Chapter 5

SMOKE SOURCE CHARACTERISTICS

Smoke Source Characteristics

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Whether you are concerned with particulate matter, carbon monoxide, carbon dioxide, or hydrocarbons, all smoke components from wildland fires are generated from the incomplete combustion of fuel. The amount of smoke produced can be derived from knowledge of area burned, fuel loading (tons/acre), fuel consumption (tons/acre), and pollutant-specific emission factors. Multiplying a pollutant-specific emission factor (lbs/ton) by the fuel consumed, and adding the time variable to the emission production and fuel consumption equations results in emission and heat release rates that allow the use of smoke dispersion models (figure 5.1). This section discusses the characteristics of emissions from wildland fire and the necessary inputs to obtain source strength and heat release rate for assessing smoke impacts.

Prefire Fuel Characteristics

Fuel consumption and smoke production are influenced by preburn fuel loading categories such as grasses, shrubs, woody fuels, litter, moss, duff, and live vegetation; condition of the fuel (live, dead, sound, rotten); fuel moisture; arrangement; and continuity. These characteristics can vary widely across fuelbed types (figure 5.2) and within the same fuelbed type (figure

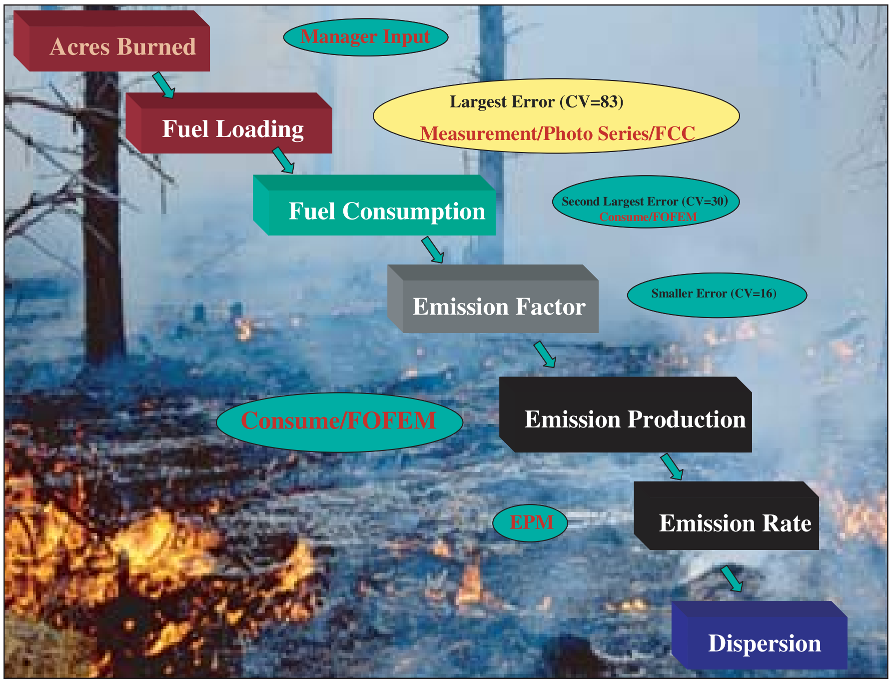

Figure 5.1. Combustion and emission processes.

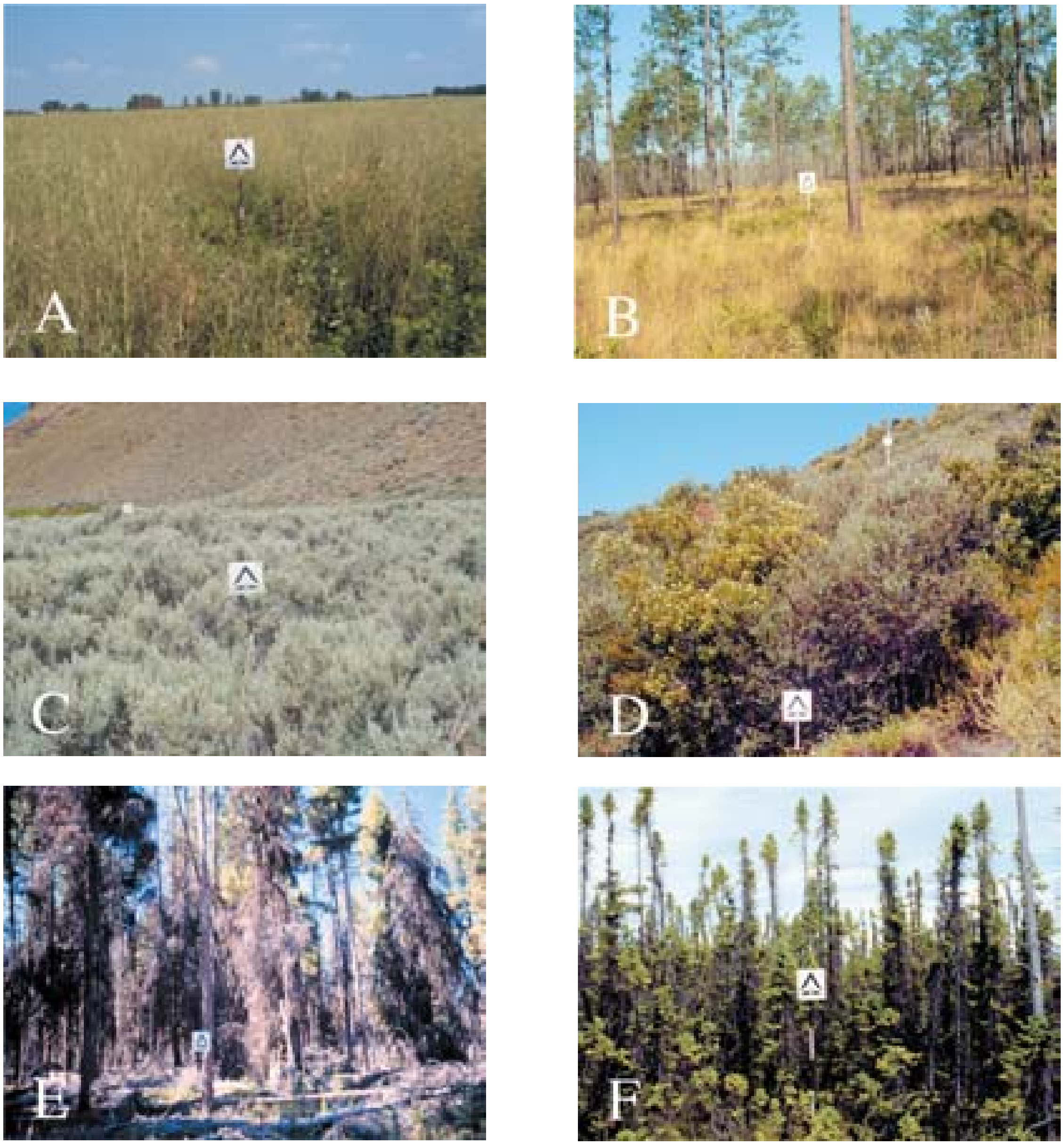

Figure 5.2. The preburn fuel loading (downed, dead woody, grasses, shrubs, litter, moss, and duff) can vary widely between fuel types as shown in (A) midwest grassland, 2.5 tons/acre; (B) longleaf pine, 4 tons/acre; (C) southwest sage shrubland, 6 tons/acre; (D) California chaparral, 40 tons/acre; (E) western mixed conifer with mortality, 67 tons/acre; and (F) Alaska black spruce, 135 tons/acre.

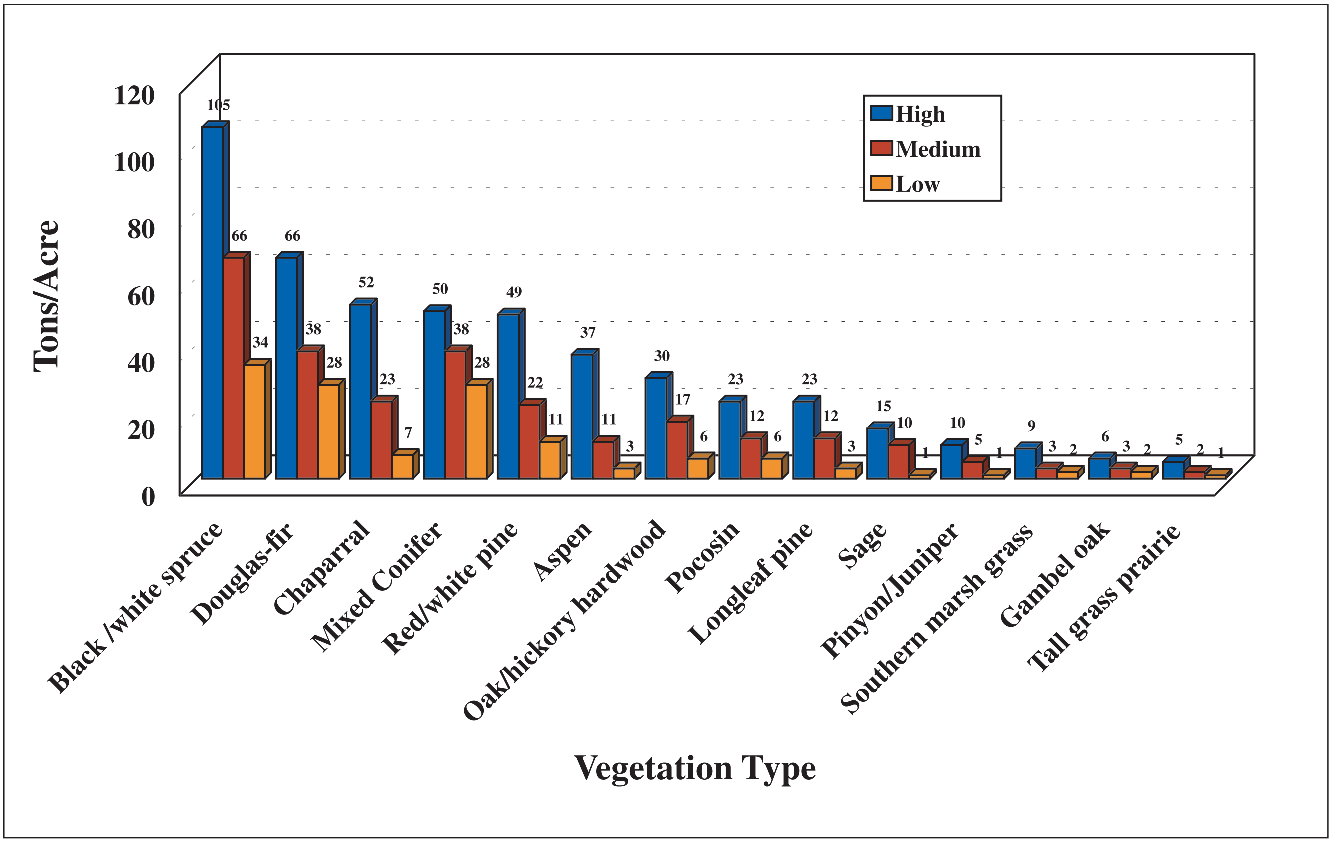

Figure 5.3. Variability of fuel loading across several fuelbed types. Sources are referenced in the text.

5.3). For instance, fuel loadings range considerably: less than 3 tons/acre for perennial grasses in the Midwest with no rotten material or duff (Ottmar and Vihnanek 1999); 4 tons per acre of mostly grass and a shallow litter and duff layers for a southern pine stand treated regularly with fire (Ottmar and Vihnanek 2000b); 6 tons/acre in a Great Basin sage shrubland (Ottmar and others 2000a); 40 tons per acre in a mature California chaparral shrubland (Ottmar and others 2000a); 67 tons per acre of 80 percent of which is rotten woody fuels, stump, snags, and deep duff in a multi-story, ponderosa pine and Douglas-fir forest with high mortality from disease and insects (Ottmar and others 1998); to 167 tons/acre in a black spruce forest in Alaska with a deep moss and duff layer (Ottmar and Vihnanek 1998). The heaviest fuel loadings encountered are normally associated with material left following logging, unhealthy forests, mature brush and tall grasses, or deep layers of duff, moss or organic (muck) soils. The large variation in potential fuel loading can contribute up to 80 percent of the error associated with estimating emissions (Peterson 1987, Peterson and Sandberg 1988).

Higher fuel loading generally equates to more fuel consumption and emissions if the combustion parameters remain constant. For example, a frequently burned southern or western pine stand may have a fuel loading of 12 tons per acre while a recently harvested pine stand with logging slash left on the ground may have a fuel loading of 50 tons per acre. Prescribed burning under a moderately dry fuel moisture situation would achieve 50 percent biomass consumption equating to 3 tons per acre consumed in the unlogged pine stand and 25 tons/acre consumed in the logged stand.

There are several techniques available for determining fuel loading (U.S. Department of Interior 1992). Collecting and weighing the fuel is the most accurate method but is impractical for many fuel types except grasses and small shrubs. Measuring some biomass parameter and estimating the biomass using a pre-derived equation is less accurate but also less time consuming (Brown 1974). Ongoing development of several techniques including the natural fuels photo series (Ottmar and others 1998, Ottmar and Vihnanek 2000a) and the Fuel Characteristic Class system (FCC) (Sandberg and others 2001) will provide managers new tools to better estimate fuel loadings and reduce the uncertainty that currently exist with assigning fuel characteristics across a landscape. The photo series is a sequence of single and stereo photographs with accompanying fuel characteristics. Over 26 volumes are available for logging and thinning slash and natural fuels in forested, shrubland, and grassland fuelbed types throughout the United States. The Fuel Characteristic Class System is a national system being designed for classifying wildland fuelbeds according to a set of inherent properties to provide the best possible fuels estimates and probable fire parameters based on available site-specific information.

Fuel moisture content is one of the most influential factors in the combustion and consumption processes. Live fuel moisture content can vary by temperature, relative humidity, rainfall, soil moisture, seasonality and species. Dead fuel moisture content varies by temperature, relative humidity, rainfall, species, material size, and decay class. Fuel moisture content affects the flame temperature that in turn influences the ease of ignition, the amount and rate of consumption, and the combustion efficiency (the ratio of energy produced compared to energy supplied). In other words, higher fuel moisture content requires more energy to drive off the water, enabling fuel to reach a point where pyrolysis can begin. Generally, fuels with low fuel moisture content burn more efficiently and produce fewer emissions per unit of fuel consumed. On the other hand, even though emissions per unit of fuel burned will be greater at higher fuel moistures because of a less efficient combustion environment, total emissions may be less if some fraction of the fuels do not totally burn—typically the large wood fuels and forest floor.

