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Recent Results from Two Fine-Scale Models for Short-Range Predictions of Residual Smoke at Night

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1. INTRODUCTION

The continued supply of our Nation's paper and other wood products increasingly depends on wood fiber produced from Southern forests. Approximately 200 million acres (81 ha) of forestland are within the 13 Southern United States—roughly south of the Ohio River and from Texas east. Although these States represent only 24 percent of America's land area, 40 percent of the Nation's forestland lies within this region. Southern forests are dynamic ecosystems that, under good land stewardship practices can continue to supply the myriad of goods and services that the American public relies on (SRFRR 1996).

Southern land managers understand that prescribed fire is the most economical way to reduce fuels, remove nutrient-competing species, and lower the wildland fire danger, which can destroy commercial fiber and threaten urban areas. Additionally, threatened and endangered species influence management of some Southern forestlands. For instance, because many threatened plant and animal species are fire-dependent—they rely on fire for reproduction and elimination of competing species—managers consider prescriptions that help to ensure the continued survival of these species.

Land managers use prescribed fire to treat 6 to 8 million acres (2–3 ha) of forest and agricultural lands in the Southern states each year with lessor acreages treated elsewhere. This practice occasionally compromises air quality and visibility. As the population increases, the number of people driving on our extensive road network grows, and highway accidents related to smoke or a combination of smoke and fog on the roadways increase. Multiple-car pileups, numerous physical injuries, extensive property damage, and fatalities are associated with visibility reductions due to smoke or smoke and fog on roadways.

Most serious accidents occur during the night or at sunrise as smoke trapped in stream valleys and basins drifts across roadways. Mobley (1989) conducted a comprehensive study on smoke related highway incidents that occurred in the South from 1979—88. During this period, Mobley found that visibility reduction caused by smoke or a combination of smoke and fog caused 28 fatalities, over 60 serious injuries, numerous minor injuries, and litigation expenses into the millions. More recently, smoke and fog from a small wildfire located near Interstate 10 in southeastern Mississippi on 8 May 2000 caused an pre-dawn accident that killed five and injured 24 (Twilley, 2000).

2. SOLUTION - NUMERICAL MODELING OF NOCTURNAL SMOKE MOVEMENT

Simulating smoke movement at night is a complex, time-dependent problem. Wind shifts transport smoke to different locations at various times during the same night. Land management personnel charged with alerting the appropriate authorities of pending transportation hazards must know where and when smoke will arrive. Wind observations from nearby weather stations are often unreliable because of the local nature of night winds. Furthermore, weather stations report wind speeds less than 2 miles per hour (1 m/sec) as calm. A wind speed of 2 miles per hour (1 m/sec) blowing for 10 hours at night can move smoke 20 miles (32 km) from its origination point thus potentially affecting roadway visibility at many locations and at great distances.

Numerical modeling constraints imposed by the forest managers were stringent. The models have to fit on laptop PC computers and run in faster-than-real-time yet be able to model smoke on the terrain scales that the smoke "sees". Smoke can move through shallow gaps in ridges and down road and stream cuts. Therefore, the mesh size for the model can be as small as 30 m, the minimum resolved grid distance in the digital elevation models (DEM) provided by the U.S. Geological Survey. The need for speed for this very fine mesh model is realized by minimizing the number of computations. It is required that the mathematics be simple and the physical terms describing complex processes be simplified or replaced with empirical terms. Turbulent mixing is not a complicating factor as air movement in light winds under stable conditions is nearly laminar.

Two models are under development - PB-Piedmont and PB-Coastal Plain. PB-Piedmont is designed to simulate smoke movement over complex inter-locking ridges and valleys with ridge to valley elevation differences less than 50 m - elevations typical of the Piedmont and upper coastal plain of the southern and eastern United States. PB-Coastal Plain is designed to simulate smoke movement over forest land within 20 miles (32 km) of coastlines where land/water circulations can significantly impact smoke movement.

