J8.9

On the Origins of "Superfog" – A Combination of Smoke and Water Vapor that Produces Zero Visibility over Roadways

Gary L. Achtemeier[•]
USDA Forest Service, Athens, GA

1. INTRODUCTION

Southern 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. Although the vast majority of prescribed burns are carried out without incident, there are occasions when meteorological conditions combine with residual smoke to compromise visibility. Multiple-vehicle pileups, numerous physical injuries, extensive property damage, and fatalities have been 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.

Although smoke/fog from prescribed burns can create roadway visibility hazards anywhere in the country, the greatest threat is in the South (Achtemeier, et al., 1998a). There are several reasons why this is. First, by far more prescribed burning is done in the South than elsewhere in the Country. Approximately 4-6 million acres of forest and agricultural land in the South (defined as the 13 states from Virginia to Texas and from the Ohio River southward) are burned each year by prescribed fire. Second, much prescribed burning is done during relative humid periods during the winter rainy season when fog formation is more likely. Some land managers use high fuel moisture as a buffer to keep fire from burning too deep into duff layers. Third, the South has an enormous wildland/urban interface problem. Here wildland/urban interface is defined as the interface between the wildland and human activity. Large urban centers such as Atlanta and Charlotte have grown into historically forested areas. Many people are retiring to communities cut into forested areas. Many people travel over Southern highways to resort areas along the Atlantic and Gulf coasts and Florida. Large areas of Southern forest have regrown within land ownership patterns and road networks of the old agricultural South.

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).

Reports of exceptionally dense fog ("superfog") with visibilities estimated in fractions of a meter (feet), have been filed by state troopers while investigating accidents. However, because the accident locations are unpredictable and remote, and accidents usually occur near sunrise, it has not been possible for smoke scientists to take observations because the fog typically dissipates shortly after sunrise. Thus, the connection between superfog and smoke, though plausible, has not been empirically verified – either through observations or modeling.

Figure 1. Superfog photographed during a prescribed burn in South Carolina in 2001.

[•] *Corresponding author address:* Gary L. Achtemeier, Forest Sciences Laboratory, 320 Green Street, Athens, GA 30602; e-mail: gachtemeier@fs.fed.us.

Recently, the occurrence of superfog has been documented. Superfog was video recorded from an aircraft flying over the Oakmulgee National Wildlife Refuge in western Alabama during a smoke experiment in 1997 (Achtemeier, et al., 1998b) although the significance of the event was not recognized until 2001. During the winter 2001 burn season, Superfog was photographed in daytime during a prescribed burn in South Carolina. A section of the photographic image is shown in Figure 1. The bluish-white smoke typical from burning duff and light woody fuels is visible throughout the image. However, near the ground is a second "smoke" plume consisting of dense white smoke that rises several meters above ground. This smoke is exceptionally dense as evidenced by the disappearance of tree trunks. Analysis of this and other photographs taken during the event, including two from a service vehicle driven through the smoke, led to the conclusion that the dense white smoke was indeed fog – Superfog.

2. HYPOTHESES FOR THE FORMATION OF SUPERFOG

The hypotheses for Superfog formation prior to 2001, were the dense smoke hypothesis and the hygroscopic nuclei hypothesis.

The dense smoke hypothesis holds that Superfog is not fog but dense smoke. If, for example, the residual smoke emissions from a hectare of smoldering timberland is just 1/10,000th of the smoke emissions during the active phase of burning, then it can be shown that ground-level smoke concentrations during the smoldering phase and the active combustion phase can be the same. If the daytime mixing height is 1000 m and the nighttime mixing height is 10 m, the mixing height ratio is 100. If the daytime transport wind speed is 10 m/sec and the nighttime transport wind speed is 1 m/sec, then the transport wind ratio is 10. If the width of the fire line is a few 10's of meters, and the width of the smoldering area is a few 100's of meters, then the area ratio is 10. Multiplying these ratios together (100x10x10) equals 10,000. Thus, according to the dense smoke hypothesis, stable, near-calm weather during night, can create conditions favorable for dense ground-level smoke concentrations. This dense smoke can significantly impair visibility to create accident-causing obstructions.

