Satellite Remote Sensing and Mesoscale Modeling of the 2007 Georgia/Florida Fires

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***Abstract*—During April and May 2007, several hundred fires burned uncontrollably in Georgia and Florida. The smoke from these fire events were visible throughout the Southeastern United States and had a major impact on particulate matter (PM) air quality near the surface. In this study, we show the strength of polar orbiting and geostationary satellite data in capturing the spatial distribution and diurnal variability of columnar smoke aerosol optical depth from these fires. We quantitatively evaluate PM air quality from satellites and ground-based monitors, near and far away (>300 km) from fire source regions. We also show the changes in organic carbon concentrations (a tracer for smoke aerosols) before, during and after these fire events. Finally, we use fire locations and emissions retrieved and estimated from satellite observations as input to a regional mesoscale transport model to forecast the spatial distribution of aerosols and their impact on PM air quality. During the fire events, near the source regions, total column 550 nm aerosol optical thickness (AOT) exceeded 1.0 on several days and ground-based PM2.5 mass (particles less than 2.5 μm in aerodynamic diameter) reached unhealthy levels (>65.5 ugm^{-3}). Since the aerosols were reasonably well mixed in the first 1–2 km (as estimated from meteorology), the column AOT values derived from both geostationary and polar orbiting satellites and the surface PM2.5 were well correlated (linear correlation coefficient, r>0.7). Several hundred miles away from the fire sources, in Birmingham, AL, the impact of the fires were also seen through the high AOT's and PM2.5 values. Correspondingly, PM2.5 mass due to organic carbon obtained from ground-based monitors showed a three fold increase during fire events when compared to background values. Satellite data were especially useful in capturing PM2.5 air quality in areas where there were no ground-based monitors. Although the mesoscale transport model captured the timing and location of aerosols, when compared to observations, the simulated mass concentrations are underestimated by nearly 70% due to various reasons including uncertainties in fire emission estimates, lack of chemistry in the model, and assumptions on vertical distribution of aerosols. Satellite products such as AOT, fire locations, and emissions from space-borne sensors are becoming a vital tool for assessing extreme events such as fires, smoke, and particulate matter air quality.**

***Index Terms*—Remote sensing, satellite applications.**

I. Introduction

BETWEEN April and June 2007, several hundred fires that were exacerbated due to extreme drought conditions burned uncontrollably near the Okefenokee swamp. Additional fires were also burning in southern Florida during this period. The fires started around April 20 and by the end of May nearly 2400 km^2 of grass, timber, and scrubland were burned. Smoke aerosols from these fires were transported hundreds of km and their effect on visibility and air quality was seen in many states in the southeastern United States. By late June the fires were fully contained and heavy rains from Hurricane Barry removed the smoke aerosols from the atmosphere.

Fires are indeed common in the United States during the spring and summer months. The location of fires and the spatial extent of smoke are readily available from satellite imagery and products. Smoke aerosols affect visibility and air quality and modify the radiation balance of the earth-atmosphere system by reflecting/absorbing solar radiation and changing cloud properties [e.g., [1]]. Fine particulate matter (PM2.5) can also be detrimental to health [2]. Both polar orbiting and geostationary satellite provide high spatial and temporal information, respectively, from their vantage points in space. On the ground, PM2.5 air quality monitors routinely provide hourly to daily information that is used to assess air quality. However, these monitors are point measurements and cannot cover vast areas. Therefore, satellite remote sensing is the only viable method for providing information at large spatial scales.

The goal of this paper is threefold. First, we show the strength of satellite imagery and products for locating fires and assessing the spatial distribution of smoke. We also show the vertical distribution of smoke aerosols from one overpass from a space-borne lidar. Next we combine the satellite data sets with ground-based measurements of PM2.5 mass to demonstrate the utility of space-borne sensors in assessing surface PM2.5 air quality. The changes in the concentrations of organic carbon (OC) and other species are also examined from locations near and far away from these fires. The Rapid Update Cycle (RUC) meteorology is used to assess wind speeds, directions and planetary boundary layer (PBL) heights. Finally, we use the geostationary satellite-based fire and smoke emission information in a mesoscale transport model (without chemistry) to demonstrate the smoke forecasting capabilities of extreme events such as fires. We also note that ongoing work is addressing the issue of using satellite-based fire locations and emissions in a more comprehensive Community Multi Scale Air Quality (CMAQ) model that incorporates detailed chemistry.

This research uses multiple satellite data sets and ground-based monitors to demonstrate the strength of combining information to assess and forecast air quality. Although several satellite data sets and products are used in this study it is important to note that the goal of this paper is not to validate the satellite products against ground-based measurements or perform inter-

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comparison studies. Validation of satellite products with data from ground-based monitors and between and among satellite products is ongoing by the various science teams [e.g., [3] for MODIS and [4] for GOES].

II. Data

While there are multiple satellite data sets that are currently available for assessing fire and smoke events, we focus only on one polar orbiting sensor, the Moderate Resolution Imaging Spectroradiometer (MODIS) and one geostationary sensor, the Geostationary Operational Environmental Satellite (GOES-12). Data from the MODIS on the Terra and Aqua polar orbiting satellites with mid morning and afternoon equatorial crossing times are especially useful for visualizing the spatial extent of smoke and clouds. We present MODIS and GOES satellite imagery from a few days (May 23–25, 2007) when the spatial extent of smoke was large. We also provide consolidated results from both the polar orbiting and geostationary satellites for the entire months of April and May for a large spatial domain and also over two specific locations to study PM2.5 air quality-one near the fire source region in Florida (81.63°W, 30.14°N) and another location far away from the source by several hundred miles in Alabama (86.67°W, 33.70°N).

A. MODIS Aerosol Product

The MODIS on the Terra and Aqua satellites measures reflected and emitted radiation from the earth-atmosphere system in 36 spectral channels between 0.405 μm–14.385 μm, with a swath width of 2330 km and near daily global coverage. While the original measurements are at 250 m, 500 m, and 1 km, the level 2 (L2) aerosol optical thickness product (collection 5) is available at 10 km^2 that is generated from a set of 20×20 (400) pixels at 500 m spatial resolution. The AOT is a columnar value of aerosol extinction and allows for global mapping of particulate matter from space. The aerosol land algorithm uses reflectance from 3 channels (0.47, 0.67, 2.13 μm) and reports AOT values in 0.47, 0.55, and 0.67 μm channels with a reported uncertainty in AOT of $\pm 0.05 \pm 0.15 * \mathrm{AOT}_{0.55}$ for the 0.55 μm channel [5].

B. GOES Aerosol and Smoke Product (GASP).

The imager on the GOES-12 satellite provides information on the reflected and emitted radiation in multiple channels. Similar to the MODIS, the GOES also provides daytime AOT at 0.55 μm but at a higher temporal resolution (every 30 minutes). The visible, mid-IR, and thermal IR channels are first used to screen clouds and aerosol pixels are then identified for retrieving AOT. Using the previous 28 days of measurements, clear sky composites for each 30 minute time step are then obtained to account for surface reflectance. AOT is then retrieved using a Look-Up Table (LUT) based on predetermined aerosol models. Further details on the GASP retrievals and uncertainties are provided elsewhere [4]. Limited intercomparisons show that the correlation between the GASP and the Aerosol Robotic Network (AERONET) [6] sunphotometers for 10 locations in the Eastern United States was 0.79 [4]. The GASP AOT's were also within 20% of the MODIS AOT values in the eastern United States under elevated AOT conditions [4].

C. IMPROVE Data

The Interagency Monitoring of Protected Visual Environments (IMPROVE) network was initiated in spring of 1988, and consists of more than 165 monitoring sites across the United States [7] that are primarily located in national parks and wilderness areas. We use two sites, one that is near the fire source (OKEF, Georgia Okefenokee National Wildlife Refuge, Okefenokee, GA, Wolf Island, GA, 82.13°W, 30.74°N) and the other that characterizes a location far away from the fire source (SIPSY, Sipsy Wilderness, Sipsy, AL, 87.33°W, 34.34°N) to examine the impact of smoke transport. At each site, sampling modules are used to collect the speciated PM2.5 mass on every third day, with a sampling duration time of 24 h. The collected samples are then analyzed to infer the concentration of speciated PM2.5 mass and other trace elements such as potassium (K) and iron (Fe), as well as the major visibility-reducing aerosol species such as sulfates, nitrates, organic compounds, elemental (light-absorbing) carbon, and wind-blown dust. In this study, we use the IMPROVE data collected in March–June 2007 to assess the changes in speciation before, during and after the fire events.

Of particular interest is the organic carbon (OC) and elemental carbon (EC) concentrations, because these species are tracers of the smoke particles originating from biomass burning [8] although a fraction of OC can be photochemically produced. Also note that there are many sources of organic carbon in the atmosphere. Sources include motor vehicles and combustion (biomass and meat cooking) and biogenic emissions. IMPROVE uses the thermal optical reflectance (TOR) method to analyze the concentration of OC and BC and the uncertainty can be 15% for OC and 18% for BC, and sometimes can be up to 50% under certain circumstances [9]. Although accurate separation of BC and OC is difficult, we merely highlight the change in these tracers before and during the fire events. In this study, we use the organic carbon mass concentration (OMC) that is assumed to be 1.4*OC where OC is the organic carbon concentration as determined by the TOR analysis. The organic carbon multiplier (1.4 used here) is an estimate of the average molecular weight per carbon weight for organic carbon aerosol and takes into account contributions from other elements associated with organic matter, such as nitrogen, oxygen and hydrogen. The value of 1.4 is an average number that has often been used to reconstruct fine mass [10]. The factor of 1.4 is the molecular weight per carbon weight ratio and corrects for other elements associated with organic molecular composition. Note that at the time of writing these data had not gone through complete quality control by the data provider.

D. CALIPSO Backscatter

The CALIOP, an active polarization sensitive, nadir-viewing, space based lidar onboard the CALIPSO satellite flying in formation with other satellites as part of A-Train constellation of satellites provides vertical profile of backscatter at 532 and 1064 nm both during day and night and samples the vertical distribution of clouds and aerosols [11]. This active lidar measures only at nadir with a lidar spot of 70 m at the surface with a maximum vertical resolution of 30 m. The repeat cycle of the A-train

TABLE I
AIR QUALITY CATEGORY AND CORRESPONDING 24 HOURLY MEAN $PM_{2.5}$ MASS (μgm^3)

Air Quality Category	Description	24 Hour Mean $PM_{2.5}$ mass (μgm^{-3})	Color Codes
Good	None	0 ~ 15.4	Blue
Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion	15.5 ~ 40.4	Green
Unhealthy for Sensitive Groups	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion	40.5 ~ 65.4	Yellow
Unhealthy	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion. Everyone else should reduce prolonged or heavy exertion	65.5 ~ 150.4	Orange
Very Unhealthy	People with heart or lung disease, older adults, and children should avoid all physical activity outdoors. Everyone else should avoid prolonged or heavy exertion	150.5 ~ 250.4	Red

satellites is 16 days. One CALIPSO overpass was available for this study to assess smoke aerosol heights. Only the level-1 backscatter information is used to infer aerosol heights since the AOT and other aerosols products retrieval from CALIOP are currently undergoing refinement and validation.

E. RUC20 Meteorological Fields

The Rapid Update Cycle (RUC) is an operational atmospheric prediction system comprised primarily of a numerical forecast model and an analysis system to initialize that model. The RUC has been developed to serve users needing short-range weather forecasts. RUC runs operationally at the National Centers for Environmental Prediction (NCEP). The RUC data used here have a horizontal resolution of 20 km with 50 vertical computational levels. Hourly data of wind speed and wind direction at 800 hPa are used in this study. [12].

F. PM2.5 Measurements and U.S. Air Quality Standards

There are several sources for ground-based information for aerosols. In this study we use the particulate matter (PM2.5) mass measurements from the US Environmental Protection Agency (USEPA) AirNow network. The PM2.5 concentrations are measured using a Tapered-Element Oscillating Microbalance (TEOM) instrument with a stated accuracy of $\pm 1.5\ \mu gm^{-3}$ for hourly averages. However, due to the volatilization of ammonium nitrate and organic carbon, the TEOM PM2.5 mass concentrations may be underestimated [13]. The EPA reports an Air Quality Index (AQI) based on the ratio between 24-hour averages of the measured dry particulate mass and NAAQS, and it can range from nearly zero in a very clean atmosphere to 500 in extremely polluted conditions. Table I gives details on PM2.5 mass, air quality categories and possible health effects.

G. The GOES Fire Product and Emissions.

The GOES Wild Fire Automated Biomass Burning Algorithm (ABBA) provides near real time locations of fires and hot spots throughout the Western hemisphere at high temporal resolutions [14]. Using these fire locations along with estimates of burned area, fuel loading, the fraction of combustion, and factors of emissions for trace gases and aerosols, biomass burning emissions can be estimated [15]. We use the fire emissions product generated by Zhang and Kondragunta [15] as input to a mesoscale transport model. It is difficult to assess uncertainties in fire detection products since validation data sets are not readily available at the required space and time scales [16].

III. RESULTS AND DISCUSSION

The first goal of this paper is to assess the spatial distribution of fires and smoke over the southeastern United States. The second goal of this paper is to derive near surface PM2.5 air quality from columnar satellite information. While ground-based monitors provide PM2.5 mass on an hourly basis, they are representative of surface values whereas the satellites provide integrated values of aerosol extinction over the entire atmospheric column. Several studies have shown the success of using satellite data in tracking surface PM2.5 in the United States [17]. In these studies, a regression relationship is established between the columnar satellite-derived AOT and surface PM2.5 mass. Then this AOT-PM2.5 relationship is used to convert the satellite measurements to air quality indices based on EPA guidelines. These values are then color coded for public dissemination where green is for good air quality and orange and red are poor quality. An excellent example of how satellite data are fused with ground-based monitors to assess PM2.5 pollution can be seen here: http://www.star.nesdis.noaa.gov/smcd/spb/aq/, where the AOD are displayed in color simultaneously with clouds along with air quality indices from ground monitors.

Although ancillary information such as aerosol mixing height and meteorology are necessary to complement this method [18], as a first approximation, we simply use the AOT-PM2.5 relationship from this study to estimate the particulate matter mass in regions where ground-based measurements are available. Since we are focusing only on Southeastern United States where this method has the most success [19], this is a reasonable approach for highlighting the capabilities of the technique.

