Sensitivity of CMAQ Simulations to Prescribed Burn Emissions under Varied Plume Core Numbers

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ABSTRACT

Recent studies with Daysmoke indicate the importance of plume-core number for smoke transport and dispersion processes. Since Daysmoke is a tool used to estimate plume rise and vertical distribution of smoke particles for our CMAQ simulations of prescribed burns, it is expected that the CMAQ simulations would be sensitive to plume-core number. This study seeks to understand this sensitivity. An experiment is first conducted using the Fourier amplitude sensitivity test (FAST) to identify the most important parameters in the calculation of plume rise with Daysmoke. This technique determines the relative contribution of individual model input parameters to the variance of the model output. A set of 13 parameters is examined with a range of values for each parameter specified based on measurements of prescribed burning or empirical estimates. The result indicates that plume-core number is among the most important parameters for the estimation of plume rise. CMAQ simulations of a prescribed burn are then conducted with different plume-core numbers. The burn was implemented at the Brush Creek unit of the Cherokee National Forest near the Tennessee-North Carolina border on March 18, 2006 with about 1656 acres burned. Fire emissions are estimated using a forest fuel and fire modeling scheme. The atmospheric conditions are obtained from an MM5 simulation. It is shown that the simulations are significantly dependent on the plume-core number. The simulated ground PM concentrations are remarkably larger for multiple-core smoke updraft than single-core one.

INTRODUCTION

Prescribed burning is a management tool extensively used in the South for reducing accumulation of understory debris and maintaining ecosystem health. Prescribed burning releases large amounts of particulate matter (PM), CO, SO_2, NO_x, and volatile organic compounds (VOC). They individually or in combination can cause degradation of air quality.

The Models-3 Community Multiscale Air Quality (CMAQ) model (Byun and Ching 1999) has been used to simulate the air quality effects of prescribed burning in the South (Liu et al. 2006). Besides the total amounts of air pollutants, the height they reach, that is, plume rise, is required by CMAQ in simulating the air quality effects of prescribed burning when smoke emissions are categorized as a point source. Studies have indicated the crucial importance of plume rise. Emissions injected into higher elevations are likely to be transported out of the burn area by prevailing winds, meaning relative smaller local ground concentrations and therefore reduced chances for exceeding the NAAQS standards, which are measured by ground concentration.

Smoke emissions and the associated plume dynamics are determined by fuel, burn, and atmospheric properties. One of the properties, the number of core updraft of smoke plume, received attention recently. Achtemeier et al. (2006) indicated the importance of this property to smoke transport and dispersion simulated with Daysmoke. Since Daysmoke is a tool used to estimate plume rise and vertical distribution of smoke particles for our CMAQ simulations of prescribed burns (Liu et al. 2006), it is expected that the CMAQ simulations would be sensitive to plume-core number. This study seeks to understand this sensitivity. After a brief description of theoretical background and prescribed burn case, an experiment is first conducted using the Fourier amplitude sensitivity test (FAST) to identify the most important parameters in the calculation of plume rise with Daysmoke. CMAQ simulations of the prescribed burn are then conducted with different plume-core numbers.

MOTHED AND DATA

Core Updraft Number in Daysmoke

Daysmoke is a dynamical model to simulate movement and deposition of smoke particles. It was first developed for burn of sugar cane (Achtemeier 1998), and recently modified for applications to prescribed burns (Achtemeier et al. 2006). It simulates the processes of particle moving up within plume, falling out of plume, and turbulent fluctuations during particle transport and dispersion (Fig.1). These processes are described in three 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, vertical velocity, effective diameter, and entrainment. (b) Detraining particle trajectory model. 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. 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 growth rates of neighboring eddies. Eddy structure is vertical. Eddies are transported by the mean wind in the PBL.

Plume rise and vertical particle profiles are determined by the relative emissions production model. Particles passing a "wall" a few miles downwind from a burning are counted for each hour during the burning period. A percent of particle number at each layer at each hour relative to the total particle number is assigned to SMOKE/CMAQ simulations.

The effective plume diameter in the ETM, D, is determined by

$$D = [\, 4\, F / (\, c\, \pi\, n\,)\,]^{1/3}$$

where n is the number of core updrafts, F volume flux, and c coefficient. The larger n, the smaller D. This will result in a lower plume rise.