The hygroscopic nuclei hypothesis is the more popular of the two hypotheses. The hygroscopic nuclei hypothesis holds that smoldering smoke contains an enormous number of hygroscopic particles – particles that have an affinity for water and assist in the formation of small water droplets. Small plumes of residual smoke become trapped in drainage flows and are carried into stream basins at night. When weather conditions favor ponding of drainage flows in basins, air temperatures there become much cooler than air temperatures over higher ground. The relative humidity is higher in the valleys. In addition, local moisture sources such as streams, lakes, and standing water can contribute moisture to the valley airmass further increasing the relative humidity there. When the relative humidity approaches 100 percent, the hygroscopic particles in smoke assist the formation of fog. The large number of hygroscopic particles competes for the available moisture. The resulting large number of smaller fog droplets is more efficient at scattering light than is a smaller number of large fog droplets. Greater reductions in visibility can be expected in smoke-enhanced fog – Superfog.

With additional information provided by the recent observations of Superfog, two new hypotheses for the formation of Superfog have been developed. These are the burnscape hypothesis and the moisture excess hypothesis. The remainder of this paper will be devoted to the moisture excess hypothesis.

2.a. The Moisture Excess Hypothesis

The moisture excess hypothesis holds that large amounts of moisture are released at high temperature in smoke from smoldering logs and stumps. Once released, this "moist smoke" cools rapidly through long wave radiation to supersaturation and dense fog – Superfog – forms. Mixing with the cooler ambient airmass will either maintain the Superfog if the ambient air is sufficiently moist or dissipate the Superfog if the ambient air is dry.

3. TESTING THE MOISTURE EXCESS HYPOTHESIS

The moisture excess hypothesis was tested as follows. A Vaisala temperature and relative humidity probe was affixed to a pole and immersed in residual smoke just above smoldering fuels.

Figure 2. Sampling the temperature and relative humidity of smoke on 18 March 2002 at a prescribed burn site located at the Hitchiti Experimental Forest in central Georgia.

Then the recorded temperature and relative humidity data were converted to dew point temperature, mixing ratio, and saturation mixing ratio. Finally, a simple model for mixing smoke and ambient air was used to determine the magnitude of moisture excess, if any.

Figure 2 shows how the sampling was done about an hour after the active burn phase had ceased. The Vaisala probe was inserted into the plume from smoldering woody debris and the temperature and relative humidity recorded on a Campbell data recorder (bag below handle) for later analysis. The Vaisala instrument proved unsuitable for this study. The rapid response relative humidity sensor functioned as advertised, however the temperature sensor was slow response (2-3min). Thus the sensor had to be held in the smoke plume for several minutes before accurate relative humidity readings were obtained. This problem was not discovered until after the measurements were taken. Reanalysis of the data produced only 35 data points that were deemed sufficiently accurate for further study.

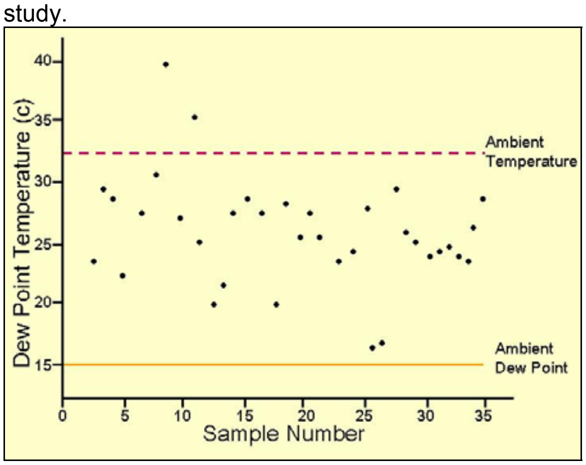

Figure 3. Dew point temperatures calculated from 35 temperatures and relative humidities measured at the Hitchiti Experimental Forest on 18 March 2002.

Figure 3 shows dew point temperatures calculated from temperatures and relative humidities measured on 18 March 2002. The ambient dew point temperature of 13.9C is shown for reference. Most of the smoke dew point temperatures ranged from 20-30 C thus showing that the residual smoke contained more moisture than did the ambient air. Two dew point temperatures exceeded the ambient temperature (31C).

