5.10 A coupled modeling system for connecting prescribed fire activity data through CMAQ for simulating regional scale air quality

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1. INTRODUCTION

The southeastern United States – states extending from Virginia to Texas and from the Ohio River southward – (hereafter called the "South") comprise one of the most productive forested areas in the United States. Although the South represents only 24 percent of the U.S. land area, approximately 200 million acres (81 million ha) or 40 percent of the Nation's forests lie within this region (SRFRR, 1996).

Southern land managers understand that prescribed fire is the most economical way to reduce fuels, remove nutrient-competing species, and manage for threatened and endangered species. Because Southern forests are dynamic ecosystems characterized by rapid growth – hence rapid deposition of fuels - within a favorable climate, the fire-return interval (3-5 years) is among the highest in the Nation. Approximately 6-8 million acres (2-3 million ha) of forest and agricultural lands are burned in the South each year (Wade et al., 2000).

The forests that cover much of the region today have been established within the matrix of the road and town networks of the old South. Furthermore, the moderate climate has made the South a favorite retirement area. This combined with rapid expansion of major urban areas such as Atlanta, GA, Charlotte, NC, and Jacksonville, FL, into traditionally forested areas has placed millions of people in exposure to smoke from prescribed burns.

The Environmental Protection Agency (EPA) has issued the Interim Air Quality Policy on Wildland and Prescribed Fire to protect public health and welfare through mitigating the impacts of air pollutant emissions from wildland fires on air quality (EPA, 1998). Interests supported by the Clean Air Act, the need to improve human health, reduce nuisance smoke, and improve visibility appear on a collision course with interests supported by the Endangered Species Act, the need for carbon sequestration, improved forest health, wildlife management, and wood fiber production (Achtemeier, et al., 1998).

The importance of prescribed fire in air quality and forest health makes it critical that air quality models incorporate the impacts of smoke accurately. One requirement is that the human element – how the burn is engineered and when the burn is conducted – must be part of air quality modeling. Prescribed fires are not simple ground sources of smoke. These fires, particularly the larger fires that contribute most to the fire emissions inventories of the South, are designed to place as much smoke as possible above ground – often above the planetary boundary layer. Furthermore, most prescribed burns are conducted during those few days during winter and early spring when wind and stability create conditions most favorable for dispersion.

With the goal of accurately representing forestry activities in air quality models, the Smoke Management Team of the U.S. Forest Service Southern Research Station has developed a coupled prescribed fire-air chemistry modeling framework called the Southern Smoke Simulation System (SHRMC-4S, Achtemeier et al. 2003). SHRMC-4S simulates and predicts chemical concentrations of smoke components and assesses their effects on regional air quality by using the EPA Models-3 Community Multi-Scale Air Quality CMAQ) modeling system (Byun and Ching, 1999), with some modifications for time and location for point source fire emissions. SHRMC-4S is described in the section that follows. Then results are presented for simulations of prescribed burns in Florida during 2002.

2. MODEL AND SIMULATIONS

SHRMC-4S consists of fuel and fire models for estimating smoke emissions (the components of Fire Data and Emission Calculation in Fig.1) and the Models-3 for modeling air quality (the components of SMOKE-Sparse Matrix Operator Kernel Emissions Modeling System (Houyoux et al. 2002), CMAQ, and Visualization).

Meteorological fields simulated by MM5 (NCAR/Penn State Mesoscale Model, Grell et al., 1994) are used for emission calculation, and SMOKE and CMAQ simulations.

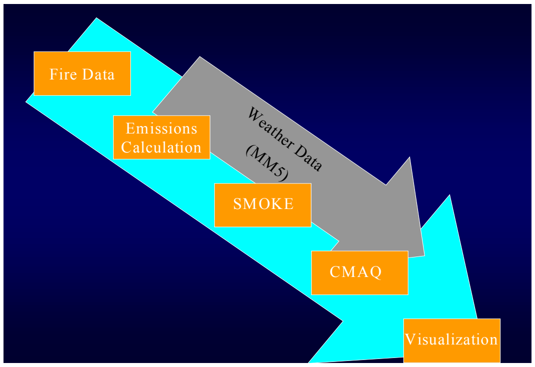

Fig.1 An overview of the SHRMC-4S framework

SHRMC-4S as a framework for wildland fire and air quality research and application differs from BlueSky (O'Neill et al., 2003) in that it is designed to couple with CMAQ with a focus on prescribed burning in the South. To be consistent with the efforts of VISTAS in air quality simulation of 2002 in the Southeast, CMAQ has been included in SHRMC-4S for air quality simulation. DAYSMOKE, a plume model designed for simulating southern prescribed fires, has been linked with CMAQ to estimate vertical distributions of smoke particles.

