Atmos. Meas. Tech. Discuss., 4, 7559–7595, 2011
www.atmos-meas-tech-discuss.net/4/7559/2011/
doi:10.5194/amtd-4-7559-2011

Atmospheric Measurement Techniques Discussions

Characterization of atmospheric aerosol in the US Southeast from ground- and space-based measurements over the past decade

E. J. Alston[1,2], I. N. Sokolik[2], and O. V. Kalashnikova[3]

[1]NASA Langley Research Center, Hampton, VA, USA
[2]Georgia Institute of Technology, School of Earth and Atmospheric Sciences, Atlanta, GA, USA
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Received: 11 October 2011 – Accepted: 7 December 2011 – Published: 16 December 2011

Correspondence to: E. J. Alston (erica.j.alston@nasa.gov)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This study examines how aerosols measured from the ground and space over the US Southeast change temporally over a regional scale during the past decade. $PM_{2.5}$ data consist of two datasets that represent the measurements that are used for regulatory purposes by the US EPA and continuous measurements used for quickly disseminating air quality information. AOD data comes from three NASA sensors: the MODIS sensors onboard Terra and Aqua satellites and the MISR sensor onboard the Terra satellite. We analyze all available data over the state of Georgia from 2000–2009 of both types of aerosol data. The analysis reveals that during the summer the large metropolitan area of Atlanta has average $PM_{2.5}$ concentrations that are 50 % more than the remainder of the state. Strong seasonality is detected in both the AOD and $PM_{2.5}$ datasets; as evidenced by a threefold increase of AOD from mean winter values to mean summer values, and the increase in $PM_{2.5}$ concentrations is almost twofold from over the same period. Additionally, there is good agreement between MODIS and MISR onboard the Terra satellite during the spring and summer having correlation coefficients of 0.64 and 0.71, respectively. Monthly anomalies were used to determine the presence of a trend in all considered aerosol datasets. We found negative linear trends in both the monthly AOD anomalies from MODIS onboard Terra and the $PM_{2.5}$ datasets, which are statistically significant for $\alpha = 0.05$. Decreasing trends were also found for MISR onboard Terra and MODIS onboard Aqua, but those trends were not statistically significant.

1 Introduction

Over the past fifty or so years global ground-based measurements of solar radiation reaching the surface have shown first a decrease (i.e., dimming) and in the last fifteen years have shown an increase (i.e., brightening) Alpert et al. (2005); Gilgen et al. (2009); Wild et al. (2009). The solar dimming relates to increases in aerosol concentration that prevent incoming solar radiation from reaching the surface. During the 1980s, many industrialized countries enacted policies for controlling emissions of aerosols

AMTD
4, 7559–7595, 2011

and their precursors. In the 1990s, a shift from dimming to brightening was reported at some locations (Streets et al., 2009). It is hypothesized that the magnitude of global warming has been masked due to solar dimming (Schwartz et al., 2010; Wild et al., 2009), thus linking this phenomenon to current climate.

Dutton et al. (2006) analyzed twenty seven years of NOAA/GMD surface solar irradiance data from five remote sites (Barrow, AK USA, Boulder, CO USA, Mauna Loa, HA USA American Somoa, and the South Pole) and concluded that while the sites span a large geographic area, the behavior of surface solar irradiance was similar (decreasing then increasing with time) across the sites. Wild et al. (2009) provide updates of surface radiation measurements through 2005 and present evidence that brightening across large areas is ongoing and that anthropogenic contributions are an important factor in this phenomena. Streets et al. (2009) use model-predicted aerosol optical depth (AOD) to determine the regional nature of solar dimming/brightening. Their results indicate that the US, Europe and Russia have decreasing AOD values over a twenty-five year (1980–2005) period, and these regions also have a strong linear relationship between AOD and surface radiation.

The regionality associated with this solar dimming/brightening is more nuanced when observed from a smaller regional perspective, e.g., regions of the US. For example, some studies found that that solar dimming/brightening is likely dominated by emissions from large urban areas (Alpert and Kischa, 2008; Alpert et al., 2005). Recent work by Wild et al. (2009) further substantiates this point by investigation of trends of solar dimming/brightening at multiple locations. The locations from the US all show a similar behavior, but each sites trend slope is different owing to the influence of differing aerosol mixtures and loading associated with each sites respective region. Long et al. (2009) investigated brightening of downwelling shortwave radiation at multiple US locations and found that collectively the brightening is significant, but that the varying degrees of brightening amongst the different sites suggested that research into dimming/brightening should address local to regional scales. Ultimately, understanding of dimming/brightening variations requires knowledge of spatiotemporal changes

AMTD
4, 7559–7595, 2011

in aerosols on a regional basis. The focus of the present study is on a regional aerosol signal in the Southeast US.

This region is of interest because of the distinct aerosol mixtures associated with this geographic region that has been studied from the ground, yet little research has been done incorporating satellite data into longer term studies. There have been, for instance, large scale ground based measurement studies in the region consisting of a US Environmental Protection Agency (EPA) Supersite Study (Solomon et al., 2003), and ongoing work through the Southeastern Aerosol Research and Characterization Study (SEARCH) (http://www.atmospheric-research.com/studies/SEARCH/index.html). According to the EPA Our Nation's Air publication (http://www.epa.gov/airtrends/2010/index.html), $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 micrometers) concentrations nationwide have decreased by 19 % since 2000, with the Southeastern US showing a decrease in annual $PM_{2.5}$ concentrations. This region is distinctly characterized by aerosols composed of primarily sulfates and organics (Edgerton et al., 2005; Weber et al., 2007). Measurements and modeling studies have shown that organic aerosol formed by secondary processes is biogenic in origin and fairly homogeneous over the region (Lee et al., 2010). Goldstein et al. (2009) hypothesize that the haze commonly seen in the region during the warmer months is formed from secondary organic aerosols (SOA) formed from biogenic vilotile organic compounds (BVOC) that tend to cause a cooling radiative effect at the top of the atmosphere (TOA) and that these BVOC SOA aerosols form a layer aloft in the atmosphere with a dominant contribution to AOD during the summer.

Ground based measurements can provide high temporal concentration data over an extended period of time, yet these measurements are generally limited in their geographic coverage. A majority of ground based measurement sites are mostly in areas with high population densities. Additionally, ground based measurements are at best representative of aerosols in the lower atmosphere, mainly in the planetary boundary layer (PBL); as such, these measurements miss aerosols aloft, especially transport events. While satellites have an advantage in that they can view regions as a whole,

AMTD
4, 7559–7595, 2011

which enables better understanding of the regional aerosol dynamics, yet the satellites are limited temporally with only one or two sunlit overpasses of a region per day. The National Aeronautics and Space Administration (NASA) has launched a couple of satellites (Terra and Aqua) that have near global coverage daily with direct application to aerosols. The MODIS and MISR sensors onboard Terra have been operational for over ten years. MODIS onboard Aqua was launched in 2002. Each sensor provides a continuous timeseries of the aerosol optical depth (AOD) that can be directly related to the dimming/brightening phenomena (Hinkelman et al., 2009; Mishchenko et al., 2007). However, retrievals of AOD (a unitless measure of the amount of light attenuation over a set distance over the entire atmospheric column) are associated with a number of problems, especially over land such as deserts or urban environments. Liu and Mishchenko (2008) found that MODIS and MISR retrievals can disagree on a regional basis; yet, (Kahn et al., 2009, 2011) attempt to disprove those findings in concluding that MISR and MODIS retrievals are in agreement and provide details on the causes of the discrepancies between the two.

There have been studies that directly relate satellite AOD to $PM_{2.5}$ concentrations in the US and the Southeastern US specifically (Engel-Cox et al., 2004; Gupta and Christopher, 2008, 2009; Zhang et al., 2009) for the purposes of predicting air quality. Our earlier work, used probabilities of AOD (based upon the linear regression relationship between AOD and $PM_{2.5}$) associated with different air quality index values as a means of prescribing air quality (Alston et al., 2011). Given the regional nature of aerosols and inherent difficulties and limitations in both satellite and ground based observations, it is important to utilize multiple sensors in aerosol analysis in order to develop as accurate understanding of aerosol behavior as possible especially when viewed over a longer time period. A review about the state of the field with regards to aerosol characterization from space, suggests that different approaches other than relating $PM_{2.5}$ and AOD through linear regressions are needed with respect to understanding the nature of these two aerosol measurements in future studies (Hoff and Christopher, 2009).

AMTD
4, 7559–7595, 2011

This is a motivation behind this study's goal to characterize aerosols in the US Southeast through analysis of ground and space based measurements from 2000–2009, with the emphasis on seasonal and interannual aerosol variations and understand these variations in the context of the radiative impact of aerosols on climate. The specific objectives are to examine the temporal changes of ground based $PM_{2.5}$ and AODs from MODIS and MISR over the past ten years, determine common features and differences between these data records, determine if there is a discernible trend, and if a trend is present, what are the implications for the region in the context of the dimming/brightening phenomena. We analyzed ten years of AOD from MODIS and MISR onboard Terra and eight years for MODIS onboard Aqua over a 5°x 5°box that encompasses the state of Georgia. This analysis also uses ten years of filter-based $PM_{2.5}$ data provided by the EPA, and all available data from Georgia-run continuous $PM_{2.5}$ monitors. This paper is organized as follows. Section 2 introduces the data and methods used in this study. Section 3 presents the results, and Sect. 4 concludes with a summary and discussion.

2 Data and methodology

2.1 Ground-based $PM_{2.5}$ data

We use surface $PM_{2.5}$ measurements from two different networks: the ten years record from the national network of filter-based $PM_{2.5}$ monitors courtesy of the EPA, and a seven year record of continuous $PM_{2.5}$ measurements provided by the Georgia Dept. of Natural Resources. The location of the sites is shown in Fig. 1. The network operated by the Georgia Dept. of Natural Resources (http://www.air.dnr.state.ga.us/amp/) performs continuous hourly measurements using TEOMs (Tapered Element Oscillating Microbalance). Across Georgia, there are eighteen network sites located primarily within or near a city. For our study we use twelve sites. Seven of those sites are within the large metropolitan area of Atlanta and the remaining sites are smaller sized cities

AMTD
4, 7559–7595, 2011

and towns. Most of the stations have seven years of data; however, sites without at least five years of data were excluded from this analysis. Henceforth, this dataset will be annotated as $PM_{2.5,TEOM}$. The time coverage of this dataset is from 2003–2009.

