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Simulating Nocturnal Smoke Movement

Gary L. Achtemeier

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

Southern land managers understand that prescribed fire is the most economical way to reduce fuels; remove nutrient-competing species; and lower the danger of wildland fire, which can destroy commercial fiber and threaten urban areas. Additionally, threatened and endangered species influence management of some Southern forests. 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 ensure the continued survival of these species.

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Prescribed fire is the most inexpensive way to reduce fuels, remove nutrient-competing species, and control the threat of wildland fire.

Problem: Smoke-Choked Highways

Land managers use prescribed fire to treat 6 to 8 million acres (2–3 million ha) of forest and agricultural lands in the Southern United States each year. This practice occasionally compromises air quality and visibility (fig. 1). The number of highway accidents related to smoke, sometimes in combination with fog, is increasing in direct proportion to the number of people driving on our Nation's extensive road network. Multiple-car pileups, many physical injuries, extensive property damage, and fatalities are associated with visibility reductions due to smoke or smoke and fog on roadways.

Many serious accidents occur at night or near sunrise as smoke trapped in stream valleys and basins drifts across roadways. Mobley (1989) conducted a comprehensive study on smoke-related highway incidents in the South from 1979 to 1988. He found that visibility reduction due to smoke or a combination of smoke and fog was related to 28 fatalities, more

Figure 1—*Smoke from smoldering embers following a prescribed fire in a Southern forest. The fire front is visible in the distant background. When smoldering continues after sunset, smoke can become trapped in the shallow, cold layers of the ground air and then be carried by local winds across roadways, creating visibility hazards for transportation. Photo: USDA Forest Service, Southern Research Station, Athens, GA.*

than 60 serious injuries, many minor injuries, and litigation expenses into the millions of dollars. On May 8, 2000, near Interstate 10 in southeastern Mississippi, a mixture of fog and smoke from a small wildland fire was tied to a predawn accident that killed five and injured 24 (Twilley 2000).

Solution: Modeling Nocturnal Smoke Movement

Simulating smoke movement at night is a complex, time-dependent problem. Wind shifts can transport smoke to different locations at various times during the night. Land management personnel charged with alerting the appropriate authorities to 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 windspeeds that are less than 2 miles per hour (1 m/s) as calm. However, a windspeed of 2 miles per hour (1 m/s) blowing for 10 hours at night can move smoke 20 miles (32 km) from its origination point—potentially affecting roadway visibility at many locations and at great distances.

The Smoke Management Team at the USDA Forest Service's Southern Research Station in Athens, GA, developed a smoke movement and dispersion model that departs from proven techniques, such as Gaussian plume models like VSMOKE (Lavdas 1996). Planned Burn—Piedmont (PB-Piedmont), version 1.2–95, designed to model smoke movement when winds are light and highly variable, is a wind model and a particle generation model. The model addresses the problem of complex terrain with ridge/valley height differences of less than 330 feet (100 m) where smoke plumes diverge and split into neighboring valleys. This type of terrain characterizes the Piedmont of the Southeast and topographically similar areas of the United States. PB-Piedmont models smoke movement as a mixture of independent particles—similar to smoke actually flowing downwind from a burn site.

Smoke trapped inside a valley gradually "bleeds" away as the valley ventilates. The team designed the smoke model so that particles could periodically "birth"—increasing the number of particles and allowing the model to simulate the "bleedoff" of smoke.

Related Smoke Simulation Model

The Smoke Management Team used the Slow Nocturnal Air Flow (SNAF) model to help develop PB-Piedmont. SNAF simulates minuscule pressure forces that could drive winds as slow as 4 inches per second (10 cm/s) (Achtemeier 1991) over ridges and valleys with height differences of less than 330 feet (100 m). In 1991, a prototype of SNAF was completed and satisfactorily tested against wind data collected with instruments that measured windspeeds as slow as 4 inches per second (10 cm/s) (Achtemeier 1993a, 1993b).