A. Satellite Data and Products

Fig. 1(a)–(f) shows the spatial distribution of smoke, clouds and fires from the MODIS on Terra and Aqua for May 23, 24, and 25, 2007. Fig. 1(a)–(c) is from Terra (∼1600 UTC) and Fig. 1(d)–(f) is from Aqua (∼1900 UTC). The mid-visible reflectances from MODIS are plotted to show the areas with

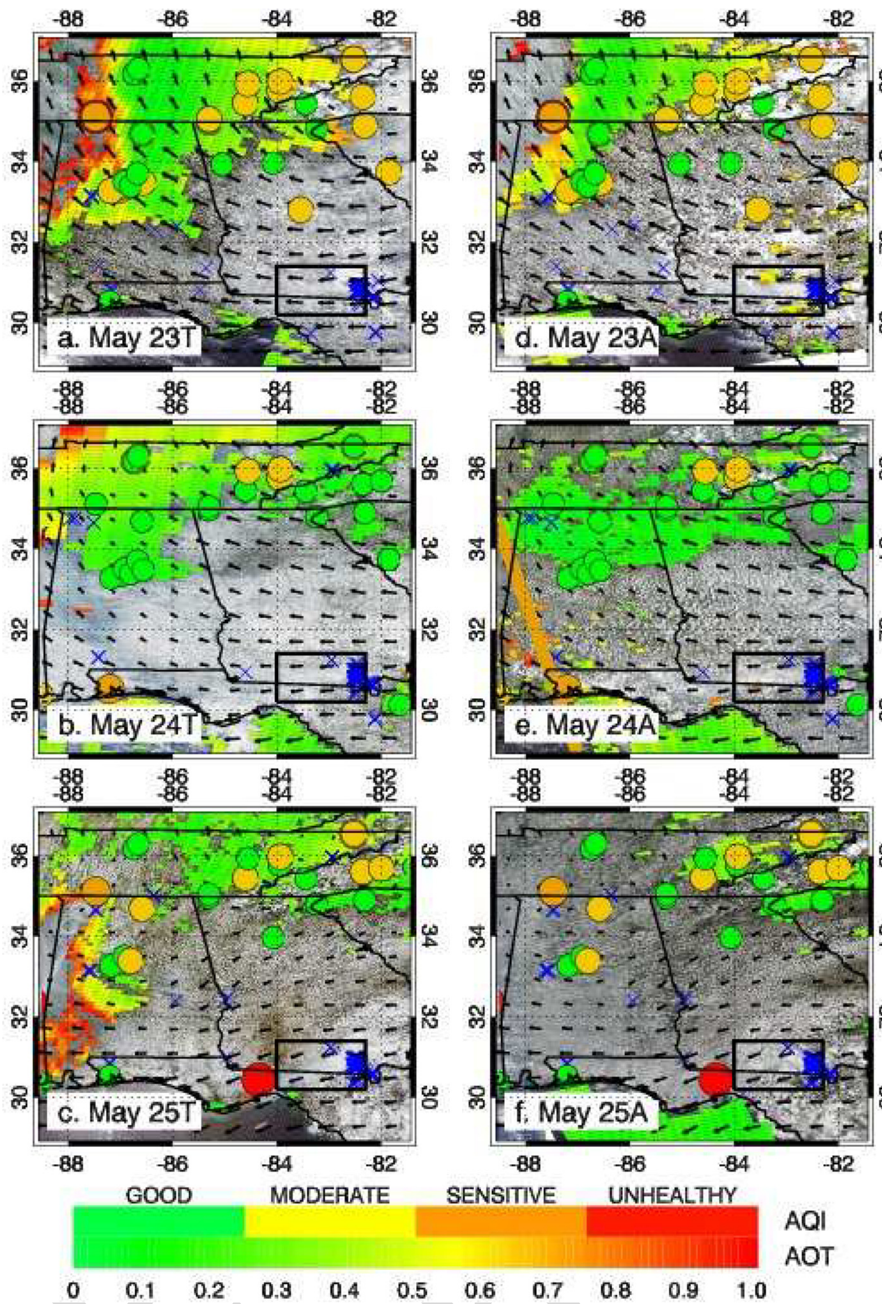

Fig. 1. Composite of MODIS level 1 and level 2 550 nm aerosol products with 800 hPa Rapid Update cycle (RUC) wind speeds and directions for Terra [Fig. 1(a)–(c), May 23–25] and Aqua [Fig. 1(d)–(f), May 23–25] . The inset in each figure shows the area where the majority of the fire events took place with fire locations shown as blue X marks. The color coded circles indicate the PM2.5 locations with air quality color categories based on the EPA guidelines (Table I). Fig. 1(e) shows the CALIPSO overpass in yellow to the left of the image running NW to SE.

smoke and clouds. Brighter regions in white are from clouds and the hazier regions are smoke aerosols from fires. Overlaid on these plots are the level 2 MODIS AOT in color. Vectors indicate wind speed and direction at 800 hPa derived from RUC model analysis. The location of PM2.5 ground-based monitors are also indicated and are color-coded according to the air quality categories shown in Table I, similar to the methods described in Wang and Christopher [17]. The location of the CALIPSO overpass at 1930 UTC 24 May is superimposed on Fig. 1(e). The attenuated backscatter at 532 nm from CALIPSO shows an aerosol layer approximately 2–3 km above the surface between 31.5° and 34°N latitude (Fig. 2). Intermixed in this aerosol layer is a field of cumulus clouds, which can be seen on the corresponding MODIS image in Fig. 1(e). (The level 2 CALIPSO product classifies backscatter in this region as from both clouds and aerosols). Still, it is the aerosol signal that is most apparent and important for this study. For aerosols to exist at 3 km above the surface, either significant updrafts must be transporting boundary-layer aerosols upward, or aerosols must are being injected into this layer. However, note that this is only overpass and generalizations regarding aerosol heights for the entire domain or period of study cannot be made.

For all three days, the general parcel trajectory in southern Georgia is from east to west, curving northward in western Al-

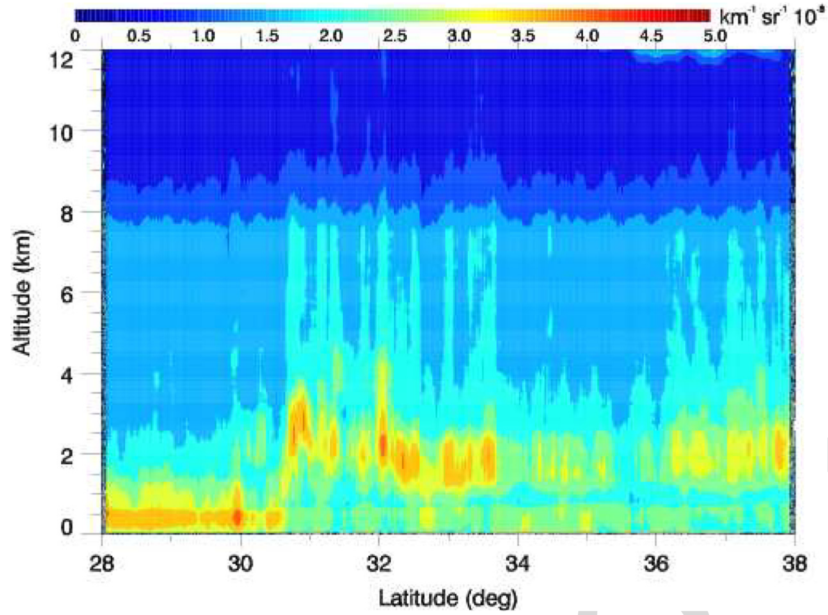

Fig. 2. Vertical distribution of clouds and aerosols from the 532 nm CALIPSO backscatter for May 24, 2007 corresponding to swath shown in Fig. 1(e).

abama and Mississippi. Wind speeds are strongest for May 23 and 24 and begin to decrease by May 25 as the high-pressure system north of the fires begins to weaken. A large area of low level cumulus clouds is present over the southeast U.S. during this timeframe, though little in the way of precipitation occurred owing to the relatively stable atmospheric profile. Easterly winds transported smoke from the fires, westward and northwestward increasing AOT in Alabama, Mississippi, and Tennessee. The individual smoke plumes are evident in the inset in each figure (with fire locations shown in blue) although the MODIS algorithm does not classify it as aerosols since the visible reflectivity is high. Smoke from late afternoon fire on May 23 is transported westward and is observed at 1930 UTC May 24 in western Alabama at a height of approximately 2 km.

The fires reach their maximum intensity on the afternoon of May 24 as seen by the blue 'X' marks in the inset. Smoke produced from these fires takes between 15 and 18 h to travel from the fires to the regions of high AOT. Thus, the high AOT values observed on May 25 are a result of the smoke being produced on May 24. Also, note that the fires are much weaker by May 25, with only a few GOES fire pixel detections and a residual smoke plume being present [Fig. 1(c), (f)].

In order for this smoke to reduce air quality far downstream of the fire, certain atmospheric conditions must exist that allow for mixing of atmospheric parcels downward. Evidence for this exists in that RUC planetary boundary layer (PBL) height decreases somewhat further west, allowing for downward transport of the smoke, decreasing air quality near the surface. HYSPLIT parcel trajectories also indicate a downward parcel motion between the source and western AL. This trend of decreasing PBL height exists for all three days with PBL heights in southern GA greater that 2 km AGL even by 1600 UTC ($\sim$11 : 00 a.m. local time), and regions with PBL greater than 2 km increasing significantly by 1900 UTC ($\sim$2 : 00 p.m. local time) as the boundary layer becomes increasingly mixed into the free atmosphere. Further west in western AL and eastern MS, PBL heights are often 1 km less than areas further east at both morning and afternoon times. The aerosol layer observed by CALIPSO is between 2 and 3 km, above the boundary layer at this time, but well below the injection height of the aerosols. As PBL decreases in the evening hours, it is likely the height of the aerosol layer decreases accordingly, impacting surface air quality.

Near Birmingham, AL, air quality is quite good during May 24 and 25 since most of the smoke aerosols for these days are transported to the south and west of the city. Slightly worse conditions exist on May 23, when parcel trajectories are slightly more favorable for transporting smoke to near the city. Closer to the fire in western Florida, air quality is consistently poor, as would be expected give its closer proximity to the fires. Further westward in Mississippi, air quality is much more a function of time of day and PBL height.

The geostationary data sets have the obvious advantage of providing diurnal information that polar orbiters cannot. This also means that there are more opportunities to observe aerosols. However, note that this is columnar diurnal information. To demonstrate this diurnal capability, Fig. 3 shows an example of hourly GASP retrievals of 550 nm AOT over land from 1215 UTC to 1615 UTC for May 23, 2007. At 1215 UTC the smoke plumes near the Georgia/Florida border are apparent as shown in Fig. 3. AOT values are high and the corresponding PM2.5 values from the ground-based monitors also indicate high values near the source regions. The high AOT values in Alabama are from transported smoke aerosols from the previous day. This smoke plume is seen throughout the day based on high AOT and PM2.5 values that is also well corroborated with the MODIS imagery [Fig. 3(a) and (d)]. At 1315 UTC cloud cover is still minimal in Southeastern United States and then it starts increasing for the rest of the day, thereby making to difficult to distinguish smoke plumes that could be below or above the cloud layers. Nevertheless, ground-based monitors of PM2.5 throughout the southeastern United States show elevated PM2.5 values during this day.

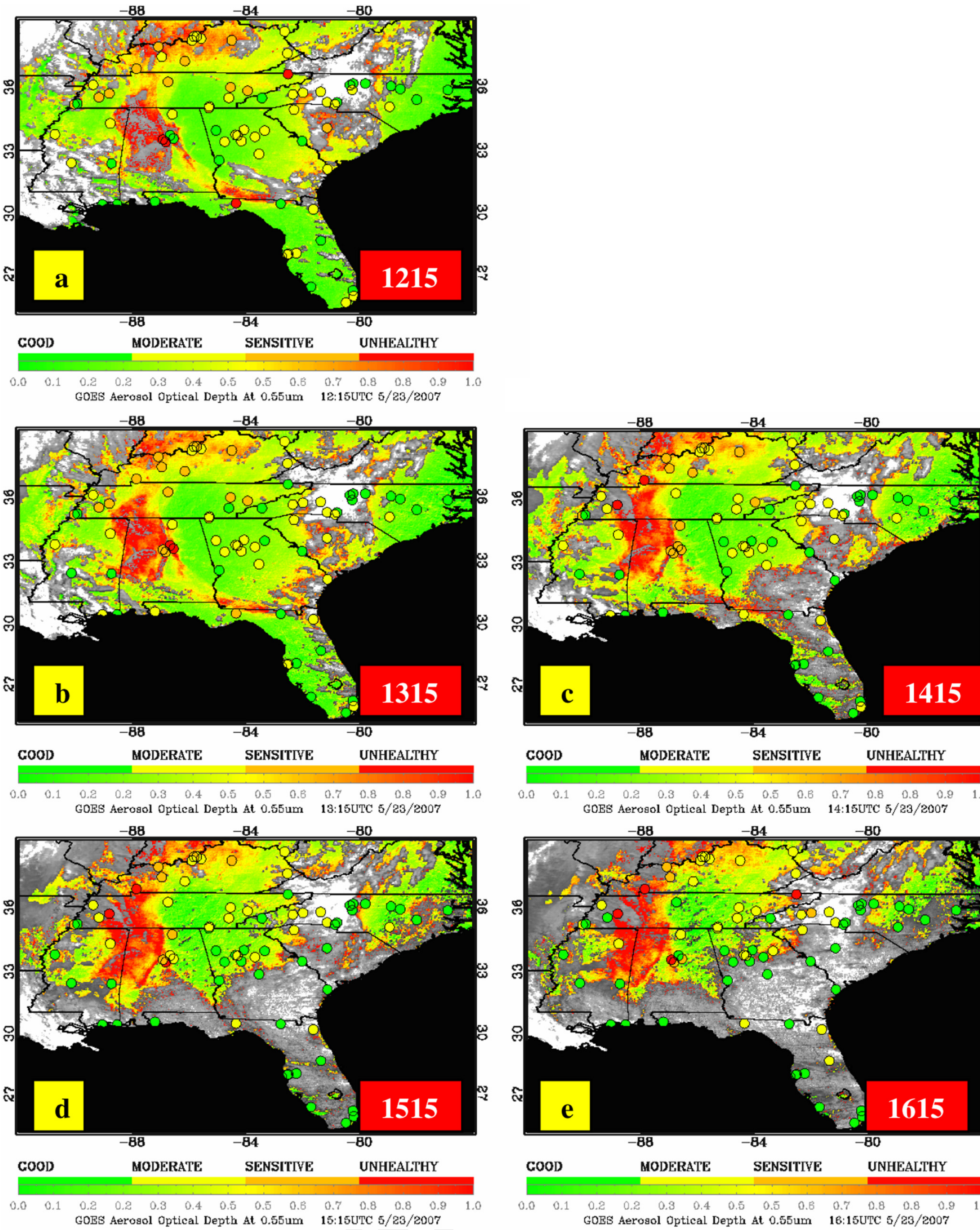

Fig. 3. The 550-nm geostationary aerosol product (GASP) for May 23, 2007 from 1215 UTC to1615 UTC. The circles indicate the location of the PM2.5 monitors and are PM2.5 are color coded similarly to Fig. 1.