The second data set is provided by the EPA Air Quality Monitoring System (http://www.epa.gov/airexplorer/index.htm). The data from this network are used for air quality regulatory purposes, e.g., attainment/non-attainment designations. Each monitor is a filter-based according to EPA-defined reference methods described in 40 CFR Part 53 (http://www.epa.gov/ttnamti1/40cfr53.html), and they must meet high quality control measures. Due to high level of quality control, there is usually a time lag from the measurement, the analysis, and finally making the data publicly available. Each station serves a different purpose; as such there are different repeat cycles. Population exposure monitors have daily concentrations; while the majority of sites have a 3-day repeat cycle. Monitors that capture background conditions have a 6-day repeat cycle. Similar to our methodology for the $PM_{2.5,TEOM}$ dataset, we only use EPA sites within Georgia state lines, subsequently we use data from 29 sites. This dataset will be annotated as $PM_{2.5,FRM}$. Over half of the $PM_{2.5,FRM}$ stations have data that encompass 2000–2009.

To separate out Atlantas influence from the remainder of the state, we split each $PM_{2.5}$ dataset into subsets depending on the geographical location of the considered sites. Ultimately, we have three subsets for each $PM_{2.5}$. We calculate a statewide mean for the *All GA* subset. The *Atlanta* subset is the mean exclusively using Atlanta sites. The last subset *Outside Atlanta* uses sites outside Atlanta for the calculated mean. For the $PM_{2.5,TEOM}$ datasets, hourly means are averaged to create daily means. Those daily means are then used in subsequent analyses. Given the repeat cycle associated with the $PM_{2.5,FRM}$ dataset, fill values were used to fill-in the gaps in the data record where measurements were not taken. Those complete timeseries were used in subsequent analyses.

AMTD
4, 7559–7595, 2011

2.2 MODIS data

The MODerate Resolution Imaging Spectroradiometer (MODIS) instrument flies onboard two NASA Earth Observing System (EOS) satellites: Terra and Aqua. Both sensors have near global coverage daily. Terra flies in the descending polar orbit with an equatorial crossing time of approximately 10:30 a.m., while Aqua flies in the ascending polar orbit with an equatorial crossing time of approximately 1:30 p.m. Generally, the satellites have overpass times over Georgia 5–15 min after their equatorial crossing times.

MODIS passively measures reflected radiances from Earth across a broad wavelength spectrum. It primarily uses three channels (0.47, 0.66, and 2.12 µm) to measure atmospheric aerosols over land (Levy et al., 2007). MODIS data are obtained from NASA LAADS (Level 1 and Atmosphere Archive and Distribution System). The analysis is performed with MODIS Collection 5 Level 2 data, which have a nominal resolution of $10 \times 10\,km^2$ at nadir. The variable of most importance to this study is *Optical Depth Land and Ocean* at the 550 nm wavelength, which incorporates only the highest quality retrievals.

2.3 MISR data

The Multi-angle Imaging SpectroRadiometer (MISR) flies onboard of the Terra satellite together with MODIS. MISR is a multi-angle imaging instrument consisting of nine cameras with view angles of $\pm 70.5^\circ$, $\pm 60.0^\circ$, $\pm 45.6^\circ$, $\pm 26.1^\circ$, and 0°(nadir), operating in four spectral bands centered at 446 nm (blue), 558 nm (green), 672 nm (red), and 867 nm (near infrared). In global observing mode, the spatial resolution of the red band is 275 m in all nine cameras, the other bands are re-sampled to 1.1 km resolution in all the cameras, except the nadir, which preserves the full 275 m resolution in all four bands. The common swath width is ≈400 km and global coverage is obtained every nine days at the equator and more frequently at higher latitudes (Diner et al., 2002). MISR operational aerosol retrievals are performed at 17.6 km horizontal

AMTD
4, 7559–7595, 2011

resolution, and particle size, shape, and single-scattering albedo are retrieved in addition to AOD (Martonchik et al., 2002, 2009) A global comparison of coincident MISR and AERONET sunphotometer data showed that overall about 70 % to 75 % of MISR AOD retrievals fall within 0.05 or 20 % of AOD, and about 50 % to 55 % are within 0.03 or 10 % of AOD, except at sites where dust or mixed dust and smoke are commonly found (Kahn et al., 2010). MISR data were obtained from NASA Langley ASDC (Atmospheric Science Data Center). The analysis is performed with MISR version 22 Level 2 aerosol data. The used AOD values are "best estimate AOD" at MISR green (558 nm) band that combines the land and ocean AOD products.

For each satellite, we create a subset based on the latitude/longitude box 30° N–35° N and 80° W–85° W. All the satellite pixels contained within that latitude/longitude box are averaged together to create a regional mean AOD value on a daily basis for each satellite sensor. The daily mean AOD values are used in the subsequent analyses. For spatial analysis the nominal Level 2 products are used to create maps of AOD from both Terra instruments. The daily granules are averaged on a global grid (0.25° × 0.25° for MODIS and 0.2° × 0.2° for MISR). These grids are then averaged to create seasonal means of AOD fields for the ten year time period covering the aforementioned latitude/longitude box.

3 Results

3.1 Seasonal cycle

Where available, we analyzed 10 yr of $PM_{2.5,TEOM}$, $PM_{2.5,FRM}$, and AOD data from MODIS Terra and Aqua, and MISR Terra to investigate the seasonal aerosol signatures over the US Southeast. Considering only spring and summer seasons in our previous study (Alston et al., 2011), we found that $PM_{2.5}$ and AOD have different seasonal traits with AOD values almost doubling during the summer compared to values in the spring. Here we calculated 10-yr (if available) averages of each month for both the satellite and $PM_{2.5}$ datasets. The results are shown in Fig. 2. In analyzing a full calendar year instead of just spring and summer, here we determine that summer (June–August) AOD (0.32–0.35) is almost tripled from wintertime (December–February) AOD (0.08–0.1). MODIS Terra has the highest average AOD. Generally speaking, both Terra sensors (MODIS and MISR) have higher AOD than MODIS Aqua. During the summer months the difference between the MODIS AOD sensors and MISR AOD is about 0.1. While the difference between the MODIS AOD sensors at its highest is about 0.025. The noted 3x increase cannot be fully attributable to $PM_{2.5}$ increases over the same period. The different $PM_{2.5}$ datasets behave differently, with $PM_{2.5,TEOM}$ doubling concentrations during the summer whereas $PM_{2.5,FRM}$ shows only a modest increase over the same period ($\approx$10.0 $\mu g\,m^{-3}$ during the winter to $\approx$18.0 $\mu g\,m^{-3}$ during the summer). It is possible that some of the differences seen between the datasets are that the $PM_{2.5,TEOM}$ dataset only has 7 yr of data compared with 10 yr of the EPA dataset. Another possibility could be due to the differences in measurement techniques used. The standard error (standard deviation/number of observations) of the means of both datasets show more variability during the warmer months, see Fig. 2.

Timeseries of monthly mean data for each year are shown in Fig. 3. The winter months have the lowest values of AOD and $PM_{2.5}$, while the summer months have the highest. Specifically, July and August have the highest AOD values with maximums over the years varying between 0.5–1.5, with January and December having the lowest values between 0.2–0.55. MODIS Aqua has a much tighter AOD envelope with wintertime AOD values between 0.05–0.08 and summertime AOD values between 0.25–0.5. The year 2007 has anomalously high values in all the datasets. For a majority of the year, the satellite datasets have small amounts of interannual seasonal variability, with the highest amounts of interannual variability occurring in the summer.

The $PM_{2.5}$ datasets have more interannual variability than the satellite datasets. Breaking the $PM_{2.5}$ datasets into different geographic regions allows us to evaluate the effect of the large urban area of Atlanta on the region as a whole. Atlanta

AMTD
4, 7559–7595, 2011

concentrations from both $PM_{2.5,TEOM}$ and $PM_{2.5,FRM}$ have more variability throughout the year when compared to stations outside the Atlanta metropolitan area, see Fig. 3d–i. Our results suggest that during the summer there is a complex dynamic relationship between regional background $PM_{2.5}$ concentrations and anthropogenic emissions that lead to Atlanta having a 50 % or more increase in surface concentrations that are not observed elsewhere in the state.

Our analysis to this point has shown relatively good agreement between the satellite sensors. To further investigate the agreement between sensors, specifically MODIS Terra and MISR Terra, we analyze seasonal coincident AOD monthly means. We define each season in standard fashion: winter (December, January and February), spring (March, April and May), summer (June, July and August), and fall (September, October and November). Figure 4 presents the comparison of AODs. In most seasons, MODIS reports higher AOD values than MISR. Although our results from Fig. 3 show that on a monthly basis the differences between the two sensors are smallest during the fall and winter, our seasonal analysis (Fig. 4) shows more variance between the sensors. Not surprisingly, the linear regression slopes (0.33 for winter and 0.54 for fall) are not close to 1, and the subsequent correlation coefficients are 0.33 and 0.57, respectively. The outliers in scatterplots are possibly due to retrieval biases, differences within the retrieval algorithms, and cloud effects. Remer et al. (2008) found that on a global scale, aerosols near clouds only occur less than 1 % of the time over land; however, they note that AOD values near clouds can double the reported AOD due to subpixel cloud contamination (Zhang et al., 2005), 3-D effects (Wen et al., 2007), and increase of AOD due to increased humidity near clouds (Koren et al., 2007). (Kahn et al., 2009) found that MODIS AOD values are lower than MISR AOD values for AOD below 0.2, which could be related to Collection 5 algorithm changes that allow for negative AOD retrievals. The spring and summer seasons produce the greatest agreement between the two sensors with correlation coefficients of 0.64 and 0.71, respectively. Hygroscopic growth of aerosols due to higher relative humidity in the summer also possibly influence the agreement between the sensors. An additional influence could

AMTD
4, 7559–7595, 2011

be the weather pattern dynamics with the spring and summer seasons experiencing large-scale high pressure systems that can persist, which likely results in increased AOD values for both sensors despite their differences in viewing geometry. Interestingly, the signs of the y-intercepts are negative for spring and summer seasons. Possible explanations for this include that we do not force our linear regressions through zero, and due to systematic underestimation of AOD by MISR (Kahn et al., 2009), the regression line is pulled downward. Nevertheless, our results suggest good agreement between the two sensors over the past ten years. Yet Liu and Mishchenko (2008) reported larger disparities between the two. We should note that (Liu and Mishchenko, 2008) only consider two months (January and July) from 2006, and they consider a region (Eastern US) that is spatially larger than our area and contains multiple sources of aerosols (e.g., large metropolitan area). While our study region only contains one large metropolitan area, i.e., Atlanta.