We linked the smoke model—research version "Pregnant Bubbles" (Achtemeier 1996)—to the Slow Nocturnal Air Flow model (see sidebar) and tested it in an accident case in Georgia in which smoke played a role. The model successfully placed smoke at the accident site and at another site at the same times that smoke was actually observed (Achtemeier 1993c, 1993d; Achtemeier and Paul 1994).

Developing PB-Piedmont

Initial results encouraged the Smoke Management Team to go with an operational version. However, the available computer technology did not meet the model's requirements. Desktop computers were too slow and lacked sufficient memory, and the methods to transfer data to the computers were still under development. Due to the prevailing climate, development of the operational version experienced the following complications (fortunately, now mostly solved):

- Because privately owned forests are prevalent in the South, the model had to be user friendly to encourage private landholder use. *Solution*—Forest managers on the Oconee National Forest, Eatonton, GA, received the new smoke model for beta testing in the spring of 1997. Their comments, and conversion to Windows 95, helped the team make the model more user friendly.
- The model had to run quickly on computers with limited processing speeds and memory storage capabilities. *Solution*—Computer technology today exceeds model requirements.

Single Particles in Smoke-Filled Rooms

The ventilation of a smoke-filled room illustrates the smoke dispersion problem. Smoke does not immediately vacate a room; rather, it thins out as fresh air gradually mixes with and replaces the smoky air. If a single particle in the smoke model represented the smoke within the room, the room would be either completely smoke filled or completely smoke free, depending on whether the particle remained within or departed from the room. PB-Piedmont simulates smoke dispersion by periodically increasing the number of smoke particles represented in the model.

- PB-Piedmont requires spatial mathematical relationships among weather data captured at many stations surrounding burn sites throughout the South. *Solution*—The model receives, decodes, and processes large amounts of weather data, which are now accessible through the World Wide Web.
- The model simulates a time-dependent process of smoke movement. Because smoke locations are constantly changing, PB-Piedmont must display results graphically while calculations are ongoing. The team did not want to stop the model after every time step to enter the results into a commercial graphics package. Also, we did not want to require users to purchase expensive graphics software to run the model. *Solution*—In 1996, we developed model-compatible graphics software, which, in 1997, we linked with the model.
- PB-Piedmont requires detailed elevation data to model the slope and valley currents that carry trapped smoke. At the time of development, the USDI U.S. Geological Survey (USGS) had not digitized large areas of the southeastern Piedmont into 98-feet (30-m) resolution digital elevation maps. *Solution*—A mechanism to easily link and transfer these data to the model is under development.

> Visibility reduction through smoke from prescribed fires has been linked to traffic fatalities and injuries, leading to costly litigation.

Continued beta testing at the Oconee National Forest revealed that the most serious ongoing problem was linking the USGS digitized elevation data to PB-Piedmont. Although the Smoke Management Team had provided the elevation data for the Oconee National Forest, smoke knows no boundaries, and the lack of elevation data for surrounding private lands degraded model performance.

In 1998, fire managers at the regional office of the Forest Service's Southern Region in Atlanta, GA, asked the Smoke Management Team to provide sufficient elevation data on a CD-ROM so that they could run the model. The team is acquiring, quality checking, and reformatting 98-feet (30-m) digital elevation model data for more than 20,000 USGS 7.5-minute quads. We named the CD-ROM version of the model PB-Piedmont—"PB" stands for both Pregnant Bubbles (the research version) and Planned Burn (the operational version). We released PB-Piedmont for Georgia in November 1999 and the South Carolina version in December 1999. Versions for Alabama and Mississippi were available in mid-2000. Elevation data processing is occurring for Louisiana, Texas, and North Carolina—other Southern States will soon follow. Comments supplied by South Carolina users will help the team further simplify the user interface for PB-Piedmont. Additionally, a World Wide Website will soon allow users easy access to new, improved versions of PB-Piedmont.

