Biomass burning impacts on PM$_{2.5}$ in the Southeastern United States

Di Tian$^1$*, Yongtao Hu$^1$, Yuhang Wang$^2$, James Boylan$^3$, Armistead Russell$^1$

$^1$School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA

$^2$School of Earth and Atmospheric Science, Georgia Institute of Technology, Atlanta, GA, 30332, USA

$^3$Environmental Protection Division, Georgia Department of Natural Resources, Atlanta, Georgia, 30354, USA

Abstract

Biomass burning is a major and growing contributor to PM$_{2.5}$ in the southeastern United States. Such impacts (especially individual impacts from each burning source) are quantified using the Community Multiscale Air Quality Model (CMAQ), a chemical transport model (CTM). Given the sensitivity of CTM results to emission inputs, simulations were conducted using three biomass burning inventories. Shortcomings in the burning emissions were also evaluated by comparing simulations with observations and results from a receptor model. Model performance improved significantly with the updated emissions and speciation profiles based on recent measurements for biomass burning: mean fractional bias is reduced from 22% to 4% for EC and from 18% to 12% for organic matter; mean fractional error is reduced from 59% to 50% for EC and from

* Corresponding author. Address: School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA. Now at Environmental Protection Division, Georgia Dept. of Natural Resources, 4244 International Parkway, Suite 120, Atlanta, GA 30354. Email: di.tian@gatech.edu. Phone: 404-363-7092. Fax: 404-363-7100.
55% to 49% for organic matter. Quantified impacts of biomass burning on PM$_{2.5}$ during January, March, May and July 2002 are 3.0, 5.1, 0.8, and 0.3 μg m$^{-3}$ domain-wide on average, with more than 80% of such impacts being from primary emissions. Impacts of prescribed burning dominate biomass burning impacts, contributing about 55% and 80% of PM$_{2.5}$ in January and March respectively, followed by land clearing and agriculture field burning. Significant impacts of wildfires in May and residential wood combustion in fireplaces and woodstoves in January are also found.

**Introduction**

Biomass burning includes the combustion of biomass fuels through either natural (e.g. wildfires) or planned processes (e.g. residential wood combustion in fireplaces and woodstoves), and can emit large amounts of air pollutants. In the United States, estimates suggest that about 35% of the fine particulate matter (PM$_{2.5}$, i.e. PM with an aerodynamic diameter less than 2.5 μm) emissions come from biomass burning\(^1\), and most of these emissions are carbonaceous (70-95%). Significant impacts of biomass burning on PM$_{2.5}$ have been found \(^2-^5\).

PM can adversely affects human health \(^6\), and there is growing evidence that the carbonaceous component may be of particular concern \(^7-^{10}\). In response, the U.S. Environmental Protection Agency (US EPA) promulgated a National Ambient Air Quality Standard (NAAQS) in 1997 for PM$_{2.5}$ and designated non-attainment areas in April 2005. Recently, the 24-hour PM$_{2.5}$ standard was reduced to 35 μg m$^{-3}$, a level at which a large number of areas are expected to exceed. Visibility reduction due to PM is also of concern, and is addressed under the Clean Air Act Amendment and the US EPA’s 1999 Regional Haze Rule. Regulators are now faced with identifying effective strategies to lower PM$_{2.5}$ levels and thus must address biomass burning.

Understanding biomass burning impacts (especially individual impacts from specific burning sources) on PM$_{2.5}$ is central for effective control strategy development.
and air quality management. Such impacts can be simulated using chemical transport models (CTMs), though their accuracy is affected by the quality of emission and meteorological inputs. In this study, impacts of uncertainties in biomass burning emissions (including magnitude, temporal and spatial distribution, and speciation) on PM$_{2.5}$ simulations are investigated. Emission shortcomings are identified by comparing simulations with observations and results from a receptor model. Improved emission estimates are used to simulate biomass burning impacts on PM$_{2.5}$ during different seasons in the southeastern US, with particular focus on the state of Georgia, where biomass burning emissions are large.