Figure 5 shows how the seasonal means for each dataset change over time. As expected, spring and summer seasons show the most variance over the years. For instance, in the year 2000 MODIS Terra and MISR Terra had summer AOD means of 0.38 and 0.29, respectively, and by 2009 the means were 0.21 and 0.24. Also, even though our considered spatial domain is relatively small (5°by 5°), our seasonal means are similar in behavior to those of East North America as shown in Remer et al. (2008) where Level 3 1° × 1°globally gridded AOD are used for regional seasonal analysis, yet our seasonal means are higher. In the $PM_{2.5}$ datasets there appear to be different behaviors. The $PM_{2.5,FRM}$ values all appear to be decreasing with time. In 2000, $PM_{2.5,FRM}$ concentrations were around 22 $\mu g\,m^{-3}$, but by the end of the decade they had decreased to around 14 $\mu g\,m^{-3}$. The spring, fall, and winter seasons have similar behaviors, with summer being the exception. The three seasons also show similar behavior across all of Georgia, yet during the summer our results suggest that Atlanta is dominating concentrations across the state. The difference between the *All GA* and *Atlanta* means at most varied around 2 $\mu g\,m^{-3}$, and there is a larger difference (4 $\mu g\,m^{-3}$) between the *All GA* means and the *Outside Atlanta* means. Alston

AMTD
4, 7559–7595, 2011

E. J. Alston et al.

et al. (2011) highlighted how the spring of 2007 was anomalous in both AOD and $PM_{2.5}$ concentrations compared with other springs due to the large wildfire that burned for almost two months. It is likely that if the wildfire had not occurred, the spring means would decrease with time. Despite increased means for 2006 and 2007, the $PM_{2.5,TEOM}$ dataset appears to generally decrease with time.

The aerosol seasonality was also examined through an analysis of satellite AOD fields over the past 10 yr. In particular, we were interested in understanding if there are any discernible AOD differences from the large metropolitan area of Atlanta and the remainder of the state. Seasonal maps of AOD from MODIS Terra and MISR Terra are shown in Fig. 6: winter mean AOD (a and d), summer mean AOD (b and e), and the difference between the two seasons in (c and f). These maps, specifically the seasonal difference maps provide comparison to similar figures in Goldstein et al. (2009), see their Fig.1. Our spatial analysis does not strongly resemble the features seen in Goldstein et al., namely the large area of AOD (AOD > 0.25) over the broader Southeastern US. It should be noted that a major difference between this study and theirs is that we use a finer resolution product (Level 2) which is gridded to finer resolution grid than is provided by the Level 3 ($1^{\circ} \times 1^{\circ}$) monthly mean product used by Goldstein et al. The Level 3 products produces smoother appearing maps that can likely mask large point sources (e.g., industrialization, large metropolitan areas). This study also uses data from 2000–2009, whereas their study encompassed 2000–2007.

The MODIS maps suggest that the Atlanta area has slightly higher AOD from the remainder of the region, see Fig. 6a–c. The MISR maps do not appear to capture the AOD signal in Atlanta as well as MODIS, see Fig. 6d–f; however, both sensors show very low AOD during the winter season with AOD values <0.1, though there are some areas near the coastlines and over the ocean where AOD > 0.1 (Chu et al., 2002; Kahn et al., 2007; Levy et al., 2005). The summer season presents a more varied spatial representation. As noted early, there is almost a 3x increase from winter AOD values. One common feature between the sensors is that the background region (the region minus Atlanta) appears fairly uniform in AOD. The difference plots (Fig. 1c and f

AMTD
4, 7559–7595, 2011

suggest variation across the region that is not seen in Fig. 1 of Goldstein et al. (2009). In summary, the spatial analysis presented here shows slight differences between Atlanta and the remainder of the region at least from the MODIS Terra perspective, and this analysis shows more marked seasonality in spatial extent and magnitude than previously shown by Goldstein et al. (2009). Finer scale spatial resolution of satellites will likely aid the differentiation of urban centers from background conditions. Until newer satellite sensors are available with finer resolution, regional scale analysis are likely to remain the current standard, which has implications for air quality forecasts that want to incorporate satellite data into these forecasts on a state or smaller scale.

3.2 Interannual variability and trends

To examine interannual variability of aerosol in the Southeast US, we analyzed monthly means of satellites AOD and ground based $PM_{2.5}$ data, including analyses of anomalies and trends. Figure 7 presents the timeseries of monthly mean AODs for MODIS Terra, MISR Terra, and MODIS Aqua, along with timeseries of monthly mean $PM_{2.5}$ concentrations for the two ground datasets. When viewed over the past ten years, the satellites have generally good agreement with each other. Though there are differences in AOD magnitudes between MODIS Terra and MISR Terra, their behavior over time is quite similar. The difference between minima (≈0.1) and maxima (≈0.4) for the MODIS sensors is about 0.3. Another way to put that is according to the MODIS sensor, AOD almost quadruples from the lowest values in winter to the highest values in summer. MISR appears to have quite dramatic fluctuations as well, with its minima ≈0.3 and its maxima ≈0.8. The interannual variability makes it difficult to determine if there is a trend over time.

In contrast, the $PM_{2.5}$ datasets show a distinctly decreasing trend over time. Both the maxima and minima for these datasets have decreased by 5–8 $\mu g\,m^{-3}$. The seasonality is present in the $PM_{2.5}$ datasets, but not as pronounced as the AOD datasets. When viewed together (both AOD and $PM_{2.5}$ datasets), the peaks and valleys in

AMTD
4, 7559–7595, 2011

the timeseries correspond well together. For instance, the correlation coefficient of MODIS Terra vs. $PM_{2.5,FRM}$ *All GA* and MISR Terra vs. $PM_{2.5,FRM}$ *All GA* is 0.72 and 0.73, respectively; however, the correlation coefficient of MODIS Aqua vs. $PM_{2.5,FRM}$ *All GA* is 0.8. Correlation analysis between the satellites and $PM_{2.5,TEOM}$ *All GA* yields 0.84, 0.81 and 0.84, respectively. Finally, Fig. 8 presents AOD and $PM_{2.5}$ concentrations over the past 10 yr in terms of yearly means calculated from monthly means. It is readily apparent that there is a decreasing trend across all datasets. One point of incongruity occurs in 2007. In the AOD datasets, 2007 is high compared with years 2006 and 2008, yet 2007 does not have this peak in the $PM_{2.5}$ dataset. Alston et al. (2011) suggested that aerosols aloft associated with aerosol transport of local and long range haze and biomass burning events could be a likely explanation.

As shown in Fig. 7 there is strong seasonality, which makes the determination of any increasing/decreasing trend difficult. The first step in the determination of a trend is to fit the timeseries with a linear regression. The second step is to access if the slope is statistically different from zero by using t-test for $\alpha = 0.05$. Though there was no trend easily detected in Fig. 7, we fit each satellite AOD with a linear regression and determined that all the datasets did not have a statistically significant slope. As mentioned earlier, the $PM_{2.5}$ datasets appear to be decreasing with time. The linear regression for $PM_{2.5,FRM}$ all have slopes that are significant for $\alpha = 0.05$. In other words, the detected decrease in the timeseries is valid with some certainty. The $PM_{2.5,TEOM}$ datasets have more varied results. The slopes for $PM_{2.5,TEOM}$ *All GA* and $PM_{2.5,TEOM}$ *Atlanta* are not statistically significant, yet $PM_{2.5,TEOM}$ *Outside Atlanta* is significant. Our previous results suggest that metropolitan area of Atlanta concentrations likely skew the statewide average towards higher values due to the majority of the TEOM monitors (7 or 60 %) being in the metropolitan area of Atlanta area. Our results also hint that the rest of the state is indeed experiencing decreasing $PM_{2.5}$ concentrations, but the anthropogenic emissions especially in the summer in the metropolitan area of Atlanta are likely masking this decreasing trend. Another possible explanation for why one $PM_{2.5}$ dataset shows a decreasing trend and the other does not is the difference in length of the data records. We believe that given the air quality control policies in place, the $PM_{2.5,TEOM}$ dataset will likely show a statistically decreasing trend given more time.

Ultimately, it is necessary to remove the seasonal signal in order to access the presence of any true trends. We calculate a ten-year mean of every month, and subtract each month from the 10-yr mean of that month. For example, if the ten-year January average is 0.18, then 0.18 is subtracted from each January in the dataset, thus we are using anomalies from the 10-yr monthly mean to detect trends over the past 10 yr. The resulting timeseries of anomalies for both satellite and $PM_{2.5}$ datasets are shown in Fig. 9a–c. The anomaly timeseries are fit with linear regressions to determine the trend and are shown by the dashed line in Fig. 8. MODIS Terra was the only satellite dataset to have a statistically significant slope. We believe the smaller range of MISR AOD is why that dataset does not have a significant slope, while the MODIS Aqua dataset is only 8 yr long. It is possible that as time progresses the MODIS Aqua dataset will show a decreasing trend with certainty. By removing the seasonal component within the $PM_{2.5}$ datasets revealed statistically significant decreasing trends, see Fig. 9b–c. The linear regression variables (slope and y-intercept) are summarized for each dataset in Table 1. The regression variables are calculated on a per decade basis. We hypothesize that removing the strong seasonality from those datasets the summertime peaks in concentrations were minimized thus allowing a true and statistically significant trend to emerge.