B. Aerosol Speciation From the IMPROVE Network

To examine the change in surface concentrations of PM2.5 we used organic carbon (OC) and elemental carbon as tracers of smoke aerosols while noting that even during fire episodes some of the measured OC is due to photochemical processes. Fig. 4 shows the monthly mean speciated mass of several constituents including ammonium nitrate, ammonium sulfate, organic and elemental carbon for two sites. We examine data from two IMPROVE locations, one far away from the source region in SIPSY

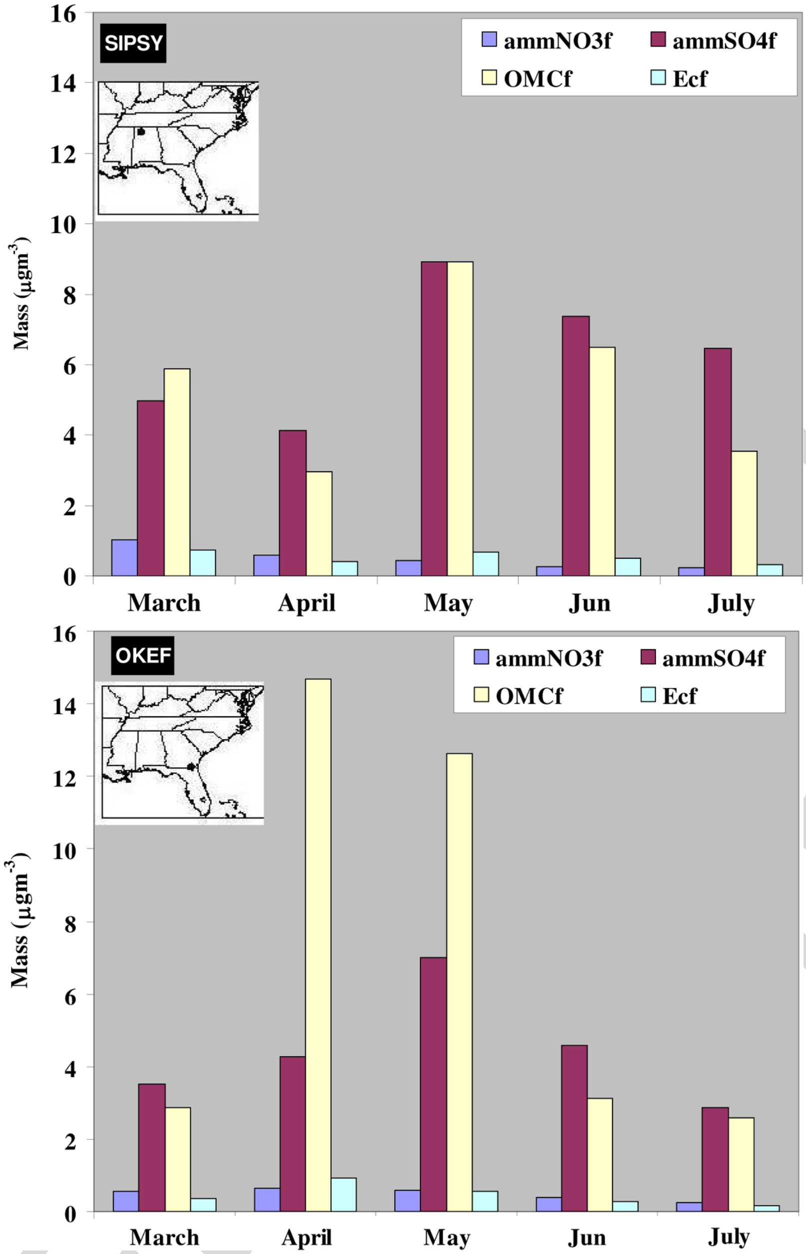

Fig. 4. Speciated mass concentrations from the IMPROVE network from March-June 2007 for two sites: (a) Sipsy, AL, and (b) Okefenokee National Wildlife Refuge, GA. The locations of the ground-based monitors are shown in the inset. Also shown are PM2.5 mass for ammonium nitrate (ammNO3f), ammonium sulfate (ammSO4f), organic carbon (OMCf), and elemental carbon (Ecf).

Alabama [Fig. 4(a)] and the other closer to the fire source region in OKEF Georgia [Fig. 4(b)]. Between March and April at OKEF (near source region), there is nearly a five fold increase in the OMC concentration that is due to the smoke from these fires. PM2.5 OMC concentrations increased from 3 μgm^{-3} in March to about 13 μgm^{-3} during the fire events in May and returned back to its near background values in June and July. The change in OMC concentrations at SIPSY is not as pronounced as at OKEF although the values increased to about 10 μgm^{-3} in May 2007. This region was not affected by the smoke from the Georgia/Florida fires during the entire period but only episodically, and, therefore, the monthly mean values are lower.

IV. Air Quality for April and May 2007

We used four months (March to June 2007) of aerosol data from ground-based monitors and satellites to examine the air quality over two stations before, during and after the fire events. Fig. 5 presents the time series of MODIS and GOES AOT along with ground-based PM2.5 mass concentrations in two locations, one near the source in Florida [Fig. 5(a)] and another away from the source region in Alabama [Fig. 5(b)]. The PM2.5 location in Florida is close to the IMPROVE site in Georgia, which is discussed in Section III. We used this location in Florida since coincident matchups between PM2.5 and IMPROVE monitors were not available. The inset in each figure shows the locations. The horizontal lines in various colors show the PM2.5 values corresponding to the EPA categories in Table I. March represents the

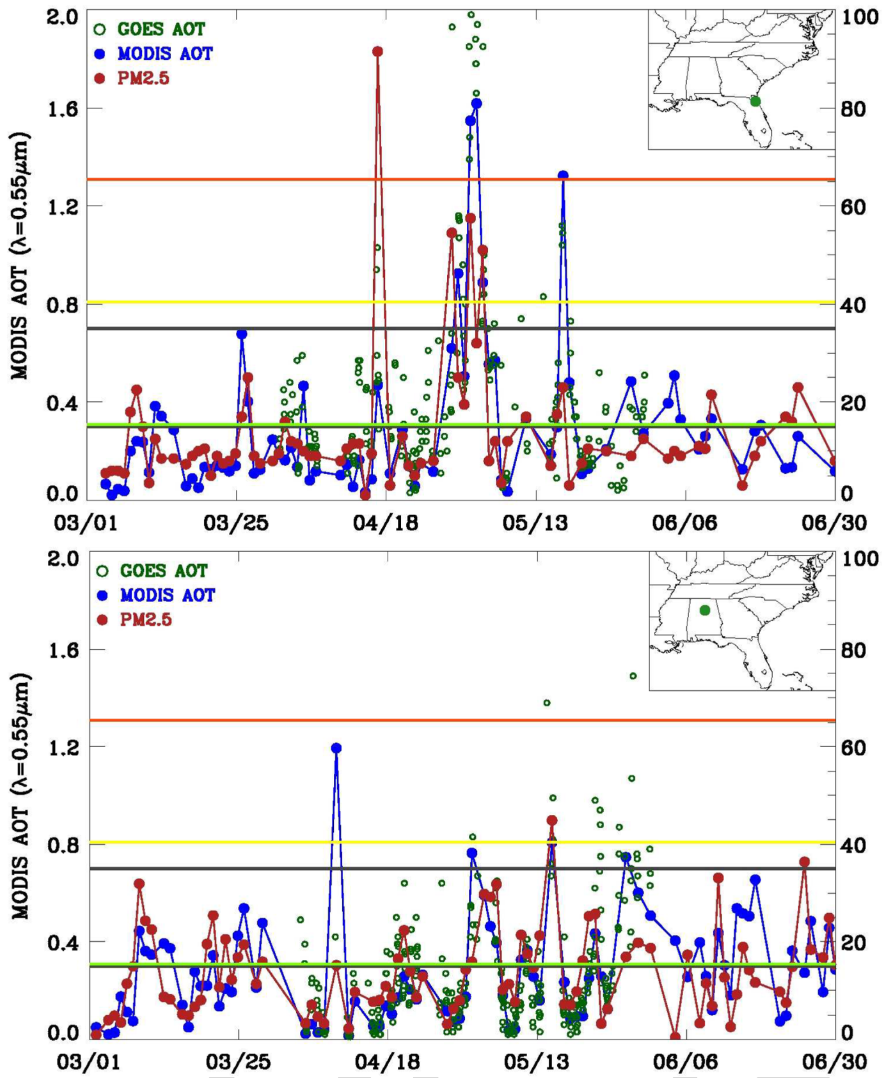

Fig. 5. MODIS AOT and PM2.5 for March–May 2007 for two sites: (a) near the source (FL), and (b) away from the source (AL). Also superimposed are the AOTs from the Geostationary GASP data set. The locations of the ground-based monitors are shown in the inset.

month before fires (pre-fires), April and May represents the time period during the fires and June is considered as post-fire activity period. Before the fires started, the air quality over Florida was under the good category ($<15\ \mu$gm^{-3}) except on a few occasions, due to local sources and prevalent meteorological conditions. The mean MODIS AOT and daily PM2.5 value for March were 0.18 and 10.9 μgm^{-3}, respectively. During the fire activity period, the surface monitors as well as satellites reported high monthly mean values. AOT and PM2.5 for April were 0.22 and 13.1 μgm^{-3}, respectively, whereas both increased to 0.53 and 19.1 μgm^{-3}, respectively, in May. The PM2.5 mass reduced to 11.7 μgm^{-3} for June with corresponding AOT values of 0.26. Ground-based monitors near the fire source reported values as high as 91.5 μgm^{-3} on April 17, 2009, that is categorized as extremely dangerous conditions by the EPA. The episodic values in PM2.5 are also seen in the AOT's derived from the polar orbiting and geostationary sensors indicating that these column measurements are good surrogates for estimating surface air quality for smoke conditions from this event.

The location in Birmingham, AL, also experienced poor air quality due to transport of smoke aerosols from fire activities in Georgia/Florida. Fig. 4(b) clearly shows that air quality in Birmingham degraded in April and May, and satellite observations in visible channels confirm the transport activities. However, note that the "background" levels of PM2.5 in March over Birmingham, AL are higher than the values in Florida due to pollution from urban areas. The GASP provides more information on diurnal pattern of transported smoke near the source and away from the source region. The GOES AOT matches well with those obtained from MODIS as seen by the similar patterns although some of the outliers in May are due to possible cloud contamination.

We next examine the relationship (linear correlation) between MODIS AOT and ground-based PM2.5 mass for 69 monitoring locations in the Southeastern United States (Fig. 6). Linear correlation coefficient between MODIS AOT and PM2.5 mass concentration is established over each ground-based PM2.5 monitoring station on a daily basis for April and May 2007. The number of coincident days when MODIS AOT is available over

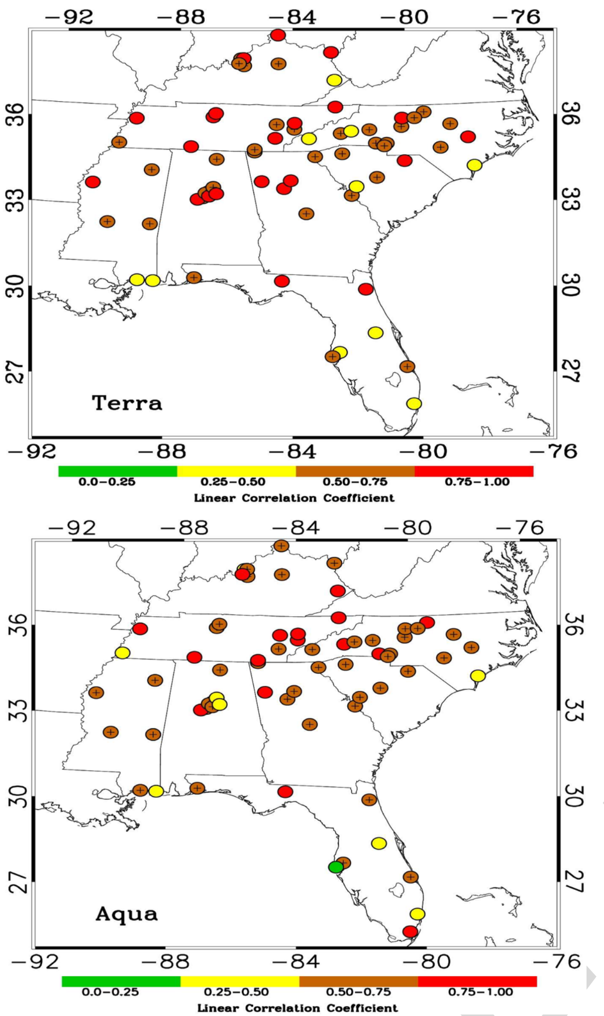

Fig. 6. Correlation between ground-based PM2.5 mass and MODIS AOT for (a) Terra and (b) Aqua.

the station varies from 18 to 46 with a mean value of about 35. Here, it is important to note that MODIS retrieval of AOT is only available under cloud free conditions. Therefore, frequent cloud cover limits the available number of data points for such analysis over any given location. Fig. 6 shows color-coded correlation maps for MODIS-Terra [Fig. 6(a)] and MODIS-Aqua [Fig. 6(b)]. We reiterate that vertical distribution of aerosols in the atmosphere and other local meteorological conditions play an important role while evaluating AOT-PM2.5 relationship over any given station. The high degree of correlation between PM2.5 concentrations and AOT during such intense fires shows the applicability of satellite data for PM air quality monitoring in areas where surface measurements are not available. This further confirms the results of Wang *et al.* [1] who assessed relationship between MODIS and PM2.5 mass concentrations in Birmingham, AL, for cases with no fire activities.

V. Smoke Aerosol and PM2.5 Forecast Using AERO-RAMS

The fire location and emission information derived from the geostationary satellites are used as input to a Regional Atmospheric Modeling system (RAMS) mesoscale transport model with Aerosols (AERO-RAMS)—without chemistry—to forecast the spatial distribution of smoke aerosols and to estimate PM2.5 values. Although more sophisticated models exist for studying fire and smoke transport with complex chemistry [20], our goal is to simply examine the transport of these smoke aerosols during these extreme fire events similar to Wang *et al.* [1]. Although fire locations and emissions are available both from the MODIS and GOES, we use the geostationary products because the transport model requires hourly information on fire emissions that is not possible to obtain from polar orbiting platforms.

The AERO-RAMS is a modified version of the one described in Wang *et al.* [1] and is based on Version 4.4 of Regional Atmospheric Modeling System (RAMS), a widely used mesoscale modeling system capable of simulating a wide range of atmospheric flows and processes. AERO-RAMS now includes modifications for aerosol transport and addition of the four-stream radiative transfer scheme that accounts for aerosol interactions [1]. The aerosol transport module in AERO-RAMS takes advantage of the modular design utilized by RAMS where additional scalar fields are implemented by incrementing a variable that defines the number of total scalars that are considered in the model. Once a new scalar is introduced, RAMS solves the conservation equation for the scalar field considering only the advective and diffusive tendencies. Source and sink tendencies are then individually specified for each new scalar species. In the current study, the only source considered is the emission term and the sink terms include dry and wet deposition [1]. Since buoyant plumes inject smoke from biomass burning fires into a relatively deep layer, smoke emissions are vertically distributed using parameterizations based on injection height that is defined as the maximum vertical intrusion of the buoyant plume. Routine observations of injection height over the entire spatial domain are difficult to obtain and, we, therefore, set the injection height to be same as the boundary layer height while fully realizing that this is only an approximation.

