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Impacts of Prescribed Fires on Air Quality over the Southeastern United States in Spring Based on Modeling and Ground/Satellite Measurements

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Prescribed burning is a large aerosol source in the southeastern United States. Its air quality impact is investigated using 3-D model simulations and analysis of ground and satellite observations. Fire emissions for 2002 are calculated based on a recently developed VISTAS emission inventory. March was selected for the investigation because it is the most active prescribed fire month. Inclusion of fire emissions significantly improved model performance. Model results show that prescribed fire emissions lead to ~50% enhancements of mean OC and EC concentrations in the Southeast and a daily increase of $PM_{2.5}$ up to 25 μg m^{-3}, indicating that fire emissions can lead to $PM_{2.5}$ nonattainment in affected regions. Surface enhancements of CO up to 200 ppbv are found. Fire count measurements from the moderate resolution imaging spectroradiometer (MODIS) onboard the NASA Terra satellite show large springtime burning in most states, which is consistent with the emission inventory. These measurements also indicate that the inventory may underestimate fire emissions in the summer.

Introduction

About 5 million acres of forest, crop, and range land are burned annually in the southeastern United States. Prescribed fires comprise 60% of the burned acreage (*1*) and are the most common type of fire because of their use for forest resource management, such as reducing hazardous fuels and improving wildlife habitats (*2*). While effective and economical, the emissions of aerosols and gases can adversely affect local and regional air quality.

Prescribed burning is one of the most important sources of carbonaceous aerosols in the Southeast (*3*). It contributes ~15% of total particulate matter (PM) emissions over this region (*1*). Since all southeastern states except Florida have $PM_{2.5}$ nonattainment areas (http://www.epa.gov/pmdesignations/statedesig.htm), this additional contribution of $PM_{2.5}$ from prescribed burning is of great concern for air quality management. A better understanding of air quality impacts from fire emissions is necessary (*4–6*).

More attention has been drawn to wildfires than prescribed fires since the intensity per event is much larger in wildfires. While less intense, prescribed fires are very frequent in the Southeast in winter and spring, leading to a potentially large impact on regional air quality. The chemical composition of prescribed fire emissions differs from wildfires due to the nature of under-story burning of prescribed fires (*7*). We use the fire emission inventories for 2002 developed by the Visibility Improvement - State and Tribal Association of the Southeast (VISTAS) program. It is the most comprehensive compilation to date on the basis of fire activities reports from county, state, and federal agencies of the southeastern states (*1*).

The fire impacts on the air pollutants, CO, organic (OC), and elemental carbon (EC) can be better evaluated using chemical transport model simulations with the improved emission inventory. The model simulations are evaluated with surface measurements of these species. We choose March 2002 as the study period, which is the month of the most burned acres in the VISTAS inventory.

The VISTAS inventory can be evaluated more directly using fire count measurements from the moderate resolution imaging spectroradiometer (MODIS) onboard the NASA Terra satellite. Its large spatial coverage has many advantages in monitoring wildfire activities (*8, 9*). However, most prescribed fires burn on the understory and the effectiveness of the MODIS fire detection algorithm (*10*) for understory fires is unknown. The temperature threshold of 310 K in the MODIS fire detection algorithm can be too high for identifying the relatively small and cool prescribed fires (*11*). To minimize uncertainties, we evaluate if spatially averaged (state-level) seasonal variations of estimated burned areas and MODIS fire counts are in agreement. We expect to find a large signal in MODIS fire count measurements in March.

Materials and Methods

EPA Models-3 Community Multiscale Air Quality (CMAQ) modeling system (*12*) is used to simulate the distributions of gas and particulates emitted from fires. Surface observations of O_3, CO, and aerosols are employed for model evaluations. Satellite measurements of lower tropospheric CO are also used to study its fire enhancements. The uncertainty of fire emissions in the VISTAS inventory is discussed in its comparison with satellite fire count products.