4 Conclusions and discussion

We analyzed aerosol data from both ground based ($PM_{2.5}$) and space based (satellite AOD) platforms to examine the seasonality and interannual variations of the regional aerosol signal, and to detect if there was any discernable trends over the past ten years. We found that strong seasonality exists in both the AOD and $PM_{2.5}$ datasets where mean summertime AOD is nearly three times higher than mean wintertime AOD, and

AMTD
4, 7559–7595, 2011

mean summertime $PM_{2.5}$ concentrations are almost twice as high as mean wintertime concentrations. Another factor that possibly influences the seasonality is the effect of hygroscopic aerosol growth during the summer months, given higher relative humidity in the summer. Though satellite retrieval algorithms do not directly incorporate relative humidity, the retrievals are affected (Wang and Martin, 2007). Additionally over the past ten years, the $PM_{2.5}$ dataset used for regulatory purposes ($PM_{2.5,FRM}$) agree quite well with the satellite AOD measurements of aerosols. The correlation coefficients between $PM_{2.5,FRM}$ and AODs from MODIS Terra are 0.72, for MISR Terra are 0.73, and for MODIS Aqua are 0.8.

We found that MODIS onboard Terra and MISR onboard Terra agree well with each other during the warmer months with correlation coefficients of 0.67 for spring and 0.71 for summer. It is possible that cloud cover and inherent differences in sensor sensitivity explain the reduced agreement during the cooler months. Trend analysis was performed to establish baselines of different aerosol measures. We use t-tests of the slopes for $\alpha = 0.05$ to determine whether the calculated slopes are statistically different from zero. Trend analysis of monthly means AOD revealed that none of the satellite datasets shows a statistically significant negative trend. Yet the $PM_{2.5,FRM}$ FRM monthly mean timeseries does have statistically significant negative trends. Given the strong seasonality, we removed the seasonal component to create monthly mean anomalies. Trend analysis of the monthly mean anomalies yielded that MODIS onboard Terra has a statistically significant negative trend, and all the $PM_{2.5}$ datasets have statistically significant negative trends. It should be noted that for MODIS onboard Terra, this detected trend could be impacted by degradation of the blue channel used in MODIS retrievals over land, yet even with this drift taken into account the retrieved values are within the acceptable error envelope (Kahn et al., 2011; Levy et al., 2010).

Our results question the Goldstein et al. (2009) hypothesis on a dominant contribution of SOA from biogenic emission to AODs in the region. AOD is a column-averaged measurement that cannot readily differentiate between sources without a

AMTD
4, 7559–7595, 2011
Characterization of aerosols of over a decade
E. J. Alston et al.

priori information. If the conversion rate between BVOC and SOA is primarily temperature driven, then if the temperature record was found to neither increase or decrease (Menne et al., 2009) then biogenic SOA is unlikely to be the driver behind the negative trends in AOD. Following this reasoning the primary driver behind the negative trend appears to be anthropogenic sources which are monitored and controlled through air quality policies. Another facet of the Goldstein et al. (2009) hypothesis is that these BVOC associated SOA are formed in an aerosol layer aloft and thus ground based sensors would not likely capture the additional aerosol load of those aerosols. One would not expect trends in the $PM_{2.5}$ records, yet our results show decreasing seasonal and yearly trends. These results suggest that ground based monitors are measuring some portion of these SOA aerosols. Of course, this result requires additional measurement of aerosol profiles in this region for confirmation purposes. However, given the current state of measurement techniques it is not a simple exercise to differentiate between SOA of anthropogenic and biogenic sources (Weber et al., 2007). Additionally observational evidence for a layer of SOA aloft as measured by aircraft field campaigns is not supported (Heald et al., 2011). Finally, the spatial analysis presented here somewhat agrees with that shown in Goldstein et al. (2009). Of significance is that our results are different in spatial features (not smooth continuous fields of AOD) and magnitude (the difference between summer and winter is higher).

Our analysis suggests that air quality policies and controls placed upon $PM_{2.5}$ precursors have resulted in appreciable decreases in aerosols in the US Southeast. Our results also suggest that this region is experiencing solar brightening associated with decreasing concentrations of aerosols. Ground based measurements of solar irradiance in the region would be necessary to confirm our conclusions. Currently, there is no such monitoring being done. Our analysis also provides a useful baseline for naturally derived aerosols representative of background conditions in this region of the US. Establishing the background helps to delineate the $PM_{2.5}$ contributions of the metropolitan area of Atlanta. Thus, it is likely that future air quality control strategies will need to focus upon the anthropogenic component, while also incorporating

AMTD
4, 7559–7595, 2011

naturally occurring aerosols. Additionally, the air quality control policies that have likely resulted in solar brightening might have potential climatic trade-offs. As such these longer-term analyses are critical for evaluation of the air pollution regulatory policies, and these analyses can serves as baselines of measures that can be used to access impacts of future policies and climate change. The methodology applied here is readily applicable to regions that have sufficient ground based aerosol measurements so long as the chosen area is large enough for sufficient satellite coverage. The need for finer scale resolution satellite sensors will aid a host of applications seeking to do more detailed regional and local scale analyses. Users of satellite data need to be aware of possible bias within the data at land-water boundaries, which is an important consideration given that so many highly populated areas are near coasts. It is possible that with newer sensors better treatment of these issues will be addressed. Our future work will focus upon the climatic impacts of the decreasing aerosol trend on this region.

Acknowledgements. E. J. Alston would like to thank the Science Directorate, NASA LaRC for its support, and Bruce G. Doddridge for his helpful discussions. I. N. Sokolik acknowledges partial support from the Radiation Sciences Programs. We thank the MISR team for providing access to data, and useful discussions. This work was partially performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

References

Alpert, P. and Kischa, P.: Quantification of the effect of urbanization on solar dimming, Geophys. Res. Lett., 35, L08801, doi:10.1029/2007GL033012, 2008. 7561

Alpert, P., Kishcha, P., Kaufman, Y. J., and Schwarzbard, R.: Global dimming or local dimming?: Effect of urbanization on sunlight availability, Geophys. Res. Lett., 32, L17802, doi:10.1029/2005gl023320, 2005. 7560, 7561

Alston, E. J., Sokolik, I. N., and Doddridge, B. G.: Investigation into the use of satellite data in aiding characterization of particulate air quality in the Atlanta, Georgia metropolitan area, J. Air Waste Manage., 61, 211–225, doi:10.3155/1047-3289.61.2.211, 2011. 7563, 7567, 7570

AMTD

4, 7559–7595, 2011

Chu, D. A., Kaufman, Y. J., Ichoku, C., Remer, L. A., Tanré, D., and Holben, B. N.: Validation of MODIS aerosol optical depth retrieval over land, Geophys. Res. Lett., 29, 1617, doi:10.1029/2001GL013205, 2002. 7571

Diner, D. J., Beckert, J. C., Bothwell, G. W., and Rodriguez, J. I.: Performance of the MISR instrument during its first 20 months in Earth orbit, IEEE T. Geosci. Remote, 40, 1449–1466, 2002. 7566

Dutton, E. G., Nelson, D. W., Stone, R. S., Longenecker, D., Carbaugh, G., Harris, J. M., and Wendell, J.: Decadal variations in surface solar irradiance as observed in a globally remote network, J. Geophys. Res., 111, D19101, doi:10.1029/2005jd006901, 2006. 7561

Edgerton, E. S., Hartsell, B. E., Saylor, R. D., Jansen, J. J., Hansen, D. A., and Hidy, G. M.: The Southeastern Aerosol Research and Characterization Study: Part II. Filter-based measurements of fine and coarse particulate matter mass and composition, J. Air Waste Manage., 55, 1527–1341, 2005. 7562

Engel-Cox, J. A., Holloman, C. H., Coutant, B. W., and Hoff, R. M.: Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality, Atmos. Environ., 38, 2495–2509, doi:10.1016/j.atmosenv.2004.01.039, 2004. 7563

Gilgen, H., Roesch, A., Wild, M., and Ohmura, A.: Decadal changes in shortwave irradiance at the surface in the period from 1960 to 2000 estimated from Global Energy Balance Archive Data, J. Geophys. Res., 114, D00D08, doi:10.1029/2008jd011383, 2009. 7560

Goldstein, A. H., Koven, C. D., Heald, C. L., and Fung, I. Y.: Biogenic carbon and anthropogenic pollutants combine to form a cooling haze over the southeastern United States, Proc. Natl. Acad. Sci. USA, 106, 8835–8840, doi:10.1073/pnas.0904128106, 2009. 7562, 7571, 7572, 7575, 7576

Gupta, P. and Christopher, S. A.: Seven year particulate matter air quality assessment from surface and satellite measurements, Atmos. Chem. Phys., 8, 3311–3324, doi:10.5194/acp-8-3311-2008, 2008. 7563

Gupta, P. and Christopher, S. A.: Particulate matter air quality assessment using integrated surface, satellite, and meteorological products: Multiple regression approach, J. Geophys. Res., 114, D14S07, doi:10.1029/2008JD011496, 2009. 7563

Heald, C. L., Coe, H., Jimenez, J. L., Weber, R. J., Bahreini, R., Middlebrook, A. M., Russell, L. M., Jolleys, M., Fu, T. M., Allan, J. D., Bower, K. N., Capes, G., Crosier, J., Morgan, W. T., Robinson, N. H., Williams, P. I., Cubison, M. J., DeCarlo, P. F., and Dunlea, E. J.: Exploring the vertical profile of atmospheric organic aerosol: comparing 17 aircraft field campaigns