Validating PB-Piedmont

Tests with PB-Piedmont show that the combination of large-scale wind systems with weak drainage winds that form over terrain typical of the southeastern Piedmont can create complex plume structures. To validate PB-Piedmont, we needed to compare the modeled smoke plumes with observed smoke plumes. The only way to observe an entire smoke plume moving along the ground at night is from the air. Since smoke scatters headlights from vehicles and creates visibility hazards, we believe it was possible that moonlight scattered by smoke would be visible from the air above the plume.

To test this idea, the Smoke Management Team conducted a project at the Oakmulgee Wildlife

Management Area on the Talladega National Forest in western Alabama. Mounting a Xybion* intensified, multispectral video camera with an infrared cutoff filter in a Beechcraft King Air aircraft, we flew the aircraft over test smoke plumes. We selected this site because it contained terrain typical for the Piedmont, provided a safe environment, and had no light sources that could contaminate the video imagery or damage light-sensitive equipment.

Because maximum moonlight was needed to permit data collection, we restricted field operations to clear skies and nearly calm winds during three 8-night windows timed to coincide with the full moon in January, February, and March 1997. Only four nights—one in January, one in February, and two in March—met both the lunar and the meteorological criteria.

Smoke behavior during the night of March 20, 1997, provided the most severe test of PB-Piedmont (Achtemeier 1998; Achtemeier et al. 1998). Because the forecast called for winds to decrease to nearly calm, we expected that rapid cooling in the basin would entrap smoke and that drainage and valley flows would favor slow movement of smoke downvalley to the northeast. Beginning at 9:45 p.m. central standard time, Forest Service ground personnel burned 50 bales of hay soaked in diesel fuel. They also detonated 60 smoke bombs that had a burn lifetime of approximately 2 minutes each. The fire began along a road next to a stream basin that flowed to the northeast. Aircraft overflights at approximately 5,000 feet (1,500 m) commenced at 9:48 p.m. and continued at 7-minute intervals for 2 hours. Video images from the Xybion camera were stored in Super Vertical Helical Scan (SVHS) format for future analysis.

Figure 2 shows actual smoke movement relative to the surrounding elevations. Elevations range from 330 feet (100 m) in the bottomlands to about 490 feet (150 m) along the ridgetops, with a few high points near 560 feet (170 m). Elevations greater than 445 feet (135 m) are shaded dark green to better identify the drainage basin. Elevations in the strip from 430 to 445 feet (130–135 m) are shaded light green to identify a gap in the ridge enclosing the southern end of the valley that is 33 feet (10 m) deep. Smoke generated at the burn site (fig. 2a) did not move down the valley as expected. Instead, the smoke moved southwest up the valley along the natural extension of the stream (fig. 2b). The plume then split around a protruding ridge (fig. 2c), flowing up a side valley and crossing the ridge through the shallow gap at the southern end of the valley. Smoke diversion through the side valley continued throughout the remainder of the burn (fig. 2d).