VISTAS Emission Inventory. The VISTAS emission inventory was developed from the 1999 National Emissions Inventory (NEI) version 2 and used 2002 as the base year (*1*). Its anthropogenic emissions are projected from NEI 99 emission inventory. Fire emissions were recalculated for the southeastern states based on the updated fire records collected from state and federal fire agencies. Complete updates for prescribed fire emissions are available in 9 of the

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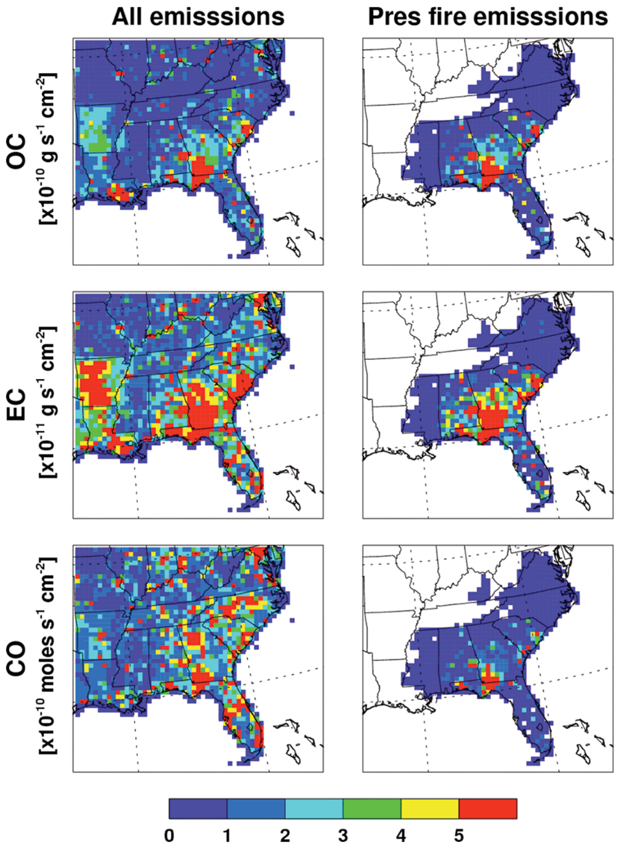

FIGURE 1. SMOKE processed OC, EC, and CO emissions from standard VISTAS emission inventory and prescribed fires over the southeastern United States in March 2002.

10 Southeastern states (except VA), with five states (AL, FL, GA, MS, and SC) having the most complete data. Among the other four southeastern states (KY, NC, TN, WV), partial updates have been done whenever the government reports were available. For model evaluation, we therefore focus more on the states with the more complete data.

Among the four fire types (wildfire, prescribed burning, agricultural fires, and land clearing fires) prescribed burning plays a dominant role in all months except May when wildfires play the largest role. Figure 1 compares the monthly mean emissions of three major fire emitted pollutants (OC, EC, and CO). Prescribed fire emissions cover large regions of the southeastern U.S., although the geographic variability is large. Most of the high emission spots appear in four states, Georgia, Florida, Alabama, and South Carolina. Burning is the most active in March when prescribed fire compromises >70% of the total burned area.

Air Quality Modeling System. CMAQ version 4.4 with the SPARC99 chemical mechanism (*13*) and AERO3 aerosol module (*14*) is used. The meteorological fields were assimilated using Penn State/NCAR MM5 with the NCEP reanalysis data (*15, 16*). The 148 × 112 model-grid domain covers the contiguous United States and part of southern Canada and northern Mexico with a grid distance of 36 km. We specified 19 vertical layers, of which 12 are below 1 km. The study period is March 2002. Nested simulation using 12 km resolution does not improve the model results due in part to the relatively coarse temporal and spatial resolution of the fire emission inventory (Supporting Information).