Burn

The Cherokee National Forest conducted the Brush Creek prescribed burn on 743 ha of woodland near the Tennessee/North Carolina State line (upper left hand corner of Fig. 2) approximately 50 km northwest of Asheville, NC on 18 March 2006. Approximately 670 ha or 90% of the land area was expected to be burned. Aerial ignition at Brush Creek began along the main and spur ridges between 1220 and 1400 EST then further ignition was done between 1620 and 1710 EST.

The leading edge of the smoke plume from the Brush Creek burn passed Asheville, NC, between 1515 and 1530 EST. Shortly after 1600, elevated fine particulate matter concentrations were measured at a particulate monitor in Asheville operated by the Western North Carolina Regional Air Quality Agency (Fig. 3). Concentrations of $PM_{2.5}$ rose from near zero to 106 μg m^{-3} at 1700 EST and to 130 μg m^{-3} by 1800 EST. These PM levels could cause some people who are sensitive to air pollutants to experience short-term health problems.

RESULTS

FAST Analysis

FAST is used to identify which parameters mostly affect the plume rise in Daysmoke. In FAST, the Daysmoke input parameters (Table 1) vary simultaneously through their ranges of possible values following their given probability density functions. All input parameters are assumed to be mutually independent. Variance, which characterizes the uncertainty due to the variability of the input parameters, is calculated for model output parameter (plume rise). 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. Partial variances show the sensitivity of model output parameters to the variation of individual input parameters in terms of a percentage of the variance. In comparison to other techniques (e.g., Monte Carlo, Latin Hypercube Sampling), the advantage of this technique is evident considering that, for instance, it requires only 1027 runs of 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.

Fig.4 depicts the partial variance of the plume rise resulting from the FAST experiment. It appears that plume rise is very sensitive to effective plume diameter and the atmospheric stability, which contribute about 45 and 32% of the total variance of plume rise, respectively. In addition, entrainment of the air into plume is also an important parameter for plume rise. Because effective plume diameter is directly related to the number of core updrafts, the latter is one of the most important parameters for plume rise in Daysmoke.

CMAQ Simulation and Experiment

Two model domains with 4 km and 12 km resolutions, respectively, are used. Each has 21 vertical layers. The Carbon Bond-IV (CB-IV) chemical mechanism is used to simulate gas-phase chemistry in CMAQ. Daysmoke is used to estimate plume rise and vertical distribution.

Daysmoke simulation of the Brush Creek burn is described in Achtemeier et al. (2006). Fig.5 shows the height of smoke plume (plume rise) and vertical profile of the smoke particle simulated with Daysmoke for 1-core and 10-core updrafts. For 1-core updraft, plume rise is about 1.5 km from 1200 to 1600 EST and increases to 2.1 km at 1700. For 10-core updraft, plume rise is about 0.75 km at 1200 EST with the largest percentage occurring at about 0.6 km. Plume rise gradually increases to 1.1 km at next hour and remains there until 1700. It reduces to 0.92 km at 1800. These results indicate two differences between 1- and 10-core updraft. First, plume rise is usually smaller for multiple-core. Thus, more smoke particles are distributed lower levels. Second and more important, plume rise for 1-core updraft is mostly over the planetary boundary-layer, while that for 10-core updraft is close to or only slightly higher than PBL. This will result in significant impacts on the ground concentrations, as shown later. The profiles are specified in SMOKE at hourly step when preparing fire emissions for the CMAQ simulation.

Fig.6 shows geographic distribution of ground $PM_{2.5}$ for 4 km resolution. The smoke plume spreads from the burn site up to the North Carolina-South Caroline border. It is oriented south to southeast. The transport track is close to what shows in the satellite image. The magnitude of concentration, however, is smaller in comparison with the measurements at Asheville. The simulated smoke plume with 12 km resolution spread wider laterally, primarily due to lower resolution. The underprediction in the magnitude becomes more series.

Fig.7 shows time-altitude across section of $PM_{2.5}$ concentration of spatial averages at the burn site. There are two temporal centers, corresponding to the two ignitions. The vertical distribution is different between 1- and 10-core updrafts. Large concentrations are found between 1.1 and 1.5 km above ground for 1-core updraft. This suggests that most smoke particles are located above planetary boundary layer (PBL) for 1-core updraft. Due to lack in turbulent mixing above PBL, few are transported to the ground. In contract, most particles are within about 1 km above ground for 10-core updraft. In other words, .most particles are within PBL, which leads to a nearly uniform distribution of smoke particle from the ground to the top of PBL by strong turbulent mixing.

