Smoke Plumes: Emissions and Effects

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Smoke can manifest itself as a towering plume rising against the clear blue sky—or as a vast swath of thick haze, with fingers that settle into valleys overnight. It comes in many forms and colors, from fluffy and white to thick and black. Smoke plumes can rise high into the atmosphere and travel great distances across oceans and continents. Or smoke can remain close to the ground and follow fine-scale topographical features.

Along the way, the gases and particles in the plumes react physically and chemically, creating additional particulate matter and gases such as ozone (O_3). If atmospheric water content is high, smoke plumes can also create "superfog" (Achtemeier 2002). Over the past decade, researchers have studied the suite of trace gases and aerosols emitted by wildland fires, along with the physical and chemical reactions and transformations that occur within a plume.

Why Do We Care?

Smoke gases and particles constitute only a tiny fraction of the air (less than 0.1 percent of the atmosphere in any location, even under the worst conditions) (table 1). Overall, dry air is made up of 78 percent nitrogen (N_2), 21 percent oxygen (O_2), and about 1 percent trace gases (about 0.9 percent argon (Ar) and 0.1 percent other trace gases). Water vapor in the air ranges from almost nothing to 5 percent. Yet the trace amount of smoke in the air can have significant impacts, such as making the air smell bad; limiting visibility; and affecting the health of vegetation and animals, including humans. Smoke can affect public health, transportation safety, and the health and well-being of firefighters.

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Due to health and safety concerns, the Clean Air Act regulates aspects of atmospheric smoke. If smoke concentrations in a region exceed the national ambient air quality standards (NAAQSs), then the region is designated as "nonattainment." Nonattainment triggers regulatory actions, such as controls on smoke emissions; fees/charges for emissions; restrictions on industry; and, in some cases, restrictions on the use of fire. Currently, the NAAQS threshold for particulate matter finer than 2.5 micrometers in diameter ($PM_{2.5}$) is 35 micrograms per cubic meter (24-hour average); for ozone, the threshold is 75 parts per billion (8-hour average). Even at levels below these standards, smoke can significantly affect visibility, degrading vistas and creating transportation hazards. Smoke combined with high humidity can produce whiteout conditions known as superfog (Achtemeier 2002).

Wildland Fire Emissions

If fire were 100-percent efficient, the only products released would be carbon dioxide, water vapor, and heat. However, the combustion of wildland fuels is never 100-percent efficient. In addition to carbon dioxide and water vapor, the process transforms some of the fuel into ash, char, particulate matter, carbon monoxide, and other carbon-containing gases—a rich and complex mixture of gases and particles. Figure 1 shows the distribution of carbon emitted by

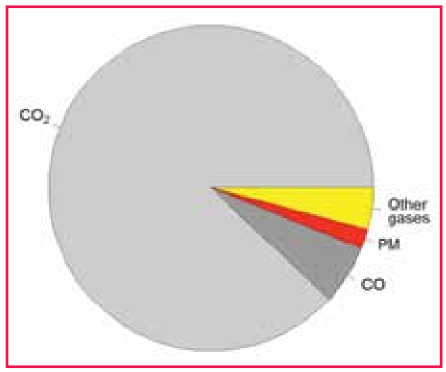

Figure 1—*The distribution of carbon emitted by a typical low-intensity understory prescribed fire in light fuels (based on Urbanski (2014)). CO_2 = carbon dioxide; CO = carbon monoxide; PM = particulate matter.*

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Table 1—*Gases and particles in the atmosphere, including those related to biomass burning.*

