

## Smoke incursions into urban areas: simulation of a Georgia prescribed burn

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**Abstract.** This study investigates smoke incursion into urban areas by examining a prescribed burn in central Georgia, USA, on 28 February 2007. Simulations were conducted with a regional modeling framework to understand transport, dispersion, and structure of smoke plumes, the air quality effects, sensitivity to emissions, and the roles of burn management strategy in mitigating the effects. The results indicate that smoke plumes first went west, but turned north-west at noon owing to a shift in wind direction. The smoke then invaded metropolitan Atlanta during the evening rush hour. The plumes caused severe air quality problems in Atlanta. Some hourly ground PM<sub>2.5</sub> (particulate matter not greater than 2.5 µm in diameter) concentrations at three metropolitan Atlanta locations were three to four times as high as the daily (24-h) US National Ambient Air Quality Standard. The simulated shift in the smoke transport direction and the resultant effects on air quality are supported by the satellite and ambient air measurements. Two sensitivity simulations indicate a nearly linear relation between the emission intensities and PM<sub>2.5</sub> concentrations. Two other simulations indicate that the impacts on air quality for the residents of Atlanta during the evening commute could have been reduced if the starting time of the burn had been altered.

### Introduction

Prescribed burning is an important forest management technique. It has long been recognized as the most economical means for managing non-commercial fuels and vegetation. Prescribed fire eliminates species that compete for nutrients and reduces buildup of dead and live fuels that increase the hazard of destructive wildfire.

Prescribed burning has been widely used in the southern United States. This region comprises one of the most productive forested areas in the USA, with 81 million ha (~200 million acres) or 40% of the nation's forests in an area occupying only 24% of the US land area (SRFRR 1996). Furthermore, southern forests are dynamic ecosystems characterized by rapid growth and hence rapid deposition of fuels within a favorable climate, and a high fire-return rate of 3–5 years (Stanturf *et al.* 2002). Prescribed burning treats 2–3 million ha (6 to 8 million acres) of forest and agricultural lands each year (Wade *et al.* 2000).

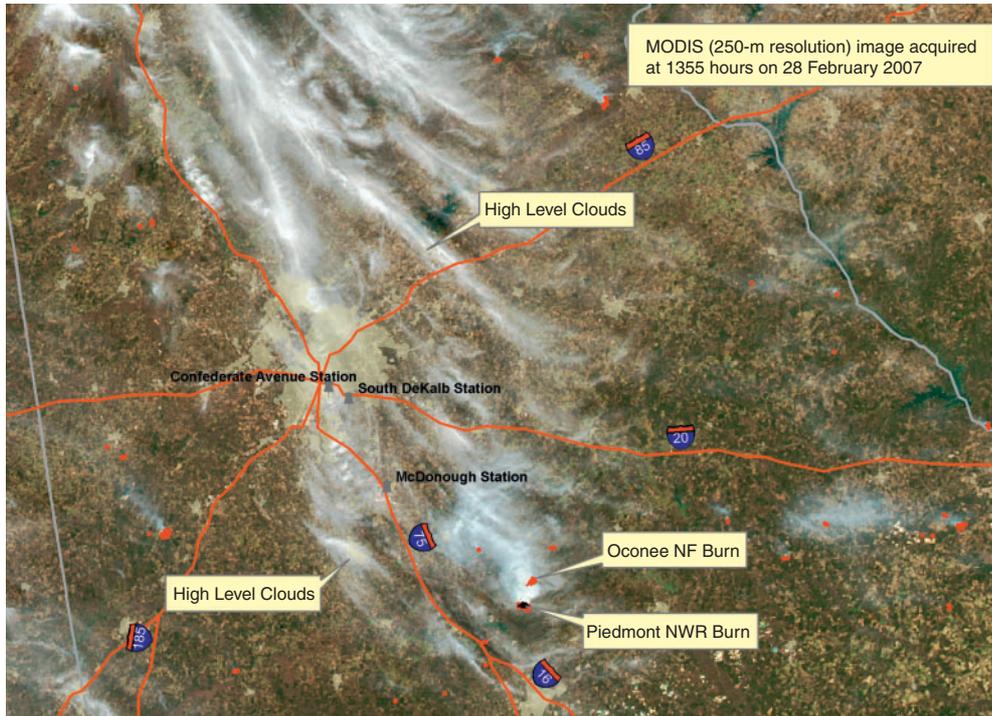
However, prescribed burning can cause degradation of air quality (Ward and Hardy 1991; Sandberg *et al.* 1999; Riebau and Fox 2001). Furthermore, wildland fires at times can be a major source of atmospheric PM<sub>2.5</sub> (particulate matter with aerodynamic diameter no greater than 2.5 µm). High concentrations of PM<sub>2.5</sub> can be a nuisance, and reduce visibility along roadways and to scenic views. In addition, high concentrations of PM<sub>2.5</sub> released from wildland fires is a risk to human health because

it is able to penetrate to the deepest parts of the lungs. The US Environmental Protection Agency (EPA) established National Ambient Air Quality Standards (NAAQS) (EPA 2003) for PM<sub>2.5</sub> in 1997 and revised these recently from 65 µg m<sup>-3</sup> to a lower value of 35 µg m<sup>-3</sup> for the daily (24-h) averaging period. The EPA has issued the Interim Air Quality Policy on Wildland and Prescribed Fire to protect public health and welfare by mitigating the impacts of air pollutant emissions from wildland fires on air quality (EPA 1998).

One of the worst environmental consequences of prescribed burning for land managers occurs when smoke plumes from burning unexpectedly invade urban areas. One such event occurred in Atlanta, Georgia, US, on 28 February 2007. Smoke plumes from two large prescribed burns in central Georgia merged together and passed over metropolitan Atlanta located ~80 km to the north-west. Hourly PM<sub>2.5</sub> concentrations were extremely high compared with the 24-h NAAQS. This caused metropolitan Atlantans coughing, wheezing and to look for fire engines (Shelton 2007). It should be noted that on the same day there were numerous other smaller fires statewide reported by the Georgia Forestry Commission, i.e. 1052 open burns permitted, which totaled almost 15 000 ha, and in addition 143 wildfires reported, totaling over 900 ha (Fig. 1).

The US Forest Service, in collaboration with the EPA and other federal agencies and universities have recently developed