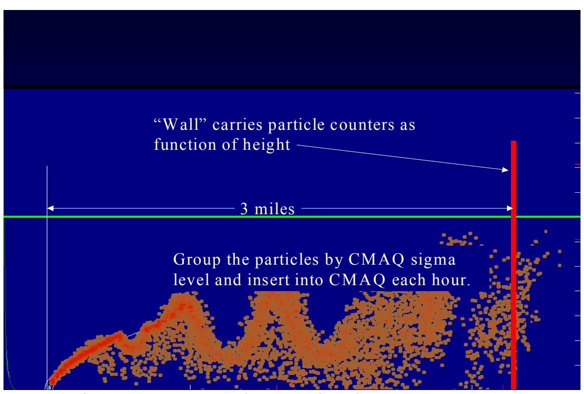

Fig.2 Construction of DAYSMOKE vertical plume profile. The red dots are smoke particles from a prescribed burn predicted by DAYSMOKE. The green line is the top of the planetary boundary layer.

DAYSMOKE consists of the following four models: (a) Entraining 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. (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. (d) Relative emissions production model. Particles passing a "wall" three miles downwind from a burning are counted for each hour during the burning period (Fig.2). A percent of particle number of each layer relative to the total particle number is assigned to SMOKE/CMAQ simulations.

Figure 3 shows how DAYSMOKE simulates a prescribed burn. Smoke tends to hug the ground as the burn ramps up (first two panels), then is transported above the mixed layer during the active burn phase (next 4 panels), and finally returns to hugging the ground during the ramp-down and smoldering phase (last 3 panels). Hourly profiles are converted into percentages of smoke released as normalized for the entire burn. Normalized hourly percentages give the relative concentration of smoke at each CMAQ level for each hour.

Simulations were conducted with SHRMC-4S for the prescribed burning in Florida during March 6-9, 2002 (Julian day 65-68). Both burning number and area were large during the late winter and early spring of this year (Fig. 4). 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.