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3. PB-Piedmont

The model design depends upon several assumptions regarding the meteorology of the Piedmont. First, because ridge-to-valley elevation differences are of the order of 50m, the airmasses containing drainage flows can be approximated by a shallow layer near the ground. This drainage layer is “vertically integrated” meaning air movements within the layer are approximated by the mean wind for the layer. The vertically integrated approach has been used successfully by Garrett and Smith (1984). Three dimensional circulations do occur within the drainage layer, however these are assumed to be insignificant for smoke transport relative to the mean flow within the layer.

Second, it is assumed that the meteorology of the Piedmont during clear sky and light wind episodes (prevailing weather when most smoke entrapment occurs) consists of two scales of motion - the synoptic scale pattern of low and high pressure centers and fronts which can be described by the National Weather Service network of surface weather stations, and the drainage scale which is characterized by the terrain of the Piedmont. Weather disturbances that are too small to be resolved by the existing network of surface stations are assumed to be negligible or non-existent. The model therefore is not appropriate for simulating nocturnal smoke movement near the coasts where there are land and sea breezes.

Third, because the domain size is limited, it is assumed that regional scale temperatures, winds, and pressure data needed by the model can be represented by single values interpolated from surrounding weather stations to the location of the prescribed burn.

Fourth, it is assumed that the drainage layer airmass is effectively “decoupled” from overlying airmasses. Near sunset, under conditions of light winds and clear skies, the ground and the air immediately above it cool rapidly. Mixing with the overlying airmasses ceases as the stable drainage airmass deepens. Decoupling makes it possible to model just the meteorology of the drainage layer.

In keeping with the above assumptions, the vertical structure of the model atmosphere is in two layers, the shallow drainage layer near the ground and a buffer that extends from it to an elevation of 100 m above the highest terrain. Figure 1 shows the layer division along with model details. The black dots signify grid points. Horizontal pressure gradients, temperatures, and wind components interpolated each hour from surrounding surface weather stations (Barnes, 1964; Caracena, 1981) form the upper boundary. Then the buffer layer extends down from the upper boundary to the top of the drainage layer. The drainage layer, which carries time dependent wind components, pressure, temperature and layer depth, can vary in depth in highly divergent drainage flows but cannot be deeper than the fixed top of the buffer layer. Elevation data define the lower boundary of the drainage layer. The model mathematics are summarized in Achtemeier (1993).

3.1 *PB-Piedmont Validation*

Tests with PB-Piedmont show that the combination of synoptic scale wind systems with weak drainage winds that form over terrain typical of the Piedmont of the Southeast can create complex plume structures. Valley orientation with respect to the winds and with respect to adjacent valleys, steepness of slopes, and valley depth can make the difference between

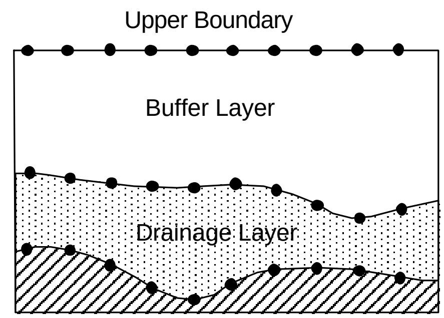

Figure 1 Vertical structure of the PB-Piedmont numerical wind model. Dots represent grid points.

entrapment and ventilation. Modeled smoke can be transported among valleys through small gaps in ridges. Whether these complex plume patterns exist is a subject for model validation.

Existing data on smoke movement at night is largely anecdotal. The only “hard” data are locations of highway accidents where smoke was involved and recorded reports of smoke by personnel who drive highways surrounding a burn site searching for smoke incursions. Data on the movement of entire smoke plumes near the ground at night are nonexistent.

The only way to observe an entire smoke plume moving along the ground at night is from an above-ground platform - either satellite or aircraft. Furthermore, as smoke scatters headlights from vehicles, smoke should be visible from aloft through scattered light from the full moon.

To test this hypothesis, a field project was designed around three 8-night windows timed to coincide with the full moon in January, February, and March 1997. However, only four nights -- one in January, one in February, and two in March -- met the meteorological criteria. Operations were restricted to clear skies and near calm winds. This approach insured data collection during maximum moonlight. A Xybion intensified multi-spectral video camera equipped with an infrared cutoff filter was mounted in a Beech Craft King Air aircraft and flown over the Oakmulgee Wildlife Management Area located in the Talladega National Forest in western Alabama. The site was selected for terrain typical of the Piedmont, safety, and the absence of light sources.

