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Variability of wildland fire emissions across the contiguous United States

Yongqiang Liu*

Forestry Sciences Laboratory, USDA Forest Service, Athens, GA 30602, USA

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Abstract

This study analyzes spatial and temporal variability of emissions from wildland fires across the contiguous US. The emissions are estimates based on a recently constructed dataset of historical fire records collected by multiple US governmental agencies. Both wildfire and prescribed fires have the highest emissions over the Pacific coastal states. Prescribed fire emissions are also found to be high over the southeastern coastal area. Temporal variations of wildfire emissions in various regions are characterized by a number of strong emissions over the past two decades, which are closely related to precipitation anomalies. Prescribed fire emissions, on the other hand, show an increasing tendency in recent years. An analysis of the emissions specifically for the three National Emissions Inventory (NEI) base years of 1996, 1999, and 2002 suggests that the average of these years would represent fairly typical wildfire emissions for all regions except the Southwest and Pacific Southwest. Prescribed fire emissions during the NEI base years, on the other hand, were much higher than the historical average for all regions except the Southeast.
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1. Introduction

Wildland (forests, rangeland and woodland) fires encompass both wild and prescribed fires. Wildfire can be a major natural disaster threatening human life and property. Each year hundreds of thousands of wildfires burn out several million acres in the US (NIFC, 2003). Prescribed fire is a forest management technique that temporarily reduces damage from wildfire by removing a portion of the accumulating dead fuels (such as duff and logs on the forest floor) and reducing the stature of the developing understory when burning conditions are not severe (Wade and Outcalt, 1999). These intentional fires also serve as a surrogate for the historical fires by recycling nutrients and restoring/sustaining ecosystem health.

*Corresponding author. Tel.: +1706-559-4240; fax: +1706-559-4245.

E-mail address: yliu@fs.fed.us (Y. Liu).

Wildland fires release large amounts of particulate matter (PM), CO, SO_2, NO_x, and volatile organic compounds (VOC), which individually or in combination can cause degradation of air quality (Sandberg et al., 1999). All these components except VOC are criteria air pollutants whose emissions are subject to the National Ambient Air Quality Standards (NAAQS) established by the US Environmental Protection Agency (EPA) (EPA, 2003a). It is estimated that the wildland fires contribute about 15% and 8% of total PM and CO emissions, respectively, over the southeastern US (Barnard and Sabo, 2003). Furthermore, high levels of O_3, which is also a criteria air pollutant, can result from photochemical processes involved with NO_x and VOC.

EPA recently established air quality standards for $PM_{2.5}$ and revised standards for ground-level O_3 and PM_{10} as an effort to reduce regional haze and smog and to improve visibility (EPA, 2003a). Because these air quality issues are directly related to forest burning (Riebau and Fox, 2001), EPA also issued the Interim Air

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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.

Numerous research projects have been initiated to investigate the air quality effects of wildland fires. For example, the Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS) were established as part of the National Fire Plan to manage impacts of wildland fires on the communities and the environment (Heilman et al., 2004). 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 (Achtemeier, 2001) to simulate and predict the effects of wildland fires on air quality.

A fundamental and yet challenging prerequisite to any meaningful assessment of the effects of wildland fire on air quality is to accurately estimate wildland fire emissions. A few large-scale fire emission inventories have been developed (Battye and Battye, 2002), including those for nation-wide prescribed fires in 1989 (Peterson and Ward, 1993; Ward et al., 1993), wildfires during 1986–1992 and prescribed fires over 10 western states in 1990 and 1995 (GCVTC, 1995), and wildfires over 11 western states (Hardy et al., 1998). In addition, EPA developed an inventory for 1985–1995 using Peterson and Ward (1993) for prescribed fires, GCVTC (1995) for wildfires in the western states, and independent estimates for wildfires in the east. 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 criteria air pollutants.

Wild and prescribed fires are closely related to atmospheric conditions. Because of the dramatic inter-annual variability in atmospheric conditions, emissions from the fires change significantly from one year to another. As a result, the concentration of any fire emission component of one NEI base year could significantly depart from its multi-year average. Also the magnitude of the departure could be different between geographic regions. These issues are of paramount importance to understanding what intensity level the NEI wildland fire emissions represent and how scenarios are established 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 US 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 across the contiguous US using the BLM historic fire data and discusses the NEI-related issues based on the analyzed results. The dependence of these emissions upon atmospheric conditions are examined to determine the impacts of environmental factors on the temporal variability in wildfire emissions.

