Investigation into the use of satellite data in aiding characterization of particulate air quality in the Atlanta, Georgia metropolitan area

Erica J. Alston [1,2] and Irina N. Sokolik [2], Bruce G. Doddridge[1]

[1] U.S. National Aeronautics and Space Administration, Langley Research Center, Science Directorate, Hampton, VA 23681, USA
[2] Georgia Institute of Technology, School of Earth and Atmospheric Sciences, Atlanta, GA 30332, USA

ABSTRACT

Poor air quality episodes occur often in metropolitan Atlanta, Georgia. The primary focus of this research is to assess the capability of satellites as a tool in characterizing air quality in Atlanta. Results indicate that intra-city $PM_{2.5}$ concentrations show similar patterns as other U.S. urban areas, with the highest concentrations occurring within the city. Both $PM_{2.5}$ and MODIS AOD show more increases in the summer than spring, yet MODIS AOD doubles in the summer unlike $PM_{2.5}$. A majority of OMI AI is below 0.5. Using this value as an ambient measure of carbonaceous aerosols in the urban area, aerosol transport events can be identified. Our results indicate that MODIS AOD is well correlated with $PM_{2.5}$ on a yearly and seasonal basis with correlation coefficients as high as 0.8 for Terra and 0.7 for Aqua. A possible alternative view of the $PM_{2.5}$ and AOD relationship is seen through the use of AOD thresholds. These probabilistic thresholds provide a means to describe the AQI through the use of past AOD for a specific area. We use the NAAQS to classify the AOD into different AQI codes, and probabilistically determine thresholds of AOD that represent the majority of a specific AQI category. For example, the majority 80% of moderate AQI days have AOD values between 0.5 - 0.6. The development of thresholds could be a tool used to evaluate air quality from the use of satellites in regions where there are sparse ground-based measurements of $PM_{2.5}$.

IMPLICATIONS

Satellites can be used successfully as a tool for characterizing air quality on an urban scale. Statistical analysis of multi-year satellite data can yield a useful and easily understandable way of describing air quality through satellite derived AQI. In areas without many monitoring sites of $PM_{2.5}$, this approach could be useful to those air quality forecasters. Additionally, the use of satellite thresholds could increase satellite utility beyond that of qualifying events for exclusion using the U.S. EPA's exceptional event rule in determination of attainment of the NAAQS.

INTRODUCTION

Any person flying into Atlanta, Georgia's Hartsfield-Jackson Atlanta International Airport during the summer will see first-hand the visible effects of poor air quality in Atlanta. Atlanta has the highest population density in the southeastern U.S. making it one of the larger urban areas in the contiguous U.S. (http://www.census.gov/popest/metro/metro.html). The metropolitan area is comprised of 28 counties, with the city boundary contained mostly within Fulton County. High population density and large amounts of environmental toxins have placed Atlanta at the top of Forbes's Most Toxic City List for 2009 (http://www.forbes.com/2009/11/02/toxic-cities-pollution-lifestyle-real-estate-toxic-cities.html). The American Lung Association declares Atlanta as the 17th worst city for year-round particle pollution (http://www.stateoftheair.org/2009/city-rankings/polluted-cities-particle-pollution-year.html). This study considers particle pollution as a mixture of small particles and liquid drops that have aerodynamic diameter less than 2.5 μm ($PM_{2.5}$). Epidemiological studies in Atlanta have linked increases in particle pollution to increased asthmatic pediatric emergency room visits [1], while Peel et al. [2] found that the risk of death increased for hypertensive people in cases of elevated PM_{10}.

Assessment of air quality is commonly based on averages of 24-hour data from ground-based measurements of $PM_{2.5}$ performed at dedicated monitoring sites. The use of 24-hour average $PM_{2.5}$ data is to relate concentrations to the air quality index (AQI), which relates the level of air pollution to possible health effects. The AQI is used to disseminate information about air quality to the public via different methods of media, e.g., local television news, radio or newspaper (Table 1). The AQI is scaled to relate the $PM_{2.5}$ concentrations to the National Ambient Air Quality Standard (NAAQS)[3]. Through the Clean Air Act of 1990, the U.S. EPA has the authority to set national air quality standards to protect the public health. In 2006, the U.S. EPA strengthened the NAAQS by reducing the 24-hour standard from 65 μgm^{-3} to 35 μgm^{-3}. In doing so, the AQI must now be revised to reflect the changes in the NAAQS, and this action by the EPA is currently under review. Table 1 gives the old AQI and the proposed AQI revisions. These changes will certainly affect a city's proportion of good, moderate, and unhealthy days. The $PM_{2.5}$ measurements that are used for AQI forecasts provide high temporal resolution, but lack spatial resolution and coverage. In a large metropolitan area like Atlanta with only seven monitoring sites for forecast purposes, the lack of spatial resolution has implications for air quality forecasts and impacts.

Satellite data has been thought of as a means to address the lack of spatial coverage by monitoring sites. Satellite observations can be used to characterize aerosols, identify aerosol transport, and identify cases of biomass burning [4-7]. Studies that relate satellite measurements to $PM_{2.5}$, generally use the aerosol optical depth (AOD) retrieved from the NASA MODIS

(Moderate Resolution Imaging Spectroradiometer) instrument. AOD is a measure of light extinction through the atmosphere for a given wavelength. Engel-Cox et al. [8] completed one of the first nationwide studies that presented results of the relationship between $PM_{2.5}$ and AOD. They demonstrated that the relationship varied by region, and the east coast of the U.S. had the highest correlation between AOD and $PM_{2.5}$. Further highlighting this regional perspective is the work of Al-Saadi et al. [9], which developed a methodology for applying AOD maps over maps of $PM_{2.5}$ concentrations for the entire U.S. to improve air quality forecasts through the IDEA (Infusing satellite Data into Environmental Applications) website (http://www.star.nesdis.noaa.gov/smcd/spb/aq/). Recently published work by Zhang et al. [10] updated the methodology of the IDEA website to account for the regional nature in the $PM_{2.5}$/AOD relationship. Gupta and Christopher [11] conducted a five-year study into assessing the relationship between AOD and $PM_{2.5}$ for most of the southeast U.S. The reported correlations showed a high degree of agreement, yet there was still interstate and intrastate variation.

Using an established methodology for relating $PM_{2.5}$ to AOD, other researchers focused on this relationship on a city-scale. Hutchinson et al. [12] report that MODIS was adept at describing an aerosol transport event that impacted air quality in parts of Texas. Research from the southern U.S. found that in Birmingham, AL, satellite data were well correlated with surface $PM_{2.5}$ measurements with a correlation coefficient as high as 0.7 [13, 14].

Most recently, Hoff and Christopher [15] provided an in-depth critical review of the field. Their study outlines issues that can prohibit wider applicability of satellite data for air quality studies. One issue is the spatial mismatch between satellite data and the $PM_{2.5}$ monitoring sites that provide point measurements. When stations are located closely together, it is likely that those sites will occur in the same satellite pixel that reduces the number of independent observations per station. Another issue lies in the assumptions used for satellite retrievals. The satellite science teams are constantly making updates to their retrieval algorithms to better represent the regionality of aerosol composition. AOD does not provide information about the location of aerosols within the atmospheric column. Aerosols that are transported into an area can be located higher in the atmosphere, where ground-based monitors do not detect it, but satellites do. Instances such as this cause a mismatch between what the satellite and ground-based monitors observe. Ultimately, one conclusion from Hoff and Christopher (2009) is that reducing the uncertainty of the $PM_{2.5}$/AOD through statistical regressions is unlikely, which is why we propose using a statistical analysis of AOD that directly relates to AQI bypassing the $PM_{2.5}$/AOD regression.

In this study, hourly and 24-hour averaged $PM_{2.5}$ measurements from seven $PM_{2.5}$ stations across the metro Atlanta area are analyzed along with MODIS AOD from March 1-August 31, 2004 – 2008. From the hourly data, subsets are created to coincide with Terra and Aqua satellite overpasses. Another satellite instrument used in this study is the Ozone Monitoring Instrument (OMI). This instrument provides measurements of aerosols in the UV-region of the electromagnetic spectrum. OMI performs many functions; however, of most interest to this study is its ability to detect light absorbing aerosols over land [16].

Here, we examine the applicability of satellite data to characterize representative urban aerosols in Atlanta. The specific goals of this research are to (1) determine the variability of $PM_{2.5}$ and satellite data on a yearly and seasonal basis; (2) assess the robustness of the $PM_{2.5}$-AOD relationship through linear regressions; and (3) statistically identify AOD thresholds that can prescribe air quality directly through AQI. We will also determine the effect of the new AQI designations in prescribing air quality through AOD thresholds.

DATA AND METHODOLOGY

$PM_{2.5}$ Monitoring Stations

As mentioned previously, the EPA makes determinations of whether states meet the NAAQS for particulate matter. That standard states that in order to receive attainment for daily $PM_{2.5}$, the 98th percentile of the three-year average at each pollution monitor cannot exceed 35 µgm-3 [3]. States usually own and operate a network of continuous measurements that are used primarily for air quality forecasts and air quality alerts. For this study, we obtained one-hour and 24-hour measurements of $PM_{2.5}$ from seven metro Atlanta Tapered-Element Oscillating Micobalances (TEOMs) from March 1 – August 31, 2004–2008, from the Georgia Department of Natural Resources, Ambient Monitoring Program (AMP) (http://www.air.dnr.state.ga.us/amp/). The type of measurements used in this research are not used for that determination; however, the Ambient Monitoring Program (AMP) assigns an exceedance whenever their 24-hour averaged TEOM-based $PM_{2.5}$ measurements exceed the NAAQS daily standard of 35.5 μgm^{-3}. Five out the seven stations have data for the entire period;

however, two stations (Confederate Ave. and Walton) only have data for 66% of 2005. These seven stations cover three types of locations; urban – Confederate Ave., suburban – Gwinnett, S. DeKalb, McDonough, and rural – Newnan, Walton, Yorkville. The $PM_{2.5,24}$ dataset is a moving average that uses the current hour's concentrations and the past 23 hours' concentrations. Two data sets were created for pairing with MODIS satellite observations, which have different equatorial crossing times. To match MODIS on Terra, hourly measurements from 10 and 11 am were averaged together to create the dataset $PM_{2.5,T}$. Similarly for MODIS on Aqua, hourly measurements from 1 and 2 pm were averaged together to create the dataset $PM_{2.5,A}$. Analyses are performed using all 3 $PM_{2.5}$ datasets ($PM_{2.5,24}$, $PM_{2.5,T}$ and $PM_{2.5,A}$).

