Simulation and Experiment of Air Quality Effects of Prescribed Fires in the Southeast

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1. Introduction

Wildfires can cause degradation of air quality by releasing large amounts of particulate matter (PM) and precursors of ozone (Sandberg et al., 1999; Riebau and Fox, 2001). 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). Development and application of modeling tools for evaluating the impacts of wildland fires on air quality are needed to assist fire and smoke managers and policymakers in meeting air quality regulations and defining implementation plans.

The Southeast has the most burned area among various U.S. regions (Stanturf et al., 2002) and has regionally some of the highest levels of PM and ozone in the nation. One of the features with wildland fires in this region is the extensive use of prescribed burning as a forest management tool to reduce accumulation of understory debris and, as a result, reduce the risk of wildfires. The magnitude of the missions from the prescribed burning is comparable to that of wildfires (Liu 2004).

Efforts have been made at the USDA Forest Service Southern High-Resolution Modeling Consortium to develop a research tool called the Southern Smoke Simulation System (SHRMC-4S, Achtemeier et al., 2003). It is a framework for modeling fire emissions, smoke movement, and the air quality effects similar to Bluesky (O'Neill et al., 2003) but specifically for prescribed burning in the Southeast. A unique feature with SHRMC-4S is the coupling of Daysmoke, a dynamical model to simulate movement and deposition of smoke particles (Achtemeier, 1998), with CMAQ/SMOKE (Byun and Ching, 1999; Houyoux et al., 2002) to provide smoke plume rise.

This study seeks to understand the importance of estimating smoke plume rise by conducting simulation of prescribed burning in the Southeast with SHRMC-4S and to identify the most important parameters in Daysmoke by conducting sensitivity experiment with the Fourier amplitude sensitivity test (FAST) technique.

2. Methodology

a. Model and simulation

SHRMC-4S consists of three components, that is, fuel and fire models for estimating smoke emissions, CMAQ and SMOKE for modeling air quality, and MM5 (Grell et al., 1994) for providing meteorological fields. In Daysmoke, 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. Movement within the plume is described by the horizontal and vertical wind velocity, turbulent horizontal and vertical velocity, 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. 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. Eddies are transported by the mean wind in the PBL. Particles passing a "wall" three miles downwind from a burning are counted for each hour during the burning period. A percent of particle number of each layer relative to the total particle number is assigned to SMOKE.

Burning number and area in Florida are large during the late winter and early spring

(Fig.1). Simulations are conducted with SHRMC-4S for the prescribed burning in Florida during March 6-9, 2002 (Julian day 65-68). There were 180, 170, 147, and 156 prescribed burnings with the burned areas of 111, 100, 73, and 30 acres in these days, respectively. Burnings are assumed to start at 10:00. The largest emissions occur at 12:00-14:00, during which three fourths of total emissions are released. A domain of 12 km resolution with 95X47 grid points is used. The integration period is from 8:00 to 18:00.

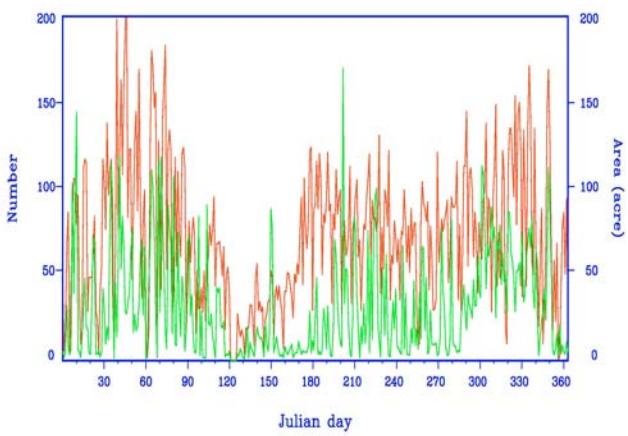

Fig.1 Variations of number (red) and averaged area (green) of daily prescribed burning in Florida, 2002.

b. Experiments

FAST is used to identify which parameters mostly affect the plume rise in Daysmoke. This technique was introduced by Cukier et al. (1973) and used by, e.g., Liu and Avissar (1999) to examine sensitivity of a forth-order land-atmosphere model.

In FAST, the Daysmoke input parameters (Table 1) are varied 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 (Derwent 1987], 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.

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

3. Results

a. Plume rise and vertical distribution

Fig.2 shows the height of smoke plume (plume rise) and vertical profile of the smoke particle number percent from the simulation of March 6, 2002. The plume rise estimated using Daysmoke first gradually increases from about 0.25 km at 9:00 to 1.2 km at 12:00 and 13:00, and then gradually decreases to 0.25 km at 17:00. This daily cycle agrees with the development of PBL. A majority of smoke particles occurs in the upper portion of smoke plume until 14:00, with the largest percent found at a level a few hundreds of meters below the plume rise. The level then lowers its height and is near the ground in the late afternoon.

The plume rise and vertical profile are much different from those estimated using the "layer fraction method" in SMOKE, in which the Briggs formulas, originally developed for stack

(Briggs, 1971), are used to calculate smoke plume rise and the plume is distributed into the vertical layers that the plume intersects based on the pressure in each layer. The plume rise calculated using the Briggs formulas reaches a height of 12 km in the afternoon with the largest percent found at about 3 km.

