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Large fire emissions in summer over the southeastern US: Satellite measurements and modeling analysis

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HIGHLIGHTS

- Compared satellite MODIS fire counts with the VISTAS fire inventory in 2002.
- Built a hybrid emission inventory from MODIS fire counts and the fire inventory.
- Improved CMAQ aerosol OM simulations with the updated fire emission inventory.

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ABSTRACT

We apply satellite fire detection products and air quality modeling to study the contribution of fire emissions to ambient aerosol concentrations over the southeastern U.S. We find that satellite MODIS fire counts show more extensive summer burnings than suggested by the bottom–up fire inventory VISTAS in the summer of 2002. We develop a hybrid emission inventory that combines information from satellite fire counts and the bottom–up inventory by scaling the data of top–down fire count in the other months with its ratio to the bottom–up burned area data in March, the month of most prescribed burning in the Southeast in 2002. Such computed burned areas in summer are higher than the bottom–up inventory in summer; the increase of fire emissions is spatially allocated over satellite observed fire pixels based on the spatial distribution of fuel loading. We show that the updated fire emission inventory leads to notably improved CMAQ model performance of OC, EC and $PM_{2.5}$, in the Southeast on a regional basis, with reduced model low bias in the summer and better agreement with the observed seasonality. Our study suggests that missing fire emissions in bottom–up inventories can partially explain the underestimated concentrations of PM2.5, OC and EC in the Southeast and demonstrates that satellite fire detection can help improve our understanding of fire emissions and their impact on air quality.

1. Introduction

Summertime aerosol loadings are largely underestimated by air quality models, especially in the southeastern United States, where secondary organic aerosol (SOA) is believed to be a large aerosol component (e.g. Mebust et al., 2003; Morris et al., 2006; Zhang et al., 2006). To overcome the model deficiency, two aspects of efforts have been made. The first is to improve the emission inventories used as model emissions inputs, such as the periodically released National Emission Inventory by US EPA, to better account for the primary aerosol components. Another aspect of efforts focuses on improving the modeling of secondary components, especially SOA, which have been shown to account for some of the 'missing sources' (e.g. Takekawa et al., 2003; Lim et al., 2005; Morris et al., 2006; Ng et al., 2007; Robinson et al., 2007). The relative contributions of primary and secondary aerosol components vary significantly in different regions (Zeng and Wang, 2011). Among those various primary emissions, biomass burning has been shown to increase total aerosol loading through emissions of carbonaceous materials (Zeng and Wang, 2011). In this study, we use satellite fire detection to constrain the fire emission inventory in the southeastern United States, followed by testing the updated fire emission inventory though evaluation of air quality modeling results with observed data of aerosol abundance and composition.

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Satellite fire products have been used to constrain bottom–up fire emission inventories by virtue of their extensive spatial coverage, especially over remote regions where missing fire activity records occur frequently in bottom–up inventories (e.g. Soja et al., 2009). Continuous fire monitoring can be achieved by geostationary satellites, such as the NOAA Geostationary Operational Environmental Satellites (GOES) (http://www.osdpd.noaa.gov/ml/land/hms.html). Hybrid fire emission products, such as the SMARTFIRE dataset (http://www.getbluesky.org/smartfire/webservice.cfm), have also been generated by combining satellite fire detection and ground reports. Soja et al. (2009) compared these two types of fire emissions products. A key challenge in combining the two types of data is the lack of temporal or spatial consistency in fire occurrence from the two approaches (van de werf et al., 2006), which calls for a careful crosscheck and consolidation of fire emissions inventory and satellite observations at different spatial and temporal scales.

In this study, we use MODIS fire products from two satellites, i.e. Aqua and Terra, in conjunction with a bottom–up fire emission inventory, to estimate the contribution of biomass burning to aerosols in the Southeast. Data from Terra and Aqua satellites are compared and merged together based on their statistical correlation. A new method is developed to combine information from satellite observations and the fire inventory into a hybrid inventory. Results from model sensitivity simulations show that using the hybrid inventory simulates carbonaceous aerosol concentrations that are in better agreement with the observations. In particular, satellite data reveal a summer burning peak in the Southeast in 2002, which is not present in the bottom–up inventory, and helps to reduce the summertime model low bias of PM2.5. In addition, we show that MODIS AOD dataset provides indirect evidence of the summer burning in the Southeast.

2. Data and methods

2.1. VISTAS fire emission inventory

A comprehensive emission inventory has been developed based on the 1999 National Emission Inventory Version 2 (final) (NEI99V2) (http://www.epa.gov/ttn/chief/net/1999inventory.html), as part of the Visibility Improvement State and Tribal Association of the Southeast (VISTAS) program, a joint effort of 10 states in the southeastern United States (Barnard and Sabo, 2003), including Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia. Fire emissions in 2002 are developed using fire events data collected from state and federal agencies. Five states (Alabama, Florida, Georgia, Mississippi, and South Carolina) have the most complete data with more extensive fire monitoring coverage and data processing.

2.2. Satellite fire detection products by MODIS and GOES

We use fire detection products from the Moderate Resolution Imaging Spectroradiometers (MODIS) onboard NASA's polar-orbit Aqua and Terra satellites. With overpass time at ~1:30 pm and 10:30 am, respectively, Aqua and Terra together provide nearly global coverage on a daily basis. Terra MODIS data are available from Terra in the full year of 2002, while Aqua MODIS data are only available for months after July 2002. The fire detection product from MODIS is derived from thermal radiance observations, and has a pixel size of 1 × 1 km^2 (Giglio et al., 2003) with possibly smaller actual burned areas. Daily fire counts from MODIS/Terra Thermal Anomalies/Fire dataset (MOD14A1 V5) were ordered through Land Processes Distributed Active Archive Center (LP DAAC, https://lpdaac.usgs.gov/). Fig. 1 shows the spatial distribution of fire counts in summer (JJA) 2002.