Since combustion generally takes place at the fuel/atmosphere interface, the time necessary to ignite and consume an individual fuel particle with a given fuel moisture content depends upon the smallest dimension of the particle. The surface area to volume ratio of a particle is often used to depict a particle’s size—the greater the ratio, the smaller the particle. Small twigs and branches have a much larger surface to volume ratio than large logs and thus a much greater fuel surface exposed to the atmosphere. Consequently, fine fuels will have a greater probability of igniting and consuming for a given fuel moisture.

The arrangement of the particles is also important. The structuring of fuel particles and air spaces within a fuel bed can either enhance or retard fuel consumption and affect combustion efficiency. The packing ratio (the fraction of the fuel bed volume, occupied by fuel) is the measure of the fuel bed porosity. A loosely packed fuel bed (low packing ratio) will allow plenty of oxygen to be available for combustion, but may result in inefficient heat transfer between burning and adjacent unburned fuel particles. Many particles cannot be preheated to ignition temperature and are left unconsumed. On the other hand, a tightly packed fuel bed (high packing ratio) allows efficient heat transfer between the particles, but may restrict oxygen availability and reduce consumption and combustion efficiency. An efficiently burning fuel bed will have particles close enough for adequate heat transfer while at the same time large enough spaces between particles for oxygen availability.

Fuel discontinuity—both horizontal and vertical—isolates portions of the fuel bed from pre-ignition heating and subsequent ignition. Sustained ignition, and combustion will not occur when the spacing between the fuel particles is too large.

Biochemical differences between species also play a role in combustion. Certain species such as hoaryleaf ceanothus (*Ceanothus crassifolius*), palmetto (*Serenoa repens)* and gallberry (*Ilex glabra*) contain volatile compounds that make them more flammable than species such as Carolina azalea (*Rhododendron carolinianum*) under similar live moisture contents.

Fire Behavior

Fire behavior is the manner in which fire reacts to the fuels available for burning (DeBano and others 1998) and is dependent upon the type, condition, and arrangement of smaller woody fuels, local weather conditions, topography and in the case of prescribed fire, lighting pattern and rate. Two aspects of fire behavior include fire line intensity (the amount of heat released per unit length of fire line) and rate of spread (activity of the fire in extending its horizontal dimensions). These aspects influence combustion efficiency of consuming biomass and the resultant pollutants produced from wildland fires. During fires with rapid rates of spread and high intensity but relatively short duration, a majority of the biomass consumed will be smaller woody fuels and will occur during the more efficient flaming period resulting in less smoke. Burning dry grass and shrublands, forestlands with high large woody and duff fuel moisture contents, clean, dry piles, and rapidly igniting an area with circular or strip-head fires will produce these characteristics. In simple, uniform fuelbeds such as pine and leaf litter with only shallow organic material beneath, a backing fire with lower rates of spreads and intensities may consume fuels very efficiently producing less smoke. In more complex fuelbeds, the backing flame may become more turbulent and this combustion efficiency may lessen. During wildland fires with a range of fire intensities and spread rates but long burning durations, a large portion of the biomass consumed will occur during the less efficient smoldering phase, producing more smoke relative to the fuel consumed. Smoldering fires often occur during drought periods in areas with high loadings of large woody material or deep duff, moss, or organic soils. The Emissions Production Model (EPM) (Sandberg and Peterson 1984, Sandberg 2000) and FARSITE (Finney 2000) take into account fire behavior and lighting pattern to estimate emission production rates.

Fuel Consumption

Fuel consumption is the amount of biomass consumed during a fire and is another critical component required to estimate emissions production from wildland fire. Fuels are consumed in a complex combustion process that adds to a variety of combustion products including particulate matter, carbon dioxide, carbon monoxide, water vapor and a variety of various hydrocarbons. Biomass consumption varies widely among fires and is dependent on the fuel type (e.g. grass versus woody fuels), arrangement of the fuel (e.g. piled versus non-piled woody debris), condition of the fuel (e.g. high fuel moisture versus low fuel moisture) and the way the fire is applied in the case of a prescribed fire (e.g. a helicopter or fixed wing aircraft ignited high intensity, short duration mass fire versus a slow, low intensity hand ignition). As with fuel characteristics, extreme variations associated with fuel consumption can contribute errors of 30 percent or more when emissions are estimated for wildland fires (Peterson 1987; Peterson and Sandberg 1988).

In the simplest terms, combustion of vegetative matter (cellulose) is a thermal/chemical reaction where by plant material is rapidly oxidized producing carbon dioxide, water, and heat (figure 5.4). This is the reverse of plant photosynthesis where energy from the sun combines with carbon dioxide and water, producing cellulose (figure 5.4).

In the real world, the burning process is much more complicated than this. Burning fuels is a two-stage process of pyrolysis and combustion. Although both stages occur simultaneously, pyrolysis occurs first and is the heat-absorbing reaction that converts fuel elements such as cellulose into char, carbon dioxide, carbon monoxide, water vapor, and highly combustible hydrocarbon vapors and gases, and particulate matter. Combustion follows as the escaping hydrocarbon vapors released from the surface of the fuels burn. Because combustion efficiency is rarely 100 percent during wildland fires, hundreds of chemical compounds are emitted into the atmosphere, in addition to carbon dioxide and water. Pyrolsis and combustion proceed at many different rates since wildland fuels are often very complex and non-homogeneous (DeBano and others 1998).

It has been recognized that there are four major phases of combustion when fuel particles are consumed (figure 5.5) (Mobley 1976, Prescribed Fire Working Team 1985). These phases are: (1) pre-ignition; (2) flaming; (3) smoldering; and (4) glowing (figure 5.4). During the pre-ignition phase, fuels ahead of the fire front are heated by radiation and convection and water vapor is driven to the surface of the fuels and expelled into the atmosphere. As the fuel's internal temperature rises, cellulose and lignin begin to decompose, releasing combustible organic gases and vapors (Ryan and McMahon 1976). Since these gases and vapors are extremely hot, they rise and mix with oxygen in the air and ignite at temperatures between 617^0 F and 662^0 F leading to the flaming phase (DeBano and others 1998).

In the flaming phase, the fuel temperature rises rapidly. Pyrolysis accelerates and is accompanied by flaming of the combustible gases and

$$\mathbf{CELLULOSE + O_2} \xrightarrow[\textbf{Heat/chemical energy}]{\qquad\qquad} \mathbf{CO_2 + H_20 + ENERGY}$$

$$\mathbf{CELLULOSE + O_2} \xleftarrow[\textbf{Sun/thermal energy}]{\qquad\qquad} \mathbf{CO_2 + H_20 + ENERGY}$$

Figure 5.4. The energy flow for combustion is reverse to that for photosynthesis.

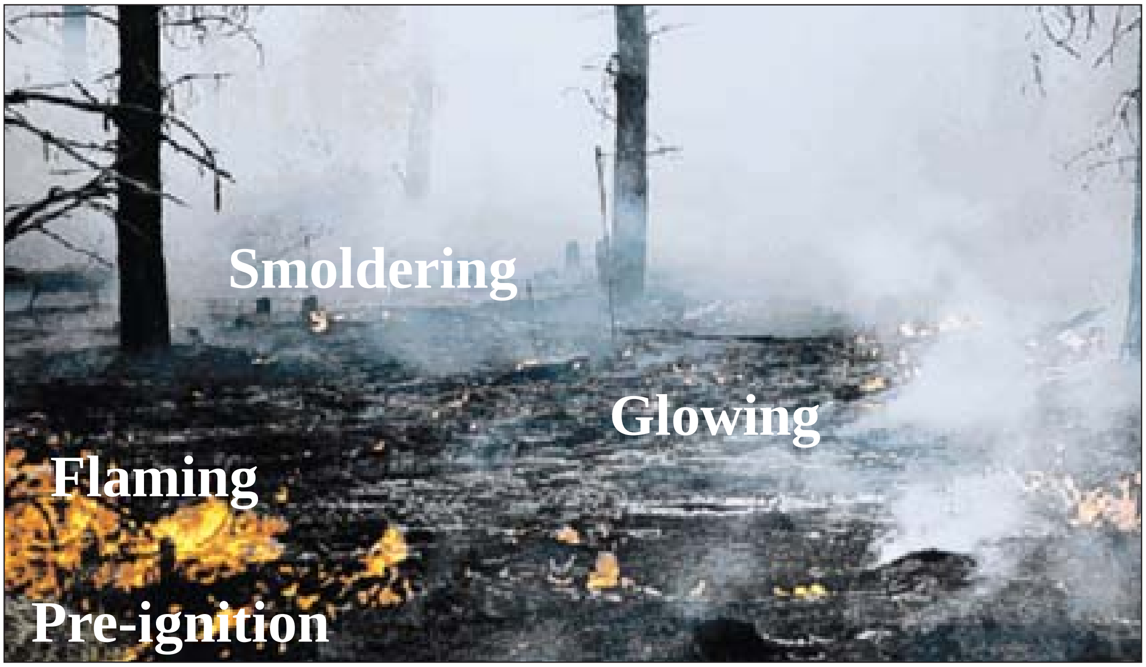

Figure 5.5. The four phases of combustion.

vapors. The combustion efficiency during the flaming stage is usually relatively high as long as volatile emissions remain in the vicinity of the flames. The predominant products of flaming combustion are carbon dioxide (CO_2) and water vapor (H_2O). The water vapor is a product of the combustion process and also derives from moisture being driven from the fuel. Temperatures during the flaming stage range between 932^0 F to 2552^0 F (Ryan and McMahon 1976). During the flaming period, the average exterior diameter reduction of round wood material occurs at a rate of 1 inch per 8 minutes (Anderson 1969). For example, a dry limb 3 inches in diameter would take approximately 24 minutes to completely consume if flaming combustion was sustained during the entire time period.

During the smoldering phase, emissions of combustible gases and vapors above the fuel is too low to support a flaming combustion resulting in a fire spread decrease and significant temperature drop. Peak smoldering temperatures range from 572^oF to 1112^oF (Agee 1993). The gases and vapors condense, appearing as visible smoke as they escape into the atmosphere. The smoke consists mostly of droplets less than a micrometer in size. The amount of particulate emissions generated per mass of fuel consumed during the smoldering phase is more than double that of the flaming phase.

Smoldering combustion is more prevalent in certain fuel types (e.g. duff, organic soils, and rotten logs) due to the lack of oxygen necessary to support flaming combustion. Smoldering combustion is often less prevalent in fuels with high surface area to volume ratios (e.g. grasses, shrubs, and small diameter woody fuels) (Sandberg and Dost 1990). Since the heat generated from a smoldering combustion is seldom sufficient to sustain a convection column, the smoke stays near the ground and often concentrates in nearby valley bottoms, compounding the impact of the fire on air quality.

Near the end of the smoldering phase, the pyrolysis process nearly ceases, leaving the fuel that did not completely consume with a layer of black char, high in carbon content.

In the glowing phase, most volatile gases have been driven off. Oxygen in the air can now reach the exposed surface of char left from the flaming and smoldering phase and the remaining fuels begin to glow with the characteristic orange color. Peak temperatures of the burning fuel during the glowing phase are similar to those found in the smoldering phase and range from 572°F to 1117°F (DeBano and others 1998). There is little visible smoke. Carbon dioxide, carbon monoxide, and methane are the principal products of glowing combustion. This phase continues until the temperature of the fuel drops or until only noncombustible, mineral gray ash remains.

The combustion phases occur both sequentially and simultaneously as a fire front moves across the landscape. The efficiency of combustion that takes place in each combustion phase is not the same, resulting in a different set of chemical compounds being released at different rates into the atmosphere. Understanding the combustion process of each phase will assist managers in employing various emission reduction techniques. Fuel type, fuel moisture content, arrangement, and the way the fuels are ignited in the case of prescribed fires, can affect the amount of biomass consumed during various combustion stages. Between 20 and 90 percent of the biomass consumed during a wildland fire occurs during the flaming stage, with the remainder occurring during the smoldering and glowing stages (Ottmar and others [in preparation]. The flaming stage has a high combustion efficiency; that is it tends to emit the least emissions relative to the mass of fuel consumed. The smoldering stage has a low combustion efficiency and produces more smoke relative to the mass of fuel consumed.

Biomass consumption of the woody fuels, piled slash, and duff in forested areas has become better understood in recent years (Sandberg and Dost 1990, Sandberg 1980, Brown and others 1991, Albini and Reinhardt 1997, Reinhardt and others 1997, Ottmar and others 1993, Ottmar and others [in preparation]). Large woody fuel consumption generally depends on moisture content of the woody fuel and duff. Approximately 50 percent of the consumption occurs during the flaming period. Duff consumption depends on fire duration of woody fuels and duff moisture content. Consumption occurs primarily during the smoldering stage when duff moisture is low. Consumption of tree crowns in forests and shrub crowns in shrublands are poorly understood components of biomass consumption and research is currently underway (Ottmar and Sandberg 2000) to develop or modify existing consumption equations for these fuel components.

Since consumption during the flaming phase is more efficient than during the smoldering phase, separate calculations of flaming consumption and smoldering consumption are required for improved assessment of total emissions. Equations for predicting biomass consumption by combustion phase are widely available in two major software packages including Consume 2.1 (Ottmar and others [in preparation]) and First Order Fire Effects Model (FOFEM 5.0) (Reinhardt and Keane 2000).

Consume 2.1 is a revision of Consume 1.0 (Ottmar and others 1993) and uses a set of theoretical models based on empirical data to predict the amount of fuel consumption from the burning of logging slash, piled woody debris, or natural forest, shrub, grass fuels. Input variables include the amount of fuel, woody fuel and duff moisture content, and meteorological data. The software product incorporates the original Fuel Characteristic System (Ottmar and others [in preparation]) for assigning default fuel loadings.

It also incorporates features that allow users to receive credit for applying fuel consumption reduction techniques. FOFEM 5.0 (Reinhardt and Keane 2000) is a revision of FOFEM 4.0 (Reinhardt and others 1997) and relies on BURNUP. a new model of fuel consumption (Albini and Reinhardt 1997). The software computes duff and woody fuel consumption for many forest and rangeland systems of the United States. Both Consume 2.1 and FOFEM 5.0 packages are updated on a regular basis as new consumption models are being developed.

Smoke Emissions

The chemistry of the fuel as well as the efficiency of combustion governs the physical and chemical properties of the resulting smoke from fire. Although smoke from different sources may look similar to the eye, it is often quite different in terms of its chemical and physical properties. Generally, the emissions we cannot see are gas emissions and the emissions we can see are particulate emissions.

Carbon dioxide and water—Two products of complete combustion during fires are carbon dioxide (CO_2) and water (H_2O) and generally make up over 90 percent of the total emissions from wildland fire. Under ideal conditions complete combustion of one ton of forest fuels requires 3.5 tons of air and yields 1.84 tons of CO_2 and 0.54 tons of water (Prescribed Fire Effects Working Team 1985). Under wildland conditions, however, inefficient combustion produces different yields. Neither carbon dioxide nor water vapor are considered air pollutants in the usual sense, even though carbon dioxide is considered a greenhouse gas and the water vapor will sometimes condense into liquid droplets and form a visible white smoke near the fire. This fog/smoke mixture can dramatically reduce visibility and create hazardous driving conditions.

