

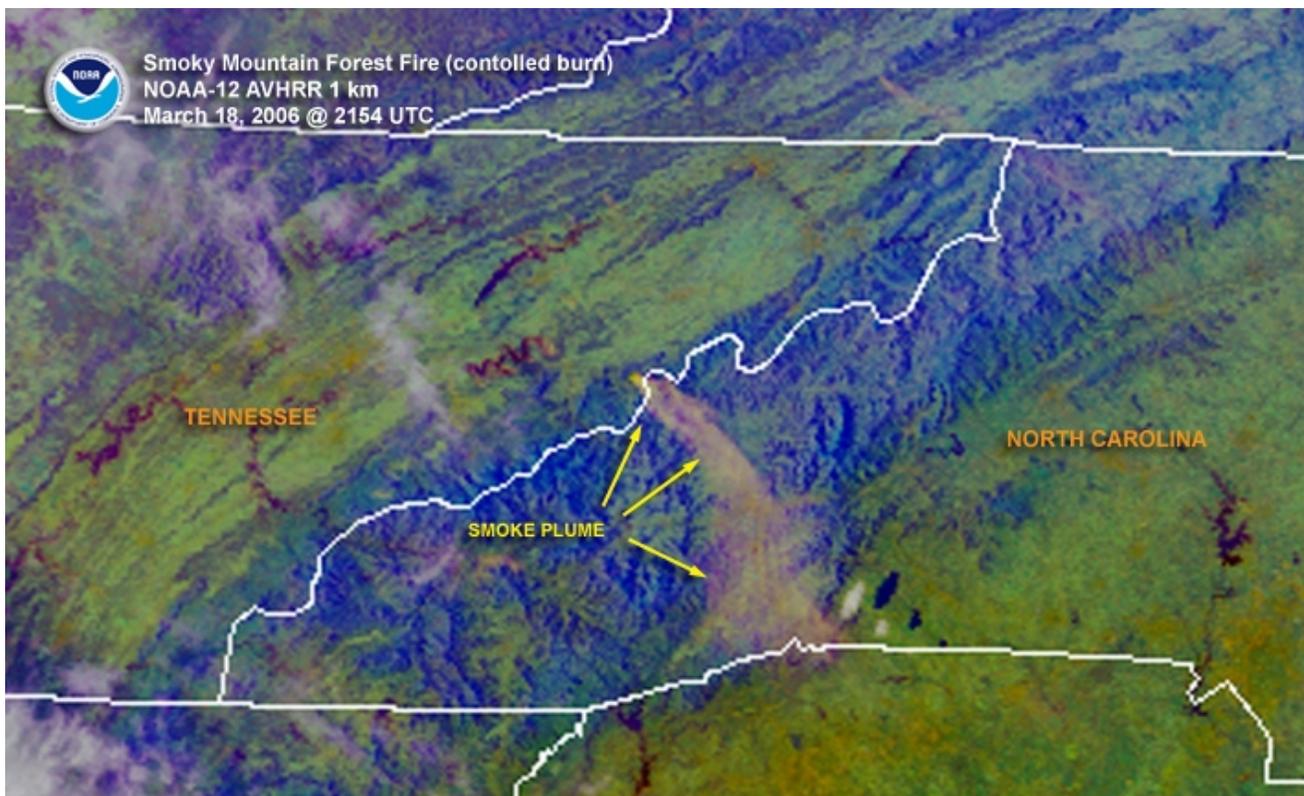
A Technical Evaluation of Smoke Dispersion from the Brush Creek Prescribed Fire and the Impacts on Asheville, North Carolina

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This paper describes a smoke incident associated with the Brush Creek prescribed burn conducted on the Cherokee National Forest. Meteorological and emission characteristics are investigated in depth to explain why the smoke dispersed as it did, and recommendations are provided that may improve smoke management on future prescribed burns.

What happened to smoke dispersed from the Brush Creek prescribed fire?

The Cherokee National Forest implemented the Brush Creek prescribed fire with the ignition beginning about 12:20 PM on March 18, 2006. The spot weather forecast by the Greenville, Tennessee office of the National Weather Service predicted the following conditions for the Brush Creek area:

Mixing Height: around 4100 feet above ground level

Transport Winds: from the Northwest at about 15 miles per hour

Sky/Weather: Partly Cloudy

Surface Temperature: 40 degrees Fahrenheit, with a possible maximum of 51⁰ F

Relative humidity: 58 percent with possible minimum of 35%

Windspeed at 20 feet above ground: from the Northwest at 8 miles per hour

The Brush Creek burn unit was 1840 acres, but the firing pattern was designed to result in a mosaic type burn with fuels being consumed in about 90 percent of the area (about 1656 acres). The unit had never had a prescribed fire, nor had a wildfire occurred recently in the unit. The District staff estimated about 12 tons of fuel would be consumed for each acre burned. Aerial ignition of the Brush Creek unit occurred along the main and spurs ridges between 12:20 and 2:00 PM and moved down the side slopes between 2:00 and 4:20 PM until no fuels were available to ignite. Further aerial ignition was accomplished between 4:20 and 5:10 PM and the active fire phase ceased in the burn unit about noon on March 19, 2006 (Figure 1).

Complaints about smoke, including concerns for a possible wildfire, were received by the Asheville Dispatch Office (National Forests in North Carolina) from concerned citizens near Hot Springs, North Carolina about 1:30 PM. Another citing of smoke occurred near the Madison and Buncombe County line about 2:00 PM. Numerous complaints were received from the public as the smoke followed the French Broad River valley between Hot Spring and Asheville, North Carolina (Figure 2). Furthermore, some people moved into their homes because they had difficulty breathing, and local fire personnel responded to numerous calls only to find no wildfire was present.

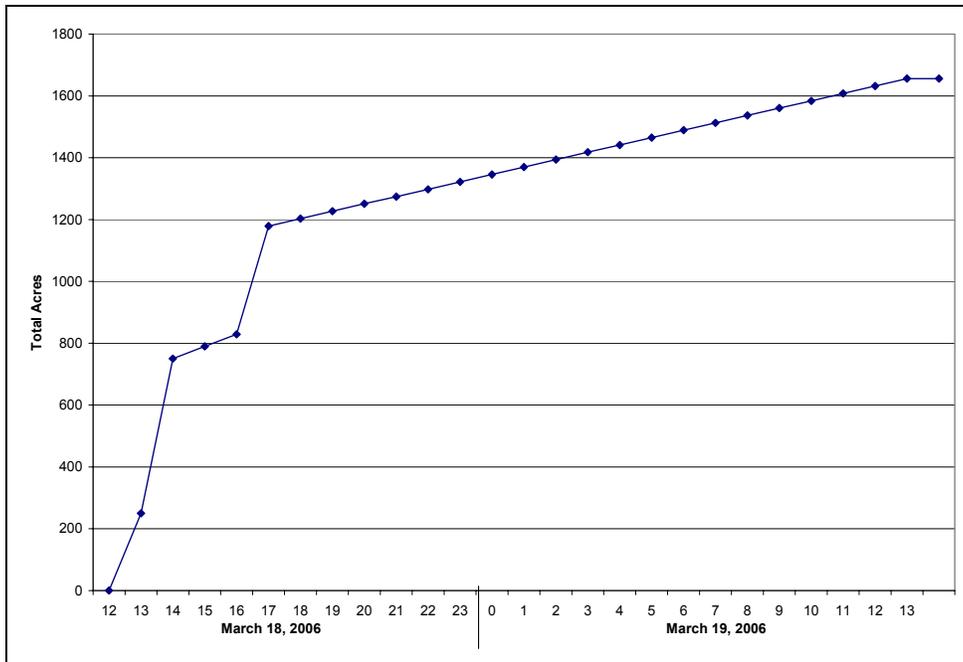


Figure 1. The estimated total number of acres each hour in an active and/or smoldering fire phase for the Brush Creek prescribed fire.

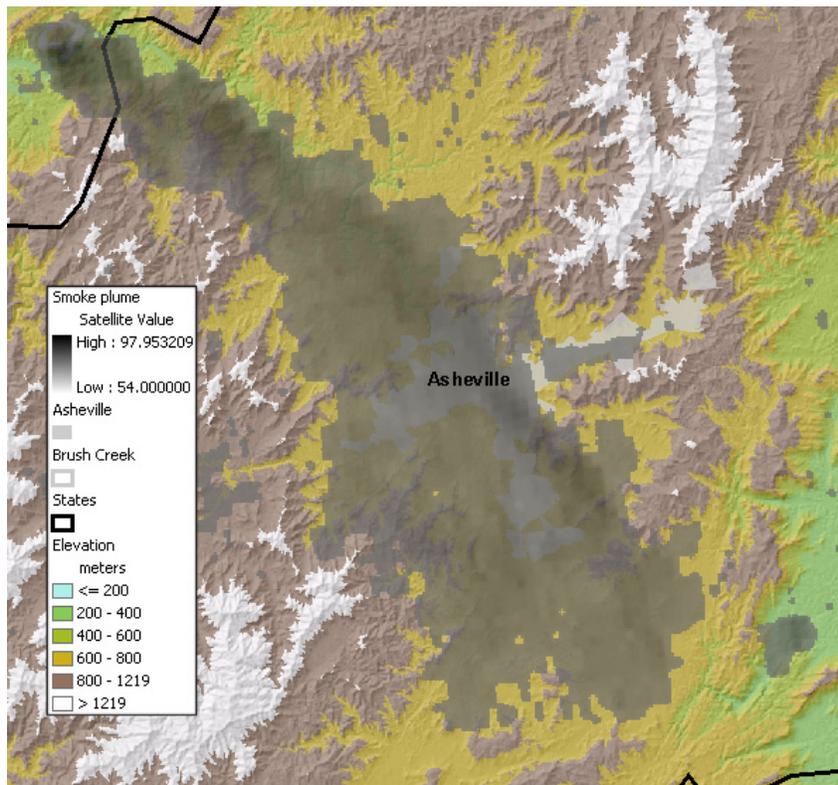


Figure 2. Smoke plume image processed from the Polar satellite (received from National Oceanic and Atmospheric Administration) showing the cloud of smoke from the Brush Creek prescribed fire at 5:15 PM.

