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Intercomparison between satellite-derived aerosol optical thickness and $PM_{2.5}$ mass: Implications for air quality studies

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[1] 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. 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 well-mixed lower boundary layer during the satellite overpass times. There is excellent agreement between the *monthly mean* $PM_{2.5}$ and MODIS AOT (R > 0.9), with maximum values during the summer months due to enhanced photolysis. 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 as defined by the U.S. Environmental Protection Agency (EPA) with an accuracy of more than 90% in cloud-free conditions. We discuss the factors that affect the correlation between satellite-derived AOT and $PM_{2.5}$ mass, and emphasize that more research is needed before applying these methods and results over other areas. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3300 Meteorology and Atmospheric Dynamics. **Citation:** Wang, J., and S. A. Christopher, Intercomparison between satellite-derived aerosol optical thickness and $PM_{2.5}$ mass: Implications for air quality studies, *Geophys. Res. Lett.*, *30*(21), 2095, doi:10.1029/2003GL018174, 2003.

1. Introduction

[2] 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 [*Kaufman et al.*, 2002]. Aerosols also reduce visibility and induce respiratory diseases when submicron sized aerosols penetrate the lungs thereby affecting air quality and health [*Krewski et al.*, 2000]. Increased exposure to particular matter with aerodynamic diameters less than 2.5 μm ($PM_{2.5}$) can cause lung and respiratory diseases and even premature death. The Environment Protection Agency (EPA) evaluates daily air quality based on the ratio between 24-hour averages of the measured dry particulate mass with the National Ambient Air Quality Standard (NAAQS). The ratio (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 (Table 1). For healthy conditions, the 24-hour averaged $PM_{2.5}$ concentration must be less than 65.5 μgm^{-3}.

[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 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 the United States. Examples of transported aerosols to the United States include smoke from Central American biomass burning fires and dust aerosols from the Saharan desert.

[4] 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. One important and common aerosol parameter retrieved from satellite sensors is aerosol optical thickness (AOT) that is a function of the aerosol mass concentration (m_{aer}), mass extinction efficiency (Q_{ext}), hygroscopic growth factor (a function of relative humidity, $f(rh)$), and effective scale height (H_{eff}) that is mainly determined by the vertical distribution of aerosols [*Kaufman and Fraser*, 1983]. Generally, a higher AOT value indicates higher column aerosol loading and therefore low visibility. 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]. 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]. For a given area, the MODIS instruments provide two daytime observations (10:30 a.m. from Terra and 1:30 p. m. from Aqua). We explore the potential of using the MODIS AOT product

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Table 1. AQI and its Corresponding 24 hourly Mean $PM_{2.5}$ (μgm^{-3}) and Air Quality Category (AQC)

	AQI						
	0 ~ 50	51 ~ 100	101 ~ 150	151 ~ 200	201 ~ 300	301 ~ 400	401 ~ 500
24 hrm $PM_{2.5}$	0 ~ 15.4	15.5 ~ 40.4	40.5 ~ 65.4	65.5 ~ 150.4	150.5 ~ 250.4	250.5 ~ 350.4	350.5 ~ 500.4
AQC	Good	Moderate	USP	Unhealthy	Very unhealthy	Hazardous	Hazardous

USP denotes unhealthy conditions for special groups such as elderly and children.

for air quality studies. A comparison between 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

[5] The data used in this study includes the MODIS AOT (Level 2, version 4) and hourly particular matter data collected at seven locations in Jefferson County, AL (Figure 1) in 2002. 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 with an accuracy of ±5 μgm^{-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 AOT is reported at $10 \times 10\ km^2$ and when compared against ground-based AERONET measurements, the MODIS AOT values are within uncertainty levels of ±0.05 ± 0.20 AOT over land [*Chu et al.*, 2002]. In this study, one year (2002) of MODIS AOT at 0.55μm from Terra and Aqua over land are used (Aqua was launched in April, 2002, and its data is only available after June 26, 2002). Since there is no sunphotometer data available in Jefferson county, AL, we obtained 3-years (2000 ~ 2002) of AOT data collected at the nearest AERONET site (Stennis, MS, 30°N, 89°W) to infer the intra-annual trend of AOT in the Southeastern United States, which is then used as a reference in the discussion. To compare the MODIS AOT with $PM_{2.5}$, we average the hourly $PM_{2.5}$ data centered on the satellite overpass time and also check for potential cloud contamination of a pixel based on the methodology outlined in *Chu et al.* [2002].

3. Results and Discussion

[6] 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 that was observed throughout the southern United Stated including eastern Texas, Mississippi, Alabama, and Georgia. A combination of a high pressure system in the northern portion of the continental U.S. 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 ideal meteorological conditions for the accumulation of haze.

