# On the Multiple-Core Updraft Smoke Plume Problem: Is the Genie Out of the Bottle?

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#### Abstract

The Daysmoke plume model is designed to simulate smoke emissions and dispersion from prescribed burns in the manner in which the burns are conducted by land managers. Recent results with Daysmoke regarding multiple-core updrafts have confirmed our suspicions that the dynamics of smoke plumes from prescribed burns are more complex than the dynamics of plumes from point sources such as industrial stacks. Therefore, simple plume rise algorithms and models designed to simulate plume rise from point sources cannot be expected to correctly place smoke vertically in the atmosphere – a critical factor for the accurate prediction of downwind smoke concentrations at ground level.

Although Daysmoke has identified the multiple-core updraft smoke plume as a significant contributor to uncertainty in predictions of smoke concentrations at the ground, the model has not offered any pathways to solve the problem. To date we cannot offer substantive explanations of why some burns develop single-core updrafts while other burns develop multiple-core updrafts. Furthermore, updraft core numbers may vary during the lifetime of some burns thus increasing the complexity of the problem.

The experimental rule-driven fire spread model (Rabbit Rules) shows promise for identifying updraft core numbers. Rabbit Rules can simulate complex fire behavior including some phenomena associated with coupled fire-atmosphere interactions. Rabbit Rules may provide updraft core data in three ways – the number of discrete low pressure centers generated by heat released from the fire on the scale of 10's to 100's of meters, the number of independent ground-level wind circulations generated by heat released from the fire on the scale of 10's to 100's of meters, and the number of heat centers contained by the burn on the scale of 1's to 10's of meters.

### 1. Introduction

The impacts of prescribed burning on regional air quality are critically important to forestry interests in the southern United States. This region comprises one of the most productive forested areas in the country with approximately 200 million acres (81 million ha) or 40% of the Nation's forests in an area occupying only 24% of the U.S. land area (SRFRR, 1996). Furthermore, southern forests are dynamic ecosystems characterized by rapid growth, hence rapid deposition of fuels within a favorable climate, and a high fire-return rate of 3-5 years (Stanturf et al. 2002). Therefore, prescribed burning has been used extensively to treat 6 to 8 million acres (2–3 million ha) of forest and agricultural lands each year (Wade et al. 2000).

One of the adverse consequences of prescribed burning is degradation of air quality (Ward and Hardy 1991, Sandberg et al. 1999, Riebau and Fox 2001). Fires have been found to be an important contributor to regional PM and ozone levels (Zheng et al. 2002). Smog, regional haze, and visibility impairment are the major air quality concerns of the U.S. Environmental Protection Agency (EPA). Prescribed burning can contribute to all these air quality problems by releasing large amounts of PM<sub>2.5</sub> and PM<sub>10</sub> (particulate matter with a size not greater than 2.5 and 10µm, respectively), NO<sub>2</sub> and volatile organic compounds (VOC), which are either direct contributors or precursors of O<sub>3</sub>. Prescribed burning also emits CO and SO<sub>2</sub> which together with PM, NO<sub>2</sub>, and O<sub>3</sub> are the criteria air pollutants subject to the U.S. National Ambient Air Quality Standards (NAAQS) (EPA 2003). 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).

High-resolution air quality/air chemistry models such as the Community Multiscale Air Quality (CMAQ) model (Byun and Ching 1999) are increasingly being used to estimate air quality within the complex mix of sources and substances. Critical to the success of these modeling efforts are accurate emissions inventories and correct placement of source material within the atmosphere. This information is supplied to CMAQ via area and point source emissions through the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE) (Houyoux et al. 2002). Area source emissions are annual amounts (or converted to daily averages) from counties, and are distributed only at the lowest model level. Point source emissions are daily or hourly amounts from individual locations like power plants, and are partitioned to multiple vertical levels.

For point-category emissions, plume rise, that is, the height the plume can reach, and the vertical distribution of smoke particles must be specified in CMAQ/SMOKE simulations. Estimate of plume rise is crucial for evaluating the air quality because plume rise determines the balance between local concentrations of pollution versus longer range transport. SMOKE is equipped with the Briggs scheme (Briggs 1971) originally developed for estimating plume rise of power plant stacks.