High concentrations of fine particles (PM_{2.5}) can have a negative impact on people's health. The Environmental Protection Agency has developed a color coding system called the Air Quality Index (AQI) to help people understand what concentrations of air pollution may impact their health. When the AQI value is color code orange then people who are sensitive to air pollutants, or have other health problems, may experience health effects. This means they are likely to be affected at lower levels than the general public. Sensitive groups of people include the elderly, children, and people with either lung disease or heart disease. The general public is not likely to be adversely affected when the AQI is code orange. Everyone may begin to experience health effects when AQI values are color coded as red. People who are sensitive to air pollutants may experience more serious health effects when concentrations reach code red levels.

Elevated fine particulate matter concentrations were measured at a monitor in Asheville which is operated by the Western North Carolina Regional Air Quality Agency. The continuous monitoring conducted by Western North Carolina Regional Air Quality Agency meets Federal Reference methods criteria established by the Environmental Protection Agency. The hourly average concentrations measured were greatest between 4:00 and 7:00 PM, with the average maximum concentration reaching 131 micrograms per cubic meter between 5:00 and 6:00 PM. These values were equivalent to a 1-hour AQI value of code orange which indicates some people who are sensitive to air pollutants or have other health problems may have experience short-term health problems. The average fine particulate matter concentrations returned to good levels between 8:00 and 9:00 PM at the monitoring site (Figure 3).

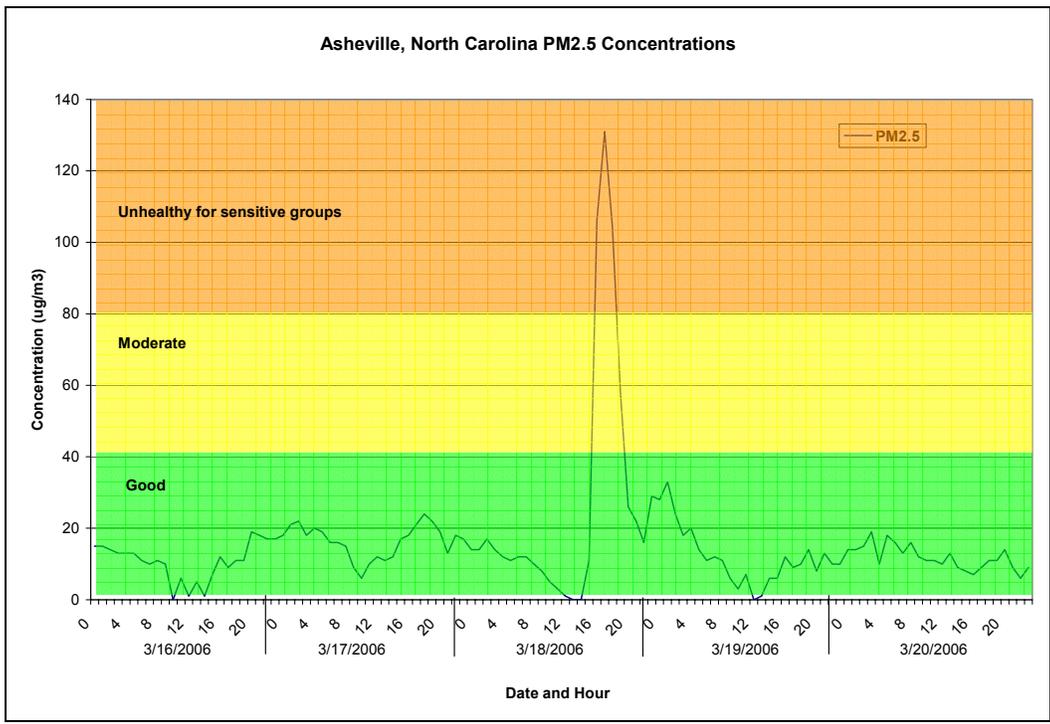


Figure 3. Fine particulate matter concentrations (micrograms per cubic meter) measured at the Buncombe County Board of Education monitoring site in Asheville, North Carolina between March 16 and March 20, 2006. Elevated fine particulate matter concentrations on March 18, 2006 were a result of emissions from the Brush Creek prescribed fire conducted in Cocke County, Tennessee.

The Smoke Management Plan: What analysis was required?

All prescribed fires conducted by the Forest Service are required to have a smoke management plan within the prescribed burn plan (Forest Service Manual 5100, Chapter 5140). The Southern Region has developed additional guidance (Supplement R8-5100-2005-1) that contains a section on smoke management (5144) for prescribed burners to follow. Two important requirements are 1) the preparation of a simple geometric smoke screening map (R8 Smoke Plume Plotter, 5144 – Exhibit 1) to see if the smoke might impact any smoke sensitive targets downwind of the prescribed fire, and 2) having a Dispersion Index (Lavdas 1996) 21 or greater.

An example of the smoke screening map for the Brush Creek prescribed fire using the R8 Smoke Plume Plotter is illustrated in Figure 4. Two lines drawn at 30 degree angles from the burn unit indicate the area where smoke could impact sensitive targets. The downwind distance from the burn unit that should be considered in the analysis depends on the fuel loading. The example in Figure 4 shows the downwind boundary (or the length of the lines) at 10 miles out, which is the recommendation for burn units greater than 250 acres. (Note that the area of concern did not extend to Asheville, NC.)

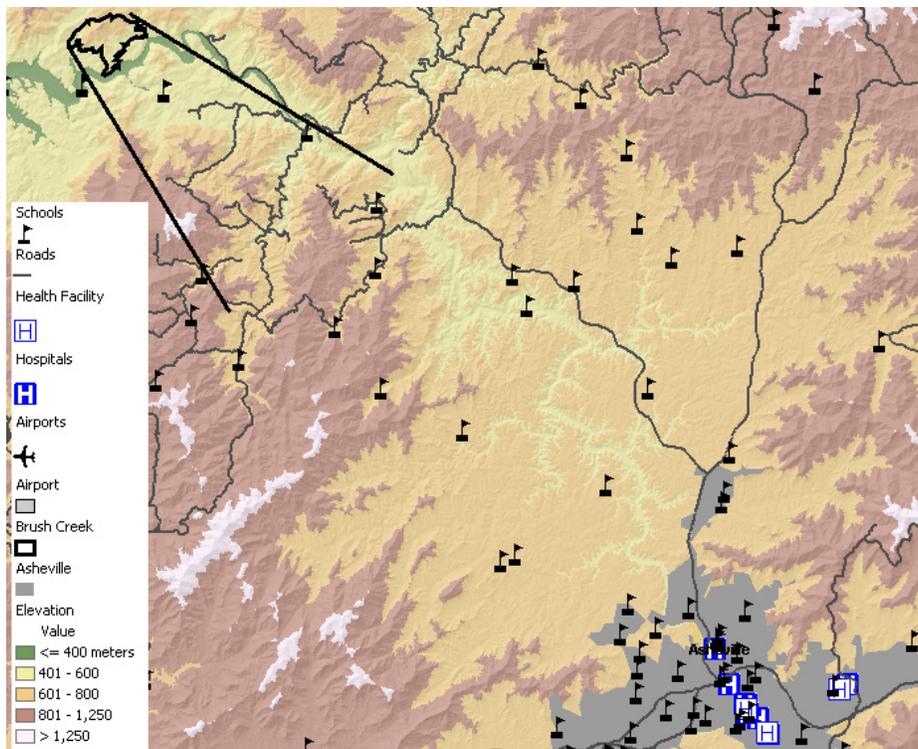


Figure 4. An example of the smoke screening map for the Brush Creek prescribed fire using the R8 Smoke Plume Plotter.

The second important parameter to consider is the Dispersion Index (Lavdas 1996). Dispersion Index (DI) is calculated using estimates of mixing height, transport wind speed, and stability class. There are several ways that fire managers can determine DI for the day of the burn. Some fire weather forecasters include the Lavdas DI (1996) in the daily forecast or in spot weather forecasts.

However if DI is not reported it can be calculated or found in other places. One way to calculate both the stability class and the DI is to use the VSMOKE computer software (found at: <http://199.128.173.141/vsmoke/>).

The USDA Forest Service staff did not know or calculate DI on the day of the burn. However, calculations done after the burn using the VSMOKE software and meteorology from the spot weather forecast indicated the DI was equal to 69. The spot weather forecast for March 18, 2006 predicted the mixing height to be 4100 feet and the transport wind speed to be 15 miles per hour. The stability class is calculated by knowing the location of the burn, time and date, surface wind speed (predicted at 8 miles per hour), and the amount and height of the cloud cover. The weather forecast predicted partly cloudy conditions. Without more specific information a person might assume this is equal to 40 percent cloud cover and a height of 4000 above ground level to the bottom of the clouds. Using these as inputs for 1:00 PM, the VSMOKE software estimated the stability class to be moderately unstable and the DI to be 69. Dispersion Index values can range between 1 and values greater than 100. A DI value of 69 indicates good weather conditions for smoke dispersion (Lavdas 1996).

The Lavdas DI can also be found on the internet. The Southern High Resolution Modeling Consortium (SHRMC) of the USDA Forest Service posts daily estimates of the Dispersion Index and other meteorological parameters on the internet (see <http://shrmc.ggy.uga.edu/>). SHRMC uses the MM5 (Mesoscale Model, 5th version) meteorological model to calculate the DI for each hour of the day at a 12 kilometer resolution. The predicted SHRMC values for the Dispersion Index at the burn site on March 18 were between 30 and 36. The MM5 predicted a mixing height of about 2600 feet, which was significantly less than predicted in the spot forecast (4100 feet). However, transport winds were in reasonable agreement at approximately 16 miles per hour.

