

J8.4 SPATIAL AND TEMPORAL VARIABILITY OF WILDLAND FIRE EMISSIONS OVER THE U.S.

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1. INTRODUCTION

Wildland fires release large amounts of particulate matter (PM), CO, SO₂, NO_x, and Volatile Organic Carbon (VOC), which can cause serious consequence of regional and local air quality (Sandberg et al., 1999). All these components except VOC are the principal pollutants whose emissions are subject to the National Ambient Air Quality Standards (NAAQS) established by the U.S. Environmental Protection Agency (EPA) (EPA, 2003a). Furthermore, high level of O₃, which is also a principal air pollutant, can build up as a result of photochemical processes involved with NO_x and VOC.

EPA recently established new air quality standards for PM_{2.5}, ground-level O₃ (commonly known as smog), and regional haze (largely caused by PM) (EPA, 2003a). These air quality issues are directly related to forest burning (Riebau and Fox, 2001). EPA in cooperation with federal land managers, States and Tribes issued the Interim Air Quality Policy on Wildland and Prescribed Fire (EPA, 1998) to protect public health and welfare by mitigating the impacts of air pollutant emissions from wildland fires on air quality.

A large number of projects have been developed to investigate the air quality effects of wildland fires. For example, the Fire Consortia for Advanced Modeling of Meteorology and Smoke (FireCAMMS) were established as part of the National Fire Plan to manage impacts of wildland fires on the communities and the environment (Heilman et al., 2003). Many research tools (e.g., BlueSky, O'Neill et al., 2003) have been developed using regional meteorological models such as the National Center for Atmospheric Center/Penn State Mesoscale Model (MM5) (Grell et al., 1994), regional chemical transport and dispersion models such as the Community Multi-scale Air Quality (CMAQ) model (Byun and Ching, 1999), and local smoke models such as PB-Piedmont (Achtmeier, 2001) to simulate and predict the effects of wildland fires on regional and local air quality.

A fundamental and yet challenging task in the air quality effect study is to estimate wildland fire emissions. A few large-scale fire emission inventories have been developed (Peterson and Ward, 1993; Ward et al., 1993; Hardy et al., 1998). The most recent and comprehensive effort was the development of the National Emissions Inventory (NEI) for the three base years of 1996, 1999,

and 2002 (EPA, 2003b). Wildland fire is among various emission sources in NEI. NEI is extremely valuable for understanding spatial distribution of wildland fire emissions and their contribution to total concentrations of various principal air pollutants.

Wild and prescribed fires, especially the former, are closely related to atmospheric conditions. Because of the dramatic interannual variability with atmospheric conditions, emissions from the fires might change significantly from one year to another. As a result, the fire emissions of one NEI base year could significantly depart from a normal intensity measured by, e.g., multi-year average of emissions. The magnitude of the departure could be different between geographic regions. This issue is of central importance for understanding what intensity level the NEI wildland fire emissions represent, and for determining scenarios to project future fire emissions based on the NEI emissions.

The US Department of Interior Bureau of Land Management (DOI BLM) recently developed the Federal Fire History Internet Map Service Interface, a wildland fire information system (BLM, 2003). The millions of historical fire records over the continental U.S. for the long period of 1980-2002 allow analyses of statistical features of fire emissions such as multi-year average, which is an important quantity for evaluating the issue concerned with the NEI fire emissions.

This study analyzes spatial and temporal variability of wildland fire emissions over the continental U.S. using the BLM historic fire data, and discusses the NEI fire emission issue based on the analyzed results. Relations with atmospheric conditions are examined to understand the environmental factors for the temporal variability of wildfire emissions.

2. DATA AND METHOD

The parameters provided by the BLM fire information system include size (in acres), number, location (states or regions), types (wildfire suppression, natural outs, support actions, prescribed fire, and false alarm), causes, and agency (BLM, Bureau of Indian Affairs, Fish and Wildlife Service, National Park Service, and USDA FS). The data used in this study are monthly burning areas of wild and prescribed fires over each of the 48 continental states during 1980-2002 for any cause from all agencies. The wildfires are composed of the types of wildfire suppression and natural outs.

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The meteorological data are monthly precipitation and the surface air temperature for each of the 48 continental states during 1980-2002. They were obtained from the U.S. National Climate Data Center of the National Atmospheric and Oceanic Administration (NOAA). Note that one state may have more than one weather regime. For example, the rain season is different between southern and northern California. As a result, it might be inappropriate to use a single relation between atmospheric conditions and fire emissions for these two regions.