## 2. The Problem: Smoke from Wildland Fire and Multiple-Core Updraft Plumes

Wildland fire, particularly prescribed fire in the southern United States, is difficult to include in regional scale air quality models because it fits neither the area source nor point source definitions. Fire cannot be treated as area sources because fire involves heat release and therefore vertical transport of smoke in buoyant plumes. Fire cannot be treated as point sources because prescribed burns are temporally transient. A prescribed burn may be done at a given location once every 3-5 years.

Smoke from wildland fire can be vertically distributed within the atmosphere with the aid of dynamical smoke models. The Bluesky modeling framework (O'Neill et al. 2003), calculates heat released from burning and distributes emissions vertically in the atmosphere and disperses emissions downwind through the plume model CalPuff. Liu et al (2007) have converted Daysmoke (Achtemeier et al 2007) for CMAQ. Further, Pouliot et al. (2005) have developed a plume rise scheme for SMOKE.

Comparisons of predictions of ground level PM2.5 smoke concentrations from BlueSky with measurements of PM2.5 (BSRW, 2006) found systematic underestimates of smoke concentrations over regions immediately downwind from the burns. The shortfall was thought be

the outcome of underestimates of emissions linked to errors in fuel loading calculations. However, increasing fuel loadings increases the amount of heat released during combustion. The increased heating increases buoyancy of the plume which can drive smoke aloft and away from the atmosphere near the ground. Thus increasing fuel loadings to increase emissions may actually decrease ground-level concentrations of smoke.

Daysmoke (Achtemeier, et al 2007) adds an additional human element – the method of firing – into the mix of factors that determine smoke plume dynamics. Aerial ignition, usually applied to large acreage prescribed burns, broadcasts fire over a large area temporarily increasing heat, emissions, and plume buoyancy, thus driving smoke out of the atmospheric boundary layer to be dispersed far downwind. Thus, according to Daysmoke, not all prescribed burns are equal. A 400 acre aerial ignition burn may yield far less ground-level smoke concentrations than ten 40 acre hand ignition burns. Figure 1 shows the conceptual plume modeled by Daysmoke. The visible plume is seen to grow from the ground to near the top of the mixing layer (atmospheric boundary layer). Depending on plume buoyancy, none, some, or much smoke may be ejected into the free atmosphere above the mixing layer. In addition, some smoke is detrained from the plume as it mixes with ambient air.

Daysmoke to date has not received rigorous validation as has BlueSky (BSRW, 2006), but preliminary results indicated it also suffered from the tendency to underestimate ground-level smoke concentrations. This problem can be addressed in Daysmoke in two ways. First, ground-level smoke concentrations can be increased by increasing the detrainment coefficient albeit unrealistically. Second, the design of Daysmoke permits multiple plume pathways.

The design of Daysmoke calls for the injection of large numbers of particles through inverted cones that define the plume volume. These cones are recalculated at 10-min intervals give the model time dependency (Figure 2). This inverted cone design of Daysmoke offers an additional "degree of freedom" that allows multiple updraft cones to exist simultaneously. Accordingly, smoke plumes from some prescribed burns may be simple in structure and may best be modeled as single-core updrafts as is done by most smoke plume models or other prescribed burns may be much more complex in plume structure and be modeled as multiplecore updrafts of varying size and intensity. Daysmoke was effectively telling us to be on the watch for complex plume structures that could impact the efficiency of smoke transport and dispersion.

Multiple-core updrafts are not as efficient as are one-core updrafts in the vertical transport of equivalent amounts of smoke mass. Multiple-core updrafts have smaller initial updraft vertical velocities and temperature anomalies and thus decreased initial buoyancy. Furthermore, entrainment more effectively reduces buoyancy of multiple core updrafts with smaller effective plume diameters. Therefore, in comparison with one-core plume updrafts, multiple-core updrafts lack vigor in transporting smoke into the free atmosphere above the mixing layer.

An opportunity to test the multiple-core updraft plume concept was presented by the Brush Creek smoke incident at Asheville, NC, on 18 March 2006 (Jackson, et al, 2006). Approximately 1840 acres of mountainous woodland was ignited by aerial ignition. The plume from the burn originated from the Cherokee National Forest near the Tennessee/North Carolina State line (upper left hand corner of Figure 3) approximately 30 miles northwest of Asheville. The site had never had a prescribed fire nor had a wildfire occurred recently. The District staff estimated 26.9 metric tons of fuel would be consumed for each hectare burned. It would be expected that this fire would generate huge emissions and a large amount of heat that would loft the emissions into the free atmosphere above the mixing layer to be carried down wind above Asheville.