Figure 4 shows the results from a simple model for Superfog formation. The model used the highest dew point temperature (38C) in Figure 2. The measured smoke temperature was 49C and the relative humidity of the smoke was 57 percent. Nighttime conditions were assumed. The temperature of the ambient air was assumed to have fallen to 14.8C and the relative humidity was 95 percent.

The model first assumed radiational cooling of the smoke from 49C to 39C. Then one cubic meter of smoke was mixed with one cubic meter of ambient air. This changed the moisture deficit in the smoke from an initial value of 30.78 gm/kg to a moisture excess of 3.4 gm/kg in the mixed airmass. Additional mixing by adding one cubic meter of ambient air to the mixture reduced the moisture excess to approximately 1.0 gm/kg by 10 mixes – a 10:1 ratio of ambient air to smoke. Another calculation without radiational cooling produced small moisture excess.

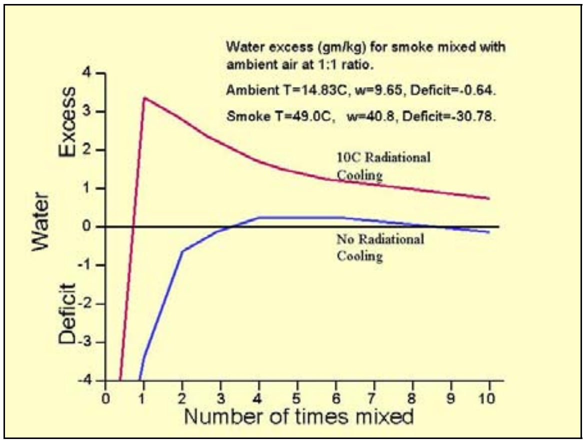

Figure 4. Water excess resulting from mixing specified cubic meters of ambient air into one cubic meter of smoke.

4. DISCUSSION

Superfog, a dense fog the reduces visibility to a few meters, occurs when residual smoke from prescribed burns combines with just the right ambient temperature and relative humidity. Three hypotheses that could explain Superfog were presented. Smoke, hygroscopic particles, and moisture are assumed to be present in all three hypotheses. Therefore hypotheses are not mutually exclusive. The moisture excess hypothesis emphasizes the role of moisture released at high temperature as a cause of Superfog.

To test the moisture excess hypothesis, residual smoke from a prescribed burn was sampled for temperature and relative humidity. These data were converted to dew point temperature, mixing ratio and saturation mixing ratio. A simple model was constructed to mix smoke with ambient air under various assumptions of pre-mixed radiational cooling of the smoke.

The simple model showed that large moisture excesses are possible when the smoke is mixed with ambient air that is already near saturation. Such ambient conditions occur frequently during the late night and predawn hours in valley bottoms in the South.

This model does not prove that the water excesses shown in Figure 4 will form Superfog. A confirming proof will have to await sophisticated laboratory experiments or application of a numerical fog/cloud model based on the physics of cloud formation.

5. ACKNOWLEDGMENTS

The support of Ken Forbus and Tim Giddens in instrumentation and in acquiring smoke data is appreciated.

6. REFERENCES

Achtemeier, G. L., W. Jackson, B. Hawkins, D. Wade, and C. McMahon, 1998a: The Smoke Dilemma: A Head-On Collision! Transactions of the Sixty-third North American Wildlife and Natural Resources Conference, 20-24 March 1998, Orlando, FL. pp. 415-421.

Achtemeier, G. L., C. W. Adkins, and P. H. Greenfield, 1998b: Airborne mapping of near-ground smoke at night using GPS and light-enhancing video imagery. Proceedings of the Seventh Forest Service Remote Sensing Applications Conference, April 6-10, 1998, 317-327. American Society for Photogrammetry and Remote Sensing, Bethesda, MD. 317–327.

Mobley, Hugh E. 1989. Summary of smoke-related accidents in the South from prescribed fire (1979—1988). American Pulpwood Association Technical Release. 90-R-11.

Twilley, T., 2000: Pileup on fogbound I-10 leaves five dead. The Sun Herald, Vol 116, No. 221, 8 May 2000. Gulf Publishing, Gulfport, MS. Div. Of Knight/Ridder Newspapers.