[7] Figure 2b shows the comparison between $PM_{2.5}$ and MODIS AOT for the seven locations in Jefferson County, Alabama, from both the Terra and Aqua satellites in 2002. 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 20 μgm^{-3} between July–September, and has smaller values of around 11μgm^{-3} during winter (January, February, and December). The monthly mean MODIS AOT follows the $PM_{2.5}$ trends well, with large values of 0.35 from 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 linear correlation coefficient between the *monthly mean* $PM_{2.5}$ and MODIS AOT is 0.91 for Terra and 0.95 for Aqua. For reference purposes, the monthly mean SP AOTs at Stennis is also shown in Figure 2c. Although the sunphotometer AOT at Stennis is generally smaller than the MODIS AOTs over Jefferson County, AL due to its distance from pollution sources, it does capture a similar intra-annual trend as that derived from the MODIS AOTs further demonstrating the reliability of MODIS AOT values. However, further examination of Figure 2c also shows that the intra-annual trend of AOT from AERONET and MODIS measurements is more distinct when compared to the intra-annual trend of $PM_{2.5}$ possibly due to the hygroscopic effect which could be largest in summer when relative humidity is higher. There-

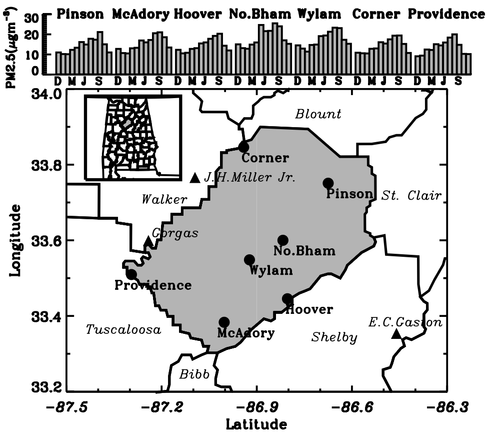

Figure 1. Study area with locations (filled circle) of the seven $PM_{2.5}$ sites in Jefferson County, AL. The shaded area is Jefferson County. The triangles show major power plant locations. The upper left inset shows all counties in AL and the upper panel shows the monthly mean $PM_{2.5}$ concentration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