As combustion efficiency decreases, less carbon is converted to CO_2 and more carbon is available to form other combustion products such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides(NOx), and sulfur oxides (SOx), all of which are considered pollutants.

Carbon Monoxide—Carbon monoxide (CO) is the most abundant emission product from wildland fires. Its negative effect on human health depends on the duration of exposure, CO concentration, and level of physical activity during the exposure. Generally, dilution occurs rapidly enough from the source of the fire that carbon monoxide will not be a problem for local citizens unless a large fire occurs and inversion conditions trap the carbon monoxide near rural communities. Carbon monoxide is always a concern for wildland firefighters however, both on the fire line at prescribed fires and wildfires, and at fire camps (Reinhardt and Ottmar 2000, Reinhardt and others 2000).

Hydrocarbons—Hydrocarbons (HC) are an extremely diverse class of compounds containing hydrogen, carbon and sometimes oxygen. Usually, the classes of hydrocarbon compounds are identified according to the number of carbon atoms per molecule. Emission inventories often lump all gaseous hydrocarbons together. Although a majority of the HC pollutants may have no harmful effects, there are a few that are toxic. More research is needed to characterize hydrocarbon production from fires.

Nitrogen Oxides—In wildland fires, small amounts of nitrogen oxides (NOx) are produced, primarily from oxidation of the nitrogen contained in the fuel. Thus the highest emissions of No_x occur from fuels burning with a high nitrogen content. Most fuels contain less than 1 percent nitrogen. Of that about 20 percent is converted to NO_x when burned.

Hydrocarbons and possibly nitrogen oxides from large wildland fires contribute to increased ozone formation under certain conditions.

Particulate Matter—Particulate matter produced from wildland fires limits visibility, absorbs harmful gases, and aggravates respiratory conditions in susceptible individuals (figure 5.6). Over 90 percent of the mass of particulate matter produced by wildland is less than 10 microns in diameter and over 80-90 percent is less than 2.5 microns in diameter (figure 5.7). These small particles are inhalable and respirable. Respirable suspended particulate matter is that proportion of the total particulate matter that, because of its small size has an especially long residence time in the atmosphere and penetrates deeply into the lungs. Small smoke particles also scatter visible light and thus reduce visibility.

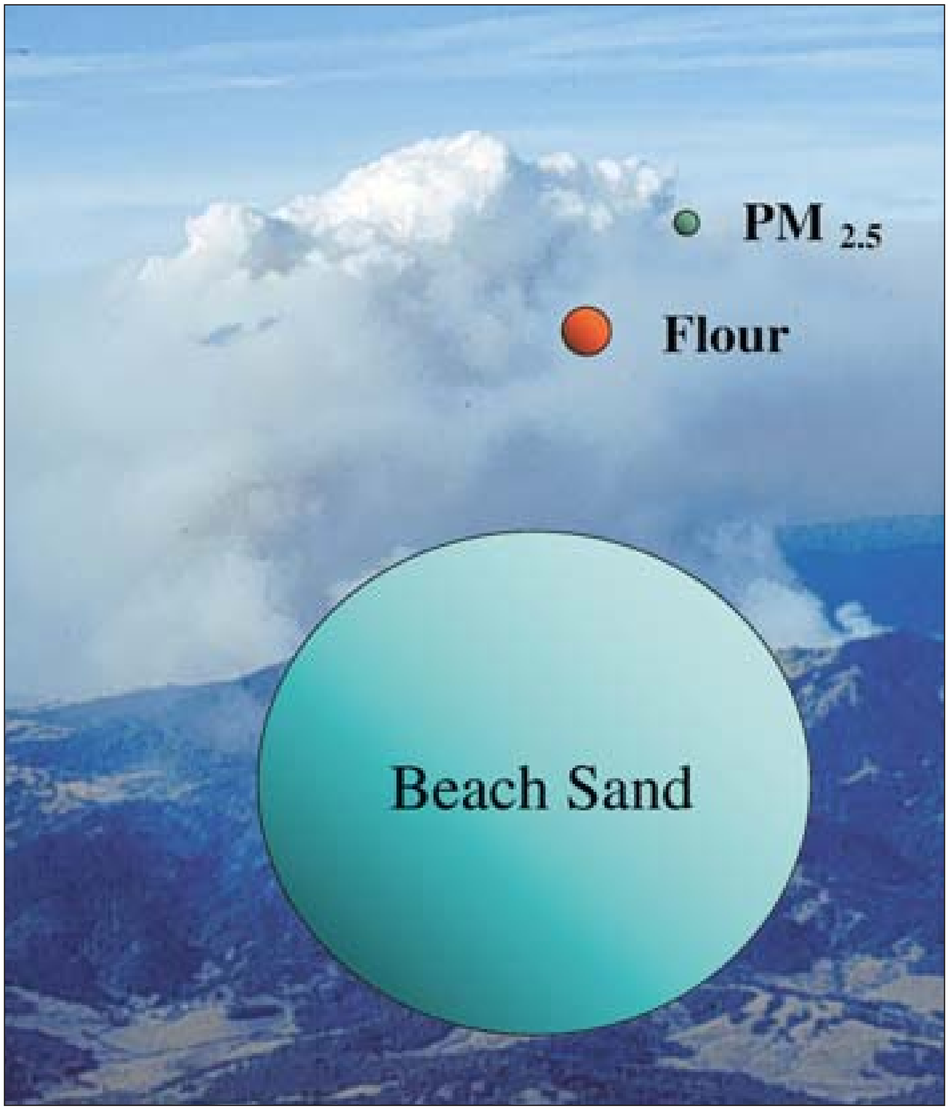

Figure 5.6. Relative sizes of beach sand, flour, and a PM2.5 particle in smoke.

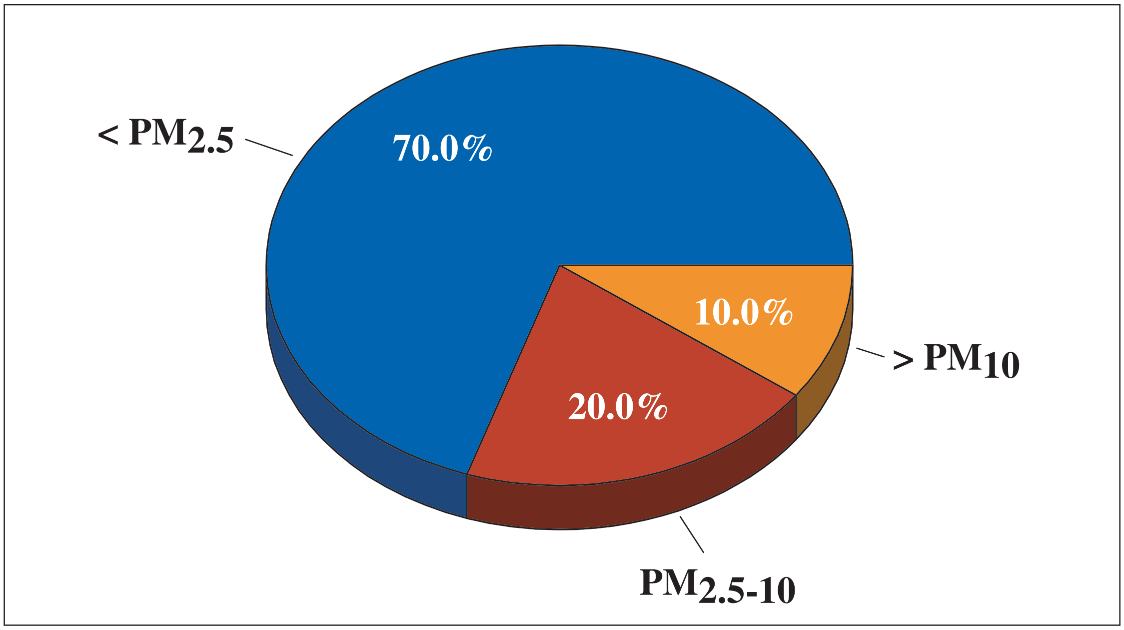

Figure 5.7. Particulate matter size-class distribution from typical wildland fire smoke.

Emission Factors

An emission factor for a particular pollutant of interest is defined as the mass of pollutant produced per mass of fuel consumed (i.e., lbs/ton in the English system or g/kg as the metric equivalent). Multiplying an emission factor in grams/kg by a factor of two will convert the emission factor to English units (pounds/ton).

Emission factors vary depending on type of pollutant, type and arrangement of fuel and combustion efficiency. The average fire emission factors have a relatively small range and contributes approximately 16 percent of the total error associated with predicting emissions production (Peterson 1987; Peterson and Sandberg 1988). In general, fuels consumed by flaming combustion produce less smoke than fuels consumed by smoldering combustion. Emission factors for several smoke compounds are presented in table 5.1 for the flaming, smoldering, and fire average for generalized fuel types and arrangements. Emission factors can be used by air quality agencies to calculate local and regional emissions inventories or by managers to develop strategies to mitigate downwind smoke impacts. Additional emission factors have been determined for other fuel types and will be available in the future.

Total Emissions, Source Strength, and Heat Release Rate

Total emissions from a fire or class of fires (that is, a set of fires similar enough to be characterized by a single emission factor) can be estimated by multiplying that emission factor by the biomass consumed and an accurate assessment of the total acreage burned. For instance, assume that 10 tons/acre of fuels will be con-

Table 5.1. Forest and rangeland emission factors [1]Ward and others 1989; [2]Hardy and others 1996; [3]Hardy and Einfield 1992).

Fuel or Fire Configuration	**Combustion Phase**[a]	**Emission Factors**						
		PM	**PM$_{10}$**[b]	**PM $_{2.5}$**	**CO**	**CO$_2$**	**CH$_4$**	**NMHC**
		(Pounds emission per ton fuel consumed)						
BROADCAST BURNED SLASH[1]								
Douglas fir/ hemlock	FLAMING	24.7	16.6	14.9	143	3385	4.6	4.2
	SMOLDERING	35.0	27.6	26.1	463	2804	15.2	8.4
	FIRE AVERAGE	29.6	23.1	21.8	312	3082	11.0	7.2
Hardwoods	FLAMING	23.0	14.0	12.2	92	3389	4.4	5.2
	SMOLDERING	38.0	25.9	23.4	366	2851	19.6	14.0
	FIRE-AVERAGE	37.4	25.0	22.4	256	3072	13.2	10.8
Ponderosa/ **l.pole pine**	FLAMING	18.8	11.5	10.0	89	3401	3.0	3.6
	SMOLDERING	48.6	36.7	34.2	285	2971	14.6	9.6
	FIRE AVERAGE	39.6	25.0	22.0	178	3202	8.2	6.4
Mixed conifer	FLAMING	22.0	11.7	9.6	53	3458	3.0	3.2
	SMOLDERING	33.6	25.3	23.6	273	3023	17.6	13.2
	FIRE AVERAGE	29.0	20.5	18.8	201	3165	12.8	9.8
Juniper	FLAMING	21.9	15.3	13.9	82	3401	3.9	5.5
	SMOLDERING	35.1	25.8	23.8	250	3050	20.5	15.5
	FIRE AVERAGE	28.3	20.4	18.7	163	3231	12.0	10.4
PILE-AND BURN SLASH[1]								
Tractor-piled	FLAMING	11.4	7.4	6.6	44	3492	2.4	2.2
	SMOLDERING	25.0	15.9	14.0	232	3124	17.8	12.2
	FIRE AVERAGE	20.4	12.4	10.8	153	3271	11.4	8.0
Crane-piled	FLAMING	22.6	13.6	11.8	101	3349	9.4	8.2
	SMOLDERING	44.2	33.2	31.0	232	3022	30.0	20.2
	FIRE AVERAGE	36.4	25.6	23.4	185	3143	21.7	15.2
"Average" Piles	FIRE AVERAGE	28.4	19.0	17.1	169	3207	16.6	11.6
BROADCAST-BURNED BRUSH[2]								
Sagebrush	FLAMING	45.0	31.8	29.1	155	3197	7.4	6.8
	SMOLDERING	45.3	29.6	26 4	212	3118	12.4	14.5
	FIRE-AVERAGE	45.3	29.9	26.7	206	3126	11.9	13.7
Chaparral	FLAMING	31.6	16.5	13.5	119	3326	3.4	17.2
	SMOLDERING	40.0	24.7	21.6	197	3144	9.0	30.6
	FIRE AVERAGE	34.1	20.1	17.3	154	3257	5.7	19.6
WILDFIRES FIRES (IN FORESTS)[3]								
	Fire-average		30.0	27.0				

[a]Fire Average values are weighted-averages based on measured carbon flux.

[b]PM$_{10}$ values are calculated, not measured, and are derived from known size-class distributions of particulates using PM and PM $_{2.5}$.

sumed during a 200 acre landscape prescribed burn in a ponderosa pine stand. Following the fire, ground surveys and aerial reconnaissance indicate a mosaic fire pattern and only 100 acres of the 200 acres within the fire perimeter actually burned. Since the emission factor for particulate matter 2.5 microns in diameter or less ($PM_{2.5}$) for pine fuels is approximately 22 lbs/ton, then total emission production would be:

$$\underset{\textbf{(lbs)}}{\textbf{Total Emissions}} = \underset{\textbf{(tons/acre)}}{\textbf{Fuel Consumed}} \ \mathbf{X} \ \underset{\textbf{(lb/ton)}}{\textbf{Emission Factor}} \ \mathbf{X} \ \underset{\textbf{(acres)}}{\textbf{Area Burned}}$$

Therefore: $10\,tons/acre * 22\,lbs/ton * 100\,acres \Rightarrow 22{,}000\ lbs \Rightarrow 11\,tons$

Managers can make better estimates of emissions produced from a wildland fire if the amount of fuel consumption in the flaming and smoldering combustion period is known. The same general approach is used although it is slightly more complicated. The fuel consumed during the flaming period and smoldering period are multiplied by the appropriate flaming and smoldering emission factor for a particular fuel type, then summed. Computer software such as Consume 2.1 (Ottmar and others [in preparation]) and FOFEM 5.0 (Reinhardt and Keane 2000) use this approach to improve estimates of total emissions produced from wildland fire as compared with the fire average approach. An emission inventory is the aggregate of total emissions from all fires in a given period for a specific geographic area and requires total emissions.