2. Data and method

2.1. Fire and meteorological data

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 for emission estimates in this study are monthly totals of area burnt by wild and prescribed fires by state (just the 48 contiguous states) during 1980–2002 for any cause from all agencies. The wildfires are comprised of the fire types of wildfire suppression and natural outs.

The meteorological data are monthly precipitation and mean surface air temperature for each of the 48 continental states during 1980–2002. They were obtained from the US 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 rainy 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.

2.2. Emission estimates

The method to calculate wildland fire emissions is the same as that used in developing NEI (EPA, 1995, 2003b): $E_i = F_i\ A$, where E_i is emission (in mass) of the component i; A land area burned; and F_i emission per unit area burned, determined by $F_i = S_i\ L$, where L and S_i are effective fuel consumption or fuel loading factor (mass of forest fuel per unit land area burned) and emission factor (mass of pollutant per unit mass of forest fuel consumed), respectively. Table 1 lists the fuel loading factors for the 10 US geographic regions (see

Table 1
Fuel loading factor (ton acre^{-1})

Fire type	Region									
	N	RM	SW	IM	PS	PN	S	SE	NC	NE
Wild	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

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.

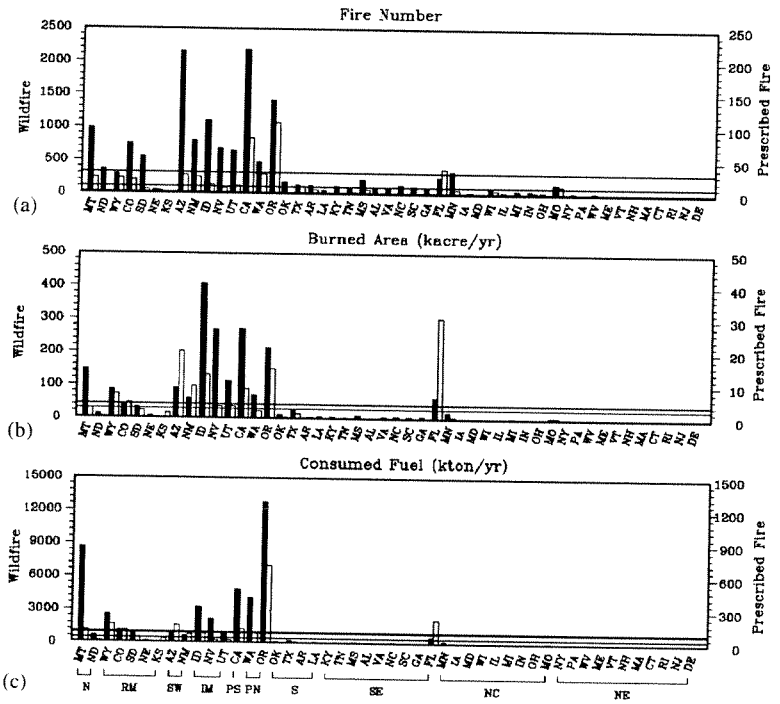

Fig. 1. The averages of the annual fire number (a), burned area (b), and consumed mass (c) of the contiguous US states over 1980–2002. The solid and void bars represent wildfires and prescribed fires. The heavy (light) horizontal line represents the average over all the states of wildfire (prescribed fire). Listed under these states are N, RM, SW, IM, PS, PN, S, SE, NC, and NE regions.

Fig. 1 for the states included in each region). The regions North (N) through Pacific North (PN) correspond to the USDA Forest Service Regions 1–6, respectively, the regions South (S) and Southeast (SE) combined correspond to Region 8, and the regions North Central (NC) and Northeast (NE) combined correspond to Region 9. The fuel loading factors for wildfire in Table 1 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). The values are the same for all pollutants.

Table 2 lists emission factors. Those for all wildfire emission components and for prescribed fire emissions of SO_2, NO_x, VOC, and CO_2 are the same for all regions. Prescribed fire emission factors for $PM_{2.5}$, PM_{10}, and CO are differentiated by regions. The values 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). Note that the regions in Table 2 do not match those in Table 1. It is assumed in this analysis that the emission factors for Rocky Mountains (RM) in Table 2 apply to N, RM, and Intermountain (IM) in Table 1, Pacific Southwest (PS) in Table 2 to SW and PS in Table 1, Southeast (SE) in Table 2 to S and SE in Table 1 and North Central and East (NCE) in Table 2 to NC and NE in Table 1.