The AERO-RAMS simulations shown here are for smoke transport for the May 23–25, 2007 time period. The domain considered in the numerical modeling study, extending from the 20°–45°N and 70°–100°W, includes most of eastern and central regions of the United States. The smoke emissions from fires [7] using the GOES fire product using are shown in Fig. 7. The spatial distribution of smoke emissions shows fire events in several states along the Gulf and Eastern coast of the United States. However, smoke emissions for the southern Georgia fire events are substantially higher compared to other events during this time period [Fig. 7(a)]. The temporal variation of the hourly total smoke emission for the burn area in southern Georgia is shown in Fig. 7(b) with maximum hourly emission reaching 120 tons on May 24. The model simulations utilized a nested grid structure with the outer grid occupying most of the area shown in Fig. 7. The outer grid utilized 80×80 grid points in the horizontal, with a grid spacing of 32 km, while the inner grid with 122×122 grid points and grid spacing of 8 km was centered over the location of the Georgia fire event. In the vertical, a stretched vertical grid with 55 levels and a stretch ratio of 1.1 was utilized, with the grid spacing varying from 20 m near the

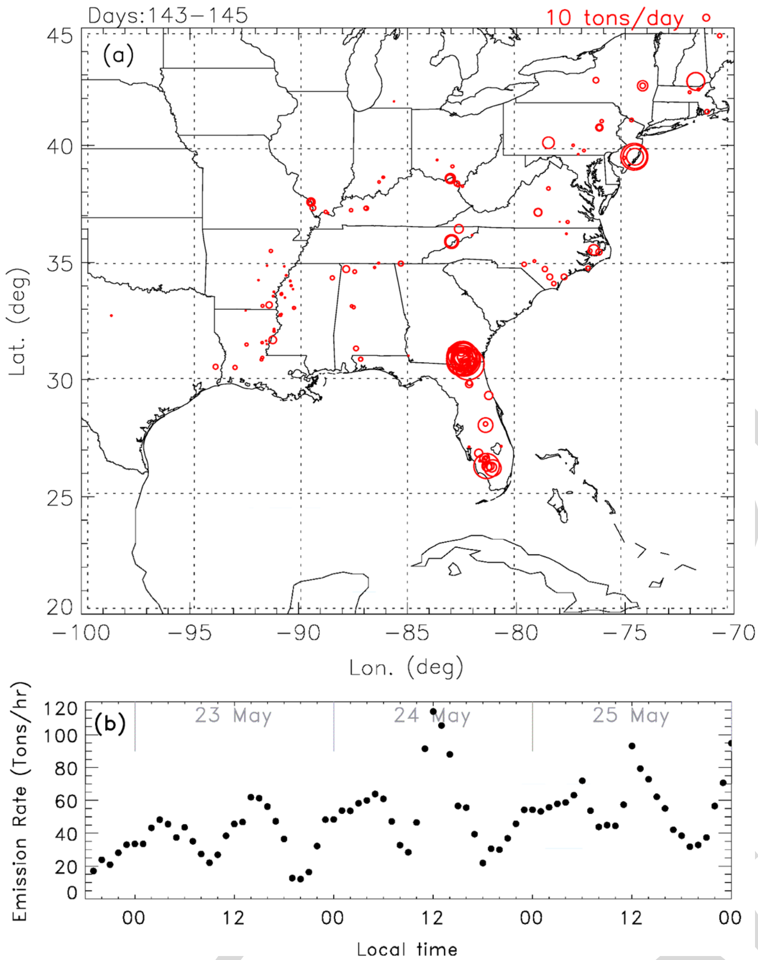

Fig. 7. (a) Location of the modeling domain and the spatial distribution of satellite observed average smoke emission fluxes in metric tons and (b) the smoke emission for the southern Georgia area during the modeling period.

surface and stretching to a maximum spacing of 1000 m higher up in the atmosphere. Atmospheric and soil state was initialized using the National Center for Environmental Prediction (NCEP) North American Model (NAM) analysis files, radiosonde and surface meteorological observations. Starting from initial conditions at 00 UTC (19 LST) of 16/17 May 2007, AERO-RAMS was integrated for 24-h periods until May 30, 2007. In the 24-h simulations, the NAM analysis fields were used to nudge the lateral boundary conditions. For each day, the smoke concentration field was initialized using smoke concentrations from the previous 24-h simulation, except for May 17, where the initial smoke concentration was assumed to be zero.

The simulated near surface smoke concentration field is compared against both surface observations of PM2.5 and also satellite observations of AOT. Assuming smoke optical properties and its hygroscopic variation in a manner consistent with Wang *et al.* [1], AOT is computed from model simulated smoke concentration that is compared against satellite-derived AOT. In these comparisons a constant AOT value of 0.1 was added to the model-derived AOT field to account for background aerosols. These comparisons are then utilized to determine the adequacy of the injection height assumptions and also the satellite derived smoke emissions. The AERO-RAMS simulation that assumed the injection height was same as the PBL height will be referred to as IHPBL experiment.

Spatial patterns of smoke optical depth from the IHPBL experiment for the May 23–25, 2007 compare reasonably well to corresponding Terra MODIS observations [Fig. 8]. On May 23, 2007, Terra MODIS observations [Fig. 8(a)] show two prominent local maxima in AOT, one centered over northern Mississippi and the other in the southern Indiana region. The IHPBL experiment [Fig. 8(b)] also show two local maxima in AOT at these locations. In the southern Georgia region, the IHPBL experiment show an elongated smoke plume aligned approximately parallel to the Georgia-Florida border. This plume is not visible in the MODIS Terra observations due to the presence of cloud cover. However, smoke AOT derived from GOES imagery show a similar smoke plume at this location during 0715–0915 LST.

On May 24, 2007, MODIS observations show higher AOT values along the eastern half of Mississippi, western areas of Tennessee and Kentucky and southern Illinois [Fig. 8(d)]. MODIS observations also show local maxima along the Great Lakes region. IHPBL experiment also shows enhanced AOT over the northeastern half of Mississippi and extends northward into southern Illinois. Local maxima in AOT are also found over the Great Lakes region. However, IHPBL simulations do

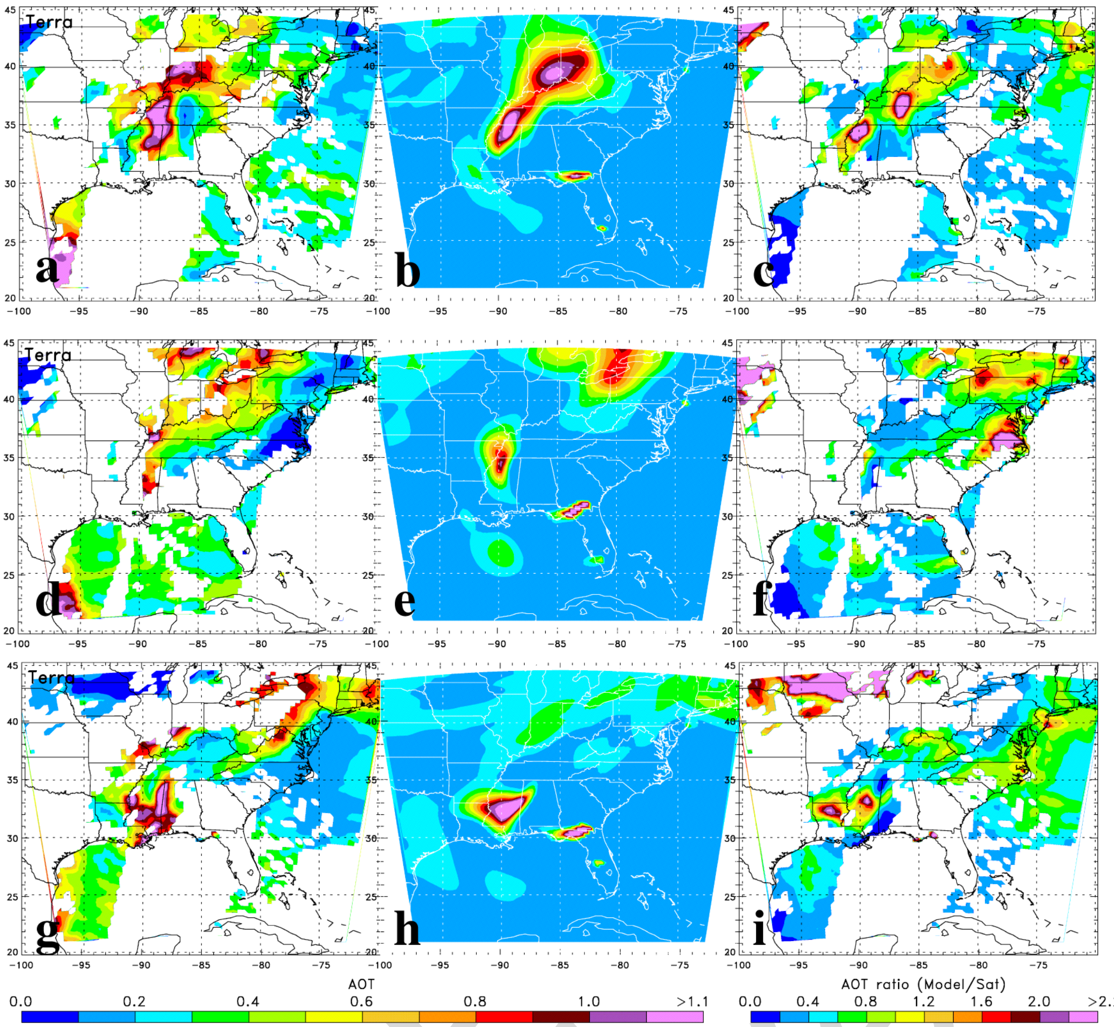

Fig. 8. MODIS AOT at 550 nm for May 23, 24, and 25, 2007 are shown in panels a,d, and g, respectively. The corresponding model simulated AOT estimates are shown in panels b, e, h. The ratio of model simulated to satellite derived AOT for these days are shown in panels c, f, i.

not capture higher AOT values over Indiana as observed in MODIS derived AOT field [Fig. 8(e)]. The IHPBL simulation also shows a smoke plume in the southern Georgia area, but the plume slopes more in a southerly direction compared to the previous day.

The MODIS AOT patterns for the May 25, 2007 shows the fire plume impacting the southern regions of Mississippi and an elongated plume along the Mississippi-Alabama border [Fig. 8(g)]. Regions of high AOT values also exist along the southern regions of Illinois and Indiana and in the northeastern regions of the US. The IHPBL experiment show higher AOT values along the southern part of Mississippi, but the elongated region of the plume slopes eastward compared to north/south orientation found in MODIS observations [Fig. 8(h)]. The IHPBL simulation does not substantially capture higher AOT values over the northeastern United States as seen in the MODIS AOT. In the southern Georgia region, IHPBL simulation shows a smoke plume extending westward into the Florida panhandle region. Due to cloud cover, the smoke plume over southern Georgia is not seen in MODIS AOT.

The average ratio of AERO-RAMS simulated AOT to MODIS AOT (IHPBL experiment generally underestimates AOT compared to MODIS Terra observations [Fig. 8(c), (f), (i)]. The ratio of simulated to MODIS AOT values show two locations where AERO-RAMS overestimate AOT on May 23, 2007, namely northwestern region of Mississippi and south central Kentucky [Fig. 8(c)]. In other areas, the IHPBL simulated AOT is comparable or less than the MODIS values. The ratio of simulated AOT to MODIS AOT for May 23 is 0.58. The IHPBL simulation overestimates AOT over northeastern part of the study area on May 24, while on May 25, there are several regions where the simulated AOT is overestimated including Mississippi, Louisiana, Kentucky, and the northeastern corner of the study area. The average value of the ratio of simulated to MODIS AOT is 0.64 and 0.7 for May 24 and 25, respectively. Assuming adequate representation of the smoke removal processes, appropriate characterization of the vertical distribution of aerosols, and long distance transport of smoke, our analysis suggests that the upper limit of factor of underestimation of satellite derived smoke emissions is approximately 1.7. This estimate is similar to the Central American case studies shown in Wang *et al.* [1]. However, note that accounting for errors in long distance transport of smoke could further reduce the factor of underestimation. For this purpose comparison be-

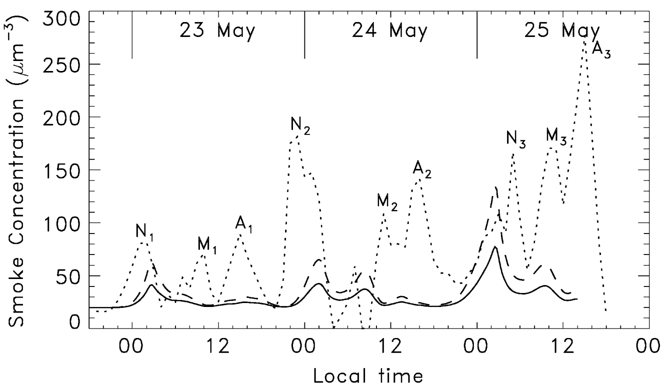

Fig. 9. Comparison of observed PM2.5 concentrations for Tallahassee, FL (small dashed line) to simulated values from IHPBL (solid line) and IHPBL2 experiment (long dashed line) for May 23–26, 2007.

tween satellite observed and model simulated AOT needs to be conducted close to the fire source region since this will reduce the uncertainties introduced by the parameterization of wet and dry deposition in AERO-RAMS. However, no AERONET data was available closer to the source regions. For the case days considered in this study this analysis was also difficult due to persistent cloud cover near the fire source regions.

Observations of surface PM2.5 concentration from Tallahassee, FL, show a general pattern where the surface concentration builds up during the night, reaching a maximum between around midnight to early morning hours (see peaks A1, A2, and A3 in Fig. 9). There is drop in surface smoke concentration approximately coinciding with the sunrise and local noon, causing two maxima of which one occur during the mid morning hours (see peaks M1, M2, and M3 in Fig. 9) after which two maxima is observed one during the mid morning hours and a more prominent one during the mid afternoon hours (see peaks A1, A2, and A3 in Fig. 9). These patterns are related to both the diurnal variation in smoke emissions [Fig. 7(b)] modulated by both boundary layer dynamics and also land-ocean circulation patterns.

Comparisons of the surface smoke concentrations from the IHPBL simulation against observations show that AERO-RAMS adequately captures the observed pattern between midnight and noon compared to afternoon to midnight hours. Note that for comparison purpose, a background aerosol concentration of 20 μgm^{-3} is added to the model simulated concentration. However, even during the midnight to afternoon period of better model performance, the peak simulated concentrations are underestimated. The peak surface concentration simulated for the first half of May 23, 24, and 25 are 41 μgm^{-3}, 41 μgm^{-3} and 77 μgm^{-3}, respectively, compared to observed values of 82 μgm^{-3}, 181 μgm^{-3} and 166 μgm^{-3}, respectively. Based on the comparison between model simulated and satellite derived AOT, the IHPBL simulation was repeated after doubling the satellite derived smoke emissions (referred from hereon as IHPBL2), leading to peak simulated surface smoke concentrations of 63 μgm^{-3}, 64 μgm^{-3} and 135 μgm^{-3} during the first half of May 23, 24, and 25, respectively. Both IHPBL and IHPBL2 simulations capture the observed pattern of smoke concentration peaking between the midnight and noon hours on May 24 and 25 but not on May 23. However, both these simulations fail to replicate the observed pattern of PM2.5 peaking between afternoon and midnight hours for all days.

The major causes for the underestimation of surface smoke concentration are: 1) Incorrect vertical distribution of smoke resulting from exaggerated vertical mixing and also inadequate assumptions regarding injection of smoke into the atmospheric column; 2) Underestimation of smoke emissions and 3) not accounting for secondary organic aerosol formation in the model. In the IHPBL2 simulation, adjustment was made to account for underestimation of smoke emissions that improved the simulated peak concentrations during the first half of the day. However, this adjustment did not improve the simulated surface smoke concentrations during the second half of the day (noon-midnight). This indicates that distributing the smoke emissions uniformly through the boundary layer may not be an adequate assumption. However, our comparison relies on a sparse observational network and further studies are required to address this issue.

VI. Summary and Conclusion

Polar orbiting and geostationary satellite data sets coupled with meteorological and ground-based information are used to assess the impact of the Florida and Georgia fires on PM2.5 air quality in Southeastern United States. Our results indicate that ground-based monitors recorded extremely high values of PM2.5 near fire source regions and also in areas downwind of these fire sources. When compared to background values, the PM2.5 mass due to organic carbon increased by nearly 5 times during these fire events. Satellite-derived columnar AOT values from both polar and geostationary satellite data sets are extremely useful for assessing the spatial distribution and diurnal variation of smoke aerosols. Coupled with meteorology, these satellite data sets showed the transport of smoke aerosols from fire sources in GA and FL to areas beyond Alabama and Mississippi. Satellite information can, therefore, be extremely useful for air quality forecasters. The columnar AOT values correlate well ($r > 0.7$) with ground-based measurements of PM2.5 since most of these aerosols were well mixed in the boundary layer. A mesoscale transport model captured the location and timing of these smoke aerosols although the emissions from these fires could be underestimated by nearly 70%. This study demonstrates the strength of satellite data in capturing the diurnal and spatial variability of fire and smoke events that are not possible using ground-based measurements alone. Work is underway to simulate the smoke from these fires with a more involved Community Multiscale Air Quality (CMAQ) model.