AMTD

4, 7559–7595, 2011

Characterization of aerosols of over a decade

E. J. Alston et al.

with a global model, Atmos. Chem. Phys. Discuss., 11, 25371–25425, doi:10.5194/acpd-11-25371-2011, 2011. 7576

Hinkelman, L. M., Stackhouse, Paul W., J., Wielicki, B. A., Zhang, T., and Wilson, S. R.: Surface insolation trends from satellite and ground measurements: Comparisons and challenges, J. Geophys. Res., 114, D00D20, doi:10.1029/2008jd011004, 2009. 7563

Hoff, R. M. and Christopher, S. A.: Remote sensing of particulate pollution from space: Have we reached the promised land?, J. Air Waste Manage., 59, 645–675, doi:10.3155/1047-3289.59.6.645, 2009. 7563

Kahn, R. A., Garay, M. J., Nelson, D. L., Yau, K. K., Bull, M. A., Gaitley, B. J., Martonchik, J. V., and Levy, R. C.: Satellite-derived aerosol optical depth over dark water from MISR and MODIS: Comparisons with AERONET and implications for climatological studies, J. Geophys. Res., 112, D18205, doi:10.1029/2006jd008175, 2007. 7571

Kahn, R. A., Nelson, D. L., Garay, M. J., Levy, R. C., Diner, D. J., Martonchik, J. V., Paradise, S. R., Hansen, E. G., and Remer, L. A.: MISR Aerosol product attributes and statistical comparisons with MODIS, IEEE T. Geosci. Remote, 47, 4095–4114, doi:10.1109/TGRS.2009.2023115, 2009. 7563, 7569, 7570

Kahn, R. A., Gaitley, B. J., Garay, M. J., Diner, D. J., Eck, T. F., Smirnov, A., and Holben, B. N.: Multiangle Imaging SpectroRadiometer global aerosol product assessment by comparison with the Aerosol Robotic Network, J. Geophys. Res., 115, D23209, doi:10.1029/2010jd014601, 2010. 7567

Kahn, R. A., Garay, M. J., Nelson, D. L., Levy, R. C., Bull, M. A., Diner, D. J., Martonchik, J. V., Hansen, E. G., Remer, L. A., and Tanr, D.: Response to "Toward unified satellite climatology of aerosol properties. 3. MODIS versus MISR versus AERONET", J. Quant. Spectrosc. Ra., 112, 901–909, doi:10.1016/j.jqsrt.2010.11.001, 2011. 7563, 7575

Koren, I., Remer, L. A., Kaufman, Y. J., Rudich, Y., and Martins, J. V.: On the twilight zone between clouds and aerosols, Geophys. Res. Lett., 34, L08805, doi:10.1029/2007gl029253, 2007. 7569

Lee, S., Wang, Y., and Russell, A. G.: Assessment of secondary organic carbon in the Southeastern United States: A review, J. Air Waste Manage., 60, 1282–1292, doi:10.3155/1047-3289.60.11.1282, 2010. 7562

Levy, R. C., Remer, L. A., Martins, J. V., Kaufman, Y. J., Plana-Fattori, A., Redemann, J., and Wenny, B.: Evaluation of the MODIS Aerosol Retrievals over Ocean and Land during CLAMS, J. Atmos. Sci., 62, 974–992, doi:10.1175/jas3391.1, 2005. 7571

Levy, R. C., Remer, L. A., Mattoo, S., Vermote, E. F., and Kaufman, Y. J.: Second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance, J. Geophys. Res., 112, D13211, doi:10.1029/2006JD007811, 2007. 7566

Levy, R. C., Remer, L. A., Kleidman, R. G., Mattoo, S., Ichoku, C., Kahn, R., and Eck, T. F.: Global evaluation of the Collection 5 MODIS dark-target aerosol products over land, Atmos. Chem. Phys., 10, 10399–10420, doi:10.5194/acp-10-10399-2010, 2010. 7575

Liu, L. and Mishchenko, M. I.: Toward unified satellite climatology of aerosol properties: Direct comparisons of advanced level 2 aerosol products, J. Quant. Spectrosc. Ra., 109, 2376–2385, doi:10.1016/j.jqsrt.2008.05.003, 2008. 7563, 7570

Long, C. N., Dutton, E. G., Augustine, J. A., Wiscombe, W., Wild, M., McFarlane, S. A., and Flynn, C. J.: Significant decadal brightening of downwelling shortwave in the continental United States, J. Geophys. Res., 114, D00D06, doi:10.1029/2008jd011263, 2009. 7561

Martonchik, J. V., Diner, D. J., Crean, K. A., and Bull, M. A.: Regional aerosol retrieval results from MISR, IEEE T. Geosci. Remote, 40, 1520–1531, 2002. 7567

Martonchik, J. V., Kahn, R. A., and Diner, D. J.: Retrieval of aerosol properties over land using MISR observations, in: Satellite Aerosol Remote Sensing Over Land, edited by: Kokhanovsky, A. A. and de Leeuw, G., Springer, Berlin, 2009. 7567

Menne, M., Williams, C., and Vose, R.: The U.S. Historical Climatology Network Monthly Temperature Data, Version 2, B. Am. Meterol. Soc., 90, 993–1007, doi:10.1175/2008BAMS2613.1, 2009. 7576

Mishchenko, M., Geogdzhayev, I., Rossow, W., Cairns, B., Carlson, B., Lacis, A., Liu, L., and Travis, L.: Long-term satellite record reveals likely recent aerosol trend, Science, 315, 1543, doi:10.1126/science.1136709, 2007. 7563

Remer, L. A., Kleidman, R. G., Levy, R. C., Kaufman, Y. J., Tanré, D., Mattoo, S., Martins, J. V., Ichoku, C., Koren, I., Yu, H., and Holben, B. N.: Global aerosol climatology from the MODIS satellite sensors, J. Geophys. Res., 113, D14S07, doi:10.1029/2007jd009661, 2008. 7569, 7570

Schwartz, S. E., Charlson, R. J., Kahn, R. A., Ogren, J. A., and Rodhe, H.: Why hasn't Earth warmed as much as expected?, J. Climate, 23, 2453–2464, doi:10.1175/2009JCLI3461.1, 2010. 7561

Solomon, P. A., Chameides, W., Weber, R., Middlebrook, A., Kiang, C. S., Russell, A. G., Butler, A., Turpin, B., Mikel, D., Scheffe, R., Cowling, E., Edgerton, E., St. John, J., Jansen, J., McMurry, P., Hering, S., and Bahadori, T.: Overview of the 1999 Atlanta Supersite Project, J. Geophys. Res., 108, 8413, doi:10.1029/2001JD001458, 2003. 7562

Streets, D. G., Yan, F., Chin, M., Diehl, T., Mahowald, N., Schultz, M., Wild, M., Wu, Y., and Yu, C.: Anthropogenic and natural contributions to regional trends in aerosol optical depth, 1980–2006, J. Geophys. Res., 114, D00D18, doi:10.1029/2008jd011624, 2009. 7561

Wang, J. and Martin, S. T.: Satellite characterization of urban aerosols: Importance of including hygroscopicity and mixing state in the retrieval algorithms, J. Geophys. Res., 112, D17203, doi:10.1029/2006JD008078, 2007. 7575

Weber, R., Sullivan, A., Peltier, R., Russell, A., Yan, B., Zheng, M., de Gouw, J., Warneke, C., Brock, C., Holloway, J., Atlas, E., and Edgerton, E.: A study of secondary organic aerosol formation in the anthropogenic-influenced southeastern United States, J. Geophys. Res., 112, D13302, doi:10.1029/2007JD008408, 2007. 7562, 7576

Wen, G., Marshak, A., Cahalan, R. F., Remer, L. A., and Kleidman, R. G.: 3-D aerosol-cloud radiative interaction observed in collocated MODIS and ASTER images of cumulus cloud fields, J. Geophys. Res., 112, D13204, doi:10.1029/2006jd008267, 2007. 7569

Wild, M., Trüssel, B., Ohmura, A., Long, C. N., König-Langlo, G., Dutton, E. G., and Tsvetkov, A.: Global dimming and brightening: An update beyond 2000, J. Geophys. Res., 114, D00D13, doi:10.1029/2008jd011382, 2009. 7560, 7561

Zhang, H., Hoff, R., and Engel-Cox, J. A.: The relation between Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth and PM2.5 over the United States: A geographical comparison by US Environmental Protection Agency regions, J. Air Waste Manage., 59, 1358–1369, doi:10.3155/1047-3289.59.11.1358, 2009. 7563

Zhang, J., Reid, J. S., and Holben, B. N.: An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products, Geophys. Res. Lett., 32, 15803, doi:10.1029/2005GL023254, 2005. 7569

Table 1. Linear regression coefficients for satellite and $PM_{2.5}$ datasets. Significance for $\alpha = 0.5$ is denoted in bold. The units for slope are (AOD $month^{-1}$ or $\mu g\,m^{-3}\,month^{-1}$), and the units for y-intercept are (AOD or $\mu g\,m^{-3}$).

