrm{H}_{\mathrm{eff}} \qquad (1)$$

$$H_{\mathrm{eff}} = \int_0^{\mathrm{TOA}} \beta_{\mathrm{exi}}(z)\, dz \Big/ \beta_{ext}(0) \qquad (2)$$

where TOA is top of atmosphere, β_{ext} is the volume extinction efficiency (m^{-1}), H_{eff} is effective scale height, $Q_{dext}(0)$ is the mass extinction efficiency (m^2g^{-1}) of dry particles at the surface, $m_{daer}(0)$ is the mass concentration (gm^{-3}) of dry aerosol particles at the surface, and *f(rh)* is a hygroscopic growth factor that considers the change of aerosol extinction efficiencies due to the solubility (hygroscopicity) of aerosols. For simplicity, wavelength dependence is not shown in the above equations. Generally, a higher AOT value indicates higher column aerosol loading and therefore low visibility. However, such positive correlations could vary depending upon the vertical distribution of aerosol mass concentration or β_{ext} [*Bergin et al.*, 2001] as shown in equation (1).

Several studies have attempted to use the AOT retrieved from satellite imagery to monitor aerosol loading and the associated air quality effects [*Kaufman and Fraser*, 1983; *Fraser et al.*, 1984]. Until recently, the use of satellite remote sensing data for air quality studies has been hampered largely due inadequate spatial, radiometric and spectral resolutions [*King et al.,* 1999]. However new data sets from the recently launched MODIS (on Terra and Aqua satellites) provide an unprecedented opportunity to monitor aerosol events and examine the role of aerosols in the earth-atmosphere system [*Kaufman et al.*, 2002]. The Terra and Aqua are both polar-orbiting satellites, with equatorial crossing times of 10:30A.M and 1:30 P.M., respectively. For a given area, the MODIS instruments provide two daytime observations, one during the morning (from Terra) and one in the afternoon (from Aqua). While several studies have applied the MODIS AOT to study the aerosol radiative forcing [e.g., *Christopher and Zhang*, 2002], the application of the MODIS AOT product for air quality studies is still largely unexplored. This paper will explore the potential of using the MODIS AOT product for air quality studies. A comparison of MODIS AOT with $PM_{2.5}$ mass is presented, followed by a discussion of the uncertainties in this approach and recommendations for further research.

2. Data and Methods

The data used in this study includes the MODIS (version 4-Level 2), aerosol product, and hourly particular matter data collected at seven locations in Jefferson County, AL (Figure 1) by the Jefferson County department of Health. The three major power plants in the area are also shown in triangles. At the top of figure 1 is the seasonal variation of $PM_{2.5}$ for the seven stations indicating large values during the summer months for all seven stations with slightly larger values for locations in the middle of the city. The $PM_{2.5}$ is measured using the Tapered-Element Oscillating Microbalance (TEOM) instrument (Rupprecht & Patashnick Co., Inc) that is widely utilized by the United States EPA agency for continuous monitoring of aerosols. The accuracy of these measurements is $\pm 5 \mu g m^{-3}$ for 10 minute-averaged data and

±1.5 μgm^{-3} for hourly averages. Only hourly averaged $PM_{2.5}$ data is available for these sites. The MODIS aerosol product is at 10km spatial resolution and contains aerosol characterization parameters such as aerosol optical thickness derived from two independent algorithms for retrievals over ocean and land, respectively [*Remer et al.,* 2002 and references there in]. When compared against ground-based AERONET measurements the MODIS AOT values are within uncertainty levels of ±0.03 ±0.05AOT over ocean [*Remer et al.*, 2002] and ±0.05±0.20 AOT over land [*Chu et al.*, 2002]. In this study, AOT at 0.55μm retrieved from both Terra and Aqua are used[2].

To compare the MODIS AOT with $PM_{2.5}$, a suitable spatio-temporal window size for the collocation must be carefully considered. Since the $PM_{2.5}$ measurements have a temporal resolution of 1 hour; for each day, we first find two continuous time periods t and $t+1$ so that the MODIS overpass is between these two observation times. Then we average the $PM_{2.5}$ at t and $t+1$ and compare this value with the MODIS AOT. In most cases, t is 10:00 a.m. for Terra and 1:00 p.m. for Aqua. Since all $PM_{2.5}$ measurements are located in one county and the distance between these sites are within 50km, we compared the $PM_{2.5}$ mass with the MODIS pixel that is centered over the observation site. During the comparison, potential cloud contamination of a pixel (i.e., centered at the PM observation site) is evaluated based on the AOT availability in a group of 3X3 pixels centered at that pixel. Only the pixel whose surrounding eight pixels have valid AOT values are considered in the comparison, thereby reducing the possibility of using the AOT retrieved near the cloud edges [*Chu et al.*, 2002].