Fire spot, which is a function of fire temperature and burned area, is detected using an improved algorithm mainly based on the observed brightness temperatures at 4 and 11 μm wavelengths (Giglio et al., 2003). While fires with large burned areas or high temperature can be well captured by the new fire detection algorithm, the probability of fire detection drops rapidly for small fires with low fire temperature (Giglio et al., 2003; Wang et al., 2007). In our study, fire pixels with low probability were screened out before analysis to ensure better data reliability. Zeng et al. (2008) found that in the southeastern US, prescribed fires in March 2002 with relative small sizes and low temperatures was under detected by Terra MODIS, due to the following possible reasons. First, the unburned tree canopy could partially block the upwelling radiance and reduce the chance of being detected by remote sensing. Secondly, prescribed fires with ignition time near or later than the overpass time of Terra (10:30 am) could not be detected, because fire temperature at the early burning stage may be lower than the minimum brightness temperature needed for fire detection. Lastly, cloud cover could interfere with fire remote sensing, although our analyses of MODIS cloudiness do not find a statistically significant relationship between fire counts and cloud coverage at state and county levels.

The GOES satellites by National Oceanic and Atmospheric Administration (NOAA) (Prins et al., 2001) provides continuous fire detections in additional to the twice-per-day MODIS fire product from Aqua and Terra. The GOES Automated Biomass Burning Algorithm (ABBA) employs 2 similar bands, 3.9 and 10.7 μm, to locate hot pixels. In 2002, fire activities were monitored every half hour by the GEOS-8 satellite over the southeastern US. It has a spatial resolution of 4 × 4 km^2 in nadir. The half-hour detection interval enables the recording of diurnal cycles of fire activities. The archived GOES ABBA data were downloaded from the Fire Locating and Modeling of Burning Emissions (FLAMBE) website (http://www.nrlmry.navy.mil/flambe/index.html). Likewise to the MODIS data analysis we discarded the fire pixels with lower probability to ensure the data quality.

We find that GOES and MODIS fire counts have similar spatial

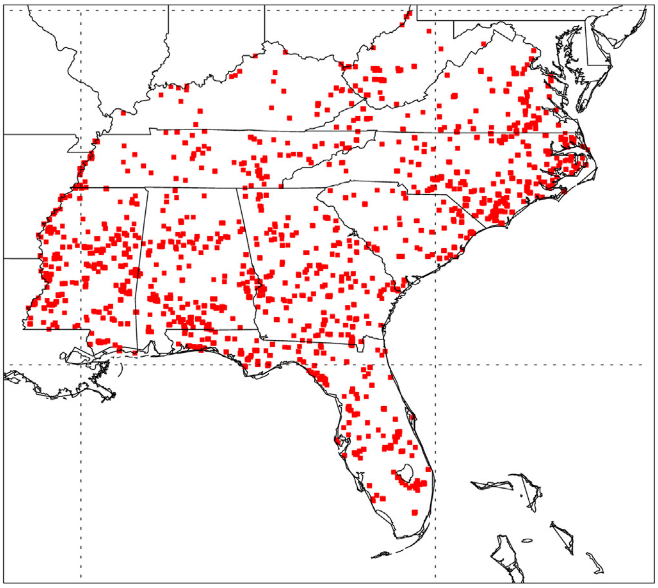

Fig. 1. Spatial distribution of MODIS Terra fire counts over the 10 southeastern states in summer (JJA) 2002.

patterns in the 10 southeastern states on a monthly basis during 2002–2006 (not shown), with spatial correlation coefficients around 0.8. This indicates spatial and temporal consistency between the two satellites on a monthly basis, although the possibility of missing small fires by both MODIS and GOES cannot be ruled out. Such consistency lends confidence in using MODIS fire counts for the following analysis of burning trends at state level.

2.3. CMAQ model setup

We use the EPA Models-3 Community Multiscale Air Quality (CMAQ version 4.5) modeling system (Byun and Ching, 1999) with the SPARC99 chemical mechanism (Carter, 2000). Emission inventories compiled by the VISTAS project (Barnard and Sabo, 2003) for 2002 are processed through the Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System (http://www.smoke-model.org/index.cfm). It includes updated anthropogenic emissions into 2002 developed from NEI 99. Biogenic emissions are calculated by BEIS3 model. The meteorological fields in 2002 are assimilated by Penn State/NCAR MM5 with the NCEP reanalysis data. The model domain covers the contiguous United States and part of southern Canada and northern Mexico with a horizontal grid of 36 km (148 × 112), and has 19 vertical layers, of which 12 are below 1 km. The model outputs for the southeastern United States are analyzed. Two model runs are designed: (1) an annual run for 2002 is conducted with the VISTAS base fire emission inventory; and (2) a sensitivity run is conducted for summer 2002 (June, July, and August) to test the sensitivity to summertime fire emissions.

