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Important parameters for smoke plume rise simulation with Daysmoke

Yongqiang Liu [1], Gary L. Achtemeier [1], Scott L. Goodrick [1], William A. Jackson [2]

[1] *Center for Forest Disturbance Science, USDA Forest Service, 320 Green St., Athens, GA 30602*
[2] *USDA Forest Service, 160A Zillicoa St., Asheville, NC 28802*

ABSTRACT

Daysmoke is a local smoke transport model and has been used to provide smoke plume rise information. It includes a large number of parameters describing the dynamic and stochastic processes of particle upward movement, fallout, fluctuation, and burn emissions. This study identifies the important parameters for Daysmoke simulations of plume rise and seeks to understand their impacts on regional air quality simulations with the Community Multiscale Air Quality (CMAQ) model. The Fourier Amplitude Sensitivity Test (FAST) was first applied to Daysmoke simulations of prescribed burning in the southeastern U.S. It is shown that, for the specified value ranges of 15 parameters, entrainment coefficient and number of updraft cores are the most important for determining smoke plume rise. Initial plume temperature anomaly, diameter of flaming area, and thermal stability also contribute to a certain extent. CMAQ simulations were then conducted for a couple of different updraft core numbers. The simulated ground $PM_{2.5}$ concentration is much closer to the measurements with multiple updraft cores than single core. The results from this study therefore suggest that simulations of Daysmoke and CMAQ could be improved by a better understanding of plume structure to aid in specifying the number of smoke updraft cores.

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Corresponding Author:
Yongqiang Liu
Tel: +1-706-559-4240
Fax: +1-706-559-4317
E-mail: yliu@fs.fed.us

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1. Introduction

Emissions from wildland fires are an important source of atmospheric air pollutants. When regional air quality modeling systems such as the Community Multiscale Air Quality (CMAQ) (Byun and Ching, 1999; Byun and Schere, 2006) were first used to simulate the air quality impacts of wildland fires, fire emissions were treated as area sources, meaning that emissions are distributed only at the lowest model layer. However, smoke from wildland fires can be injected at heights reaching up to a few kilometers above the ground, indicating that smoke emissions are point sources. This difference in how fires are represented in the simulations can substantially affect simulated surface smoke concentrations (e.g., Liu et al., 2008).

As point sources, smoke plume rise and vertical distribution are required as initial and boundary conditions for CMAQ. The early version of the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE v2.0) (Houyoux et al., 2002), an emission processing model for CMAQ, provides plume rise schemes, including the Briggs scheme (1971; 1975). This scheme is a two–thirds law integral model based on differential equations governing fluxes of mass, momentum and energy through a plume cross section (Weil, 1988). The foundation for this type of model was laid by Morton et al. (1956). The major factors are initial buoyancy flux, wind, stability, convective velocity scale, and exit velocity. These formulations have been successful at describing plume rise in cases where buoyantly produced turbulence due to the plume dominates over ambient turbulence in the flow (e.g., power plant stacks). However, this condition is not met under most conditions for fires. Mechanical turbulence generated at the earth's surface can be of similar magnitude to the buoyantly produced turbulence of the fire.

The recent version of SMOKE (v2.4) adds the WRAP and BlueSky–EM approaches. The Western Regional Air Partnership (WRAP) approach uses a climatological method by specifying a pre–defined plume bottom and plume top and a pre–defined diurnal temporal profile for each fire (WRAP, 2005). The plume top and bottom are simply a function of the fire size in virtual acres. A smoldering fraction is used to estimate the emissions placed in layer 1. This method results in a "gap" in the vertical distribution of emissions, with a portion in layer 1 and the remaining portion several layers above that and disjoint from layer 1. Additionally, the plume bottom and top heights are calculated independently from any dynamic meteorological data. The BlueSky–EM approach estimates the heat flux from each fire, which has been converted to a buoyancy flux suitable for use with the Briggs plume rise algorithm (Pouliot et al., 2005a). Many recent studies, however, reported that, even with Briggs scheme currently available in SMOKE and other fire emission process models, CMAQ and other air quality prediction systems often under–predicted plume rise and therefore over–predicted surface $PM_{2.5}$ concentrations. For example, the National Oceanic and Atmospheric Administration's Smoke Forecasting System showed a tendency to over–predict the measured $PM_{2.5}$ concentrations in the western United States during September 2006 – November 2007 (Stein et al., 2009). The prediction was very sensitive to the injection height of fire emissions. Raffuse et al. (2009) found that the simulated heights of smoke plume with the Briggs scheme was systematically lower than the detected values from the Multi–angle Imaging SpectroRadiometer (MISR) and the Cloud–Aerosol Lidar and Infrared Pathfinder. Fire emission and released sensible heat calculation is one of the major uncertainties in plume rise estimate and air quality simulation (Pouliot et al., 2005b). In addition, biomass burning also releases water; evaporation of the water releases latent heat energy, which may enhance buoyancy and overcomes the entrainment effects. As a result, actual plume rise could be higher. It is a big challenge to accurately estimate fire emission and heat release and properly describe them in a plume rise model like Briggs scheme.

There are also smoke plume rise schemes developed for smoke and regional air quality modeling. A one–dimensional dynamic entrainment plume model (Latham, 1994; Freitas et al., 2007) was developed to explicitly simulate smoke plume rise and was modified recently to include the impacts of winds (Freitas et al., 2009). An extended set of equations, including the horizontal motion of the plume and the additional increase of the plume size, is solved to explicitly simulate the time evolution of the plume rise and determine the final injection layer. A scheme for Calpuff dispersion modeling system (Scire et al., 2000) has a number of modifications to the traditional integral model to better simulate large–area buoyant sources such as forest fires. These improvements included the ability to use a variety of wind/temperature profiles, any size emission source, plume radiative heat loss, and removes assumptions regarding plume versus ambient density (Boussinesq approximation). However, this improved formulation assumes a circular distribution of plume quantities about a plume centerline at any given time. This assumption may not be valid as burning conditions, and therefore plume dynamics, can have substantial spatial variability as different parts of the fire move through different phases of combustions and/or fuel parameters change.