Modeling emissions from wildland fires requires not only total emissions, but also source strength. Source strength is the rate of air pollutant emissions in mass per unit of time or in mass per unit of time per unit of area and is the product of the rate of biomass consumption and an emission factor for the pollutant(s) of interest. Source strength can be calculated by the equation:

$$\underset{\textbf{(lbs/minute)}}{\textbf{Source Strength}} = \underset{\textbf{(tons/acre)}}{\textbf{Fuel Consumption}} \ \mathbf{X} \ \underset{\textbf{(acre/minute)}}{\textbf{Rate of Area Burned}} \ \mathbf{X} \ \underset{\textbf{(lb/ton)}}{\textbf{Emission Factor}}$$

Emission rates vary by fuel loading, fuel consumption, and emission factors. Figure 5.8 graphically depicts general trend differences in emission production rate and total emissions production (area under each curve) for various prescribed fire scenarios. Mechanically treating fuels before burning, mosaic burning, burning under high fuel moisture contents, and burning piles are specific ways emission rates can be reduced to meet smoke management requirements.

The consumption of biomass produces thermal energy and this energy creates buoyancy to lift smoke particles and other pollutants above the fire. Heat release rate is the amount of thermal energy generated per unit of time or per unit of time per unit of area. Heat release rate can be calculated by the equation:

$$\underset{\textbf{(BTU/minute)}}{\textbf{Heat Release Rate}} = \underset{\textbf{(tons/acre)}}{\textbf{Fuel Consumption}} \ \mathbf{X} \ \underset{\textbf{(acre/minute)}}{\textbf{Rate of Area Burned}} \ \mathbf{X} \ \underset{\textbf{(BTU/ton)}}{\textbf{Heat Output}}$$

Both source strength and heat release rate are required by all sophisticated smoke dispersion models (Breyfogle and Ferguson 1996). Dispersion models are used to assess the impact of smoke on the health and welfare of the public in cities and rural communities and on visibility in sensitive areas such as National Parks, Wilderness areas, highways, and airports. The Emissions Production Model (EPM) (Sandberg and Peterson 1984; Sandberg 2000) is the only model that predicts source strength and heat release rate for wildland fires. The EPM software package imports fuel consumption predictions from Consume 2.1 or FOFEM 5.0 and uses ignition pattern, ignition periods, and burn area components to calculate source strength, heat release rate, and plume buoyancy.

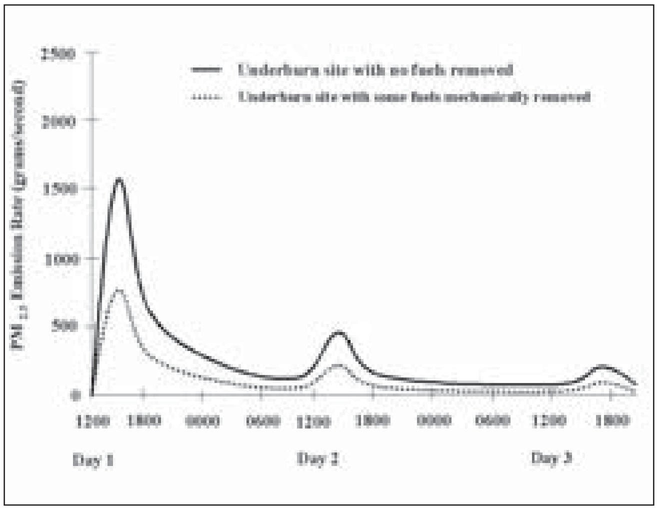

Figure 5.8a. Emission production rate over time for $PM_{2.5}$ during an underburn with and without fuels mechanically removed.

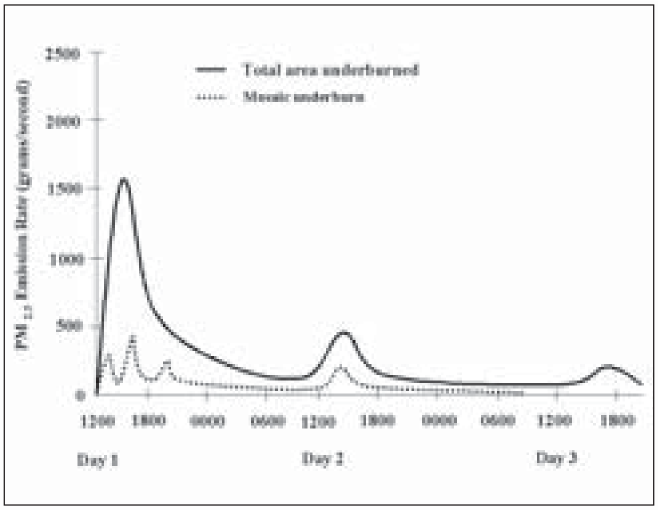

Figure 5.8b. Emission production rate over time for $PM_{2.5}$ during a mosaic burn and a burn where fire covers the entire area within the perimeter.

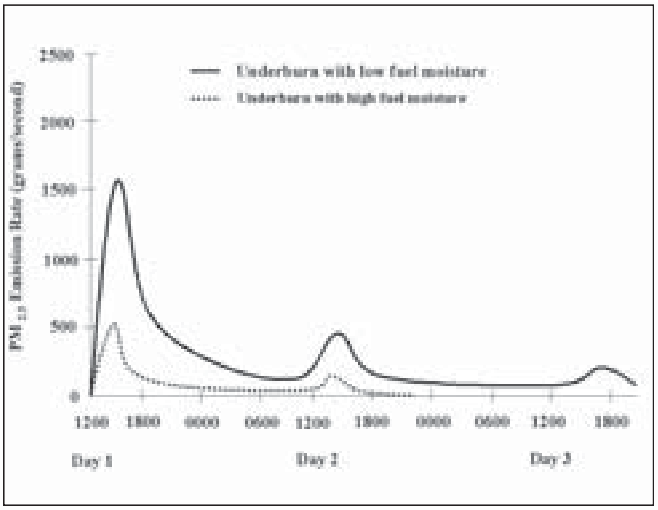

Figure 5.8c. Emission production rate over time for $PM_{2.5}$ during an underburn with low and high fuel moisture content.

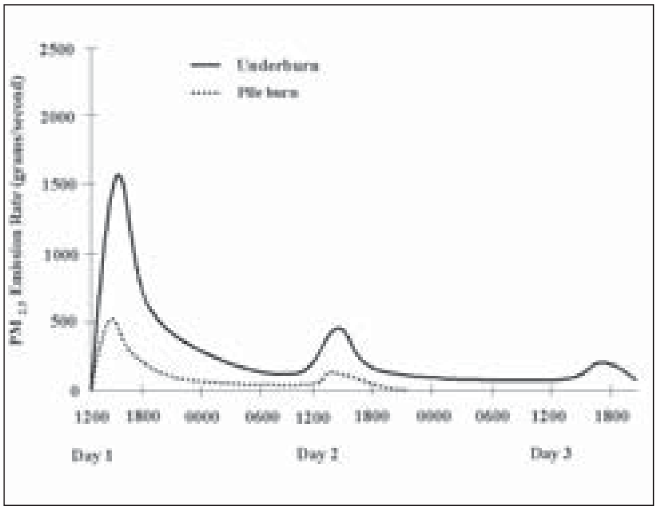

Figure 5.8d. Emission production rate over time for $PM_{2.5}$ during an underburn and a pile burn.

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Chapter 6

FIRE USE PLANNING

Fire Use Planning

Tom Leuschen

Dale Wade

Paula Seamon

The success of a fire use program is in large part dependent on a solid foundation set in clear and concise planning. The planning process results in specific goals and measurable objectives for fire application, provides a means of setting priorities, and establishes a mechanism for evaluating and refining the process to meet the desired future condition. It is an ongoing process, beginning months or even years in advance of actual fire use, with plans becoming increasingly specific as the day of the burn approaches. Although details differ between fire practitioners, the general planning process is essentially the same.

Land and Resource Management Planning

Fire use planning should begin as a component of the overall land and resource management planning for a site. Consideration of the intentional use of fire to achieve stated resource management goals should be an integral part of this process. In deciding whether or not fire use is the best option to accomplish a given objective, an analysis of potential alternative treatments should be completed. This analysis should describe the risks associated with use of a given treatment and include expected negative as well as beneficial outcomes. Care should be exercised to separate statements that are supported by data (preferably local and ecosystem-specific), from those only purported to be true.

Many private landowners do not have written resource management plans, but most have a vision of what natural resource attributes they want to favor and what they want their lands to look like. We recommend they put this vision on paper to provide guidance to themselves and their heirs.

The plans should identify any barriers to implementing a treatment judged best from a resource management standpoint, such as regulations, cost, or insufficient resources. If such a treatment is not recommended because of these barriers, the probable ecological ramifications of this decision should be documented. On sites where fire is selected as the best alternative to accomplish the desired resource management objectives, the next step in fire use planning is to develop a fire management plan.

The Fire Management Plan

The fire management plan addresses fire use at the level of the administrative unit, such as a forest, nature preserve, park, ranch or plantation. It ensures that background information about the area has been researched, legal constraints reviewed, and a burn program found to be both justified and technically feasible. It proposes how fire will be applied to the landscape, both spatially and temporally. When managing for multiple resources (e.g., range, wildlife, and timber) on a tract, guidance should be provided regarding the allocation of benefits; i.e., should benefits to the same resource always be maximized on given burn units, or should the focus be rotated among benefits on some, or all burn units over time?

Items commonly addressed in the fire management plan are:

- Background information on the area, such as topography, soils, climate and fuels
- Applicable fire laws and regulations, including any legal constraints
- Landowner policy governing fire use on this tract of land
- Fire history of the area, including the natural fire regime, and recent fire occurrence or use
- Justification for fire management
- Fire management goals for the area, including a description of the desired future condition. (Objectives for specific burns are set in the burn unit plan, see below.)
- Fire management scheduling, qualitatively describing how fire will be applied to the site over time to achieve stated resource objectives. (Quantitative descriptions of fireline intensity, fire severity, and season of burn are set in the burn unit plan, see below.)
- Species of special concern, wildlife habitat issues, invasive species issues
- Definition and descriptions of treatment units or burning blocks
- Air quality and smoke management considerations
- Neighbor and community factors
- Maps illustrating fuels distribution, treatment units, smoke sensitive areas, etc.

When complete, this document should enable the resource manager to gain the support (both internal and external) and identify the resources needed to effectively and efficiently use fire as a management tool.

Community involvement in the fire planning process is crucial to public acceptance of fire use. At what stage to involve the public in the process will depend on regional issues, regulations, and organizational policy. In general, the earlier the public is involved, the easier it is to reach agreement on any concerns. Whenever it is done, it is important to remember that public support is key to the long-term success of a fire management program. Unexpected results, including under-achievement and over-achievement of objectives, are bound to occur. A full, honest discussion of the potential for such results, and their ramifications, can defuse negative reaction to the occasional bad outcome, especially if the public was involved early in the planning process.

Further guidance for developing a fire management plan is available from a number of federal sources, including *Wildland and Prescribed Fire Management Policy: Implementation Procedures Reference Guide* (USDI and USDA Forest Service 1998), and from The Nature

Conservancy's *Fire Management Manual* (www.tncfire.org/manual).

The Burn Plan

Once the fire management plan is completed and approved, the next step is implementation—not an easy task. Resource managers are usually faced with numerous constraints, such as budget and staff limitations, equipment availability, timing of good burning conditions, and a lack of information on potential effects. A successful prescribed fire program requires the complete dedication of the fire management staff, full cooperation of all personnel and functional areas involved, and unwavering support and commitment throughout the chain of command.

Although the overall resource management goals for an individual burn unit often remain unchanged for long periods, the specific burn objectives for a given unit will likely vary over time, necessitating modifications to the unit plan for each burn. For example, the use of a heading fire during the growing season to promote biodiversity and flowering of ground layer plants may be the current burn objective, while a backing fire during the dormant season may have been used to reduce hazardous fuels loads the last time the unit was burned.

A written burn plan serves several important purposes:

- It makes the planner think about what he/she wants to achieve, and how it will be accomplished.
- It allows the fire manager to prioritize between burn units based on constraints and objectives.
- It functions as the operational plan that details how a burn will be safely and effectively conducted.
- It serves as the standard by which to evaluate the burn.
- It provides a record for use when planning future burns (which makes it essential to document any changes when the burn is conducted, directly on the plan).
- It becomes a legal record of the intended purpose and execution of the burn project.

There is no standard format for a burn unit plan; numerous examples are available which can be consulted for guidance. Sources include state and federal land management agencies, The Nature Conservancy's internet site (www.tncfire.org), or publications such as *A Guide to Prescribed Fire in Southern Forests* (Wade and Lunsford, 1989), which is available online from the Alabama Private Forest Management Team website (www.pfmt.org/standman/prescrib.htm), and from the Florida Division of Forestry (flame.fl-dof.com/Env/Rx/guide/).

Although formats differ, certain components should be included in all burn plans. They should address at least the following 12 topics:

1. **Assessment and Description of the Burn Unit.** The first step in developing a burn plan is to evaluate and document existing conditions. Factors to include depend on the site itself, as well as the complexity of the planned burn. The information recorded here will serve as the baseline from which success of the burn will be determined, so parameters used in the burn objectives should be assessed and described. Include details on the unit size (broken into single-day burn units); date of the last burn; overstory and under-

story vegetation, density and size; fuel type, density and size; soil type and topography; threatened and endangered species present; invasive species present; and current wildlife use.

2. **Maps.** Good maps of the treatment area are a key component of the burn plan. The map scale should be adequate to show pertinent information in meaningful detail. Be careful not to include too much information on a single map, making it difficult to read. The burn plan should include a series of maps showing the following: unit boundaries; adjacent land ownerships, including contact person and phone numbers; topography and manmade obstacles such as canals, ditches, and erosion gullies that would impede equipment or people; natural and constructed fire control lines; areas to be protected or excluded such as sawdust piles, utility poles and sensitive vegetation areas; firing plan; initial placement of equipment and holding personnel, and; escape routes and safety zones. Every crew member should receive a map with the information essential to personnel safety and burn operations.

3. **Measurable Burning Objectives**. Unit-specific treatment objectives identify the desired changes in affected resources from the present to the future condition. Treatment objectives are prepared within the context and intent of all resource management objectives. They are the measures against which the success of a burn is determined. Burn objectives make clear to everyone involved what is expected - including the burners, cooperators, managers, and the public. The objectives should be detailed statements that describe what the treatment is intended to accomplish, and as such, must be specific and quantifiable.

4. **Weather and Fuel Prescription**. The prescription defines the range of conditions under which a fire is ignited and allowed to burn to obtain given objectives. Fuel moisture (by size class) and weather conditions (temperature, humidity, wind, drought, dispersion index) are key factors in achieving objectives because they in large part determine fire behavior (intensity and severity), which in turn, governs ease of fire control and effects. These same parameters also affect smoke production and transport. Considerable care should therefore be taken in defining the window of conditions under which the projected burn may take place. Although there may be an ideal set of conditions that will maximize a single objective, the likelihood of this set of conditions occurring at the right time is typically extremely low. Therefore, a range of fuel and weather conditions are usually specified in the burn prescription that allow the skilled burner to compensate between various parameters to safely and efficiently conduct a successful burn—a burn which meets both the resource and smoke management objectives.