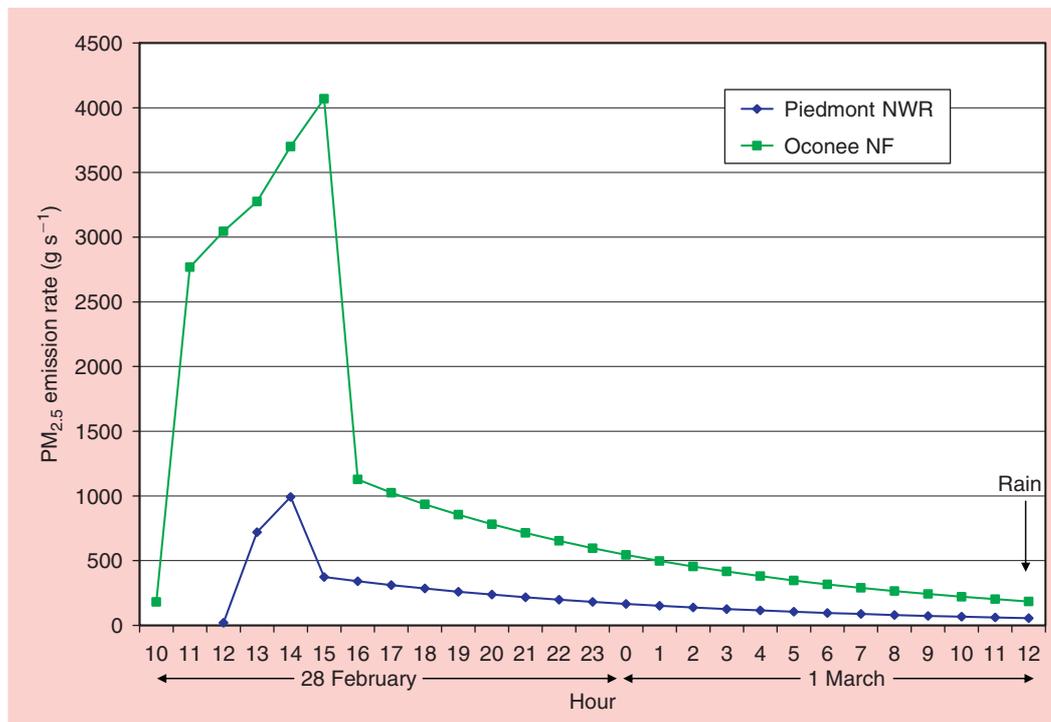
(a) Burn sites



(b) Smoke plume



**Fig. 1.** Prescribed burning information. Burning sites at the Oconee National Forest and Piedmont National Wildlife Refuge of Georgia, USA, and other wildland fires reported by the Georgia Forestry Commission on 28 February 2007 (a). Also shown are the Georgia Environmental Protection Division measurement stations at McDonough, South DeKalb, and downtown Atlanta (horizontal and vertical directions indicate east–west and north–south, respectively). Smoke plumes from the prescribed burning (b).



**Fig. 2.** The estimated amount of fine particulates (PM<sub>2.5</sub>) released from the prescribed fire each hour in an active or smoldering fire phase on 28 February and 1 March 2007. Estimates were obtained from the Fire Emission Production Simulator model (Sandberg *et al.* 2005).

some smoke and air quality modeling tools to assist fire and air quality managers in preventing such incursion events. Designed specifically for assessing air quality impacts from prescribed burning in the South, a tool called the SHRMC-4S, the Southern High-Resolution Modeling Consortium Southern Smoke Simulation System, was developed.

The purpose of the present study is to evaluate the usefulness of the SHRMC-4S to predict potential smoke impacts by examining the Atlanta smoke incursion event on 28 February 2007. The issues examined include smoke plume transport and dispersion processes, structure, the air quality effects, and roles of burning management strategy. These issues were examined by model simulations and the results were evaluated using satellite data and ambient measurements.

## Methods

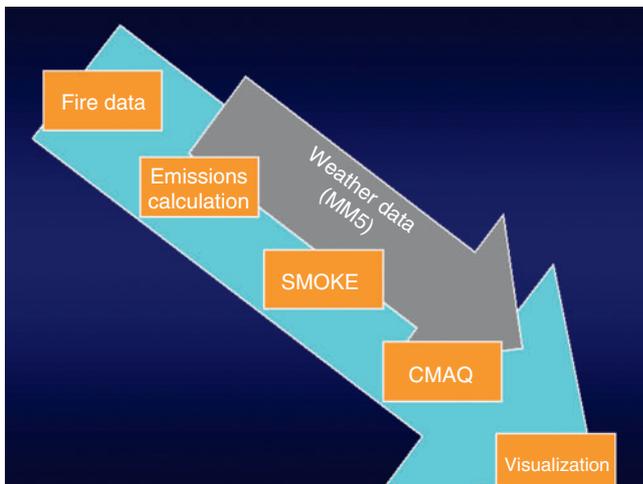
### *Fire and smoke data*

Only the two largest prescribed burns at two separate sites in central Georgia on 28 February 2007 (Fig. 1a) were evaluated. The US Forest Service set an understory prescribed fire and burned vegetation on ~824 ha (~1542 acres) in the Oconee National Forest (NF). The US Fish and Wildlife Service Piedmont National Wildlife Refuge (NWR) executed a prescribed fire on ~590.8 ha (~1460 acres) on the same day. Both prescribed fires produced smoke that lifted into the atmosphere (Fig. 1b). The fires did have differences in when active fire phases began and ended, and how much PM<sub>2.5</sub> (Fig. 2) and heat were released each hour.

The prescribed fire data were obtained from the Oconee NF and Piedmont NWR. The portion of the total fuel load consumed at the Oconee site was estimated to be at 13.54 t ha<sup>-1</sup> (5.48 tons per acre) as predicted with CONSUME 3.0 (Ottmar *et al.* 1993), whereas the Piedmont NWR estimated 0.73 to 0.93 t ha<sup>-1</sup> (1.8 to 2.3 tons per acre) were consumed by using estimates from the First Order Fire Effects Model (Reinhardt *et al.* 1997). Fire emissions were calculated by multiplying the consumed fuel by an emission factor appropriate for the fuel type and ignition plan (Mobley *et al.* 1976). These total emission values were transformed into hourly values using equations provided in Sandberg and Peterson (1984).

Note that only fire emissions were included in the simulations. Other emissions could also contribute to the actual PM<sub>2.5</sub> concentrations at Atlanta, but the measured concentrations before the arrival of the smoke plumes were very small (as shown in the *Results* section below). Thus, the contributions of other emissions should be negligible for this case.

Two types of measurements were used to evaluate simulation results. One is the Geostationary Operational Environmental Satellite (GOES-M) Imagers (Schmit *et al.* 2001) on board the geostationary satellite GOES-12. GOES images have proved useful for active fire and smoke detection research (e.g. Prins *et al.* 1998; Alfaro *et al.* 1999; Christopher *et al.* 2002; Prados *et al.* 2007). GOES-M image data from visible channel 1 (0.52–0.74 μm), with spatial resolution 0.57 × 1 km, were used to identify smoke masks during this fire event. As the area under examination was mainly covered by clear sky in the first few hours of burning, we set a threshold to identify smoke mask



**Fig. 3.** A diagram of the Southern High-Resolution Modeling Consortium Southern Smoke Simulation System (SHRMC-4S).

and validate the results by visual inspection as described below: (i) finding the potential smoke pixels: digital value at band 1 > 3560; (ii) finding the number of potential smoke pixels ( $t_1$ ,  $t_2$ ,  $t_3$ ) within three windows for every potential smoke pixel. The three windows are centered at a potential smoke pixel and window sizes are  $3 \times 3$ ,  $5 \times 5$ ,  $7 \times 7$ . (iii) If  $t_1 \leq 2$  or  $t_1 \leq 2$  and  $t_2 \leq 3$  and  $t_3 \leq 4$  or  $t_1 \leq 3$  and  $t_1 = t_2$ , then the potential smoke pixel is not a real smoke pixel; otherwise, the potential smoke pixel is identified as such.

The other measurements are the ambient  $PM_{2.5}$  concentrations. Hourly measurements were conducted at three stations: McDonough, South DeKalb, and downtown Atlanta (Confederate Avenue) (Fig. 1a). Data were obtained from the Georgia Environmental Protection Division.