A local smoke model, Daysmoke (Achtemeier et al., 2007), was developed specifically for prescribed burning, which is a management tool extensively used in the southeastern U.S. for reducing accumulation of understory debris and maintaining ecosystem health. Daysmoke itself is a smoke transport and dispersion model for simulating three–dimensional local smoke distributions and their temporal variations (Achtemeier et al., 2006). It can also be used to estimate smoke plume rise for CMAQ simulations. It was shown in a Florida prescribed burn study that both Daysmoke and Briggs scheme derived plume rise information improved smoke and air quality simulations, but plume rise calculated with Daysmoke was smaller than that with the Briggs scheme, which led to larger ground level $PM_{2.5}$ (particulate matter with a size not greater than 2.5 μm) concentrations (Liu et al., 2008). This is related to the difference between fire smoke plumes and power plant stacks. For example, fire smoke plumes usually are much larger in size and located at ground level. Thus, their interactions with the ambient atmosphere through entrainment are more significant. This would suppress the upward motion and therefore lead to small plume rise.

It is essentially important to understand uncertainty in Daysmoke modeling of smoke plume rise. A useful approach to achieve this is to analyze sensitivity of Daysmoke plume rise simulations to model parameters that were specified without observation and/or solid physical basis. Daysmoke is a dynamic and stochastic model that uses a large number of parameters to represent fuel and burn properties, emissions, smoke plume upward and downward movements, and atmospheric conditions. Some parameters are obtained from measurements or simulations, while others are specified empirically. Some may play more important roles than others. Identifying these important parameters and analyzing their properties is useful for understanding uncertainty in Daysmoke simulations of smoke plume rise and its potential impacts on CMAQ air quality simulations.

This study explores the sensitivity of smoke plume rise modeling and its impacts on regional air quality modeling. Smoke plume rise is estimated using Daysmoke simulations for a prescribed burn case in the southern U.S. Sensitivity is analyzed using the Fourier Amplitude Sensitivity Test (FAST) to identify those parameters that most significantly affect smoke plume rise simulations. The impact on air quality modeling is investigated by conducting CMAQ simulations of the burn case with various values of the identified parameters. The methods are described in Section 2. Results are presented and discussed in Section 3, and conclusions are given in Section 4.

2. Methods

2.1. Burn case

A prescribed burning was implemented in Brush Creek, Tennessee (TN) on March 18, 2006 by the Cherokee National Forest of the U.S. Forest Service. The burn site is near the border with North Carolina (NC) and about 50 km northwest of Asheville, NC. The Brush Creek unit is 7.45 km^2 (1 840 acres) of woodland, but the firing pattern was to result in a mosaic type burn with fuels being consumed in about 90 percent of the area 6.7 km^2 (about 1 656 acres). The unit never had a prescribed fire, nor had a wildfire occurred recently. Fuel consumption for the unit was estimated as approximately 3 kg km^{-2} (12 tons per acre) burned. Aerial ignition occurred along the main and spur ridges between 1220 and 1400 U.S. east standard time (EST, same hereafter) and then further ignition was accomplished between 1620 and 1710. Between 1400 and 1620 the fire moved down the side slopes until no fuels were available to ignite. This burn case has been documented and simulated with VSMOKE and Daysmoke (Jackson et al., 2007; Achtemeier et al., 2006).

2.2. Daysmoke

The 2006 version of Daysmoke (Achtemeier et al., 2007) was used. It is an extension of ASHFALL, a plume model developed to simulate deposition of ash from sugar cane fires (Achtemeier, 1998). Daysmoke consists of four sub–models: (a) Entraining turret plume model (ETM). 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 and vertical velocity, effective diameter, and entrainment. (b) Detraining particle trajectory model (DTM). Movement within the plume is described by the horizontal and vertical wind velocity within the plume, turbulent 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 absolute value of large eddy velocity exceeds plume rise rate. (c) A large eddy parameterization (LED). 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 transported by the mean wind in the PBL. (d) Relative emissions production model (REM). The total fuel load consumed was estimated as predicted with CONSUME 3.0 (Ottmar et al., 1993). 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). Particles passing a "wall" three miles downwind from a burn were counted for each hour during the burning period. A percent of particle number at each layer relative to the total particle number was assigned to SMOKE/CMAQ simulations.

One issue with Daysmoke is that it has not been systematically evaluated against measurements. Evaluation was not conducted in this study because no plume rise measurements were available for the Brush Creek burn. Here we use a measurement of smoke plume from another prescribed burn (Tsai et al., 2009) to have a brief comparison with Daysmoke simulation of smoke plume rise. The measurement displayed in Figure 1 was a 40–minute Radar reflectivity at Ft Benning, Georgia on April 15, 2008. There were no ground measurements that could be used to evaluate Daysmoke simulation of smoke concentrations. Three plumes were detected by Radar. All had the height about 1.5 km. The plume rise simulation with 10 updraft cores is 1.5 km, matching the measurement well for this specific case. On the other hand, the first plume detected by Radar showed two elevations of larger reflectivity (higher smoke concentrations) near the bottom and top layers of the smoke. Similar vertical structure was seen in the two other plumes. The simulated smoke vertical profile has two larger peaks too, one near the ground, and the other around 0.75 km. The latter one, however, seems lower than the corresponding height in the Radar measurement.

2.3. FAST analysis

Many sensitivity analysis techniques are available. They can be divided into two types based on the number of parameters to be examined. The most commonly used one is so called "change and response" method, which obtains different model outputs in response to changes in a single parameter. This gives a quantitative estimate to the dependence of the simulated property on the parameter. The other type obtains different model outputs in response to changes in a group of parameters. This technique is often used to identify the most important parameters for the model.

The FAST analysis used for this study is a technique for a group of parameters. It was introduced by Cukier et al. (1970). In FAST, the input parameters are varied simultaneously through their ranges of possible values following their given probability density functions (i.e., values which have a greater probability are chosen more often). All input parameters are assumed to be mutually independent and each is assigned a different frequency, which determines the number of times that the entire range of values is traversed. With each input parameter oscillating at a different characteristic frequency, a different set of input parameter values is obtained for each model run with every value used once. The mean and variance, which characterize the uncertainty due to the variability of the input parameters, are calculated for model output parameters. Fourier analysis of each output for all model runs is used to separate the response of the model to the oscillation of particular input parameters. Summation of those Fourier coefficients corresponding to a particular input parameter frequency and its harmonics determines the contribution of that input parameter to the model output variances. Finally, by scaling the relative contribution of the input parameters to the total variance, partial variances are obtained, which show the sensitivity of model output parameters to the variation of individual input parameters in terms of a percentage of the variance. The Fourier coefficients corresponding to input parameter frequencies and their harmonics do not account for the total variance of the model outputs. The Fourier coefficients corresponding to linear combinations of more than one input parameter frequency account for the remaining percentage of the variance, which can be attributed to the combined influences of two or more parameters.