However, burning a large amount of acres in a short amount of time will release a large amount of water (seen as smoke) into the atmosphere, which will act like clouds (see Figure 2). Assuming the smoke will act like a cloud layer then it would be safe to assume a 60 percent cloud cover. Using this as an input into the VSMOKE model then the stability class is decreased to near neutral and the calculated Dispersion Index is 40, or fair conditions for smoke dispersal. Both of the calculated values (69 and 40) presented are above the Regional Guidelines of a Dispersion Index of 21 or greater.

Following the current guidelines for preparing the smoke screening map (Figure 4), District staff concluded smoke from the Brush Creek prescribed fire would not impact any sensitive target within 10 miles of the burn unit. If the Dispersion Index had been calculated or estimated from the SHRMC website then a person may have concluded the atmosphere had adequate capacity to disperse the smoke from the prescribed fire. So, implementing the minimum required Regional guidelines for estimating smoke dispersion and downwind impacts from the Brush Creek prescribed fire did not protect air quality for up to 30 miles downwind of the prescribed fire.

In addition to using the R8 Smoke Plume Plotter, the Region 8 Supplement for Fire Use (Forest Service Manual 5100, Chapter 5140) says “utilize where appropriate, computerized dispersion models such as Program VSMOKE ... to determine ground level movement of residual smoke and concentrations ...”

Both VSMOKE (Lavdas 1996) and VSMOKE-GIS are simple (Gaussian) dispersion models that predict the downwind concentration of particulate matter from a prescribed or wildfire. These models are conservative in that they tend to over-predict the downwind concentration of particulate matter (PM_{2.5}) and are best suited for flat to gently rolling terrain. Therefore, caution must be employed in mountainous terrain when interpreting the results. For example, the smoke plume will not go through the mountain, but instead will move to one side or the other and follow the valleys, or travel over the peaks and ridgelines (see Figure 5). Despite this limitation, the VSMOKE and VSMOKE-GIS can provide more information to consider than using only the Dispersion Index and/or geometric screening.

The inputs into VSMOKE and VSMOKE-GIS models included the weather parameters from the spot weather forecast and an assumption there was 60 percent cloud cover at 4000 feet elevation. The fine particulate matter emissions release rate followed the profile shown in Figure 1. The Fire Emission Production Simulator (FEPS) (<http://www.fs.fed.us/pnw/fera/feps/>) was used to estimate the fine particulate and heat release rates. The inputs to the FEPS model included a FCCS fuel bed classified as chestnut oak - white oak – red oak (FCCS: 275) and the consumption was set to moderate fuel moisture. This resulted in an estimated 13.1 tons per acre of fuel consumed, which is close to the District estimate of 12 tons per acre. The hour with the maximum release of particulate matter was 2:00 PM, so this was used to predict the “worst case” concentrations down wind of the burn unit. The VSMOKE estimated maximum 1-hour fine particulate matter concentration at a distance approximately the same as the Buncombe County monitors (31 miles) was 173.49 micrograms per cubic meter (Figure 5). This estimate is slightly higher than the monitored value of 131 micrograms per cubic meter between 5:00 and 6:00 PM (Figure 3). Had the fire managers had the VSMOKE modeling results (Figure 5) then they may have chosen **to not** ignite the prescribed fire.

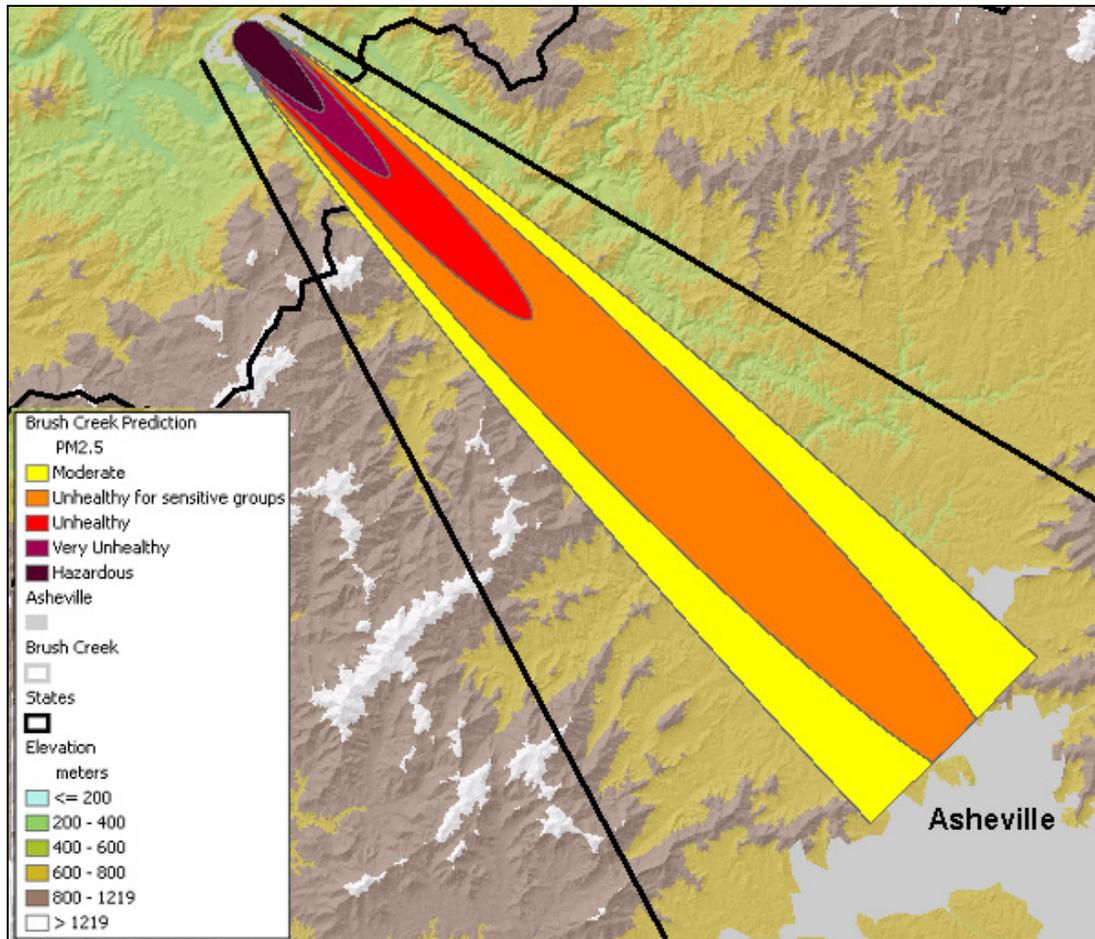


Figure 5. Predicted fine particulate matter concentrations from VSMOKE-GIS for the Brush Creek prescribed fire. The inputs included information from the spot weather forecast and the hour with the maximum emissions using the Fire Emission Production Simulator (FEPS) model.

What went wrong?

The mixing height, or the depth of the atmospheric layer in which smoke is diluted, can change throughout the course of a day and this can affect smoke dispersion. Plume collapse may have occurred on the Brush Creek prescribed fire and is one factor that could have contributed to the smoke incident. Plume collapse is a meteorological situation that fire managers currently have difficulty predicting.

Previous atmospheric modeling experience (with a model call Daysmoke, which is discussed below) has shown most of the PM_{2.5} ground-level concentrations from a well-managed prescribed fire occur at the beginning and end of the burn. This occurs because smoke mixes down (caused by unstable atmospheric conditions) to the ground during the weakly buoyant “ramp-up” stage at the beginning of the burn, and is then dispersed within a deep mixed layer during the “ramp-down” stage at the end of the burn. Significant departures from this simple scenario can occur if mixing layer growth differs

from what may be regarded as a “typical day.” As smoke rises it is also transported by winds throughout the atmosphere from an area of high concentration above the burn site and is diluted as it travels downwind. Part of the dilution of the smoke is also a result of circular motions in the atmosphere (called unstable atmospheric conditions).

During a “typical day” the depth of the mixing layer grows rapidly during the late morning. It is during this period that smoke from the “ramp-up” stage of a burn gets mixed back to the ground. Mixing layer growth levels off during the early afternoon reaching a maximum around 2-4 PM. When “mass ignition” is used on a burn and a strong convective column is formed, it is possible for the plume to penetrate into the free atmosphere above the mixing layer to an altitude sufficient to place the plume above the remaining growth of the mixing layer during the afternoon. Thus the bulk of smoke mass remains aloft to be carried long distances downwind and dispersed. It has been estimated that 30 percent of the particulate matter released from a prescribed fire is dispersed above the mixing layer (Achte-meier, unpublished results).

In the event that deepening of the mixing layer is slow to develop in the morning and does not reach the maximum until the afternoon, then afternoon mixing layer may grow above the altitude of a smoke plume that had been in the free atmosphere earlier. If the smoke released earlier in the day is found below the mixing height in the afternoon then the smoke becomes available to be mixed to the ground in high concentrations. This phenomenon is called “plume collapse” and prescribed fire professionals do not have information available before the ignition has begun to predict when plume collapse is likely to occur.