CMAQ emission inputs were prepared from the VISTAS inventory using the Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System (http://www.smoke-model.org/index.cfm) version 2.2. Annual county-level fire emissions were allocated to each month based on VISTAS reported burned areas in each state. These emissions are distributed

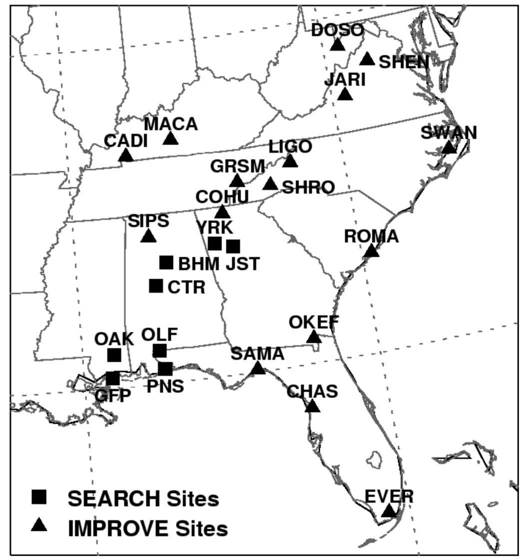

FIGURE 2. Eight SEARCH (squares) and 16 IMPROVE (triangles) sites over the southeastern United States.

in SMOKE using forest distributions as surrogates. The monthly temporal resolution of fire emissions contributes to the discrepancies between model results and measurements. The default EPA daily emission profile in SMOKE is applied to distribute prescribed fire emissions (mostly from 10 a.m. to 8 p.m.). Biogenic emissions are calculated with the BEIS3 model. The detailed model configurations are described in the Supporting Information.

Considering active boundary layer mixing in daytime, the effect from plume rise mainly comes from the fraction injected above the top of the boundary layer. Since controlled prescribed burning is smaller in scale and cooler in temperature than wildfires (*17*), the injected fraction from prescribed fires is also smaller. There is currently not enough information from the VISTAS inventory to properly treat plume rise in the model and hence plume rise above the boundary layer is not included. We consider this uncertainty in model evaluations with measurements and find some support for plume rise in analyzing MOPITT data although it is qualitative (Supporting Information).

Default CMAQ initial and boundary conditions are used except for CO. For CO with a relatively long chemical lifetime, the default CO concentration at 80 ppbv in the surface layer leads to underestimations with the observations at surface sites (*18*) and in the free troposphere (*19*). We therefore specify CO initial and boundary conditions with GEOS-CHEM simulations (*20*), which have been evaluated extensively (*19, 21*).

We performed two CMAQ runs, one base run with all emissions and one sensitivity run without prescribed fire emissions over 10 VISTAS states. A comparison is then conducted between the two simulations to reveal the enhancements of certain air pollutants from fire emissions, such as CO and carbonaceous particles. Modeled distributions of fire pollutants are spatially consistent with the spatial distributions of the fire emissions (Supporting Information).

Surface CO and Aerosol Observations. Model simulations are evaluated with surface observations from two networks, the Southeastern Aerosol Research and Characterization project (SEARCH) (*18*) and Interagency Monitoring of Protected Visual Environments (IMPROVE) (*22*) (Figure 2). Both gases and aerosols are measured at the four pairs of urban−rural SEARCH stations. Only aerosols are measured at the IMPROVE stations, located mainly in rural areas. OC and EC measurements from SEARCH and IMPROVE are comparable since the thermo-optical reflectance (TOR)

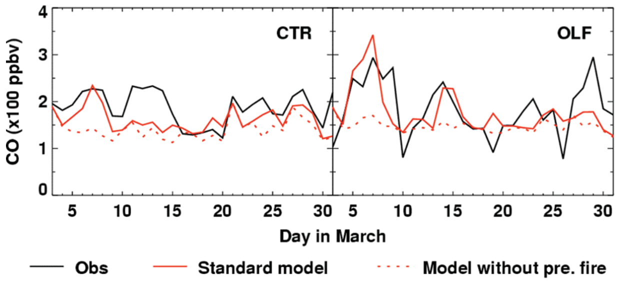

FIGURE 3. Daily mean CO concentrations (ppbv) at 2 SEARCH sites in March 2002 from observations (black lines), model simulations with (red solid lines) and without (red dotted lines) prescribed fire emissions, respectively. The site locations are shown in Figure 2.

method was used in both networks. More extensive CO measurements from the EPA AIRNow network cannot be used since only values >0.5 ppmv were reported and CO concentrations at rural sites were lower than the reporting limit.