**Methods**

Biomass burning sources investigated here include wildfires, prescribed burning, agriculture field burning, land clearing, and residential wood combustion in fireplaces and woodstoves (RWC). Their air quality impacts during four months in 2002 (January, March, May and July) are simulated using a state of the science CTM. Theses months are chosen as they have very different levels of biomass burning emissions, as well as different meteorological conditions. Using month-long simulations allows a number of synoptic meteorological conditions to be captured during each period, as opposed to concentrating on the periods of highest impact alone.

**Air quality modeling using a CTM**

Air quality for January, March, May and July of 2002 are simulated with the Community Multiscale Air Quality (CMAQ) model v. 4.3 using SAPRC-99 as the chemical mechanism. Initial and boundary conditions are supplied by simulations from a 36-km resolution grid covering the United States (Unified RPO modeling domain) and results of the first two days for each month are discarded as model initialization periods to further minimize the role of spurious initialization problems. The modeling
domain covers the southeastern United States with a 12-km grid, and has 19 vertical
layers reaching to about 15 km vertically, with a 36 m bottom layer. Meteorological
fields for the episodes are simulated with the NCAR/Penn State 5th generation Mesoscale
Model (MM5)\textsuperscript{12,13}. Emissions are from the Visibility Improvement State and Tribal
Association of the Southeast (VISTAS) 2002 inventory (hereafter referred to as
VISTAS2002)\textsuperscript{14}, and then processed using the Sparse Matrix Operator Kernel Emissions
(SMOKE) Modeling System v. 2.1\textsuperscript{15}. PM$_{2.5}$ simulations are evaluated by comparing
model results with observations collected from a variety of monitoring networks (Figure
1). Organic carbon (OC) observations are converted to organic matter (OM) using a 1.4
multiplication factor, which has been widely used although recent studies suggest it is
low\textsuperscript{16}. Six performance metrics: including mean bias (MB), mean error (ME),
normalized mean bias (NMB), normalized mean error (NME), mean fractional bias
(MFB), and mean fractional error (MFE), are calculated\textsuperscript{17}. 
Figure 1 Observation sites in a variety of monitoring networks, including the Interagency Monitoring of Protected Visual Environments (IMPROVE, http://vista.cira.colostate.edu/improve), the SouthEastern Aerosol Research and Characterization (SEARCH)\(^{18}\), the Assessment of Spatial Aerosol Composition in Atlanta (ASACA)\(^{19}\) and the Speciation Trends’ Network (STN, http://www.epa.gov/ttn/airs/airsaqs).

**Biomass burning emission inventories**

Two different emission inventories are used for wildfires, prescribed burning, agriculture field burning and land clearing, both specific to Georgia. One inventory is from the VISTAS2002 inventory mentioned above, and the other is from the US EPA (hereafter referred to as EPA2001)\(^1\) (Figure 2). Biomass burning emissions are typically calculated as the product of the amount of biomass consumed and emission factors (ratios of the mass of pollutants emitted per unit biomass). In the EPA2001 inventory, the amount of biomass consumed is estimated by burned area or crop production at state- or regional-level, and then allocated to county-level according to specific spatial surrogates (e.g. forest areas). In the VISTAS2002 inventory, the amount of biomass consumed is estimated from burned area records obtained by surveying state and federal agencies.
Such records are location-specific for wildfires, and by county for other types of burning. Emissions from the two inventories differ significantly (Figure 2). In EPA2001, emissions are almost equally distributed among the four biomass burning sources. In comparison, the difference among the burning sources in VISTAS2002 is large, and prescribed burning contributes about 70% of the total emissions from the four sources combined.

In the VISTAS2002, emissions from prescribed burning, agriculture field burning and land clearing in Georgia are inventoried as annual totals, which are processed by SMOKE to model-ready hourly emissions using source-specific monthly, daily or diurnal temporal profiles obtained from VISTAS. Since the profiles are same for all counties in Georgia, the difference in burning seasons between counties is not captured by the temporal allocation process. To address this difference, a third inventory is developed (hereafter referred to as MONTHLY), using detailed monthly burned area data. Fuel consumption and emissions factors are the same as in VISTAS2002. Given the same annual burned area, the MONTHLY inventory has the same annual total emissions as the VISTAS2002. In simulations with the three inventories, emissions from RWC are from VISTAS2002, as well as are biomass burning emissions in other states.
Figure 2 Biomass burning emissions in Georgia during 2002 (10³ tons/year). CO emissions are divided by 10, and NH₃ and SO₂ emissions are multiplied by 10 for better visual effect. Emissions from all biomass burning sources except RWC are obtained from two inventories: EPA2001 (labeled as E) and VISTAS2002 (labeled as V). All RWC emissions are from the VISTAS2002 inventory. There are no estimates for NH₃ and SO₂ emissions from agriculture burning and land clearing, or NH₃ emissions from RWC.