5. **Season and Time of Day**. The season of burn influences many burn parameters. Typically, acceptable burning conditions are more predictable during certain seasons, making it easier to plan and prepare for burns days in advance, but not all burn objectives may be achievable under those weather and fuel conditions. Regional effects are important in decision-making for this factor. For example, in the southeast, dormant season burns are generally more uniform in effects while growing season burns are more likely to be patchy. Backing fires are much easier to conduct during the dormant season when ground layer herbaceous plants are dead and burn readily, rather than green and succulent

thereby retarding fire spread. In the Pacific Northwest, season of burn can be used to reduce emissions. Broadcast burning of slash in the wet spring has been shown to produce 50% fewer emissions when compared to burning periods in the dry fall (Sandberg and Dost 1990). Selecting the correct season to execute a burn will help maximize the probability of achieving the burn objectives.

The timing of ignition determines whether the burn can be completed and mopped up as scheduled during the burning period. Timing is also important when considering factors such as: when solar radiation will break a nighttime inversion or dissipate any dew which formed during the night, when atmospheric conditions will support adequate transport and dissipation of smoke, when surface winds may develop or change speed or direction, or when a sea breeze front may reach the unit. Experienced burners become familiar with the area, and learn how to factor these time-sensitive influences into their burn plans.

6. **Smoke Management**. Planning a fire use project that has the potential to impact areas sensitive to smoke requires assessment of airshed and meteorological conditions that influence both the movement and concentration of smoke. The expected effects of wind speed and direction, air stability, and nighttime inversions should be specifically outlined. Specific regional issues should be addressed, such as mountainous terrain, fog, or sea breeze effects. This information normally will be developed by fire managers using their personal experience and knowledge of fire behavior, smoke transport and dispersion in the area, along with more formal emissions prediction and dispersion modeling.

Sensitive areas downwind of the burn unit should be identified and plotted on a map. Information such as distance and direction from the burn unit, the nature of the sensitivity, and when the area is considered sensitive should be included. Examples of smoke sensitive areas include Class I areas (generally, international parks, and large national parks and national wilderness areas), nonattainment areas, communities or individual residences, airports, highways, and medical facilities. Several procedures for predicting the potential impact of smoke on sensitive areas are discussed in chapter 9.

Smoke dispersion in areas prone to inversions, such as deep, mountainous valleys, is especially problematic in fire use planning. If the smoke remains trapped by the inversion, all of the emissions produced will remain trapped within the airshed.

The following smoke-related questions should be addressed in every plan:

- What quantity of emissions will it take to saturate this airshed?
- Where will the smoke concentrate if it settles under an inversion?
- Do special arrangements need to be made to protect populations impacted by these emissions?
- How many burning projects will it take cumulatively to exceed acceptable levels within this airshed?
- How long will the airshed remain stable and harbor the emissions?

In instances where a burn may affect an area especially sensitive to smoke, the use of air quality monitors may be advisable to ensure that an agreed-upon emission level or limit is not exceeded. Factors to consider in using monitors include placement of the device, personnel to operate the instrument, quality checks, data analysis, and provisions for real-time feedback if data is to be used in making a decision to terminate a burn in progress. Monitors are not commonly accessible and are costly to use, so this option is chiefly available to federal and state agencies. Air quality monitoring for evaluating a fire management program is discussed in Chapter 10.

Smoke impacts to fireline personnel should also be considered in a smoke management plan. The burn planner should consider projected exposure when determining the size of the burn crew and the duration of the work shift. More information on smoke exposure to fireline personnel can be found in Chapter 3.4.

Once an analysis of significant factors is complete, the planner should set specific, measurable smoke management objectives for the burn. These may include, for example, minimum visibility standards for roads or viewsheds, and an emissions limit if air quality monitors are to be used. Objectives provide a common understanding for all individuals involved in or affected by the burn, of what constitutes acceptable smoke impacts. They also provide a tool for the burn boss when deciding whether to terminate a fire because of problematic smoke behavior. If the decision is made to terminate a burn because of smoke problems, it should be remembered that direct suppression often temporarily exacerbates smoke problems. If ignition has been completed, the best strategy may be too let the fire burn out.

The amount of air quality analysis required at all levels of fire planning will be influenced by air quality laws and smoke management regulations. Formal state smoke management programs are becoming increasingly common, but are not yet universal. Some states include only regulatory language regarding “nuisance smoke.” Complying with all applicable laws and regulations is a basic tenet of conscientious land stewardship, but responsible fire use and air quality planning include looking beyond the requirements of the law. Communities likely to be impacted by a fire-use program should be involved in determining what their threshold of acceptance is for smoke from wildland fire. Thorough attention to smoke management planning can prevent future problems.

7. **Notification of Local Authorities and the Public**. Early development of a notification plan will assist in the necessary communication with local authorities and the public. A wide variety of methods have proven successful, including distribution of pamphlets or flyers, public meetings, newspaper and radio announcements, and Internet postings. The public should be notified well in advance of the proposed burn day, and again within a few days of executing the burn. Generally, there is a list of individuals to be notified on the actual burn day. This list is often unit-specific, and should be included along with telephone numbers in the burn plan.

8. **Environmental and Legal Constraints**. If constraints to the burn plan have not already been addressed in a fire management plan for the entire site, they should be addressed here because they can limit or determine how a burn is implemented. These may include environmental, economic, operational, administrative, and legal constraints.

9. **Operations**. The burn plan must describe in detail how fire will be used. This section of the plan may take any number of formats, but the topics to be addressed include:
    - Safety. What provisions will be made to ensure the safety of the crew?
    - Communications. How will the crew communicate with each other, and with dispatch or emergency support?
    - Equipment and Personnel. What resources are needed to effectively accomplish the burn and how will they be deployed?
    - Fire Lines. What is the width and condition of existing fire lines? How many chains of fireline need to be prepared or cleared? How will this be accomplished?
    - Ignition Pattern and Sequence. How will the burn be ignited? Ignition duration and firing patterns play an important role in production and lofting of emissions. Rapid ignition may reduce consumption, therefore emissions, and be successful in lofting a smoke column high into the atmosphere. Backing fires produce fewer emissions than heading fires. More information on using ignition to manage emissions production can be found in Chapter 8, Techniques to Reduce Emissions and Impacts.
    - Holding. How will the fire be kept within its predetermined boundaries? How will snags be dealt with?
    - Mop-up. How will the burn be extinguished? What standard will be used to consider the burn unit safe to leave?

10. **Contingency Planning**. Contingency plans outline procedures for dealing with a burn gone awry. They are a normal part of a burn plan and should include provisions to deal not only with escaped fire, but also with unexpected smoke intrusions during an otherwise controlled burn. Some of the issues to be addressed include safety of the general public and the fire crew, sources of assistance for fire control and smoke-related problems, deployment of resources, actions to be taken to rectify the problem, notification of authorities and the public, and measures to mitigate smoke on roadways. It should be recognized that in some cases where smoke problems dictate shutting down a burn after ignition has been completed, the most prudent action may be to allow the unit to burn out rather than to immediately extinguish it, which can temporarily exacerbate smoke production.

11. **Preburn Checklist**. Every burn plan should include a checklist to be reviewed immediately prior to ignition. The checklist should include the factors essential to safe execution of the burn project, and a list of points to review with the crew during the preburn briefing. The use of the checklist ensures that some detail does not slip by the burn manager's attention in the busy moments preceding a fire.

12. **Monitoring and Evaluation**. Monitoring and evaluation of the burn are key to learning from the process and making refinements for subsequent burns. Where appropriate and practical, monitoring and post-fire evaluation protocols describing the effects on soil, water, air, vegetation, and wildlife should be included in the burn unit plan. Alternatively, the information can be included in a post-burn evaluation report or form, which is attached to the burn plan after completion.

- Documenting air quality conditions before, during, and after a fire is useful in identifying nuisance smoke thresholds and assuring that air quality standards have not been exceeded. Additionally, monitoring and documenting smoke transport, dilution, or concentrations in each airshed can help develop local knowledge that is the basis of predicting smoke impacts. In addition to environmental effects, the following topics should be addressed: adequacy of preburn treatments, fire behavior, degree to which objectives were achieved, discrepancies between planned fuel and weather components and on site measurements, observations, accidents or near-accidents, slopovers, and recommend changes for future burns. A series of photographs over time at permanent photo points is an excellent inexpensive method to document vegetation changes.

Fire Use Planning for Federal Land Managers

The *Wildland and Prescribed Fire Management Policy: Implementation Procedures Reference Guide* (USDI and USDA Forest Service 1998) represents an effort by Federal wildland fire management agencies to establish standardized procedures to guide implementation of the policy described in the 1995 Federal Wildland Fire Management Policy and Program Review. It uses new terminology and definitions to provide consistency and interpretation to facilitate policy implementation, and describes relationships between planning tiers to fire management objectives, products, and applications.

The federal process generally follows the planning process described above. The flow of information begins with the land and resource management plan, variously called the Forest Management Plan (FS), Integrated Resource Management Plan (BIA), Resource Management Plan (NPS), Comprehensive Conservation Plan (FWS) and the Forest Management Plan (FS). This plan determines the availability of land for resource management, predicts levels of resource use and outputs, and provides for a variety of resource management practices.

The next step is preparation of the Fire Management Plan (FMP). The FMP is the primary tool for translating programmatic direction developed in the land management plan into on-the-ground action. The FMP must satisfy NEPA requirements, or follow direction provided by a Forest Plan that has been developed through the NEPA process. Comparisons between fire use activities and no fire use should be described in the NEPA process. This includes implications of wildland fire and prescribed fire use over extended periods of time.

The most detailed step in the process involves the tactical implementation of strategic objectives for the wildland and prescribed fire management programs. It is at this level where specific plans are prepared to guide implementation of fire-related direction on the ground. This step includes Prescribed Fire Plans, Wildland Fire Implementation Plans, and the Wildland Fire Situation Analysis.

More information on the smoke management requirements and federal planning process is contained in Chapter 4.

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Chapter 7

SMOKE MANAGEMENT METEOROLOGY

Smoke Management Meteorology

Sue A. Ferguson

Once smoke enters the atmosphere, its concentration at any one place or time depends on mechanisms of transport and dispersion. By transport, we mean whatever carries a plume vertically or horizontally in the atmosphere. Dispersion simply is the scattering of smoke.

Vertical transport is controlled by the buoyancy of the smoke plume and stability of the atmosphere. Horizontal transport is controlled by wind. The larger the volume of space that smoke is allowed to enter and the farther it can be transported, the more disperse and less concentrated it will become. To begin understanding stability and wind that control transport and dispersion, we begin with a few elemental concepts.

Air Pressure

It is helpful to understand air pressure because storms and stagnant air conditions are described in terms of low pressure and high pressure, respectively. Lines of constant pressure are used to illustrate the state of the atmosphere on weather maps, and pressure influences the expansion and contraction of smoke parcels as they travel through the atmosphere. Air pressure is the force per unit area exerted by the weight of the atmosphere above a point on or above the earth’s surface. More simply it can be thought of as the weight of an overlying column of air. Air pressure is greatest near the ground, where the overlying column of air extends the full height of the atmosphere. Pressure decreases with increasing altitude as the distance to the top of the atmosphere shortens.

In a *standard* atmosphere, which represents the horizontal and time-averaged structure of the atmosphere as a function of height only, pressure decreases approximately exponentially with height. With 1,013 millibars (mb) being the standard atmospheric pressure at sea level, the average height of the 850 mb pressure level typically occurs at about 5,000 feet (~1,500 m), the 700 mb pressure level typically occurs at about 10,000 feet (~3,000 m), and the 500 mb height averages around 20,000 feet (~6,000 m). In the lowest part of the atmosphere (less than about 8,000 feet) pressure decreases by approximately 30 mb per 1000 feet. These are useful values to remember when analyzing meteorological data and maps for smoke management. Actual pressure is nearly always within about 30% of standard pressure.

Lapse Rates

Lapse rate is the decrease of temperature with height. Lapse rates help determine whether smoke will rise from a fire or sink back to the surface and are used to estimate atmospheric stability. When air is heated it expands, becomes less dense and more buoyant. This causes it to rise. A parcel of air that is heated at the ground surface by fire or solar radiation becomes warmer than its surroundings, causing it to lift off the surface. As it rises, it encounters lower pressure that causes further expansion. The more air expands, the cooler it becomes. If a parcel of air becomes cooler than its surroundings, it will sink.

Cooling by expansion without an exchange of heat at the parcel boundaries is called adiabatic cooling. In dry air, rising air parcels typically cool at a rate of about 5.5 °F per 1,000 feet (~ 10 °C/km). This is called the dry adiabatic lapse rate (DALR). For example, on a clear day if a heated parcel of air begins at sea level with a temperature of 70 °F (~21 °C), it will cool dry-adiabatically as it rises, reaching a temperature of 53.5 °F (~12 °C) at 3,000 feet (~915 m).

Rising moist air (relative humidity greater than about 70%) is said to undergo a saturation-adiabatic process. The saturated adiabatic lapse rate (SALR) or moist adiabatic lapse rate is a function of temperature and water content. This is because as moist air cools its water vapor condenses, giving off latent heat in the condensation process and causing a saturated parcel to cool more slowly than a dry parcel. Near the ground in mid-latitudes the SALR can be approximated at a rate of about 3 °F per 1,000 feet (~ 5.5 °C/km). For example, on a humid or rainy day, a heated parcel with a 70 °F (~21 °C) initial temperature at sea level, will reach a temperature of 61 °F (~16 °C) at 3,000 feet (~915 m).

Lapse rates are determined by comparing temperatures between different elevations. The temperature from a ridge-top weather station can be subtracted from the temperature at a nearby valley-located weather station to calculate lapse rate. More commonly, radiosonde observations (raobs) are used to determine lapse rates. These balloon-mounted instruments measure temperature, wind, pressure, and humidity at several elevations from the ground surface to thousands of feet. Raobs are available from weather services or at several sites on the Internet twice each day: at 0000 Universal Time Coordinated (UTC)[1] and 1200 UTC.

There are several ways of plotting raob data. Typically a pseudo-adiabatic chart is used. This chart shows measured values of temperature vs. pressure over lines of DALR and SALR. Figure 7.1 illustrates how the above examples would appear on a standard pseudo-adiabatic chart. More recently, skew-T/log-P diagrams (skew-T for short) have become popular. Instead of plotting temperature and pressure on linear, orthogonal axes, skew-T diagrams plot the log of pressure and skew the temperature axis by 45°. The skew-T/log-P view of raob data allows features of the atmosphere to be more obvious than when plotted on a standard pseudo-adiabatic chart. Figure 7.2 illustrates the above examples on a skew-T diagram. On both standard pseudo-adiabatic charts and skew-T diagrams, elevation in meters or feet (corresponding to the pressure of a standard atmosphere) may be shown and wind direction and speed with height is represented parallel to or along the right-hand vertical axis. Many other features also may be included.