SUMMARY

Simulations with CMAQ and Daysmoke have been conducted for a prescribed burn at the Tennessee /North Carolina border on March 18, 2006. The simulated smoke plume moves southeastward across the northwestern North Carolina. The ground-layer $PM_{2.5}$ concentrations reach the point where some people who are sensitive to air pollutants or have other health problems may have experience short-term health problems. The simulated path of the smoke particles is close to that showed in the satellite image. But the magnitude of the ground-layer $PM_{2.5}$ concentrations is lower in comparison with the measurements at Asheville. Daysmoke simulation and the resultant plume rise are dependent on the number of core updrafts. This property has an important impact on CMAQ simulation. The simulated ground PM level with CMAQ is larger for multiple-core updraft than single-core updraft.

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KEY WORDS

Smoke
Core Number
Plume Rise
Daysmoke
CMAQ Simulation

ACKNOLEDGEMENTS

We would like to thank the National Fire Plan, USDA Cooperative State Research, Education, and Extension Service (CSREES) Air Quality Program and EPA for funding and William Jackson of Cherokee National Forest for providing burn information and satellite images.

Table 1 Parameters for FAST experiment

Para	Meaning	Range
cp	Plume turbulence coefficient	0.05-0.2
cu	Air horizontal turbulence coefficient	0.05-0.2
cw	Air vertical turbulence coefficient	0.01-0.08
kx	Thermal horizontal mixing rate	0.5-1.5
kz	Thermal vertical mixing rate	0.5-1.5
wc	Plume-to-environ. cutoff velocity	0.1-0.5
w*	Air induced ash downdraft velocity	0.0-0.01
wr	Maximum rotor velocity	0.25-0.75
pk	Entrainment coefficient for plume	0.05-0.25
w1	Initial plume vertical velocity	1.0-3.0
TD	Initial plume temperature anomaly	2.0-8.0
fd	Diameter of flaming area	2.5-100.0
tm	Surface temperature	75.0-85.0
dm	Dew-point temperature	60.0-80.0
wm	Surface wind	1.0-5.0

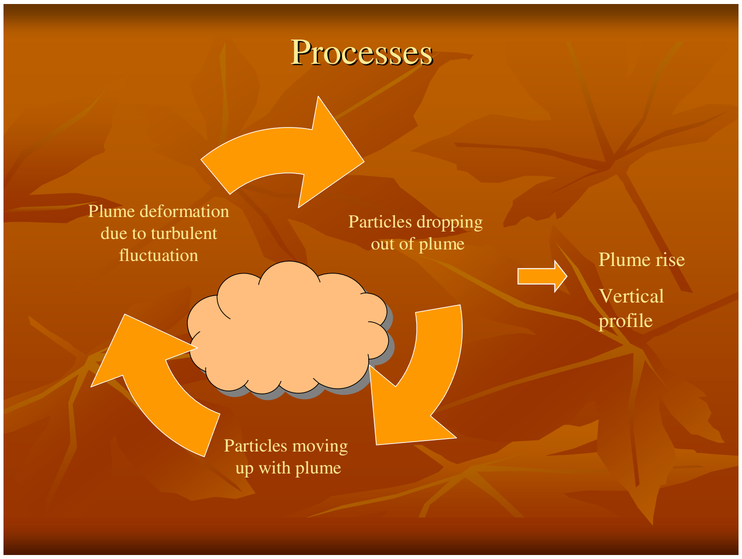

Fig.1 Smoke particle transport and dispersion processes in Daysmoke.