MODIS Data

The MODerate Resolution Imaging Spectroradiometer (MODIS) instrument flies onboard two of NASA's Earth Observing System (EOS) satellites. The first MODIS instrument is on the Terra platform, and the second MODIS instrument is on the Aqua platform. Terra flies in descending polar orbit with an equatorial crossing time of approximately 10:30 am; while Aqua, flies in ascending polar orbit with an equatorial crossing time of approximately 1:30 pm. Generally, the satellites have overpass times over Georgia 5 -15 minutes after their equatorial crossing times. Both satellites orbit 700 km above the Earth in low earth orbit, and they have near global coverage daily.

MODIS passively measures reflected radiances from Earth across a broad wavelength spectrum. It primarily uses three wavelength channels (0.47, 0.66 and 2.12 μm) to measure atmospheric aerosols over land [17]. We use over five GB and 3700 files of Collection 5 data from NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS). Collection 5 is the most recent release of the data products from the MODIS science team. The analysis is performed with MODIS Level 2 data, which have a resolution of 10x10 km^2. The variable of most importance to this study is "Optical_Depth_Land_and_Ocean" at the 0.55μm wavelength. AOD is an unitless measure of the amount of light attenuation over a set distance, i.e., path. AOD can vary between 0 and 5, with values above unity being ascribed as heavy haze, biomass burning, or dust [8].

Following similar methodologies from Gupta and Christopher [18] and Engel-Cox et al. [8], satellite data are matched with station data using a 0.5° degree box around each ground station. Only days where both data types are available are considered for additional correlation analysis.

The time period of March 1 – August 31, 2004–2008, is considered for this research. Thus each MODIS instrument has seven different datasets that correspond to the AOD measurements over the seven ground-based $PM_{2.5}$ measurement stations. Another dataset is created for comparisons with the OMI sensor, i.e., city-scale AOD. This dataset is considered to be Atlanta AOD and covers a lat/lon box of 33 – 34.5° N and 83.5 – 85.3°W. Additionally the time period for this dataset matches the OMI dataset.

OMI Data

The Ozone Monitoring Instrument (OMI) takes measurements in the near-ultraviolet (UV) for retrievals of gases and aerosols [16]. OMI flies onboard the NASA satellite Aura. Aura and Aqua (MODIS) fly together in a satellite constellation called A-Train. A great advantage of the satellite constellation is multiple measurements made from different sensors within 15 minutes of each other.

In this study we consider the aerosol products only, primarily the UV Aerosol Index (AI). The time period of March 1- August 31, 2005–2008, is considered, which is one year shorter than the $PM_{2.5}$ and MODIS data because Aura did not launch until July 2004. OMI data were obtained from the NASA GSFC DAAC. The most recent release of data is in Collection 3. The OMI instrument has a swath of 2600 km and provides mostly global coverage daily. Aerosol products are retrieved at a spatial resolution of 13 x 24 km at nadir, however the spatial resolution increases at the extremes of the satellite swath [16].. In the presence of UV-absorbing aerosols, the AI has positive measures with values above 0.5 considered significant [6]. Due to OMI's larger footprint, it is difficult to match OMI measurements with specific station locations. Thus OMI measurements are taken for a lat/lon box of 33 – 34.5° N and 83.5 – 85.3°W. Although, AI is a qualitative measure, it does provide information about the spatial pattern of UV-absorbing aerosols over land. This data product is uniquely able to identify the carbonaceous aerosols associated with biomass burning and urban pollution.

RESULTS

Characterization of urban aerosols through $PM_{2.5}$

We first want to determine the variability of $PM_{2.5}$ on a yearly and seasonal basis. The analysis of yearly means reveals that there is year-to-year variability within all three $PM_{2.5}$

datasets ($PM_{2.5,T}$, $PM_{2.5,A}$ and $PM_{2.5,24}$). Barplots of the five years of selected months (1 March – 31 August) of the $PM_{2.5,A}$ and $PM_{2.5,T}$, $PM_{2.5,24}$ datasets for Gwinnett (33.96°, -84.07°) and Newnan (33.40°, -84.74°) sites are shown in Figure 1 (A & B). Gwinnett and Newnan are used to contrast differences between urban/suburban vs. rural stations. These barplots display how $PM_{2.5}$ averages varied over the study period. The years of 2006 and 2007 have the highest means for all seven sites. The means for each year all the stations are shown in Table 1; though we only consider spring and summer, our $PM_{2.5}$ averages agree well other published work of $PM_{2.5}$ in Atlanta [19]. The years 2004 and 2008 are below the five-year average, while 2006 and 2007 are the highest above the five-year average for Gwinnett, and 2005–2007 are the highest above the five-year average for Newnan. $PM_{2.5,24}$ for all stations is in between $PM_{2.5,T}$ and $PM_{2.5,A}$, but it behaves similarly to the other $PM_{2.5}$ datasets. Both Table 1 and Figure 1 (A&B) show that the average $PM_{2.5}$ concentrations vary about 10 μgm^{-3} from each other. There are some instances where the difference between $PM_{2.5,A}$ and $PM_{2.5,T}$ are significant for $\alpha = 0.05$, and those instances are bolded in Table 1. Edgerton et al. [19] found that during the day, hourly measurements can vary by as much as 50 μgm^{-3} in the Atlanta area comparable to observations in this study

$PM_{2.5}$ data show a distinct seasonality having higher values in the summer compared to spring. Figure 1 (C and D) show seasonal averages of the three $PM_{2.5}$ datasets for Gwinnett and Newnan. During the spring at Gwinnett, $PM_{2.5,T}$ varies from around 15 – 21 μgm^{-3}, $PM_{2.5,A}$ varies between 10 -14 μgm^{-3}, and $PM_{2.5,24}$ varies between 13 – 16 μgm^{-3}. Summer averages show increases of 30 – 45% over spring averages. All stations show similar values. The similarity between stations is shown through timeseries analysis of $PM_{2.5}$ (not shown), and the analysis also indicates that summer has more variability than spring. Research by Butler et al. [20] and Edgerton et al. [21]provide additional information on seasonality of $PM_{2.5}$ in metro Atlanta. However, there is recent work that hypothesizes that secondary organic aerosols (SOA) which have a summertime maximum could be a previously underestimated portion of $PM_{2.5}$ [22]. It should be noted that the reduced seasonality of 2007 is likely a product of the late spring wildfire of 2007, which produced the additional influx of aerosols to the metro area [23].

We have discussed the yearly and seasonal trends within the $PM_{2.5}$ data; however, we also want to understand how each of the satellite-overpass datasets relate to each other and to $PM_{2.5,24}$. To assess the similarity between $PM_{2.5,T}$ and $PM_{2.5,A}$ we created scatterplots of the two datasets and calculated linear regression statistics. Scatterplots of $PM_{2.5,A}$ vs. $PM_{2.5,T}$ for 2004–2008 and all years combined are shown in Figure 2. Correlation coefficients (r or r-values) between $PM_{2.5,T}$ and $PM_{2.5,A}$ vary around 0.78 – 0.85. The coefficient of determination (R^2), which is a measure of variance, varies between 0.61 – 0.72. When seasonality was examined between these two datasets, the summertime showed higher r-values than spring. Our results are consistent with Butler et al [20], which shows diurnal variation of $PM_{2.5}$ in Atlanta as a function of season, and during the summer the diurnal variation is less pronounced than during other seasons. From these statistical measures we conclude that both datasets have similar observations, but there are instances where the diurnal cycle and meteorology change the conditions between Terra and Aqua. When the $PM_{2.5,24}$ dataset is compared to the $PM_{2.5,A}$ and $PM_{2.5,T}$ datasets, statistics show that they are well correlated with r-values between 0.65 – 0.83. $PM_{2.5,T}$ correlates slightly better than $PM_{2.5,A}$, but 30% of the variance shown by the satellite-overpass datasets is not represented in the 24-hour average. This could have implications for studies that relate MODIS AOD to the 24-hour average of $PM_{2.5}$.

We have shown that during our study period the $PM_{2.5}$ concentrations across metro Atlanta are similar but have differences due to location. A majority of stations have their highest means during 2006 and 2007, with 2004 and 2008 as local minima. The year 2007 was dominated by a wildfire that changed the nature of $PM_{2.5}$ in Atlanta by lessening the difference between spring and summer seasons. Across all stations summer months have increased $PM_{2.5}$ concentrations as shown by increased means and variances. Additionally, we have shown that $PM_{2.5,24}$ captures 70% of the variability within the satellite-overpass $PM_{2.5}$ datasets; this could impact the strength of the AOD and $PM_{2.5}$ correlations. For instance, during short (hours) duration exceedance events, the $PM_{2.5}$/AOD correlation will be lower if $PM_{2.5,24}$ is considered rather than hourly data centered around the satellite overpass. In the following section we will compare satellite measurements to the $PM_{2.5}$ measurements to determine how well the satellites capture the $PM_{2.5}$ behavior spatiotemporally.

Characterization of urban aerosols with satellite products (MODIS AOD and OMI AI)

In this section, we focus upon comparing the variability of MODIS AOD to $PM_{2.5}$ and we assess OMI's ability to characterize urban aerosols in Atlanta. Over 5GB and 3700 files of MODIS AOD data were analyzed. In comparing yearly averages of MODIS Terra to MODIS Aqua, Aqua has higher AOD at all stations for 2004-2006 and 2008. However, in 2007 Terra is markedly higher than Aqua. This finding is different from the $PM_{2.5}$ yearly averages where $PM_{2.5,T} > PM_{2.5,A}$,which might imply that Terra should record higher values of AOD, yet this is not the case. Yearly averages of MODIS AOD at Gwinnett and Newnan are presented in Figure 3 (A and B). Like the trend shown in Figure 1 (A and B), MODIS AODs have their highest averages in 2006 and 2007 and minima in 2004 and 2008. Aerosols that are trapped within a shallow boundary layer are more difficult to assess from space than well-mixed aerosols within a deep planetary boundary layer (PBL) typically found in the early afternoon [14].