Atmospheric Stability

Atmospheric stability is the resistance of the atmosphere to vertical motion and provides an indication of the behavior of a smoke plume. Full characterization of a smoke plume requires a complete estimation of the atmosphere’s turbulent structure that depends on the vertical patterns of wind, humidity, and temperature,

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[1] Universal Time Coordinated (UTC) is Standard Time in Greenwich, England. UTC is 9 hours ahead of Alaska Standard Time (AST), where 0000 UTC = 1500 AST and 1200 UTC = 0300 AST. UTC is 5 hours ahead of Eastern Standard Time (EST), where 0000 UTC = 1900 EST and 1200 UTC = 0700 EST.

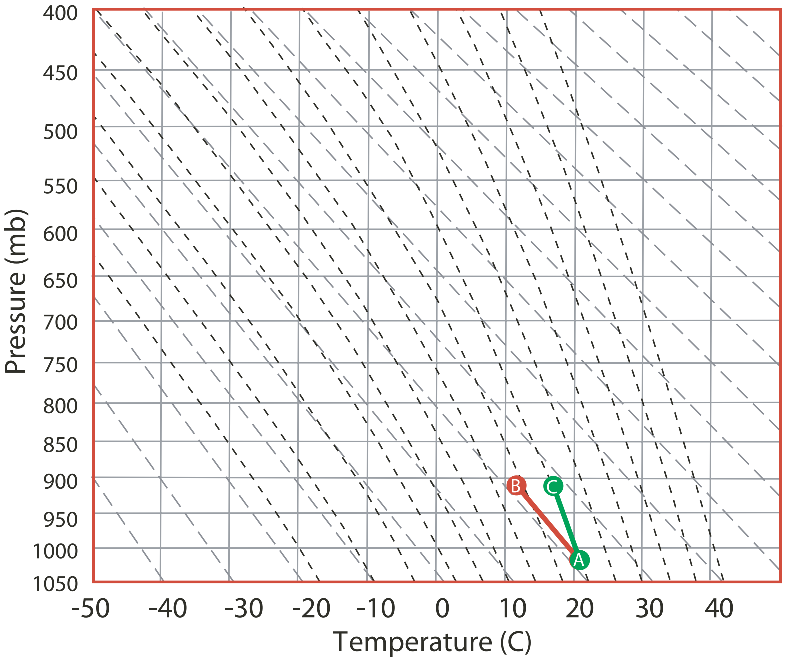

Figure 7.1. Standard pseudo-adiabatic chart. Short-dashed lines show the saturated adiabatic lapse rate (SALR) and long-dashed lines show the dry adiabatic lapse rate (DALR). Point A marks a parcel of air at the surface with a temperature of 21 °C (70 °F). If the atmosphere is dry, the parcel will follow a DALR as it rises and reach point B with a temperature of 12 °C (53.5 °F) at 915m (3000 ft). If the atmosphere is saturated, the parcel will follow a SALR as it rises and reach point C with a temperature of 16°C (61 °F) at 915m (3000 ft).

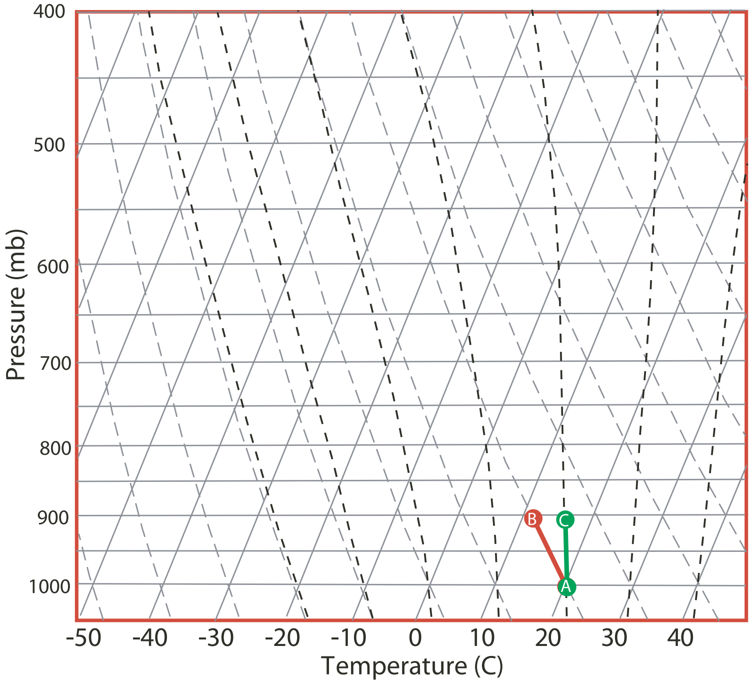

Figure 7.2. Skew-T pseudo-adiabatic chart. Short-dashed lines show the saturated adiabatic lapse rate (SALR) and long-dashed lines show the dry adiabatic lapse rate (DALR). Point A marks a parcel of air at the surface with a temperature of 21 °C (70 °F). If the atmosphere is dry, the parcel will follow a DALR as it rises and reach point B with a temperature of 12 °C (53.5 °F) at 915m (3000 ft). If the atmosphere is saturated, the parcel will follow a SALR as it rises and reach point C with a temperature of 16°C (61 °F) at 915m (3000 ft).

which are highly variable in space and time. Because this can be a complex calculation, it often is approximated by estimates of static stability. The static stability of the atmosphere is determined by comparing the adiabatic lapse rate with ambient, environmental lapse rates (as would be measured from instruments on a rising balloon). By this approximation, an unstable air mass is one in which the temperature of a rising parcel of air remains warmer than its surroundings. In a stable air mass, a rising parcel's temperature is cooler than ambient and a neutral air mass is one in which the ambient temperature is equal to the adiabatic lapse rate.

The most common way of estimating static stability is to note the slope of vertically measured temperature in relation to the slope of the dry (or moist) adiabatic line from a pseudo-adiabatic chart. Figure 7.3 shows raob-measured dry-bulb and dew-point temperatures and the theoretical trajectory of a parcel being lifted from the surface. The parcel trajectory begins at the current surface temperature then follows a DALR until it becomes saturated. The point of saturation is called the lifting condensation level (LCL). Its height in meters can be approximated as 120 x ($T_0 – T_d$), where T_0 is the temperature at the surface and T_d is the mean dew-point temperature in the surface layers, both in degrees Celsius. From the LCL, the parcel trajectory follows a SALR.

Throughout the depth of the diagram in figure 7.3, the slope of the measured temperature is nearly always steeper than the slope of the adiabatic temperature, suggesting that a lifted parcel always will remain cooler than the ambient temperature, which is a sign of stability. The large distance between the measured temperature and the temperature of the theoretical parcel trajectory also gives an indication of strong

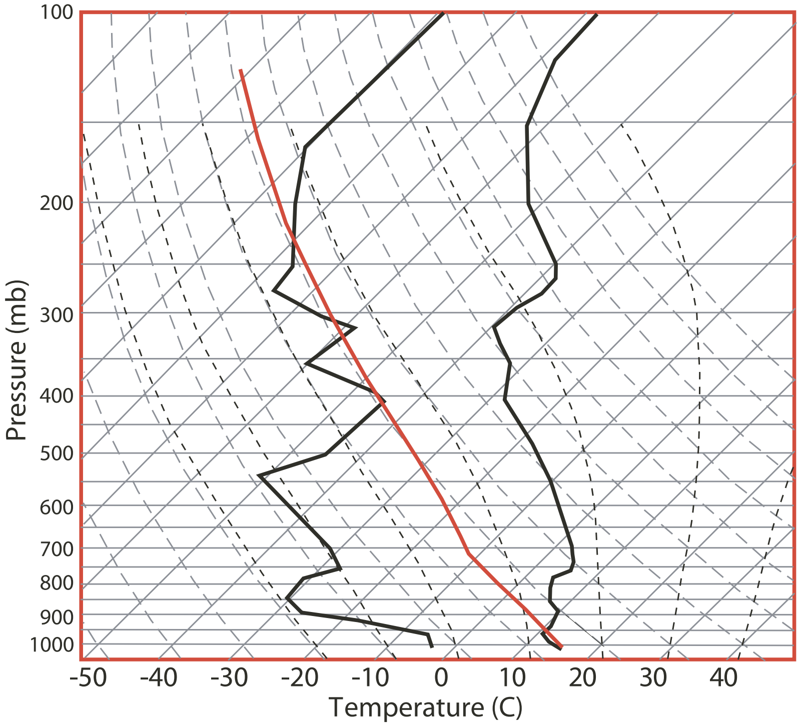

Figure 7.3. Skew-T plot of a stable atmosphere. The thick black line on the right is the measured environmental dry-bulb temperature. The thick black line on the left is the measured environmental dew-point temperature. The red line is a theoretical parcel trajectory. Short-dashed lines are the SALR and long-dashed lines are the DALR.

stability. In a stable atmosphere, smoke emanating from relatively cool fires will stay near the ground. Hot fires may allow plumes to loft somewhat through a relatively stable atmosphere but fumigation of smoke near the ground remains common. Figure 7.4 shows smoke from a vigorous wildfire under a stable atmosphere. Smoke plumes are trying to develop but a strongly stable layer is trapping most smoke just above the ridge tops.

Parcel trajectories in an unstable atmosphere remain warmer than the measured environmental temperatures (figure 7.5). During unstable conditions, smoke can be carried up and away from ground level. Downwind of the source the instability causes smoke plumes to develop a looping appearance (figure 7.6). Obviously there are many variations between stable and unstable atmospheres that cause various patterns of lofting, fanning, coning, looping, and fumigation. Each situation shows characteristic signatures on a pseudo-adiabatic chart but some experience may be required to distinguish the subtle differences.

Because upper-air observations and observations from significantly different elevations are not always available, Pasquill (1961 and 1974) developed a scheme to estimate stability from ground-based observations. Not only is this classification system used to estimate plume characteristics; it also is used in many smoke dispersion models as a proxy for atmospheric turbulence. Table 7.1 shows the Pasquill classification criteria as modified by Gifford (1962) and Turner (1961, 1964, 1970). In this example, surface wind is measured at 10 meters above open terrain. With clear skies, the class of incoming solar radiation is considered strong, moderate, or slight if the solar altitude angle is greater than 60°, between 35° and 60°, or less than 35°, respectively. If more than 50 per cent opaque cloud cover is present and the cloud

Figure 7.4. A smoke plume from a vigorous wildfire during stable atmospheric conditions. Photo by Roger Ottmar.

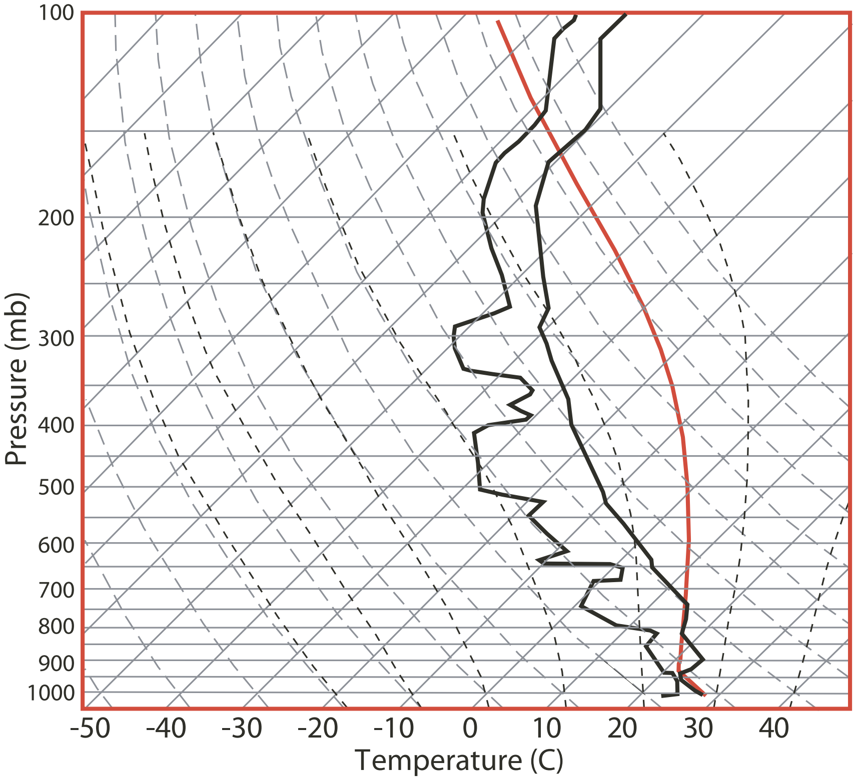

Figure 7.5. Skew-T plot of an unstable atmosphere. The thick black line on the right is the measured environmental dry-bulb temperature. The thick black line on the left is the measured environmental dew-point temperature. The red line is a theoretical parcel trajectory. Short-dashed lines are the SALR and long-dashed lines are the DALR.

Table 7.1. Pasquill stability classification criteria, where A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral, E = slightly stable, and F= moderately stable. See text for an explanation of the incoming solar radiation classes.

Surface Wind (m/s)	Daytime Incoming Solar Radiation			Nighttime Cloudiness	
	Strong	Moderate	Slight	≥ 4/8	≤ 3/8
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Figure 7.6. A smoke plume during unstable atmospheric conditions. Photo by Roger Ottmar.

ceiling height is less than 7,000 feet (~2,100m), the solar class is slight. If ceiling height is between 7,000 feet and 16,000 feet (~4,800m), then the solar class is one step below what it would be in clear sky conditions. At night, classification is based on the amount of sky that is obscured by clouds. An objective way of determining stability classification is shown in Lavdas (1986) and Lavdas (1997).

Mixing Height

Mixing height (also called mixing depth) is the height above ground level through which relatively vigorous vertical mixing occurs. Low mixing heights mean that the air is generally stagnant with very little vertical motion; pollutants usually are trapped near the ground surface. High mixing heights allow vertical mixing within a deep layer of the atmosphere and good dispersion of pollutants. As such, mixing heights sometimes are used to estimate how far smoke will rise. The actual rise of a smoke plume, however, considers complex interactions between atmospheric stability, wind shear, heat release rate of the fire, initial plume size, density differences between the plume and ambient air, and radiant heat loss. Therefore, an estimate of mixing height provides only an initial estimate of plume height.