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Satellite Remote Sensing and Mesoscale Modeling of the 2007 Georgia/Florida Fires

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***Abstract*—During April and May 2007, several hundred fires burned uncontrollably in Georgia and Florida. The smoke from these fire events were visible throughout the Southeastern United States and had a major impact on particulate matter (PM) air quality near the surface. In this study, we show the strength of polar orbiting and geostationary satellite data in capturing the spatial distribution and diurnal variability of columnar smoke aerosol optical depth from these fires. We quantitatively evaluate PM air quality from satellites and ground-based monitors, near and far away (>300 km) from fire source regions. We also show the changes in organic carbon concentrations (a tracer for smoke aerosols) before, during and after these fire events. Finally, we use fire locations and emissions retrieved and estimated from satellite observations as input to a regional mesoscale transport model to forecast the spatial distribution of aerosols and their impact on PM air quality. During the fire events, near the source regions, total column 550 nm aerosol optical thickness (AOT) exceeded 1.0 on several days and ground-based PM2.5 mass (particles less than 2.5 μm in aerodynamic diameter) reached unhealthy levels (>65.5 ugm^{-3}). Since the aerosols were reasonably well mixed in the first 1–2 km (as estimated from meteorology), the column AOT values derived from both geostationary and polar orbiting satellites and the surface PM2.5 were well correlated (linear correlation coefficient, $r>0.7$). Several hundred miles away from the fire sources, in Birmingham, AL, the impact of the fires were also seen through the high AOT's and PM2.5 values. Correspondingly, PM2.5 mass due to organic carbon obtained from ground-based monitors showed a three fold increase during fire events when compared to background values. Satellite data were especially useful in capturing PM2.5 air quality in areas where there were no ground-based monitors. Although the mesoscale transport model captured the timing and location of aerosols, when compared to observations, the simulated mass concentrations are underestimated by nearly 70% due to various reasons including uncertainties in fire emission estimates, lack of chemistry in the model, and assumptions on vertical distribution of aerosols. Satellite products such as AOT, fire locations, and emissions from space-borne sensors are becoming a vital tool for assessing extreme events such as fires, smoke, and particulate matter air quality.**

***Index Terms*—Remote sensing, satellite applications.**

I. Introduction

BETWEEN April and June 2007, several hundred fires that were exacerbated due to extreme drought conditions burned uncontrollably near the Okefenokee swamp. Additional fires were also burning in southern Florida during this period. The fires started around April 20 and by the end of May nearly 2400 km^2 of grass, timber, and scrubland were burned. Smoke aerosols from these fires were transported hundreds of km and their effect on visibility and air quality was seen in many states in the southeastern United States. By late June the fires were fully contained and heavy rains from Hurricane Barry removed the smoke aerosols from the atmosphere.

Fires are indeed common in the United States during the spring and summer months. The location of fires and the spatial extent of smoke are readily available from satellite imagery and products. Smoke aerosols affect visibility and air quality and modify the radiation balance of the earth-atmosphere system by reflecting/absorbing solar radiation and changing cloud properties [e.g., [1]]. Fine particulate matter (PM2.5) can also be detrimental to health [2]. Both polar orbiting and geostationary satellite provide high spatial and temporal information, respectively, from their vantage points in space. On the ground, PM2.5 air quality monitors routinely provide hourly to daily information that is used to assess air quality. However, these monitors are point measurements and cannot cover vast areas. Therefore, satellite remote sensing is the only viable method for providing information at large spatial scales.

The goal of this paper is threefold. First, we show the strength of satellite imagery and products for locating fires and assessing the spatial distribution of smoke. We also show the vertical distribution of smoke aerosols from one overpass from a space-borne lidar. Next we combine the satellite data sets with ground-based measurements of PM2.5 mass to demonstrate the utility of space-borne sensors in assessing surface PM2.5 air quality. The changes in the concentrations of organic carbon (OC) and other species are also examined from locations near and far away from these fires. The Rapid Update Cycle (RUC) meteorology is used to assess wind speeds, directions and planetary boundary layer (PBL) heights. Finally, we use the geostationary satellite-based fire and smoke emission information in a mesoscale transport model (without chemistry) to demonstrate the smoke forecasting capabilities of extreme events such as fires. We also note that ongoing work is addressing the issue of using satellite-based fire locations and emissions in a more comprehensive Community Multi Scale Air Quality (CMAQ) model that incorporates detailed chemistry.

This research uses multiple satellite data sets and ground-based monitors to demonstrate the strength of combining information to assess and forecast air quality. Although several satellite data sets and products are used in this study it is important to note that the goal of this paper is not to validate the satellite products against ground-based measurements or perform inter-

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comparison studies. Validation of satellite products with data from ground-based monitors and between and among satellite products is ongoing by the various science teams [e.g., [3] for MODIS and [4] for GOES].

II. Data

While there are multiple satellite data sets that are currently available for assessing fire and smoke events, we focus only on one polar orbiting sensor, the Moderate Resolution Imaging Spectroradiometer (MODIS) and one geostationary sensor, the Geostationary Operational Environmental Satellite (GOES-12). Data from the MODIS on the Terra and Aqua polar orbiting satellites with mid morning and afternoon equatorial crossing times are especially useful for visualizing the spatial extent of smoke and clouds. We present MODIS and GOES satellite imagery from a few days (May 23–25, 2007) when the spatial extent of smoke was large. We also provide consolidated results from both the polar orbiting and geostationary satellites for the entire months of April and May for a large spatial domain and also over two specific locations to study PM2.5 air quality-one near the fire source region in Florida (81.63°W, 30.14°N) and another location far away from the source by several hundred miles in Alabama (86.67°W, 33.70°N).

A. MODIS Aerosol Product

The MODIS on the Terra and Aqua satellites measures reflected and emitted radiation from the earth-atmosphere system in 36 spectral channels between 0.405 μm–14.385 μm, with a swath width of 2330 km and near daily global coverage. While the original measurements are at 250 m, 500 m, and 1 km, the level 2 (L2) aerosol optical thickness product (collection 5) is available at 10 km^2 that is generated from a set of 20×20 (400) pixels at 500 m spatial resolution. The AOT is a columnar value of aerosol extinction and allows for global mapping of particulate matter from space. The aerosol land algorithm uses reflectance from 3 channels (0.47, 0.67, 2.13 μm) and reports AOT values in 0.47, 0.55, and 0.67 μm channels with a reported uncertainty in AOT of $\pm 0.05 \pm 0.15 * \mathrm{AOT}_{0.55}$ for the 0.55 μm channel [5].

B. GOES Aerosol and Smoke Product (GASP).

The imager on the GOES-12 satellite provides information on the reflected and emitted radiation in multiple channels. Similar to the MODIS, the GOES also provides daytime AOT at 0.55 μm but at a higher temporal resolution (every 30 minutes). The visible, mid-IR, and thermal IR channels are first used to screen clouds and aerosol pixels are then identified for retrieving AOT. Using the previous 28 days of measurements, clear sky composites for each 30 minute time step are then obtained to account for surface reflectance. AOT is then retrieved using a Look-Up Table (LUT) based on predetermined aerosol models. Further details on the GASP retrievals and uncertainties are provided elsewhere [4]. Limited intercomparisons show that the correlation between the GASP and the Aerosol Robotic Network (AERONET) [6] sunphotometers for 10 locations in the Eastern United States was 0.79 [4]. The GASP AOT's were also within 20% of the MODIS AOT values in the eastern United States under elevated AOT conditions [4].

C. IMPROVE Data

The Interagency Monitoring of Protected Visual Environments (IMPROVE) network was initiated in spring of 1988, and consists of more than 165 monitoring sites across the United States [7] that are primarily located in national parks and wilderness areas. We use two sites, one that is near the fire source (OKEF, Georgia Okefenokee National Wildlife Refuge, Okefenokee, GA, Wolf Island, GA, 82.13°W, 30.74°N) and the other that characterizes a location far away from the fire source (SIPSY, Sipsy Wilderness, Sipsy, AL, 87.33°W, 34.34°N) to examine the impact of smoke transport. At each site, sampling modules are used to collect the speciated PM2.5 mass on every third day, with a sampling duration time of 24 h. The collected samples are then analyzed to infer the concentration of speciated PM2.5 mass and other trace elements such as potassium (K) and iron (Fe), as well as the major visibility-reducing aerosol species such as sulfates, nitrates, organic compounds, elemental (light-absorbing) carbon, and wind-blown dust. In this study, we use the IMPROVE data collected in March–June 2007 to assess the changes in speciation before, during and after the fire events.

Of particular interest is the organic carbon (OC) and elemental carbon (EC) concentrations, because these species are tracers of the smoke particles originating from biomass burning [8] although a fraction of OC can be photochemically produced. Also note that there are many sources of organic carbon in the atmosphere. Sources include motor vehicles and combustion (biomass and meat cooking) and biogenic emissions. IMPROVE uses the thermal optical reflectance (TOR) method to analyze the concentration of OC and BC and the uncertainty can be 15% for OC and 18% for BC, and sometimes can be up to 50% under certain circumstances [9]. Although accurate separation of BC and OC is difficult, we merely highlight the change in these tracers before and during the fire events. In this study, we use the organic carbon mass concentration (OMC) that is assumed to be 1.4*OC where OC is the organic carbon concentration as determined by the TOR analysis. The organic carbon multiplier (1.4 used here) is an estimate of the average molecular weight per carbon weight for organic carbon aerosol and takes into account contributions from other elements associated with organic matter, such as nitrogen, oxygen and hydrogen. The value of 1.4 is an average number that has often been used to reconstruct fine mass [10]. The factor of 1.4 is the molecular weight per carbon weight ratio and corrects for other elements associated with organic molecular composition. Note that at the time of writing these data had not gone through complete quality control by the data provider.

D. CALIPSO Backscatter

The CALIOP, an active polarization sensitive, nadir-viewing, space based lidar onboard the CALIPSO satellite flying in formation with other satellites as part of A-Train constellation of satellites provides vertical profile of backscatter at 532 and 1064 nm both during day and night and samples the vertical distribution of clouds and aerosols [11]. This active lidar measures only at nadir with a lidar spot of 70 m at the surface with a maximum vertical resolution of 30 m. The repeat cycle of the A-train

TABLE I
AIR QUALITY CATEGORY AND CORRESPONDING 24 HOURLY MEAN $PM_{2.5}$ MASS (μgm^3)

Air Quality Category	Description	24 Hour Mean $PM_{2.5}$ mass (μgm^{-3})	Color Codes
Good	None	0 ~ 15.4	Blue
Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion	15.5 ~ 40.4	Green
Unhealthy for Sensitive Groups	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion	40.5 ~ 65.4	Yellow
Unhealthy	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion. Everyone else should reduce prolonged or heavy exertion	65.5 ~ 150.4	Orange
Very Unhealthy	People with heart or lung disease, older adults, and children should avoid all physical activity outdoors. Everyone else should avoid prolonged or heavy exertion	150.5 ~ 250.4	Red

satellites is 16 days. One CALIPSO overpass was available for this study to assess smoke aerosol heights. Only the level-1 backscatter information is used to infer aerosol heights since the AOT and other aerosols products retrieval from CALIOP are currently undergoing refinement and validation.

E. RUC20 Meteorological Fields

The Rapid Update Cycle (RUC) is an operational atmospheric prediction system comprised primarily of a numerical forecast model and an analysis system to initialize that model. The RUC has been developed to serve users needing short-range weather forecasts. RUC runs operationally at the National Centers for Environmental Prediction (NCEP). The RUC data used here have a horizontal resolution of 20 km with 50 vertical computational levels. Hourly data of wind speed and wind direction at 800 hPa are used in this study. [12].

F. PM2.5 Measurements and U.S. Air Quality Standards

There are several sources for ground-based information for aerosols. In this study we use the particulate matter (PM2.5) mass measurements from the US Environmental Protection Agency (USEPA) AirNow network. The PM2.5 concentrations are measured using a Tapered-Element Oscillating Microbalance (TEOM) instrument with a stated accuracy of $\pm 1.5\ \mu gm^{-3}$ for hourly averages. However, due to the volatilization of ammonium nitrate and organic carbon, the TEOM PM2.5 mass concentrations may be underestimated [13]. The EPA reports an Air Quality Index (AQI) based on the ratio between 24-hour averages of the measured dry particulate mass and NAAQS, and it can range from nearly zero in a very clean atmosphere to 500 in extremely polluted conditions. Table I gives details on PM2.5 mass, air quality categories and possible health effects.

G. The GOES Fire Product and Emissions.

The GOES Wild Fire Automated Biomass Burning Algorithm (ABBA) provides near real time locations of fires and hot spots throughout the Western hemisphere at high temporal resolutions [14]. Using these fire locations along with estimates of burned area, fuel loading, the fraction of combustion, and factors of emissions for trace gases and aerosols, biomass burning emissions can be estimated [15]. We use the fire emissions product generated by Zhang and Kondragunta [15] as input to a mesoscale transport model. It is difficult to assess uncertainties in fire detection products since validation data sets are not readily available at the required space and time scales [16].

III. RESULTS AND DISCUSSION

The first goal of this paper is to assess the spatial distribution of fires and smoke over the southeastern United States. The second goal of this paper is to derive near surface PM2.5 air quality from columnar satellite information. While ground-based monitors provide PM2.5 mass on an hourly basis, they are representative of surface values whereas the satellites provide integrated values of aerosol extinction over the entire atmospheric column. Several studies have shown the success of using satellite data in tracking surface PM2.5 in the United States [17]. In these studies, a regression relationship is established between the columnar satellite-derived AOT and surface PM2.5 mass. Then this AOT-PM2.5 relationship is used to convert the satellite measurements to air quality indices based on EPA guidelines. These values are then color coded for public dissemination where green is for good air quality and orange and red are poor quality. An excellent example of how satellite data are fused with ground-based monitors to assess PM2.5 pollution can be seen here: http://www.star.nesdis.noaa.gov/smcd/spb/aq/, where the AOD are displayed in color simultaneously with clouds along with air quality indices from ground monitors.

Although ancillary information such as aerosol mixing height and meteorology are necessary to complement this method [18], as a first approximation, we simply use the AOT-PM2.5 relationship from this study to estimate the particulate matter mass in regions where ground-based measurements are available. Since we are focusing only on Southeastern United States where this method has the most success [19], this is a reasonable approach for highlighting the capabilities of the technique.