*SHRMC-4S*

SHRMC-4S is a modeling framework designed to provide land managers with a say in how their prescribed fire practices are incorporated into air quality or air chemistry models. Fig. 3 provides an overview of this framework. Each box along the blue arrow represents steps that are needed to accomplish the objective of including emissions from wildland fires in regional-scale air quality models. The first box, Fire Data, gets SHRMC-4S started. Information on the size of the tract of land to be burned, the date and time of the burn, the location of the burn, plus pertinent data on the kinds and state of fuels are supplied by the land manager. Fire activity data are processed through combustion models that calculate emissions inventories for the burns (the Emissions Calculation box) (Goodrick and Brenner 1999; Liu 2004). The outputs are hourly productions of heat and the masses of gases and particulate compounds – fire products. The Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE) (Houyoux *et al.* 2002) processes emission data and provides initial and boundary chemical conditions for the Community Multiscale Air Quality (CMAQ) model (Byun and Ching 1999) for chemical modeling (fourth box). Visualizing the modeling results is the last step. The National Center for Atmospheric Research and Penn State Mesoscale Model (MM5) (Grell *et al.*

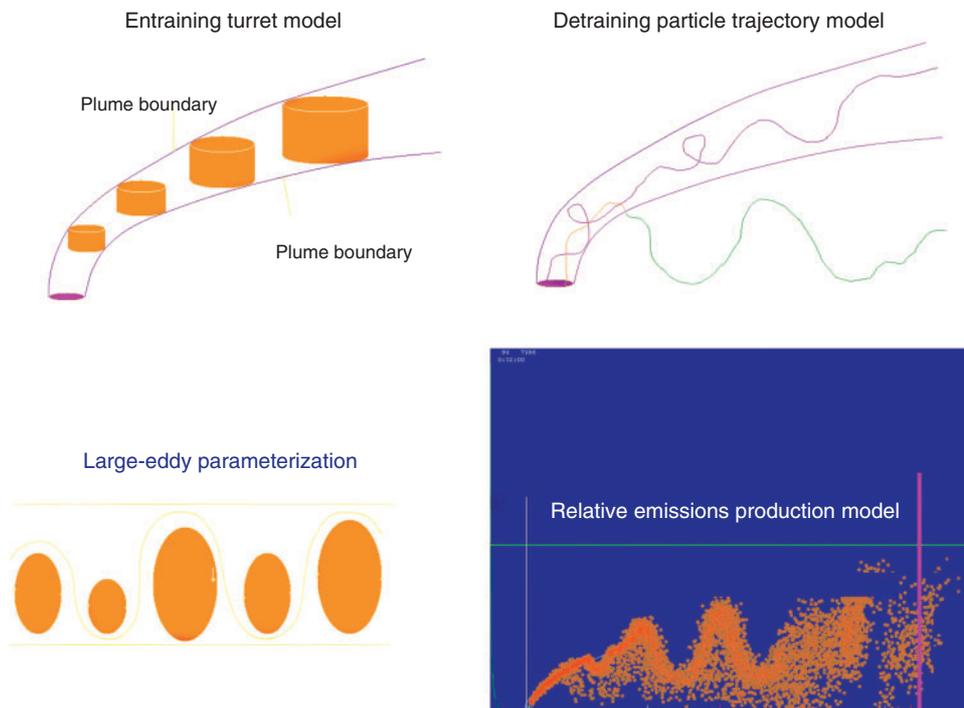
1994) is used for providing meteorological conditions for both the emission calculation and SMOKE and CMAQ simulations.

*Daysmoke and other techniques for fire applications*

Several modifications were made to SMOKE for prescribed burning applications (Liu *et al.* 2006). Area and point sources are among the various emission categories in SMOKE. Area source emissions are annual amounts (or converted to daily averages) from counties, and are emitted only into the lowest model level, whereas point-source emissions are emitted daily or hourly, like power plants. Point sources are then partitioned to multiple levels. Fires traditionally have been simulated as an area source, but large fires have much in common with point sources because: (1) they occur as individual events geographically with hourly and daily variability, and (2) smoke may be partitioned through a depth of a few kilometres to account for plume rise. Fire emission files for SMOKE were created to include the two prescribed fires as a point source in SHRMC-4S. The fires were identified through their latitude and longitude in an emission file in the Inventory Data Analyzer (IDA) format. All fire properties (height, diameter, exit temperature, exit velocity, and flow rate) are included in this file. Day- or hour-specific emissions of various chemical species are stored in separate files in the Emissions Modeling System’95 (EMS-95) format. It should be noted that no other emission sources (such as coal-fired power plants, vehicle emissions, other wildland fires) were included in the SMOKE file, which is likely to result in underprediction of the  $PM_{2.5}$  concentrations at the monitoring sites in Atlanta.

One unique feature of SHRMC-4S is linkage of Daysmoke (see description in the next paragraph) to SMOKE as an addition to the Laypoint algorithm (Byun and Ching 1999) for estimating plume rise and specification of plume vertical profiles. Information on plume rise, that is, the height smoke plumes can reach and the vertical distribution of smoke particles, is needed in SMOKE for point-source emissions and is crucial for evaluating the air quality effects of prescribed burning. Emissions, if injected into higher elevations, are likely to be transported out of the burn area by prevailing winds, meaning relatively smaller local ground concentrations and therefore reduced chances of exceeding the NAAQS standards, which are measured by ground concentration. SMOKE is equipped with the Briggs scheme (Briggs 1971) for calculating plume rise and this scheme was originally developed for the stacks of power plants. Many efforts have been made to develop plume rise schemes for fires (e.g. Pouliot *et al.* 2005), including the development of Daysmoke.

Daysmoke (G. L. Achtemeier, S. A. Goodrick, Y.-Q. Liu and W. A. Jackson, unpubl. data) is a dynamical-stochastic plume model designed to simulate smoke from prescribed burns in a manner consistent with how the burns are engineered by land managers. It is an extension of ASHFALL, a plume model developed to simulate deposition of ash from sugarcane fires (Achtemeier 1998). Daysmoke consists of four models (Fig. 4): (i) entraining the turret plume model. The plume is assumed to be a succession of rising turrets. The rate of rise of each turret is a function of its initial temperature, vertical velocity, effective diameter, and entrainment. (ii) Detraining the particle trajectory model. Movement within the plume is described by the horizontal and vertical wind velocity within the plume, turbulent



**Fig. 4.** Four components of Daysmoke.

horizontal and vertical velocity within the plume, and particle terminal velocity. Detrainment occurs when stochastic plume turbulence places particles beyond plume boundaries, plume rise rate falls below a threshold vertical velocity, or the absolute value of large-eddy velocity exceeds plume rise rate. (iii) A large-eddy parameterization. Eddies are two-dimensional and oriented normal to the axis of the mean layer flow. Eddy size and strength are proportional to depth of the planetary boundary-layer (PBL). Eddy growth and dissipation are time-dependent and are independent of the growth rate of neighboring eddies. Eddy structure is vertical and eddies are transported by the mean wind in the PBL. (iv) Relative emissions production model. Particles passing a ‘wall’  $\sim 5$  km (3 miles) downwind from a burn are counted for each hour during the burning period. A percentage of particle number at each layer relative to the total particle number is assigned to SMOKE simulations.

#### Simulations

The model domain covers Georgia and parts of Alabama in the west, South Carolina in the east, Tennessee in the north-west, and North Carolina in the north-east. It has  $193 \times 148$  horizontal grid points and has a grid spacing of 4 km. The integration period is from 0900 to 2400 Eastern Standard Time (EST; EST is 5 h behind GMT) on 28 February.