From a seasonal perspective, MODIS AOD has higher summer averages than spring averages, which is in agreement with $PM_{2.5}$ (see Figure 1 (C and D)). In fact, for many cases the summertime AOD as shown in Figure 3 (C and D) is almost double that of the springtime, yet this doubling is not found in the $PM_{2.5}$ record. Barplots of seasonally averaged AOD from MODIS at Gwinnett and Newnan are shown in Figure 3 (C and D). Our results indicate that the difference between Aqua and Terra spring AOD is smaller than the difference between the two during the summer. However, examination of the $PM_{2.5}$ record yields that the largest difference between the datasets occurs during the spring rather than the summer. Goldstein et al. [24] hypothesize that the high summertime AOD values are driven by SOA from biogenic volatile organic compounds (BVOC) that occur aloft within the ABL thus not impacting surface mass measurements of $PM_{2.5}$.

Our previous analysis focused on AOD at specific stations, but we want to establish background levels of absorbing aerosols in Atlanta to determine if there is any relationship between MODIS AOD and OMI AI. We conduct the following analysis using city-scale datasets (see OMI Section for explanation). $PM_{2.5}$ in Atlanta is mostly carbonaceous in nature with 35.9% being organic carbon and 8.9 % being black carbon. The other dominant species is sulfate which comprise 25.3% of average $PM_{2.5}$ mass [21]. Aerosols in the U.S. southeast are small in diameter and are predominantly light-scattering. Maps of time averaged (March 1- Aug 31) Angstrom exponent from MODIS (not shown) confirm this result with values ranging from 1 – 1.6. Since the background is predominately made of light scattering particles, AI will be in a unique position to detect absorbing aerosols against this background. Averages of OMI AI show little variability from year to year, with a slight maximum occurring in 2007. As viewed from space, the carbonaceous portion of urban aerosols in Atlanta is fairly constant around 0.3 for 2005 – 2008. Also, across all years a majority (80%) of AI values are below 0.5. Using the yearly average or 80% cutoff to establish background conditions of Atlanta implies that if AI rises above these values it could be indicative of aerosol transport.

OMI AI does not appear to have the same seasonality as MODIS AOD. The mean and median values of AI vary little between spring and summer. Scatterplots of OMI AI vs. MODIS AOD Terra/Aqua are shown in Figure 4 to access the relationship between the datasets. As seen in Figure 4, there is not a discernable linear relationship between the AI and AOD. One feature shown in Figure 4 is that the same AI values correspond to lower AOD values in the spring and higher AOD values in the summer, which implies that any improvement of the AI/AOD relationship is solely due to larger AOD associated with summer. The lack of a linear relationship results in very low correlation coefficients as shown in Table 2. The correlation analysis of OMI and MODIS yielded low linear correlation values shown in Table 2. Having shown that AI and AOD are not related further substantiates the effectiveness of AI as an indicator for transport events. For instance, the small box in Figure 4(A) shows that AI is almost 1.4, but AOD is around 0.3 on 13 April 2005. There are no $PM_{2.5}$ exceedances on this day, and considering that AI is sensitive to aerosol height this implies that the transport is occurring above the PBL. This is an example of smoke remnants being transported into the area from the western U.S. Another example occurs in 2007 (see box in Figure 4C), where smoke aerosols are transported into the area. There were large active wildfires in Idaho and Montana during the time period August 2007. Those wildfires caused a large haze event across the eastern U.S. During this event there were $PM_{2.5}$ exceedances in Atlanta on 13, 15-18 August 2007. The carbonaceous aerosols detected by OMI on 14 August are aloft and most likely become entrained in the ABL on the following days. Jacob and Winner [25] conclude that wildfires could become an important and more frequent contributor to $PM_{2.5}$. The aerosols associated with this additional aerosol burden will most likely be carbonaceous in nature, and the baseline of AI already established would help to better assess the impact these potential wildfires will have on air quality.

We have shown that satellites adequately describe the general nature of urban aerosols in the metro Atlanta area. Though there are some differences between what times of day results in the highest values, the overall patterns of MODIS AOD match well with the $PM_{2.5}$ observed patterns on a yearly and seasonal basis. OMI AI allowed us to identify specific cases of aerosol transport into the metro area by detecting the absorbing signature associated with these events.

$PM_{2.5}$ and AOD Analysis

We perform a statistical analysis to assess the $PM_{2.5}$/AOD relationship in the Atlanta metropolitan area. Figure 5 presents a linear relationship between MODIS Terra and Aqua. The two satellites are well correlated with r-values > 0.78. While the coefficients of determination for the different years are above 0.6, the diurnal loading of aerosols, meteorological conditions, and boundary layer dynamics as well as technical issues between the two satellite instruments are all possible reasons why the R^2-values are not higher. During the summer in Georgia, the timing of convective systems growth often occurs in the early afternoon, which coincides with Aqua's overpass. In this study, MODIS Aqua has fewer observations than MODIS Terra, but both satellites have between 50 – 65% data available. Other U.S. locations have shown similar satellite data loss [26].

Across all seven stations and for both satellites, a majority of the points lie below the NAAQS exceedance standard of 35 μgm^{-3} and have AOD less than 0.7 as represented in Figure 6. Scatterplots of $PM_{2.5}$ vs. MODIS Terra and Aqua at Gwinnett and Newnan are shown for each year in Figure 6, where each year is represented by different symbols. The scatterplots can be divided into quadrants, the NE quadrant is Q1, the NW quadrant is Q2, the SW quadrant is Q3 and the SE quadrant is Q4. These quadrants are representative of certain meteorological dynamic conditions. For instance, Q1 and Q3 are most likely associated with a well-mixed boundary layer such that aerosols are well distributed throughout the atmospheric column, thus satellite and ground-based measurements are in sync together. A vast majority of the data points lie within Q3. Q3 contains points that have low AOD and good to moderate AQI. However, Q1 describes data points with both high AOD and high $PM_{2.5}$ measurements (i.e., orange and higher AQI).

The remaining two quadrants in most cases can distinguish between different sources of air pollution. The points within Q2 have high AOD but low $PM_{2.5}$ concentrations. This situation could arise from long-range transport of aerosols into the area. The long-range transport of aerosols generally occurs above the boundary layer. Subsequently, these aerosols do not necessarily impact ground-based measurements (see discussion in previous section). However, it is possible that those aerosols can become entrained within the boundary layer due to changing dynamics and can impact ground-based measurements further downwind of the source. Finally, Q4 has data points that coincide with high $PM_{2.5}$ concentrations and relative low AOD. More than likely, these points represent increasing $PM_{2.5}$ concentrations of local source emissions. A possible scenario where this could occur is a strong inversion. In late spring and summer in Georgia strong inversions occur that trap all the local sources of pollution, e.g., cars and power plants, close to the surface by hindering vertical mixing. Low-level aerosols are more difficult for satellites to detect, and again this could lead to a satellite and ground-based measurement mismatch.

We have discussed what factors could possibly influence the $PM_{2.5}$/AOD relationship; the following analysis involves determining the robustness of the $PM_{2.5}$/AOD relationship through correlations. For a majority of the stations, both Aqua and Terra are correlated with $PM_{2.5}$. Correlation coefficients for Aqua vary between 0.37 – 0.76, and Terra has r-values of 0.25 – 0.68 (see Tables 4 and 5). MODIS Terra and Aqua produce correlations that are similar to each other. In Tables 4 and 5, the correlation coefficient (r), the slope, y-intercept, and the number of observations are summarized. In 2007, MODIS Terra and Aqua have the highest correlations across all of the stations. The higher means of Terra AOD do not result in better agreement with $PM_{2.5}$, except in 2007 where Terra has higher r-values than Aqua. Terra also produces more variability in the correlation coefficients across the stations in comparison to Aqua. The seasonality of AOD and $PM_{2.5}$ is reflected in the values as well. Spring produces higher correlations than summer. The results presented here are somewhat different than the results from Gupta and Christopher [11]. In their study, they presented correlations between estimated $PM_{2.5}$ from both a two-variable model and multivariate model. Our correlations and slopes show more variance than their reported values. Some of the difference could be due to the different time periods under consideration.

To determine how robust the AOD is at characterizing $PM_{2.5}$, the AQI designations of $PM_{2.5}$ concentrations are used to categorize the AOD. For instance, all AOD data points that correspond to $PM_{2.5}$ concentrations between 0 – 15.4 μgm^{-3} are considered to be good/green AOD. This classification methodology is used for all six categories of AQI. This categorized AOD is then used to determine a threshold that can probabilistically separate days of air quality exceedances from days without exceedances.

Figures 7 and 8 show AQI classified Aqua/Terra MODIS AOD for 2004 – 2008. The top figure is for Terra and the bottom is for Aqua. For Figure 7 the upper panels are green AOD and the bottom panels are yellow AOD. The panels on the left are frequency histograms and on the right are cumulative histograms of AOD. In Figure 7, green and yellow AOD have similar frequency and cumulative distributions. The cumulative distributions for both satellites are interpreted as 80% of Code Green AOD are below 0.35, and 80% of Code Yellow AOD are below 0.65. In Figure 8 the upper panel is Code Orange AOD and if present the bottom panel is Code Red AOD. Code Orange and Red AOD have different distributions. It is not surprising that red AOD is skewed toward higher AOD. The closely related relationship between AOD and $PM_{2.5}$ suggests that high AOD will occur in cases of high $PM_{2.5}$. Code Orange AOD is associated with AOD of 0.75 for Aqua and 0.65 for Terra. The lack of Code Red AOD makes determination of thresholds difficult.

The broad thresholds (80%) discussed above yielded overestimation in the orange and red categories. To more accurately match the $PM_{2.5}$-derived AQI we used different thresholds from each satellite. For this we calculated AOD thresholds for Gwinnett for all years. The yearly threshold levels, e.g., 80%, 90%, and 95% were averaged to create AQI categorized AOD thresholds specifically tuned for Gwinnett. Figure 9 shows our AOD-derived AQI and $PM_{2.5}$-dervived AOD at Gwinnett. Specifically for Terra we used the 80% threshold for green AQI and 95% for yellow and orange AQI. The exact cut-offs for Terra AOD are: green is below 0.26, yellow is 0.26 – 0.72, orange 0.72 – 1.0, and red is everything greater than 1. For Aqua we used the 80% threshold for green AQI and 90% for yellow and orange AQI. While AOD cut-offs for Aqua are slightly different than for Terra. Aqua AOD thresholds are: green is below 0.28, yellow is 0.28 – 0.69, orange is 0.69 – 1.15, and red is everything over 1.15.