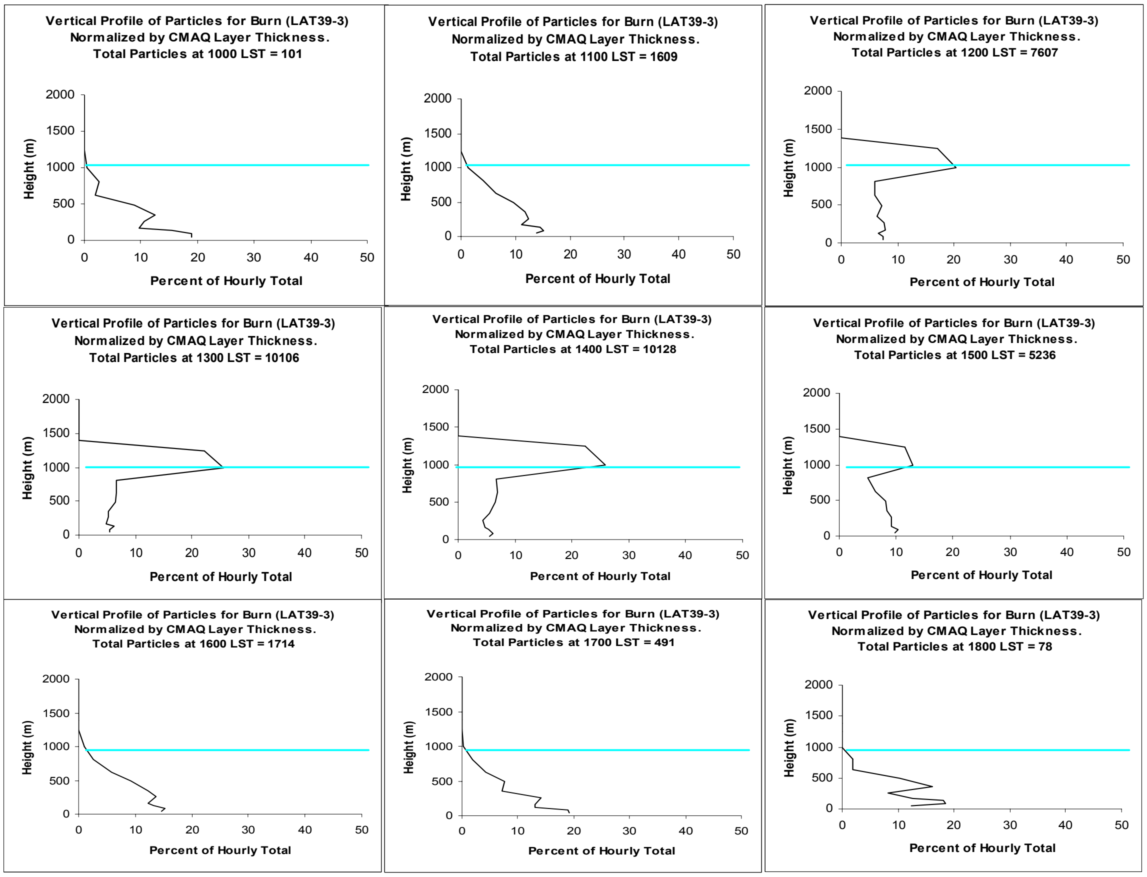

Fig. 3. Hourly vertical profiles of smoke developed by DAYSMOKE for the duration of a southern prescribed burn. Horizontal blue line identifies the top of the mixed layer (held constant for this simulation).

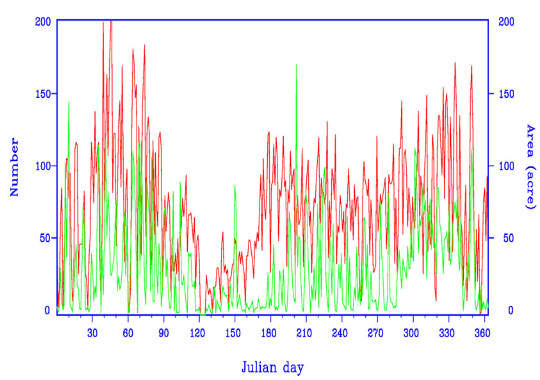

Fig.4 Seasonal variations of number (red) and averaged area (green) of daily prescribed burning in Florida, 2002.

3. RESULTS

3.1 Plume Rise and Vertical Distribution

The simulation of March 6 is used to illustrate the results. Fig.5 shows the height of smoke plume (plume rise) and vertical profile of the smoke particle number percent. 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/CMAQ, 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.

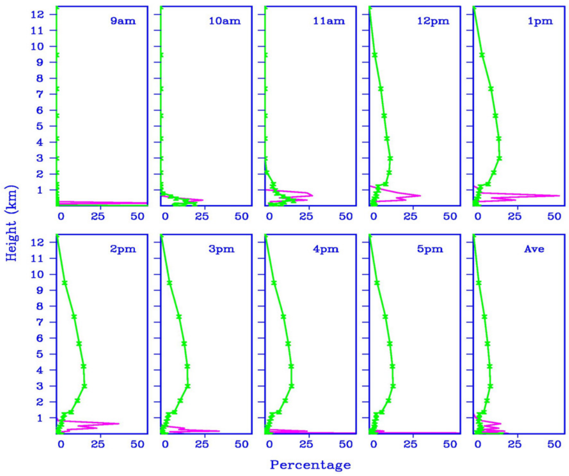

Fig. 5. Vertical distribution of smoke particles estimated using DAYSMOKE (pink) and Briggs scheme (green) on March 6, 2002.

3.2 Spatial Distribution

Fig. 6 shows the simulated PM at the surface layer. There is a large concentration in northwestern Florida. The magnitude simulated using DAYSMOKE is about 1 $\mu g\ m^{-3}$. The magnitude simulated using the layer fraction method is much smaller. This difference, visible at the height up to about 1 km (Fig.7), indicates that CMAQ with DAYSMOKE produces larger concentrations on the ground and in PBL. Apparently, this is resulted from the differences in the plume rise and vertical profile between DAYSMOKE and the layer fraction method, as shown in Fig.5.

3.3 Temporal Variations

The PM concentration simulated by CMAQ with DAYSMOKE increases with time until 15:00 and decreases thereafter (Fig.8). 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.

4. DISCUSSION

SHRMC-4S has been developed as a framework for smoke and air quality research focused on prescribed fires in the South.