In comparison to other techniques, e.g., Monte Carlo and Latin Hypercube Sampling (McKay et al., 1979; Derwent, 1987), the advantages of FAST technique are evident considering that, for instance, it requires only 1 027 runs for a model with 15 input parameters. For comparison, if 10 values would be used within the range of all input parameters, a total of 10^{15} model runs would be needed with a stratified sampling technique. Moreover, FAST provides information on the model sensitivity to particular input parameters, unlike other techniques for sensitivity analysis. A complete description of the theory and implementation of FAST and approximations used in computer implementation, mainly following Cukier et al. (1970) and Uliasz (1988), is given in Liu and Avissar (1996; 1999).

2.4. CMAQ simulation

CMAQ (v4.4) and SMOKE (v2.1) were used, same as a recent prescribed smoke case simulation (Liu et al., 2009). The SMOKE inputs included $PM_{2.5}$, PM_{10}, SO_2, CO, NO_X, NH_3, and 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 lognormal sub–distributions. $PM_{2.5}$ is represented by two interacting sub–distributions (or modes) of the nuclei or Aitken (i) mode and the accumulation (j) mode. The CMAQ vertical component of the grid was divided into 21 layers. The model domain covers parts of the southeast U.S. states of TN, NC, South Carolina (SC), and Georgia (GA) with a resolution of 4 km. The integration period was from 0900 to 2400 on March 18, 2006.

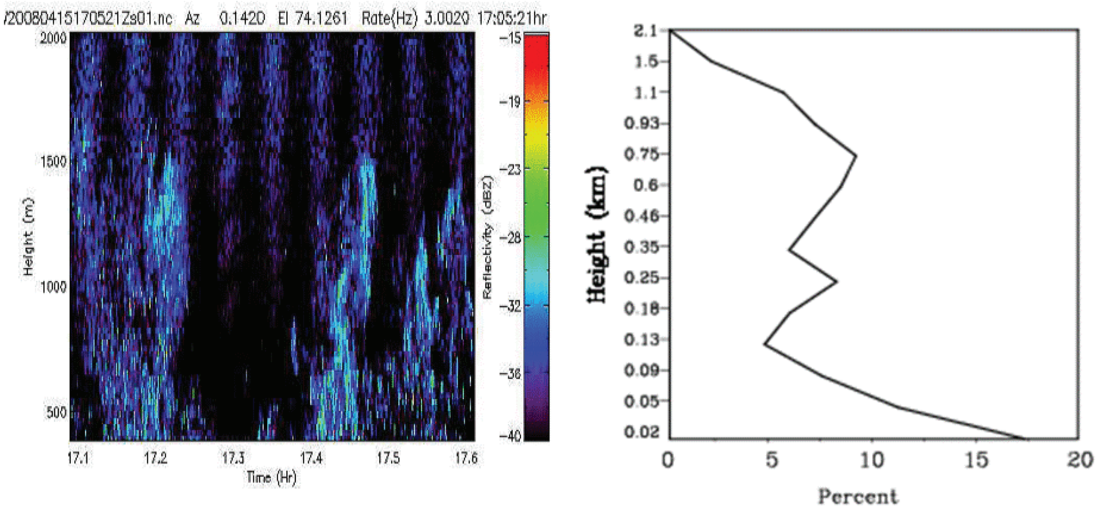

Figure 1. *Smoke plume structure at Ft Benning, Georgia on April 15, 2008 measured by a Radar (left) and simulated with daysmoke (right). The Radar image was from Tsai et al. (2009).*

The meteorological conditions for CMAQ and Daysmoke simulations were simulated with the National Center for Atmospheric Research/Penn State mesoscale meteorological model (MM5) (Grell et al., 1994). MM5 was configured with the Kain and Fritsch (1993) convective parameterization, the Medium Range Forecast (MRF) planetary boundary layer (PBL) scheme (Hong and Pan, 1996), and the simple ice microphysics scheme and a 5–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). 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 boundary conditions for the MM5 simulations were provided by the National Centers for Environmental Prediction (NCEP) ETA model on the 211 grid (80 km grid spacing). Boundary condition values were updated every 3 hours. The MM5 outputs were processed through the Meteorology–Chemistry Interface Processor (MCIP) v2.2 for use of SMOKE and CMAQ.

3. Results and Discussion

3.1. Most important parameters

Fifteen parameters in Daysmoke were selected for the FAST analysis (Table 1). One of them used in ETM is entrainment coefficient, C_e, which measures how intense the ambient air interacts with the plume. Because the ambient air is cooler relative to the plume, the interaction will suppress the vertical development of the smoke plume. Thus, the stronger the interaction is, the lower the plume rise is. Sophisticated schemes are needed to describe the interactions which include complex smoke plume and turbulent and eddy processes occurring across multiple space and time scales (e.g., Latham, 1994; Freitas, 2007). However, a constant coefficient is often used as a first approximation. For example, Briggs (1975) gave different values for several types of power plant stack plumes. A value of 0.18 was used in Daysmoke.

Seven parameters in DPM, C_p, C_u, C_w, K_x, K_z, W_c and $w*$, determine the fallout processes of smoke particles from the plume. These processes are controlled by turbulence, stability, and gravity. One parameter in LED, W_r, measures the impact of large eddies on smoke plumes. Their values were specified mostly based on empirical understanding of the related processes instead of measurements.

Three out of four parameters in REM, W_0, dT, and D_f, were computed based on burning information. Initial plume vertical velocity and temperature anomaly measure the intensity of a burn. Diameter of flaming area measures total released energy. Another one, number of updraft cores, N_c, was specified. The concept of smoke updraft core number was described in Achtemeier et al. (2006; 2007). A single smoke plume may consist of several updraft cores (Figure 2). They result from multiple ignitions at different locations within a burning site, smoke interactions, and other processes. The number of updraft cores can change with time and vertical level. There might be no clear separation between two adjacent updraft cores in some cases. Number of updraft cores is related to effective diameter of flaming area in Daysmoke using the formula $D_f = [4F/(c \pi N_c)]^{1/3}$, where F is the volume flux and c is a constant. A larger N_c leads to a smaller D_f and lower plume rise. Two ambient parameters, thermal lapse rate T_z and background wind speed V, were obtained from meteorological simulations.