While we only show pie charts based upon the new AQI designations, there are small differences between them and pie charts produced with AOD-derived AQI using old designations. The differences occur mostly within the yellow and orange AQI categories. Though these figures are not an exact match for the $PM_{2.5}$-based AQI, they provide information at an easily understandable and relatable manner. Additionally, the best guesses used in determining quadrants agree well with the probabilistic measures of AOD given by this type of analysis. Having probabilistic means to describe the incidence of AOD over metro Atlanta allows for this threshold approach to be extrapolated for use in areas without $PM_{2.5}$ monitors. AQI categorized AOD has great applicability to rural areas in Georgia and the other rural areas across the country, because this approach is not bound strictly by achieving high correlations between $PM_{2.5}$ and AOD.

CONCLUSIONS

Utilization of remotely sensed data allows for a broader perspective view of air quality. Local air quality is affected by a number of factors including regional emissions, temperature, atmospheric dynamics, and traffic patterns. Satellite data also allows for viewing features that could impact air quality in the near future. This research presented a multi-year analysis of spring and summer data from 2004- 2008 in metropolitan Atlanta. Our research focused upon the synergy between ground-based measurements of $PM_{2.5}$ and NASA satellite observations in the terms of Aerosol Optical Depth (AOD) from MODIS and the Aerosol Index (AI) from OMI. MODIS AOD (τ) is a derived measurement from both MODIS instruments onboard the Terra and Aqua satellites. OMI onboard Aura is an instrument that measures the absorbing aerosols in the UV-spectrum. Our research goals were to understand the variability within the $PM_{2.5}$ and AOD data records, assess the strength of the $PM_{2.5}$/AOD relationship, and probabilistically determine AOD thresholds that relate directly to AQI categories.

Results for the $PM_{2.5}$ analysis show that $PM_{2.5}$ differences are likely due to station location, with the highest averages of $PM_{2.5}$ occurring at an urban site and the lowest averages occurring at a rural site. The spring months show less variability than summer months in the $PM_{2.5}$ record. MODIS AOD has captured the same yearly behavior shown in $PM_{2.5}$, yet on a seasonal basis the summertime has AOD values double that of the spring. Remotely sensed data, such as MODIS AOD, are a valuable tool for use in air quality applications. Our results suggest that SOA formation in the region could have an impact on local PM2.5 concentrations. Satellite data are uniquely able to provide information about SOA levels on an almost daily basis. This information could aid air quality forecasters by allowing them to fine tune their models to more accurately describe conditions in the U.S. Southeast. OMI AI does not have a discernable seasonal component. Background levels of AI for the metro area are around 0.3. Eighty percent of AI is below 0.5, therefore, AI values significantly higher than this could be indicative of long-range aerosol transport into the area. The results of linear regressions between $PM_{2.5}$ and AOD are r-values above 0.5 for a majority of sites. Interestingly, Terra produced higher correlation coefficients than Aqua in 2007, while in other years the satellites have similar r-values. We propose using statistical analysis of AOD data to relate AOD directly to AQI via probabilistic measures based upon past AOD values for a specific area. The research also determined that 80% of Code Green days occur with AOD of 0.35 or less, and 80% of Code Yellow days occur with AOD of 0.65. These probabilistic AOD cutoffs can be used to quickly access the AQI classifications without the dependence upon ground-based measurements. There is some agreement between $PM_{2.5}$ based AQI and satellite based AQI. Further work will need to be done to better tune the methodology for orange and red AQI.

Future plans are to continue this type of analysis using the data from the Multi-angle Imaging SpectroRadiometer (MISR) instrument onboard Terra. A portion of that research would be a comparison between MODIS and MISR in the U.S. southeast. Additional analysis would be done to apply the proposed probabilistic approach with MISR data. Also, the methodology for using AOD thresholds to understand general tendencies about AQI can be tuned to specific states, regions, and areas with few $PM_{2.5}$ measurements. The data from these satellites also provide an important means for determination and understanding of "normal" conditions, which can allow air quality policy makers to make better use of satellite data for possible application to the U.S. EPA's Clean Air Interstate Rule as well as the exception events rule for NAAQS designations.

ACKNOWLEDGEMENTS

E. J. Alston would like to thank the Science Directorate, NASA LaRC for its support. I.N. Sokolik acknowledges support from the NASA Radiation Program.

ABOUT THE AUTHORS

Erica J. Alston is a Ph.D. candidate with the Department of Earth and Atmospheric Sciences at the Georgia Institute of Technology, and she is an engineer with NASA LaRC. Irina N. Sokolik is a professor with Department of Earth and Atmospheric Sciences at the Georgia Institute of Technology. Bruce G. Doddridge is a supervisory research scientist at NASA LaRC. Please address correspondence to: Erica J. Alston, Chemistry and Dynamics Branch, 21 Langley Blvd., MS 401B, Hampton, VA 23681; phone: 757.864.7247; e-mail: erica.j.alston@nasa.gov.

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TABLES

AQI Category	Color	Index Values	$PM_{2.5}$ 24-hour (µg/m^3)	
			Current	Proposed
Good	Green	0 - 50	0.0 - 15.4	No change
Moderate	Yellow	51 - 100	15.5 - 40.4	15.5 - 35.4
Unhealthy for Sensitive Groups	Orange	101 - 150	40.5 - 65.4	35.5 - 55.4
Unhealthy	Red	151 - 200	65.5 - 150.4	55.5 - 150.4
Very Unhealthy	Purple	201 - 300	150.5 - 250.4	No change
Hazardous	Maroon	301 - 400	250.5 - 350.4	No change
		401 - 500 (this level used for emergency episode planning only.)	350.5 - 500	No change

Table 1. AQI designations. Source: U.S. EPA

Location	2004		2005		2006		2007		2008	
	Terra	Aqua	Terra	Aqua	Terra	Aqua	Terra	Aqua	Terra	Aqua
Con. Ave.	-	-	18.61	18.87	**23.63**	**21.25**	23.42	21.31	**20.68**	**17.89**
Gwinnett	**16.69**	**14.12**	17.72	15.63	**19.94**	**17.02**	**21.64**	**17.22**	**15.90**	**13.70**
McDonough	**17.26**	**14.74**	18.41	16.59	**21.13**	**17.32**	**21.54**	**16.63**	**17.29**	**13.51**
Newnan	**16.63**	**14.14**	18.05	16.14	**19.94**	**16.10**	**22.55**	**17.01**	**17.13**	**14.29**
S. Dekalb	**17.24**	**14.33**	**18.54**	**15.50**	**19.20**	**16.96**	23.04	21.42	**18.22**	**15.42**
Walton	-	-	16.80	15.23	**18.81**	**16.48**	**19.70**	**15.79**	**15.84**	**13.17**
Yorkville	14.86	14.64	16.30	16.24	18.60	16.87	19.45	19.33	14.30	13.58

Table 2. Means of $PM_{2.5}$ concentrations for each station. Bold numbers are significantly different from each other for $\alpha = 0.05$.

Year	Season	r		#	
		Terra	Aqua	Terra	Aqua
2005	Spring	-0.13	-0.05	57	53
	Summer	0.06	0.23	46	48
2006	Spring	-0.12	-0.09	65	64
	Summer	0.30	0.42	66	67
2007	Spring	0.03	-0.13	65	69
	Summer	0.08	0.10	58	61
2008	Spring	-0.35	-0.31	60	62
	Summer	0.18	0.15	60	59

Table 3. Correlation coefficient and number of observations for OMI AI vs. MODIS AOD