2.4. Observational data of PM2.5, OC and EC

Measured concentrations of PM2.5, OC, and EC are obtained from IMPROVE and SEARCH networks (Fig. 2). IMPROVE sites mostly locate in clean rural area (Class I) to monitor the long-term trends of aerosols degrading. Daily averaged samples are collected every 3 days. More frequent data were collected at 8 SEARCH sites as four rural-urban/suburban pairs in Alabama, Florida, Georgia, and Mississippi. We analyze OC and EC observations from 16 IMPROVE sites and 8 SEARCH sites in the 10 southeastern States. Rural sites are not heavily impacted by anthropogenic emissions, so that fire emissions might be more pronounced in the observations. Additional surface ozone and aerosol data at other 55 sites from US EPA Air Quality System (http://www.epa.gov/ttn/airs/airsaqs/) are also used to evaluate the model performance over the Southeast.

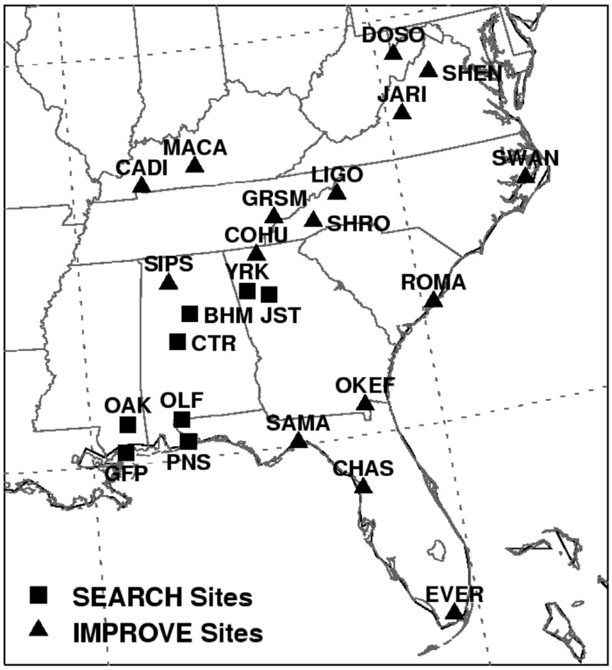

Fig. 2. 8 SEARCH (squares) and 16 IMPROVE (triangles) sites in the 10 states in the southeastern United States.

3. Comparison of two fire products

3.1. VISTAS fire inventory vs. Terra MODIS fire counts

We compare the spatial consistency of fire activities recorded in bottom–up reports and satellite-detected datasets on a monthly basis (daily information is missing in the ground fire reports for some southern states). Fig. 3 compares the monthly total burned areas at state level during 2002 from VISTAS fire inventory and Terra MODIS fire counts. Moderate correlation is found between the 2 fire products. Similar correlation coefficients (0.57 and 0.52) are found for all fire types and for prescribed fire only, respectively, indicating the dominance of prescribed fires in the Southeast. However, we do not find a good correlation at county level in 2002. This can be understood considering that (1) the temporal randomness of fire activities makes them hard to be captured by one satellite snapshot per day; (2) prescribed burning is generally at its early stage at the overpass time (10:30 am LT) of Terra; and (3) the upwelling thermal signal may not be always strong enough to be sensed by MODIS instrument. Such deficiency underscores the need for more observational information from another satellite with a different overpass time. In the next, the fire detection product from Aqua MODIS is introduced to obtain an improved representation of prescribed burning.

3.2. Extrapolated Aqua and merged Aqua and Terra MODIS fire products

The local equatorial crossing time for Aqua satellite is 1:30 pm when more burnings occur, according to the fire diurnal pattern from GOES. Prescribed fire becomes more visible to satellite detection after several-hour development. Therefore, Aqua MODIS is expected provide information complementary to Terra MODIS data. Unfortunately, Aqua fire detection product is only available after July 2002, which precludes the possibility of directly combining information from the two satellites for the full year of 2002. Aqua MODIS (MODIS Flight Model) is a similar instrument as Terra MODIS (MODIS ProtoFlight Model) with some improvement in the thermal band (Xiong et al., 2003). Aqua scans the same area after Terra with a 3-h interval. The same fire detection algorithm (Giglio et al., 2003) has been employed to determine active fire for both fire products. Therefore, one should expect a close correlation between the two MODIS fire products.

We examine the correlation of fire counts from the two similar MODIS instruments onboard Terra and Aqua in the years of 2003–2006 (Fig. 4), with the goal of establishing a relationship between the two fire products, which can be further used to extrapolate fire counts at 1:30 pm LT, the overpass time of Aqua, for the first half of the year 2002 when Aqua data is not available.

Fig. 4 shows the monthly total fire counts in the Southeast from Terra and Aqua from 2003 through 2006. As expected, the two MODIS instruments detected similar regional fire patterns on a monthly basis. In general, Aqua MODIS detects more fire spots than Terra, which is consistent with the early afternoon peak in the diurnal fire pattern from GOES. This may reflect the dynamics of prescribed fires, as discussed earlier, with less developed fires at