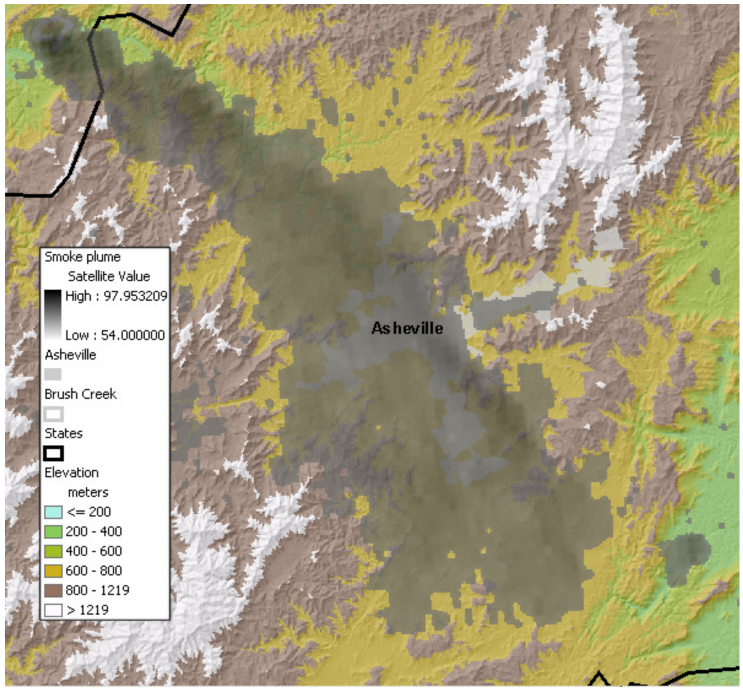

Fig.2. Smoke plume image processed from the Polar satellite (received from National Oceanic and Atmospheric Administration) showing the cloud of smoke from the Brush Creek prescribed fire at 1715 EST. (Obtained from William Jackson of UDFS Cherokee National Forest)

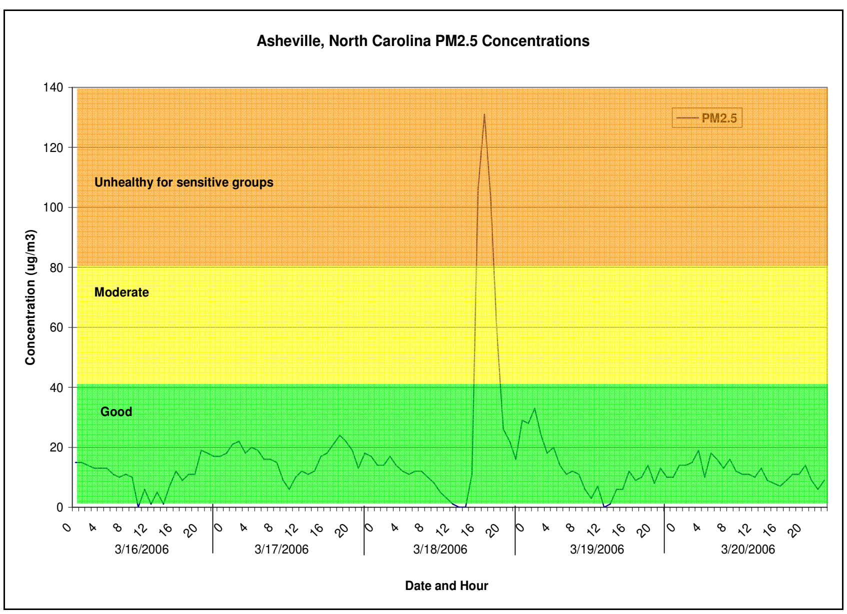

Fig.3. Fine particulate matter concentrations (μg m^{-3}) measured at the Buncombe County Board of Education monitoring site in Asheville, North Carolina between March 16 and March 20, 2006. (Obtained from William Jackson of UDFS Cherokee National Forest)

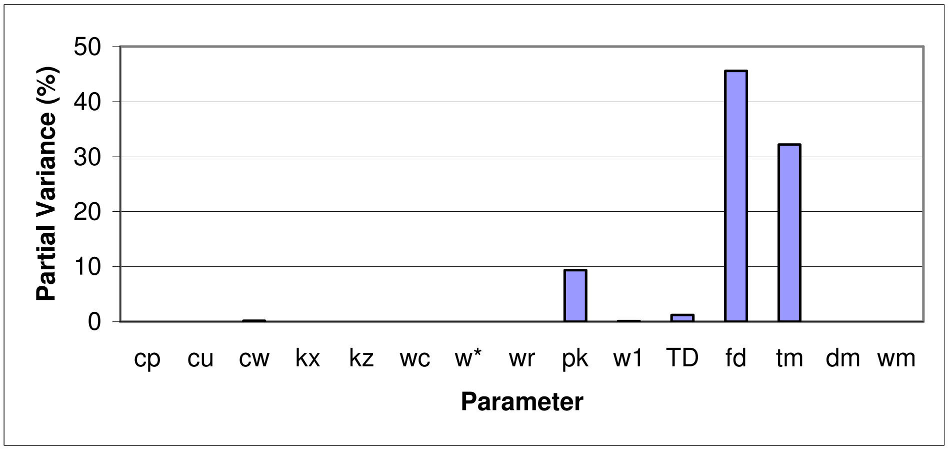

Fig.4 Partial variance of plume rise corresponding to various Daysmoke parameters.