Chemical/particle		Description
Symbol	**Name**	
Ar	Argon	About 0.9 percent of the atmosphere.
BC	Black carbon	Particles from combustion that strongly absorb incoming solar radiation and emit longwave radiation.
CO	Carbon monoxide	Emitted from the incomplete combustion of biomass.
CO_2	Carbon dioxide	A primary product of biomass burning.
H_2O	Water	A primary product of biomass burning.
N_2	Nitrogen	About 78 percent of the atmosphere.
NH_3	Ammonia	A precursor of inorganic particle formation; trace amounts emitted from biomass burning.
NO_X	Oxides of nitrogen	NO and NO_2, precursors to ozone and particle formation.
NO	Nitrogen oxide	Part of NO_X; released from biomass burning as a function of the fuel nitrogen content and combustion phase.
NO_2	Nitrogen dioxide	Part of NO_X.
O_2	Oxygen	About 21 percent of the atmosphere.
O_3	Ozone	Created by the reaction of NO_X and VOCs in the presence of sunlight; regulated under the Clean Air Act.
OC	Organic carbon	Carbon and hydrogen compounds, oxygenated carbon/hydrogen compounds, and other trace elements; a major constituent of particulate matter from biomass burning.
PAN	Peroxyacetyl nitrate	Can sequester NO_X and travel long distances in the atmosphere; mixed back down near the surface, warmer temperatures break it apart, freeing up NO_X to generate more O_3 far from the fire.
$PM_{2.5}$	Particulate matter (aerodynamic diameter < 2.5 µm)	Fine particulate matter; can comprise organic and inorganic compounds; regulated under the Clean Air Act.
SO_2	Sulfur dioxide	A precursor of inorganic particle formation; trace amounts emitted from biomass burning.
SOA	Secondary organic aerosol	Particles formed by a series of physical and chemical reactions.
VOC	Volatile organic compound	Precursors of O_3 and SOA formation; hundreds identified from biomass burning, hundreds yet to be identified; examples: methane, ethane, benzene, furan, formaldehydes, methanol, monoterpenes.

a typical low-intensity understory prescribed fire in light fuels. Minor smoke constituents such as carbon monoxide, particulate matter, and "other gases" are mainly responsible for smoke impacts on visibility and air quality.

Over the past decade, scientists have made tremendous progress in identifying the "other gases" produced by wildland fires (fig. 1). Multiple research projects have gotten support from the Forest Service's Research and Development, the multiagency Joint Fire Science Program, the U.S. Department of Defense Strategic Environmental Research and Develop Program, and others. Researchers have studied the composition of smoke from simulated fires in the large-scale combustion facility operated by the Rocky Mountain Research Station's Missoula Fire Sciences Laboratory and from operational prescribed fires in the Southeastern and Southwestern United States. Recent advances in instrumentation and chemical analytical techniques have allowed scientists to identify nearly 200 volatile organic compounds (VOCs) in fresh smoke. The gases include methane, ethane, benzene, furan, formaldehydes, methanol, monoterpenes, and more. Despite such advances, a large percentage of VOCs remain unidentified, including 30 to 40 percent of them in forest fuels and over 70 percent of them in organic soils and duff.

Particulate Matter

Particulates released from fire are mostly carbon based and are typically referred to as organic carbon and black carbon. Organic carbon consists of carbon and hydrogen compounds, oxygenated carbon/hydrogen compounds, and other trace elements. Black carbon is the fraction of the particle that strongly absorbs incoming solar radiation and emits longwave radiation into the atmosphere. It is a product of combustion; in its purest form, it would be graphite. It has been identified as a short-lived climate forcer, bolstering the greenhouse effect; deposition of black carbon on snow accelerates snowmelt.

> Smoke particles are quite small, making them very efficient at scattering light, thereby reducing visibility and generating "haze."

Particles rarely exist solely as organic or black carbon. Instead, they form a continuum, ranging from pure graphite to mostly organic compounds. Smoke particles from wildland fires tend to have a higher percentage of organics than do particles from anthropogenic combustion sources, which tend to have a higher black carbon content.

New particles form in the atmosphere through gas-to-particle reactions involving VOCs, oxides of nitrogen (nitrogen monoxide and nitrogen dioxide), ammonia, and sulfur dioxide. Factors such as time, temperature, sunlight, and the proportion of gases in the atmosphere influence these reactions. The result is ultrafine particles; water vapor and other gas-phase species can easily attach and other reactions can occur, resulting in particle growth. These small particles can also grow through particle-to-particle coagulation.