3. Results and Discussion

A haze event in 2002 is first selected to illustrate the spatial distribution of AOT from the MODIS data (Figure 2a). During September 11~14, 2002, the air quality in Texas was classified as unhealthy due to a large haze event[3] that was observed throughout the southern United Stated including eastern Texas,

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[2] Note that Aqua was launched in April, 2002, and data is only available after June 26, 2002.

[3] This haze event is well documented by the Texas Natural Resources Conservation Commission (http://www.tnrcc.state.tx.us/updated/air/monops/airpollevents/2002/event2002-09-11txe.html).

Mississippi, Alabama, Georgia and part of southern Carolina. A combination of a high pressure system in the northern portion of the continental United States along with a low pressure located in gulf of Mexico, resulted in a stagnant air mass centered near the junction of the lower Ohio River Valley and the middle Mississippi River Valley for several days, producing optimum meteorological conditions for the accumulation of haze [*Stull*, 1988].

Figure 2b shows the comparison between $PM_{2.5}$ and MODIS AOT for the seven locations from both the Terra and Aqua satellites. The linear correlation coefficient (R) is 0.7 (R=0.67 for Terra and R = 0.76 for Aqua), suggesting that the $PM_{2.5}$ mass that is indicative of near surface values is still reflected in the MODIS column AOT data. The majority of $PM_{2.5}$ values are around 20 μgm^{-3} with less than 20% of $PM_{2.5}$ values greater than 40 μgm^{-3} indicating that the air quality was rated as good to moderate**.** Figure 2c shows the monthly mean distribution of $PM_{2.5}$ and MODIS AOT from both the Terra and Aqua satellites for 2002. The $PM_{2.5}$ has peak values of 20μgm^{-3} between July ~ September, and have smaller values of around 11μgm^{-3} during winter (January, February, and December). The monthly mean AOT follows the $PM_{2.5}$ trends well, with large values of 0.35 in July ~ September, and smaller values of 0.1 in winter. The large values of $PM_{2.5}$ from July-September are due to enhanced photolysis during the summer months.

The inset in figure 2c shows the diurnal changes of $PM_{2.5}$ mass over the area of study in different seasons. The largest diurnal change occurs in the morning, where $PM_{2.5}$ concentrations increase sharply from 6:00 to 8:00 a.m. The $PM_{2.5}$ then decreases between 8:00 a.m. to 1:00 p.m. and increases again after 1:00 to 2:00 a.m. The $PM_{2.5}$ generally shows little variations in the night from 8:00 p.m. to 6:00 a.m. of the next day. Such diurnal patterns are mainly affected by two factors including local traffic flow patterns and diurnal changes of the atmospheric boundary layer (ABL). In the early morning, the ABL usually is low and sometime could be stratified due to temperature inversions. Increased traffic flow during the morning hours coupled with the possible build up of residual precursors during the night time result in higher $PM_{2.5}$ values in the shallow ABL. Similar results from $PM_{2.5}$ measurements were also observed over Atlanta, Georgia [*Butler et al.*, 2003]. As the morning progresses, due to the solar heating, the ABL starts to grow and reach maximum values in the afternoon around 1:00~2:00 p.m. The strong vertical turbulence produces a well mixed ABL where aerosol concentration is almost constant [*Stull*, 1988], therefore decreasing the $PM_{2.5}$ mass at the surface between 8:00 a.m.~1:00 p.m. Due to the decrease of solar heating and the increase of longwave radiation emitted from the hot surface, the ABL starts to decline after 2:00p.m., and reaches minimum values during the night. Consequently, $PM_{2.5}$ at the surface slightly increases during this time period.