Evaluation of the Greensboro, North Carolina morning (0700 EST) sounding after the smoke incident showed that March 18, 2006 may have been an “atypical day” with regard to mixing layer growth. A second inversion (3000 to 4000 feet) was present and this would have reduced mixing layer growth rate as temperatures recovered from early morning lows. The mixing heights for Asheville (Figure 6) were calculated by subtracting the difference between the Asheville and Greensboro elevations from the height of the mixing layer in the Greensboro soundings. The depth of the mixing layer increased from 1300 feet at 12:00 PM EST (approximate time of ignition) to 1650 feet at 1:00 PM EST, then remained nearly unchanged to 2:00 PM EST (the end of the first ignition period). Then the mixing layer increased to approximately 3300 feet at 3:00 PM EST. At 5:00 PM EST, during the time of maximum surface temperatures, the mixing layer increased further to 5634 feet. The predicted mixing height development near Asheville (based upon the Greenville, NC data) is an example of meteorological conditions where plume collapse can occur.

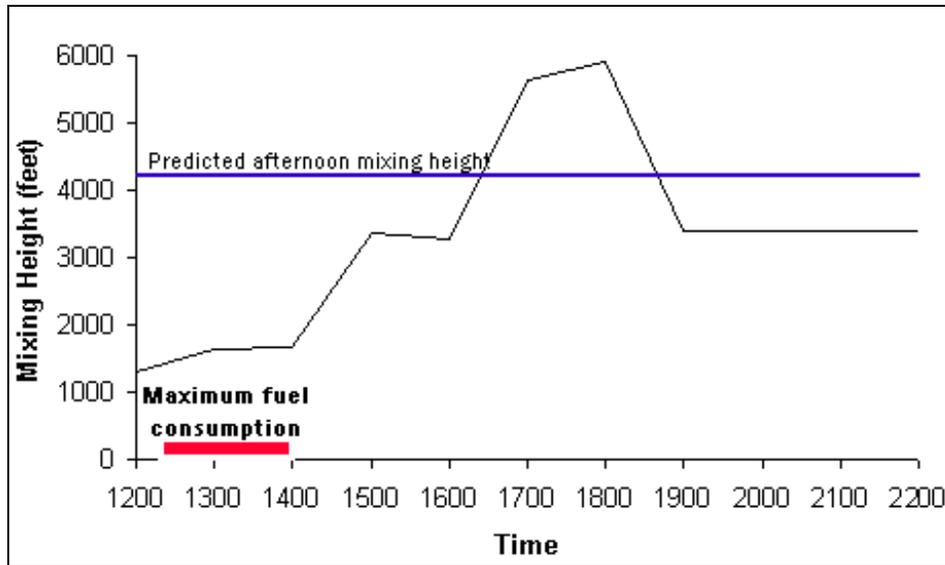


Figure 6. Mixing heights calculated for Asheville from the Greensboro, NC, rawinsonde temperature profiles modified by the Knoxville, TN hourly surface temperatures.

A second factor that probably contributed to the smoke incident is too many tons of fuel was consumed in too short of a time period for the forecasted meteorological conditions. Smoke dispersion modeling was utilized to evaluate this possibility. The VSMOKE and VSMOKE-GIS dispersion models have been used effectively in the planning of prescribed fires throughout the southeastern United States. Perhaps the greatest strength of an atmospheric modeling system is the ability to evaluate different scenarios.

The two main inputs that can change the predicted outcome of VSMOKE and VSMOKE-GIS (or any other smoke dispersion model) results shown in Figure 5 are the amount of particulate matter released over time and the meteorological conditions. The Brush Creek prescribed fire was started at approximately 12:30 PM, so the first scenario evaluated was to use the models to explore what might have happened if the control burn would have been started at 10:00 AM and had a constant fire rate (Figure 7) until 3:00 PM. This would have reduced the maximum number of acres burned in any hour to 250 acres, and by 1:00 there would have been 947 acres in an active fire phase or smoldering phase instead of 750 acres as had occurred on the day of the burn. However, the emission rate would have been reduced from 7636.7 grams per second to 3945.3 grams per second, which may have reduced the cloud cover from 60 percent to 50 percent. Comparing VSMOKE-GIS results in Figure 8 to Figure 5, it is evident the smoke impact would have significantly been reduced in Asheville. The VSMOKE results predicted the fine particulate matter concentration at approximately 31 miles as 48.58 microgram per cubic meter, which would be classified as “Moderate” according to the AQI.

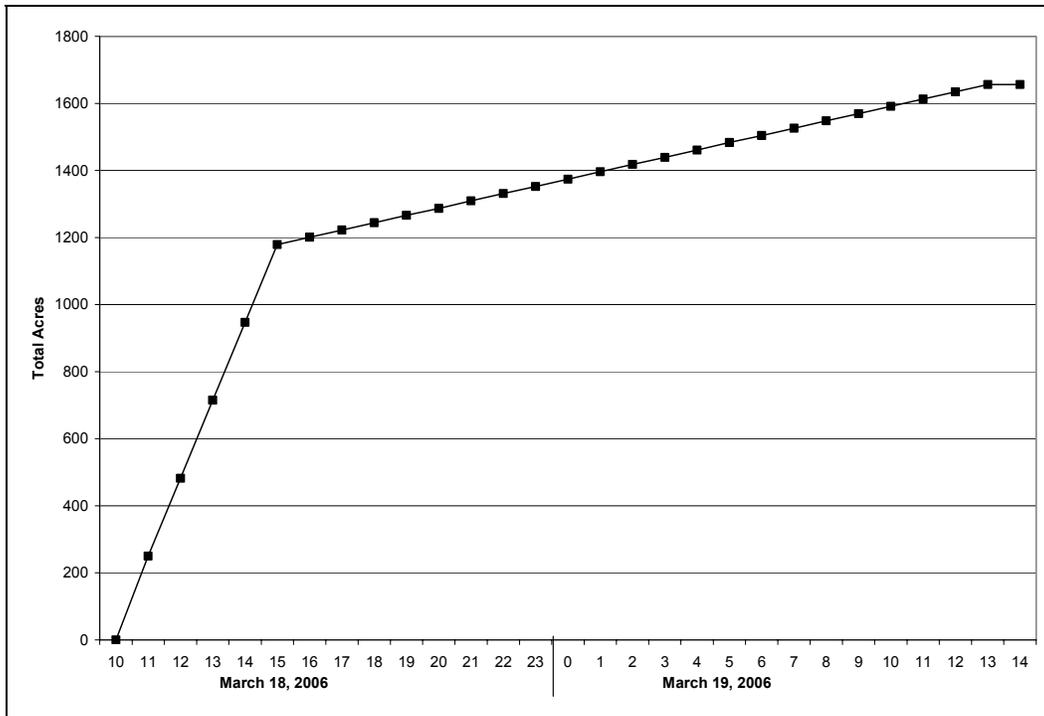


Figure 7. The estimated total number of acres each hour in an active and/or smoldering fire phase for the Brush Creek prescribed fire if the fire was started at 10:00 am and there was a constant fire rate of spread until 3.00 PM.

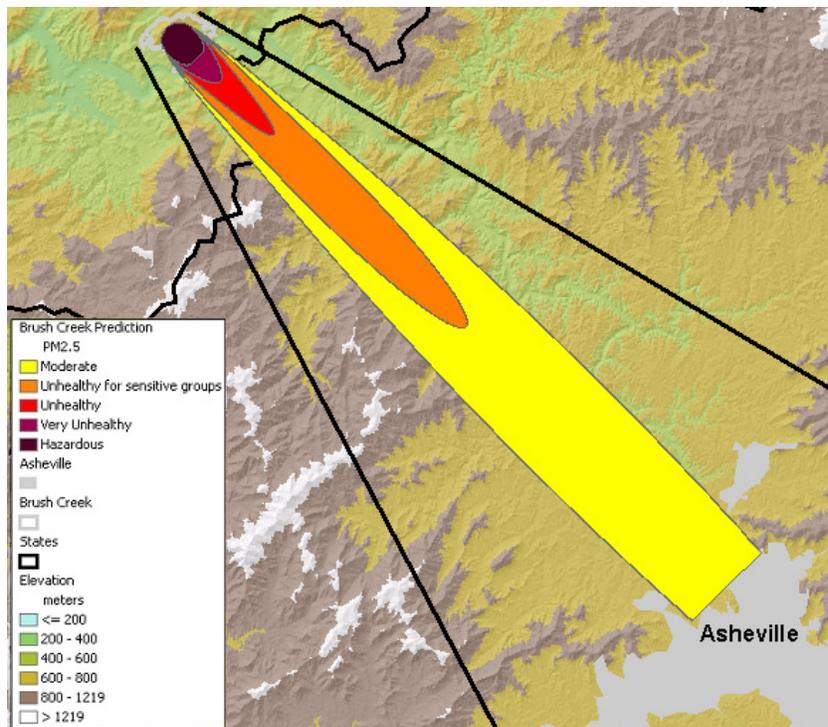


Figure 8. Predicted fine particulate matter concentrations from VSMOKE-GIS for the Brush Creek prescribed fire if the ignition had been started at 10:00 AM.

A second scenario was performed where the emission rate was the same as the first scenario and the mixing height was increased from 4100 feet to 6000 feet above ground level. Figure 9 shows the VSMOKE-GIS results and it is evident the smoke impact would have been significantly reduced in comparison to Figure 5. For this scenario, the VSMOKE results predicted the fine particulate matter concentration at approximately 31 miles as 32.45 microgram per cubic meter, which would be classified as “Good” according to the AQI.