Smoke was successfully observed and recorded during the evenings of 20 and 21 March 1997. Raw video images, methods of image analysis, and resulting smoke distribution relative to surrounding landforms were described for 20 March 1997 by Achtemeier (1998) and Achtemeier, Adkins, and Greenfield (1998). These results along with results from

21 March 1997 are compared with simulations from PB-Piedmont in the following paragraphs.

20 March 1997

Modeling smoke movement for the night of 20 March 1997 was a difficult test for PB-Piedmont. Beginning at 2145 CST, Forest Service ground personnel ignited 50 bales of hay soaked in diesel fuel along a road next to a stream basin that flowed to the northeast. Once the hay bales were flaming vigorously, the fire was extinguished with water. The bales then smoked profusely. Ground crews also detonated 60 smoke bombs that had burn lifetimes of approximately two minutes each. Aircraft overflights at approximately 1,500 m (5,000 ft) commenced at 2148 CST and continued at seven minute intervals for two hours.

The project forecast called for winds to decrease to near-calm with rapid cooling in the basin to entrap smoke there. Drainage and valley flows favored slow movement of smoke down-valley to the northeast.

The left panel of Figure 2 shows raw video imagery of smoke movement at 2258 CST 20 March 1997. Contrary to expectations, smoke moved up-valley, diverted into a side valley and crossed a road at the southern end of the drainage basin. The middle panel of Figure 2 shows the smoke plume at 2258 CST rectified and projected onto the underlying terrain. Elevations range from 100 m in the bottom lands to around 150 m along the ridge tops with a few high points near 170 m. Elevations greater than 130 m (430 ft) are shaded to better identify the drainage basin. Smoke had moved up-valley, diverted around a projecting ridge and escaped the drainage basin through a 10 m deep in the surrounding ridge.The right panel of Figure 2 shows the smoke plume simulated by PB-Piedmont at 2258 CST. The gap in the ridge is identified by the arrows.

An explanation for the smoke movement observed on the evening of 20 March 1997 draws on the opposition between regional scale winds and drainage layer winds. As expected, drainage layer winds entrapped smoke within the stream valley. A weak low pressure center over the northern Gulf of Mexico turned the synoptic scale winds to blow from the north. These winds diminished after sunset and became light and variable during the course of the experimental burn.

However, the pressure forces that drove the regional scale winds did not diminish. They opposed the minuscale pressure forces that drove the drainage flows and dammed up the cooled airmasses at the southwestern end of the valley. The deepened, smoke-filled drainage layer was easy to observe from the air. (An observer reported zero visibility in smoke and fog along the road leading up-valley from the burn.) However, once the smoke passed through the gap in the ridge at the southern end of the valley, it was no longer visible from the air, presumably because the smoke layer became too shallow as the air accelerated downslope into the neighboring valley. A large tract of land located just south of the gap had been clear cut the previous year.