Some parameters may depend on others, as seen from the relation between D_f and N_c. Modifications were made so that the parameters become independent to each other as required by the FAST analysis. The ranges of all parameters for the FAST analysis were specified empirically. This is one of the uncertainties in this sensitivity analysis.

The FAST results are shown in Figure 3. The ratio of partial variance of a parameter to total variance varies from one hour to another throughout the simulation period, but it only slightly affects the relative importance of this parameter to others. The results for two hours are shown to indicate this variation. The 15 parameters can be divided into three categories in terms of their importance. The first category includes the two most important parameters: the plume entrainment coefficient and number of plume updraft cores. Their ratios are about 35 and 26%, respectively, at 1400, and 35 and 32% at 1500. In the other words, each parameter contributes one fourth to one third to the total variance. The second category includes three important parameters: the initial plume temperature anomaly, diameter of flaming area, and thermal stability. Their ratios are about 10% at 1400 and vary between 6 and 12% at 1500. Thus, each contribute about one tenth to total variance on average. The third category includes the remaining parameters, whose ratios are 1% or less. They are not important to Daysmoke plume rise simulation.

Table 1. *Parameters used in the FAST sensitivity analysis for Daysmoke*

Model	Parameter	Meaning	Average	Range [a]	Unit
ETM	C_e	Entrainment coefficient	0.18	0.1-0.5	(-)
DPM	C_p	Plume detrainment coefficient	0.03	0.01-0.2	(-)
	C_u	Air horizontal turbulence coefficient	0.15	0.1-0.2	(-)
	C_w	Air vertical turbulence coefficient	0.01	0.01-0.1	(-)
	K_x	Thermal horizontal mixing rate	1	1-1.5	km(m s^{-1}) ^{o}C^{-1}
	K_z	Thermal vertical mixing rate	1	1-1.5	km(ms^{-1}) ^{o}C^{-1}
	W_c	Plume-to-environment cutoff velocity	0.5	0.2-0.8	m s^{-1}
	$w*$	Air induced particle downdraft velocity	0.01	0.01-0.02	m s^{-1}
LED	W_r	Large eddy reference vertical velocity	1	1-1.5	m s^{-1}
REM	W_0	Initial plume vertical velocity	Computed	5-15	m s^{-1}
	dT	Initial plume temperature anomaly	Computed	5-15	^{o}C
	D_f	Effective diameter of flaming area	Computed	-25-25%	m
	N_c	Number of updraft core	1	1-20	(-)
	T_z	Atmospheric thermal lapse rate	Observed	-25-25%	^{o}C km^{-1}
	V	Average wind speed	Observed	-25-25%	m s^{-1}

[a] *The ranges shown for D_f, T_z, and V are relative changes.*

Figure 2. *Smoke plume with multiple updrafts from the Brush Creek prescribed burning.*

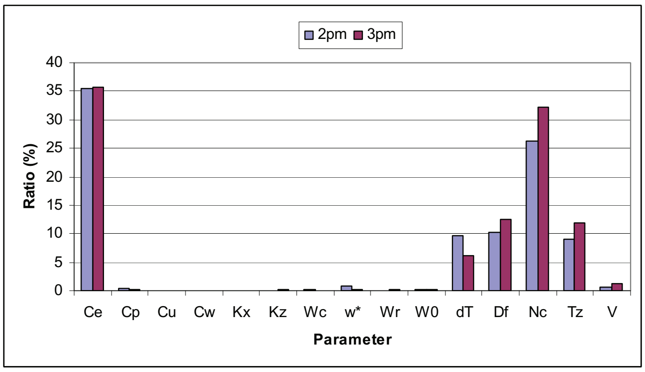

Figure 3. *Fast sensitivity analysis of Daysmoke. The horizontal coordinate lists the model parameters (see Table 1 for their meanings). The vertical coordinate is the ratio (%) of partial variance of the parameter to total variance.*

The important parameters identified by FAST are basically related to ETM and REM and atmospheric conditions. This suggests that plume rise is mainly determined by emissions and the smoke particle rising process, while smoke particle fallout and large eddy processes have little roles. Emissions measure the heat energy released for smoke plume, which together with the ambient thermal energy measured by the stability determines how high the smoke plume will rise. Entrainment, on the other hand, reduces the thermal energy in the plume by mixing the ambient cool air with the warm plume and therefore reduces plume rise. The detrainment determines how much smoke particles fall out of the plume and the large eddy process determines smoke particle fluctuations. They are important for the spatial distribution and temporal variations of smoke particles, but not for plume rise.

The result suggests that the knowledge of entrainment process and number of updraft cores is critical for improving Daysmoke plume rise simulations. Measurement of smoke entrainment is very difficult because of, among others, the risk with fire and smoke processes. There is a similar issue with simulation of cumulus clouds. Many schemes have been developed to parameterize the cumulus entrainment, first through engulfment by large eddies, then with a subsequent increase in surface area by straining, and finally by mixing at the smallest scales (Baker et al., 1984; Agrawal, 2005). Parameterization schemes similar to those for cloud entrainment can be developed for smoke entrainment (Latham, 1994; Freitas, 2007). There are, however, other challenges for smoke. Unlike cumulus clouds, few field measurements have been conducted to provide theoretical and empirical guidance to the development of parameterization schemes for smoke entrainment.

It is also a challenge to obtain information of number of updraft cores. The number can vary throughout a burn period. There are many potential methods to obtain this information. Photographing with cameras may be a direct solution, though it takes considerable labor. Satellite remote sensing from the sky may be a useful solution for some large burns. Parameterization schemes can be developed based on fire behavior.

The FAST result may also have some implications for other plume rise models. All models include parameters measuring heat energy released from burning and therefore have to deal with the issue of multiple updraft cores. Entrainment is a process that is included in most dynamical plume rise models. It is useful to analyze the importance of the two parameters to these models and compare with what was learned here for Daysmoke.