The MM5 was configured with the Kain–Fritsch convective parameterization (Kain and Fritsch 1993), the Medium Range Forecast (MRF) PBL scheme (Hong and Pan 1996), the simple ice microphysics scheme and a five-layer soil model for the land surface scheme. The MRF PBL scheme was chosen for computational efficiency to allow for timely delivery of forecast products. This choice is not necessarily a limitation for air quality studies,

as a comparison of CMAQ results using the MRF PBL scheme and the more complex Asymmetric Convective Model, or ACM (Pleim and Chang 1992), revealed little benefit from the ACM scheme (Elleman *et al.* 2003). Initial and boundary conditions for the MM5 forecasts are provided by the NCEP (National Centers for Environmental Prediction) ETA model on the 211 grid (80-km grid spacing). Boundary condition values are updated every 3 h.

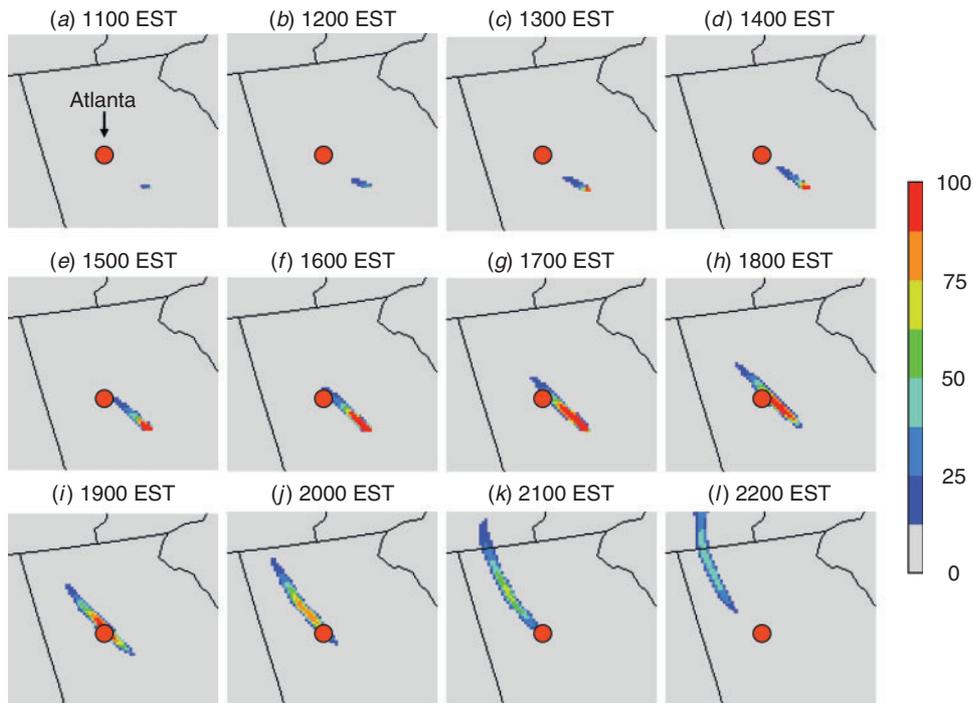
The MM5 outputs were processed through the Meteorology–Chemistry Interface Processor (MCIP) v2.2 for use of SMOKE and CMAQ. The MM5 vertical component of the grid was divided into 41 irregular layers, providing maximum resolution near the surface (minimum vertical grid spacing is 10 m). Initial and 6-hourly boundary conditions were provided by the NCEP reanalysis data.

CMAQ (v4.4) and SMOKE (v2.1) were used. The SMOKE inputs included  $PM_{2.5}$ ,  $PM_{10}$ ,  $SO_2$ , CO,  $NO_x$ ,  $NH_3$ , and volatile organic compound (VOC). The Carbon Bond-IV (CB-IV) chemical mechanism was used to simulate gas-phase chemistry in CMAQ. In CMAQ, the particle-size distribution is represented as the superposition of three log-normal subdistributions.  $PM_{2.5}$  is represented by two interacting subdistributions (or modes) of the nuclei or Aiken (i) mode and the accumulation (j) mode. The CMAQ vertical component of the grid was divided into 21 layers.

SHRMC-4S model performance was evaluated by comparing the reference simulation (SIMU1) results with satellite images and measured ambient  $PM_{2.5}$  concentrations. In SIMU1, emissions from the two burns were combined into a single burn. A total of  $\sim 1225$  ha ( $\sim 3000$  acres) of fuels was burned from 1100 to 1500 EST. This simulation was analysed to understand the smoke incursion processes and the air quality effects, and

**Table 1. Burn and emission in simulations**

Simulation	Burning period	Emission location	Emission amount
SIMU1	1100–1500 EST	Emissions from Oconee National	Calculated
SIMU2	Same as SIMU1	Forest and Piedmont National	50% less
SIMU3	Same as SIMU1	Wildlife Refuge were released at the	50% more
SIMU4	3 h earlier	Oconee National Forest location	Same as SIMU1
SIMU5	3 h later		Same as SIMU1
SIMU6	Same as SIMU1	Equally split between the two locations	Same as SIMU1



**Fig. 5.** Simulated spatial distribution of ground  $PM_{2.5}$  concentrations (in  $\mu g m^{-3}$ ) from SIMU1. Panels (a–l) are each hour during 1100–2200 EST. Horizontal and vertical directions indicate east–west and north–south, respectively.

evaluate SHRMC-4S performance. Also, three other simulations (SIMU2–SIMU6) were conducted to evaluate SHRMC-4S predictions on air quality and sensitivity to emissions. SIMU2 and SIMU3 are the same as SIMU1 except with 50% smaller and larger emissions, respectively (see Table 1). SIMU4 and SIMU5 are the same as SIMU1 except with a burning period 3 h earlier and later, respectively. SIMU6 is the same as SIMU1 except that two burning locations are considered, each with half of the total emissions. It should be kept in mind that the Oconee NF did emit a greater amount of emissions for a longer time-period than the Piedmont NWR prescribed fire (Fig. 2).