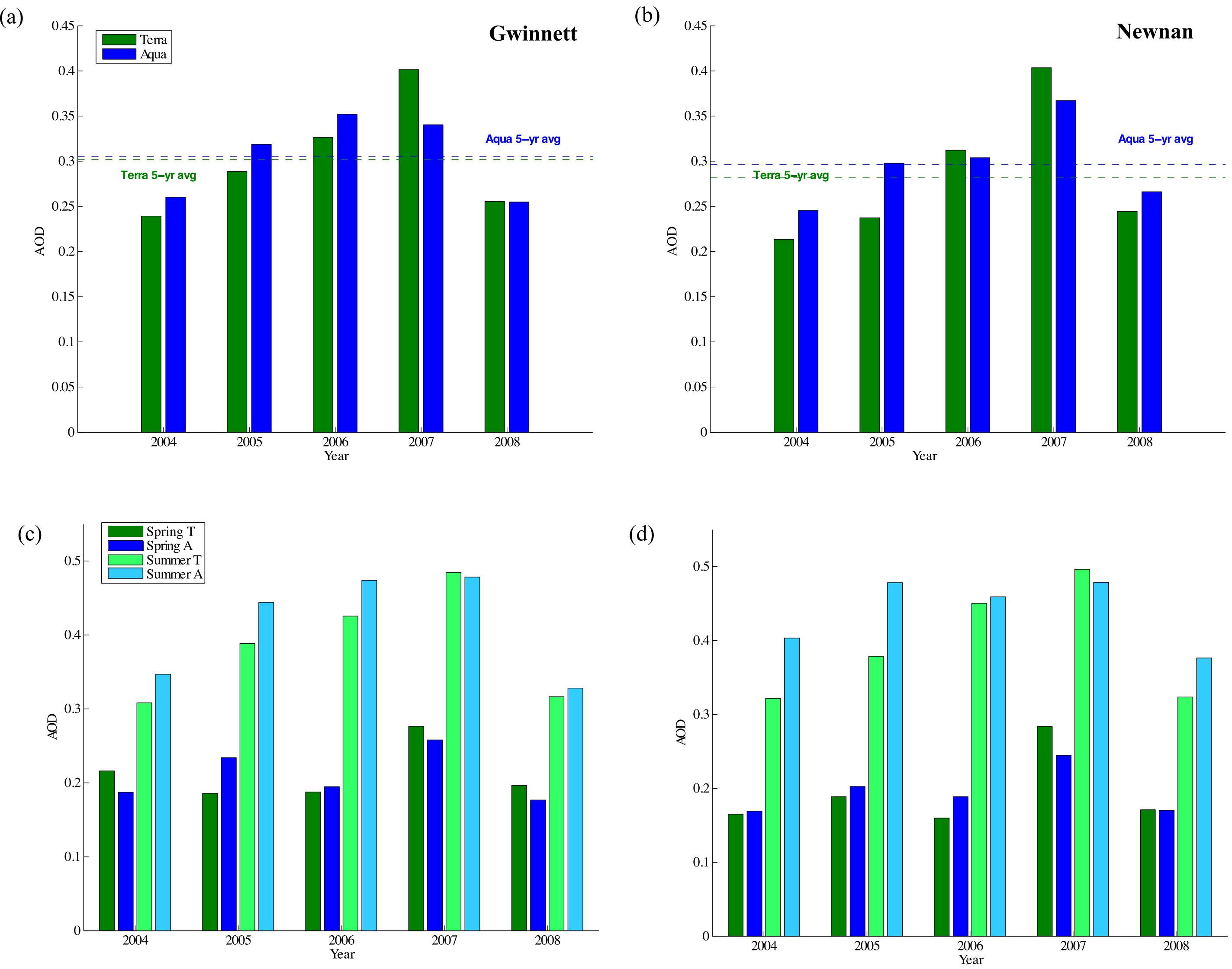
Location	Year	2004		2005		2006		2007		2008	
	Season	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
Confederate Ave.	Slope	-	-	0.03	0.01	0.01	0.01	0.02	0.02	0.00	0.01
	Y-intercept	-	-	-0.24	0.30	-0.05	0.14	-0.12	-0.03	0.11	0.11
	r	-	-	**0.87**	0.22	**0.62**	**0.37**	**0.81**	**0.62**	0.15	**0.44**
	#	-	-	6	35	59	66	57	53	54	61
Gwinnett	Slope	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.02	0.01	0.01
	Y-intercept	-0.05	0.13	-0.02	0.23	0.00	0.11	-0.01	0.08	0.10	0.16
	r	**0.68**	**0.51**	**0.66**	**0.50**	**0.62**	**0.44**	**0.76**	**0.67**	**0.29**	**0.41**
	#	53	48	46	38	67	53	61	53	54	63
McDonough	Slope	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01
	Y-intercept	-0.03	0.09	0.04	0.25	0.02	0.18	-0.05	0.03	0.09	0.17
	r	**0.54**	**0.64**	**0.51**	**0.38**	**0.53**	**0.40**	**0.70**	**0.67**	0.25	**0.34**
	#	54	44	56	39	57	70	59	59	51	61
Newnan	Slope	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.02	0.00	0.01
	Y-intercept	0.00	0.16	0.02	0.28	-0.03	0.21	-0.05	0.09	0.11	0.08
	r	**0.44**	**0.46**	**0.57**	0.30	**0.73**	**0.37**	**0.78**	**0.61**	0.16	**0.56**
	#	55	32	40	35	57	63	57	57	49	62
S. Dekalb	Slope	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.02	0.01	0.01
	Y-intercept	-0.02	0.14	0.06	0.33	-0.01	0.15	-0.04	-0.03	0.10	0.19
	r	**0.54**	**0.49**	**0.56**	0.22	**0.59**	**0.40**	**0.78**	**0.69**	0.19	**0.33**
	#	54	44	56	35	55	63	59	55	54	66
Walton	Slope	-	-	0.01	0.00	0.01	0.02	0.02	0.02	0.01	0.01
	Y-intercept	-	-	-0.03	0.28	0.03	0.06	-0.03	0.05	0.05	0.19
	r	-	-	**0.65**	0.28	**0.51**	**0.51**	**0.76**	**0.68**	**0.35**	0.23
	#	-	-	32	36	55	64	53	56	49	59
Yorkville	Slope	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.01
	Y-intercept	-0.02	0.08	-0.04	0.24	-0.06	0.08	-0.05	0.00	0.03	0.11
	r	**0.45**	**0.60**	**0.74**	**0.38**	**0.62**	**0.51**	**0.74**	**0.76**	**0.50**	**0.51**
	#	55	42	47	40	57	60	55	57	50	57

Table 4. Slope, Y-intercept, correlation coefficient, and number of observations of seasonal $PM_{2.5,24}$ vs. MODIS Terra AOD. Dash denotes missing data. Bold numbers are significant at $\alpha = 0.05$.

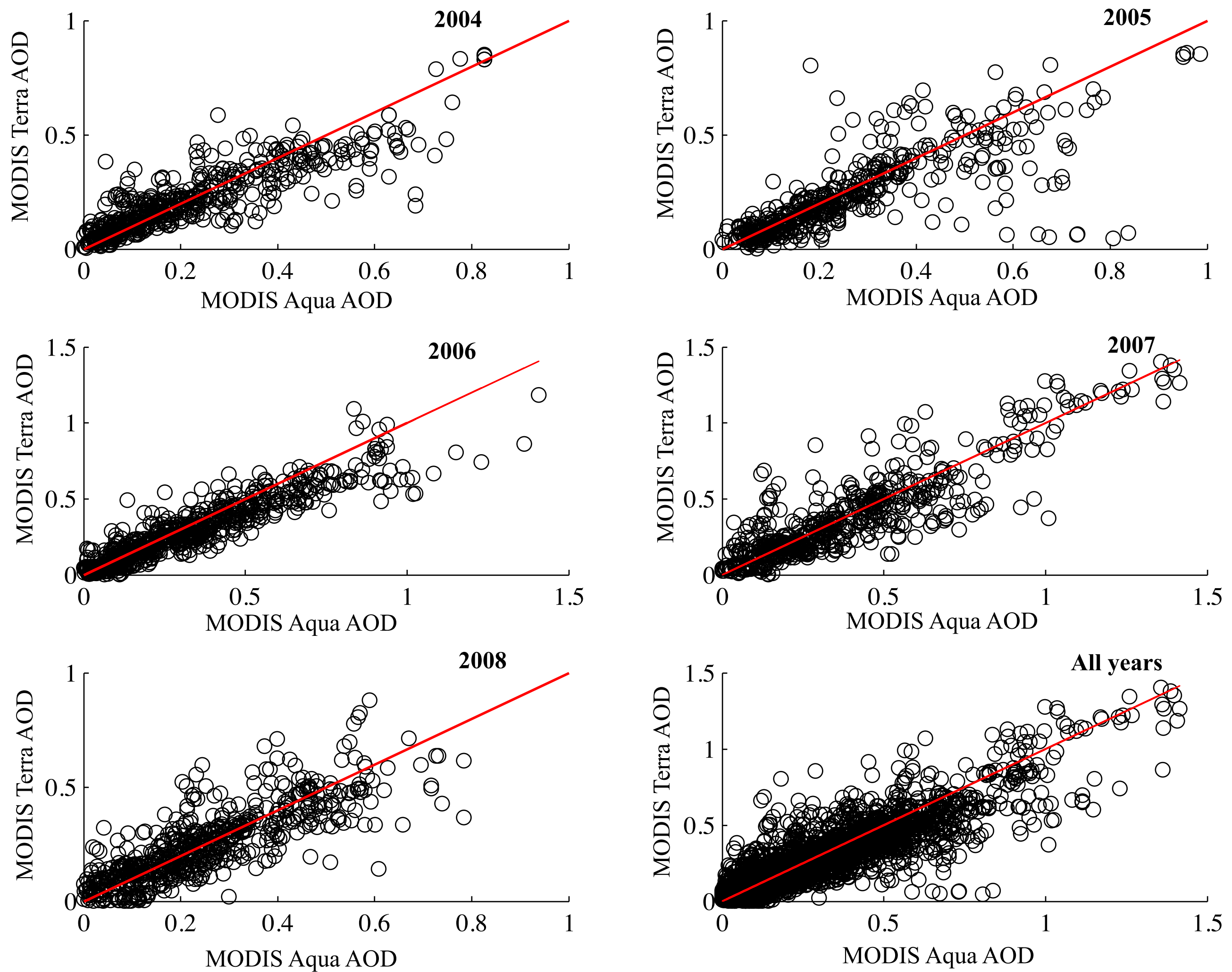
Location	Year	2004		2005		2006		2007		2008	
	Season	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
Confederate Ave.	Slope	-	-	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01
	Y-intercept	-	-	0.10	0.29	-0.09	0.11	0.03	0.02	-0.09	0.07
	r	-	-	0.18	**0.37**	**0.70**	**0.41**	**0.54**	**0.51**	**0.54**	**0.51**
	#	-	-	6	42	57	59	45	47	49	58
Gwinnett	Slope	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01
	Y-intercept	0.00	0.19	0.10	0.21	-0.04	0.11	0.10	0.10	0.02	0.14
	r	**0.51**	**0.40**	**0.39**	**0.49**	**0.70**	**0.46**	**0.56**	**0.59**	**0.46**	**0.46**
	#	60	54	47	44	60	50	51	50	48	67
McDonough	Slope	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01
	Y-intercept	-0.07	0.12	0.08	0.29	-0.02	0.14	-0.01	0.07	-0.02	0.07
	r	**0.56**	**0.54**	**0.47**	**0.38**	**0.67**	**0.46**	**0.62**	**0.65**	**0.58**	**0.53**
	#	58	46	49	43	54	58	43	55	52	61
Newnan	Slope	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01
	Y-intercept	-0.01	0.23	0.12	0.21	-0.05	0.17	-0.02	0.09	0.05	0.15
	r	**0.40**	**0.43**	0.26	**0.56**	**0.70**	**0.45**	**0.71**	**0.61**	**0.37**	**0.50**
	#	56	38	39	44	57	56	42	52	49	58
S.Dekalb	Slope	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.01
	Y-intercept	0.02	0.13	0.10	0.30	-0.07	0.09	0.05	0.01	0.02	0.06
	r	**0.41**	**0.52**	**0.42**	**0.42**	**0.76**	**0.54**	**0.53**	**0.63**	**0.40**	**0.56**
	#	60	48	51	42	54	55	46	53	52	61
Walton	Slope	-	-	0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.01
	Y-intercept	-	-	0.14	0.23	-0.04	0.06	0.07	0.08	0.02	0.04
	r	-	-	0.23	**0.41**	**0.61**	**0.51**	**0.50**	**0.63**	**0.42**	**0.51**
	#	-	-	36	39	52	61	44	50	45	57
Yorkville	Slope	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
	Y-intercept	-0.01	0.06	0.04	0.20	-0.02	0.06	0.08	0.05	-0.04	0.15
	r	**0.41**	**0.59**	**0.51**	**0.56**	**0.59**	**0.57**	**0.49**	**0.72**	**0.59**	**0.47**
	#	52	44	44	42	58	53	49	55	50	61