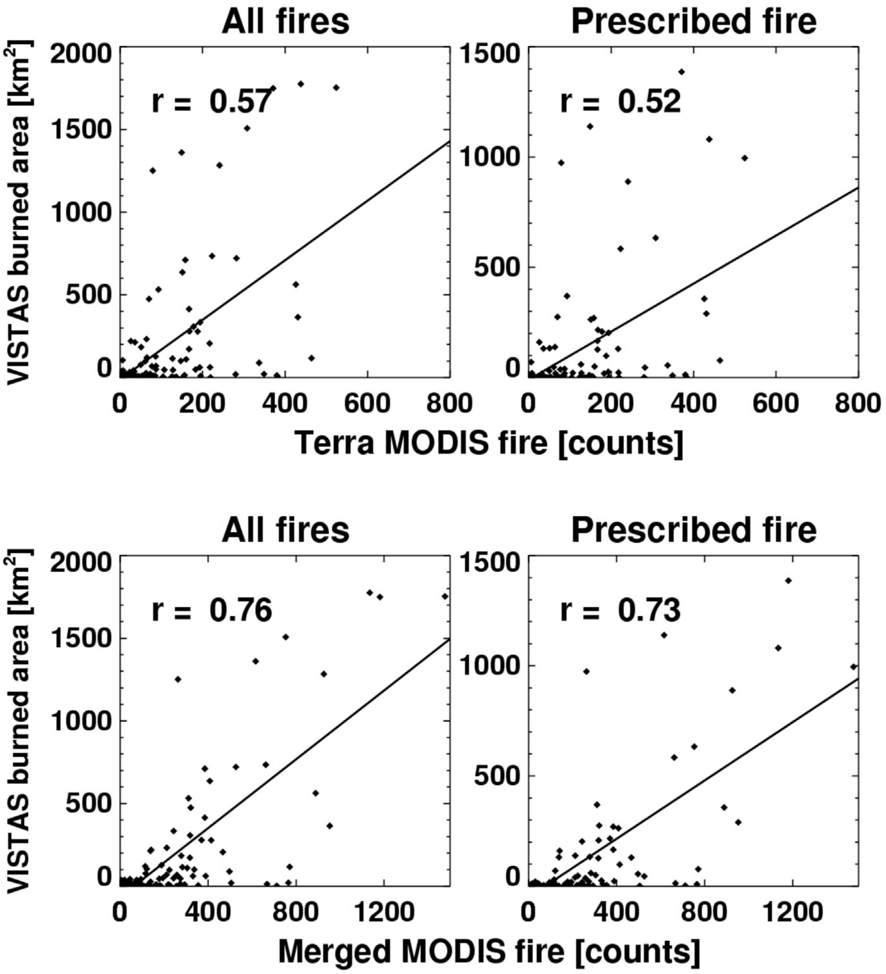

Fig. 3. Monthly total burned areas of all fires (left) and prescribed fire (right) by VISTAS inventory have been compared to fire counts by Terra MODIS (top) and merged MODIS (bottom), respectively, in the 10 SE states. The correlation coefficients are shown.

10:30 am than at 1:30 pm. In cold seasons, Aqua MODIS detects 2 times more fire counts than Terra MODIS. The two satellites observed similar number of fire counts in warm season, with two exceptions in June 2004 and July 2005, when Terra monitored very few fire counts. The spring burning peaks in Terra and Aqua are consistent with the VISTAS inventory in 2002. Fall peaks were only shown in 2003 and 2005. The percentages of spatial coincidence between the 2 satellite products, defined as their overlap on the same grid in the same day, are mostly below 5%. This can be understood because active fires could spread from one grid to another during the 3-h interval of the two satellite detections. The other reason could be the late ignition time of prescribed fire in cold season leads to less thermal emissions in the morning and therefore reduces the possibility of detection by Terra MODIS. It would have less impact on the afternoon detection by Aqua MODIS.

The correlation between Aqua and Terra MODIS during 2003–2006 is used to estimate fire counts that would have been observed by Aqua at 1:30 pm for January through July in 2002. Specifically, we first calculated the 4-year mean monthly ratios of Aqua and Terra MODIS fire counts for each state, and then extrapolated Aqua fire counts by multiplying fire counts from Terra for the months of January through July in 2002 with those Aqua-to-Terra ratios for the same months of 2003–2006. Fig. 5 shows the extrapolated monthly Aqua MODIS fire counts from January through July 2002 and the observed Aqua MODIS fire counts in the rest 5 months of 2002. In spring 2002, the extrapolated Aqua MODIS fire counts based on the 4-year monthly and state mean Aqua-to-Terra ratios shows a larger spring peak than Terra MODIS, and become similar to Terra in the summer (April, June, and July). In winter, Aqua MODIS detected more fire counts than Terra.

A new satellite fire dataset in 2002 is constructed by merging Terra and Aqua (observed and extrapolated) MODIS detected fire counts. Compared to Terra fire counts, the new merged MODIS fire counts have a better correlation with the state-level monthly total burned areas from the VISTAS fire inventory (Fig. 3 lower panel, the correlation coefficients increase from 0.57 to 0.76 for all fire types and 0.52 to 0.73 for prescribed fire only, respectively), indicating that the twice-per-day satellite scans at different hours over the same region capture the more fire activities than those from one satellite alone. For the five states (AL, FL, GA, MS, and SC) with detailed fire burn data, similar R improvement by the merged dataset are found from 0.52 to 0.76 for all fire types and 0.46 to 0.72 for prescribed fire alone. A main reason for the improved correlation in Fig. 3 is that in spring 2002, the addition of extrapolated Aqua data in the early afternoon results in much more fire activities in the merged MODIS data and better agreement with VISTAS. In the next section, we analyze the seasonal pattern of fires in the Southeast, by combining information from the two satellites Terra and Aqua and the VISTAS bottom–up inventory.