Updated PM₂.₅ speciation for biomass burning emissions

PM₂.₅ emissions from biomass burning are speciated into five components (primary organic aerosol (POA), elemental carbon (EC), sulfate (SO₄²⁻), nitrate (NO₃⁻), and other unspecified mass) using speciation profiles obtained from US EPA. In the EPA profiles, EC and POA are the major components of biomass burning, accompanied by negligible sulfate and nitrate levels (Table 1). POA fractions have been calculated by multiplying the OC measurements by a factor of 1.2 to account for the other elements bound to C. However, molecular level analyses of POA have indicated that the POA/OC ratio for wood burning is about 1.9. In addition, these analyses only measure less polar organics and do not account for water-soluble species which comprise 20-80% of organic aerosols. Since water-soluble organic compounds tend to have higher POA/OC ratios than less water-soluble organic compounds, the POA/OC ratio for wood burning may be larger than 1.9. Here, the fractions of EC ($f_{EC}$), SO₄²⁻ ($f_{SO4^{2-}}$), and NO₃⁻
\( f_{\text{NO}_3^-} \) and other unspecified mass \( (f_{\text{other}}) \) for wildfires/prescribed burning and RWC are updated using recent field and lab measurements \(^{23,26-29}\). The corresponding POA fractions \( (f_{\text{POA}}) \) are recalculated by a mass balance method:

\[
f_{\text{POA}} = 1 - f_{\text{EC}} - f_{\text{SO}_4^{2-}} - f_{\text{NO}_3^-} - f_{\text{other}}
\]  

The updated fractions are presented in Table 1. Measurements for species other than EC, OC, \( \text{SO}_4^{2-} \) and \( \text{NO}_3^- \) (e.g. potassium and chloride) are treated as other unspecified mass.

The speciation profiles for agriculture field burning and land clearing are not updated due to lack of data.

Table 1 PM\(_{2.5}\) speciation profiles for different biomass burning sources. Emissions of each species are calculated by multiplying the total PM\(_{2.5}\) emissions and corresponding fractions in the speciation profile. Values from EPA are the profiles recommended by EPA in 2005 (http://www.epa.gov/ttn/chief/emch/speciation\(^*)\). Updated values are recalculated using recent measurements.

<table>
<thead>
<tr>
<th>Sources</th>
<th>POA</th>
<th>EC</th>
<th>( \text{SO}_4^{2-} )</th>
<th>( \text{NO}_3^- )</th>
<th>Other</th>
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<td>0.003</td>
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</table>

**Biomass burning impacts on PM\(_{2.5}\) and CMB analysis**

PM\(_{2.5}\) concentrations during January 2002 (a month when emissions from the various biomass burning sources are all significant) are simulated using the different biomass burning emission inventories and the updated PM\(_{2.5}\) speciation profiles. Corresponding biomass burning impacts on PM\(_{2.5}\) are estimated by comparing CMAQ simulations with and without biomass burning emissions. In order to identify shortcomings in biomass burning emissions, such simulated impacts are compared with receptor modeling results at JST and YRK (JST is an urban SEARCH station at Jefferson Street, Atlanta, Georgia and YRK is a rural SEARCH station at Yorkville, Georgia.) from the Chemical Mass Balance (CMB) model for this period. The CMB modeling employs observations of both identified individual organic compounds (molecular markers) and
elemental species (e.g. sulfate, nitrate, ammonium, elemental carbon, organic carbon, and trace metals) $^{30-32}$. Relative distributions of organic compounds in source emissions provide additional means to identify source contributions that cannot be uniquely identified by elemental species alone.