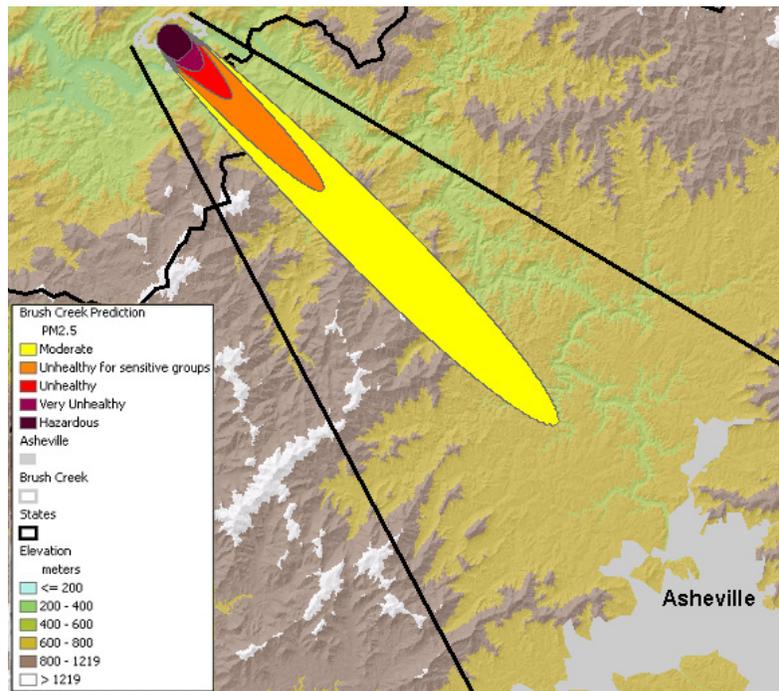


Figure 9. Predicted fine particulate matter concentrations from VSMOKE-GIS for the Brush Creek prescribed fire if the fire had been started at 10:00 AM and increasing the mixing height to 6000 feet above ground level.

A third scenario evaluated was if the prescribed fire was conducted on another day when the fuel moisture was greater. Greater fuel moisture will reduce the amount of fuel consumed by a prescribed fire. However, it should be noted the spread of the fire can be limited if fuel moisture is too high, which may result in the resource objectives not being achieved. The initial FEPS model inputs used moderate fuel moisture content and this resulted in an estimate of 13.1 tons per acres of fuel could be consumed. If the fuel moisture was increased to a moist classification (1-hour fuel moisture content of 10 percent) then the FEPS estimated fuel consumption was 9.8 tons per acres. Burning under conditions with higher fuel moisture will reduce the amount of fine particulate matter released over time. Consequently, with a greater fuel moisture, a fire spread as in Figure 7, and a mixing height of 4100 or 6000 feet above ground level the VSMOKE-GIS model results predict a significant reduction (in comparison to Figure 5) in the downwind distance for the AQI value of code orange (Figure 10). The VSMOKE model predicted the fine particulate matter concentration at approximately 31 miles to be 32.33 micrograms per cubic meter if the mixing height was 4100 feet, and 23.68 micrograms per cubic meter if the mixing height was 6000 feet.

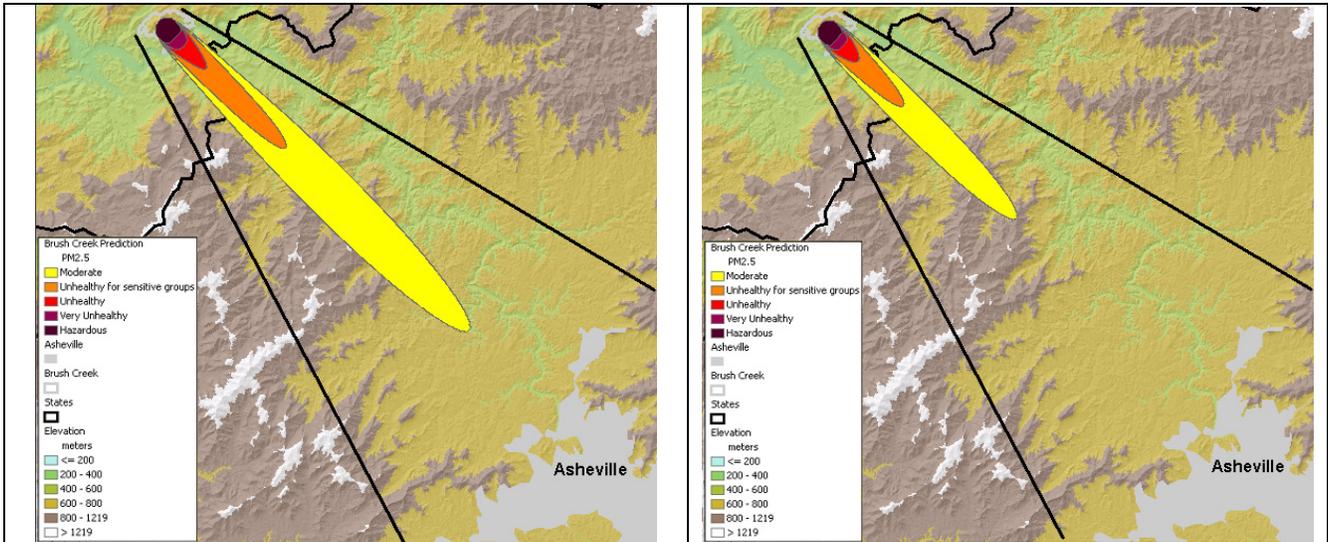


Figure 10. Predicted fine particulate matter concentrations from VSMOKE-GIS for the Brush Creek prescribed fire by starting the fire at 10:00 AM and decreasing the fuel consumed from 13.1 tons per acre to 9.8 tons per acre. The figure on the left has a mixing height of 4100 feet, while the figure on the right had a mixing height of 6000 feet.

A Preview of Future Smoke Dispersion Modeling Tools Designed for Mountainous Terrain

New tools are currently being developed to help predict smoke dispersal using the most advanced meteorological predictions. To demonstrate how these tools will aid fire managers in planning prescribed fires and deciding when to burn, the Brush Creek prescribed fire was evaluated using the results from advanced meteorological predictions (MM5), implementation of the BlueSky atmospheric model framework, and the Daysmoke model

MM5: The SHRMC MM5 results from March 18, 2006 were retrieved and used to examine the meteorology associated with the Brush Creek smoke incident. Weather predicted by MM5 produced reasonable results even though predicted mixing heights (2600 feet) were considerably lower than that forecast by the National Weather Service (4100 feet). Aerial observation of the height of the smoke from the District staff between 1:00 and 2:00 PM indicate the mixing height may have been 3000 feet above the ground, but the total height is unknown. Hourly observations of surface wind speed at the Asheville airport indicated winds exceeding 12 mph which were in good agreement with those predicted by MM5 (12-16 mph) during the time of the incident. Examination of observed upper atmospheric soundings from Atlanta, Georgia; Nashville, Tennessee; and Greensboro, North Carolina indicated a building mass of stable air aloft as indicated by warming at the 700 and 500 millibar levels. The building of this stable air mass was well captured by MM5 and may have played a role in the model producing lower mixing height values than the spot weather forecast.

BlueSky: Application of the BlueSky Smoke Modeling Framework, developed by the USFS Pacific Northwest Research Station, utilizes the MM5 results in combination with the CalPuff (California Puff) atmospheric dispersion model. CalPuff is a non-steady state model that keeps track of the location and concentration of pollutants from one time period to the next. The BlueSky model was

run using 12 km resolution terrain and meteorological inputs, which may have contributed to the poor predictions for Brush Creek prescribed fire. Predictions of ground level PM_{2.5} concentrations revealed no evidence of the plume until 10:00 PM local time (Figure 11) at which time a plume similar to the satellite image (Figure 2) appears. The overall plume shape indicates that BlueSky did a reasonable job in predicting the overall transport however the timing and concentration values are suspect. It should be noted that SHRMC is still evaluating BlueSky and attempting to best configure the system for use in the Southeast. Therefore, the poor results in timing and concentration are likely to be a result in improper inputs and other decisions made in the modeling configuration for a single prescribed fire.

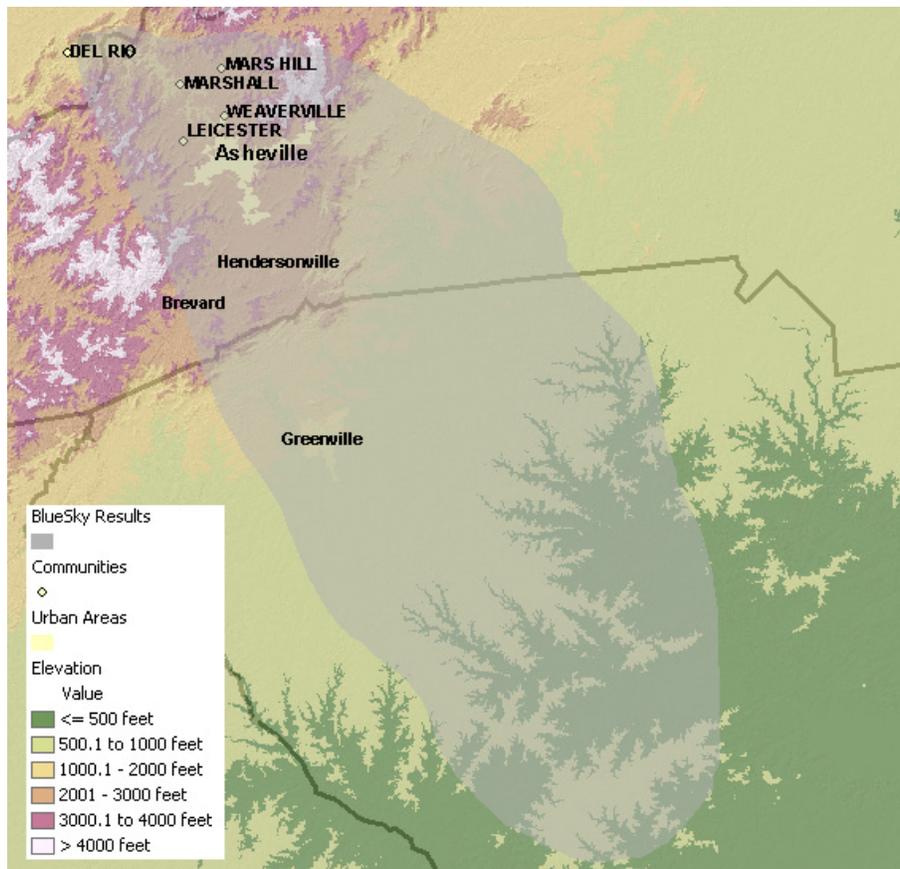


Figure 11. Results from the BlueSky Modeling Framework showing the location of the Brush Creek plume at 10:00 PM.