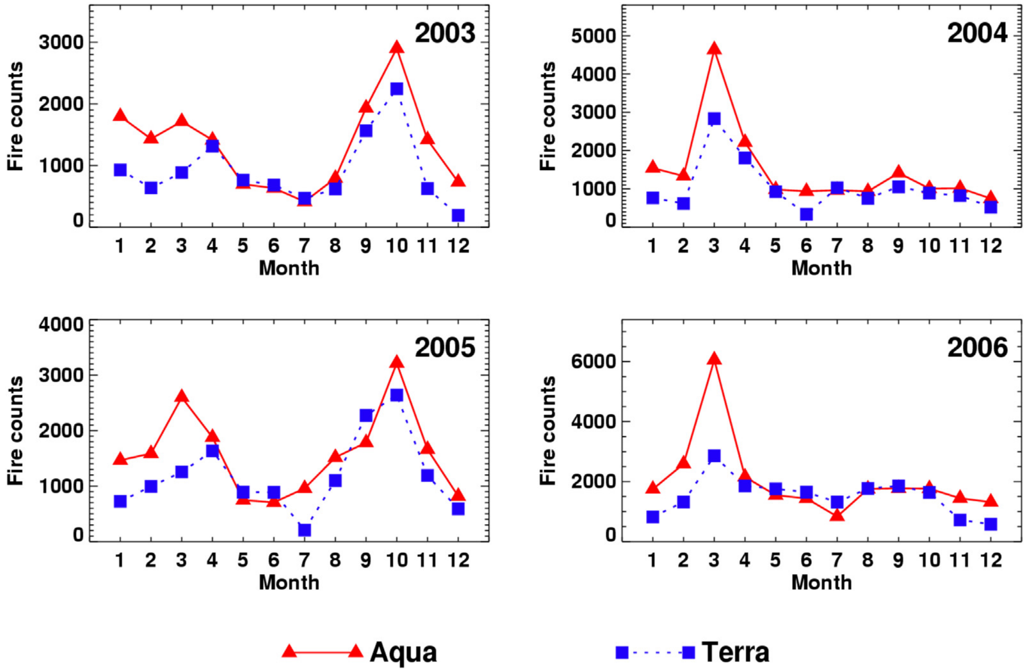

Fig. 4. Monthly fire counts over the 10 SE states by Terra (blue dotted line with square) and Aqua (red solid line with triangle) MODIS instruments from 2003 to 2006. Note: The colors refers to the online version only.

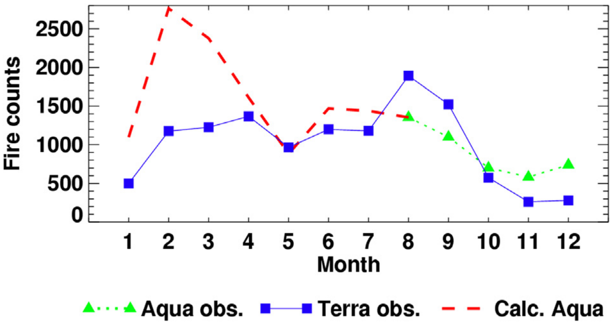

Fig. 5. Terra (blue solid line with square) and Aqua (green dotted line with triangle) MODIS observed monthly fire counts over the Southeastern US in 2002. Predicted Aqua fire counts (red dash line) are also shown. Note: The colors refers to the online version only.

3.3. Seasonal variations of fires in the southeastern US

Fig. 6 shows the monthly VISTAS burned area and merged MODIS fire counts in the Southeast. Both data consistently suggest that the largest fire peak occur in spring (January–March). However, the secondary fire peak in August 2002 in the merged MODIS fire dataset is not seen in VISTAS inventory. The majority of the satellite observed summer burnings occurred in Georgia and Alabama. Such an anomaly among different years, is not very uncommon; for example, increased fire counts were detected in October in 2003 and 2005, but not in 2004 or 2006. The discrepancy between MODIS and VISTAS may be due to missing burning activities in the military bases by the bottom–up inventory. In terms of MODIS fire detection, although the possibility of false alarm can increase in summer (Giglio et al., 2003), it is more common to have omission error rather than commission error (Csiszar et al., 2006). Zeng and Wang (2011) found that biomass burning instead of SOA production is more likely the cause of a ‘missing’ source of OC and EC (as indicated by higher OC/EC ratios) in summer 2002 in the SE US. Accounting for the emissions from these missing fire activities might mitigate the severe underestimation of organic carbonaceous aerosols in the Southeast. In the next section, in order to test this hypothesis, a new fire emission inventory is developed based on the merged MODIS data. CMAQ simulations are conducted to test the sensitivity of the abundance of fire pollutants (e.g. EC and OC) to the change of fire emissions. Ambient observations are used to evaluate the model performance.

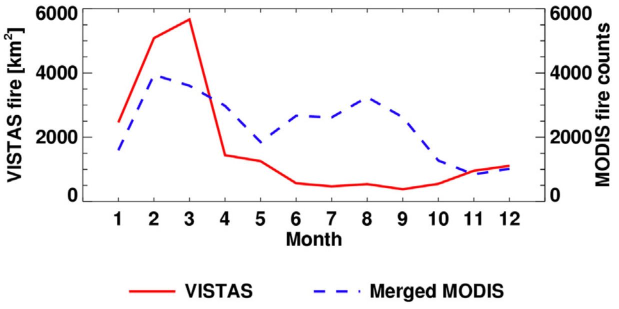

Fig. 6. Comparison of VISTAS burned area (red solid line) and merged MODIS fire counts (Terra + predicted Aqua, blue dash line) in the SE United States. Note: The colors refers to the online version only.