Secondary organic aerosols are particles formed in the atmosphere through a series of gas-phase chemical reactions that lower the volatility of VOCs to the point where they can condense into or onto particulates. These organic compounds can continue reacting until the carbon is oxidized to carbon monoxide or carbon dioxide or until the particles are removed from the atmosphere through deposition. Cooler temperatures help semivolatile gases condense into particulates. As compounds react and age in the atmosphere, they tend to more readily attach to water, increasing the amount of water in the particulate. Most semivolatile compounds formed in the atmosphere remain to be identified. Secondary organic aerosols are an important area of current research.

Most smoke particles are quite small, often less than 1 micrometer in diameter. They are very efficient at scattering light, reducing visibility and generating "haze." Smoke plumes lofted high into the atmosphere can also interact with cloud-forming processes.

Smoke and Ozone

Ozone is created in the atmosphere through the reactions of oxides of nitrogen (nitrogen monoxide and nitrogen dioxide) with VOCs in the presence of sunlight. Nitrogen dioxide undergoes photolysis (the separation of molecules by light) into nitrogen monoxide and oxygen, with the oxygen atoms (O) then reacting with the abundant oxygen in the atmosphere (O_2) to generate ozone (O_3). In an atmosphere without VOCs, the ozone would then react with nitrogen monoxide (NO) to regenerate nitrogen dioxide (NO_2) and oxygen (O_2). However, the abundant VOCs in the atmosphere provide for the regeneration of nitrogen dioxide without removing ozone.

Smoke plumes are rich sources of VOCs and also contain oxides of nitrogen (NO_X). The NO_X are a function of the nitrogen content of the fuel and the fuel combustion phase. Smoke plumes are said to be "NO_X-limited" in that the generation of ozone is limited by the amount of NO_X available. By contrast, many urban areas tend to be VOC-limited in that they have an abundance of NO_X in the atmosphere. In the simplest case, when smoke plumes mix with emissions from urban areas with lots of NO_X, the extra NO_X they get can generate more ozone.

However, smoke is smoky: it blocks solar radiation, hindering photolysis. Oxides of nitrogen can also be sequestered in peroxyacetyl nitrate, limiting the generation of ozone. However, peroxyacetyl nitrate can travel long distances in the atmosphere before mixing into the air back down near the ground, where temperatures are warmer. Warmer temperatures lead to thermal disassociation, freeing up NO_X to generate more ozone long distances away from a wildland fire.

Plume Interactions

Wigder and others (2013) analyzed measurements of fine particulate matter, carbon monoxide, and ozone at Mount Bachelor Observatory during 32 wildfires from 2004 to 2011. The observatory is located in central Oregon atop the mountain at 9,064 feet (2,763 m) above sea level. It is a remote site, with measurements that have identified episodes of Asian air transport and biomass burning across North America. Many of the air masses measured were local to Oregon; but wildfire events from British Columbia, California, Idaho, Montana, and Washington have also affected the site.

For smoke plumes with less than 2 days transport time, fine particulate matter ($PM_{2.5}$) increased over the period, indicating the generation of secondary organic aerosols. For older events, however, the generation of fine particulate matter was low, indicating that aerosol removal from the air could exceed generation. Only 13 of the 32 plumes measured had significant ozone generation. The two plumes that traveled over the Seattle metropolitan area had greater ozone generation but not necessarily the highest. Transport time did not necessarily equate to greater ozone generation.

Superfog

A major component of the emissions from the combustion of vegetation is water vapor. Although water vapor is not a pollutant, the emission of water vapor and particulate matter under the right environmental conditions can result in extremely low visibilities near a wildland fire. The very dense fog that results is called superfog, with visibilities of less than 10 feet (3 m) and often less than 3 feet (1 m) (Achtemeier 2002).