Daysmoke: Daysmoke is a computer model currently under development by USDA Forest Service Research scientists. Daysmoke is designed specifically to model prescribed burns in the manner the burns are planned by land managers. Daysmoke is a dynamical model that can simulate smoke plume collapse at long distances from a burn and can also partition smoke between the mixed layer and the free atmosphere above the mixed layer in the event the burn is designed to “punch through” the mixing layer (inversion). Daysmoke simulates the four-dimensional evolution of plumes through changing mixing layer depth in an evolving wind field.

Daysmoke was originally designed as a “smoke injector” into the most sophisticated atmospheric chemistry simulation model, called the Community Multiscale Air Quality (CMAQ) model. Since then, the Daysmoke is being converted into a stand-alone model for predicting local smoke concentration. At the current time, Daysmoke is not configured with an interface model utilizing weather data from high resolution meteorological models (such as MM5). Therefore, although Daysmoke does simulate smoke in time-dependent veering-sheering wind field, it does not count for differences in the wind field downstream from the burn site. Further, Daysmoke as now configured does not account for smoke movement through complex terrain, an issue of some concern as regards the Brush Creek incident. However, given the wide expanse of the French Broad river basin between the Brush Creek burn site and Asheville, the impact of complex terrain on model accuracy should be secondary to other factors.

Daysmoke consists of four computer models that simulate meteorology and smoke. They are:

- 1) An entraining turret model. The entraining turret model breaks a smoke plume into a series of turrets (or cylinders) that draw air in from the outside as they rise and expand with the plume. The turrets sweep out an inverted-cone-shaped volume as they rise. The boundary of this volume defines the smoke plume boundary.
- 2) A detraining particle trajectory model. Particles released at the base of the plume are transported upward through the plume by the turbulent wind velocity within the plume. Detrainment occurs when stochastic plume turbulence places particles beyond plume boundaries or when the plume is weak enough to be torn apart by turbulence within the surrounding air.
- 3) A large eddy parameterization. Large eddies are convectively-driven turbulent circulations that transport smoke from the ground to the top of the mixed layer and from the top of the mixed layer back to the ground. Large eddies are the most efficient distributors of smoke throughout the mixed layer. Large eddies get stronger as the mixing layer deepens during the day.
- 4) A multiple plume model creates new entrainment turret model plumes for each hour that new weather data becomes available or for each 10-minutes as burning conditions change.

Daysmoke simulates smoke plumes much like the schematic shown in Figure 12. The visible plume is seen to rise above the fire and carried aloft downwind. However, a nearly invisible “pall” of smoke has detrained from the plume and spreads downwind in the mixed layer beneath it. The PM2.5 sampler detects the presence of the pall of smoke.

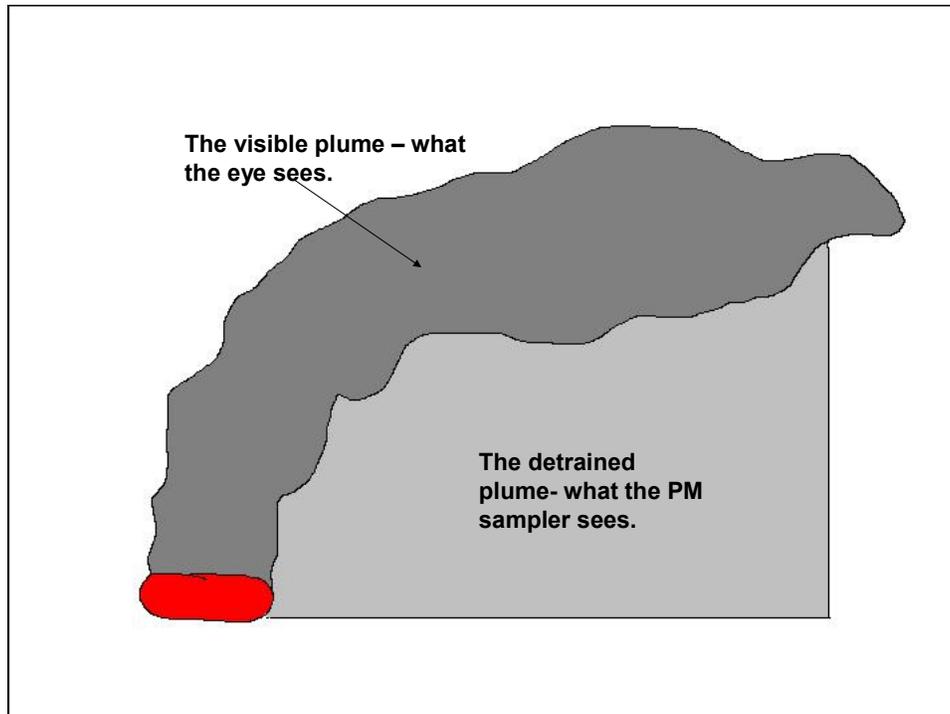


Figure 12. Schematic showing vertical distribution of smoke generated by Daysmoke.

One strength of the Daysmoke model is it takes into account how a prescribed fire is planned and/or conducted. The Brush Creek fire was accomplished by igniting the ridgelines. Helicopter-assisted mass ignition burns were used to set a large area ablaze simultaneously with the goal of organizing heat from multiple flaming sources into a single updraft carrying fire products into the free atmosphere above the mixing layer and thence harmlessly downwind. Mass ignition ridgeline burns create “line burns” – the length of the burn is much greater than the width of the burn. Line burn smoke plumes do not typically organize into a single updraft. Instead line burns produce a string of plume updraft cores that maintain individual core structure through the depth of the mixed layer to the top of the plume. Although a string of updraft cores can transport an equivalent mass of smoke as does a single updraft, they are less efficient at doing so. Updrafts are smaller and smoke will not be ejected as high into the atmosphere as would be done by a single updraft.

Photographs of the Brush Creek prescribed burn were taken from several locations during the burn. Figure 13 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 defined the Brush Creek plume.



Figure 13. Plumes from the Brush Creek prescribed burn on March 18, 2006 showing two distinct updraft cores.

Daysmoke has the capability of simulating multiple updraft core plumes. The model was set first for a single updraft plume and then was run for multiple core plumes with the number of cores ranging from three to six. Hourly $PM_{2.5}$ concentrations at Asheville were tallied for each of the simulations.

Figure 14 shows that the hourly $PM_{2.5}$ concentrations simulated for Asheville were directly proportional to the number of updraft cores. That is because a large number of small updraft cores are less efficient at transporting smoke than is a single large updraft. The smoke plume for a single updraft core was predicted to rise to roughly 10,000 feet at 2:00 PM EST before rapid deepening of the mixing layer began. The six core smoke plume was predicted to rise to only 5,200 feet at 1400 EST. Thus most of the smoke in the single core plume would have remained above the mixed layer whereas most of the smoke contained in the six core plume would have been subject to plume collapse later in the day. Had the Brush Creek plume been a single core plume, hourly $PM_{2.5}$ concentrations at Asheville were predicted to increase above background concentration by 36 $\mu g/m^3$. Had the background concentration in Asheville been 10 $\mu g/m^3$, then the impact of the Brush Creek burn at Asheville would have been to raise the $PM_{2.5}$ concentration to 46 $\mu g/m^3$, which is a “Moderate” AQI value. Had the Brush Creek burn been a six core plume, the predicted impact at Asheville would have been to raise the $PM_{2.5}$ level to 302 $\mu g/m^3$ above background (Figure 14).

Figure 15 compares the simulated (Four Core) $PM_{2.5}$ concentrations with observed $PM_{2.5}$ concentrations at Asheville. The shapes of the curves matched fairly well meaning that the magnitude of the impact and the residence time of smoke in Asheville were similar to that observed.

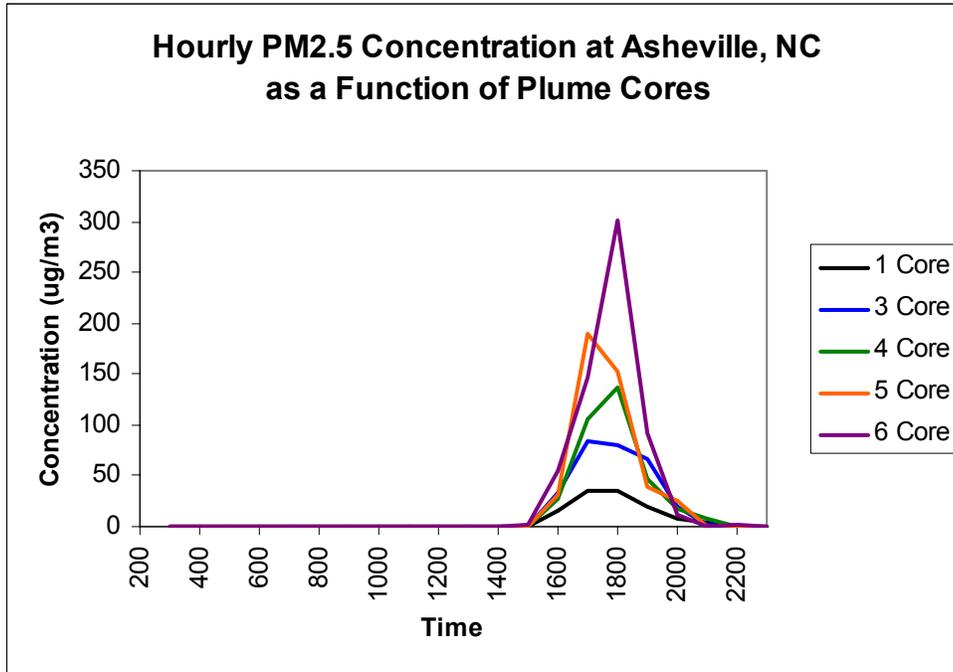


Figure 14. Hourly PM_{2.5} concentrations at Asheville, NC, on 18 March 2006.