Dataset	Slope		Y-intercept	
	With trend	Without trend	With trend	Without trend
MODIS Terra	−0.000415	**−0.000434**	0.214	0.025
MISR Terra	−0.000177	−0.000112	0.15	0.11
MODIS Aqua	−0.000219	−0.000275	0.196	0.17
$PM_{2.5,FRM}$ *All GA*	**−0.46**	**−0.0448**	17.75	2.781
$PM_{2.5,FRM}$ *Atlanta*	**−0.0488**	**−0.0472**	18.187	2.951
$PM_{2.5,FRM}$ *Outside Atlanta*	**−0.0301**	**−0.302**	16.029	1.821
$PM_{2.5,TEOM}$ *All GA*	−0.0317	**−0.0319**	15.876	2.501
$PM_{2.5,TEOM}$ *Atlanta*	−0.0324	**−0.0319**	16.325	2.561
$PM_{2.5,TEOM}$ *Outside Atlanta*	**−0.0335**	**−0.0385**	15.876	2.696

AMTD
4, 7559–7595, 2011

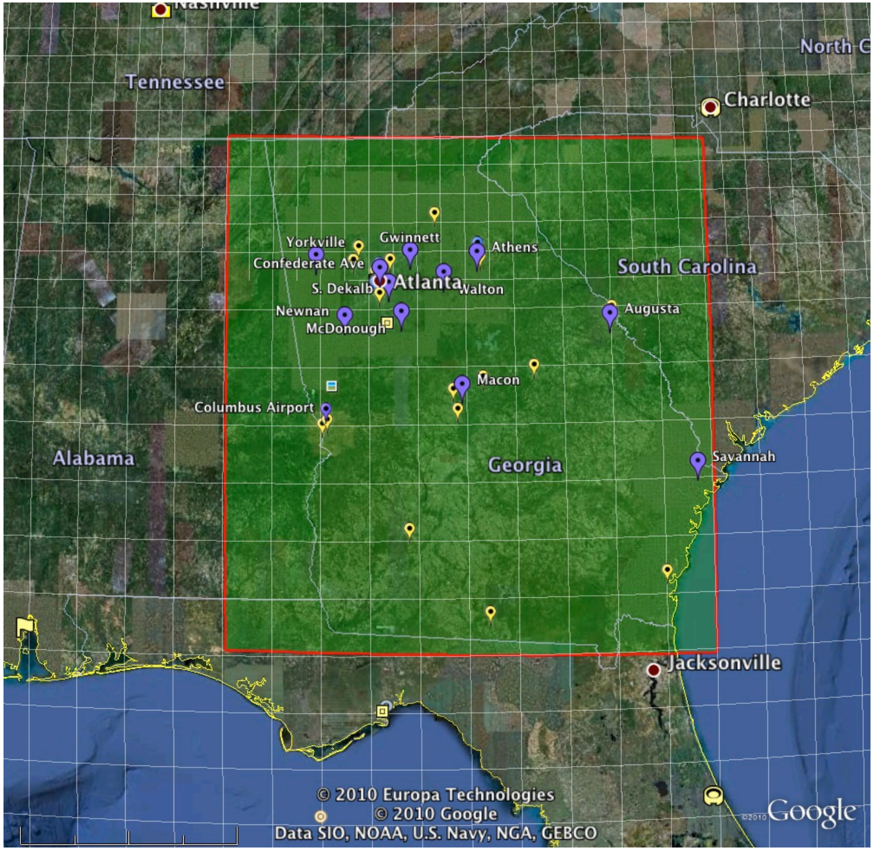

Fig. 1. Map of the US Southeast. Green box with red outline denotes study spatial domain for satellites 5° × 5°. Yellow markers represent EPA active $PM_{2.5}$ monitors ($PM_{2.5,FRM}$). Blue markers represent EPA inactive $PM_{2.5}$ monitors. Purple markers represent TEOM $PM_{2.5}$ monitors ($PM_{2.5,TEOM}$).

AMTD
4, 7559–7595, 2011

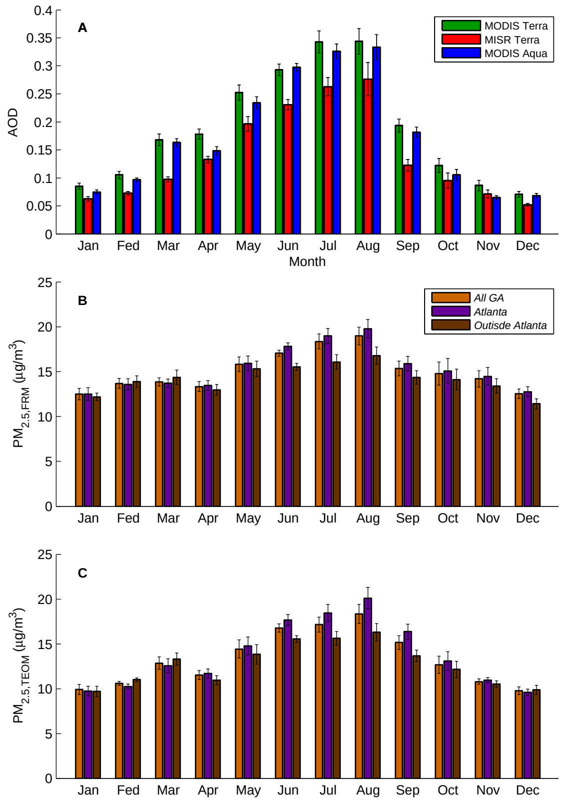

Fig. 2. **(A)** Bar plots of ten-year means by month for MODIS Terra AOD, MISR Terra AOD and MODIS Aqua AOD. **(B)** Same as **(A)** except for $PM_{2.5,FRM}$ *All GA*, $PM_{2.5,FRM}$ *Atlanta* and $PM_{2.5,FRM}$ *Outside Atlanta*. **(C)** Same as **(A)** except for $PM_{2.5,TEOM}$ *All GA*, $PM_{2.5,TEOM}$ *Atlanta* and $PM_{2.5,TEOM}$ *Outside Atlanta*. The units for all $PM_{2.5}$ are $\mu g\,m^{-3}$. Whiskers represent ± standard error of the mean for each respective dataset.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

4, 7559–7595, 2011

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

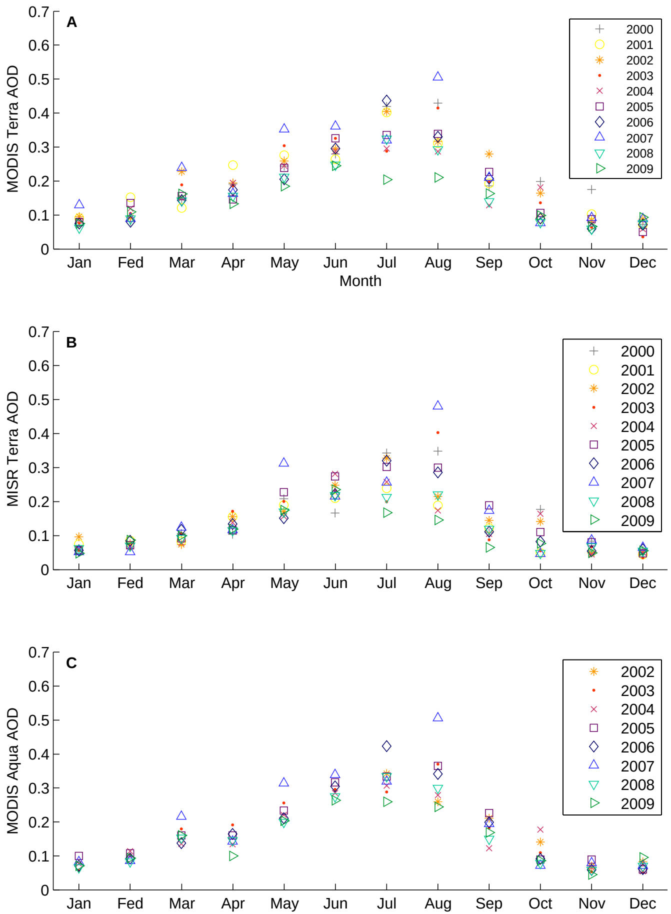

Fig. 3a. (A–C) Multi-year plots of monthly means for MODIS Terra AOD, MISR Terra AOD, and MODIS Aqua AOD.

AMTD
4, 7559–7595, 2011

Characterization of aerosols of over a decade

E. J. Alston et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

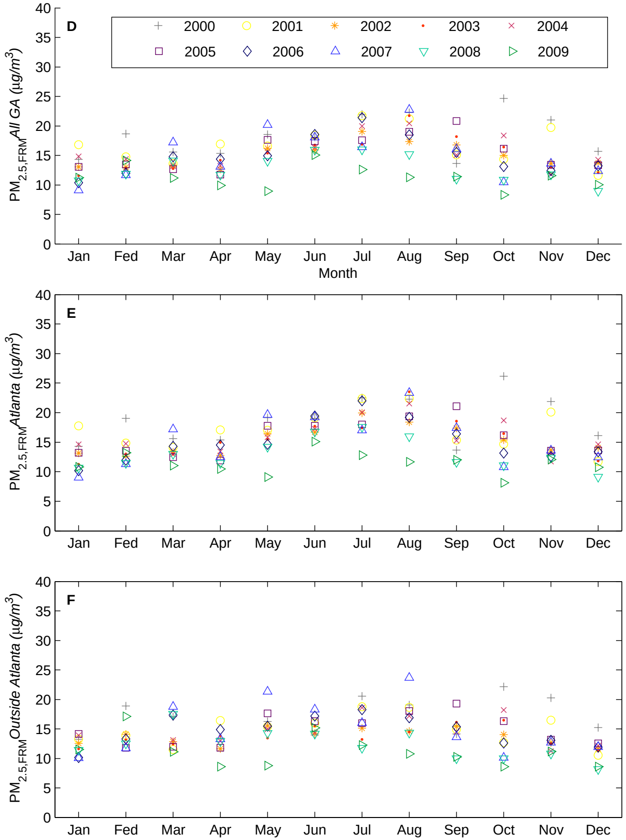

Fig. 3b. (D–F) Multi-year plots of monthly means for $PM_{2.5,FRM}$*All GA*, $PM_{2.5,FRM}$*Atlanta* , and $PM_{2.5,FRM}$*Outside Atlanta*. The units for all $PM_{2.5}$ are $\mu g\,m^{-3}$.