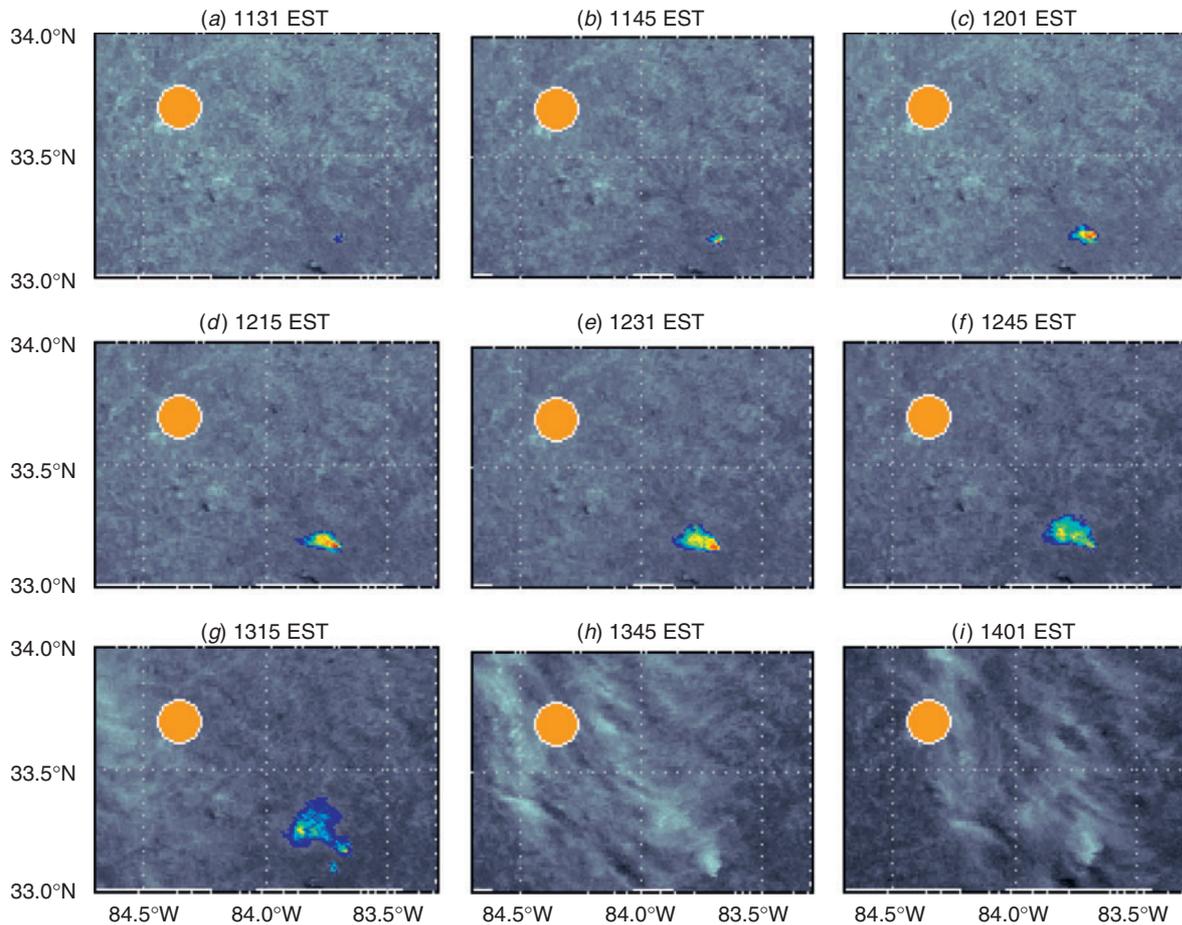
**Results**

*Plume incursion*

Fig. 5 shows simulated spatial patterns of a smoke plume indicated by distributions of ground-layer  $PM_{2.5}$  concentrations

from SIMU1. Note that only a portion of the simulation domain is shown in order to have a zoom-in view of smoke plumes. The incursion of smoke plumes into Atlanta is clearly caught in the simulation. At 1100 EST, a smoke plume moves westward but, starting from 1200 EST, it turns clockwise gradually toward the north-west. The plume heads directly towards Atlanta at 1400 EST. It moves across Atlanta during 1500–2100 EST with its core (the portion of plume with the largest  $PM_{2.5}$  concentrations) passing over Atlanta at ~1700 EST. The core moves further north-west in the next few hours and reaches the Georgia–Tennessee border at midnight.

Satellite images confirm that the simulated shift in the smoke transport direction from westward to north-westward actually occurred. Fig. 6 shows the GOES images between ~1130 and 1400 EST with an interval of 15 or 30 min. In this figure, the smoke masks are presented by blue-red false color. It is scaled according to the reflectance from the visible channel, which



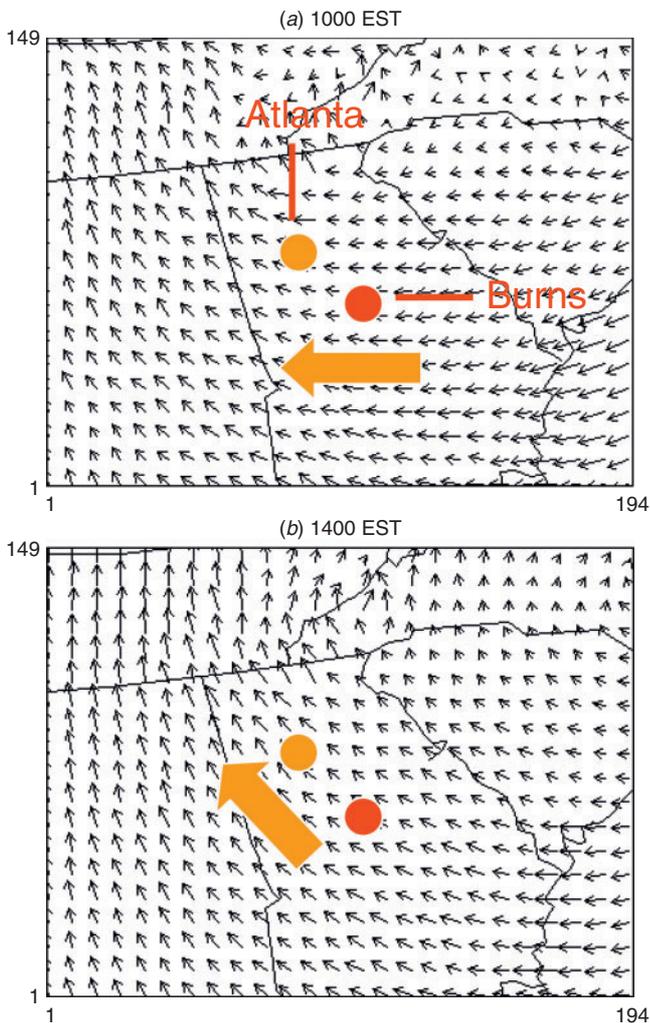
**Fig. 6.** Geostationary Operational Environmental Satellite (GOES) images. Panels (a–i) are at different times during 1130–1400 EST with an interval of 15 min or 30 min. Atlanta is located at the yellow dot. Horizontal and vertical directions indicate east–west and north–south, respectively.

represents the density of smoke plumes with highest density in red and lowest density in blue. The background images are the reflectance from the visible channel in gray-scale. The location of Atlanta is symbolized by the orange dot. The images present the dispersion of a smoke plume at the burn site of the Oconee NF  $\sim$ 1130 EST (panel *a*). The plume expands in size and propagates west by 1145 EST (panel *b*). The shift in the smoke direction from west to north-west occurs at 1200 EST (panel *c*). This trend continues while the smoke plume expands further in size as seen from three images during the next hour (panels *d–f*). The heavy smoke plume (bright part in the image) continues in the same direction at 1315 EST (panel *g*), but smoke on the right side of the plume disperses northward. Meanwhile, another plume at the Piedmont NWR appears and is located south-west of the Oconee NF burn site. In the last two scenes (panels *h* and *i*), smoke plumes are mixed with high clouds. As a result, we cannot distinguish the smoke plumes from the high clouds given the data from only one visible band. However, we still can visually tell the approximate range of the smoke plumes, which continuously expand north-west, although no satellite images are provided at the time when smoke reached metropolitan Atlanta.

The simulated shift of the smoke plume  $\sim$ 1200 EST resulted from the change in the atmospheric circulation simulated with

MM5. The MM5 forecast captured the observed general structure of the atmosphere quite well for this case. The burn location was in the warm sector ahead of an advancing cold front that would impact the area on the following day. Examination of the 0Z sounding for 1 March from Peachtree City (not shown) shows  $2.5 \text{ m s}^{-1}$  (5 knot) winds from the south-east veering to westerly at  $15 \text{ m s}^{-1}$  (30 knots) near 500 hPa. MM5 with no strong inversions were shown below this height. MM5 produced a similar wind structure with the exception of stronger low-level flow ( $5.0\text{--}7.5 \text{ m s}^{-1}$ , 10–15 knots) initially from the east-south-east, which caused an increase in low-level (below 850 hPa) moisture a few hours earlier than observed. This addition of moisture dropped the lifting condensation level to 827 hPa compared with 676 hPa for the observed sounding.