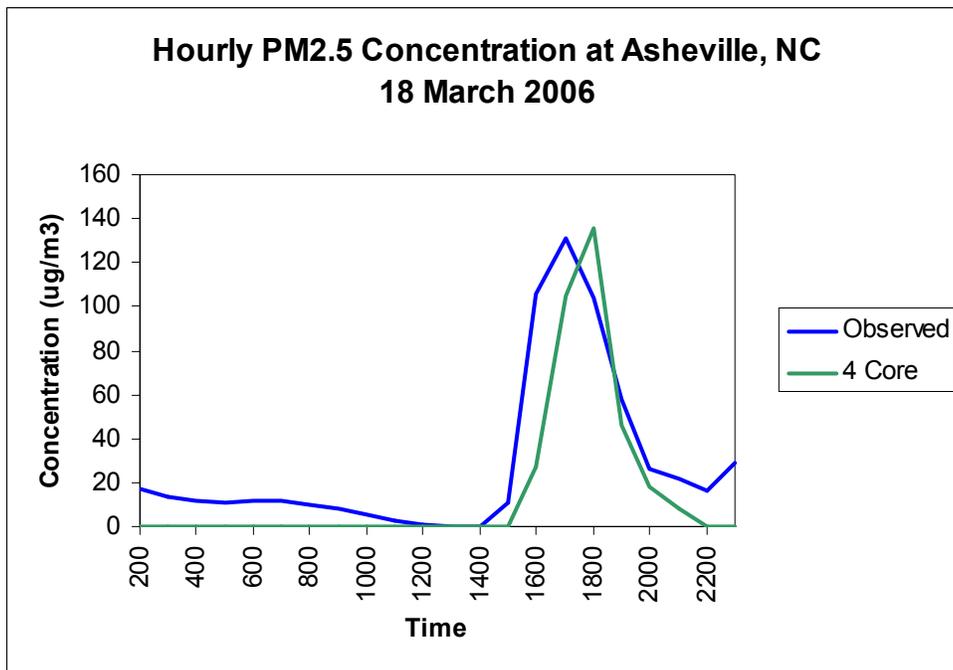


Figure 15. Hourly PM_{2.5} concentrations at Asheville from the Daysmoke simulation of the Four Core plume (green line) compared with PM_{2.5} concentrations observed at a sampler located at Asheville (blue line).

The timing of the arrival of the peak PM_{2.5} concentration being one hour later in the simulation would seem curious given that winds observed by rawinsonde at Greensboro were undoubtedly stronger than were the winds at Asheville. Therefore the plume should have arrived at Asheville earlier and the peak concentration should have been simulated before it was detected by the sampler. A movie prepared (see [http:// 199.128.173.141/smoke/](http://199.128.173.141/smoke/)) utilizing satellite imagery (Figure 2) indicates the visible plume arriving at Asheville at about 1515 EST. The Daysmoke simulation predicted ground-level PM_{2.5} concentrations into the Asheville area by 1430 EST but places them west of the sampler site. As wind directions back slightly later in the day, the predicted concentration pattern shifted slightly to the east to create a broad smoke impact area.

The 24-hour PM_{2.5} concentration observed at Asheville was 26 ug/m³. The 24-hour PM_{2.5} concentration from the Daysmoke simulated Four Core plume was 14 ug/m³. A background PM_{2.5} concentration of 10 ug/m³ (Daysmoke does not include background) would have increased the Daysmoke PM_{2.5} concentration to 24 ug/m³.

A complicating factor for the Brush Creek burn is that aerial ignition ceased at 2:00 PM EST and was resumed at 4:20 PM EST. This allowed for the fire to enter a premature “ramp-down” phase then to enter a second “ramp-up” phase during which the weakly rising plumes would have deposited smoke within the mixed layer – smoke available to be returned to the ground. Figure 16 shows the history of a three-core plume simulated by Daysmoke with the timing of aerial ignition done for the Brush Creek prescribed fire. The first panel shows the plume rising from the burn site and transported downwind about 40 miles. The top of the plume is at approximately 5600 feet. The time is 2:30 PM EST and the plume is entering the “ramp-down” phase. The top-middle panel shows the plume at 3:30 PM EST. The “ramp-down” has occurred and the “ramp-up” for the second phase of the burn has begun leaving a depression where the weakened plume drifts downwind. By 4:10 PM EST (upper-right panel), the mixing layer has deepened to contain the weakened part of the plume. Large eddy convective circulations have completely collapsed that part of the plume. By 5:05 PM EST (lower left panel), the plume has been reestablished. The last two panels show the plume in the final “ramp-down” stage.

Three Plume Cores - Hot

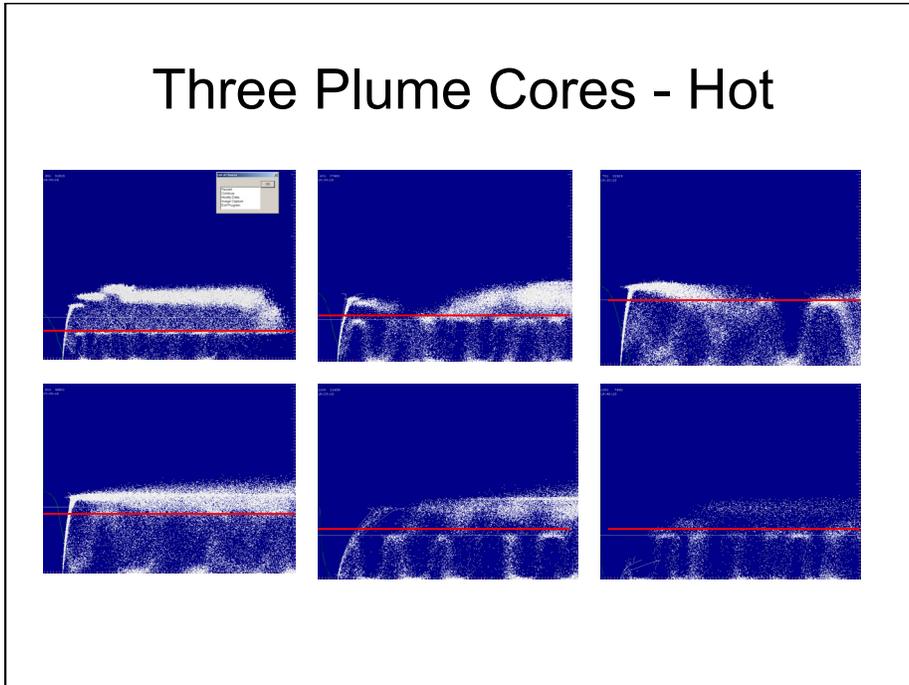


Figure 16. Six panels read from left to right showing the history of a three-core plume simulated by Daysmoke for the Brush Creek fire. Times are 2:30, 3:30, 4:10, 5:05, 6:25, and 7:40 PM EST. The red lines identify top of the mixing layer.

So why didn't the smoke disperse from the Brush Creek prescribed fire?

The VSMOKE and VSMOKE-GIS model results clearly indicate a potential existed for the smoke to travel down the French Broad River valley (Figure 5) and impact Asheville and other communities. There is always uncertainty in trying to explain why the smoke did not disperse as was expected, but there were a number of factors which contributed to the event. First, a large amount of smoke (water and other pollutants) was released into the atmosphere in a short time period. Between 1:00 and 2:00 PM about 500 acres were burned and released approximately 71.5 tons of fine particulate matter into the atmosphere. Many prescribed fires conducted have enough heat generated to inject a portion of the smoke above the mixing height. However, the SHRMC MM5 results and the upper atmosphere sounding from three locations indicate a mass of warm stable air aloft that the smoke from the Brush Creek prescribed fire may have not penetrated into.

The prescribed fire probably released too much particulate matter during the first two hours of the prescribed fire. Based upon the VSMOKE scenarios, the downwind concentration of particulate matter could have been significantly reduced if the rate of the fire spread was decreased (Figure 8), or the tons of fuel consumed was reduced (Figure 10). Furthermore, the smoke released could have acted as a cloud to prevent the sun's solar radiation from reaching the earth (Figure 17). Consequently, the stability may have decreased to near neutral which slowed the smoke dispersing throughout the atmosphere from the ground to the mixing height. Bill Jackson observed this behavior of the smoke at 5:00 PM in Asheville. Having a near neutral stability class may have also

contributed to the high particulate matter concentrations as the smoke was transported by the winds down the French Broad River valley.