Fog forms when water vapor condenses into tiny liquid water droplets suspended in the air. It normally occurs at a relative humidity of nearly 100 percent. The presence of particles in the air can boost the condensation process at humidities as low as 80 percent if the particles attract moisture. Such particles, referred to as hygroscopic, serve as cloud condensation nuclei.

The smoldering combustion of moist fuels such as organic soil, duff, and logs emits considerable amounts of water vapor and hygroscopic cloud condensation nuclei. When the warm, moist smoke mixes with cold air that already has a relative humidity approaching 100 percent, the result is a supersaturated atmosphere and the formation of superfog. The abundance of cloud condensation nuclei from the fire makes for very small condensed droplets. Small droplets are more effective at scattering light than larger droplets, leading to greater reductions in visibility.

Smaller droplets also have less mass and a slower settling velocity, letting them remain suspended in the atmosphere for longer periods of time. Achtemeier (2009) estimated the liquid water content of superfog to be about 23 times greater than in regular fogs. He also found that 1 percent of the particulate emissions from a wildland fire formed enough cloud condensation nuclei to shift the distribution of droplet sizes in superfog toward smaller droplets, reducing visibility to as low as 0.3 feet (0.1 m).

The water vapor and particulate matter in smoke can result in superfog, with visibilities of less than 10 feet.

Achtemeier (2013) created a Superfog Index. Ranging from 0 to 100, the index represents the probability of superfog formation. The index increases rapidly at air temperatures of less than 55 °F (13 °C) when the relative humidity is 90 percent or higher. Figure 2 shows Superfog Index curves for two ambient relative humidity scenarios.

Fire managers should be aware of the possibility of superfog formation. Other critical questions to raise in assessing fog-related risk include the following:

- Do you have a smoldering fire that will burn all night?
- Is there a transportation route within 3 miles (4.8 km)?
- Is the wind direction toward the road?
- Do drainages lead from the fire to the road?
- Are temperatures predicted to be less than 50 °F (10 °C)?

Smoke in Complex Terrain

As the sun goes down, the surface of the Earth cools and inversions form within valleys, trapping smoke and causing smoke concentrations to be higher than they would be if the atmosphere were mixing in cleaner, fresher air. Nighttime drainage flows can also carry smoke for tens of miles down valleys, allowing smoke to affect areas at night that had little or no smoke impacts during the day.

The result is that smoke impacts in valleys near or downwind of fires can be significantly higher than in flat terrain. Figure 3 gives a satellite view of smoke pooled in valleys across northern Idaho and western Montana in September 2012, before daytime heating dispersed the smoke. New advances in fine-scale meteorological and smoke modeling can now simulate patterns of smoke dispersion, including inversions.