Adjusted biomass burning emissions based on January 2002 analyses and the updated PM$_{2.5}$ speciation profiles are then applied to the other three months (March, May and July of 2002) to study corresponding biomass burning impacts. Impacts from individual biomass burning sources are computed by tracing POA emissions in CMAQ. These tracers are treated as non-reactive species, and go through similar physical processes as other primary carbonaceous aerosol species $^{33}$.

**Results**

**PM$_{2.5}$ simulations with different biomass burning emissions**

As expected from the amount of information used in the inventories, the spatial distributions of POA (the major PM$_{2.5}$ component for biomass burning) emissions and concentrations are quite different during January 2002 (Figure 3). POA emissions with EPA2001 are more intense in the Atlanta area than with VISTAS2002, which have denser emissions in southwestern Georgia (Figure 3). POA concentrations simulated with EPA2001 are 0.7 $\mu$g m$^{-3}$ higher than those with VISTAS2002 for the Atlanta PM$_{2.5}$ non-attainment area, but 0.6 $\mu$g m$^{-3}$ lower than VISTAS2002 on average for Georgia. POA concentrations simulated using the MONTHLY inventory are similar to the simulations with the VISTAS2002. However, peak concentrations with the MONTHLY inventory are more eastward (Figure 3). Model performance statistics find that OM concentrations simulated using VISTAS2002 agree better with the observations than those using EPA2001. Such statistics for simulations using VISTAS2002 and MONTHLY are similar, despite the significant differences in spatial distributions of POA.
emissions and concentrations (Figure 4). The negligible difference in model performance statistics, in part, is because most observations are outside of the regions affected by the updated monthly emissions from biomass burning (Figure 3 and Figure 1).

Figure 3 Monthly average POA emissions (first row, g/s) and simulated concentrations (second row, μg m\(^{-3}\)) using three different biomass burning emission inventories during January 2002. Monthly average values are used since allocation of emissions from prescribed burning, agriculture field burning, and land clearing are not day dependent by default in SMOKE.
Figure 4 Mean, mean fractional bias and error for EC and OM with different emission inventories and speciation methods during January 2002. Case 1: simulations with the EPA2001 emission inventory; Case 2: simulations with the VISTAS2002 emission inventories; Case 3: simulations with the MONTHLY emission inventory; Case 4: simulations with the MONTHLY emission inventory and updated speciation profiles; and Case 5: simulation with the MONTHLY emission inventory and updated speciation profiles, as well as 90% reduction in RWC emissions. The horizontal lines are the mean of EC and OM observations.

**PM$_{2.5}$ Simulations with updated PM$_{2.5}$ speciation profiles of biomass burning**

EC and OM concentrations simulated using the EPA speciation profiles during January 2002 are overestimated, as indicated by the model performance statistics (Figure 4, Case 1-3). Simulations with the updated speciation profiles lead to decreased EC and increased OM concentrations. Model performance for EC is significantly improved, while OM deteriorates (Figure 4, Case 4). High sensitivities of model performance statistics to the speciation profiles for biomass burning also indicate the importance of developing more representative profiles. Time series of daily simulated and observed EC and OM concentrations during January 2002 show the same overestimation of EC and OM (Supporting Information. Figure 3)
Comparison with results from CMB analysis

The CMB analysis for January 2002 suggests that wood burning contributes 1.59 $\mu g \, m^{-3}$ of PM$_{2.5}$ at JST and 0.45 $\mu g \, m^{-3}$ at YRK, in comparison with CMAQ-simulated levels of 13.2 $\mu g \, m^{-3}$ at JST and 4.2 $\mu g \, m^{-3}$ at YRK. High bias in biomass burning emissions is the only possible explanation for the EC and OM overestimation. Simulated POA tracer concentrations for individual biomass burning sources show that RWC has the largest impact on PM$_{2.5}$ simulations, contributing about 90% (9.7 $\mu g \, m^{-3}$) of total POA concentrations from biomass burning at JST and 70% (2.2 $\mu g \, m^{-3}$) at YRK despite its small annual emissions (Figure 2). An approximate 90 percent reduction in RWC emissions is suggested so as to minimize the difference between simulated source contributions and results from CMB analysis. EC and OM simulations with the reduced RWC emissions agree better with observations (Figure 4: Case5 and Supporting Information. Figure 3), though discrepancies between simulations and observations still remain due to other sources of uncertainties that are not investigated here. The abnormally large impact of RWC at JST and YRK is due to concentrated emissions in the Atlanta area. The RWC emissions are calculated using regional wood consumption and spatially allocated to each county using number of houses or fireplaces/woodstoves. As suggested by the above comparison, such spatial surrogates are not representative of actual RWC activities.