4. Development and validation of a hybrid fire inventory

4.1. A new hybrid fire emission inventory

A new ‘hybrid’ fire emission inventory is developed by combining the information from satellite and ground-based fire products. These two types of fire data complement each other with their own advantages and limitations. Satellite fire products provide continuously monitoring of large areas and the extensive spatial coverage, while possibly missing some small fires; bottom–up fire inventory has more detailed information of fires, but may not include fires from some remote areas and military bases.

The purpose of combining bottom–up and satellite fire products is to account for those omitted fires by the bottom–up inventory as observed from the satellites. The process of deriving the hybrid emissions inventory for each state involves two steps.

First, we assume that the under-detection error in satellite fire measurements does not vary seasonally (monthly), and use the variability satellite observed monthly in state total fire counts to represent the seasonal variations of state total fire emissions. The regional total fire emissions in the 10 SE states in VISTAS 2002 inventory are scaled to follow the trend of the merged satellite fire counts (Eq. (1)) on a monthly and state-level basis. March 2002 has the largest fire emission as shown in both bottom–up and satellite data, and is set as the month with a 'true' emission-to-fire count ratio. State fire emissions in other months of 2002 are scaled to have a consistent emission-to fire count ratio in March 2002, such that the monthly variation of state-level emissions matches that of satellite observed fire counts (activities).

$$\mathit{New\ Fire\ Emission}_m = \mathit{VISTAS\ Fire\ Emission}_{March} \times \frac{\mathit{MODIS\ Fire\ Counts}_m}{\mathit{MODIS\ Fire\ Counts}_{March}} \tag{1}$$

$$\mathit{Scaling\ Factor}_m = \frac{\mathit{New\ Fire\ Emission}_m}{\mathit{VISTAS\ Fire\ Emission}_m} = \frac{\mathit{MODIS\ Fire\ Counts}_m}{\mathit{MODIS\ Fire\ Counts}_{March}} \times \frac{\mathit{VISTAS\ Fire\ Emission}_{March}}{\mathit{VISTAS\ Fire\ Emission}_m} \tag{2}$$

As computed using Eq. (2), a scaling factor is by definition 1 for March 2002 and the fire emissions do not need to change, whereas a scaling factor greater than 1 indicates extra fire emissions called for by satellite fire counts but omitted by VISTAS. The scaling factors (Eq. (2)) for June, July, and August 2002 are 7.837, 5.383, and 9.462, indicating substantial increase of emissions in summer after accounting for those omitted fire activities.

In the second step, regional totals of extra emissions as indicated by satellite data are spatially distributed into those satellite fire pixels following the spatial distribution of fuel loading across a state, and aggregated into county totals for SMOKE model processing. Fire emission associated with each satellite fire count is computed following Eq. (3) such that the ratio of this pixel level emission and the state-total emission equals the fraction of fuel loading at each fire pixel in the total fuel loading over all the satellite fire pixels in each state on a monthly basis.

$$\mathit{Fire\ Emission}_{pixel} = \mathit{Extra\ Fire\ Emission}_{State} \times \frac{\mathit{Fuel\ Loading}_{pixel}}{\mathit{Total\ Fuel\ loading}_{State}} \tag{3}$$

Fuel Characteristic Classification System (FCCS) (Sandberg et al., 2001) provides the fuel loading information in this study. Eq. (3) assumes the same emission-to-fuel loading ratio for different fire types, i.e. wild fire or prescribed fire. In general, satellite fire remote sensing cannot identify fire categories, such as agriculture burning, land clearing, prescribed fire, and wild fire. Prescribed fire is the dominant fire type in the Southeast (Zeng et al., 2008), and the satellite observed fires are mostly located in rural area.

4.2. Validation of the hybrid fire emission inventory using air quality modeling

The new inventory is processed by SMOKE emission model as CMAQ model inputs. Model performance of the base CMAQ run with VISTAS emission inventory for annual and summer (JJA) 2002 is examined using the EPA recommended statistic measures (EPA, 1999) for (Table 1). Ozone is simulated well with mean bias <10% and mean error <15%. There is almost no difference between annual and summer statistics for ozone simulations. EC, OM, and $PM_{2.5}$ are found to be under-predicted (Table 1), with larger negative mean biases (−47%) in summer than annually (−20%). The mean errors for aerosols are close in summer and whole year. Overall, CMAQ simulations are well within EPA recommended uncertainty range but with larger uncertainties for aerosol species in summer.

Fig. 7 compares the seasonal variations of OC and EC concentrations in the southeastern 10 states. With the original VISTAS emission inventory, the base model run under predicts OC and EC concentrations in all four seasons. The largest under-prediction is in summer, with a low bias of 73% for OC (0.63 vs 2.32 $\mu g/m^3$) and 64% for EC (0.13 vs. 0.36 $\mu g/m^3$) (Table 2). The more severe underestimate for OC than for EC might be due to underestimated summertime SOA formation, as discussed in many previous studies. In other 3 non-summer seasons, the OC bias is around ~25%, while the EC bias ranges from 45% in fall to 7% in winter. Simulated OC and EC do not follow the observed seasonal trend, mainly because they are severely underestimated in summer.

Compared to the base run, the sensitivity run with the new hybrid fire emissions shows much improved OC and EC simulations in summer (Fig. 7). The model biases in summer for OC and EC decrease to 25% (1.75 vs. 2.32 $\mu g/m^3$) and 17% (0.30 vs. 0.36 $\mu g/m^3$), respectively. As a result, the seasonal trend of OC in the sensitivity run matches the observed trend very well. Although including information from satellite observations helps to improve the simulations of seasonal mean OC and EC concentrations, the standard variations increase from 0.42 to 1.27 $\mu g/m^3$ for OC and 0.10–0.20 $\mu g/m^3$ for EC. We also examine the model performance of OC and EC 24 individual sites in the Southeast. Using the hybrid fire emission inventory lowers biases at individual sites, with increased slopes of data-model linear regression (from 0.5 to 0.6 for OC and from 0.3 to 0.4 for EC).