A. Satellite Data and Products

Fig. 1(a)–(f) shows the spatial distribution of smoke, clouds and fires from the MODIS on Terra and Aqua for May 23, 24, and 25, 2007. Fig. 1(a)–(c) is from Terra (~1600 UTC) and Fig. 1(d)–(f) is from Aqua (~1900 UTC). The mid-visible reflectances from MODIS are plotted to show the areas with

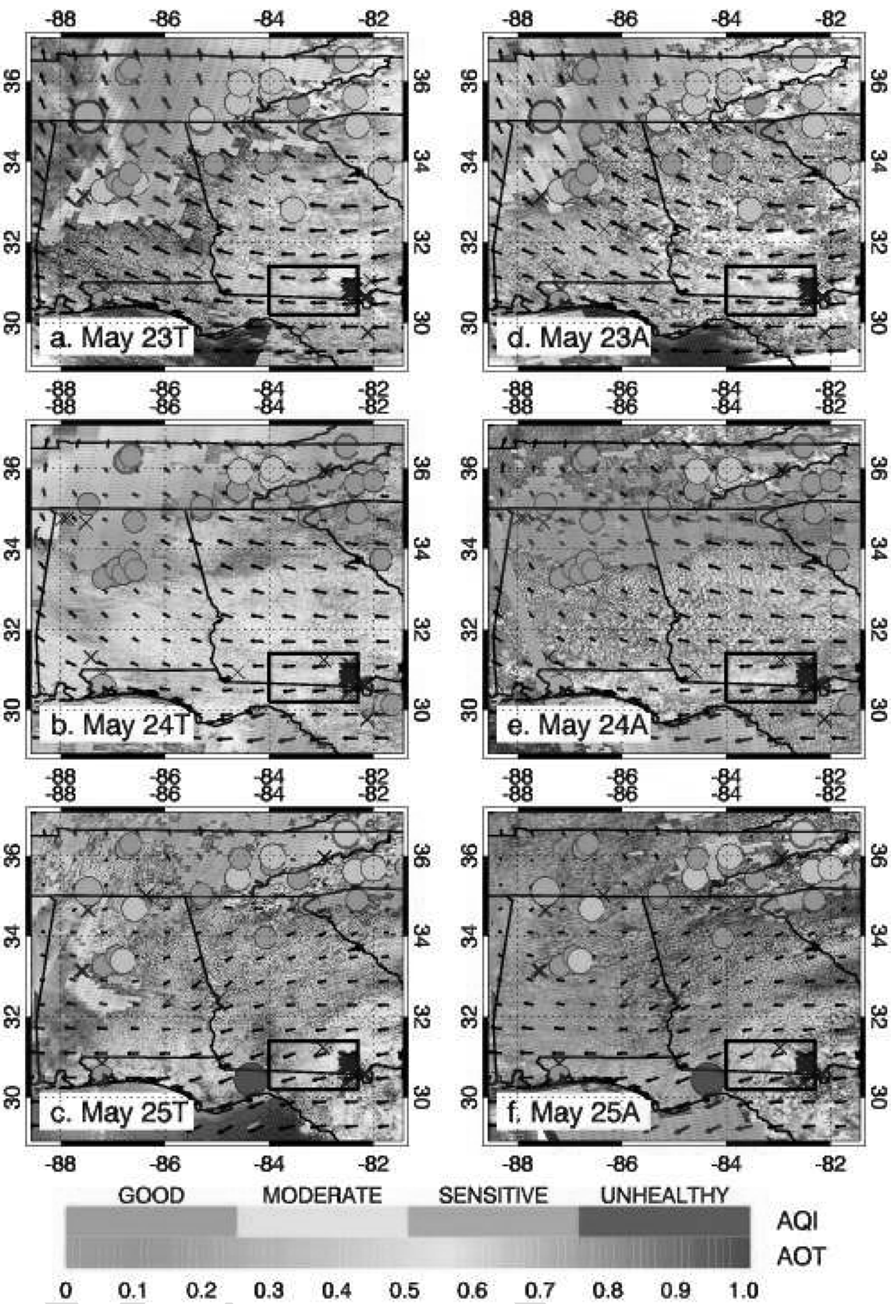

Fig. 1. Composite of MODIS level 1 and level 2 550 nm aerosol products with 800 hPa Rapid Update cycle (RUC) wind speeds and directions for Terra [Fig. 1(a)–(c), May 23–25] and Aqua [Fig. 1(d)–(f), May 23–25] . The inset in each figure shows the area where the majority of the fire events took place with fire locations shown as blue X marks. The color coded circles indicate the PM2.5 locations with air quality color categories based on the EPA guidelines (Table I). Fig. 1(e) shows the CALIPSO overpass in yellow to the left of the image running NW to SE.

smoke and clouds. Brighter regions in white are from clouds and the hazier regions are smoke aerosols from fires. Overlaid on these plots are the level 2 MODIS AOT in color. Vectors indicate wind speed and direction at 800 hPa derived from RUC model analysis. The location of PM2.5 ground-based monitors are also indicated and are color-coded according to the air quality categories shown in Table I, similar to the methods described in Wang and Christopher [17]. The location of the CALIPSO overpass at 1930 UTC 24 May is superimposed on Fig. 1(e). The attenuated backscatter at 532 nm from CALIPSO shows an aerosol layer approximately 2–3 km above the surface between 31.5° and 34°N latitude (Fig. 2). Intermixed in this aerosol layer is a field of cumulus clouds, which can be seen on the corresponding MODIS image in Fig. 1(e). (The level 2 CALIPSO product classifies backscatter in this region as from both clouds and aerosols). Still, it is the aerosol signal that is most apparent and important for this study. For aerosols to exist at 3 km above the surface, either significant updrafts must be transporting boundary-layer aerosols upward, or aerosols must are being injected into this layer. However, note that this is only overpass and generalizations regarding aerosol heights for the entire domain or period of study cannot be made.

For all three days, the general parcel trajectory in southern Georgia is from east to west, curving northward in western Al-

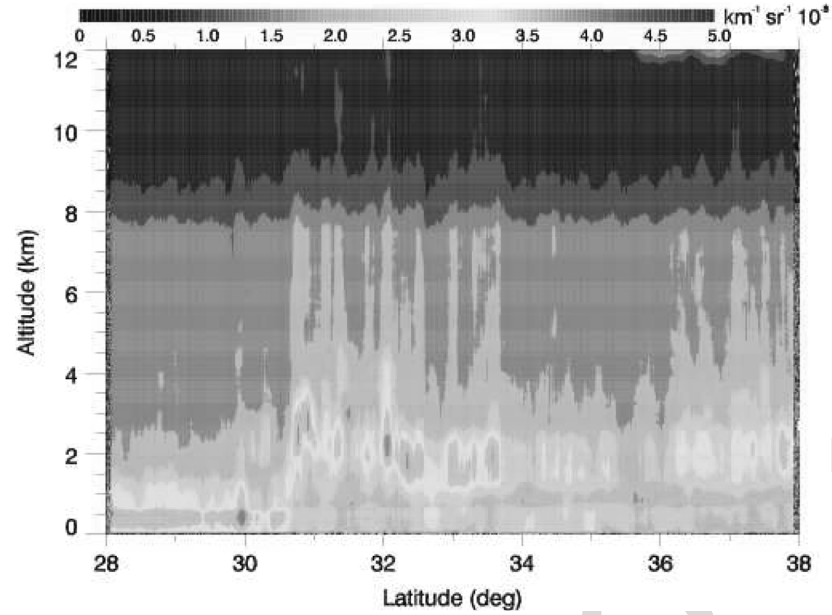

Fig. 2. Vertical distribution of clouds and aerosols from the 532 nm CALIPSO backscatter for May 24, 2007 corresponding to swath shown in Fig. 1(e).

abama and Mississippi. Wind speeds are strongest for May 23 and 24 and begin to decrease by May 25 as the high-pressure system north of the fires begins to weaken. A large area of low level cumulus clouds is present over the southeast U.S. during this timeframe, though little in the way of precipitation occurred owing to the relatively stable atmospheric profile. Easterly winds transported smoke from the fires, westward and northwestward increasing AOT in Alabama, Mississippi, and Tennessee. The individual smoke plumes are evident in the inset in each figure (with fire locations shown in blue) although the MODIS algorithm does not classify it as aerosols since the visible reflectivity is high. Smoke from late afternoon fire on May 23 is transported westward and is observed at 1930 UTC May 24 in western Alabama at a height of approximately 2 km.

The fires reach their maximum intensity on the afternoon of May 24 as seen by the blue 'X' marks in the inset. Smoke produced from these fires takes between 15 and 18 h to travel from the fires to the regions of high AOT. Thus, the high AOT values observed on May 25 are a result of the smoke being produced on May 24. Also, note that the fires are much weaker by May 25, with only a few GOES fire pixel detections and a residual smoke plume being present [Fig. 1(c), (f)].

In order for this smoke to reduce air quality far downstream of the fire, certain atmospheric conditions must exist that allow for mixing of atmospheric parcels downward. Evidence for this exists in that RUC planetary boundary layer (PBL) height decreases somewhat further west, allowing for downward transport of the smoke, decreasing air quality near the surface. HYSPLIT parcel trajectories also indicate a downward parcel motion between the source and western AL. This trend of decreasing PBL height exists for all three days with PBL heights in southern GA greater that 2 km AGL even by 1600 UTC ($\sim$11 : 00 a.m. local time), and regions with PBL greater than 2 km increasing significantly by 1900 UTC ($\sim$2 : 00 p.m. local time) as the boundary layer becomes increasingly mixed into the free atmosphere. Further west in western AL and eastern MS, PBL heights are often 1 km less than areas further east at both morning and afternoon times. The aerosol layer observed by CALIPSO is between 2 and 3 km, above the boundary layer at this time, but well below the injection height of the aerosols. As PBL decreases in the evening hours, it is likely the height of the aerosol layer decreases accordingly, impacting surface air quality.

Near Birmingham, AL, air quality is quite good during May 24 and 25 since most of the smoke aerosols for these days are transported to the south and west of the city. Slightly worse conditions exist on May 23, when parcel trajectories are slightly more favorable for transporting smoke to near the city. Closer to the fire in western Florida, air quality is consistently poor, as would be expected give its closer proximity to the fires. Further westward in Mississippi, air quality is much more a function of time of day and PBL height.

The geostationary data sets have the obvious advantage of providing diurnal information that polar orbiters cannot. This also means that there are more opportunities to observe aerosols. However, note that this is columnar diurnal information. To demonstrate this diurnal capability, Fig. 3 shows an example of hourly GASP retrievals of 550 nm AOT over land from 1215 UTC to 1615 UTC for May 23, 2007. At 1215 UTC the smoke plumes near the Georgia/Florida border are apparent as shown in Fig. 3. AOT values are high and the corresponding PM2.5 values from the ground-based monitors also indicate high values near the source regions. The high AOT values in Alabama are from transported smoke aerosols from the previous day. This smoke plume is seen throughout the day based on high AOT and PM2.5 values that is also well corroborated with the MODIS imagery [Fig. 3(a) and (d)]. At 1315 UTC cloud cover is still minimal in Southeastern United States and then it starts increasing for the rest of the day, thereby making to difficult to distinguish smoke plumes that could be below or above the cloud layers. Nevertheless, ground-based monitors of PM2.5 throughout the southeastern United States show elevated PM2.5 values during this day.

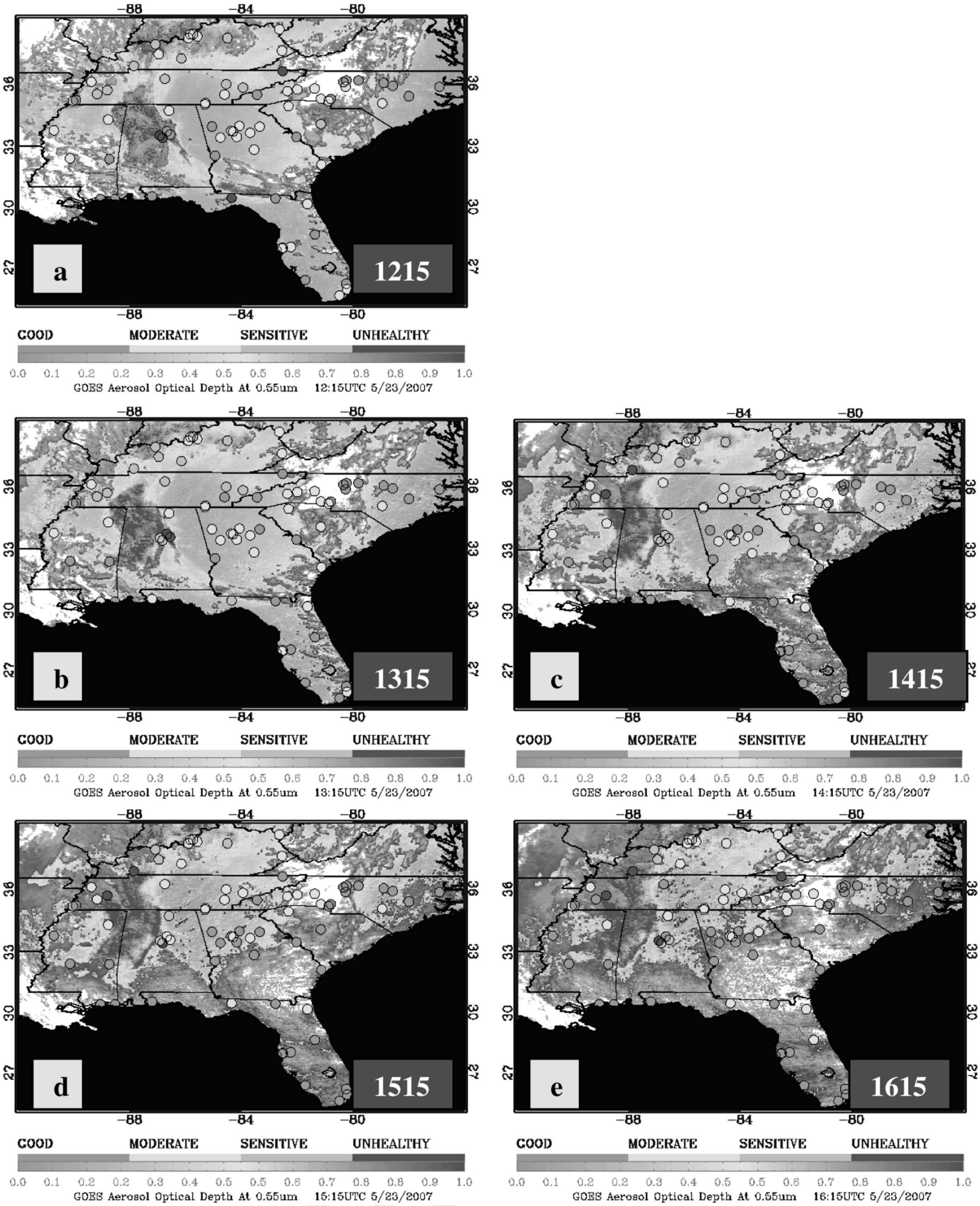

Fig. 3. The 550-nm geostationary aerosol product (GASP) for May 23, 2007 from 1215 UTC to1615 UTC. The circles indicate the location of the PM2.5 monitors and are PM2.5 are color coded similarly to Fig. 1.