The method to calculate wildland fire emissions is the same as that used in developing NEI (EPA, 1995, 2003b):

$$E_i = F_i A \quad (1)$$

where E_i is emission (in mass); A land area burned; and F_i emission per unit area burned, determined by

$$F_i = S_i L_i \quad (2)$$

where S_i is emission factor (mass of pollutant per unit mass of forest fuel consumed) and L_i effective fuel consumption or fuel loading factor (mass of forest fuel per unit land area burned); The subscript i indicates a distinct emission component.

The burning area A is obtained from the BLM fire historical data. The emission factors S_i (Table 1) for all compounds except CO_2 are adopted from AP-42 Tables 12.1-2 and 13.1-4 (EPA 1995). The CO_2 emission factor is adopted based on the flaming fire emission factor (Battye and Battye, 2002, Table 39) and Hao et al. (2002). Those for wildfire emissions are geographic region independent. So are those of SO_2 , NO_x , VOC, and CO_2 for prescribed fire emissions. Those of $PM_{2.5}$, PM_{10} , and CO for prescribed fire emissions distinguish among five regions. The fuel loading factors L_i (Table 2) for wildfire are adopted from AP-42 Table 13-1.2 and those for prescribed fire are obtained by multiplying the corresponding values for wildfire by a factor of 8.2/10.4 (EPA, 2003b). All values are pollutant independent, but vary with region.

Table 1 Emission factor S_i (lbs/ton). PN, PS, SE, RM, and NCE represent Pacific Northwest, Pacific Southwest, Southeast, Rocky Mountain, and North Central and Eastern.

Fire Type	Region	Emission Component						
		$PM_{2.5}$	PM_{10}	CO	SO_2	NO_x	VOC	CO_2
Wildland	All	11.7	13.0	140.0	0.15	4.0	19.2	3500.0
Prescribed	PN	18.8	20.6	222.2	0.15	5.0	12.8	3500.0
	PS	23.4	26.0	202.0				
	SE	33.84	37.6	268.0				
	RM	21.42	23.8	166.8				
	NCE	25.20	28.0	287.6				

Table 2 Fuel loading factor L_i (ton/acre). N, RM, SW, IM, PS, PN, S, SE, NC and NE represent Northern, Rocky Mountain, Southwestern, Intermountain, Pacific Southwest, Pacific Northwest, Southern, Southeast, North Central, and Northeast.

Fire Type	Region ¹									
	N	RM	SW	IM	PS	PN	S	SE	NC	NE
Wildland	60	30	10	8	18	60	9	9	11	11
Prescribed	47.3	23.7	7.9	6.3	14.2	47.3	7.1	7.1	8.7	8.7

¹ The region division is as follows: N(MT, ND), RM (WY, CO, SD, NE, KS), SW (AZ, NM), IM (ID, NV, UT), PS (CA), PN (WA, OR), S (OK, TX, AR, LA), SE (KY, TN, MS, AL, VA, NC, SC, GA, FL), NC (MN, IA, MD, WI, IL, MI, IN, OH), and NE (NY, PA, WV, ME, VT, NH, MA, CT, RI, NJ, DE, MA).

3. RESULTS

3.1 Spatial Variability

Because of the differences in climate and landscape types and fire management practice, wildfire as well as prescribed fire emissions vary across the continental U.S. Figure 1 shows geographic distribution of annual PM_{2.5} emissions (Distributions of other components are similar). An interpolation technique (Endlich, 1968) was used to convert the values from states to a mesh of 22×15 grid points. This technique applies a weight factor, which is inversely proportional to the distance between a grid point and a state. Wildfire emissions are found the largest in the west with a center of 157 kg km⁻² over Pacific Northwest. The largest value in the east, 6.4 kg km⁻² over the Florida Peninsula, is only about 4% of that over Pacific Northwest.