Since the AQI is classified as several categories based on the 24hr mean $PM_{2.5}$ content, we derive a simple empirical relation between MODIS AOT and AQI categories by dividing the $PM_{2.5}$ into 9 bins in $5\mu gm^{-3}$ intervals. The correlation between bin-averaged AOT and $PM_{2.5}$ content is very high (figure 2d), with linear correlation coefficient larger than 0.9 for both Terra and Aqua. The regression equations are: $AOT = 0.013\ PM_{2.5} + 0.003$ for Terra and $AOT = 0.015\ PM_{2.5} -0.029$ for Aqua. Using these relationships, the $PM_{2.5}$ derived from MODIS AOTs can be quantitatively used to estimate the air quality categories (see color bar in Figure 1a) with an accuracy of more than 90%, indicating that the MODIS AOT has tremendous potential for air quality applications. For example, air quality in eastern Texas is classified as unhealthy on Sep 11 by the EPA and our derived air quality categories, as shown in figure 2a is consistent with this classification. This example illustrates an advantage of using the MODIS AOT product to infer the AQI and air quality categories over large spatial scales and where ground point measurements are limited or unavailable. However, several factors including $f(rh)$, Q_{dext} and H_{eff}, affect the relationship between column AOT and $PM_{2.5}$. While the satellite-derived AOT is a measure of column AOT in ambient conditions, $PM_{2.5}$ is indicative of the mass of dry particles near the surface. As shown in previous studies [*e.g.,Tsay et al.*, 1991; *Corbin et al.*, 2002], $f(rh)$ and H_{eff} have large variations and are highly dependent on ambient meteorological conditions. The varying amount of water vapor could result in the swelling (hygroscopic growth) of hygroscopic particles, or condensation on hydrophobic particles. In either case, the microstructure and chemical composition of the particle will change, resulting in uncertainties in the air quality index through changes in $\beta_{ext}(z)$ in equation 1 [*Tsay et al.,* 1991]. These effects should be explored in future studies.

We note that fluctuations of aerosol mass concentration profile could also induce uncertainties in the relationship between MODIS AOT and $PM_{2.5}$ mass. Several studies have assumed that the aerosol mass concentration is mainly suspended and well mixed in the atmosphere boundary layer [*Corbin et al*., 2002; *Bergin et al*., 2002]. Although this assumption may be valid for most cloud-free conditions and also make it easier to define H_{eff} and directly link the AOT into $PM_{2.5}$, it may be invalid for some conditions such as the transport of aerosols associated with a passage of a cold front [*Bergin et al*., 2002]. To accurately derive the aerosol mass from column AOT, the aerosol extinction profile must be inferred from ground-based lidars or future space-borne lidars like the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO).

4. Summary

Using 1 year of the MODIS aerosol optical thickness from the Terra/Aqua satellites collocated with hourly particular matter content measured at 7 ground stations in Jefferson county, Alabama, we show that the MODIS AOT has a good correlation with $PM_{2.5}$ (R = 0.67 for Terra and R = 0.76 for Aqua). Through statistical analysis, we derive an empirical relationship between the MODIS AOT and 24hr mean $PM_{2.5}$ mass and conclude that the satellite-derived AOT is a useful tool for air quality studies over large spatial domains to track and monitor aerosols. The MODIS AOT product can be used to discern air quality categories such as good, moderate and unhealthy to a relatively high degree of confidence. We also conclude that the aerosol extinction profile from ground based LIDAR or from satellite measurements such as CALIPSO are highly important for further enhancing the use of satellite data for air quality studies. Currently, $PM_{2.5}$ data sets covering broad areas with high temporal resolution are still lacking. A concerted effort is needed to create a data base of high temporal resolution $PM_{2.5}$ data across the United States to further explore the relationship between $PM_{2.5}$ and satellite derived aerosol properties. In the future, the MODIS AOT products may also be important in initializing photochemical models for air quality forecasts.