MODIS Fire Counts. MODIS fire detection products from the NASA Terra satellite (*10*) are used to evaluate the seasonal variations of the VISTAS fire inventory. Cloud pixels were removed before the fire detection algorithm was applied (*10*). Level 3 daily Terra MODIS global products (MOD14A1) include daytime and nighttime observations (~10:30 a.m. and pm). Most fire counts are observed during daytime, consistent with the diurnal profile in SMOKE. The horizontal resolution of this data set is 1×1 km^2. Given the difference in temporal resolutions of MODIS measurements and the VISTAS inventory, we focus on the monthly statistics.

Air Quality Impacts at Surface Sites

We first examined model simulations with available surface observations using published statistical metrics (Supporting Information). Model results capture the general characteristics of observed O_3, CO, EC, OC, and PM2.5.

Ozone. Prescribed burning has very little influence on simulated O_3 during this period. At SEARCH sites, it only leads to a 1.5% ozone increase, which is much smaller than the impacts by biomass burning in the tropics (e.g., refs *23, 24*). More extensive evaluation using the measurements from the EPA AIRNow network in the Southeast shows similar results. One of the reasons is that emissions of NO_x from prescribed fire are much smaller than those from fossil fuel sources over North America. NO_xconcentrations only increase by 1% at SEARCH sites. Another reason is that photochemistry is relatively slow in March.

Carbon Monoxide. We use the relatively long-lived biomass burning tracer CO to examine the influence of fire emissions in the region. On average, fire emissions increase surface CO concentrations by 6%. Since the EPA AIRNow measurement sites report CO only when its mixing ratios are CO > 0.5 ppmv, we are limited to SEARCH sites. Among these, we only find two sites (CTR and OLF) with significant signals (Figure 3). These peaks are identified as simultaneous increases of CO, EC, and OC and the model captures better high CO concentrations in the measurements with fire emissions. During the period of March 5−10, both sites show high concentrations of CO. Without prescribed fire emissions, the model would underestimate CO by up to 200 ppbv (or 130%).

The observations also show another high-CO episode between March 12 and 16. However, the model is only able to simulate high CO at the OLF site. A few reasons may contribute to this discrepancy. Chief among them is the quality of the emission inventory. There are uncertainties in the magnitudes of emissions and the temporal and spatial

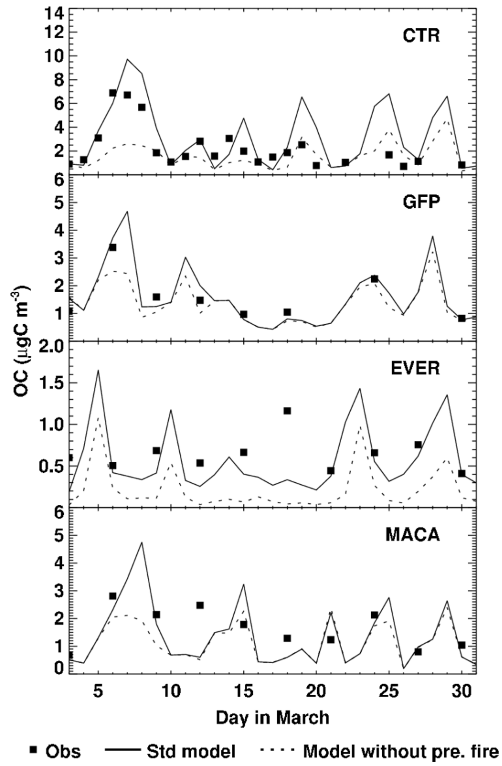

FIGURE 4. Daily mean OC concentrations (μgC m^{-3}) at four stations in March 2002 from observations (squares), model simulations with (solid lines) and without (dotted lines) prescribed fire emissions, respectively. The site locations are shown in Figure 2.

resolutions are not high enough to capture all impact peaks driven by fire emissions at a specific site. Nonetheless, the evaluation presented here indicates that the CMAQ model with the currently available emission inventory has some predicting skills and provides a useful way to assess the typical impacts of fire emissions.