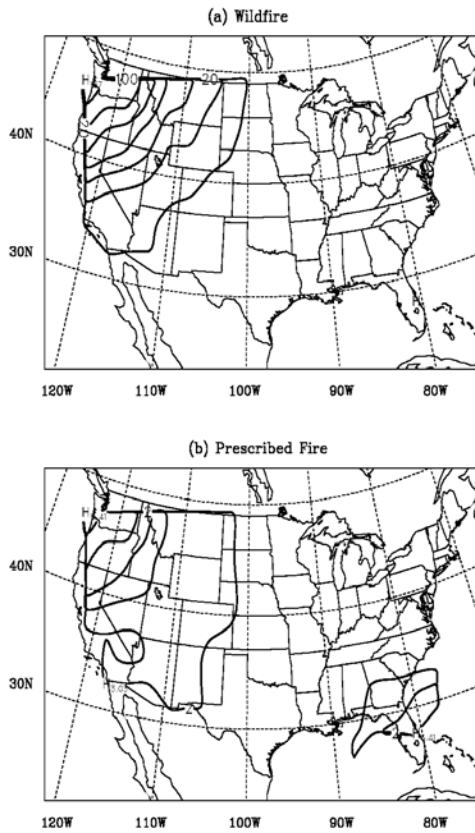


Figure 1 Spatial distribution of annual emissions of PM_{2.5} from wild (a) and prescribed (b) fires. Unit is kg km⁻². Contour intervals are 20 (a) and 2 (b).

Prescribed fire emissions are also largest over Pacific Northwest. However, the emissions in the southeastern coast become important. This region has an emission intensity comparable to Pacific Northwest (6.4 vs 11.4 kg km⁻²). Prescribed fire emissions are

much smaller than those of wildfire in most regions. The maximum prescribed fire emissions over Pacific Northwest, for example, are less than one tenth the corresponding wildfire emissions.

Figure 2 shows multi-year average, \bar{E} , and standard deviation (SD), defined as $E_{i,sd} = \left\{ \frac{1}{T} \sum_{t=1}^T [E_i(t) - \bar{E}_i]^2 \right\}^{\frac{1}{2}}$, of PM_{2.5} emission at various regions. Here T is the number of years. Pacific Northwest, Pacific Southwest, and Northern have the largest wildfire emissions, and the first two regions together with Southwest have the largest prescribed fire emissions among various regions. Note that, despite the large prescribed fire emissions over the southeastern coast, the average over entire Southeast is small due to the small emission intensity over most of its inland area.

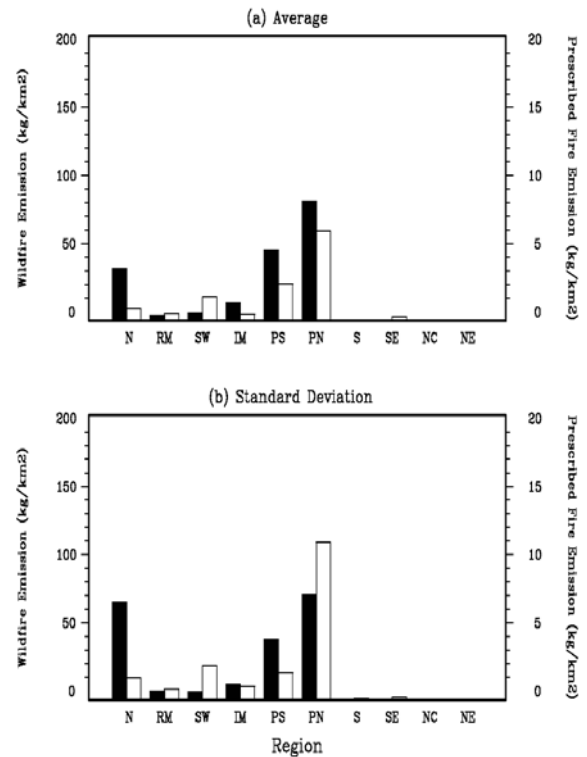


Figure 2 Average (a) and standard deviation (b) of regional PM_{2.5} emissions. The solid and empty bars represent wildfire and prescribed fire emissions, respectively.

The SD is twice as large as the average at Northern and almost the same at Pacific Northwest and Pacific Southwest for wildfire emissions, and twice as large as the average at Pacific Northwest for prescribed fire emissions. This result indicates large

variability over time in some regions. Further results about the variability will be given later.

PM₁₀, VOC and NO_x each has a comparable emission intensity to PM_{2.5}, while intensity of any other emission component is significantly different. CO and CO₂ are about 10 and 100 times larger, respectively, while SO₂ is about 100 times smaller. They reflect the differences in the emission factors shown in Table 1. The spatial patterns of these emission components are similar to that of PM_{2.5}.

3.2 Interannual Variations

Figure 3 depicts temporal variations of annual wildfire emissions at various regions. The emissions are normalized by subtracting the original emissions from multi-year average divided by SD, that is,

$$E_{i,normal}(t) = [E_i(t) - \bar{E}_i] / E_{i,SD}$$

All regions display remarkable variability, characterized by a number of strong emission events and a relatively quiet episode up to a decade long between two strong emission events. During the event around 1988, strong emissions occur at Northern, Rocky Mountain, Intermountain, Pacific Southwest, Southeast, and North Central. The departure from the multi-year average could be four times as large as the SD. Other strong emission events occur during 1994-1996 and 1999-2002 at some regions.