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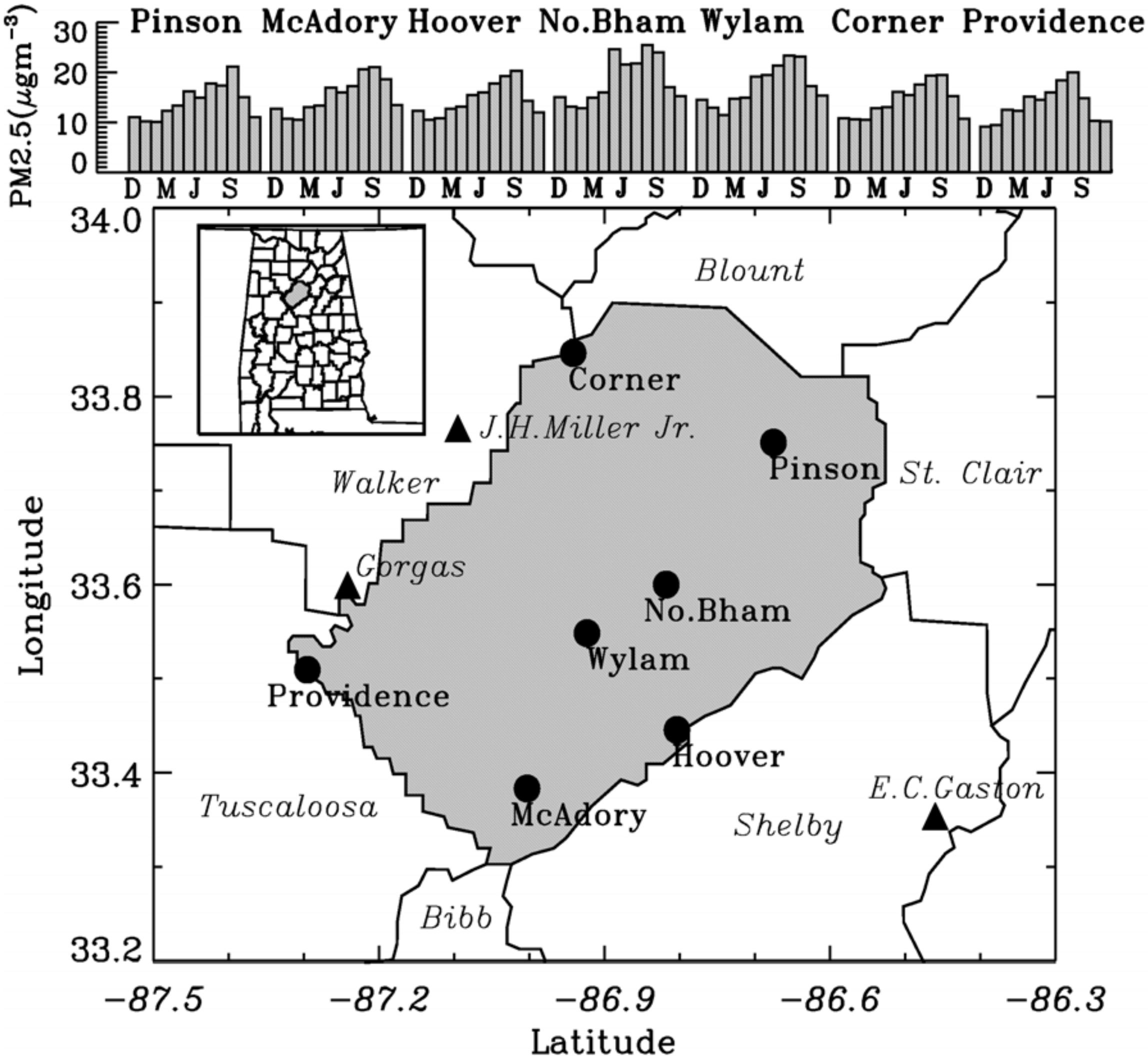
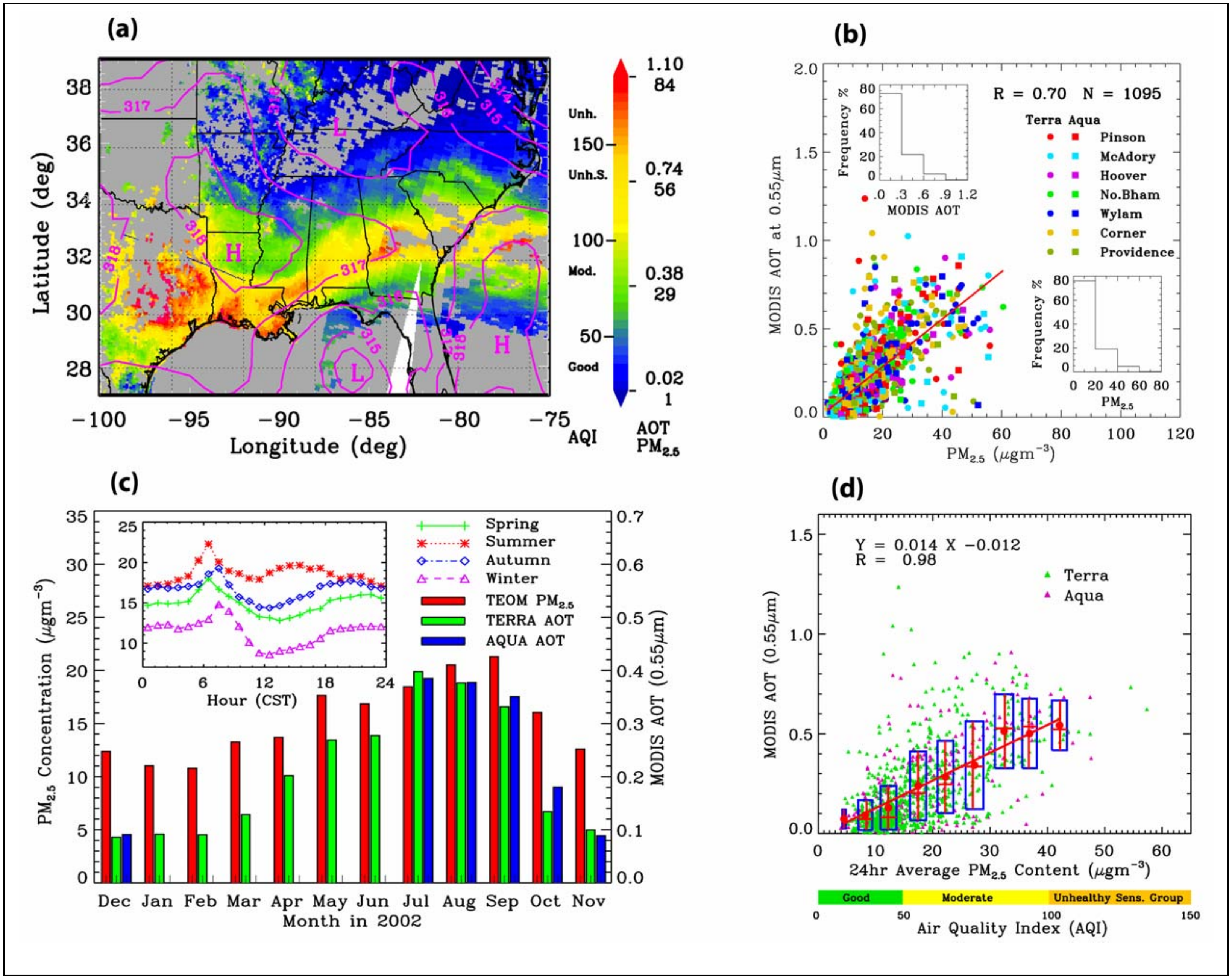
Figure legends