In the morning hours of the burn day, there was a high-pressure system (anti-cyclone circulation, that is, air flows counter-clockwise) on the mid-Atlantic coast. Georgia was in the south-western portion of the system (Fig. 7*a*). The airflows moved westward over central Georgia (located in the bottom portion of the simulation domain) and toward the north-west over Alabama (located in the western portion of the domain). The system, however, moved east in the early afternoon (Fig. 7*b*). As a result, airflows turned toward the north-west over central



**Fig. 7.** Ground wind vectors simulated by National Center for Atmospheric Research and Penn State Mesoscale Model (MM5) at 1000 EST (a); and 1400 EST (b). Horizontal and vertical directions indicate east–west and north–south, respectively.

Georgia. It was this change in airflow direction that led to the shift in smoke plume transport and dispersion direction.

*Plume structure*

Fig. 5 shows that the length of the smoke plume increases with time, whereas its width does not change much. The portion of the plume with  $PM_{2.5}$  concentrations of  $10 \mu g m^{-3}$  is  $\sim 140$  km long and 24 km wide at the time when the plume core approaches Atlanta. The length is almost doubled but the width remains approximately the same by 2200 EST. In addition, the plume appears as a straight line in the first few hours, but slightly curved in later hours. This agrees with the change in wind direction. The simulation (SIMU1) may suggest that smoke particles were transported mainly by the prevailing winds, while dispersion due to turbulence and eddy activity was insignificant.

The height of the smoke plume changes with time. Fig. 8 shows the hourly vertical profile of  $PM_{2.5}$  concentrations above

the ground. It is calculated with the following steps. At each hour, a grid point in the simulation domain with the largest concentration on the ground layer is identified; an average over nine grid points around this point is obtained, and similar averaging is obtained for each of the layers over the point. The entire period can be divided into two stages. The first one is the burning period up to 1500 EST. Particulate matter and other smoke components are emitted continuously throughout this stage. The ground  $PM_{2.5}$  concentrations therefore gradually increase owing to accumulation of emissions over time. Smoke particles are ejected to a height of just below 1 km. The second stage is the post-burning period. Without further emissions, the ground  $PM_{2.5}$  concentrations gradually decrease with time. The height of the smoke plume reduces rapidly by approximately half during the first 2 h of this stage and remains little changed thereafter. But it increases a little after 2100 EST, probably owing to the elevated topography at the Georgia–Tennessee border.

*Air quality effects*

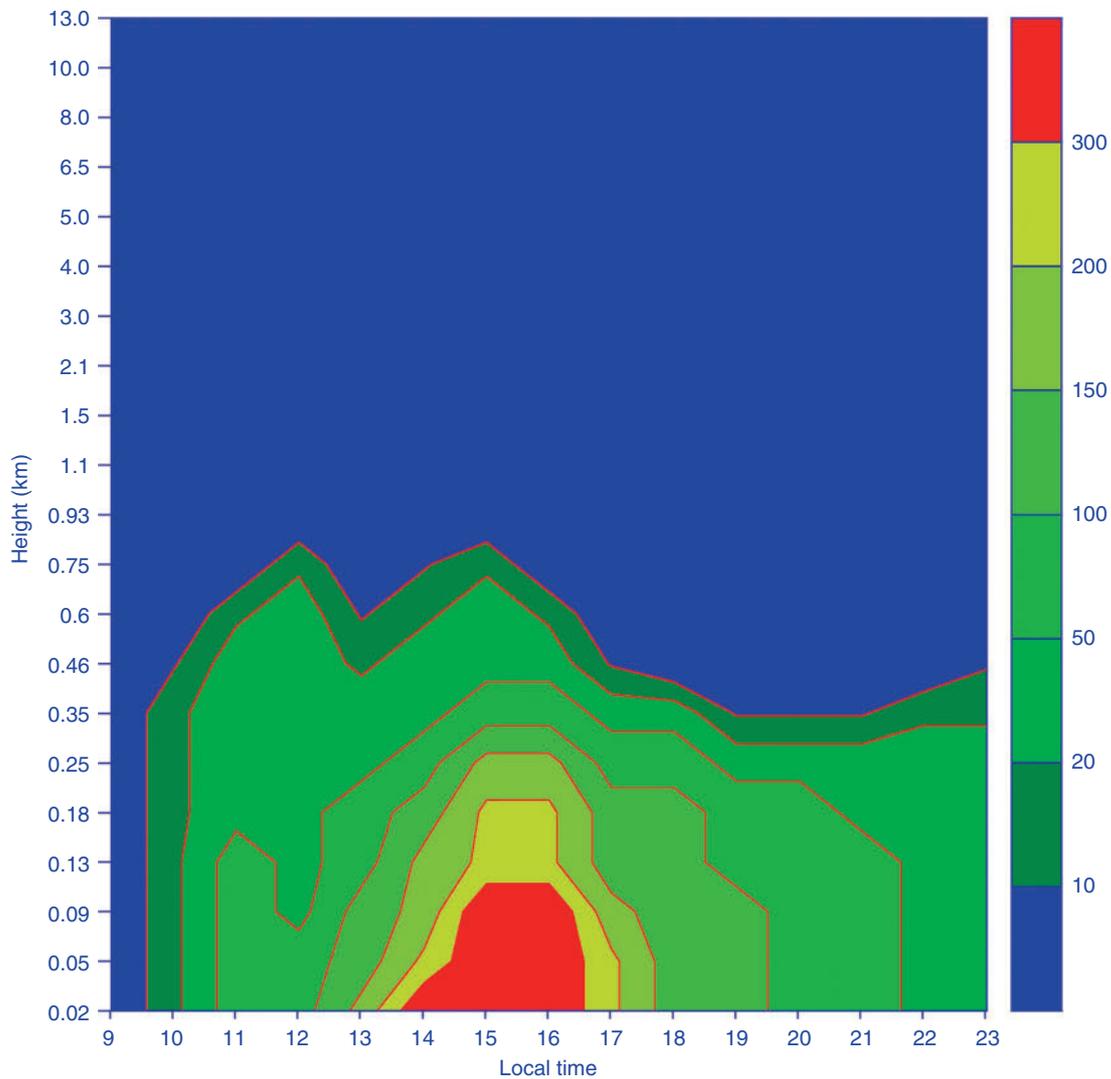
Fig. 9 shows temporal variations of ground  $PM_{2.5}$  concentrations at the three metropolitan Atlanta locations of McDonough, South DeKalb, and downtown Atlanta (see Fig. 1 for their locations). The measured concentrations at the monitors include the influence of typical daily emissions sources (vehicles, coal-fired power plants, etc.) and the emissions from prescribed fires (Fig. 1a). McDonough is approximately half-way from the burn site to Atlanta and South DeKalb is east of Atlanta and north of McDonough. The smoke plume approaches these locations in the early afternoon. The largest concentrations are above  $125 \mu g m^{-3}$  at 1700 and 1800 EST for McDonough, and  $\sim 100 \mu g m^{-3}$  at 1800 and 1900 EST for South DeKalb and downtown Atlanta.

Fig. 10 shows ground measurements at these locations. The largest ground  $PM_{2.5}$  concentrations are  $140\text{--}150 \mu g m^{-3}$  at 1700 EST for McDonough, 1900 EST for South DeKalb, and 1900 and 2000 EST for downtown Atlanta. Thus, there is general agreement in the magnitude and peak time in  $PM_{2.5}$  concentrations between the simulation and measurements. However, the simulated concentrations are smaller and the peak times are  $\sim 1$  h earlier at South DeKalb and downtown Atlanta. In addition, the measurements show a second peak at 2300 EST at McDonough, which is missed in the simulation.