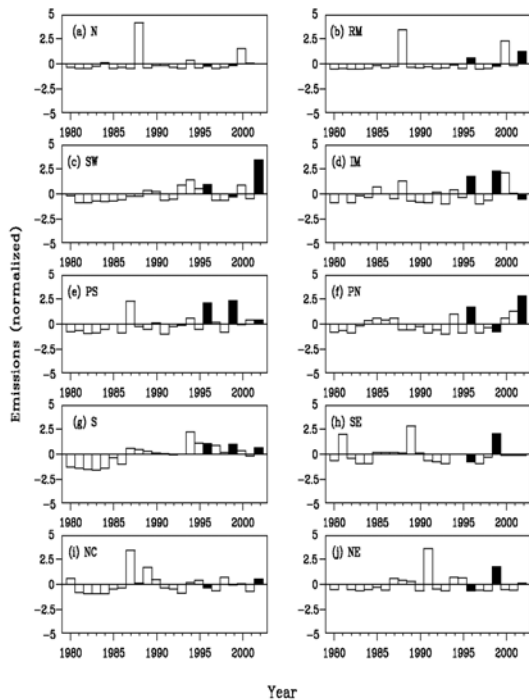


Figure 3 Temporal variations of normalized wildfire PM_{2.5} emissions in various regions (a-j). The solid bars are the values for the three NEI base years (1996, 1999, and 2002).

The number of the strong emission events varies between geographic regions. For example, there are two such events around 1988 and 2000 at Northern and Rocky Mountain, while three are observed in 1981, 1989, and 1999 at Southeast.

Prescribed fire emissions (Figure 4) vary in a totally different way at all regions except Southeast. They remain very small until the late 1990s. The intensity of the emissions varies significantly from one year to another in recent years.

3.3 Seasonal Cycle

Fire emissions display strong seasonal dependence, in response to the seasonal variations in frequency and intensity of wildland fires in the U.S. At the six western regions, large percentage of 15 or more is found over a period of 2-4 months during spring through fall. This period is referred to as wildfire season hereafter. The percentage in one or two summer month during wildfire season can be as high as 30. At the remaining regions, on the other hand, large percentage is found in spring or even winter. Northeast has two periods of large emissions, one in winter and spring, and the other in early fall. Not a single month is found with a percentage over 15, indicating a weak seasonal cycle.

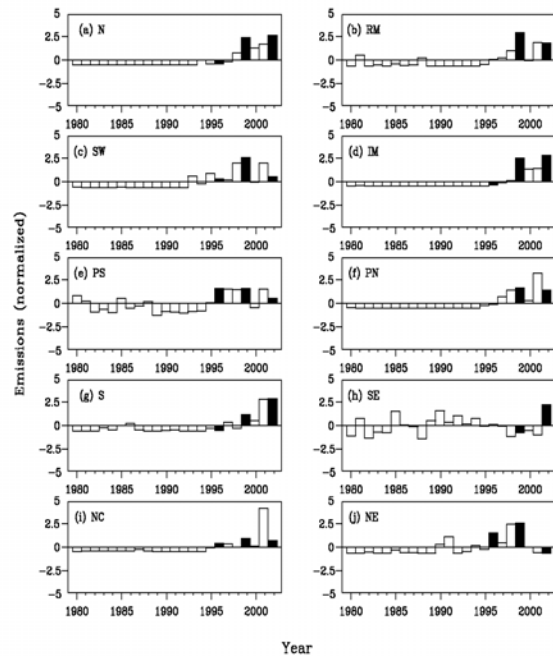


Figure 4. Same as Figure 4 except for prescribed fire.

In comparison with wildfire, prescribed fires at the first six regions are more frequent during spring and fall, when weather is not as hot or dry as in summer and, therefore, burning is earlier to control. The seasonal cycle at the remaining regions is more or less

similar to that of wildfire emissions except that the percentage becomes larger (smaller) in spring at Southern and Northeast (Southeast).