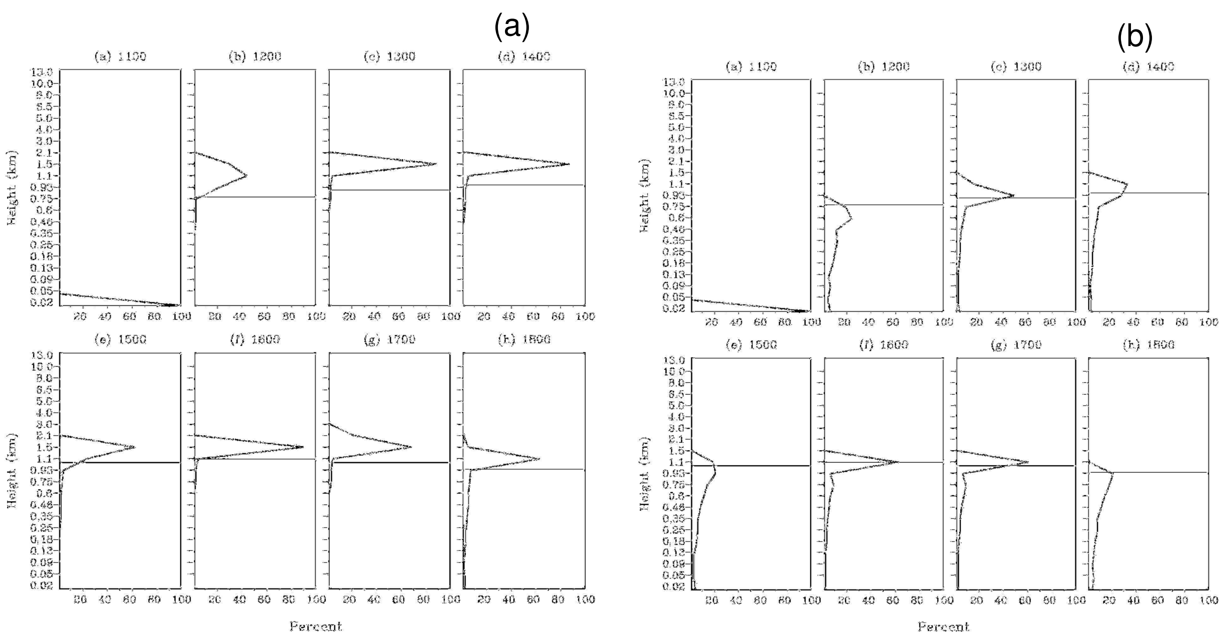

Fig.5 The vertical distribution of smoke particles (in %) at the hours from 1100 throughout 1800 LST calculated using Daysmoke. The light horizontal lines indicate the top of planetary boundary layer. (a) one-core updraft. (b) 10-core updraft. The light horizontal lines indicate the top of planetary boundary layer.