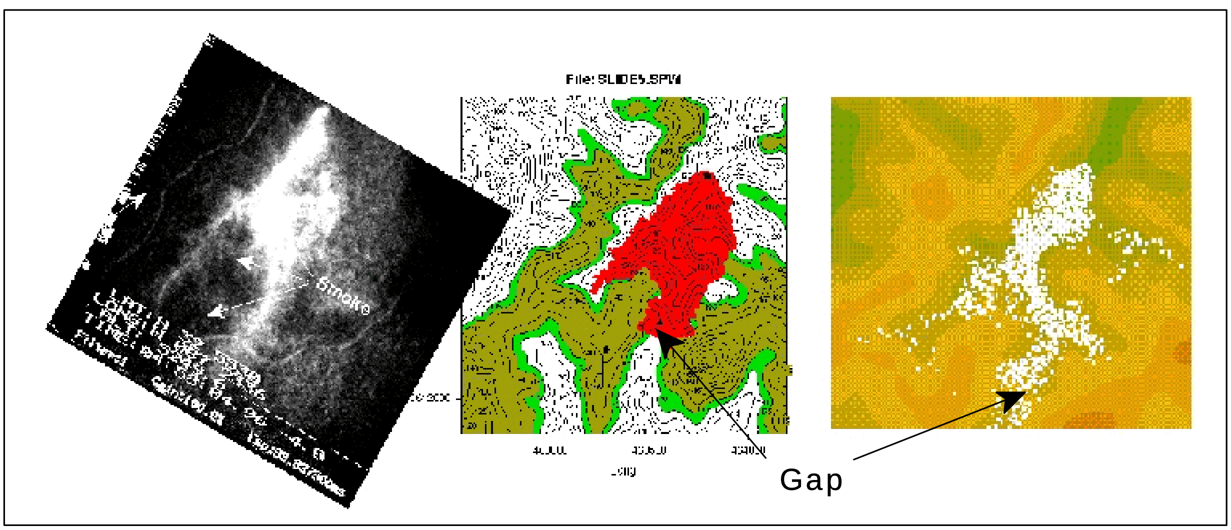

Figure 2 For 2258 CST 20 March 1997. Left panel, raw video image of smoke entrapped up valley from test burn; middle panel, smoke plume rectified to underlying terrain (shaded area represents elevations greater than 130 m); right panel, PB-Piedmont simulation of the same smoke plume. Arrow identifies 10 m deep gap in the surrounding ridge.

Therefore, there were few if any large trees to obstruct areal smoke observation.

21 March 1997

The procedures for conducting the experimental burn during the night of 21 March 1997 were nearly identical to those for 20 March 1997. The fire was started at the same location. Beginning at 2110 CST, Forest Service ground personnel ignited 50 bales of hay soaked in diesel fuel and detonated 60 smoke bombs. Aircraft overflights at approximately 1,500 m (5,000 ft) commenced at 2121 CST and continued at seven minute intervals for approximately two hours.

The project forecast called for winds to decrease to near-calm with rapid cooling in the basin to entrap smoke there. Drainage and valley flows favored slow movement of smoke down-valley to the northeast. Thus synoptic scale pressure forces reinforced the drainage flows to drive smoke down valley.

Figure 3a shows the location of the smoke plume relative to the burn site and surrounding landforms at 2121 CST. The plume was defined as the locus of points taken from video imagery by image analysis methods described by Achtemeier (1998) and Achtemeier, Adkins, and Greenfield (1998). Plume structure and orientation remained unchanged during the period of overflights. Drainage winds confined the plume within the stream basin. The synoptic scale pressure forces reinforced the drainage winds to increase the strength of the down-valley winds. There was no damming and deepening of the drainage airmass as on the previous night and therefore the smoke layer was shallower. Relative humidities were lower than on the previous night; fog did not form. The much fainter smoke plume was observable for a distance of approximately 1 km. Smoke may have been partially obscured by overarching trees or the smoke layer thinned by spreading of the plume as it moved down-valley to the extent that it was no longer observable from the aircraft.

The smoke plume simulated by PB-Piedmont at 2150 CST (Figure 3b) was selected for comparison with the length of the observed smoke plume. PB-Piedmont entrapped the smoke and moved it down-valley at approximately 0.50 m/sec, a speed less than the observed smoke movement given that smoke had arrived adjacent to the slope A by the first overflight at 2121 CST.

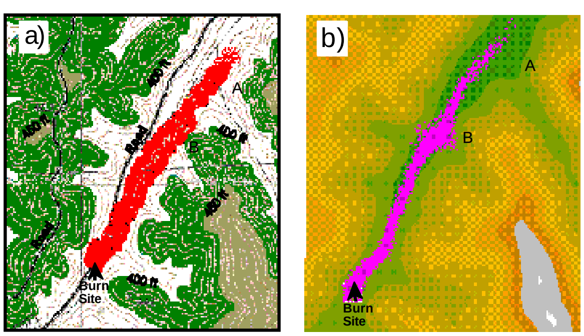

Figure 3. a) Image analysis of smoke plume at 2121 CST on night of 21 March 1997 overlain onto 30 m DEM elevation data and b) PB-Piedmont simulation of smoke at 2150 CST.