3. Statistical features of fires and weather conditions

Fire number, burned area, and consumed fuel of each state averaged over the period of 1980–2002 are first

Table 2
Emission factor (lb ton^{-1})

Fire type	Region	Emission component						
		$PM_{2.5}$	PM_{10}	CO	SO_2	NO_x	VOC	CO_2
Wild	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		(All regions)		
	SE	33.84	37.6	268.0				
	RM	21.42	23.8	166.8				
	NCE	25.20	28.0	287.6				

PN, PS, SE, RM, and NCE represent Pacific Northwest, Pacific Southwest, Southeast, Rocky Mountain, and North Central and Eastern.

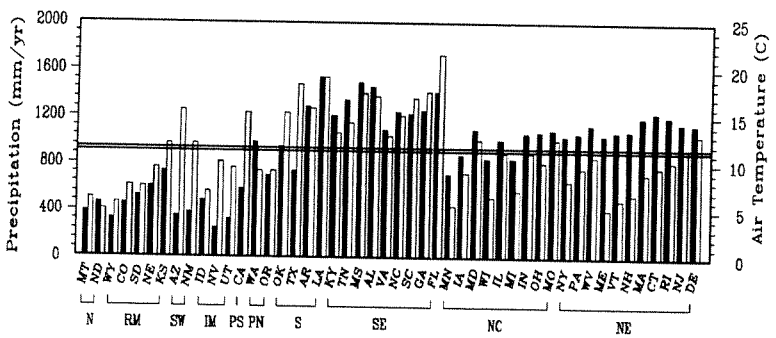

Fig. 2. The averages of annual precipitation (solid bars) and air temperature (void bars) of the contiguous US states over 1980–2002. The horizontal line represents the average of each variable over all the states (see Fig. 1 for the definition of the regions showing below the states).

presented to understand the relationships between fires and associated emissions of various gaseous and PM pollutants (Fig. 1). On average one state had about 310 wildfire events per year (Fig. 1a). The fire numbers were close to or above the average in the states of the western regions (N, RM, SW, IM, PS, and PN) except Nebraska and Kansas. The number in California, Arizona, Oregon, Idaho, and Montana each was about 3–7 times of the average. Minnesota was the only state in the other regions whose fire number was above the average. On an average each state had about 10 prescribed fire events per year. The number in Oregan, California, Florida, or Washington was well above the average.

The areas burned by wild and prescribed fires were about 41,000 and 2660 acres per year, respectively, averaged over the contiguous US states (Fig. 1b). In accordance with the larger fire numbers, most states in the western regions had more burned areas than the average. Among the states with large wildfire number, California, Oregon, and Montana also had large burned areas. The burned area in Arizona, however, was only about twice of the average. Nevada, on the other hand, had a burned area about six times of the average, though it had the wildfire number only about one-third as many as Arizona. This indicated that individual wildfires in Nevada were more intensive in most cases. For prescribed fires, the most significant feature was the large burned area in Florida, which was even much larger than that in every western state.

The consumed fuel, obtained from the product of the fuel loading factor listed in Table 2 and the burned area depicted in Fig. 1b, was about 940,000 and 41,900 tons averaged over the contiguous US states for wild and prescribed fires, respectively (Fig. 1c). Because of the large fuel loading factors for the N and PN regions, the values in Oregon for both wild and prescribed fires and in Montana for wildfires were extremely large. In contrast, the value in Florida for prescribed fires was relatively small despite the large burned area.

Precipitation and the surface air temperature of each state averaged over the period of 1980–2002 are also presented to understand the relationships between atmospheric conditions and the fire emissions (Fig. 2). Annual precipitation and air temperature averaged over the contiguous states were about 900 mm and 12°C, respectively. Both meteorological variables were mostly below their corresponding averages in the states of N, RM, and IM. It was opposite for the states of S and SE.

SW and PS had below-average precipitation but above-average air temperature, while NC and NE mostly had above-average precipitation and below-average air temperature. Precipitation and air temperature were close to or a little below their corresponding averages.

4. Emissions

4.1. Spatial variability

Because of differences in climate, fuels, topography and fire management practice, wildfire as well as prescribed fire emissions vary across the continental US. Fig. 3 shows geographic distribution of annual $PM_{2.5}$ emissions averaged over the analyzed period (distributions of other components are similar). An interpolation technique (Englich, 1968) was used to convert the values from states to a mesh of 97×61 grid points. This technique applies a weight factor, which is inversely proportional to the distance between a grid point and a state. Wildfire emissions of about $120\,kg\,km^{-2}$ are found in the Pacific Northwest. The emissions are relatively small in the east. Prescribed fire emissions are also the highest over Pacific Northwest (about $10\,kg\,km^{-2}$). However, the emissions in the SE coast become important. In addition, there are large emissions in the SW and Northern regions. Prescribed fire emissions are much smaller than those from wildfire in most regions. The prescribed fire emissions in the Pacific Northwest, for example, are less than one-tenth the corresponding wildfire emissions.