3.2. Importance to CMAQ regional air quality simulation

Accounting for the number of updraft cores resulted in an improvement of the CAMQ simulation with smoke plum rise simulated by Daysmoke using multiple updraft cores. Figures 4 and 5 are the Daysmoke simulations with single updraft core (1–core) and 10 updraft cores (10–core), respectively. The vertical coordinate is the height of model layers and horizontal is the ratio in percent of number of smoke particles of each layer to the total number of particles of all layers. Plume rise was calculated from 1200 when the burning started. For the 1–core case, plume rise is 1.5 km (the highest layer with non–zero smoke particles) at this time. It remains at this height thereafter. The layer with the largest number of smoke particles, about 40%, has a height of 1.1 km at 1200 and increases to 1.5 km next hour and remains at this height until 1700 with up to 90% of smoke particles. It retreats to 1.1 km at 1800.

Plume rise for the 10–core case shows a similar temporal trend to that for the 1–core case. However, there are two major differences between the two cases. First, plume rise is lower by 0.4 km at most hours for the 10–core case than the 1-core case. Plume rise is 0.75 km at 1200, increases to 1.1 km thereafter until 1700, and decreases to 0.93 km at 1800. The layer with the largest number of smoke particles, about 25%, is 0.6 km at 1200 and has the same height as plume rise thereafter with up to 60% of smoke particles. This difference means that more smoke particles are distributed in lower layers for the 10–core case. This difference was also found in Achtemeier et al. (2006).

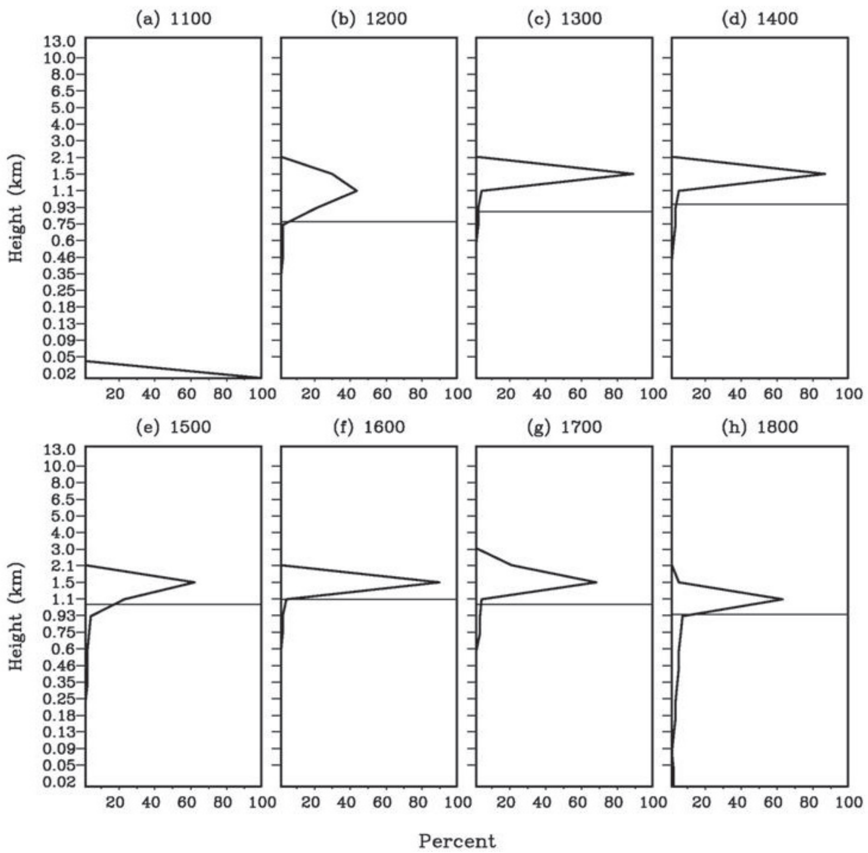

Figure 4. *Hourly smoke plume profiles during 1100 and 1800 EST (panels a to h) on March 18, 2006 at the burn site simulated with Daysmoke for 1 updraft core. The horizontal coordinate is the ratio (%) of smoke particles of a layer to total smoke particles of all layers. The vertical coordinate is height of model layers. The horizontal lines are the heights of planetary-boundary layer.*