In addition, the observed plume moved up-slope at B and drifted toward the right hand side of the valley. Synoptic scale pressure forces oriented more cross-valley than those calculated for PB-Piedmont could explain the plume behavior. A more likely explanation holds that the bulk of the observed plume was moving 5 -10 m above ground and thus was not as constrained by the terrain as was the plume generated by PB-Piedmont. Ground crews had difficulty with flaming in the hay bales. Additional heating from flaming could have increased plume buoyancy sufficiently to elevate the plume above the ground and into faster-moving air.

4. PB-Coastal Plain

PB-Coastal Plain extends PB-Piedmont in two ways. First, PB-Coastal Plain must include land use. Because the coastal plain of the Southeast is mostly flat, there are no significant terrain features to drive drainage winds. Land use can become a factor in the transport of smoke in the following ways.

1) Vegetation can impede air flow. The presence of leaves, stems, and tree trunks increases frictional drag on slow-moving airmasses.
2) Dense stands of trees, especially hardwoods, can create nearly impenetrable barriers to slow-moving airmasses. In addition, dense undergrowth/understory vegetation around the boundaries of large pine stands can also impede or block slow-moving airmasses. Therefore, dense vegetation can act as an "artificial terrain" by diverting slow-moving air around or over the obstacle.
3) Cooling rates vary depending upon soil type and exposure to the sky. Open fields cool faster than closed canopies.
4) Land use also includes water surfaces. Cooling rates between land and water differ because of the higher heat capacity of water. The many estuaries and streams located within the coastal plain present warm surfaces during the night which can initiate weak land/water circulations. Furthermore, with the absence of vegetation, frictional drag over water surfaces is much smaller than that over land. Thus water surfaces also serve as pathways for smoke transport.

Second, the fine scale part of PB-Coastal Plain must nest within a larger scale model that simulates land and sea breeze circulations. Although land/sea breeze circulations are most notable at the coast lines, the pressure fields that drive these circulations can extend approximately 50 km seaward and 50 km landward. Thus the mesoscale grid of PB-Coastal Plain must extend at least 50 km seaward.

Computational constraints listed for PB-Piedmont also apply for PB-Coastal Plain. Therefore, the mesoscale component also uses the vertically integrated assumption, but through a 600 m deep layer. Thus the sea/land breezes are modeled as density currents. Horizontal grid spaces of 900 m seem adequate to resolve most large coastal features. However the need to reduce the horizontal grid space may become necessary if further tests show that the mesoscale pressure fields generated with the 900 m grid prove too coarse to resolve land/water structures that impact the fine scale component of PB-Coastal Plain.

4.1 *PB-Coastal Plain Validation*

Validation of PB-Coastal Plain is ongoing. The following describes the use of the model (sans landuse) to simulate nocturnal smoke movement that was implicated in a multiple vehicle pile-up that killed five and injured 24 on the early morning of 07 May 2000. The accident occurred on Interstate 10 on the coastal plain of extreme southeastern Mississippi. The site was located approximately 12 km inland from the Gulf of Mexico.

A wildfire had erupted on a 200 acre tract of land located approximately 500 m north of the expressway. The wildfire had been extinguished with water. The source of the smoke was smoldering which occurred throughout the night and into the next day.

Prevailing weather conditions were characterized by persistent southerly winds blowing onshore within a pressure field established by a high pressure ridge located over Alabama, Georgia, and northern Florida and a stalled low pressure system located over the Great Plains. The weather pattern had existed for several days and was predicted to continue.

Smoke from the wildfire blew north away from I-10 and was not considered to be a threat to highway visibility. However, during the early morning of 07May, winds shifted to blow the smoke south over the expressway. The smoke, accompanied by dense fog that rendered visibility to zero, became a contributing factor to the accident.

PB-Coastal Plain was run from 1700 on 06 May through 1000 on 07 May. The 200 acre burn site was converted into a square centered on GPS coordinates of the fire provided by personnel from the Fish and Wildlife Service (Figure 4). Grid spacing was 150 m. The model was updated with hourly surface pressure observations to provide synoptic scale boundary conditions.

The dark patches running vertically through the grid in Figure 4 are a tidal river that flows at sea level. Elevation differences within the areas of interest are less than 10 m. Since the area of smoldering within the 200 acre burn site was unknown, it was assumed smoke was emanating from whole field.