The underestimation of OC in CMAQ has been reported in a number of studies (e.g. Mebust et al., 2003; Morris et al., 2006; Zhang et al., 2006), and can be caused by under-prediction of SOA formation, inaccuracy of emission inventory, and errors in the modeling of other processes, including boundary layer mixing, dry/wet deposition, and advection. The negative bias of EC is more direct indicative of errors in EC emissions, if assuming insignificant contribution from model transport errors.

Overall, these results suggest that satellite fire counts are helpful in capturing seasonal variations of fire emissions on a regional basis, thereby improving the model simulations of the background concentrations of carbonaceous aerosols in rural (Class I) areas. Further understanding of aerosol spatial distribution at finer temporal and spatial scales, can be facilitated by high quality satellite data that help capture the random fire burning events, which are not well documented in current fire inventory but essential for quantifying the impact from fires on air quality.

5. Fire impact on MODIS fine AOD

Smoke from biomass burning contains large amount of organic carbon and black carbon. It can change the column aerosol concentrations and the atmospheric optical property in a very short time horizon. The increase of aerosol concentrations can be potentially monitored by MODIS instrument as a measure of ambient aerosol optical depth (AOD) (Kaufman et al., 2002; Chu et al., 2002; Remer et al., 2005). We compare MODIS AOD before and after fires to see if it can be a useful indicator of emissions from small fire events in the SE US. It can be a challenge to disentangle

Table 1
Model performance of the simulations of EC, OM, $PM_{2.5}$, and ozone (ppbv) for CMAQ base run in 2002 and summer 2002[a].

	Species	Num. obs	Obs_mean (μg m^{-3})[b]	Sim_mean (μg m^{-3})[b]	MB (μg m^{-3})[b]	ME (μg m^{-3})[b]	NMB (%)	NME (%)	MFB (%)	MFE (%)
Annual	EC	2694	0.46	0.34	−0.13	0.32	−27.3	69.3	−20.6	46.9
	OM	2700	2.89	2.57	−0.32	2.13	−11.2	73.7	−14.7	48.9
	$PM_{2.5}$	3897	10.97	7.94	−3.03	5.90	−27.6	53.7	−20.5	40.4
	1hr max O_3[c]	355,277	56.0	58.2	2.2	11.6	7.6	11.7	–	–
	8hr max O_3	168,171	53.3	48.6	−4.7	10.4	−5.4	29.6	–	–
Summer	EC	738	0.44	0.23	−0.21	0.29	−47.8	65.9	−34.2	50.2
	OM	742	3.4	1.79	−1.61	2.34	−47.4	68.7	−43.5	55.1
	$PM_{2.5}$	992	13.54	6.83	−6.71	7.65	−49.5	56.5	−39.1	45.4
	1hr max O_3[c]	25,403	60.1	61.8	1.8	13.8	7.6	11.2	–	–
	8hr max O_3	10,150	56.2	49.0	−7.2	12.3	−8.9	29.9	–	–

[a] MB, ME, NMB, NME, MFB, and MFE are acronyms of mean bias, mean error, normalized mean bias, normalized mean gross error, mean fractional bias, and mean fractional error, respectively.

[b] Ozone unit is ppbv.

[c] Observations with daily max O_3 > 40 ppbv are considered.

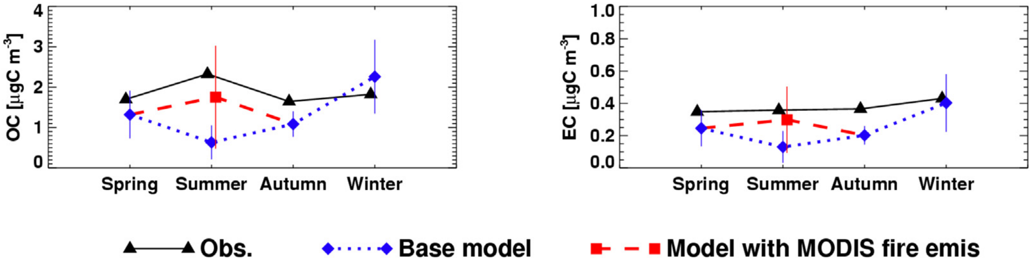

Fig. 7. Seasonal mean OC and EC concentrations from the observation (black solid line with triangle) and two CMAQ simulations with standard fire emissions (blue dotted line with diamond) and with MODIS fire emissions (red dash line with square). Note: The colors refers to the online version only.

Table 2
The observed and two model simulated monthly mean and median OC and EC concentrations (Unit: μg/m^3) at the 24 southeastern sites in summer 2002 (JJA).

	Mean OC	Median OC	Mean EC	Median EC
Observations	2.32	2.31	0.36	0.37
Base model	0.63	0.57	0.13	0.11
Model w. MODIS Fire	1.75	1.52	0.30	0.20

the enhancement of AOD due to fires and that due to anthropogenic emissions plumes from urban areas, except for some large fires such as the Okefenokee Swamp fire in 2007, which had more than 100,000 acres of burned area (http://en.wikipedia.org/wiki/Bugaboo_scrub_fire). MODIS fire pixels are generally in the forest area with small anthropogenic impact, therefore, if observed, the enhancement of aerosol optical thickness nearby should be mostly due to fire emissions.