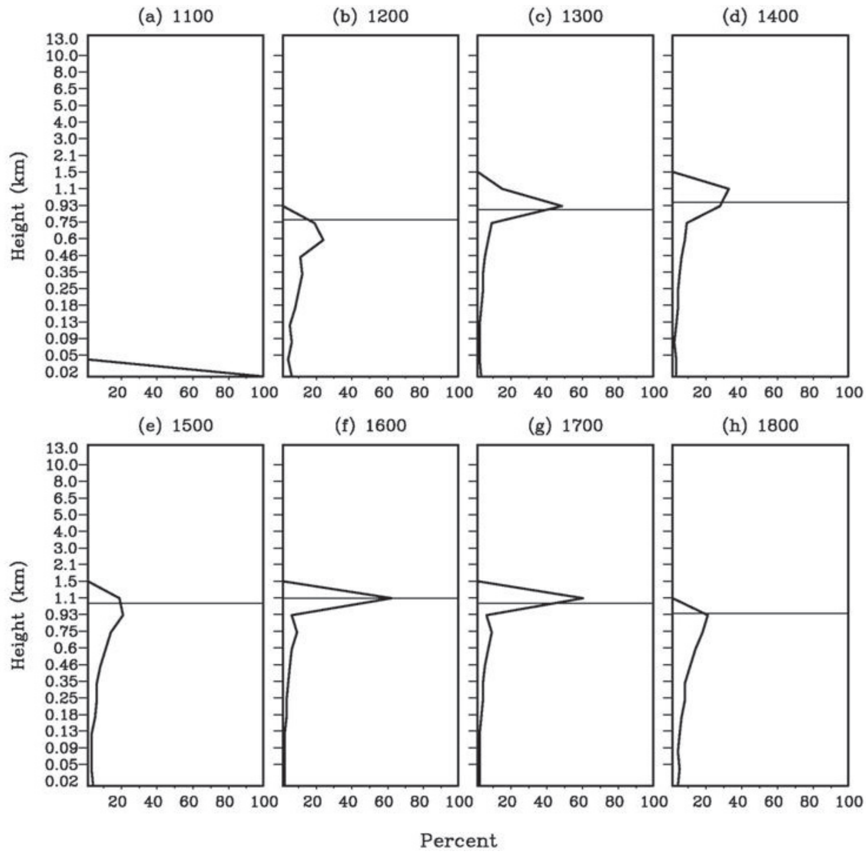

Figure 5. *Same as Figure 4 except for 10 updraft cores.*

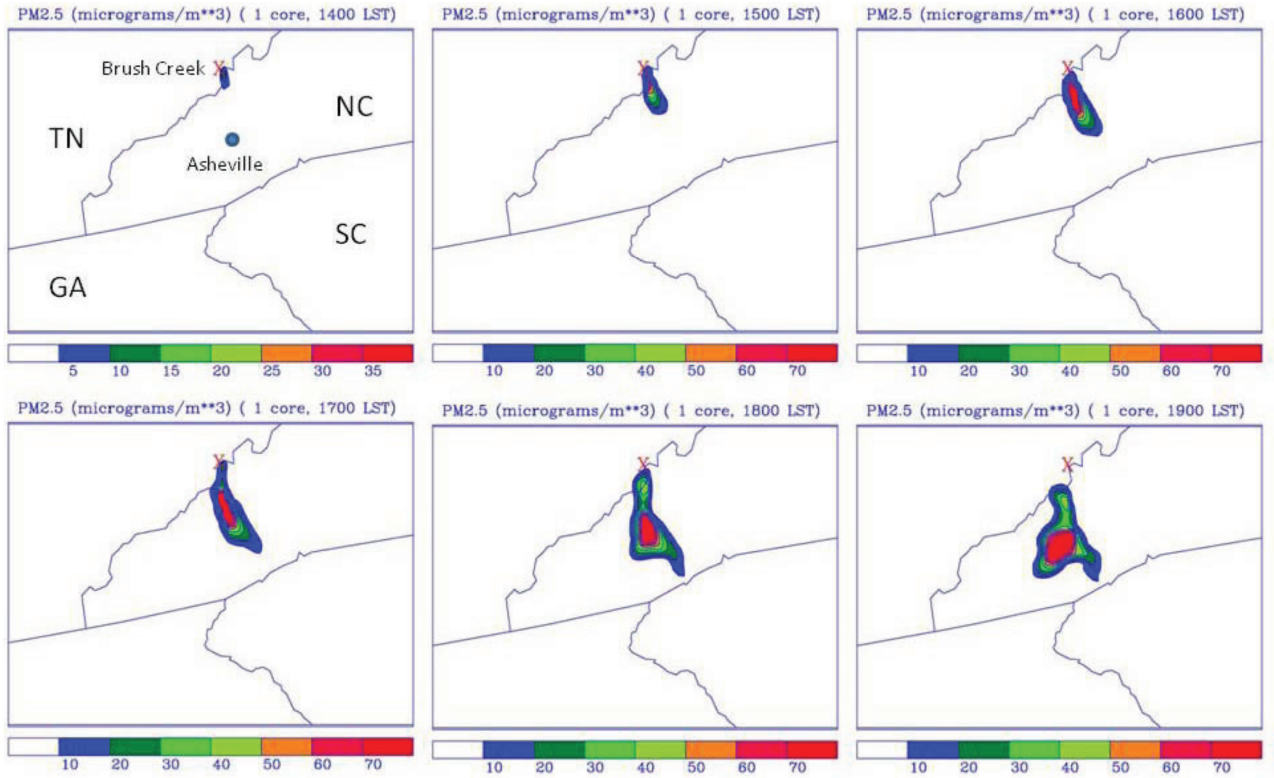

Figure 6. *Ground $PM_{2.5}$ concentrations during 1400 and 1900 EST on March 18, 2006 simulated with CMAQ for 1 updraft core. TN, NC, SC, and GA stand for Tennessee, North Carolina, South Carolina, and Georgia.*