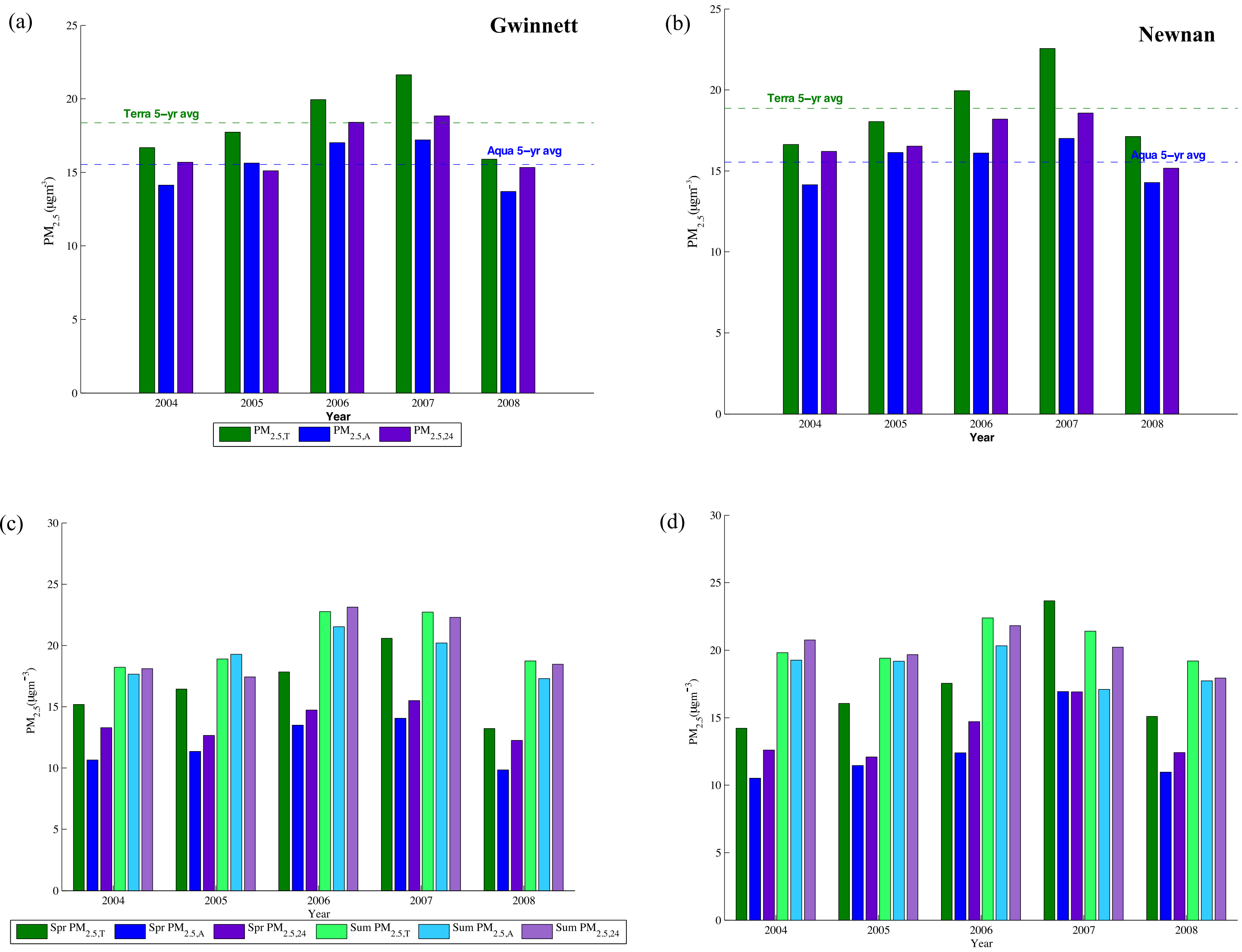
Table 5. Slope, Y-intercept, correlation coefficient, and number of observations of seasonal $PM_{2.5,24}$ vs. MODIS Aqua AOD. Dash denotes missing data. Bold numbers are significant at $\alpha = 0.05$.

LIST OF FIGURES

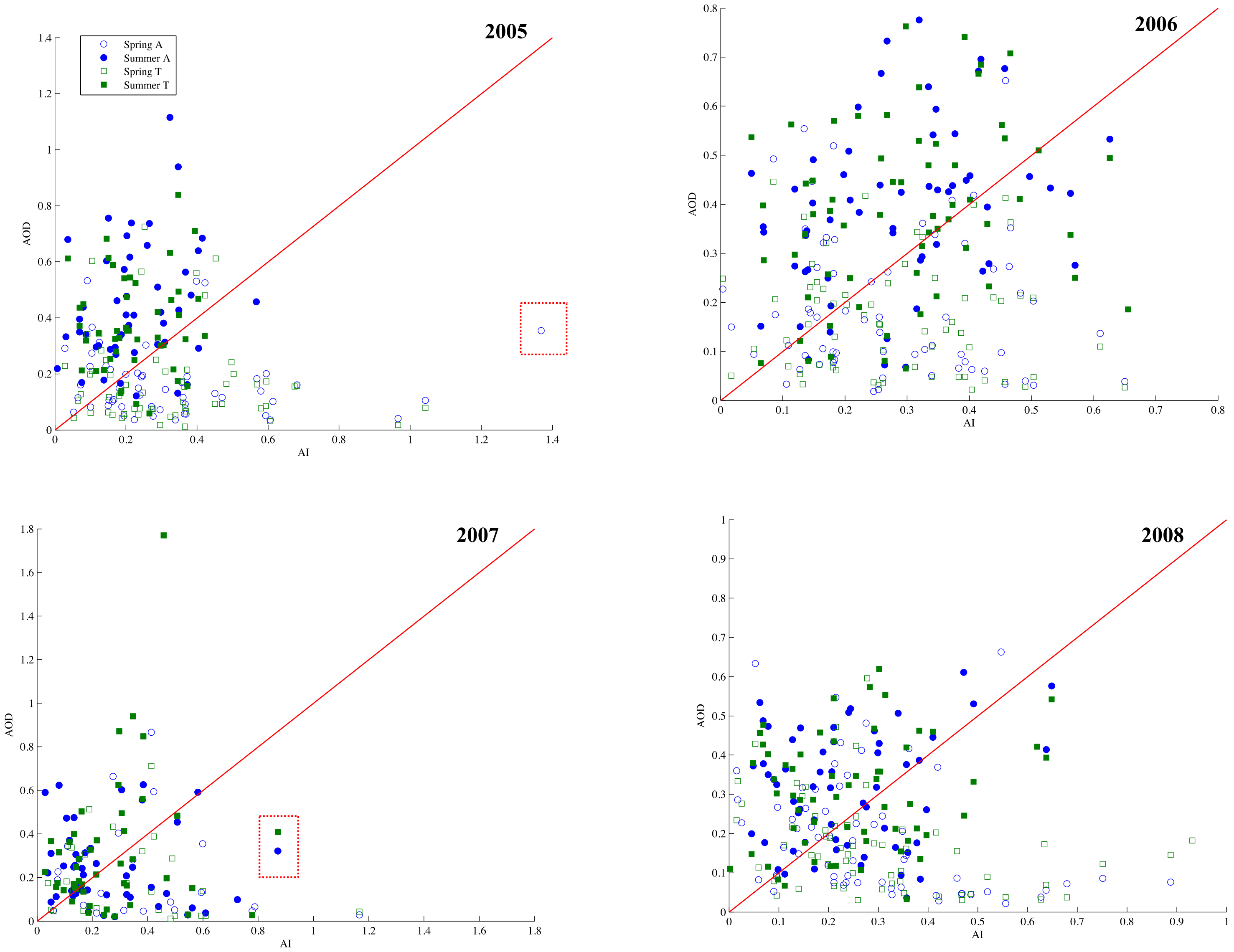


(a)
Gwinnett
Terra
Aqua
Aqua 5−yr avg
Terra 5−yr avg
AOD
Year
(b)
Newnan
Aqua 5−yr avg
Terra 5−yr avg
AOD
Year
(c)
Spring T
Spring A
Summer T
Summer A
AOD
Year
(d)
AOD
Year

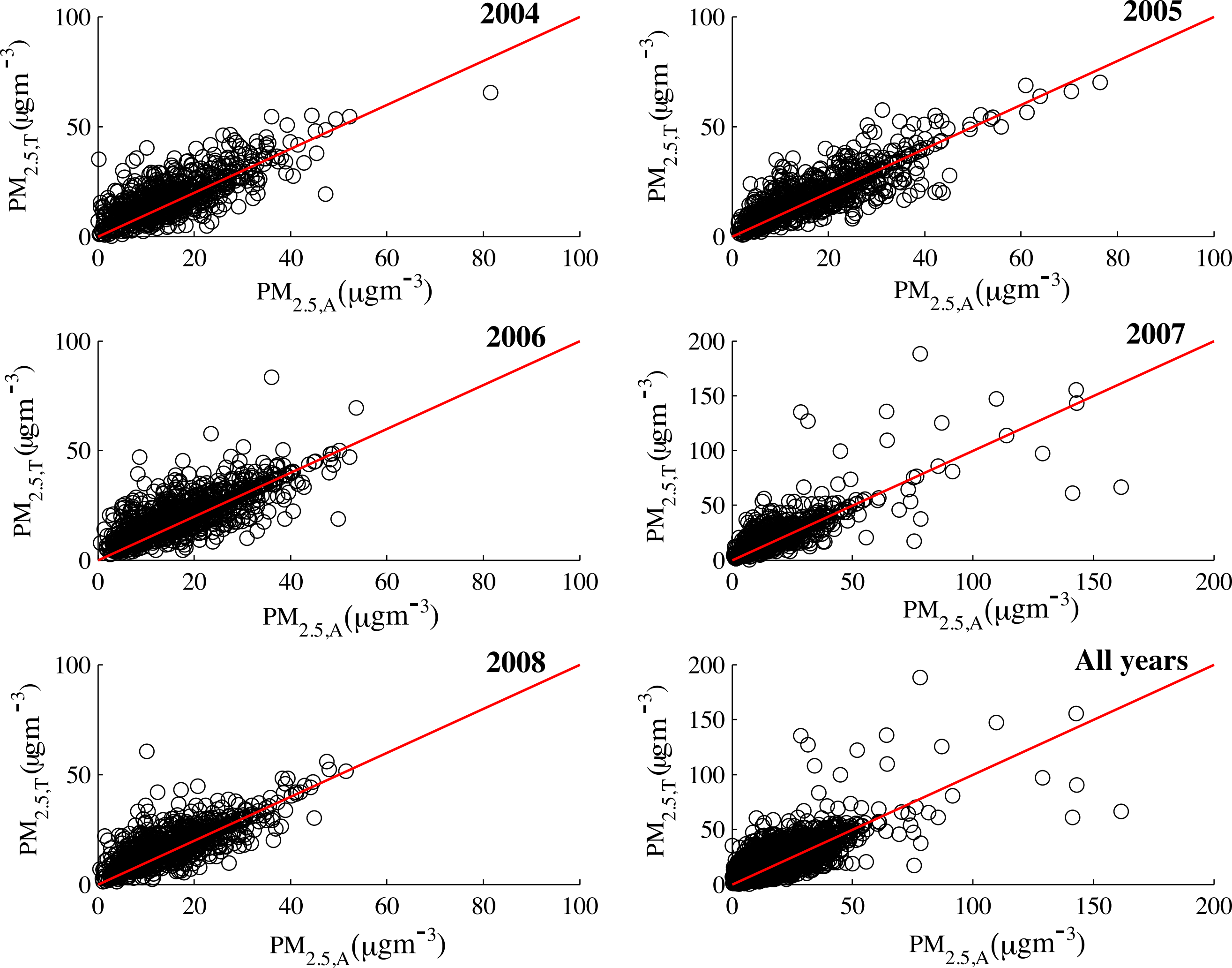

2004
2005
2006
2007
2008
All years
MODIS Terra AOD
MODIS Aqua AOD
0
0.2
0.4
0.6
0.8
1
0.5
1.5