Performance summary of improved PM$_{2.5}$ simulations

Updated emissions, including monthly county-level emissions for prescribed burning, agriculture field burning and land clearing (MONTHLY), a 90% reduction of RWC emissions, and the improved speciation profiles, are applied to other episodes (March, May and July 2002). Overall performance of simulated PM$_{2.5}$ species during these episodes are well within recent performance suggestions 17, except for OM during May and July (Supporting Information. Figure 2 and Table 1). Underestimation of OM is
common in the current CMAQ model, and it is likely due to underestimation of secondary organic aerosol (SOA) formation from biogenic sesquiterpene and isoprene emissions, and oligomerization of SOA into nonvolatile particles. Time series at JST and YRK show that simulated daily OM and EC follow observations well (Supporting Information. Figure 3).

**Biomass burning impacts on PM$_{2.5}$**

Biomass burning emissions contribute 3.0, 5.1, 0.8, and 0.3 μg m$^{-3}$ of PM$_{2.5}$ (averaged over the whole modeling domain), constituting 25%, 40%, 9% and 4% of total PM$_{2.5}$ during January, March, May and July respectively (Figure 5 and Figure 6). Analyses using receptor models, e.g Positive Matrix Factorization (PMF) model and CMB, indicated similar seasonal trends. Biomass burning impacts during January and March are concentrated in southwestern Georgia, where large amounts of prescribed burning are conducted. Such impacts in the Atlanta PM$_{2.5}$ non-attainment area are 2.3 and 3.9 μg m$^{-3}$ during January and March respectively (Figure 6).

Figure 5 Monthly average PM$_{2.5}$ concentrations (first row, μg m$^{-3}$) and source contributions from biomass burning (second row, μg m$^{-3}$) during January, March, May and July 2002. Source contributions are also presented using different scales (Supporting Information. Figure 4)
Figure 6 Monthly-average speciated PM$_{2.5}$ concentrations (CONC, μg m$^{-3}$) and source contributions from biomass burning (BIOM, μg m$^{-3}$) during January, March, May and July 2002. Domain refers to results averaged over all modeling grids and Atlanta NAA refers to results averaged over all grids within the Atlanta PM$_{2.5}$ non-attainment area.

More than 80% of PM$_{2.5}$ concentrations caused by biomass burning are primary (mainly POA) and the rest is secondary in origin (Figure 6). During January and March, biomass burning contributes about 66% and 86%, respectively, of the POA domain wide, and about 48% and 70% for the Atlanta PM$_{2.5}$ non-attainment area. Smaller impacts in the Atlanta area are results of longer distances to biomass burning emissions. In addition, NH$_3$ emissions from biomass burning also lead to increased NH$_4^+$, contributing about additional 2% of PM$_{2.5}$. Extra NH$_3$ and NO$_X$ emissions from biomass burning lead to increased NO$_3^-$ as well (about 4% of PM$_{2.5}$). No significant increases in SO$_4^{2-}$ levels are found, contrary to findings in a recent study in Texas$^{35}$. Spatial distributions of speciated PM$_{2.5}$ concentrations and source contributions from biomass burning during January 2002 are also provided (Supporting Information, Figure 5).

**Individual biomass burning impacts on PM$_{2.5}$**

Simulated POA concentrations from individual biomass burning sources indicate that prescribed burning is the largest single biomass burning source over most of the modeling domain and the Atlanta PM$_{2.5}$ non-attainment area during most periods, except for May 2002 (Figure 7 and Supporting Information, Figure 6). The POA contributions from prescribed burning peak in March (2.9 μg m$^{-3}$ for the whole modeling domain),
followed by January (1.2 μg m⁻³), May (0.1 μg m⁻³) and July (0.1 μg m⁻³). Prescribed burning concentrates in the southwest of Georgia, though influencing much of the region. Overall impacts from wildfires are much smaller in spite of a severe local impacts and peaks in May. Source contributions peak in March in southern Georgia for agriculture burning, and are more spatially sporadic for land clearing. RWC has the largest impact in January and is centered in the Atlanta area which is characterized with higher population densities.