MODIS MOD04_L2 (http://modis-atmos.gsfc.nasa.gov/MOD04_L2/index.html) product is employed in the analysis. It is a daily product with a spatial resolution of 10 × 10 km^2. MODIS AOD fine component at 550 nm is chosen to represent the variations of columnar aerosol concentrations. Fire locations are obtained from MODIS fire counts. The MODIS AOD pixels within 10 km radius from the fire location are searched and the maximum AOD is used to represent the aerosol abundance for that day. To track the AOD changes due to fire burning, we chose 3-day period (before, fire, and after) with continuous MODIS AOD observations and MODIS fire detection in the 2nd day. Cloud pixels are excluded from the satellite observations of fire and AOD (Chu et al., 2002).

A total of 1005 cases have been found to meet the criteria in the 10 SE states in summer 2002 (JJA). Fig. 8 shows that on average, MODIS AOD increases by 27% from 0.35 on the day before fire to 0.45 on the day with fire. On the day after fire, only 13% increase is obtained comparing to the day before fire. The 0.1 AOD enhancement is larger than the AOD uncertainty over land of ±0.03 ± 0.05 (Remer et al., 2005). Since the fire detection is for cloudless and smoke free areas only (Giglio et al., 2003), the AOD enhancement would have been larger if including those excluded small and cold fires at smoke pixels with an updated fire detection algorithm (Wang et al., 2007).

6. Discussion and conclusions

In this work, we have studied the contribution of fire emissions to ambient aerosols in summer 2002 in the Southeast, using satellite MODIS fire counts and air quality modeling. Satellite observations indicate more extensive burnings in the Southeast in summer than suggested by the bottom–up fire inventory VISTAS, possibly due to those uncounted fires in remote regions. We developed a hybrid fire emission inventory with a new method that combines information from the bottom–up inventory and satellite fire detection by scaling the data of top–down fire count in the other months with its ratio to the bottom–up burned area data in March, the month of most prescribed burning in the Southeast in 2002. Such computed burned areas in summer are higher than the bottom–up inventory in summer; the increase of fire emissions is spatially allocated over satellite observed fire pixels based on the spatial distribution of fuel loading. We show that the updated fire emission inventory leads to notably improved CMAQ model performance of OC, EC and $PM_{2.5}$, in the Southeast on a regional basis, with reduced model low bias in the summer and better agreement with the observed seasonality. The satellite fire counts based fire emissions are also consistent with satellite MODIS AOD at 550 nm, which shows an average enhancement by about 0.1 (larger than instrument uncertainty) is found on the days with satellite detected fires compared to the day before fires. Our results suggest that satellite can help account for emissions from some fires missed in the bottom–up inventory.

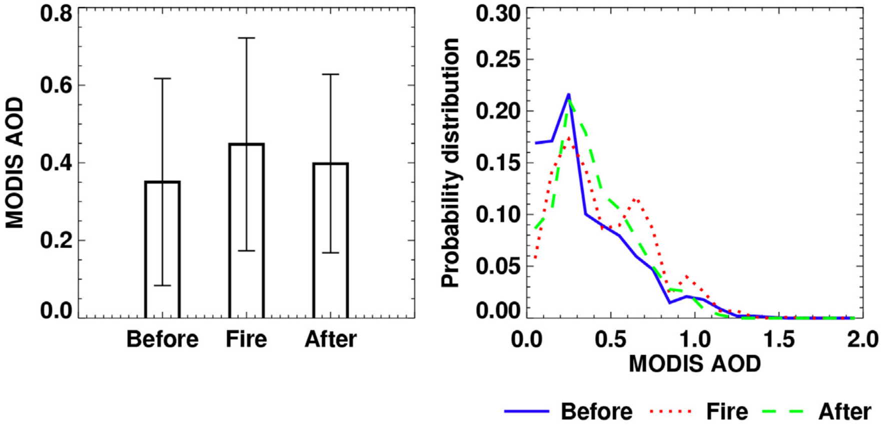

Fig. 8. (Left) Averaged MODIS AOD (unitless) for the days before fire (Before), with fire (Fire), and after fire (After) over the SE US in summer (JJA) 2002. The day with fire is defined for MODIS pixels on the day with MODIS fire detection. Standard deviations are shown for each case. (Right) Probability distributions of MODIS AOD for the days before fire (blue solid line), with fire (red dotted line), and after fire (green dash line) over the SE US in summer (JJA) 2002. Note: The colors refers to the online version only.

The results from this study is also consistent with our previous study that used OC/EC ratio as an indicator of fine aerosol contributions from the combination of a variety of sources such as biomass burning and SOA production (Zeng and Wang, 2011). Summertime peaks of OC/EC ratios have been observed over the Southeast, and SOA and biomass burnings found to be two major contributors, based on global GEOS-Chem model simulations using a fire emission inventory based on MODIS and other satellite observations (Zeng and Wang, 2011). A main finding from Zeng and Wang (2011) is that summertime fire emissions may be underestimated in the existing bottom–up fire inventories in the Southeast.

This hybrid emission inventory has been shown to help improve OC and EC simulations in the Southeast. Missing fire emissions in bottom–up inventories can partially explain the underestimated PM2.5 concentration in the Southeast. While our study shows that satellite fire detection can help improve our understanding of PM distribution on a regional basis, the ubiquitous and random nature of fire emissions call for future efforts to further constrain fire contributions to particulate pollution on finer spatial and temporal scales.

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