3.4 Relations with Atmospheric Variability

In most cases, large emissions are accompanied by dry and hot weather. For example, for the strong emission event in 1988 at Northern, precipitation anomaly is negative and temperature anomaly is positive. Similar situation is found for the events in 1988 and 2000 at Rocky Mountain, 2002 at Southwest, 1988, 1996, and 2000 at Intermountain, 1996 at Pacific Southwest, 2002 at Pacific Northwest, 1999 at Southern and Southeast, and 1987 at North Central. For other events such as those in 1987 and 1999 at Pacific Southwest and 1996 at Pacific Northwest, precipitation is well below normal but there is little or even negative temperature anomaly. There are also a couple of events in 1981 and 1989 at Southeast accompanied with little anomalies in both precipitation and temperature.

This result suggests that dry and hot weather, especially large negative precipitation anomalies, would be a necessary condition for most large emissions. The correlation coefficients (Figure 5) provide a quantitative measure of how closely the wildfire emissions are related to atmospheric conditions. The correlation with precipitation exceeds the 95% significance level (the critical correlation value is nearly 0.4) at most regions, including all western ones and North Central. This level is only barely missed at Southeast. The correlation with the surface air temperature, on the other hand, exceeds the level only at three regions of Northern, Rocky Mountain, and Southwest. This result suggests different wildfire emission-favorite atmospheric conditions for distinct geographic regions. In general, atmospheric moist condition is more important than thermal one, and the atmosphere-emission relations are more important in the west and east.

4. SUMMARY AND DISCUSSION

Spatial and temporal variability of wildfire and prescribed fire emissions in the continental U.S. has been analyzed using a historical fire dataset developed by the U.S. Bureau of Land Management (BLM). The major findings are as follows:

- (1) Large wildfire emissions occur only in Pacific coastal region, while prescribed fire emissions have comparable intensity in the Pacific and southeastern coastal regions.
- (2) Wildland fire emissions have significant interannual variability, featured by the occurrence of some strong wildfire emission events over the past two decades, and dramatic increase in prescribed fire emissions in recent years.

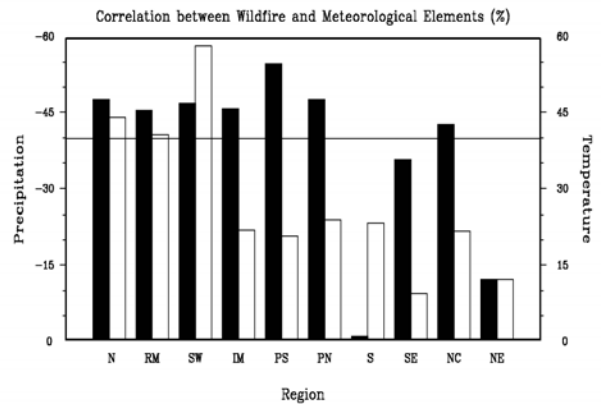


Figure 5 Correlation coefficients between wildfire $PM_{2.5}$ emissions and precipitation (solid bars), and the surface air temperature (empty bars) of the fire seasons at various regions. The horizontal line indicates the critical correlation value at the 95% significance level.

- (3) The favorite atmospheric condition for strong wildfire emissions in most regions is dry weather. High temperature also contributes to strong emissions in the Rocky Mountain area. But atmospheric condition plays a relatively small role in the wildfire emissions in the southern and eastern regions.

These results may have important implications for the National Emissions Inventory (NEI) fire emissions. In Figures 4 and 5, the emissions estimated based the BLM data corresponding to the three NEI base years are highlighted. Wildfire emissions for each of the three years are strong at three or four out of the ten regions. These regions are Intermountain, Pacific Southwest, and Pacific Northwest in 1996, the first two regions plus Southeast and Northeast in 1999, and Rocky Mountain, Southwest, and Pacific Northwest in 2002. For other about 60-70% cases, the emissions are close to multi-year averages. On the other hand, prescribed fire emissions of 1999 and 2002 are much larger than multi-year averages at most regions, which, of course, is due to the increasing tendency in recent years of prescribed fire emissions. Those of 1996 are mostly close to the averages at all regions except Pacific Southwest and Northeast. These features suggest that the NEI emissions of the three base years would mostly represent normal intensity wildfire emissions, while the NEI emissions of the later two years would mostly represent high intensity prescribed fire emissions.

Fire weather elements such as precipitation and temperature have certain predictability at seasonal and interannual scales (e.g., Klein et al., 1996), attributed to atmospheric interactions with longer-memory processes with sea surface temperature (SST) and soil moisture (e.g., Cane, 1992; Liu, 2003). The close relations between wildland fire emissions and precipitation at most regions as well as temperature at some regions

provide a basis for predicting possible strong emissions during a fire season at these regions based on long-term variations of the two meteorological elements.

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