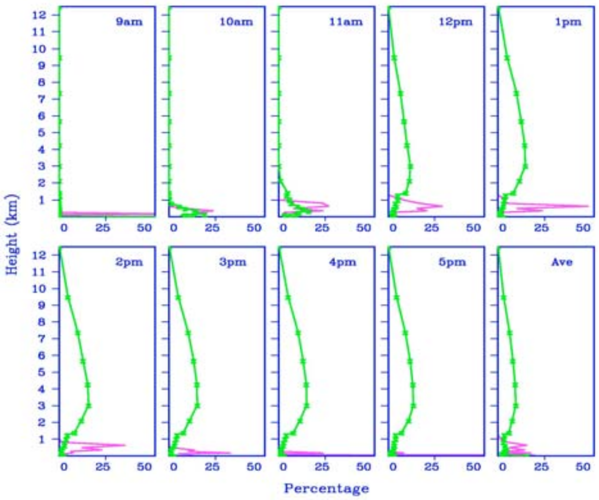

Fig.2 Vertical distribution of smoke particles estimated using Daysmoke (pink) and Briggs scheme (green) on March 6, 2002.

b. PM distribution

Fig.3 shows the simulated surface PM. There is a large concentration in the northwestern Florida with the magnitude of 1 μg m^{-3} simulated with Daysmoke. The magnitude simulated using the layer fraction method is much smaller. This difference, visible at the height up to about 1 km (Fig.4), indicates that CMAQ with Daysmoke produces larger concentrations on the ground and in PBL.

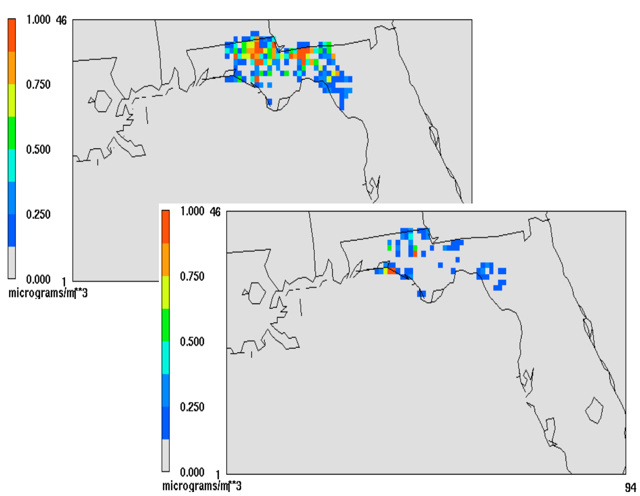

Fig.3 CMAQ simulation of PM concentration with plume rise estimated using Daysmoke (background) and Briggs scheme (foreground) of the surface layer at 14:00 on March 6, 2002.

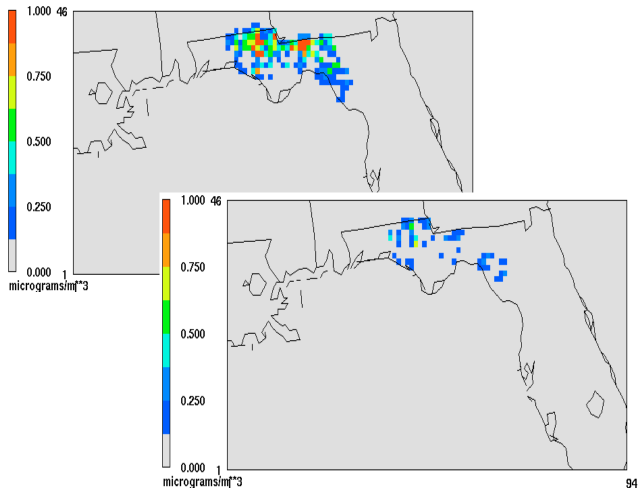

Fig.4 Same as Fig.3 except for σ=0.91.

The PM concentration simulated by CMAQ with Daysmoke increases with time until 15:00 and decreases thereafter. The largest concentration occurs near the top of the plume before 13:00 and on the ground after that hour, respectively. The plume reaches about 1 km by 12:00, 1.2 km by 14:00, and 2 km in the late afternoon. In comparison, the simulated plume using the layer fraction method extends up to about 7 km. The concentrations on the ground and in PBL are relatively smaller. The magnitude is about one third of that simulated using Daysmoke.

c. Most important parameters

Fig.5 depicts the partial variance of the plume rise resulting from the FAST experiment. It appears that plume rise is very sensitive to burning size 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.

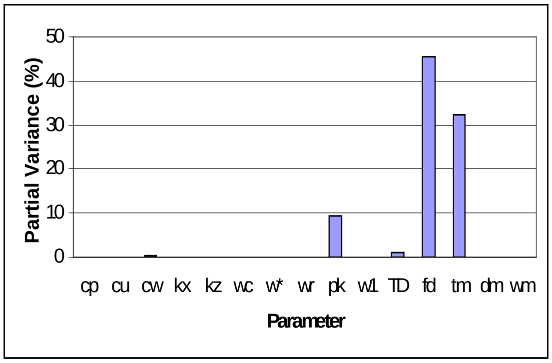

Fig.5 Partial variance of plume rise corresponding to various Daysmoke parameters.

4. Concluding Remarks

The SHRMC-4S simulations of the Florida cases using Daysmoke obtained lower plume rise and larger concentration in PBL than those obtained using the layer fraction method. This result could have important implications for the adverse impacts of prescribed fires on health of human being and ecosystem because more smoke particles are trapped near the ground.

The FAST experiment result suggests that result it is critically important to know the proper forms and to specify the correct values of size of the burning, temperature perturbation, and plume entrainment in simulations with CMAQ-Daysmoke.

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