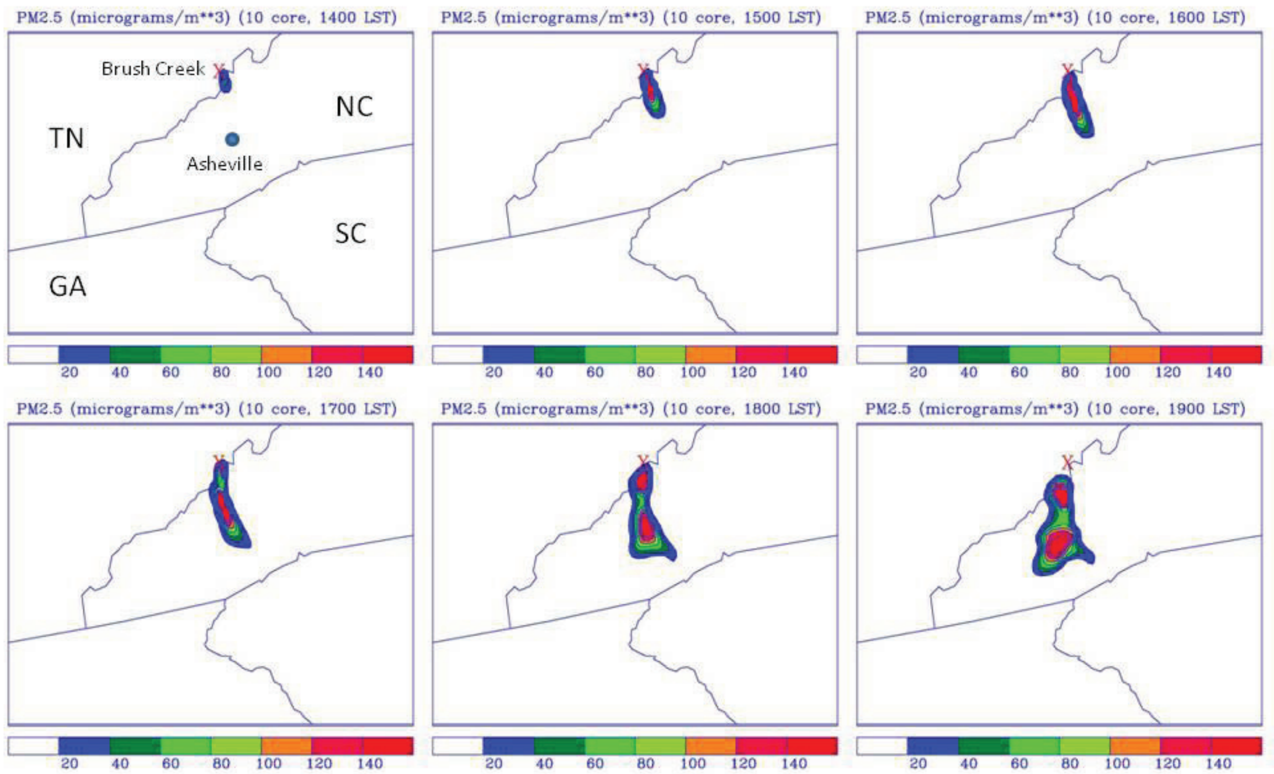

Figure 7. *Same as Figure 6 except for 10 updraft cores.*

Second, there are different amounts of smoke particles within PBL. The PBL height simulated with MM5 is about 0.75 km at 1200, increases gradually to 1.1 km at 1600, and decreases to about 0.9 km at 1800. Smoke particles occur mostly above PBL for the 1–core case, while are close to or only slightly higher than PBL for the 10–core case. No plume rise measurements were conducted for the Brush Creek burn for validation of the simulated plume rise. However, it is unusual for most particles of a prescribed burn smoke plume to penetrate the PBL layer into the free atmosphere, although it is possible for some smoke particles. This suggests that the simulated plume rise for the 1–core case would likely be an overestimate. The validation of the CMAQ simulations described below provides an evidence for this suggestion.

The differences in plume rise simulation have substantial impacts on CMAQ simulation. Figures 6 and 7 show hourly ground level $PM_{2.5}$ for the 1–core and 10–core cases, respectively. The spatial patterns are similar for the two cases. The simulated smoke plume from the burn moves mainly southward and across the Tennessee–North Carolina border by 1400. Its direction shifts a little towards east thereafter. After passing Asheville around 1600, the smoke plume continues to move towards southeast and reaches the North Carolina–South Carolina border three hours later. In the mean time, the center of the plume with the largest $PM_{2.5}$ concentrations turns to south and southwest.

Figure 8 shows the smoke plume at about 1700 from the satellite remote sensing with topography in the background. It seems that the measured smoke plume mainly stayed below the highest elevations. The plume first moved towards the southeast and eventually the south before reaching Asheville. It is apparent that the simulated smoke pattern is similar to the remote sensed one. However, some differences can be found. One of them is that the simulated smoke plume first moves towards the south, climbing the mountain rather than staying in the valley.

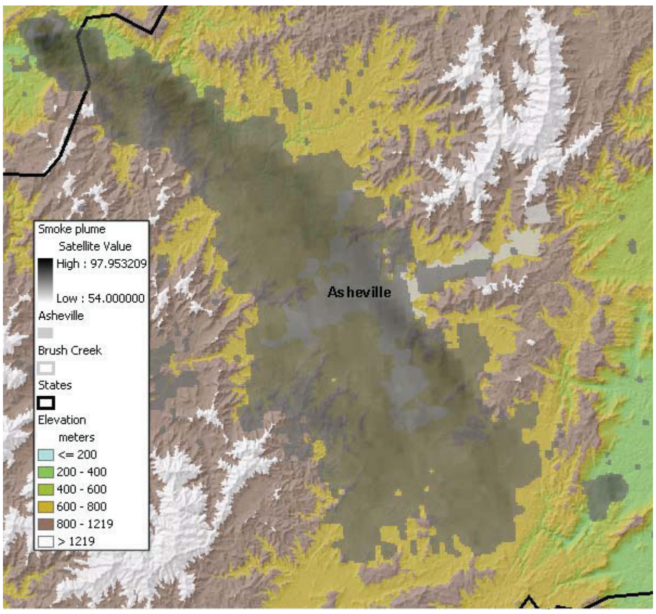

Figure 8. *Smoke plume image processed from the Polar satellite (received from National Oceanic and Atmospheric Administration) showing the cloud of smoke from the Brush Creek prescribed fire at 1715 EST. The lines in the upper–left and lower–right corners are Tennessee-North Carolina border and North Carolina–South Carolina border, respectively.*

The difference in the CMAQ simulation between the 1-core and 10–core cases lies mainly in the magnitude of $PM_{2.5}$ concentration. This can be seen more clearly in the time–altitude across section of $PM_{2.5}$ concentration at Asheville (Figures 9 and 10). For both cases, the smoke plume reaches Asheville around 1500. The $PM_{2.5}$ concentration increases gradually and peaking at 1700 and decreases gradually thereafter. Due to strong vertical turbulent mixing, there is a nearly uniform distribution of smoke particle from the ground to the top of PBL. The peak ground level $PM_{2.5}$ concentration is about 75 $\mu g\ m^{-3}$ for the 1–core case, but about 120 $\mu g\ m^{-3}$ for the 10–core case.

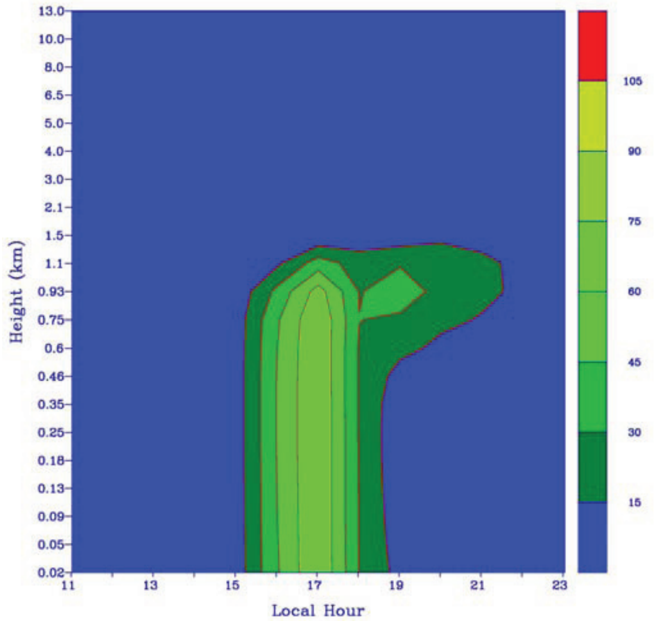

Figure 9. *Time–height across section of $PM_{2.5}$ concentration ($\mu g\ m^{-3}$) at Asheville simulated with CMAQ with Daysmoke simulation of plume rise for 1 updraft core.*