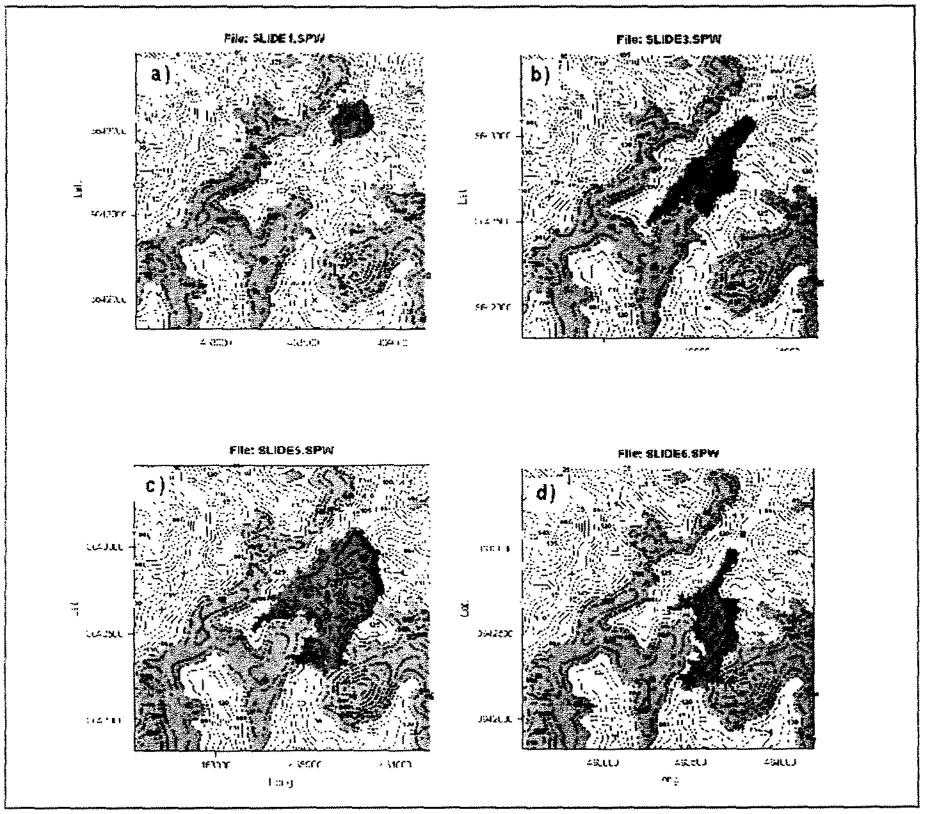

Figure 2—*Image analysis of smoke movement relative to the surrounding elevations, as extracted from video imagery during the night of March 20, 1997. (a) Plume shortly after ignition at 9:47 p.m. central standard time. (b) Plume drifting up the valley along the road at 10:02 p.m. (c) Plume diverting into the adjacent valley at 10:58 p.m. (d) Plume dissipating at 11:51 p.m. Black dots identify the burn site; red identifies the smoke plume; dark green identifies elevations above 445 feet (135 m); light green identifies elevations between 430 and 445 feet (130–135 m). Illustration: Smoke Management Team, USDA Forest Service, Southern Research Station, Athens, GA, 2000.*

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The PB-Piedmont model simulates the problem of complex terrain where smoke plumes diverge and split into neighboring valleys.

Figure 3 shows smoke movement modeled by PB-Piedmont for the same times as in figure 2. From the point of ignition (fig. 3a), model smoke moves up the valley (fig. 3b), divides around the protruding ridge (fig. 3c), turns up the side valley, and crosses the ridge through the gap at the southern end of the valley (fig. 3d). PB-Piedmont results were nearly identical to the observed smoke movement, with the exception that PB-Piedmont later showed some smoke drifting down the valley (fig. 3d). No smoke was actually observed downvalley from the burn site.

PB-Piedmont Can Help Land Managers

The current version of PB-Piedmont (1.2–95) helps managers monitor where residual smoke from a prescribed burn, if present, might be going. PB-Piedmont provides numerical "eyes" to "see" smoke at night. The model's predictive time is about 30 minutes, which is usually long enough to make decisions about posting roadway signs, diverting traffic, or alerting law enforcement to possible visibility hazards. The model does not predict smoke concentrations, because residual smoke emissions are usually unknown.

A future version of PB-Piedmont will link with models developed by the U.S. Department of Commerce, National Center for Environmental Prediction, that predict weather 48 hours into the future. When forecast data become routinely available for PB-Piedmont users, land managers might have enough information to make before-event decisions about whether to burn.