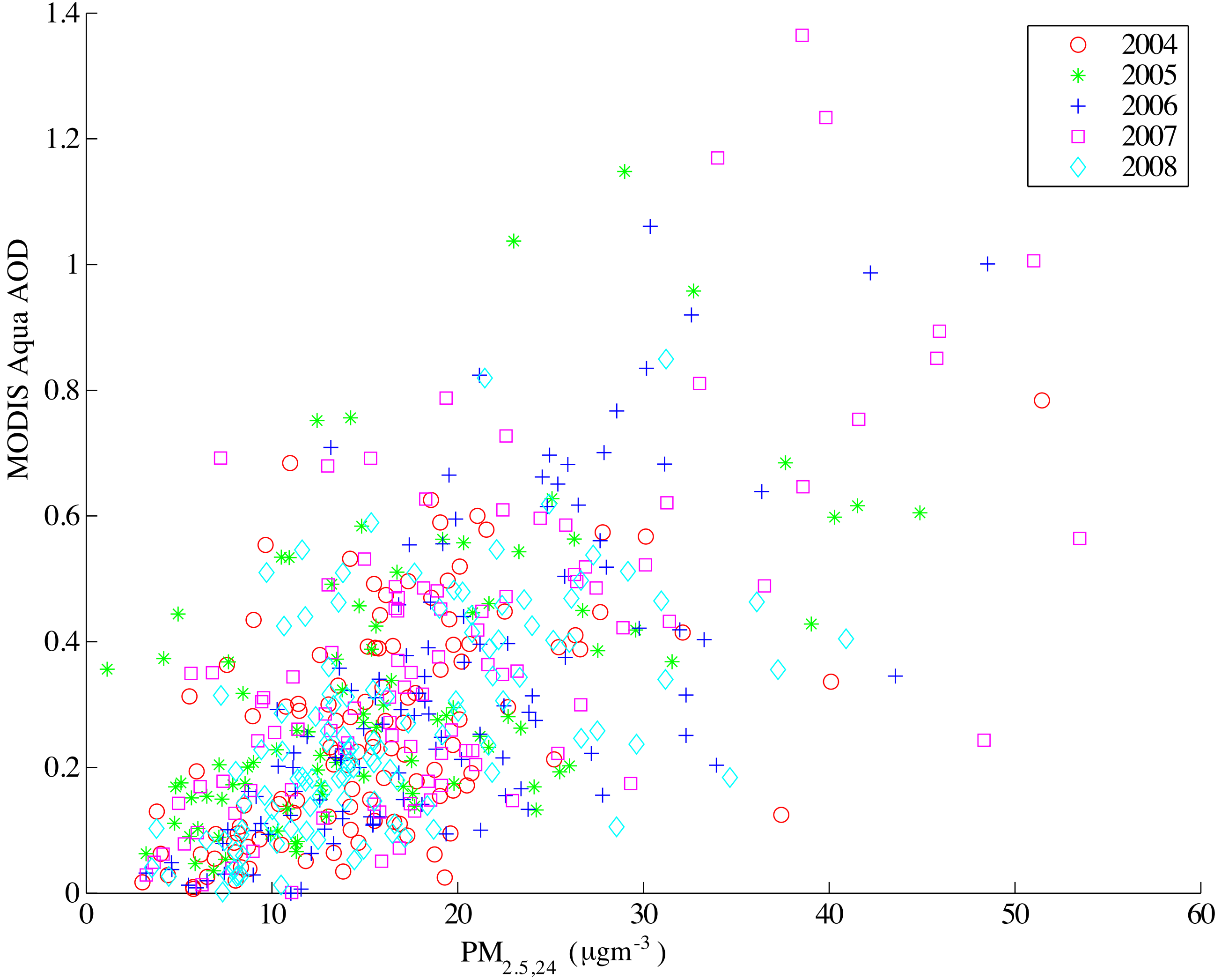


(a)
Gwinnett
Terra 5−yr avg
Aqua 5−yr avg
PM2.5 (μgm-3)
Year
2004
2005
2006
2007
2008
PM2.5,T
PM2.5,A
PM2.5,24
(b)
Newnan
Terra 5−yr avg
Aqua 5−yr avg
PM2.5 (μgm-3)
Year
(c)
PM2.5(μgm-3)
Year
Spr PM2.5,T
Spr PM2.5,A
Spr PM2.5,24
Sum PM2.5,T
Sum PM2.5,A
Sum PM2.5,24
(d)
PM2.5(μgm-3)
Year



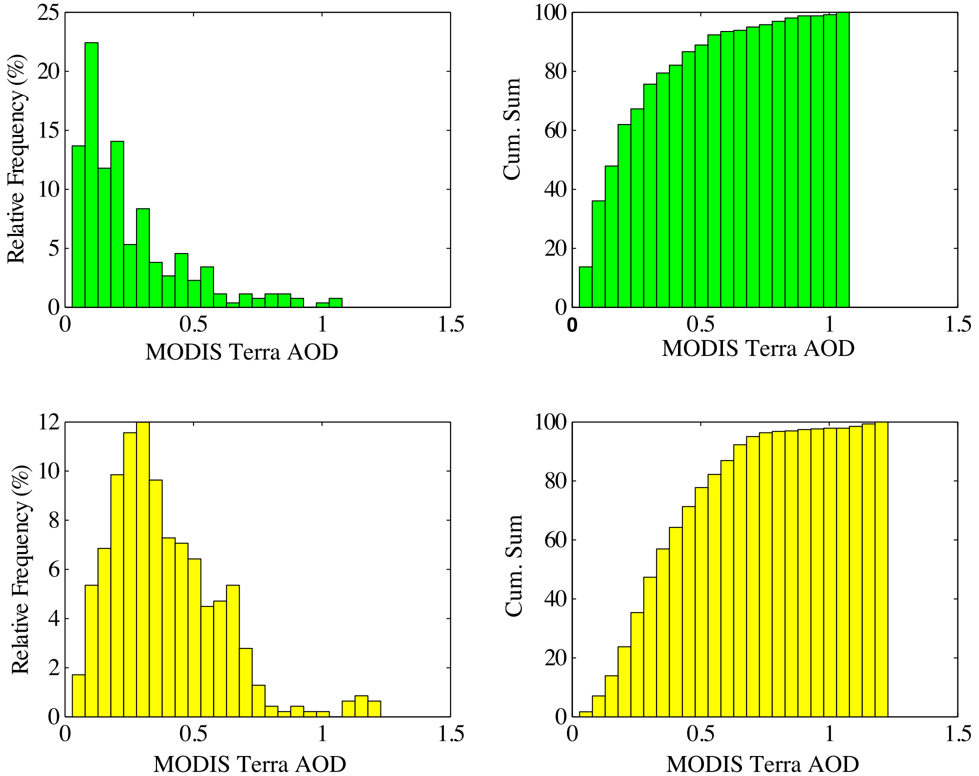
2005
Spring A
Summer A
Spring T
Summer T
AOD
AI
2006
AOD
AI
2007
AOD
AI
2008
AOD
AI


2004
2005
2006
2007
2008
All years
PM2.5,T(μgm-3)
PM2.5,A(μgm-3)