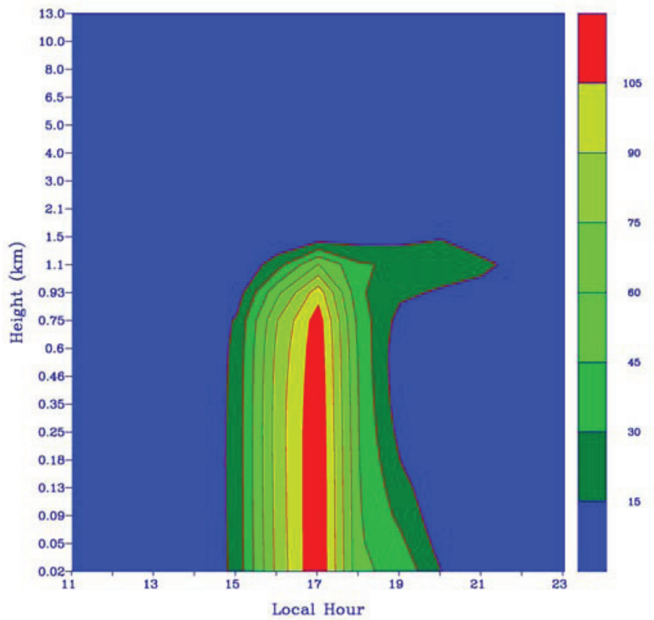

Figure 10. *Same as Figure 9 except for 10 updraft cores.*

Figure 11 shows the ground level $PM_{2.5}$ concentration measured at Asheville between March 16 and 20, 2006. The background $PM_{2.5}$ concentrations resulted from non–wildland burn sources fluctuated with time. The concentrations were larger during the nighttime when PBL was lower and therefore a large portion of air pollutants was staying near the ground, and lower during the day time when the well developed turbulences and eddies brought some air pollutants to higher elevation. The largest background concentrations had a magnitude of about 20 $\mu g\ m^{-3}$. $PM_{2.5}$ concentrations jumped to extremely high from near zero to

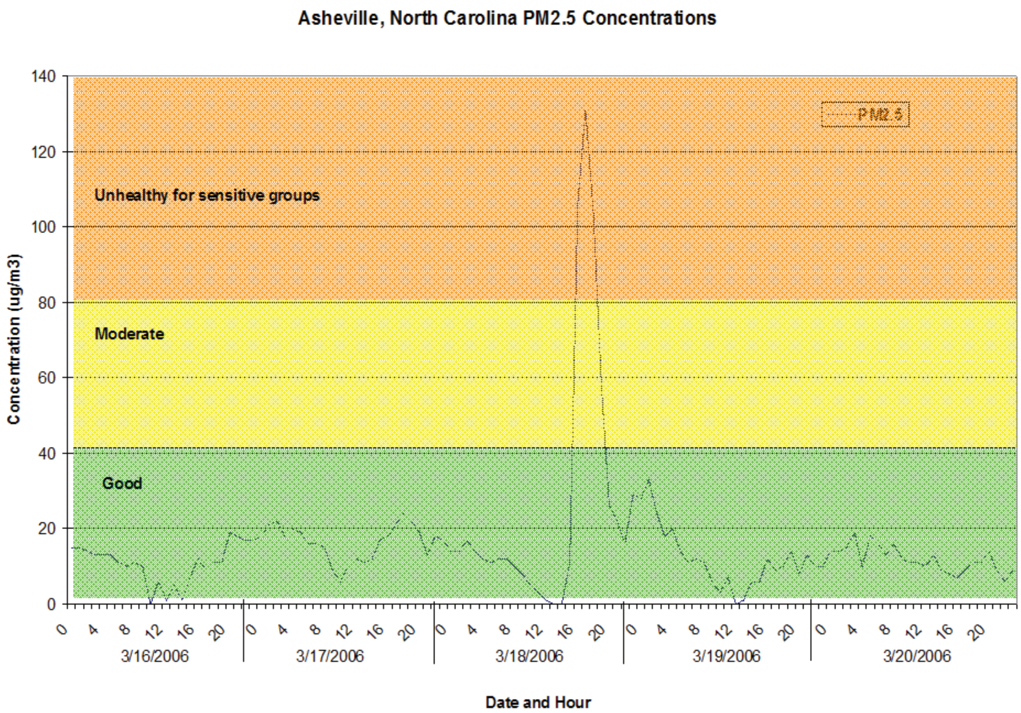

Figure 11. *Fine particulate matter concentrations (µg m^{-3}) measured at the Buncombe County Board of Education monitoring site in Asheville, North Carolina between March 16 and 20, 2006.*

106 µg m^{-3} at 1700 and to 130 µg m^{-3} by 1800 on March 18 in response to the smoke plume from the Bruch Creek burn. These $PM_{2.5}$ values could cause people who are sensitive to air pollutants to experience short-term health problems. It is apparent that the simulated $PM_{2.5}$ concentrations for the 10–core case agree with the observed magnitude, while those for the 1–core case are too small.

This result provides a new evidence for the importance of smoke plume rise for CMAQ air quality simulation of wildland fires, which has been emphasized in previous studies. Furthermore, the result indicates the specific importance of number of updraft cores, an aspect of plume structure that has received little attention. This also suggests a way to improve CMAQ simulation by obtaining correct information on smoke updraft cores.

4. Conclusion

Simulations with Daysmoke and CMAQ of a prescribed burn at the Tennessee/North Carolina border on March 18, 2006 have been conducted and sensitivity to Daysmoke parameters has been analyzed using the Fourier Amplitude Sensitivity Test. For the specified value ranges of the Daysmoke input parameters, entrainment coefficient and number of updraft cores were found to be the most important for Daysmoke plume rise simulation. Initial plume temperature anomaly, diameter of flaming area, and thermal stability also contribute to a certain extent to plume rise simulation. The simulated ground level $PM_{2.5}$ concentrations are much larger for multiple updraft cores than single updraft core and much closer to the observations. Thus, Daysmoke and CMAQ simulations can be substantially improved with the information of number of updraft cores.

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