Even though the plume may be clearly visible as a single plume by satellite (Figure 3) thus implying the existence of a single plume updraft, plume dynamics may be much more complex. Photo images of the Brush Creek prescribed burn were taken from several locations during the burn. Figure 4 shows an enhanced image of the smoke plume. Two distinct updraft cores are visible in the image. These updraft cores are part of a string of weaker updraft cores that define the long line axis of the burn. Therefore, at least three and possibly more separate updraft cores define the Brush Creek plume.

Figure 5 shows the maximum hourly  $PM_{2.5}$  concentration at Asheville as calculated by Daysmoke for updraft cores of equal size. The figure gives the mean and range for tensimulations. Maximum hourly concentrations range from 42 µg m<sup>-3</sup> for a one-core plume updraft to 244 µg m<sup>-3</sup> for a ten-core plume updraft.  $PM_{2.5}$  concentrations from the 1-core solutions were all under-predictions of observed levels at Asheville (130 µg m<sup>-3</sup> – dashed line). Furthermore, concentrations from the 10-core solutions were all over-predictions of observed levels. Although the mean of the 4-core solution (141 µg m<sup>-3</sup>) was closest to the Asheville observation, some results from the 3-core and 5-core solutions also bracketed the 130 µg m<sup>-3</sup> concentration.

To the extent the Brush Creek results can be extrapolated to a wider range of prescribed burns, it can be expected that one-core and ten-core updraft plume solutions by Daysmoke can differ by as much as a factor of 6 in ground-level PM concentrations. This range of variability may exceed most or all of the error ranges inherent in fuel type, fuel loading, and combustion modules. Thus the multiple-core updraft plume problem identified by Daysmoke may be the singlemost limitation to the accuracy of modeling frameworks such as BlueSky or SHRMC-4S (Liu et al, 2007).

Daysmoke has identified a cause for underestimated ground-level smoke concentrations yet Daysmoke offers not a clue as to how the number of cores should be specified before the model is executed. Three key factors in the organization of smoke plumes are wind speed, heat production from burning fuels, and distribution of fire over the landscape. Conceptually, these factors can be linked through high-resolution coupled fire-atmosphere models (Clark et al, 1996; Linn et al, 2002; Cunningham and Linn, 2007). However, the complexity of initial conditions, the number of simulations required to classify causes and effects, and the magnitude of computer resources and time required to obtain the simulations, precludes meaningful results for the foreseeable future.

#### **3. A Solution? Rabbit Rules**

Rabbit Rules (Achtemeier, 2003) is a rule-based fire spread model designed to simulate relative emissions production for Daysmoke. It is based on the premise developed by Wolfram (2002) that complex partial differential equations can be replaced by simple rules that can be formulated as computer algorithms and solved recursively. A "rabbit" is an "autonomous agent" representing a "unit area of fire" defined internally in the model. The rabbit is subject to rules that govern production, elimination, and behavior over a landscape of heterogeneous fuels, complex terrain, and variable weather. Rabbit behavior is also impacted by the locations and behaviors of neighboring rabbits. The outcomes are complex distributions of fire, fire behavior, fire spread, and fire weather.

A coupled fire/weather rule requires Rabbit Rules to manage the distribution of temperature within the plumes of heated air discharged from burning areas. The warm smoke plumes impact hydrostatic air pressure at the ground via,

$$\Delta p = \frac{P_0 g}{R} \Delta z \left( \frac{1}{T_1} - \frac{1}{T_0} \right) \tag{1}$$

where  $P_0 g/R = 34.83$  for a typical surface pressure of 1020 mb (102 kpa). If the ambient and plume temperatures are, respectively, (T<sub>0</sub> =280K) and (T<sub>1</sub>=290K), then, for a plume thickness ranging from 10m to 100m, the surface pressure anomaly ranges from -0.04 mb to -0.40 mb. These pressure anomalies are sufficient to perturb the local wind field thus giving a ground-level signal of the location of the smoke plume.