OC and EC. Observations of OC and EC come from SEARCH and IMPROVE networks. We compare the model results with the observations at four selected sites, CTR (SEARCH), GFP (SEARCH), EVER (IMPROVE), and MACA (IMPROVE) (Figure 4 and Supporting Information, Figure S4). The effects on OC and EC are similar. The base run with full emissions agrees better with observations than the sensitivity run without prescribed fire emissions. The differences between the two simulations are due to fire emissions, which can be significant. The increases of OC and EC from fire emissions are up to 5 times at the CTR site, where local burning is large. Here we define local burning as that in the county where the site is located. What is perhaps unexpected are that the increases of OC and EC (by 100% on some occasions) at the MACA site, where there is almost no local burning. Simulated enhancements are entirely due to regional transport. It is evident from this comparison that the measurement frequencies of once per 3 days (as in most sites used here) can miss the effects of fire emissions.

The dispersion of episodic fire emitted pollutants highly depends on the meteorological conditions. Although the fire emissions are continuously distributed in the model due to the lack of burning timing information, the model did not simulate continuous aerosol enhancement at surface. The episodic aerosol enhancements are evident in fire induced high OC and EC concentrations (Figure 4). It indicates a combined influence of fire emissions and meteorological conditions.

We compared all OC and EC at 24 stations available in the Southeast (Figure 5). The scattering around the 1:1 line reflects

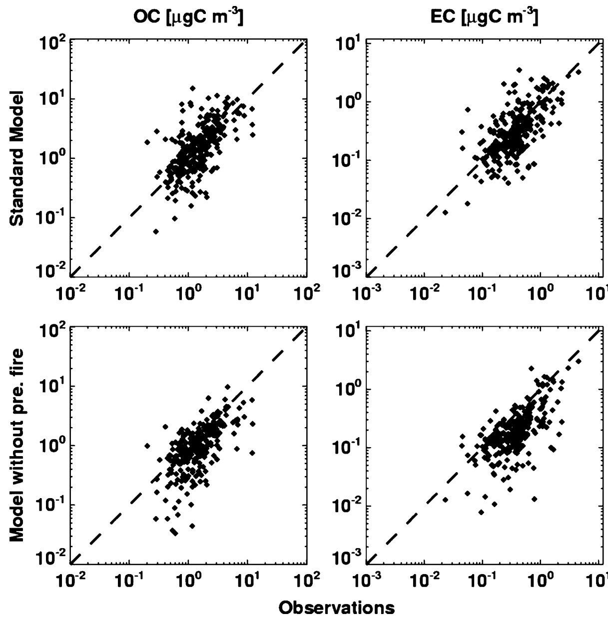

FIGURE 5. Comparisons between daily OC and EC observations and two simulations with and without prescribed fire emissions at 24 SEARCH and IMPROVE sites.

TABLE 1. Mean and Median OC and EC Concentrations from Observations and Model Simulations with and without Prescribed Fire Emission at 24 Stations in the Southeast in March 2002

		observation (μgC m^{-3})	model w/ fire (μgC m^{-3})	model w/o fire (μgC m^{-3})
OC	mean	1.92	2.24	1.33
	median	1.49	1.54	1.00
EC	mean	0.51	0.49	0.29
	median	0.37	0.30	0.18

the uncertainties in model formulation and inputs, which includes emission uncertainties. Without fire emissions, the model results have clear low biases. Table 1 shows the observed and simulated mean concentrations of EC and OC. Prescribed fire emissions lead to a simulated mean OC increase from 1.33 to 2.24 μgC m^{-3} (or 68%) compared with the observed mean of 1.92 μgC m^{-3} and a simulated mean EC increase from 0.29 to 0.49 μgC m^{-3} (or 69%) compared with the observed mean of 0.51 μgC m^{-3}. The inclusion of fire emissions does not significantly reduce scattering of simulated data against the measurements (Supporting Information), which reflects the uncertainties in simulated impacts of individual fire events. Averaged over the 10 southeastern states, the monthly simulated mean contributions of prescribed fires to OC and EC are 28% (0.8 μgC m^{-3}) and 31% (0.2 μgC m^{-3}), respectively. However, the simulated maximum increases of daily OC and EC from prescribed emissions are much larger, 13.4 and 3.2 μgC m^{-3}, respectively. Prescribed fire can lead to an enhancement of daily carbonaceous matter (CM = OM + EC, organic matter (OM) = 1.4 × OC) up to 22 μg m^{-3}, or 63% of the EPA standard of 24 h $PM_{2.5}$ concentration of 35 μg m^{-3}.