Figure 1. Study area with locations (filled circle) of the seven $PM_{2.5}$ sites in Jefferson County, AL. The shaded area is Jefferson County. The triangles show major power plant locations. The upper left inset shows all counties in AL and the upper panel shows the monthly mean $PM_{2.5}$ concentration (μgm^{-3}) as a function of season in 2002.

Figure 2. a) Spatial distribution of MODIS AOT and linearly derived AQI from Terra on Sep 11, 2002. Also shown are the 700mb geopotential heights. Grey regions are areas where MODIS AOT is not available due to possible sun glint or cloud contamination. b) Relationship between MODIS aerosol optical thickness and $PM_{2.5}$ mass, c) Seasonal variation AOT and $PM_{2.5}$, inset shows the diurnal variations (in Central Standard Time CST) of $PM_{2.5}$ in different seasons. d) Air quality index derived from MODIS data. The box shows the ±1 standard deviation of PM2.5 and AOT centered in the mean value (red filled circles) in each bins. The red line in the box shows the median value in each bin.


Pinson
McAdory
Hoover
No.Bham
Wylam
Corner
Providence
PM2.5(μgm⁻³)
30
20
10
0
D M J S
34.0
33.8
33.6
33.4
33.2
Longitude
−87.5
−87.2
−86.9
−86.6
−86.3
Latitude
Blount
Corner
J.H.Miller Jr.
Walker
Pinson
St. Clair
Gorgas
No.Bham
Wylam
Providence
Hoover
E.C.Gaston
Tuscaloosa
McAdory
Shelby
Bibb


(a)
Latitude (deg)
Longitude (deg)
38
36
34
32
30
28
−100
−95
−90
−85
−80
−75
317
316
315
318
H
L
AQI
AOT
PM2.5
1.10
84
0.74
56
0.38
29
0.02
1
Unh.
150
Unh.S.
100
Mod.
50
Good
(b)
R = 0.70 N = 1095
Terra Aqua
Pinson
McAdory
Hoover
No.Bham
Wylam
Corner
Providence
MODIS AOT at 0.55μm
PM2.5 (μgm−3)
Frequency %
MODIS AOT
.0 .3 .6 .9 1.2
0 20 40 60 80
0.0
0.5
1.0
1.5
2.0
0
20
40
60
80
100
120
(c)
PM2.5 Concentration (μgm−3)
MODIS AOT (0.55μm)
Spring
Summer
Autumn
Winter
TEOM PM2.5
TERRA AOT
AQUA AOT
Hour (CST)
0 6 12 18 24
10 15 20 25
0
5
10
15
20
25
30
35
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Month in 2002
(d)
Y = 0.014 X −0.012
R = 0.98
Terra
Aqua
MODIS AOT (0.55μm)
24hr Average PM2.5 Content (μgm−3)
0
10
20
30
40
50
60
0.0
0.5
1.0
1.5
Good
Moderate
Unhealthy Sens. Group
0
50
100
150
Air Quality Index (AQI)