Rabbit Rules can therefore identify and locate multiple-core updrafts on the scale from 10's to 100's of meters through both the surface pressure anomalies and disturbances within the surface wind field. Figure 6 shows a Rabbit Rules simulated fire at 1513 local time following a point ignition at 1500. The colors, yellow, orange, and red identify rabbits subject to differing bookkeeping rules in the model. Wind directions (shanks) and speeds (barbs: short barb=5 kt and long barb=10 kt) are spaced at 60 m intervals. Surface pressure anomaly is contoured in intervals of tenths of millibars. The figure shows a single pressure center of -0.4 mb located at the head of the fire. A disturbed wind field extends downwind from the pressure center along the axis of low pressure. Both the pressure field and the wind field support the inference that this fire was producing a single-core updraft smoke plume.

Figure 7 shows the simulated fire at 1517. The fire has burned to a fire break (thick black line) and the winds have shifted to blow more toward the remaining flanks. The pressure anomaly has separated into two distinct centers with supporting local wind fields. However, the more distant downwind wind field still shows the single outflow pattern shown in Figure 6. The wind and pressure patterns shown in Figure 7 support the inference that the burn was supporting a 2-core updraft smoke plume or a 2-core updraft plume that merged into a single-core updraft plume higher up.

By 1523 (Figure 8) both the pressure field and the wind field had separated into two separate centers. These patterns support the inference that the burn was supporting a 2-core updraft plume if not two separate plumes.

Rabbit Rules can also show variability within the flaming areas on the scale of 1's to 10's of meters. Figure 9 shows the number of rabbits found within a 9x9 pixel area at 1513. Local variability in the number of rabbits can be explained by unlevel terrain, the wind field directed toward the head, and the rules controlling the response of each rabbit to the behavior of its neighbors. Thus Rabbit Rules identifies "hot spots" that can support local updraft cores.

## 3. Discussion

Daysmoke has identified a mechanism of smoke plume dynamics - multiple-core updraft plumes - within wildland fire that may be the singlemost limitation to the accuracy of modeling frameworks such as BlueSky and SHRMC-4S and to air quality models in general that include emissions inventories from prescribed burns. Daysmoke offers no assistance on solving the problem and we must look to complex coupled fire/atmosphere models or to rule-driven models such as Rabbit Rules to supply the needed information on plume core dynamics.

From a science perspective, what additional modeling efforts must be undertaken to gain the needed understanding of how plume cores organize? How many layers of models and how much computer power will be eventually needed to solve the problem? What kinds of field experiments must be set to gain data needed to demonstrate that the models are telling the truth? From a regulatory perspective, when is it decided that "enough is enough"? Why not simply assign core number randomly for a large number of burns and run air quality models with the assumption that, in the mean, the solution tends toward the right answer? Would it not be just as easy to argue that, in the mean, the solution tends toward the wrong answer? How would such an argument hold up in a litigious environment?

From a land manager perspective, the conflict between managing for natural resources and managing for air quality has placed Southern land managers in the difficult position of "getting it right all of the time." The land manager can select a day with near-optimal wind conditions from the 15 or so days during a typical year that fit his burn prescription. He can determine how fire is distributed over his landscape and how much fire to distribute. He can, at least in theory, determine the core number of his plume. What information does the land manager need to engineer his burn to minimize ground-level smoke? What scale of research program and what resources must be marshaled to get him the information he needs?

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**Figure 1.** A conceptual model of a "typical" smoke plume (darkened area) and a trailing "pall" of detrained particulate matter. The top of the mixing layer is given by the dashed line.



**Figure 2.** Centerline cross section through inverted cones that define Daysmoke plume volumes for a typical prescribed burn. Vertical tic lines at the bottom of the image are at 1 km intervals. Horizontal tic lines up the right hand side of the image are at 100m intervals. The horizontal line identifies the top of the mixing layer.



**Figure 3.** 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.



Figure 4. Plume from the Brush Creek prescribed burn on 18 March 2006.



Figure 5. The means and distributions for each updraft core number compared with the maximum hourly  $PM_{2.5}$  concentration (dashed line) observed at Asheville, NC.



**Figure 6.** Rabbit Rules simulated fire moving through uniform fuels over complex terrain at 1513 LT. Wind directions (shanks) and speeds (barbs: short barb=5 kt and long barb=10 kt) are spaced at 60 m intervals. Surface pressure anomaly is contoured in intervals of tenths of millibars.



Figure 7. Same as Figure 6 but for the simulated fire at 1517.



Figure 8. Same as for Figure 6 but for the simulated fire at 1523.



Figure 9. The number of rabbits found within a 9x9 pixel area at 1513. (See Figure 6)

Key words: Daysmoke, plume model, updraft, core, smoke, fire, emissions,