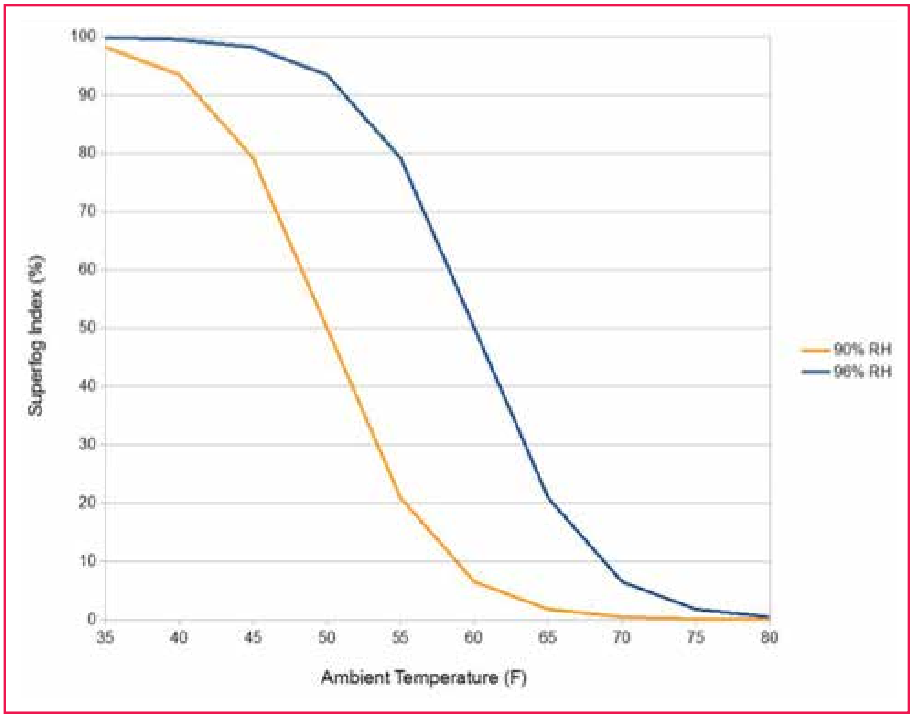

Figure 2—*Superfog Index indicating the probability of superfog formation as a function of ambient air temperature for two different relative humidity (RH) scenarios (yellow = 90 percent; blue = 96 percent) (adapted from Achtemeier (2013)).*

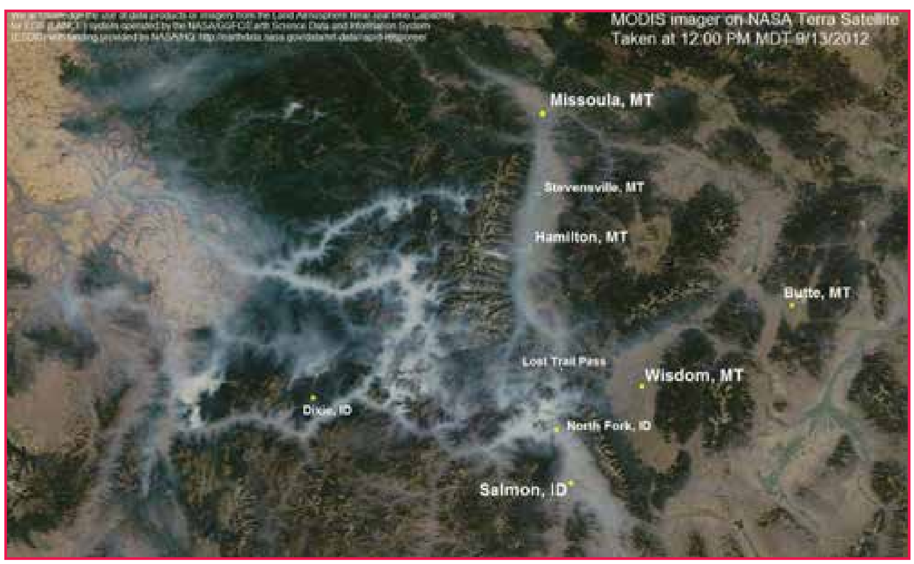

Figure 3—*Satellite view of smoke in valleys over northern Idaho and western Montana on September 13, 2012, at 1200 mountain daylight time, from the Moderate Resolution Imaging Spectroradiometer instrument aboard the National Aeronautics and Space Administration Terra satellite. Cities range from Missoula, MT, in the north; to Salmon, ID, in the south; to Butte, MT, in the east.*

The Challenge of Smoke

Smoke is challenging. It can be lofted high into the atmosphere to interact with cloud processes. It can smolder near the ground, depositing emissions.

The combination of aerosols and trace gases create their own chemical mix, with reactions that are as yet unidentified. Temperature and atmospheric water content interact with the smoke plume and fog processes. Smoke also blocks the transmission of solar radiation, hindering photolysis reactions.

Many of the trace gases emitted from wildland fires have yet to be identified, as do the intermediary products produced in a plume. With the outlook for more wildfires in the future, especially in a changing climate—and with tighter health standards—understanding these processes will become more critical in the years to come.

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