Mixing heights usually are lowest late at night or early morning and highest during mid to late afternoon. This daily pattern often causes smoke to be concentrated in basins and valleys during the morning and dispersed aloft in the afternoon. Average morning mixing heights range from 300 m (~980 ft) to over 900 m (~2,900 ft) above ground level (Holzworth 1972). The highest morning mixing heights occur in coastal areas that are influenced by moist marine air and cloudiness that inhibit radiation cooling at night. Average afternoon mixing heights are typically higher than morning heights and vary from less than 600 m (~2,000 ft) to over 1400 m (~4,600 ft) above ground level. The lowest afternoon mixing heights occur during winter and along the coasts. Mixing heights vary considerably between locations and from day to day.

Ferguson and others (2001) generated detailed maps and statistics of mixing heights in the United States.

Smoke plumes during the flaming stage of fires often can penetrate through weak stable layers or the top of mixed layers. Once the plume dynamics are lost, however, the atmosphere retains control of how much mixing occurs. Low-level smoke impacts increase once a convective column collapses.

The depth of the mixed layer depends on complex interactions between the ground surface and the atmosphere in a region called the planetary boundary layer (PBL). As such, it is difficult to measure exactly and there are many ways in which it is calculated. At times, it is possible to estimate the mixing height by noting the tops of cumulus clouds or the presence of an upper-level inversion, which may appear as a deck of strata-form clouds.

Typically, National Weather Service (NWS) smoke management forecast products will estimate the mixing height by the so-called parcel method. This method considers turbulence related only to buoyancy. When a parcel is lifted adiabatically from the surface, the point at which it intersects the ambient temperature profile, or where it becomes cooler than its surroundings, is the mixing height. Usually the maximum daily temperature is used as the parcel's starting temperature and its adiabatic lapse rate is compared with the afternoon (0000 UTC) sounding profile. Conversely, the minimum daily temperature is used to compare with the morning (1200 UTC) raob for calculating morning mixing heights. If an elevated inversion (see next section) occurs before this height is reached, the height of the inversion base would determine the mixing height. If a surface inversion exists, then its top marks the mixing height. For example, the mixing height in figure 7.3 is at the top of the surface-based inversion at about 750 mb (approximately 2,400 meters or 7,800 feet above ground level).

Instead of approximating a mixing depth, physical calculations of the PBL are possible through numerical meteorological models. These calculations are more precise than the parcel method because they consider turbulence generated by wind shear as well as buoyancy. Each prognostic model, however, may calculate the PBL slightly differently as some functions are approximated while others are explicitly derived to enhance computational efficiency and the vertical resolution, which varies between models, affect PBL calculations.

Temperature Inversions

When the ambient temperature increases with height, an inversion is said to be present. It usually marks a layer of strong stability. When a heated air parcel from the surface encounters an inversion, it will stop rising because the ambient air is warming faster than the expanding parcel is cooling. The parcel being cooler than its surroundings will sink. Although the heat from some fires is enough to break through a weak inversion, inversions often are referred to as lids because of their effectiveness in stopping rising air and trapping pollutants beneath it. Smoke trapped under an inversion can substantially increase concentrations of particles and gases, aggravating respiratory problems and reducing visibility at airports and along roadways.

There are three ways that surface-based inversions typically form: (1) valley inversions are very common in basins and valleys during clear nights when radiation heat losses cause air near the ground to rapidly cool: the cold surface air flows from the surrounding slopes and collects in hollows and pockets, allowing warmer air to remain aloft; (2) advective inversions are caused by cold air moving into a region from a nearby lake or ocean, usually during the afternoon when onshore lake and sea breezes tend to form; and (3) subsidence inversions can occur at any time of day or night as cold air from high altitudes subsides or sinks under a region of relatively stagnant high pressure. Valley inversions cause tremendous problems when managing long-duration fires that continue into the night. Advective inversions can surprise smoke managers who are unfamiliar with local lake- and sea-breeze effects, creating poor dispersal conditions in an afternoon when typically good dispersion is expected. Subsidence inversions are difficult to predict even for a well-trained meteorologist. Figure 7.7 shows smoke caught under a valley inversion that is being transported by down-valley winds in the early morning.

Surface inversions also occur in the gaps (passes and gorges) of mountain ranges. Approaching storms usually have an associated center of low pressure that causes a pressure gradient across the range. If cold air is on the opposite side of the range, the gradient in pressure causes the cold air to be drawn through the gap, creating an inversion in the gap. Gap inversions are most common in winter but also are frequent during spring and autumn.

In addition to surface-based inversions, temperature inversions also occur in layers of the atmosphere that are above the ground surface, which sometimes are called thermal belts. Upper-level inversions usually are associated with incoming warm fronts that bring moisture and warmth to high altitudes well ahead of a storm. The inversion lowers to the ground as the front approaches. Upper-level inversions also may be associated with subsidence or surface-based inversions that have been lifted, usually by daytime heating.

Wind

Not only does smoke mix and disperse vertically, the horizontal component of wind readily transports and disperses pollutants. The stron-

Figure 7.7. A plume of smoke flowing out of a mountain valley with down-slope winds during the early morning. Photo by Roger Ottmar.

ger the wind, the more scattered particles become and the less concentrated they will be. Strong winds at the surface, however, can increase fire behavior and associated emission rates. Also, significant surface winds may "lay-down" a plume, keeping smoke close to the ground for long distances.

Friction with the ground causes winds to slow down. Therefore, wind speed usually increases with height, causing a smoke column to gradually bend with height as it encounters increasingly strong winds. This pattern is complicated in regions of complex terrain, however, and it is common to find stronger surface winds in mountain passes, saddles, and gorges as air is squeezed and funneled through the gap. Forest clearings also allow surface winds to accelerate because surface friction is lower in a clearing than over a forest canopy.

Because smoke from different stages of a fire rises to different levels of the atmosphere, it is important to know wind speed and direction at several different heights. For example, smoldering smoke at night responds to surface winds while daytime smoldering and smoke from the ignition and flaming phase of a fire will respond to upper-level winds. Depending on the buoyancy of the smoke and stability of the atmosphere, winds that influence the upper-level smoke trajectories may be from just above a forest canopy to 10,000 feet (about 3,000 meters) or more. Because flaming heat can create convective columns with strong vertical motion, most smoke during the flaming portion of a fire will be carried to at least the top of the mixing height or an upper-level inversion height before dispersing. In this way, a fire hot enough to pull itself into a single convection column can reduce concentrations near the ground and knowledge of winds at the top of the mixing height or inversion level will determine smoke trajectory and dispersion. Smoldering smoke, on the other hand, has very little forced convection so it often fumigates away from a fire as it rises with daytime buoyancy. Knowledge of wind all the way from the surface to top of the mixing height may be needed to determine smoldering trajectories.

Storm Winds – Storms change the structure of winds entirely. Because storms often bring high instability and good dispersion, it is common to plan fires slightly ahead of an approaching storm. Knowing storm wind patterns can help anticipate associated smoke impacts. Figure 7.8 shows surface wind directions[2] typically associated with a passing cyclonic storm. Because air flows from high pressure to low pressure (like the rush of air from a punctured tire) and storms usually have a center of low pressure at the surface, surface winds ahead of a storm in the northern hemisphere will be from the east or southeast. As the low center approaches, surface winds will become southerly to southwesterly. After the storm passes, surface winds may become more westerly or northwesterly. This pattern can cause smoke to move toward the west to northwest then north to northeast ahead of a cyclonic storm, moving toward the east and southeast following storm passage.

Each cyclonic storm usually contains at least one front (a boundary between two different air masses). A typical storm has a warm front aligned northwest to southeast ahead of the low center, a cold front trailing northeast to southwest near and closely behind the low, and an occluded front (formed when a cold front overtakes a warm front) to the north of the low. Winds change direction most rapidly and become gusty when fronts pass by. Warm fronts can bring increasing stability and cause upper-

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[2] Wind direction is the direction from which the wind is blowing. For example, a west wind is coming from the west and blowing toward the east. If you face east, a west wind will hit your back.

level inversions, while cold fronts usually are associated with strong instability. The stronger the front, the more dramatic the wind shift and the stronger the gusts. Cold frontal passage typically improves dispersion of smoke with stronger winds and an unstable air mass that can scour away existing inversions. Smoke trajectories should be expected to change direction with the passage of a storm front and storms can cause significant changes in fire behavior and resulting emission rates. Storm fronts are not always typical, however, and the number, strength, and orientation of fronts are quite variable.

Strong winds above the influence of the earth's surface experience forces associated with the earth's rotation in addition to pressure gradient and other forces. This causes winds in the upper atmosphere to follow lines of constant pressure instead of moving across lines of constant pressure as surface or lower-speed winds do when air flows from high pressure to low pressure. In the upper atmosphere the pressure pattern of a typical storm is shaped like a trough (figure 7.9). As air follows the pressure contours around the trough, southwesterly upper-level winds occur ahead of the storm, becoming westerly as the storm trough passes, and northwesterly following the trough. The upper-level trough usually trails the surface low center in most moving fronts, causing smoke trajectories aloft to change directions sometime after trajectories at the surface have changed following a storm passage.

Thunderstorms, which are the result of strong convection, create much different wind patterns

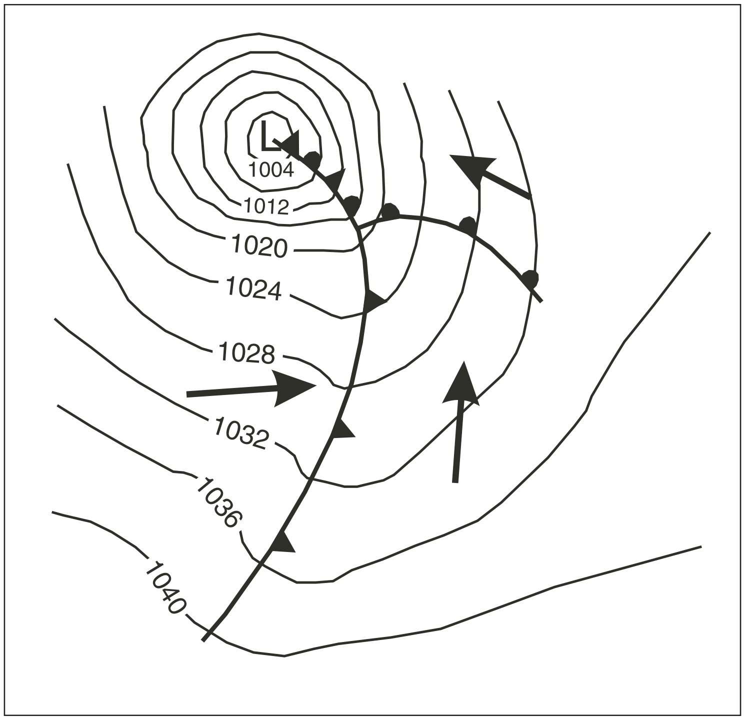

Figure 7.8. Schematic of surface winds associated with a typical cyclonic storm in the Northern Hemisphere. The letter, L, marks position of the surface low pressure center. Thin lines represent isobars (constant pressure contours that are labeled in millibars) at sea level. The thick line marked with barbs represents a surface cold front, marked with half-circles is a warm front, and marked with both is an occluded front. East to southeast surface winds are common ahead of a warm front, south to southwest winds are common ahead of a cold front, and west to northwest winds are common following a cold front.

than cyclonic storms. Gusty, shifty winds are common at times of strong convection. Strong down bursts of wind in a direction away from the thunder cell may occur several minutes ahead the storm, while winds around the cell may be oriented towards it. Although mixing heights usually are quite high during thunderstorms, allowing for well-lofted plumes, the shifting wind directions and strong gusts can cause variable and unpredictable smoke trajectories and fire behavior in close proximity to thunderstorms.

Diurnal Winds – In the absence of storms, diurnal wind patterns dominate trajectories of smoke near the ground. Diurnal patterns are caused by differences between radiational cooling at night and solar heating during the day, and by different thermal properties of land and sea surfaces that cause them to heat and cool at different rates. The differential heating causes changes in surface pressure patterns that control air movement. Slope winds and sea and lake breezes, all of which are common in wildland smoke management situations, typify diurnal patterns.

Slope winds are caused by the same mechanisms that cause valley and basin inversions. When cold air from radiation cooling at night drains into a valley or basin, it causes a downslope wind. The cold air, being denser

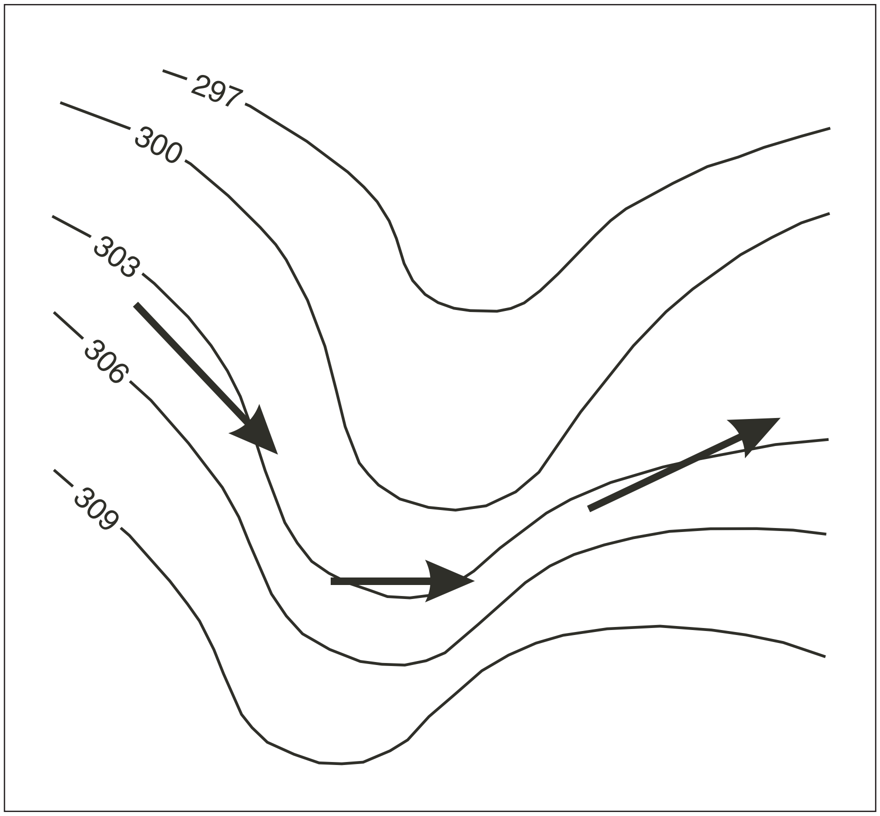

Figure 7.9. Schematic of upper-level (700 mb) winds associated with a typical stormy trough pattern in the Northern Hemisphere. Thin lines represent pressure height contours that are labeled in tens of meters. South to southwest upper-level winds are common ahead of a 700 mb trough, westerly winds are common as the trough passes, and northwesterly winds are common following an upper-level trough.

than its surroundings, usually hugs the terrain in such a way that smoke following a drainage wind will follow contours of the terrain. During the day, heated air from the surface rises, causing upslope winds. Because daytime heating causes more turbulence than nighttime cooling, the daytime winds do not follow terrain as readily as nighttime winds, causing thermally-induced upslope winds to be less noticeable than downslope winds.