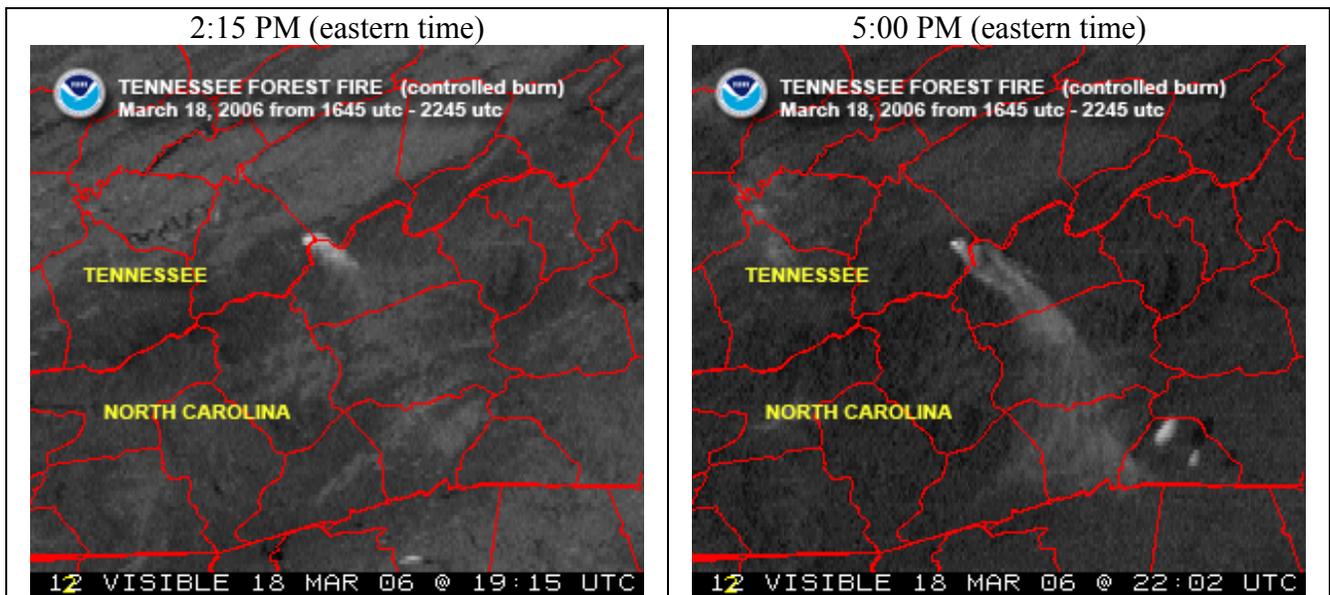


Figure 17. Smoke plume image processed from the GOES satellite (received from National Oceanic and Atmospheric Administration) showing the cloud of smoke from the Brush Creek prescribed fire.

The Daysmoke simulations for the Brush Creek prescribed burn focused on three factors that could have explain the unexpectedly high concentrations of $PM_{2.5}$ at Asheville. All three of these factors could have contributed to the occurrence of a phenomenon called “plume collapse” – the re-entry of smoke carried in the free atmosphere above the mixed layer back into the mixed layer and subsequent mixing of the smoke in high concentration back to the ground.

The first factor was meteorological – the “atypical” growth of the mixing layer throughout the day (Figure 6). Rapid deepening of the mixing layer occurred late in the afternoon in contrast with the usual rapid deepening of the mixing layer late in the morning. Smoke lofted late in the morning and early afternoon would have been subjected to re-entry into the mixing layer and subsequent mixing back to the ground.

The second factor was how the ridgeline fires were ignited – the length of the burn being much longer than the width of the burn. Line-type burns produce what is observed by sight and by satellite as a single plume (Figure 2), however the plume is supported by a string of updraft cores (Figure 13) that are smaller and less efficient than is a single updraft core that transports the same smoke mass as does the smaller cores. The outcome is lower plume heights with line-type burns. Lower plume heights increase the chances that plume collapse will occur with smoke re-entering the mixing layer.

The third factor was the timing of the aerial ignition. A gap of more than two hours allowed the fire to cool down and the plume to enter a premature ramp-down phase. During the ramp-down phase and the following ramp-up phase, more smoke remained in the mixed layer to be returned to the ground downwind (Figure 16).

All three of these factors are to some extent tied to the meteorology of the growth of the mixing layer. Had “atypical” growth not occurred, plume collapse would have been less likely with the outcome that ground-level concentrations of PM_{2.5} would have been much reduced.

Immediate changes in the prescribed fire program to prevent future smoke incidents.

Cherokee National Forest staff did meet in April 2006 and discussed what had occurred with the Brush Creek prescribed fire. As a result, it was decided that no more prescribed fires will be conducted on the northern portion (northeast of the Great Smoky Mountains National Park) of the Cherokee National forest when the predicted or observed winds are toward Asheville.

Additional recommendations to prevent future smoke incidents.

- 1. We recommend the Cherokee National Forest staff should utilize the VSMOKE and VSMOKE-GIS model until an atmospheric dispersion modeling package is available for mountainous terrain.** The use atmospheric dispersion models will provide more information to consider (such as predicted downwind PM_{2.5} concentrations) then just using the geometric screening procedure.
- 2. Forest staff should utilize the predicted Dispersion Index, and other meteorological results from the MM5 model produced by SHRMC (<http://shrmc.ggy.uga.edu/>).** One of the goals of the SHRMC is to use high resolution weather models to accurately predict mixing layer growth. Mixing layer growth data can be made available to land managers up to two days prior to the execution of prescribed burns.
- 3. Plan burns to minimize the development of multiple core plumes especially if the burn involves the combustion of heavy fuel loads as was the case for the Brush Creek burn.** Currently, no research has been conducted in mountainous terrain that can guide Forest staff on the ways to prevent multiple cores from developing. Until research studies can be completed, the Forest Staff should maintain notes under which ignition techniques and meteorological parameters the prescribed fires appear to be forming single and multiple cores.
- 4. Also, when planning and implementing prescribed fires there needs to be a careful evaluation to determine if too much forest fuels are being consumed in too short of a time period.** The Category Day is one way to estimate how many tons of forest fuels can be consumed depending on atmospheric conditions. This method is utilized by numerous State air quality and/or forestry agencies when issuing permits for prescribed fires. Several State Smoke Management Programs (SMP) rely on two pieces of information to determine how many tons of fuel can be consumed within an area: 1) the downwind distance to the nearest smoke sensitive target, and 2) the ventilation rate. The ventilation rate is determined by multiplying the transport wind speed (miles per hour) by the mixing height (feet). The

National Weather Service measures the transport wind speed and mixing height each morning and an estimate is made for the afternoon by 8:00 a.m. each day. Also, estimates of the transport wind speed and mixing height can be obtained from SHRMC. The predicted afternoon mixing height and transport wind speed are used to calculate the ventilation rate and category day. For example, Table 1 and 2 lists the category day for each combination of mixing height and transport wind speed developed by the Arkansas Forestry Commission for their SMP.

Table 1. Range in ventilation rate values for each Category Day in the Arkansas Smoke Management Program.

<u>Afternoon Ventilation Rate</u>	<u>Category Day</u>	<u>Guidelines</u>
0-14,999	1	No burning
15,000-29,999	2	No burning until after 11 a.m. and not before surface inversion has lifted. Burn should be substantially burned out by 4:00 p.m.
30,000-59,999	3	Burn only after surface inversion has lifted.
60,000-118,999	4	Burn anytime.
119,000 or greater	5	“Unstable” and windy. Excellent smoke dispersal. Burn with caution.

Table 2. Relationship between category day, transport wind speed – TWS - (miles per hour), and mixing height (feet). Exercise caution with high transport wind speeds and low mixing height, or low transport wind and high mixing height. These conditions can cause poor smoke dispersion and adverse burn behavior problems.* Taken from the Arkansas Smoke Management Program.

TWS Wind (m.p.h.)	CATEGORY DAY												
	Mixing Height (feet)												
	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500
7	(1)*	(1)*	(1)*	(1)*	(1)*	(2)*	(2)*	(3)*	(3)*	3	3	3	3
8	(1)*	(1)*	(1)*	(2)*	2	3	3	3	3	3	3	3	4
9	(1)*	(1)*	(1)*	(2)*	3	3	3	3	3	3	3	4	4
10	(1)*	(1)*	(1)*	(3)*	3	3	3	3	3	4	4	4	4
11	(1)*	(1)*	2	3	3	3	3	3	4	4	4	4	4
12	(1)*	(1)*	3	3	3	3	3	4	4	4	4	4	4
13	(1)*	2	3	3	3	3	3	4	4	4	4	4	4
14	(1)*	2	3	3	3	3	4	4	4	4	4	4	4
15	(2)*	3	3	3	3	4	4	4	4	4	4	4	4
16	(2)*	3	3	3	3	4	4	4	4	4	4	4	5
17	2	3	3	3	4	4	4	4	4	4	4	5	5
18	2	3	3	3	4	4	4	4	4	4	4	5	5
19	2	3	3	3	4	4	4	4	4	4	5	5	5
20	3	3	3	4	4	4	4	4	4	5	5	5	5

*/ Mixing height and transport wind speed conditions (with a slightly unstable stability class) that are likely to have a dispersion index below 30. Numbers in a parenthesis may have a dispersion index of 30 or above if the stability class is moderately unstable.

In Arkansas, once the Category day is determined then Table 3 provides guidelines on the total amount fuel that can be consumed in the 36 square mile area. The estimates in Table 3 were developed where the VSMOKE (Lavdas 1998) model predicted between 159 to 175 ug/m³. All of the model calculations had a stability class of slightly unstable and fine particulate release rate and heat release rate were estimated by using the FEPS model.

Table 3. The tons of fuel that can be consumed based upon the downwind distance to the nearest smoke sensitive target and the category day. Taken from the Arkansas Smoke Management Plan.

Distance to Smoke Sensitive Target (miles)*	Category Day 2	Category Day 3	Category Day 4	Category Day 5
0-0.19	--	--	--	--
0.2-4.9	488	560	720	1,280
5-9.9	1,000	1,200	1,840	3,200
10-19.9	1,840	2,240	4,200	7,200
20-29.9	2,880	3,280	6,400	11,600

5. Currently, the State of Tennessee does not have an EPA approved SMP. **We strongly recommend a SMP should be developed for Tennessee.** The development of a SMP along with our other recommendations should significantly reduce the likelihood of another smoke incident occurring as did with the Brush Creek prescribed fire.

Acknowledgment

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