The NAAQS for the daily (24-h) mean ground  $PM_{2.5}$  standard is exceeded when the 3-year average of the annual 98th percentile value is greater than or equal to  $35 \mu g m^{-3}$ .  $PM_{2.5}$  concentrations exceeding the NAAQS are of concern because they indicate people’s health may have been adversely impacted. On 28 February 2007, the hourly concentrations of fine particles were between  $80$  and  $150 \mu g m^{-3}$ , which could have caused some people who are sensitive to air pollutants to experience short-term health problems.

*Other burning simulations*

In the experimental simulations of 50% smaller (SIMU2) and larger (SIMU3) emissions, the simulated time when the plume arrives at Atlanta is the same as that in SIMU1, but the ground



**Fig. 8.** Vertical profile of simulated  $\text{PM}_{2.5}$  concentrations (in  $\mu\text{g m}^{-3}$ ) from SIMU1 over the plume core at each hour during simulation.

$\text{PM}_{2.5}$  concentrations are  $\sim 50\%$  smaller and larger, respectively (Fig. 11). This indicates a nearly linear relation between the intensities of emissions and  $\text{PM}_{2.5}$  concentrations.

In the experimental simulations of burning starting 3 h earlier (SIMU4) or later (SIMU5), the smoke plumes also invade metropolitan Atlanta (Figs 12 and 13), but there are positive responses regarding the severity of the air quality effects. Atlanta is among the major USA metropolitan cities with poor traffic conditions for people commuting to and from work. As seen above, the smoke plume core in SIMU1 reaches downtown Atlanta at 1900 EST during the evening rush-hour traffic, affecting commuters by reducing visibility and causing problems with breathing. In SIMU4, a large portion of particles is emitted before the shift in wind direction. This portion would not be transported to metropolitan Atlanta. The other portion of emissions after the shift reaches Atlanta at the same time as those in SIMU1 (Fig. 12), but produces much smaller concentrations

(Fig. 11), which could have reduced the impacts in the Atlanta urban area on visibility and people's breathing. In SIMU5, smoke particles are emitted later than those in SIMU1. Therefore, the smoke plume core reaches Atlanta at a later time (in the late evening). With almost all smoke particles being transported northward, the concentrations at Atlanta are a little larger than those in SIMU1. Nevertheless, the effects on traffic and breathing conditions are expected to be less severe because the rush hour is already over. Thus, severity of the air quality effects of the smoke plume is less in both SIMU4 and SIMU5 cases than in SIMU1.

The experiment in which burning occurs at two separate locations (SIMU6) produces almost the same results as SIMU1 (Fig. 11). Only a small difference occurs in the first couple of hours, when there are two smoke plumes instead of one in SIMU1 (spatial pattern of smoke plumes simulated in SIMU6 not shown).

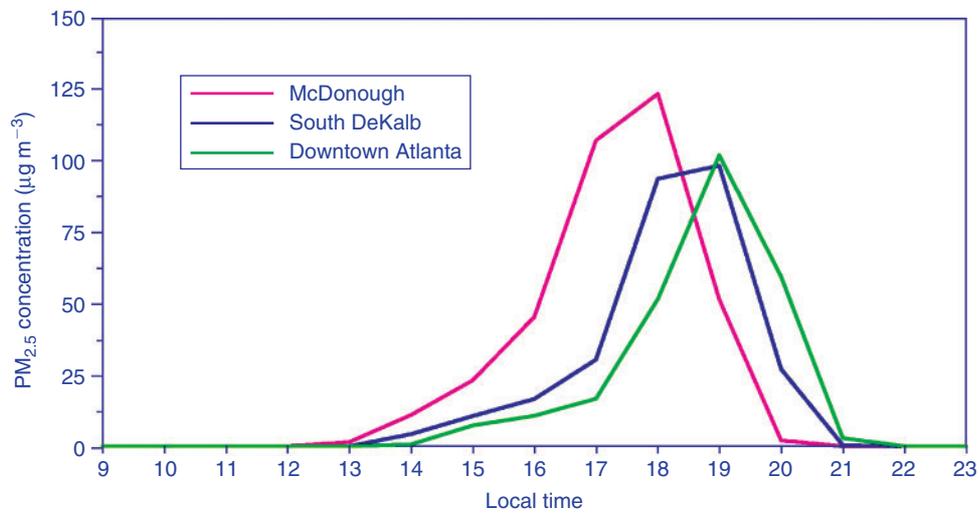


Fig. 9. Simulated temporal variations of ground PM<sub>2.5</sub> concentrations (in µg m<sup>-3</sup>) at three metropolitan Atlanta sites from SIMU1.

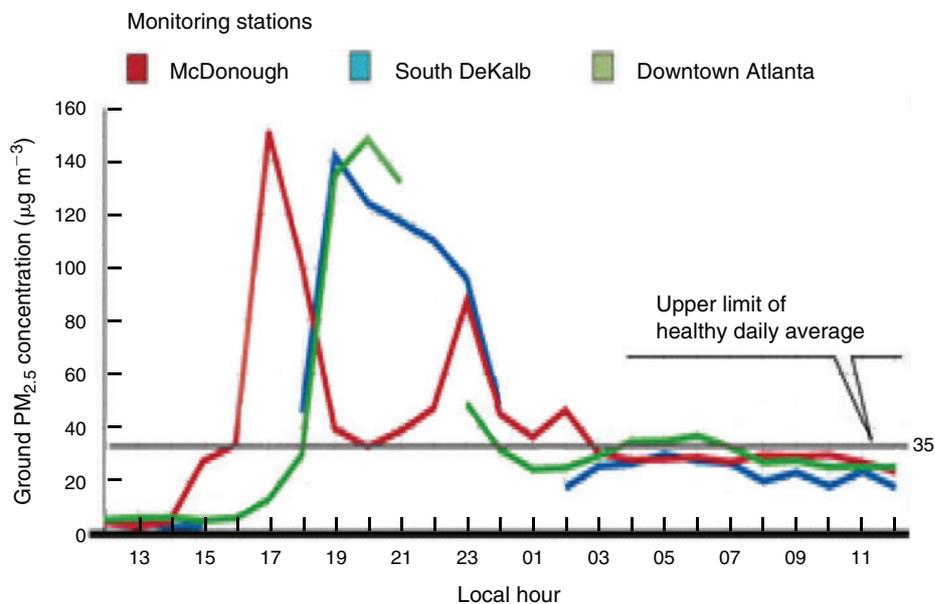
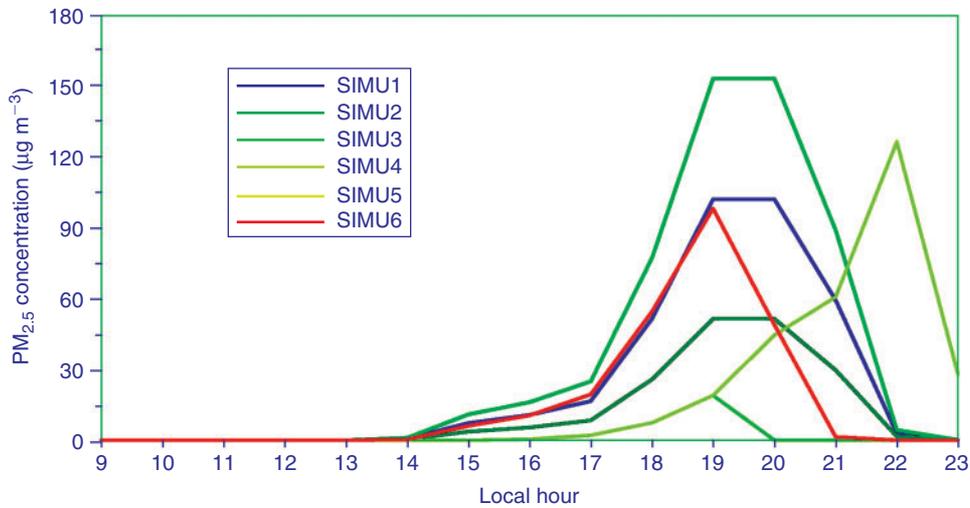


Fig. 10. Same as Fig. 8 except for measurements.