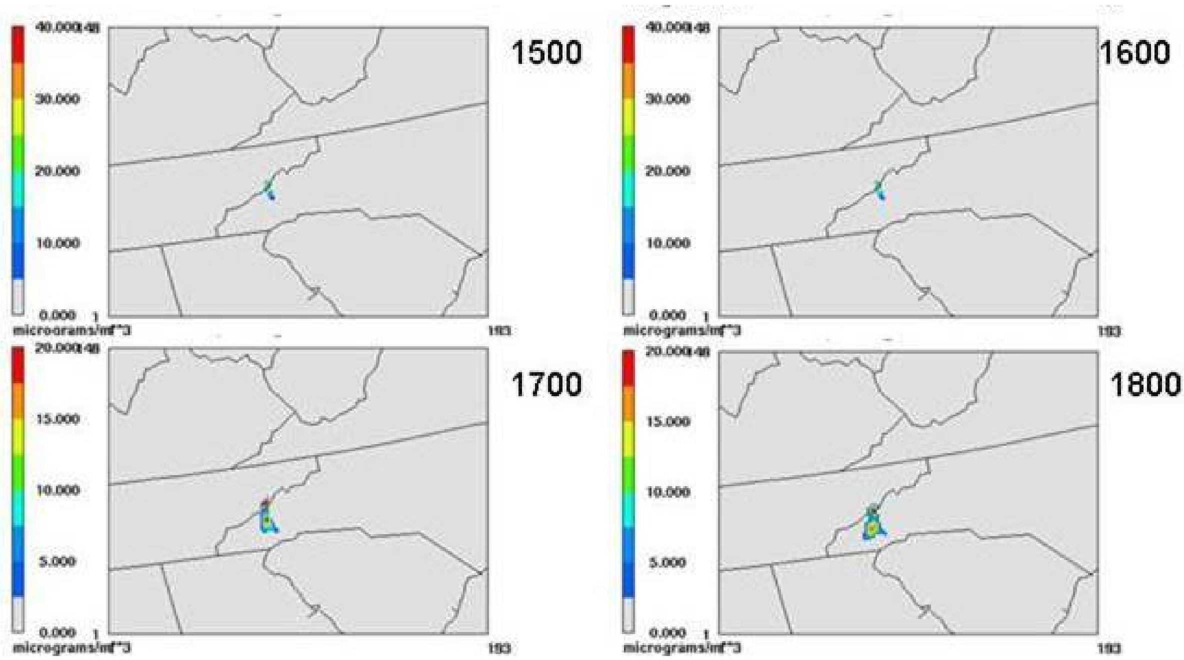

Fig.6 Ground PM2.5 concentrations from 1500 to 1800 simulated with CMAQ with a resolution of 4 km.

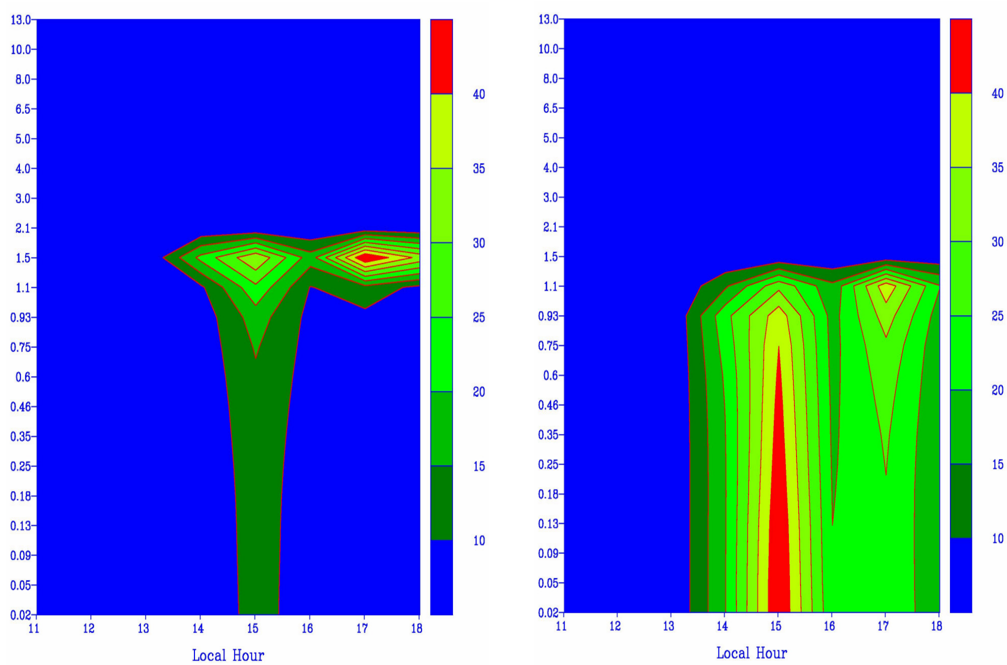

Fig.7 Time-height across section of $PM_{2.5}$ concentration (μg m^{-3}) at the burn site simulated with CMAQ with 4 km resolution for one-core (left) and 10-core (right) updraft.