Downslope winds at night are notorious for carrying smoke into towns and across roadways (e.g., Achtemeier et al. 1988), especially where roads and bridges cross stream channels or when towns are located in valleys, basins, or near outwash plains. Downslope winds are most likely to occur when skies are clear and ambient winds are nearly calm. The speed and duration of a downslope wind is related to the strength of its associated valley inversion. Downslope winds usually begin around sunset and persist until shortly before sunrise.

Sea and lake breezes usually occur during the afternoon when land surfaces have had a chance to heat sufficiently. The heated air rises, as if lifting the overlying column of air. This causes a region of low pressure at the surface. Because land heats more rapidly than water, the differential heating causes a pressure gradient to form. Relatively cool air remaining over a lake or ocean will flow into the low pressure formed over heated land surfaces. The sea or lake breeze not only can change smoke trajectories but the incoming cool air can cause surface based inversions that will trap smoke at low levels near the ground. Also, strong sea breezes can knock plumes down, causing increasing smoke concentrations near the ground.

Terrain-Influenced Wind – Surface winds are strongly influenced by small undulations in terrain that channel, block, or accelerate air as it tries to move around or over features. For example, if upper-level winds are oriented perpendicular to a terrain barrier, surface winds on the lee side of the barrier often are light and variable. Upper-level winds oriented in the same direction as a valley will enhance upvalley or downvalley winds. Cross-valley winds will be 90° different than those in the valley itself.

The combination of wind and atmospheric stability determine whether smoke will collect on the windward side of a terrain barrier, move up, over and away, or traverse the barrier only to accumulate on the leeward side. Weak winds and a stable atmosphere will enhance blocking and windward accumulations of smoke. Stronger winds in a stable atmosphere may allow accumulations of smoke in leeward valleys and basins. An unstable atmosphere allows smoke to be lifted over and above the terrain. The height, steepness, and orientation of the terrain to the wind direction determine how strong the wind or unstable the atmosphere must be to influence smoke trajectories.

Often very small-scale undulations in topography can affect smoke trajectories, especially at night when atmospheric stability keeps smoke close to the ground. Gentle saddles in ridges may offer outflow of smoke from a valley. Small streambeds can collect and transport significant amounts of smoke even with only shallow or weak downslope winds. A simple band of trees or brush may provide enough barrier to block or deflect smoke. As the urban-wildland interface becomes increasingly complex, the role of subtle topographic influences becomes increasingly important.

Higher in the atmosphere, away from the earth's surface, topography plays a decreasing role in controlling wind speed and direction. Upper-level winds above the influence of underlying terrain are referred to as "free-air" winds and tend to change slowly from one place to another, except around fronts and thunderstorms.

The Role of Inversions on Wind – Temperature inversions significantly influence wind direction and speed. Under many inversions there is little or no transport wind and smoke tends to smear out in all directions. Some inversions, such as advected inversions that are associated with sea breezes and valley inversions, may have significant surface wind but it usually is in a different direction to winds aloft. In these cases, surface smoke may be transported rapidly under the inversion in one direction while lofted smoke may be transported in an opposite direction.

Wind Observations – Because surface winds are strongly influenced by small undulations in terrain, vegetation cover, and proximity to obstacles and water bodies, it is important to know where a surface wind observation is taken in relation to the burn site. For example, observations from a bare slope near the ridgeline will give a poor indication of winds affecting surface smoke trajectories if most of the burn area is on a forested slope or in a valley, even if the two sites are very close. Also, if a burn site is in an east-west oriented valley and the nearest observation is in a north-south oriented valley, observed winds can be 90° different from those influencing the fire and its related smoke. Sometimes, a nearby Remote Automated Weather Station (RAWS) will be less representative of burn-site conditions than one that is farther away if the distant station is in a location that better matches terrain effects expected at the burn site.

There are four principle sources of surface wind data: (1) on-site measurements with a portable RAWS or hand-held anemometer, (2) observations that estimate winds using the Beaufort wind scale[3] or wind sock,[4] (3) local measurements with a standard RAWS, and (4) measurements from NWS observing stations. Because stations vary in their surroundings, from small clearings on forested slopes to open fields, and different types of anemometers are used that are mounted at different heights, wind data is very difficult to compare between one site and another. Therefore, it is useful to become familiar with measurements and observations from reliable sites and understand local effects that make data from that site unique. Also, smoke near the ground can be transported by winds that are too light to spin the cups or propeller of an anemometer or turn its tail. Frequently light and variable wind measurements actually are responding to very light winds that have a preferred direction, often influenced by surrounding topography or land use.

Because free-air winds are above the influence of topography, often it is possible to use an upper-level observation from some point well away from the burn site to estimate upper-level smoke trajectories. Also, surface RAWS that are mounted on the tops of ridges or mountains may compare well with free-air winds at a similar elevation. If clouds are in the area, upper-level winds can be estimated by their movement relative to the ground. High clouds look fibrous or bright white. Because the base of high clouds ranges between 5 km and 13 km (about 16,000 to 45,000 feet) their movement can indicate wind at those high levels. Mid-level clouds may have shades of gray or bulbous edges with bases ranging from 2 km to 7 km (about 6,6000 to 24,000 feet). Mid-level clouds often have a strata-form or layered appearance, which may indicate the presence of an inversion.

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[3] The Beaufort wind scale estimates wind speed using observations of wind-effects in the landscape. For example, wind speeds of 1.6 to 3.3 m/s (4 to 7 mph) will cause leaves to rustle slightly. If leaves move around vigorously then the wind speed is approximately 3.4 to 5.4 m/s (8 to 12 mph).

[4] Wind socks continue to be used at airports and are useful if trying to monitor winds on a nearby ridge that is visible.

Therefore, movement of these types of clouds may closely approximate steering winds for a rising smoke plume.

In addition to observations, it is becoming increasingly common to have available the output from wind models. These data do not provide the detail of a point observation the way an individual site measurement does, but they do provide a broad view of wind patterns over the landscape. Standard analyses from the NWS use models to interpolate between observations. These products help illustrate upper-level wind patterns and typically are available for 850 mb, 700 mb, and 500 mb heights, either from a state, federal, or private meteorological service, or a variety of Internet sites. For surface winds, standard NWS analyses are helpful in regions of flat or gently rolling terrain but mesoscale meteorological models typically are needed to resolve surface wind fields in regions of complex topography. Several regions throughout the country are beginning to employ mesoscale models (e.g., MM5, RAMS, and MASS) producing wind maps with less than 15 km horizontal spacing. Local universities, research labs, state offices, and consortia of local, state, and federal agencies have undertaken mesoscale modeling efforts. Output usually can be found on a local Internet site through the NWS forecast office, a fire weather office, university, state regulator, EPA office, or regional smoke manager. Also, many smoke dispersion models have built-in wind models to generate surface winds at very fine spatial resolutions (less than 5 km grid spacings) from inputs of surface and upper-air observations or data from coarser meteorological models. Smoke dispersion models and their related wind models may be available through a regional smoke manager or EPA office (see Chapter 9—Smoke Dispersion Prediction Systems).

Atmospheric Moisture

Because water vapor in the atmosphere reduces visibility, if smoke is added to an already humid environment, visibility can be severely degraded. Also, if the air is saturated with water vapor, particles from smoke may act as condensation nuclei causing water droplets to form. This promotes the formation of clouds or fog, which further degrades visibility. Often a deadly combination occurs during the darkness of night as smoldering smoke drains down-valley to encounter high humidities from condensing cold air under a valley inversion. The effect can be fatal, especially along transportation corridors (Achtemeier and others 1998).

Favorable conditions for fog occur when the dew point temperature is within a few degrees of the dry bulb temperature, wind is less than a few meters per second, and there is a high content of moisture in the soil. Fog is most common at night when temperatures often drop to near the dew point value and winds are most likely to be weak. Common places for fog to form are over lakes and streams and in the vicinity of bogs and marshes.

There are times when atmospheric moisture can improve visibility, however. Smoke particles can adhere to rain droplets, causing them to be carried with the rain as it falls. This "scavenging" effect removes smoke particles out of the atmosphere, reducing smoke concentrations and improving visibility.

Weather Forecasts

Weather forecasts typically are produced twice each day and become available within 3 to 6 hours after 0000 UTC and 1200 UTC observations are complete. This is because prognostic models require input data from the 0000 UTC and 1200 UTC upper-air observations and a few hours of run-time on a super computer. Prognostic models (progs) form the basis of most forecast products. For example, the first forecast of the day should be available by 7 am to 10 am local daylight time from Anchorage and by 10 am to 1 pm local standard time from Miami. Earlier forecasts or forecasts updated throughout the day are possible if the most recently available upper-air observations and prognostic model outputs are combined with updated surface observations. While public forecasts issued by the NWS and the media are useful, they typically lack the detail needed for smoke management. For this reason, spot-weather forecasts may be requested from state, federal, or private weather services that provide predictions of critical variables that influence smoke at specified times and locations.

Even though there are increasing numbers of numerical guidance tools, weather forecasting still is an art, especially in places with few observations or where there are complex local interactions with terrain, water bodies, and vegetation cover. The primary source of smoke weather forecasts remains the National Weather Service. Their rigorous training, fire weather program, and state-of-the art equipment and analysis tools help maintain a unique expertise. Most NWS fire weather forecast offices now issue special dispersion and transport forecasts. In addition to NWS forecasters, many states maintain a smoke management program with highly skilled meteorologists. Also, the number of inter-agency fire weather offices and private meteorological services is growing and can provide reliable forecast products specifically designed for smoke management. Whatever the source of a forecast, it is helpful to combine the forecast with your own general understanding of weather conditions by reviewing the many satellite pictures, current observation summaries, and prognostic model output products now available on the World Wide Web. In this way, apparent trends and local influences can be determined and the need for last minute changes can be recognized more quickly. For example, increasing afternoon cloudiness in the forecast may have indicated an approaching storm that was predicted for the following morning. If clouds do not increase when predicted, however, it could be suspected that the storm has been delayed or it was diverted elsewhere. A check with the forecaster or updated satellite picture may confirm the suspicion and the management plan may be altered.

Because the atmosphere behaves chaotically, the accuracy of a weather forecast improves as time to an event shortens. For example, it is possible to provide an indication of storminess within 30 to 90 days. A storm passage, however, may not be predicted until about 14 days in advance with about 2 days accuracy. Within 5 days, 1-day accuracy on storm passage may be possible. Increasing accuracy should be expected within 48 hours and the timing of storm passage within 1/2 hour may be possible with 12 hours advance notice. Spot weather forecasts usually are available 24 to 48 hours in advance of a scheduled burn. This allows a smoke manager to anticipate a potential burning window well in advance. Specific timing, however, should not be made before 2 days in advance if the situation is highly dependent on an accurate weather forecast.

Our increasing knowledge of air-sea interactions is making it possible to predict some aspects of weather up to a year in advance as certain regions of the country respond to the El Niño Southern Oscillation (ENSO). Precipitation and temperature during winter and spring are most strongly related to ENSO. Relating key factors for smoke management such as wind and mixing height or stability is more difficult, especially during summer. Nevertheless, an ENSO-based seasonal prediction gives prescribed burners an idea of general weather conditions to be expected, thereby helping prioritize scheduled burns and decide if marginal days or weekends early in the burning season should be used or whether a more optimum season will ensue.

Climate

Climate simply describes the prevailing weather of an area. Understanding climate patterns can help develop long-range smoke management plans or adapt short-range plans. For example, afternoon mixing heights in most coastal regions of the United States are typically lower than the interior because moist, marine air is relatively stable. This means that there may be fewer days with optimum dispersion along the coast than interior. It usually is windier along the coast, however, and burns might be scheduled in the early morning if offshore breezes are desired to reduce smoke impacts on cities and towns.

It is possible to infer climate just by local proximity to oceans, lakes, rivers, and mountains. Also, vegetation cover can give an indication of climate. Desert landscapes, with a lot of bare soil or sand, heat and cool rapidly, causing them typically to have high daytime mixing heights and very low nighttime mixing heights. Natural landscapes of lush green forests tend to absorb sunlight while transpiring moisture, both of which help to modify heating and cooling of the ground surface. This can reduce daytime mixing heights and keep nighttime heights relatively high, with respect to deserts. Also, the structural deformation of trees often indicates high winds, where the direction of branches or flagging point away from prevailing wind directions.

Quantitative summaries of climate can be obtained from the state climatologist or Regional Climate Center (RCC), many of whom also maintain informative Internet sites and can be reached through the National Climatic Data Center (NCDC) <www.ncdc.noaa.gov>. It is most common to find temperature and precipitation in climate summaries. Monthly or annual averages or extremes are readily available while climate summaries of daily data are just beginning to emerge. For example, a recently generated climate database by Ferguson and others (2001) provides information on twice-daily variations in surface wind, mixing height, and ventilation index over a 30-year period.

We know that there are year-to-year variations in climate (e.g., ENSO) so at least 10 years of weather data are needed to obtain a preliminary view of climate in a particular area. There also are natural, “decadal” patterns in climate that last from 7 to 20 years. Therefore, it is appropriate to acquire 30 to 50 years of weather observation data for any reliable climate summary.

Summary

Managing smoke in ways that prevent serious impact to sensitive areas from single burns or multiple burns occurring simultaneously requires knowledge of the weather conditions that will affect smoke emissions, trajectories, and dispersion. Not only is it necessary to anticipate the weather ahead of time through the use of climatology and forecasts, but it also is useful to monitor conditions prior to and during the burn with regional, local, and on-site observations. On-site observations are helpful because air movement, and therefore smoke movement, is influenced by small variations in terrain and vegetation cover, and proximity to lakes and oceans, which off-site observations usually cannot capture. Also, forecasts are not always accurate and last-minute changes in a burn or smoke management plan may be needed. To gain more insight into the physical process of weather in wildland areas and its effect on biomass fires, refer to the Fire Weather handbook (Schroeder and Buck 1970).

In using weather observations, forecasts, and climate summaries effectively for smoke management there are 3 general guidelines; (1) become familiar with local terrain features that influence weather patterns, (2) develop a dialogue with a reliable local weather forecaster, and (3) ask for and use climate summaries of wind and mixing height. By combining your knowledge of local weather effects, trust and communication with an experienced forecaster, and understanding of climate patterns, it is possible to fine-tune or update forecasts to meet your specific smoke management needs.

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