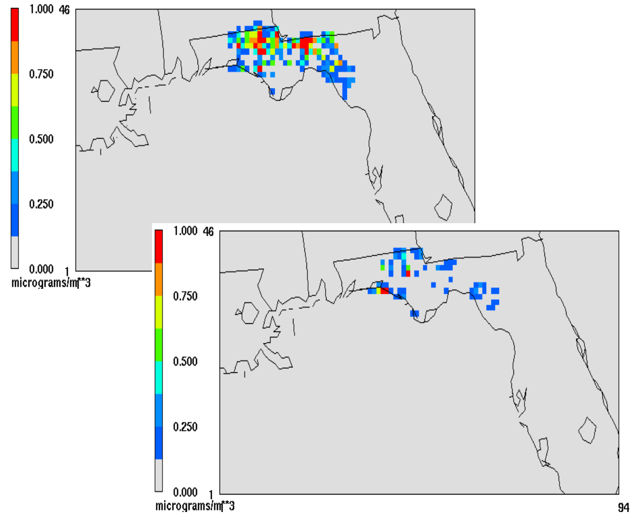

Fig.6. CMAQ simulation of PM concentration with plume rise estimated using DAYSMOKE (background) and Briggs scheme (foreground) of the surface layer at 14:00 on March 6, 2002.

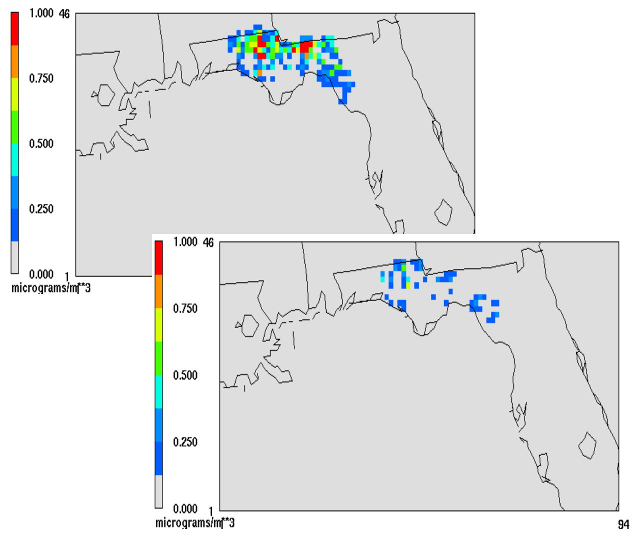

Fig.7. Same as Fig.6 except for σ=0.91.

DAYSMOKE has been linked as an alternate to the layer fraction method in SMOKE/CMAQ for smoke plume rise calculation and vertical profile specification. 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. From observations of prescribed burns, the DAYSMOKE-derived smoke profiles are considered to be more accurate than the smoke profiles calculated from the layer fraction method. The results with DAYSMOKE 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.

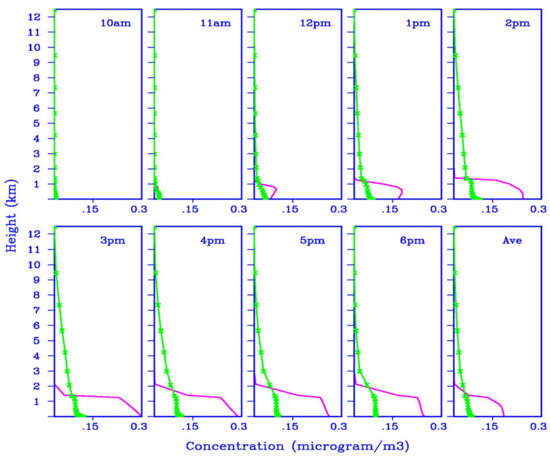

Fig.8 CMAQ simulation of PM concentration with plume rise estimated using DAYSMOKE (pink) and Briggs scheme (green) on March 6, 2002.

Although some measurements were used for the development and validation of DAYSMOKE, more measurements are needed for further validation of this model and comparison with the existing methods in SMOKE/CMAQ. In addition, more fuel and fire information are needed for improving the performance of SHRMC-4S. A number of efforts have been proposed, including radar observations of prescribed burn plumes, comparisons with high-resolution simulations of smoke plume using the Weather Research and Forecast (WRF) model, and applications of aerial photographs of smoke plumes.

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