Figure 4a shows the simulation of smoke from the burn site at 0300 CDT 07 May 2000. The figure represents the movement of smoke for the whole period from 1700 to 0300 as winds blew steadily from the southeast. After 0300 CDT, winds gradually shifted from the southeast to the northeast to blow smoke across I-10. Figure 4b shows the simulated smoke plume at the time of the accident. The front edge of the simulated plume overlaps the back edge of the accident site. After 0800, winds shifted to blow again from the southeast.

Analysis of the output from the 900 m grid mesoscale model is suggestive that the wind shifts at the burn/accident site were connected to pressure fields established as part of the land breeze. The timing of the event - wind shifts near sunrise to blow toward the Gulf - coincides with the maximum inland development of the land breeze.

5. DISCUSSION

Two time-dependent numerical models have been designed to simulate smoke movement near the ground at night over the Piedmont and Coastal Plains of the South. The purpose of these models is to provide land managers with information that can assist them in decisionmaking when smoke from prescribed fires and wildfires threatens Southern roadways. Both models currently are connected with hourly weather observations to provide synoptic scale boundaries. Therefore, the predictive range is approximately one half hour. The current versions should be considered as "nowcast" rather than "forecast" models.

It is planned to connect the PB models with either or both of the ETA or MM5 weather prediction models. MM5 is currently being set up as part of the Southern High-Resolution Modeling Consortium (SHRMC). MM5 can provide boundary conditions for the PB models, thus making them predictive out to 48-hours or longer.

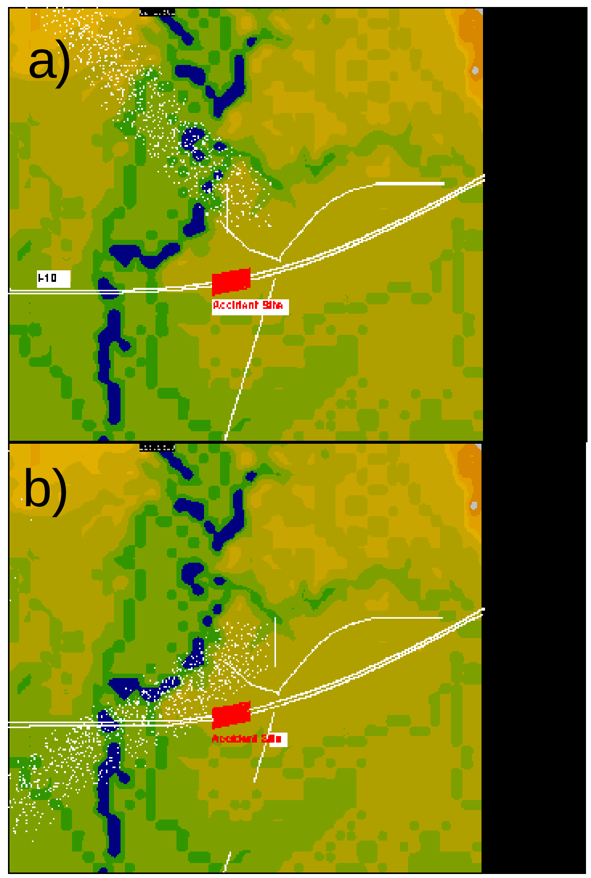

Figure 4. PB-Coastal Plain simulation of smoke on the ground relative to multiple vehicle accident on I-10 in eastern Mississippi on 07 May 2000. a) smoke plume at 0300 CDT, b) smoke plume at 0630 CDT.

Both PB-Piedmont and PB-Coastal Plain are simplified models designed to be run for specific weather conditions that are associated with smoke entrapment near the ground. Therefore they should not be used in conditions that violate the modeling assumptions. The validation results shown in this paper are encouraging that the models are performing as designed. However more validation studies must be done before the models can be accepted with confidence. As they are models, they will fail at times. Part of the validation work will be to determine the conditions under which the models fail and use these to make improvements and/or to advise users on the application limits.

6. ACKNOWLEDGMENTS

The ongoing work of Ken Forbus and Tim Giddens in preparing data sets for the PB models and in acquiring validation data is appreciated.

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