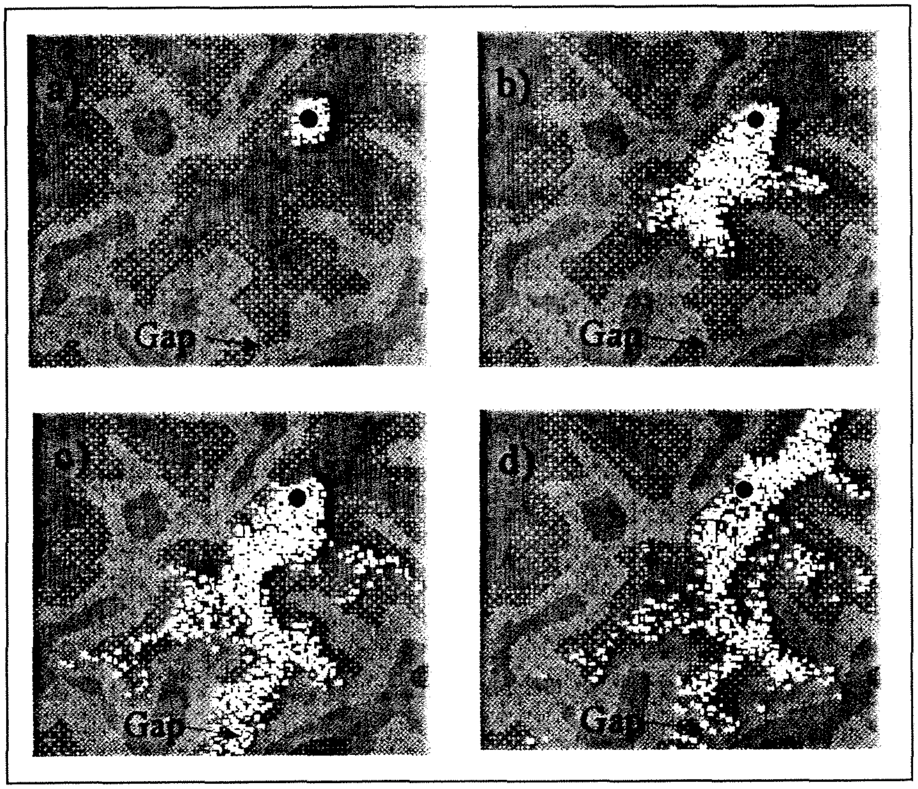

Figure 3—*Simulated smoke movement generated by the model PB-Piedmont for the night of March 20, 1997. (a) Plume shortly after ignition at 9:47 p.m. central standard time. (b) Plume drifting up the valley along the road at 10:02 p.m. (c) Plume diverting into the adjacent valley at 10:58 p.m. (d) Plume dissipating at 11:51 p.m. Red dots identify the burn site; white identifies the smoke plume; green identifies terrain at the lowest elevation, 330 feet (100 m); dark orange identifies terrain at the highest elevation, 490 feet (149 m). Illustration: Smoke Management Team, USDA Forest Service, Southern Research Station, Athens, GA, 2000.*

The Smoke Management Team is developing two sister models. PB-Coastal Plain will incorporate land use data and land/water information, along with small variations in elevation, to model smoke movement over the lower Coastal Plain. PB-Mountains will simulate smoke over the mountainous areas of the South.

Acknowledgements

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and Wayne Adkins (ret.) of the Southern Research Station's Smoke Management Team for technical and electronic contributions to the project; and ground crews on the Talladega National Forest, Oakmulgee Ranger District, Centreville, AL, for helping the project succeed.

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Fireline Humor From 1931

Gerald W. Williams

This bit of 1930's humor is from an old newsletter (*Six Twenty Six*, volume 15(4)) published by the USDA Forest Service's Pacific Northwest Region.

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HOW TO EXTINGUISH A FOREST FIRE

1. Throw patent cigarette lighter into midst of fire. There is a natural antipathy between fire and cigarette lighters. Flames will die out at once.

2. Spread luncheon cloth on grass, produce plate of sandwiches and announce in loud voice that it looks like a nice day for a picnic. Rain will pour down immediately, destroying forest fire and sandwiches.

3. Walk nonchalantly through fire and complain about feeling chilly. Flames will become discouraged and quit.

4. Whistle "Dixie" and start marching toward nearest river. Stirring music will cause flames to strut along behind you. Wade across river. Forest fire will try to follow you and will get its ardor dampened.

5. Borrow fire-eaters from [a circus] side-show and yell, "Free lunch – go to it, boys!" Flames will disappear rapidly.

(Clipped, D. J. Stoner)