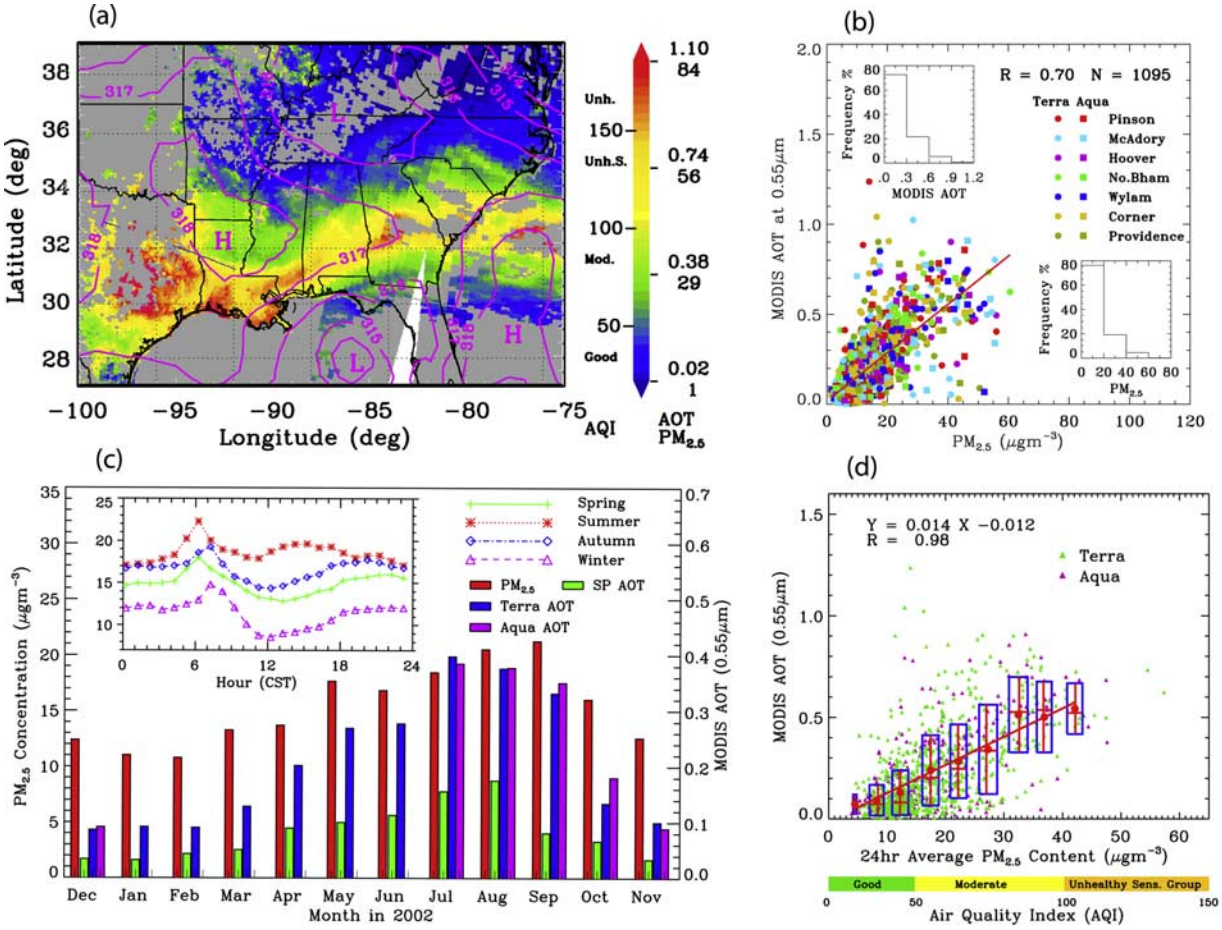

Figure 2. (a) Spatial distribution of MODIS AOT and linearly derived AQI from Terra on Sept 11, 2002. Also shown are the 700mb geopotential heights. Grey regions are areas where MODIS AOT is not available due to possible sun glint or cloud contamination. (b) Relationship between MODIS AOT and $PM_{2.5}$ mass, (c) Monthly variation of $PM_{2.5}$ and MODIS and Sunphotometer (SP) AOT, inset shows the diurnal variations (in Central Standard Time, CST) of $PM_{2.5}$ in different seasons. (d) AQI derived from MODIS data. The box shows the ±1 standard deviation of $PM_{2.5}$ 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.

fore, for the same amount of dry $PM_{2.5}$ mass, the corresponding AOT will be larger in summer than in winter, which is also seen in Figure 2c.

[8] 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; decrease between 8:00 a.m. to 2:00 p.m. and increase again after 2:00 p.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 often stratified due to temperature inversions. Increased traffic flow during the morning hours coupled with the possible build up of residual precursors during the night 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, therefore decreasing the $PM_{2.5}$ mass at the surface between 8:00 a.m. ~2:00 p.m. We infer that the ABL usually is well mixed in cloud-free conditions during the satellite overpass times thereby resulting in favorable positive correlations between MODIS AOTs and $PM_{2.5}$ mass.

[9] Since the AQI is classified as several categories based on the 24-hr mean $PM_{2.5}$ content (Table 1), we derive a simple empirical relation between MODIS AOT and AQI categories by dividing the 24-hr mean $PM_{2.5}$ into 9 bins in 5 μgm^{-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 the MODIS AOTs can be quantitatively used to estimate the air quality categories (see color bar in Figure 2d) 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 was classified as unhealthy on Sept 11, 2002 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 air quality categories over large spatial scales where ground point measurements are limited or unavailable.

[10] However, we emphasize that several factors including $f(rh)$, Q_{ext} 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, the $PM_{2.5}$ mass 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], $f(rh)$ could vary due to different ambient meteorological conditions and hysteresis effects. The varying amount of water vapor could result in the swelling (hygroscopic growth) of particles, or condensation on hydrophobic particles. In either case, the microstructure and chemical composition of the particle will change, causing uncertainties in Q_{ext} and consequently affecting the relation between $PM_{2.5}$ and AOT [*Tsay et al.*, 1991]. Using measurements and models these effects should be explored in future studies. Nevertheless, the results in Figure 2b and 2d are very promising and also agree well with previous studies [e.g., *Smirnov et al.*, 2000; *Bergin et al.*, 2000; *Corbin et al.*, 2002]. *Smirnov et al* [2000] reported that the correlation coefficient R between daily Sunphotometer inferred AOT and daily mean aerosol mass at Barbados was 0.70, while R for monthly comparisons was 0.93.

[11] We note that the 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.*, 2000]. 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.*, 2000]. To accurately derive the aerosol mass from column AOT, the aerosol extinction profile could be inferred from chemical transport models [e.g., *Corbin et al.*, 2002], ground-based lidars or future space-borne lidars like the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO).

4. Summary

[12] Using one year of the MODIS AOT 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 positive correlation with $PM_{2.5}$ mass (R = 0.7). Through statistical analysis, we derive an empirical relationship between the MODIS AOT and 24-hr 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. However we have outlined several factors that could affect the relationship between $PM_{2.5}$ and satellite-derived AOT and further research is needed to quantify these effects. We also conclude that the aerosol extinction profile from ground based lidars or from satellite measurements such as CALIPSO are highly important for further enhancing the use of satellite data for air quality studies. Although selected locations provide hourly $PM_{2.5}$ data, *high temporal resolution* data sets are unavailable for most locations from the EPA network. 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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