AMTD
4, 7559–7595, 2011

Characterization of aerosols of over a decade

E. J. Alston et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

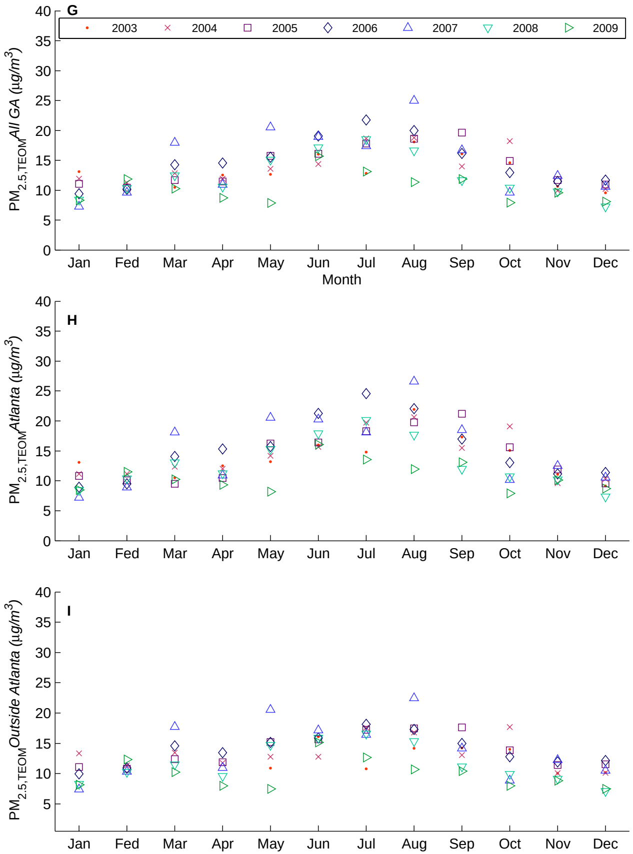

Fig. 3c. (G–I) Multi-year plots of monthly means for $PM_{2.5,TEOM}$ *All GA*, $PM_{2.5,TEOM}$ *Atlanta* , and $PM_{2.5,TEOM}$ *Outside Atlanta*. The units for all $PM_{2.5}$ are $\mu g\,m^{-3}$.

AMTD

4, 7559–7595, 2011

Characterization of aerosols of over a decade

E. J. Alston et al.

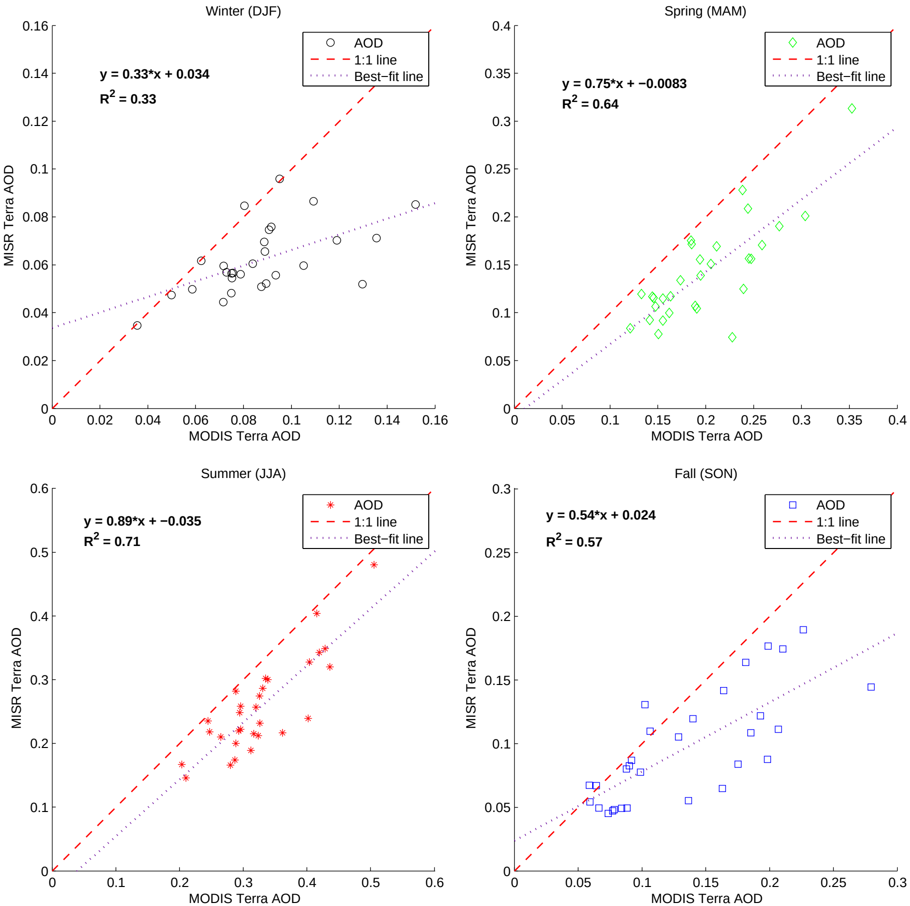

Fig. 4. Seasonal scatterplots of MODIS Terra AOD vs. MISR Terra AOD. Red dashed line denotes 1:1. Purple dotted line denotes linear regression line.

AMTD
4, 7559–7595, 2011

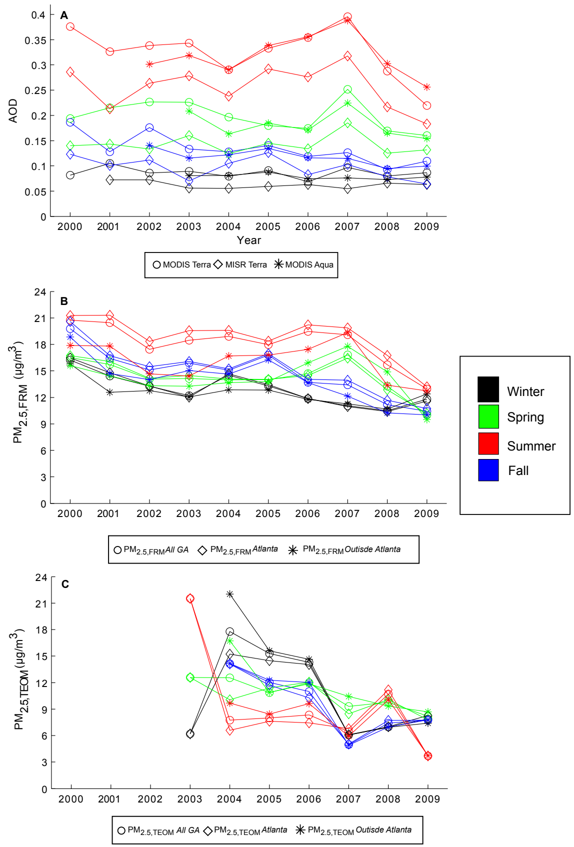

Fig. 5. **(A)** Timeseries of seasonal means for MODIS Terra AOD, MISR Terra AOD and MODIS Aqua AOD. **(B)** Same as **(A)** except for $PM_{2.5,FRM}$*All GA*, $PM_{2.5,FRM}$*Atlanta* , and $PM_{2.5,FRM}$*Outside Atlanta*. **(C)** Same as **(A)** except for $PM_{2.5,TEOM}$*All GA*, $PM_{2.5,TEOM}$*Atlanta* , and $PM_{2.5,TEOM}$*Outside Atlanta*. The units for all $PM_{2.5}$ are $\mu g\,m^{-3}$.

AMTD
4, 7559–7595, 2011

Characterization of aerosols of over a decade

E. J. Alston et al.

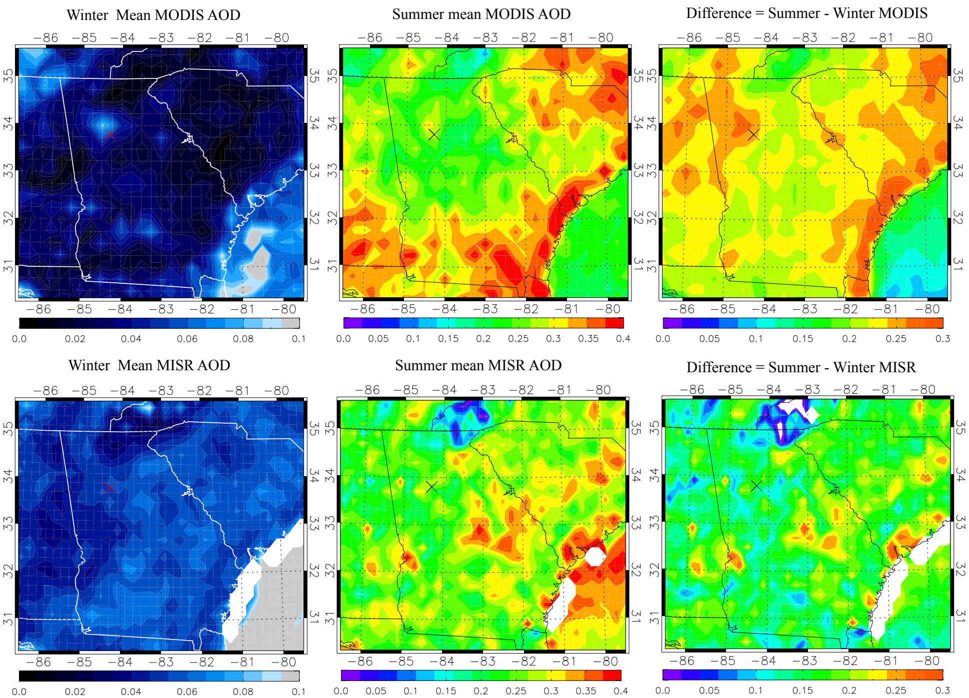

Fig. 6. Maps of satellite AOD. **(A)** Winter mean AOD for MODIS Terra. **(B)** Summer mean AOD for MODIS Terra. **(C)** Difference between summer mean AOD minus winter mean AOD for MODIS Terra. **(D)** Same as **(A)** except for MISR Terra. **(E)** Same as **(B)** except for MISR Terra. **(F)** Same as **(C)** except for MISR Terra. In (**A** and **D**) the red "X" denotes Atlanta, GA. In (**B–C** and **E–F**) the navy X denotes Atlanta, GA.