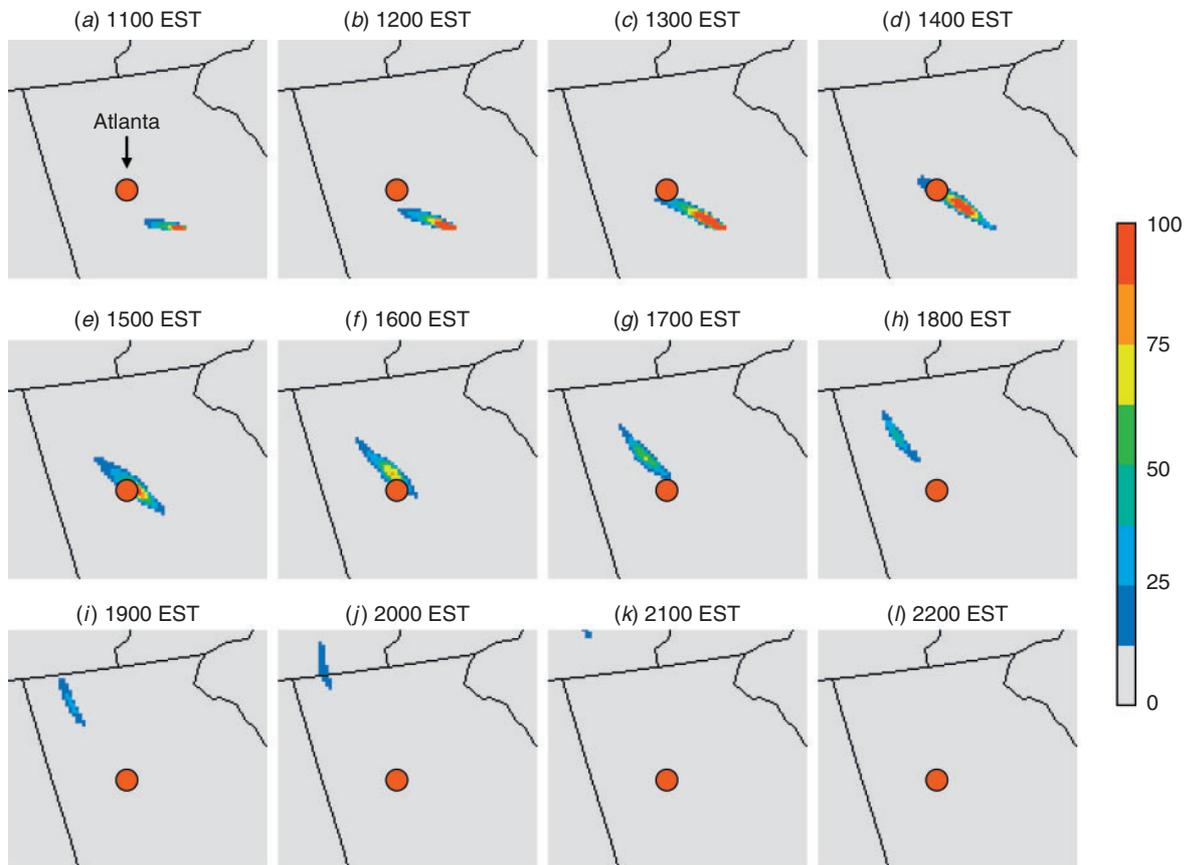
**Concluding remarks**

Simulations have been conducted for prescribed burning in central Georgia on a late-winter day of 2007 with SHRMC-4S. The major findings are:

- (1) The simulated smoke plume from the burn impacted metropolitan Atlanta during the evening rush hour owing to the amount of fuel consumed and a shift in prevailing wind direction at burning sites at approximately noon;
- (2) The simulated smoke plume appears as a belt horizontally. It rises to a height of nearly 1 km during the burning stage and rapidly reduces by approximately half thereafter;
- (3) The smoke plumes cause severe air quality problems in Atlanta with the ambient hourly PM<sub>2.5</sub> concentrations greater than 80 µg m<sup>-3</sup> for several hours;
- (4) The simulated shift in smoke transport direction, which leads to the smoke plume incursion into metropolitan Atlanta, and the air quality effects are in general agreement with the satellite and ground measurements;
- (5) The air quality effects in Atlanta are nearly linearly proportional to the intensity of fire emissions; and
- (6) The severity of the air quality effects due to the smoke plume incursion can be reduced by altering burn start time. Change in burn number from one to two while keeping the same total



**Fig. 11.** Simulated temporal variations of ground PM<sub>2.5</sub> concentrations (in µg m<sup>-3</sup>) at downtown Atlanta from six simulations.



**Fig. 12.** Same as Fig. 5 except for SIMU4.

burned area and plume rise, however, has little impact on the simulation of smoke incursion and the air quality effects.

Smoke modeling tools are necessary for predicting such incursion events and the resultant air quality consequences. The

results from the present study suggest that SHRMC-4S could be a useful tool to help fire and air quality managers in planning prescribed burning. In the future, the authors plan to utilize SHRMC-4S to simulate the actual emissions profile (Fig. 2) along with other smoke management techniques. For example,



Fig. 13. Same as Fig. 5 except for SIMU5.

starting the burn 3 h earlier was not possible on 29 February 2007 because the fuel moisture would have been too high for the vegetation to ignite. Other reasonable scenarios to evaluate include:

- (1) Evaluating the air quality impacts if only the Oconee NF or Piedmont NWR prescribed fire were conducted on 28 February 2007. It is possible that removal of one of the burns may have resulted in minimal impacts to the air quality in the Atlanta area.
- (2) Starting the Piedmont NWR burn at 1000 hours and then beginning the Oconee NF prescribed fire at 1200 hours when the Piedmont NWR was completed.
- (3) Starting the Oconee NF burn at 1000 hours and then beginning the Piedmont NWR prescribed fire at 1500 hours when the Oconee NF was completed.
- (4) Evaluating what combination of fuel consumption and hectares burned per hour would have resulted in minimal air quality effects to Atlanta with the meteorological conditions present on 28 February 2007.

There are other remaining issues with SHRMC-4S. First of all, fuel consumption is an important factor for emissions and smoke properties. Second, plume rise is another important factor; no evaluation of plume rise calculations is given. Third, the simulated lateral smoke dispersion seems weaker than that detected by satellite, as indicated above. And finally, local

circulations caused by topography and urban heat island effects can impact smoke transport and dispersion. Further studies are needed to understand these issues.

**Acknowledgements**

The ground measurement and satellite data were obtained from the Georgia Environmental Protection Division, and National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA), respectively. The present study was supported by the USDA Forest Service National Fire Plan 01-SRS-A-1, the USDA Cooperative State Research, Education, and Extension Service under grant number 2005-35112-15325, the US EPA STAR program under grant number RD-83227601, and the USDA SRS Cooperative-Agreement with George Mason University. We would like to thank two anonymous reviewers for their useful comments and suggestions.

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Manuscript received 29 May 2007, accepted 24 June 2008