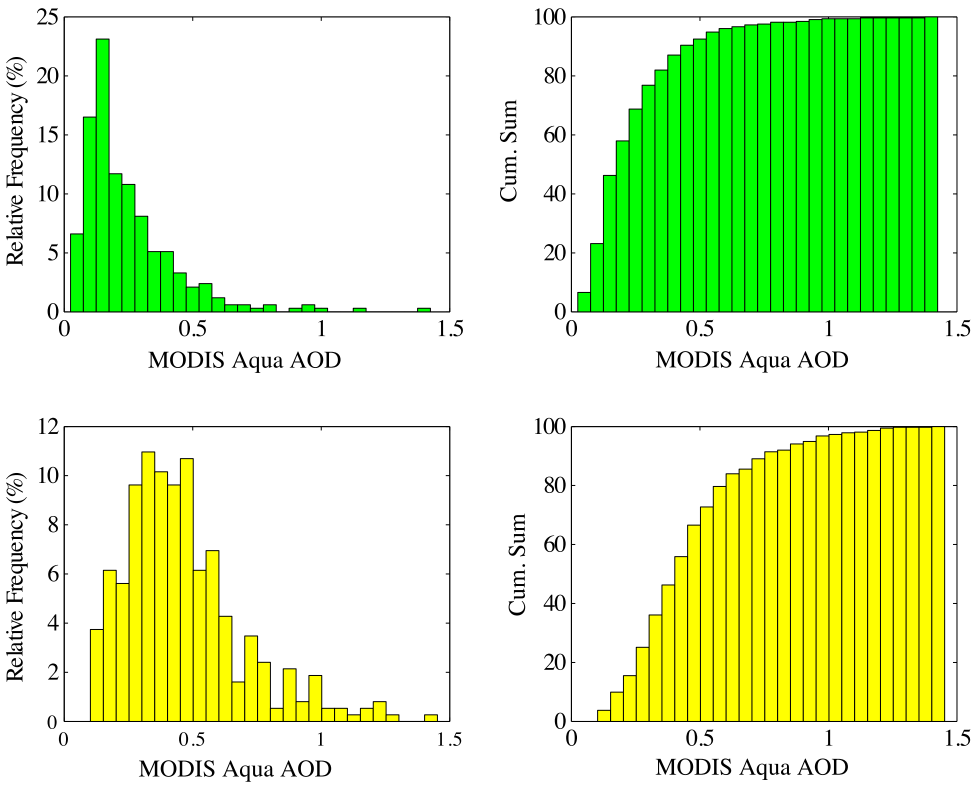


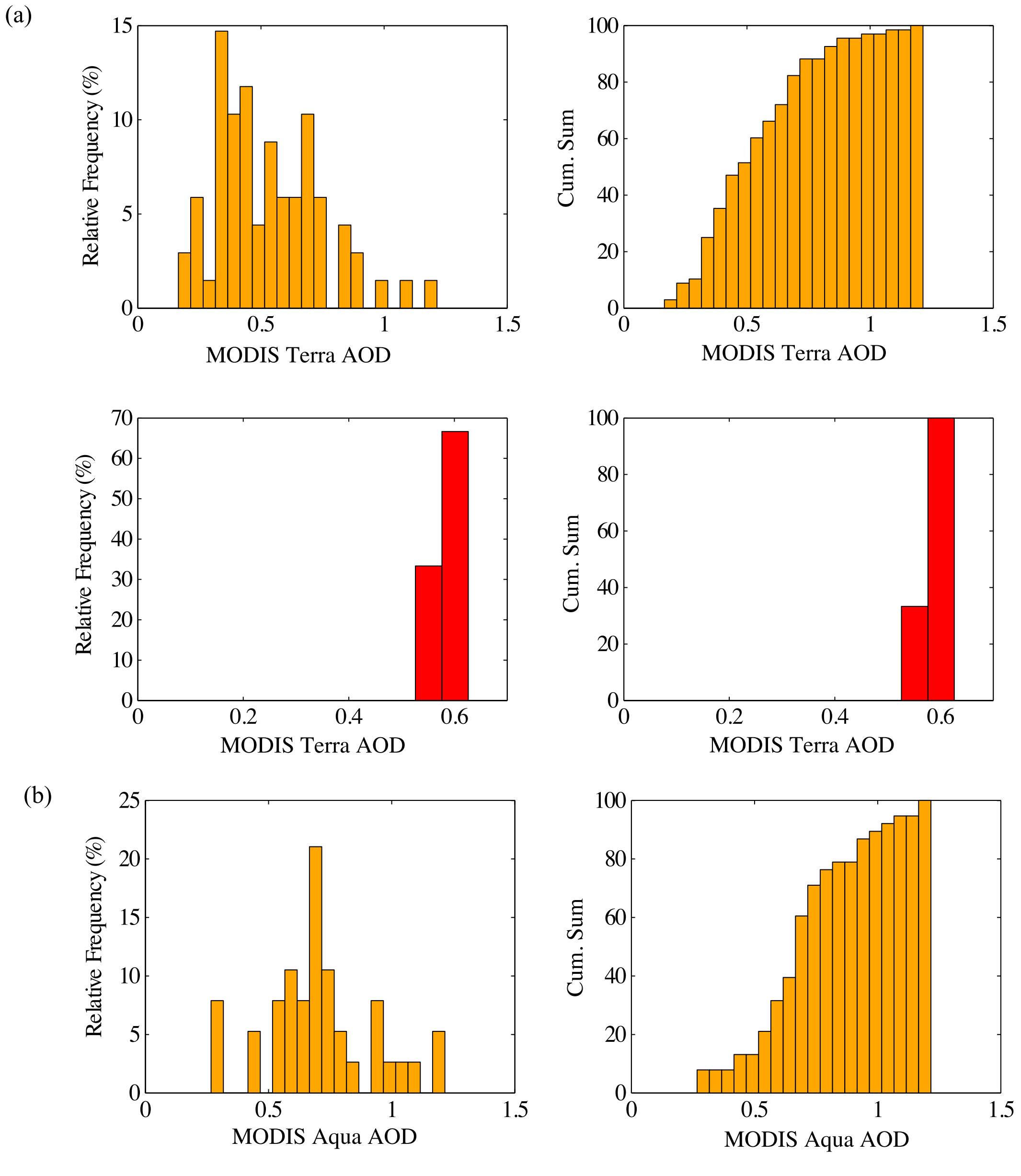
2004
2005
2006
2007
2008
MODIS Aqua AOD
PM2.5,24 (μgm-3)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
10
20
30
40
50
60

(a)

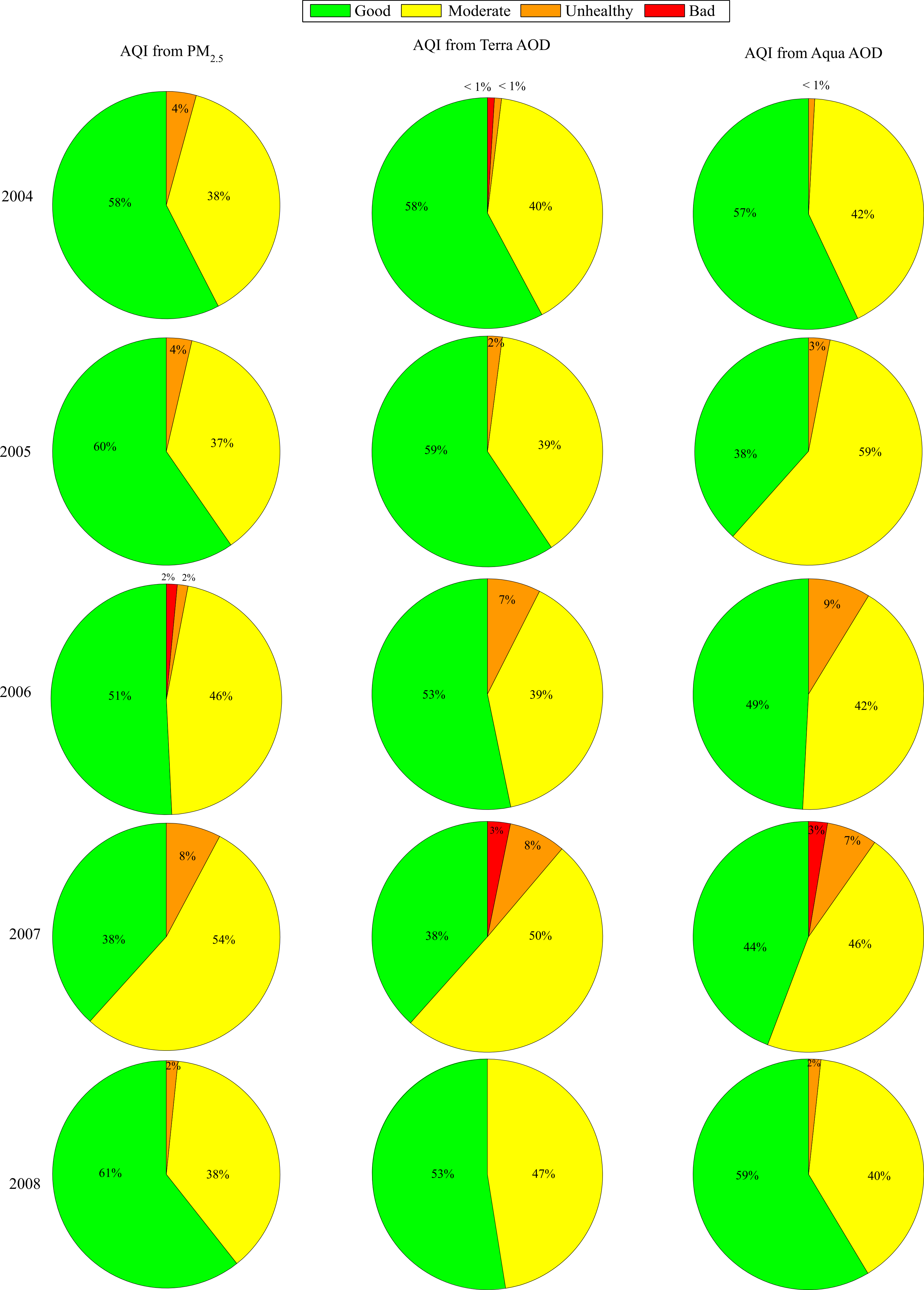

25
20
15
10
5
0
Relative Frequency (%)
0
0.5
1
1.5
MODIS Terra AOD
100
80
60
40
20
0
Cum. Sum
0
0.5
1
1.5
MODIS Terra AOD
12
10
8
6
4
2
0
Relative Frequency (%)
0
0.5
1
1.5
MODIS Terra AOD
100
80
60
40
20
0
Cum. Sum
0
0.5
1
1.5
MODIS Terra AOD

(b)


25
20
15
10
5
0
Relative Frequency (%)
0
0.5
1
1.5
MODIS Aqua AOD
100
80
60
40
20
0
Cum. Sum
0
0.5
1
1.5
MODIS Aqua AOD
12
10
8
6
4
2
0
Relative Frequency (%)
0
0.5
1
1.5
MODIS Aqua AOD
100
80
60
40
20
0
Cum. Sum
0
0.5
1
1.5
MODIS Aqua AOD



(a)
Relative Frequency (%)
0
5
10
15
0
0.5
1
1.5
MODIS Terra AOD
Cum. Sum
0
20
40
60
80
100
0
0.5
1
1.5
MODIS Terra AOD
Relative Frequency (%)
0
10
20
30
40
50
60
70
0
0.2
0.4
0.6
MODIS Terra AOD
Cum. Sum
0
20
40
60
80
100
0
0.2
0.4
0.6
MODIS Terra AOD
(b)
Relative Frequency (%)
0
5
10
15
20
25
0
0.5
1
1.5
MODIS Aqua AOD
Cum. Sum
0
20
40
60
80
100
0
0.5
1
1.5
MODIS Aqua AOD



Good
Moderate
Unhealthy
Bad
AQI from $PM_{2.5}$
AQI from Terra AOD
AQI from Aqua AOD
2004
4%
58%
38%
< 1%
< 1%
58%
40%
< 1%
57%
42%
2005
4%
60%
37%
2%
59%
39%
3%
38%
59%
2006
2%
2%
51%
46%
7%
53%
39%
9%
49%
42%
2007
8%
38%
54%
3%
8%
38%
50%
3%
7%
44%
46%
2008
2%
61%
38%
53%
47%
2%
59%
40%