B. Aerosol Speciation From the IMPROVE Network

To examine the change in surface concentrations of PM2.5 we used organic carbon (OC) and elemental carbon as tracers of smoke aerosols while noting that even during fire episodes some of the measured OC is due to photochemical processes. Fig. 4 shows the monthly mean speciated mass of several constituents including ammonium nitrate, ammonium sulfate, organic and elemental carbon for two sites. We examine data from two IMPROVE locations, one far away from the source region in SIPSY

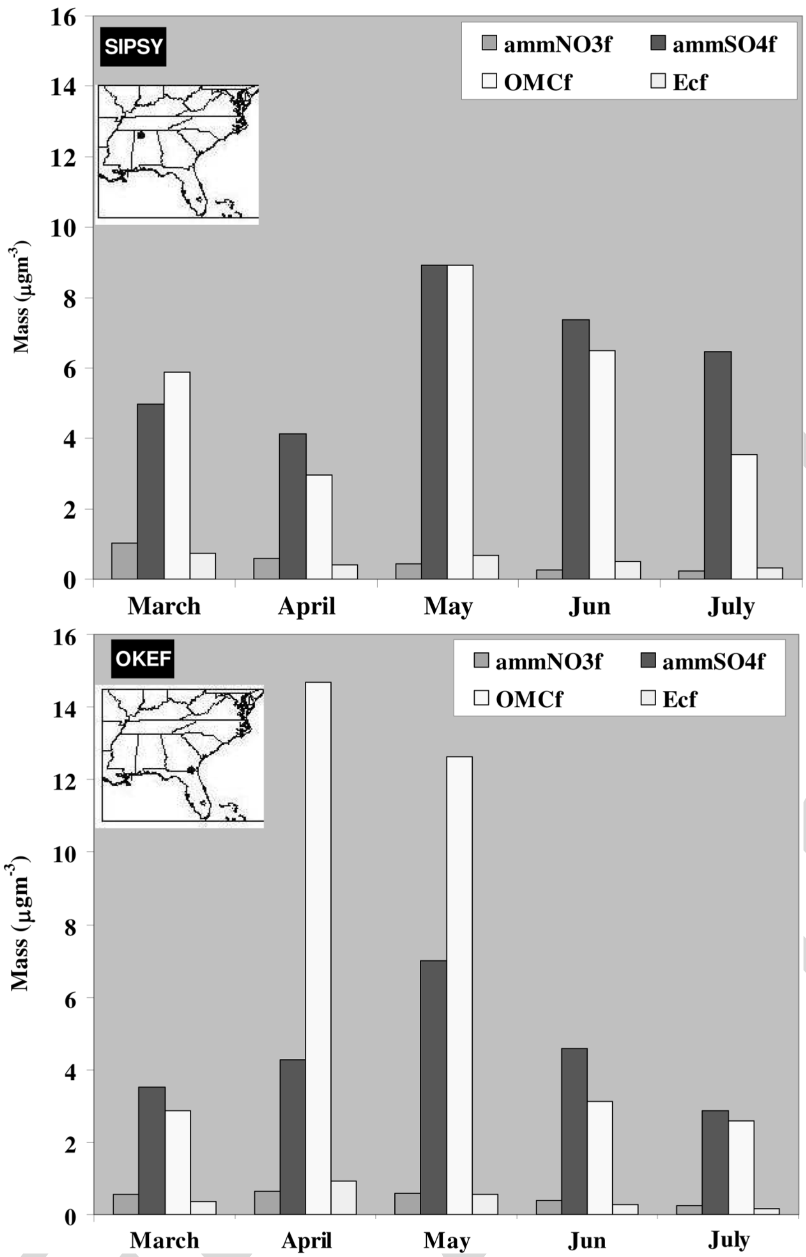

Fig. 4. Speciated mass concentrations from the IMPROVE network from March-June 2007 for two sites: (a) Sipsy, AL, and (b) Okefenokee National Wildlife Refuge, GA. The locations of the ground-based monitors are shown in the inset. Also shown are PM2.5 mass for ammonium nitrate (ammNO3f), ammonium sulfate (ammSO4f), organic carbon (OMCf), and elemental carbon (Ecf).

Alabama [Fig. 4(a)] and the other closer to the fire source region in OKEF Georgia [Fig. 4(b)]. Between March and April at OKEF (near source region), there is nearly a five fold increase in the OMC concentration that is due to the smoke from these fires. PM2.5 OMC concentrations increased from 3 μgm^{-3} in March to about 13 μgm^{-3} during the fire events in May and returned back to its near background values in June and July. The change in OMC concentrations at SIPSY is not as pronounced as at OKEF although the values increased to about 10 μgm^{-3} in May 2007. This region was not affected by the smoke from the Georgia/Florida fires during the entire period but only episodically, and, therefore, the monthly mean values are lower.

IV. Air Quality for April and May 2007

We used four months (March to June 2007) of aerosol data from ground-based monitors and satellites to examine the air quality over two stations before, during and after the fire events. Fig. 5 presents the time series of MODIS and GOES AOT along with ground-based PM2.5 mass concentrations in two locations, one near the source in Florida [Fig. 5(a)] and another away from the source region in Alabama [Fig. 5(b)]. The PM2.5 location in Florida is close to the IMPROVE site in Georgia, which is discussed in Section III. We used this location in Florida since coincident matchups between PM2.5 and IMPROVE monitors were not available. The inset in each figure shows the locations. The horizontal lines in various colors show the PM2.5 values corresponding to the EPA categories in Table I. March represents the

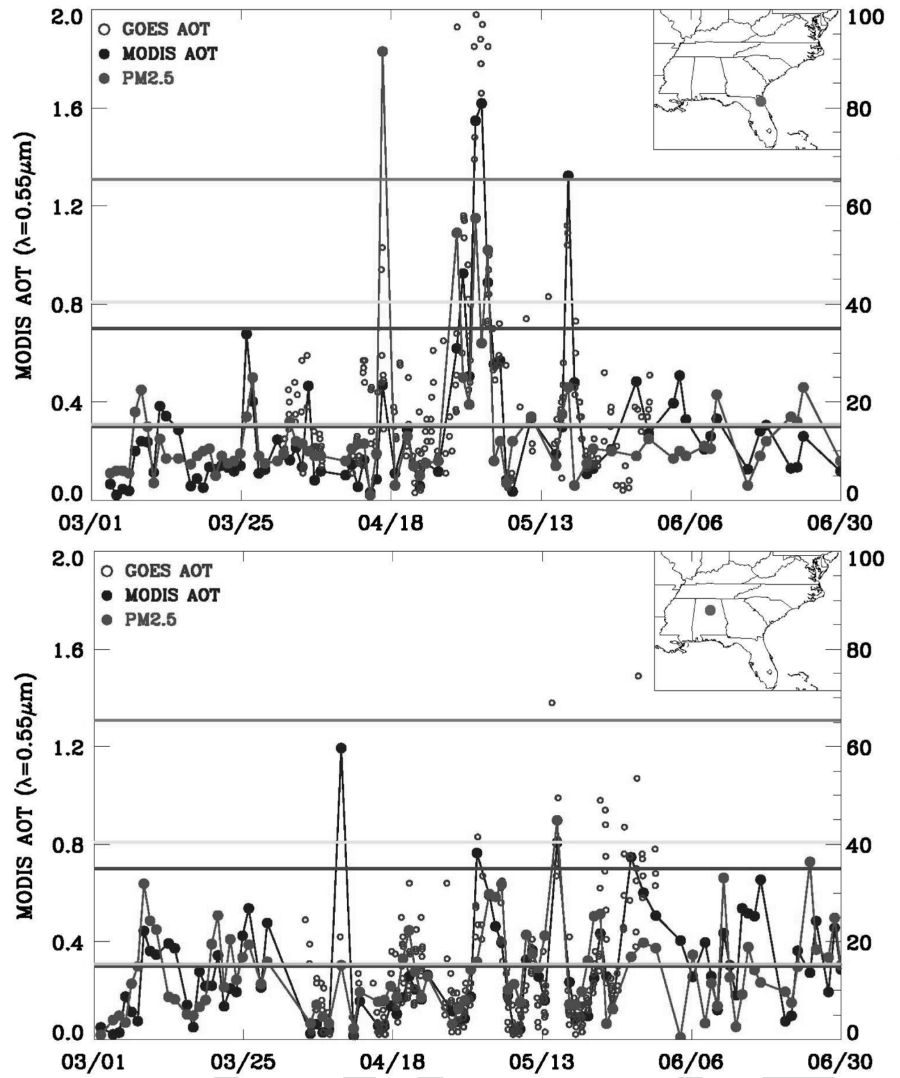

Fig. 5. MODIS AOT and PM2.5 for March–May 2007 for two sites: (a) near the source (FL), and (b) away from the source (AL). Also superimposed are the AOTs from the Geostationary GASP data set. The locations of the ground-based monitors are shown in the inset.

month before fires (pre-fires), April and May represents the time period during the fires and June is considered as post-fire activity period. Before the fires started, the air quality over Florida was under the good category ($<15\ \mu gm^{-3}$) except on a few occasions, due to local sources and prevalent meteorological conditions. The mean MODIS AOT and daily PM2.5 value for March were 0.18 and 10.9 μgm^{-3}, respectively. During the fire activity period, the surface monitors as well as satellites reported high monthly mean values. AOT and PM2.5 for April were 0.22 and 13.1 μgm^{-3}, respectively, whereas both increased to 0.53 and 19.1 μgm^{-3}, respectively, in May. The PM2.5 mass reduced to 11.7 μgm^{-3} for June with corresponding AOT values of 0.26. Ground-based monitors near the fire source reported values as high as 91.5 μgm^{-3} on April 17, 2009, that is categorized as extremely dangerous conditions by the EPA. The episodic values in PM2.5 are also seen in the AOT's derived from the polar orbiting and geostationary sensors indicating that these column measurements are good surrogates for estimating surface air quality for smoke conditions from this event.

The location in Birmingham, AL, also experienced poor air quality due to transport of smoke aerosols from fire activities in Georgia/Florida. Fig. 4(b) clearly shows that air quality in Birmingham degraded in April and May, and satellite observations in visible channels confirm the transport activities. However, note that the "background" levels of PM2.5 in March over Birmingham, AL are higher than the values in Florida due to pollution from urban areas. The GASP provides more information on diurnal pattern of transported smoke near the source and away from the source region. The GOES AOT matches well with those obtained from MODIS as seen by the similar patterns although some of the outliers in May are due to possible cloud contamination.

We next examine the relationship (linear correlation) between MODIS AOT and ground-based PM2.5 mass for 69 monitoring locations in the Southeastern United States (Fig. 6). Linear correlation coefficient between MODIS AOT and PM2.5 mass concentration is established over each ground-based PM2.5 monitoring station on a daily basis for April and May 2007. The number of coincident days when MODIS AOT is available over

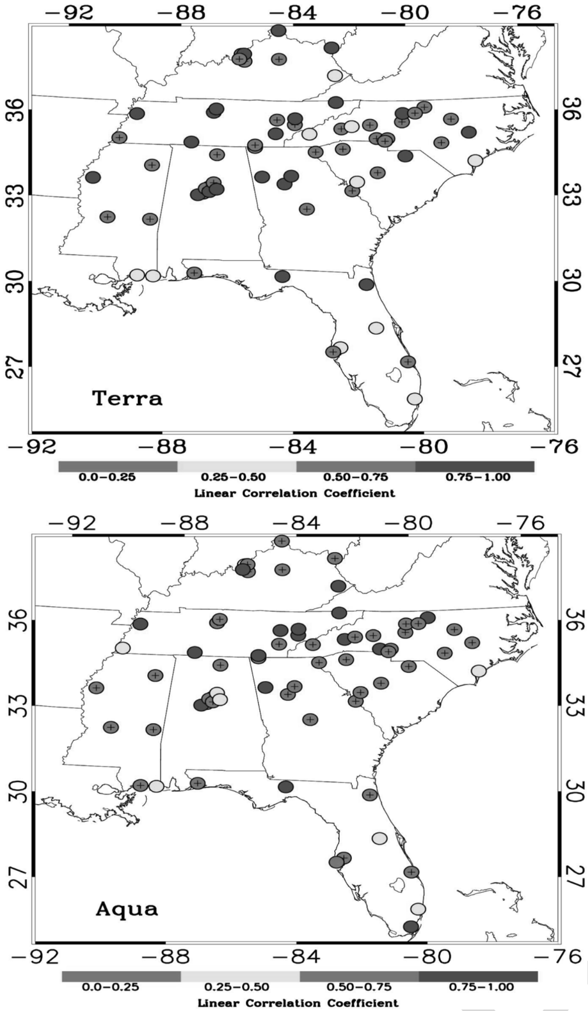

Fig. 6. Correlation between ground-based PM2.5 mass and MODIS AOT for (a) Terra and (b) Aqua.

the station varies from 18 to 46 with a mean value of about 35. Here, it is important to note that MODIS retrieval of AOT is only available under cloud free conditions. Therefore, frequent cloud cover limits the available number of data points for such analysis over any given location. Fig. 6 shows color-coded correlation maps for MODIS-Terra [Fig. 6(a)] and MODIS-Aqua [Fig. 6(b)]. We reiterate that vertical distribution of aerosols in the atmosphere and other local meteorological conditions play an important role while evaluating AOT-PM2.5 relationship over any given station. The high degree of correlation between PM2.5 concentrations and AOT during such intense fires shows the applicability of satellite data for PM air quality monitoring in areas where surface measurements are not available. This further confirms the results of Wang *et al.* [1] who assessed relationship between MODIS and PM2.5 mass concentrations in Birmingham, AL, for cases with no fire activities.

V. Smoke Aerosol and PM2.5 Forecast Using AERO-RAMS

The fire location and emission information derived from the geostationary satellites are used as input to a Regional Atmospheric Modeling system (RAMS) mesoscale transport model with Aerosols (AERO-RAMS)—without chemistry—to forecast the spatial distribution of smoke aerosols and to estimate PM2.5 values. Although more sophisticated models exist for studying fire and smoke transport with complex chemistry [20], our goal is to simply examine the transport of these smoke aerosols during these extreme fire events similar to Wang *et al.* [1]. Although fire locations and emissions are available both from the MODIS and GOES, we use the geostationary products because the transport model requires hourly information on fire emissions that is not possible to obtain from polar orbiting platforms.

The AERO-RAMS is a modified version of the one described in Wang *et al.* [1] and is based on Version 4.4 of Regional Atmospheric Modeling System (RAMS), a widely used mesoscale modeling system capable of simulating a wide range of atmospheric flows and processes. AERO-RAMS now includes modifications for aerosol transport and addition of the four-stream radiative transfer scheme that accounts for aerosol interactions [1]. The aerosol transport module in AERO-RAMS takes advantage of the modular design utilized by RAMS where additional scalar fields are implemented by incrementing a variable that defines the number of total scalars that are considered in the model. Once a new scalar is introduced, RAMS solves the conservation equation for the scalar field considering only the advective and diffusive tendencies. Source and sink tendencies are then individually specified for each new scalar species. In the current study, the only source considered is the emission term and the sink terms include dry and wet deposition [1]. Since buoyant plumes inject smoke from biomass burning fires into a relatively deep layer, smoke emissions are vertically distributed using parameterizations based on injection height that is defined as the maximum vertical intrusion of the buoyant plume. Routine observations of injection height over the entire spatial domain are difficult to obtain and, we, therefore, set the injection height to be same as the boundary layer height while fully realizing that this is only an approximation.