<table>
<thead>
<tr>
<th>Domain</th>
<th>POA concentrations (μg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>1.5</td>
</tr>
<tr>
<td>Mar</td>
<td>3</td>
</tr>
<tr>
<td>May</td>
<td>2.5</td>
</tr>
<tr>
<td>Jul</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 7 Monthly-average POA source contribution (μg m⁻³) from individual biomass burning sources during January, March, May and July 2002. Domain refers to results averaged over all modeling grids and Atlanta NAA refers to results averaged over all grids within the Atlanta PM₂.₅ nonattainment area.

**Discussion**

Model simulations of biomass burning impacts on PM₂.₅ are crucial in understanding sources that cause elevated PM₂.₅ concentrations and can help develop effective control strategies and smoke management plans. The simulated impacts are highly dependent on emission estimates, as indicated by simulations using the three inventories (EPA2001, VISTAS2002 and MONTHLY). Similar PM₂.₅ emissions from each biomass burning source in EPA2001 imply similar contributions, though prescribed burning is the dominant source based on simulations using more representative
inventories (VISTAS 2002 and MONTHLY). In addition, due to the inherently large temporal and spatial variation of biomass burning emissions, detailed information on not only the magnitude of emissions but also when and where burning actually occurs is important for simulating burning impacts. Here, MONTHLY has the most detailed information.

Simulated impacts and the corresponding emissions can be improved by comparing with findings from other analyses (e.g. CMB analysis, POA tracers, and EC/OC observations). While CMB analysis is not affected by the emission uncertainties, such analyses seldom differentiate between impacts from individual biomass burning sources due to similar source profiles, and provide less information about the spatial and temporal distribution of impacts. Total burning impacts estimated by CMB are here used to help evaluate corresponding simulations. This comparison suggests about 90% reduction in biomass burning emissions impacting Atlanta in January. POA tracer analysis which is used to assess impacts from individual burning sources indicates that only RWC emissions (instead of total biomass burning emissions) should be reduced by 90%. This analysis assumes that wintertime biomass burning impacts on PM$_{2.5}$ in an urban area are mainly primary, though recent analyses suggest that SOA formation from forest fires may be significant, even in February$^{36}$. However, the processes leading to SOA formation involve release of isoprenoids from leaves and needles during forest fires, while the excess OC found is linked to RWC, which laboratory studies suggest would not have similar emissions.

Impacts of biomass burning on annual PM$_{2.5}$ are simulated during the four months, assuming that impacts per unit emissions during February, April and June are average of those during adjacent months, unit impacts during November and December are similar to January, and the rest is similar to July. Generally, biomass burning can cause 1.2 µg m$^{-3}$ of PM$_{2.5}$ in the Atlanta PM$_{2.5}$ nonattainment area during 2002 (the annual PM$_{2.5}$ NAAQS is 15 µg m$^{-3}$). In addition, biomass burning can lead to a violation
of 24-hr PM$_{2.5}$ NAAQS, especially with promulgation of the new 24-hr PM$_{2.5}$ standard (35 μg m$^{-3}$). For example, simulated impacts of biomass burning on 24-hr PM$_{2.5}$ concentrations during March 2002 are higher than 35 μg m$^{-3}$ in more than 20 counties in Georgia. Given that such PM$_{2.5}$ simulations are based on emissions from prescribed burning, agriculture field burning, land clearing and RWC without daily dependence, the possibility of violating 24-hr PM$_{2.5}$ NAAQS might be higher. Due to the large impacts of biomass burning on PM$_{2.5}$, air quality and forest land managers are tasked with identifying practices to reduce related air quality impacts. Fortunately, most biomass burning impacts in the southeastern US are from planned burning processes (e.g. prescribed burning). Unlike wildfires, prescribed burning is planned by forest managers and its air quality impacts can be reduced by adopting proper forest management practices. Practices like choosing appropriate burning seasons and frequencies, as well as controlling smoldering emissions are strongly desired for better air quality.