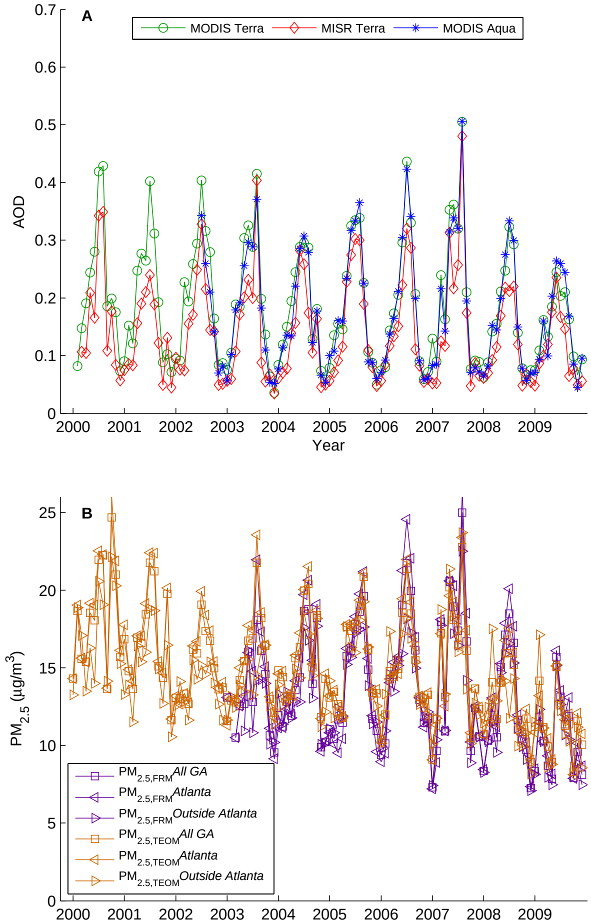

Fig. 7. Timeseries of monthly means for satellite AOD and $PM_{2.5}$ datasets. The units for all $PM_{2.5}$ are $\mu g\,m^{-3}$.

AMTD
4, 7559–7595, 2011

Characterization of aerosols of over a decade

E. J. Alston et al.

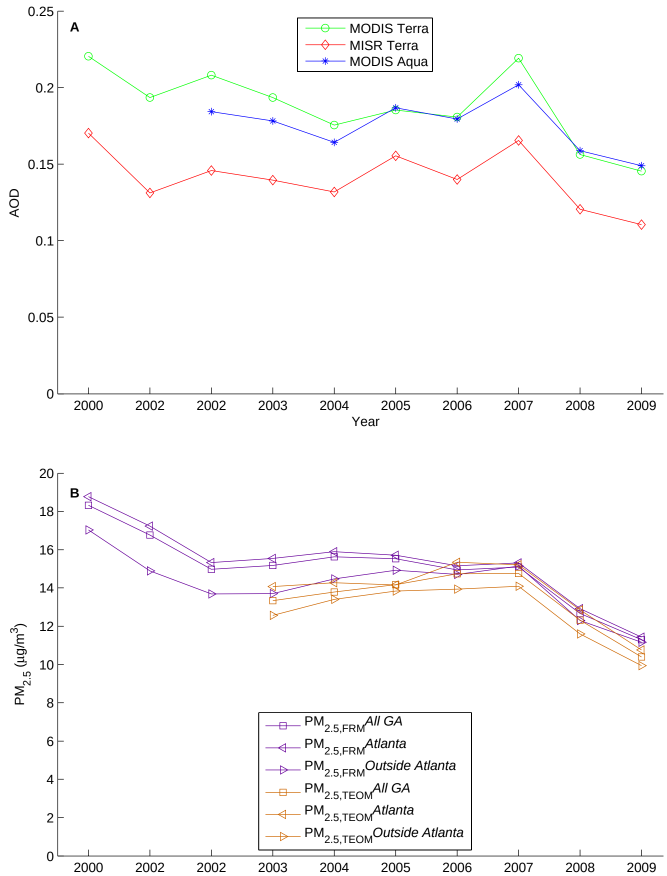

Fig. 8. Timeseries of multi-year means for satellite AOD and $PM_{2.5}$ datasets.The units for all $PM_{2.5}$ are $\mu g\,m^{-3}$.

AMTD
4, 7559–7595, 2011

Characterization of aerosols of over a decade

E. J. Alston et al.

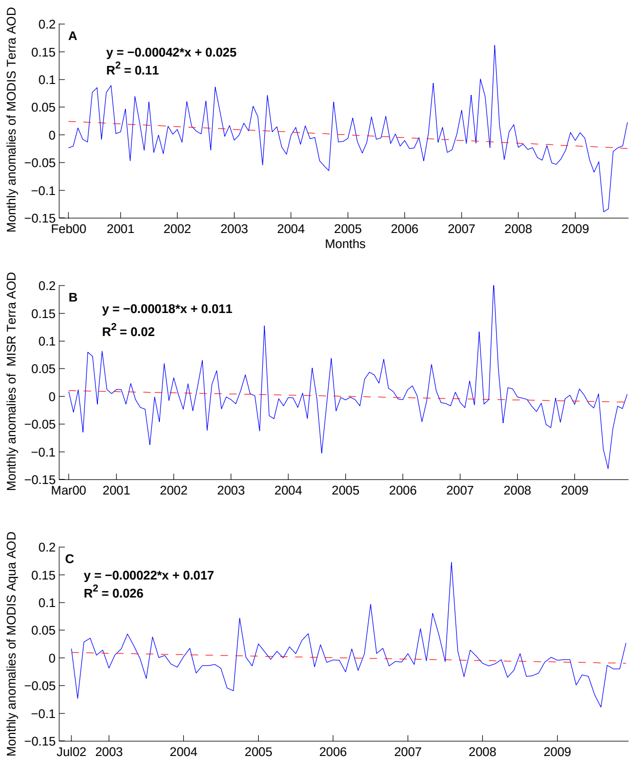

Fig. 9a. (A–C) Timeseries of monthly anomalies for MODIS Terra AOD, MISR Terra AOD, and MODIS Aqua AOD.

AMTD
4, 7559–7595, 2011

Characterization of aerosols of over a decade

E. J. Alston et al.

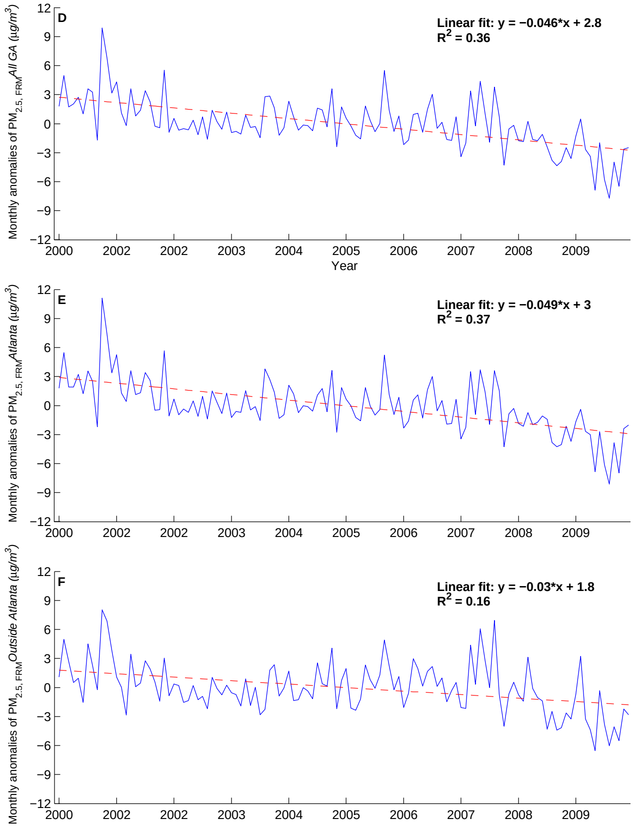

Fig. 9b. **(D–F)** Timeseries of monthly anomalies for $PM_{2.5,FRM}$ *All GA*, $PM_{2.5,FRM}$ *Atlanta* , and $PM_{2.5,FRM}$ *Outside Atlanta*. The units for all $PM_{2.5}$ are μg m^{-3}.

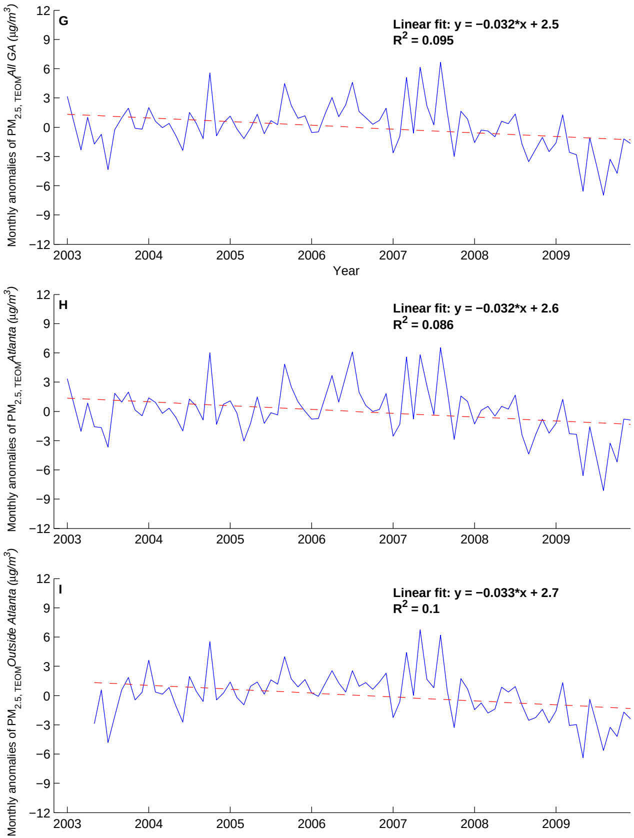

Fig. 9c. **(G–I)** Timeseries of monthly anomaliesfor $PM_{2.5,TEOM}$ *All GA*, $PM_{2.5,TEOM}$ *Atlanta* , and $PM_{2.5,TEOM}$ *Outside Atlanta*. The units for all $PM_{2.5}$ are $\mu g\,m^{-3}$.

AMTD
4, 7559–7595, 2011