A positive correlation is found between the local (county) burned areas and OC and EC enhancements at 24 sites. The correlation coefficients for OC and EC are 0.65 and 0.63 respectively. Therefore, local burning only explains about 40% of fire induced variance. Regional transport is an important factor. To further study the transport effects, we divided the 10 VISTAS states into two groups. In the states with high fire emissions (AL, GA, FL, and SC), prescribed fires contribute to 39 and 42% of OC and EC, respectively. In the states with low fire emissions (KY, MS, NC, TN, VA, and WV), its mean contributions to OC and EC are smaller but still significant at 14% and 17%, respectively.

To further estimate the effects of prescribed fire emissions, we compute the concentrations of organic matter and carbonaceous matter. The simulated mean concentrations of OM, CM, and $PM_{2.5}$ at 24 sites are 2.9, 3.3, and 9.3 μg m^{-3}, respectively. CM accounts for 37% and 25% of $PM_{2.5}$ in states with high and low fire emissions, respectively. The simulated mean contributions of prescribed fires to $PM_{2.5}$ are 12 and 3%, respectively, over states with high and low local burning emissions. The average OC/EC ratio in high burning areas is smaller than in low burning area (*25*), consistent with previous studies (*26, 27*).

Fire Emission Evidence from Satellite Measurements

MOPITT CO at 850 hPa. Based on model comparison with surface measurements (Figure 3), we selected two episodes to compare the model results to the integrated lower tropospheric CO column measurements (reported as 850 hPa) by the measurements of pollution in the troposphere (MOPITT) satellite (*28*) in the Southeast (Supporting Information). Generally, MOPITT shows CO enhancements over regions where the model simulates impacts from fire emissions, although the enhancement levels are lower in the model. The simulated CO vertical distribution may be problematic due to inadequate simulations of plume rise or vertical transport.

Terra MODIS Fire Counts. Direct detection of burned areas from satellite instruments is ineffective for prescribed fires, since the burning is understory by design. Fire count measurements based on surface temperature changes are more useful. The spatial resolution of MODIS fire counts is 1 × 1 km^2. The detection efficiency of prescribed fires with scales <1 km is unknown. Quantitative comparison is therefore difficult between burned areas in the VISTAS inventory and MODIS fire counts. The correlation coefficient is 0.57 between the monthly MODIS fire counts and the burned areas in VISTAS inventory at the state level in 2002. We focus on the qualitative aspect in the comparison by examining if March is the month with the largest amount of fires as found in the VISTAS inventory.

We show the comparisons for the four states (AL, FL, GA, and SC) with large fire emissions in Figure 6. The secondary peak in May in the VISTAS inventory for Georgia is due to wildfires. Generally, the VISTAS inventory shows consistent spring maximum and summer minimum in the Southeast. MODIS fire counts show clear spring maximum in Florida and South Carolina, in good agreement with the VISTAS inventory. In Georgia, the May fire counts are larger than in March, likely because of wildfires. In the VISTAS inventory, wildfires account for ~80% of the total burned areas in May in GA. It has higher burning temperature than prescribed fires due to less control (*13*). These large wildfires are much easier for satellite to detect than prescribed fires.