CTMs (such as CMAQ) are generally required to be used to project future air quality for regulatory applications. For example, most states will use CTMs to perform attainment demonstration for areas that are not currently meeting annual PM$_{2.5}$ NAAQS. Inaccurate estimations of POA and EC emissions can affect the regulatory decisions aimed at bringing nonattainment areas (such as Atlanta) back into attainment with the annual PM$_{2.5}$ NAAQS. According to EPA modeling guidance, future PM$_{2.5}$ concentrations are calculated by scaling the measured base-year speciated PM$_{2.5}$ concentrations by a species-specific relative response factor (RRF). Species-specific RRFs are calculated by taking the ratio of the future modeled concentration to the base-year modeled concentration for each individual PM$_{2.5}$ species. Lower RRFs will result in lower projected future PM$_{2.5}$ concentrations. If POA and EC emissions and modeled concentrations of OC and EC are overestimated, the resulting RRFs will be less responsive to controls on a relative basis. As a result, the benefits from such controls will be underestimated by the model resulting in a higher future PM$_{2.5}$ concentration than
would have otherwise been projected if the POA and EC emissions were more accurately reflected in the inventory. Applying a 90% reduction in RWC emissions along with the updated speciation profiles will allow Atlanta to more accurately determine if the annual PM$_{2.5}$ NAAQS will be met in the future.

Acknowledgment

This work is funded by United States Environmental Protection Agency through grants (Nos. RD83096001, RD82897602 and RD83107601) and Georgia Department of Natural Resources. Authors are grateful for the VISTAS metrological and emissions data. Thanks are also due to Dr. Mei Zheng for CMB analysis results.

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1 School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA

2 School of Earth and Atmospheric Science, Georgia Institute of Technology, Atlanta, GA, 30332, USA

* Corresponding author. Address: School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA. Now at Environmental Protection Division, Georgia Dept. of Natural Resources, 4244 International Parkway, Suite 120, Atlanta, GA 30354. Email: di.tian@gatech.edu. Phone: 404-363-7092. Fax: 404-363-7100.
Supporting Information. Figure 1. Monthly temporal profiles for biomass burning. Sum of the monthly fractions for each source equals to 1.
Supporting Information. Figure 2. Air quality modeling performance of total and speciated PM$_{2.5}$ during four months in 2002. (Solid and dashed lines are suggested criteria from Boylan, 2006) January (purple), March (green), May (red), July (blue).
Supporting Information. Figure 3. Comparison of daily EC and OM simulations with observations in January, March, May and July 2002. JST refers to an urban SEARCH station at Jefferson Street, Atlanta, Georgia. YRK refers to a rural SEARCH station at Yorkville, Georgia. OM(EC)\_sim: simulated OM(EC) concentrations. OM(EC)\_obs: observed OM(EC) concentrations. w/o 90% reduction refers to simulations without 90% reduction of emissions from residential wood combustion.
Supporting Information. Figure 4. Monthly average PM$_{2.5}$ source contributions from biomass burning ($\mu$g m$^{-3}$) during January, March, May and July 2002. (Note different scales used.)

Supporting Information. Figure 5. Monthly averages of POA, EC, SOA, NH$_4^+$, NO$_3^-$ and SO$_4^{2-}$ concentrations ($\mu$g m$^{-3}$) and source contributions from all biomass burning ($\mu$g m$^{-3}$) during January 2002. (Note different scales used.)
Supporting Information. Figure 6. Monthly average POA contributions from all biomass burning sources and individual biomass burning sources during January, March, May and July 2002. Impacts from fireplaces and woodstoves combustion emissions during May and July are negligible. (Note different scales used.)
Supporting Information. Table 1 Air quality modeling performance of total and speciated PM$_{2.5}$ during January, March, May and July 2002

<table>
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<th>Month</th>
<th>Species</th>
<th>NOBS</th>
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<th>SIM_mean (μg m$^{-3}$)</th>
<th>MB (μg m$^{-3}$)</th>
<th>ME (μg m$^{-3}$)</th>
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