The AERO-RAMS simulations shown here are for smoke transport for the May 23–25, 2007 time period. The domain considered in the numerical modeling study, extending from the 20°–45°N and 70°–100°W, includes most of eastern and central regions of the United States. The smoke emissions from fires [7] using the GOES fire product using are shown in Fig. 7. The spatial distribution of smoke emissions shows fire events in several states along the Gulf and Eastern coast of the United States. However, smoke emissions for the southern Georgia fire events are substantially higher compared to other events during this time period [Fig. 7(a)]. The temporal variation of the hourly total smoke emission for the burn area in southern Georgia is shown in Fig. 7(b) with maximum hourly emission reaching 120 tons on May 24. The model simulations utilized a nested grid structure with the outer grid occupying most of the area shown in Fig. 7. The outer grid utilized 80×80 grid points in the horizontal, with a grid spacing of 32 km, while the inner grid with 122×122 grid points and grid spacing of 8 km was centered over the location of the Georgia fire event. In the vertical, a stretched vertical grid with 55 levels and a stretch ratio of 1.1 was utilized, with the grid spacing varying from 20 m near the

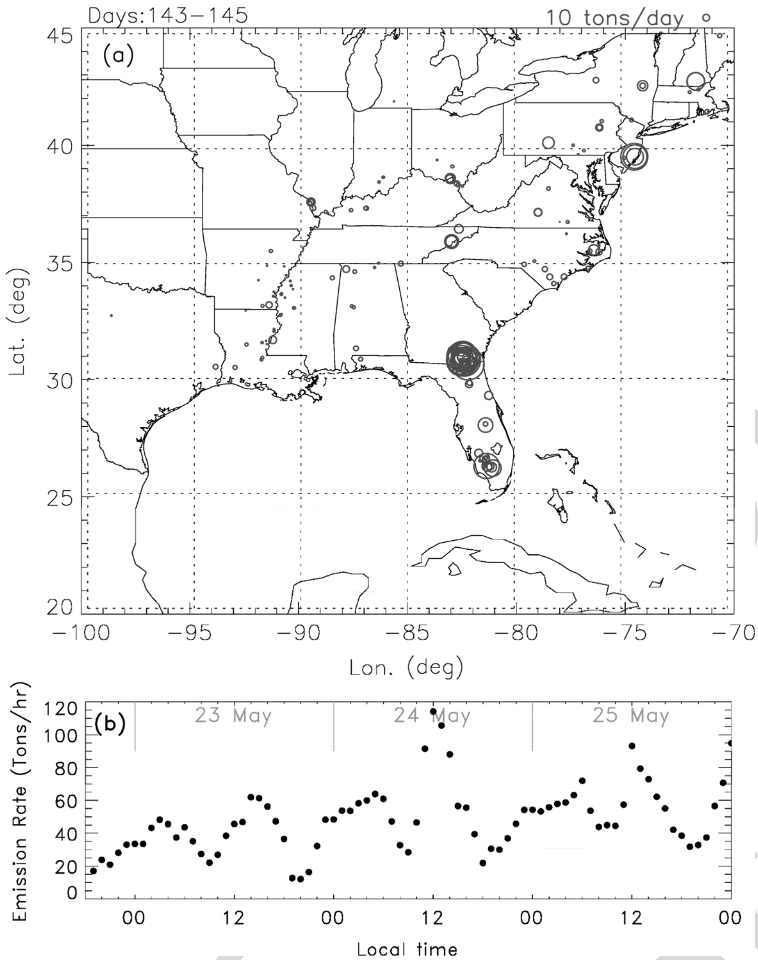

Fig. 7. (a) Location of the modeling domain and the spatial distribution of satellite observed average smoke emission fluxes in metric tons and (b) the smoke emission for the southern Georgia area during the modeling period.

surface and stretching to a maximum spacing of 1000 m higher up in the atmosphere. Atmospheric and soil state was initialized using the National Center for Environmental Prediction (NCEP) North American Model (NAM) analysis files, radiosonde and surface meteorological observations. Starting from initial conditions at 00 UTC (19 LST) of 16/17 May 2007, AERO-RAMS was integrated for 24-h periods until May 30, 2007. In the 24-h simulations, the NAM analysis fields were used to nudge the lateral boundary conditions. For each day, the smoke concentration field was initialized using smoke concentrations from the previous 24-h simulation, except for May 17, where the initial smoke concentration was assumed to be zero.

The simulated near surface smoke concentration field is compared against both surface observations of PM2.5 and also satellite observations of AOT. Assuming smoke optical properties and its hygroscopic variation in a manner consistent with Wang *et al.* [1], AOT is computed from model simulated smoke concentration that is compared against satellite-derived AOT. In these comparisons a constant AOT value of 0.1 was added to the model-derived AOT field to account for background aerosols. These comparisons are then utilized to determine the adequacy of the injection height assumptions and also the satellite derived smoke emissions. The AERO-RAMS simulation that assumed the injection height was same as the PBL height will be referred to as IHPBL experiment.

Spatial patterns of smoke optical depth from the IHPBL experiment for the May 23–25, 2007 compare reasonably well to corresponding Terra MODIS observations [Fig. 8]. On May 23, 2007, Terra MODIS observations [Fig. 8(a)] show two prominent local maxima in AOT, one centered over northern Mississippi and the other in the southern Indiana region. The IHPBL experiment [Fig. 8(b)] also show two local maxima in AOT at these locations. In the southern Georgia region, the IHPBL experiment show an elongated smoke plume aligned approximately parallel to the Georgia-Florida border. This plume is not visible in the MODIS Terra observations due to the presence of cloud cover. However, smoke AOT derived from GOES imagery show a similar smoke plume at this location during 0715–0915 LST.

On May 24, 2007, MODIS observations show higher AOT values along the eastern half of Mississippi, western areas of Tennessee and Kentucky and southern Illinois [Fig. 8(d)]. MODIS observations also show local maxima along the Great Lakes region. IHPBL experiment also shows enhanced AOT over the northeastern half of Mississippi and extends northward into southern Illinois. Local maxima in AOT are also found over the Great Lakes region. However, IHPBL simulations do

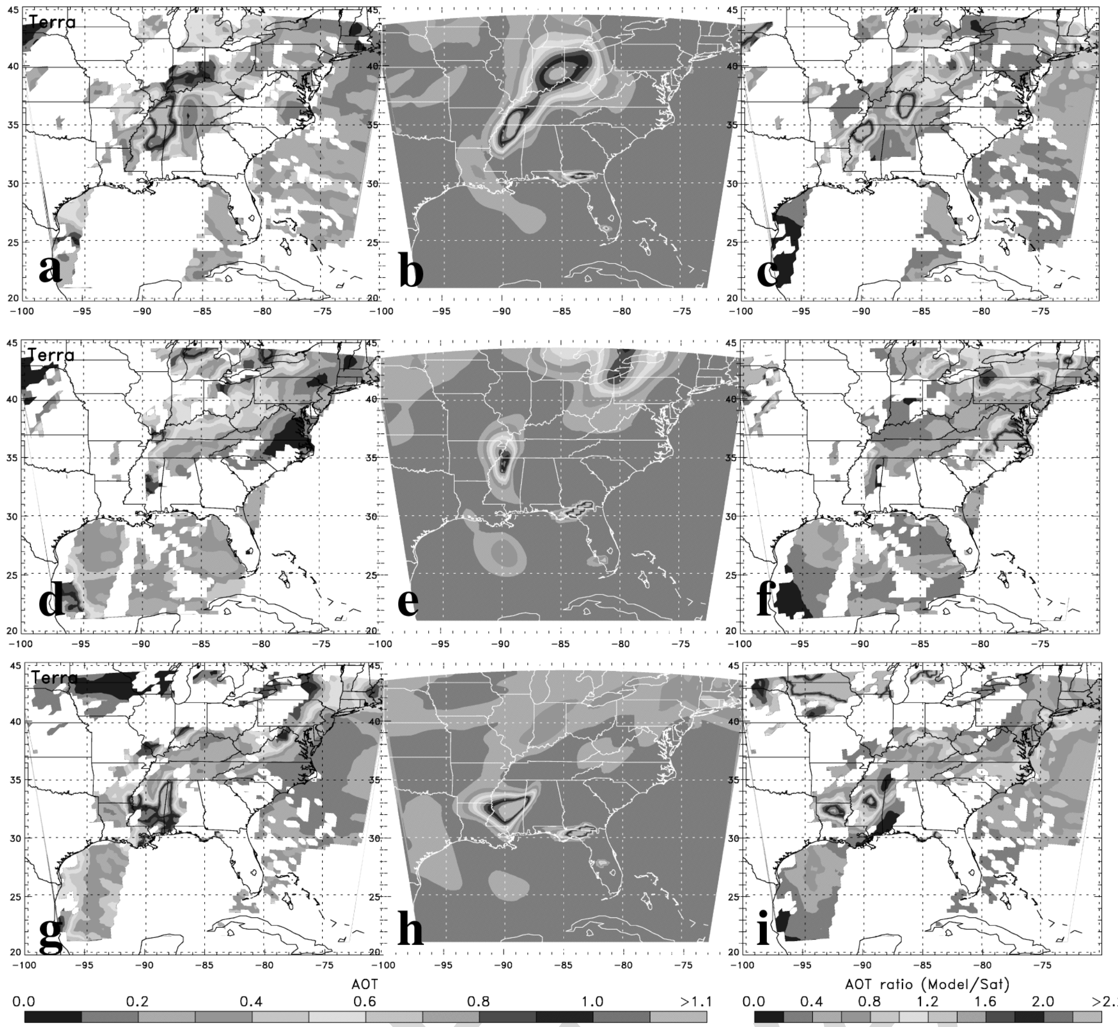

Fig. 8. MODIS AOT at 550 nm for May 23, 24, and 25, 2007 are shown in panels a,d, and g, respectively. The corresponding model simulated AOT estimates are shown in panels b, e, h. The ratio of model simulated to satellite derived AOT for these days are shown in panels c, f, i.

not capture higher AOT values over Indiana as observed in MODIS derived AOT field [Fig. 8(e)]. The IHPBL simulation also shows a smoke plume in the southern Georgia area, but the plume slopes more in a southerly direction compared to the previous day.

The MODIS AOT patterns for the May 25, 2007 shows the fire plume impacting the southern regions of Mississippi and an elongated plume along the Mississippi-Alabama border [Fig. 8(g)]. Regions of high AOT values also exist along the southern regions of Illinois and Indiana and in the northeastern regions of the US. The IHPBL experiment show higher AOT values along the southern part of Mississippi, but the elongated region of the plume slopes eastward compared to north/south orientation found in MODIS observations [Fig. 8(h)]. The IHPBL simulation does not substantially capture higher AOT values over the northeastern United States as seen in the MODIS AOT. In the southern Georgia region, IHPBL simulation shows a smoke plume extending westward into the Florida panhandle region. Due to cloud cover, the smoke plume over southern Georgia is not seen in MODIS AOT.

The average ratio of AERO-RAMS simulated AOT to MODIS AOT (IHPBL experiment generally underestimates AOT compared to MODIS Terra observations [Fig. 8(c), (f), (i)]. The ratio of simulated to MODIS AOT values show two locations where AERO-RAMS overestimate AOT on May 23, 2007, namely northwestern region of Mississippi and south central Kentucky [Fig. 8(c)]. In other areas, the IHPBL simulated AOT is comparable or less than the MODIS values. The ratio of simulated AOT to MODIS AOT for May 23 is 0.58. The IHPBL simulation overestimates AOT over northeastern part of the study area on May 24, while on May 25, there are several regions where the simulated AOT is overestimated including Mississippi, Louisiana, Kentucky, and the northeastern corner of the study area. The average value of the ratio of simulated to MODIS AOT is 0.64 and 0.7 for May 24 and 25, respectively. Assuming adequate representation of the smoke removal processes, appropriate characterization of the vertical distribution of aerosols, and long distance transport of smoke, our analysis suggests that the upper limit of factor of underestimation of satellite derived smoke emissions is approximately 1.7. This estimate is similar to the Central American case studies shown in Wang *et al.* [1]. However, note that accounting for errors in long distance transport of smoke could further reduce the factor of underestimation. For this purpose comparison be-

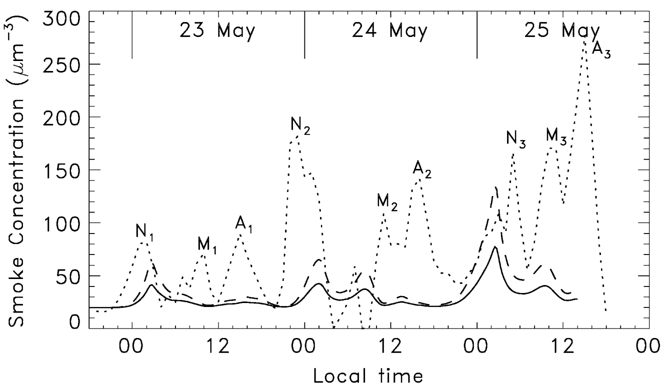

Fig. 9. Comparison of observed PM2.5 concentrations for Tallahassee, FL (small dashed line) to simulated values from IHPBL (solid line) and IHPBL2 experiment (long dashed line) for May 23–26, 2007.

tween satellite observed and model simulated AOT needs to be conducted close to the fire source region since this will reduce the uncertainties introduced by the parameterization of wet and dry deposition in AERO-RAMS. However, no AERONET data was available closer to the source regions. For the case days considered in this study this analysis was also difficult due to persistent cloud cover near the fire source regions.

Observations of surface PM2.5 concentration from Tallahassee, FL, show a general pattern where the surface concentration builds up during the night, reaching a maximum between around midnight to early morning hours (see peaks A1, A2, and A3 in Fig. 9). There is drop in surface smoke concentration approximately coinciding with the sunrise and local noon, causing two maxima of which one occur during the mid morning hours (see peaks M1, M2, and M3 in Fig. 9) after which two maxima is observed one during the mid morning hours and a more prominent one during the mid afternoon hours (see peaks A1, A2, and A3 in Fig. 9). These patterns are related to both the diurnal variation in smoke emissions [Fig. 7(b)] modulated by both boundary layer dynamics and also land-ocean circulation patterns.

Comparisons of the surface smoke concentrations from the IHPBL simulation against observations show that AERO-RAMS adequately captures the observed pattern between midnight and noon compared to afternoon to midnight hours. Note that for comparison purpose, a background aerosol concentration of 20 μgm^{-3} is added to the model simulated concentration. However, even during the midnight to afternoon period of better model performance, the peak simulated concentrations are underestimated. The peak surface concentration simulated for the first half of May 23, 24, and 25 are 41 μgm^{-3}, 41 μgm^{-3} and 77 μgm^{-3}, respectively, compared to observed values of 82 μgm^{-3}, 181 μgm^{-3} and 166 μgm^{-3}, respectively. Based on the comparison between model simulated and satellite derived AOT, the IHPBL simulation was repeated after doubling the satellite derived smoke emissions (referred from hereon as IHPBL2), leading to peak simulated surface smoke concentrations of 63 μgm^{-3}, 64 μgm^{-3} and 135 μgm^{-3} during the first half of May 23, 24, and 25, respectively. Both IHPBL and IHPBL2 simulations capture the observed pattern of smoke concentration peaking between the midnight and noon hours on May 24 and 25 but not on May 23. However, both these simulations fail to replicate the observed pattern of PM2.5 peaking between afternoon and midnight hours for all days.

The major causes for the underestimation of surface smoke concentration are: 1) Incorrect vertical distribution of smoke resulting from exaggerated vertical mixing and also inadequate assumptions regarding injection of smoke into the atmospheric column; 2) Underestimation of smoke emissions and 3) not accounting for secondary organic aerosol formation in the model. In the IHPBL2 simulation, adjustment was made to account for underestimation of smoke emissions that improved the simulated peak concentrations during the first half of the day. However, this adjustment did not improve the simulated surface smoke concentrations during the second half of the day (noon-midnight). This indicates that distributing the smoke emissions uniformly through the boundary layer may not be an adequate assumption. However, our comparison relies on a sparse observational network and further studies are required to address this issue.

VI. Summary and Conclusion

Polar orbiting and geostationary satellite data sets coupled with meteorological and ground-based information are used to assess the impact of the Florida and Georgia fires on PM2.5 air quality in Southeastern United States. Our results indicate that ground-based monitors recorded extremely high values of PM2.5 near fire source regions and also in areas downwind of these fire sources. When compared to background values, the PM2.5 mass due to organic carbon increased by nearly 5 times during these fire events. Satellite-derived columnar AOT values from both polar and geostationary satellite data sets are extremely useful for assessing the spatial distribution and diurnal variation of smoke aerosols. Coupled with meteorology, these satellite data sets showed the transport of smoke aerosols from fire sources in GA and FL to areas beyond Alabama and Mississippi. Satellite information can, therefore, be extremely useful for air quality forecasters. The columnar AOT values correlate well ($r > 0.7$) with ground-based measurements of PM2.5 since most of these aerosols were well mixed in the boundary layer. A mesoscale transport model captured the location and timing of these smoke aerosols although the emissions from these fires could be underestimated by nearly 70%. This study demonstrates the strength of satellite data in capturing the diurnal and spatial variability of fire and smoke events that are not possible using ground-based measurements alone. Work is underway to simulate the smoke from these fires with a more involved Community Multiscale Air Quality (CMAQ) model.

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