The largest difference for spring is found over Alabama, where MODIS fire counts are fairly low. Previous model evaluations with surface measurements of CO at the CTR and OLF sites (Figure 3) and OC and EC at the CTR site (Figure 4) clearly demonstrate the large impacts of fire emissions in Alabama. Chemical mass balance (CMB) (*29*) and positive matrix factorization analyses (*30*) showed a spring peak of wood burning in the Southeast. Therefore, we believe that MODIS fire counts failed to detect fire activities in Alabama in spring 2002. The mean temperature for prescribed fires is 440 K (*13*); the detection sensitivity of MODIS begins to decrease in this temperature range (*10*). Moreover, prescribed fires may still in the early burning stage

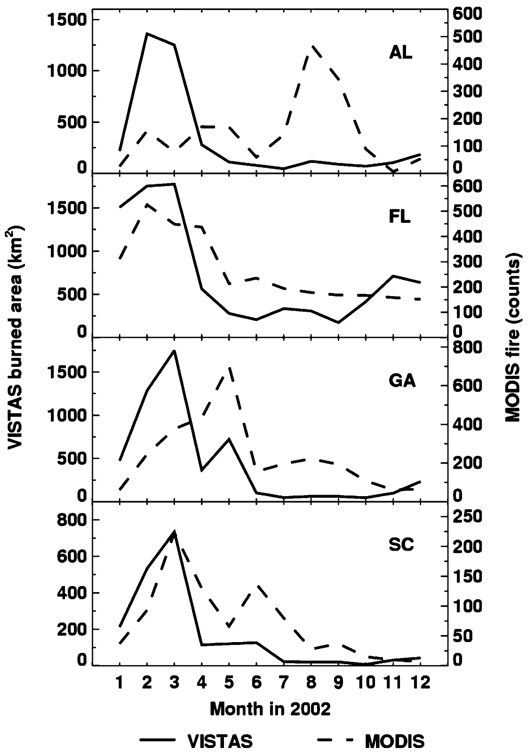

FIGURE 6. Monthly variations of total burned areas for all fire types from VISTAS inventory (solid lines) and the corresponding Terra MODIS fire counts (dashed lines) over Alabama, Florida, Georgia, and South Carolina in 2002.

when Terra satellite passes over at 10:30 a.m. local time. Some underestimation is expected. The reason for much lower detection in Alabama than Georgia or South Carolina, however, is unclear.

Three out of four states (AL, GA, and SC) show peaks of fire activities (fire counts) in the summer, which is not present in the VISTAS inventory. First, the fully grown forest canopies in summer shield the upwelling radiation from fires and reduce the thermal signal and detection probability of the MODIS instrument than spring. The second potential interference factor is the presence of cloud. We examined MODIS cloud fractions in 2002 over the Southeast. There are 10−30% monthly variations through this year. But no large decrease of cloud fraction is found from spring to summer. Another possible factor is hot and dry surfaces in summer, such as the urban and industrial regions, which could trigger false positives (*10*). It is however not supported by spatial analysis of MODIS fire spots in Alabama in August. It shows locations mostly over forest areas with a few on cropland or grassland. Indications are that the VISTAS inventory may have underestimated fire emissions in summer. More detailed analysis is currently under way.

CMAQ analyses of surface pollutant concentrations and satellite measurements suggest large enhancements of OC, EC, and CO due to fire emissions in March. CO is a good tracer to understand the transport of fire emissions. However, surface observational evidence is limited. More CO measurements are available from the EPA AIRNow network, but the current lower limit of 0.5 ppmv in reported values is too high and renders the data unusable. To explore in greater detail MOPITT measurements, measurements of CO vertical profiles are needed. The monthly mean enhancement of $PM_{2.5}$ is 8% (0.8 μg m^{-3}) and daily enhancement is up to 25 μg m^{-3}, posing a problem for the attainment of the daily national $PM_{2.5}$ standard of 35 μg m^{-3}. For more detailed analysis, fire emission inventories with better spatial and temporal resolutions than VISTAS are needed. A higher temporal resolution is critical to simulate better episodic $PM_{2.5}$ enhancements. A higher measurement frequency of OC and EC aerosols at the surface networks is needed to more adequately characterize the fire impacts.

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Note Added after ASAP Publication

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Supporting Information Available

Simulated regional enhancements from fire emissions, model performance evaluation, model comparisons with 36 and 12 km grids, MOPITT observed CO enhancement at 850 hpa, and model configurations. This material is available free of charge via the Internet at http://pubs.acs.org.

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