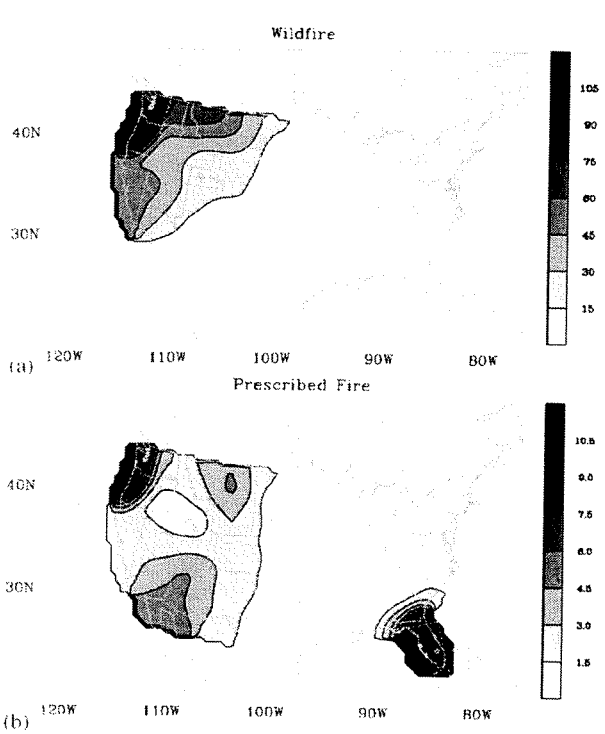

Fig. 3. Spatial distribution of annual $PM_{2.5}$ emissions from wild (a) and prescribed (b) fires ($kg\,km^{-2}$).

Fig. 4 shows the multi-year averages of wildfire and prescribed fire emissions for the contiguous US by regions. For $PM_{2.5}$ emissions, the Pacific Northwest, Pacific Southwest, and Northern regions have the highest wildfire emissions, and the first two regions together with the SW have the highest prescribed fire emissions. Note that, despite the high prescribed fire emissions over the southeastern coast, the average over entire SE is low due to the small emission intensity over most of its inland area. The emissions for PM_{10}, VOC and NO_x are roughly comparable to $PM_{2.5}$, while the emissions of other components are significantly different. CO and CO_2 are about 10 and 100 times larger, respectively, while SO_2 is about 100 times smaller. They reflect the differences in the emission factors shown in Table 2. The spatial patterns of these emission components are similar to that of $PM_{2.5}$.

4.2. Interannual variations

Fig. 5 depicts temporal variations of annual $PM_{2.5}$ wild and prescribed fire emissions between 1980 and 2002 by regions. The emissions are normalized by subtracting the original emissions from the multi-year average divided by the standard deviation (SD), that is, $E_{i,\mathrm{normal}}(t) = [E_i(t) - \bar{E}_i]/E_{i,\mathrm{sd}}$, where $\bar{E}$ is the multi-year average and $E_{i,\mathrm{sd}} = \left\{1/T \sum_{t=1}^{T} [E_i(t) - \bar{E}_i]^2\right\}^{1/2}$ is SD, with being the number of years. All regions display remarkable variability of wildfire emissions, characterized by a number of strong emission events and a relatively quiet episode up to a decade long between two strong emission events. Peak annual emissions by region are as follows: N (1988), RM (1988), SW (2002), IM (1999), Pacific Southwest (1987), Pacific Northwest (2002), S (1994), SE (1989), NC (1987), and NE (1991). The departure from the multi-year average was up to four times as large as the SD. All regions had at least one above average year between 1987 and 1989, between 1999 and 2002 and, except for the Southeast between 1994 and 1996.

The number and strength of emission events above the regional average varies between geographic regions. For example, all regions except IM, Pacific Southwest and S have experienced a year where departure from the average was at least 2.5 times the SD. The N region had the highest positive departure while the Southern had the highest negative departure. The N and RM regions exceeded the average the fewest times, 5 and 4, respectively, while the S and NC exceeded the norm the greatest number of times, 13 and 10, respectively. The number of years in a row that the average has been exceeded and the number of such episodes also varies by

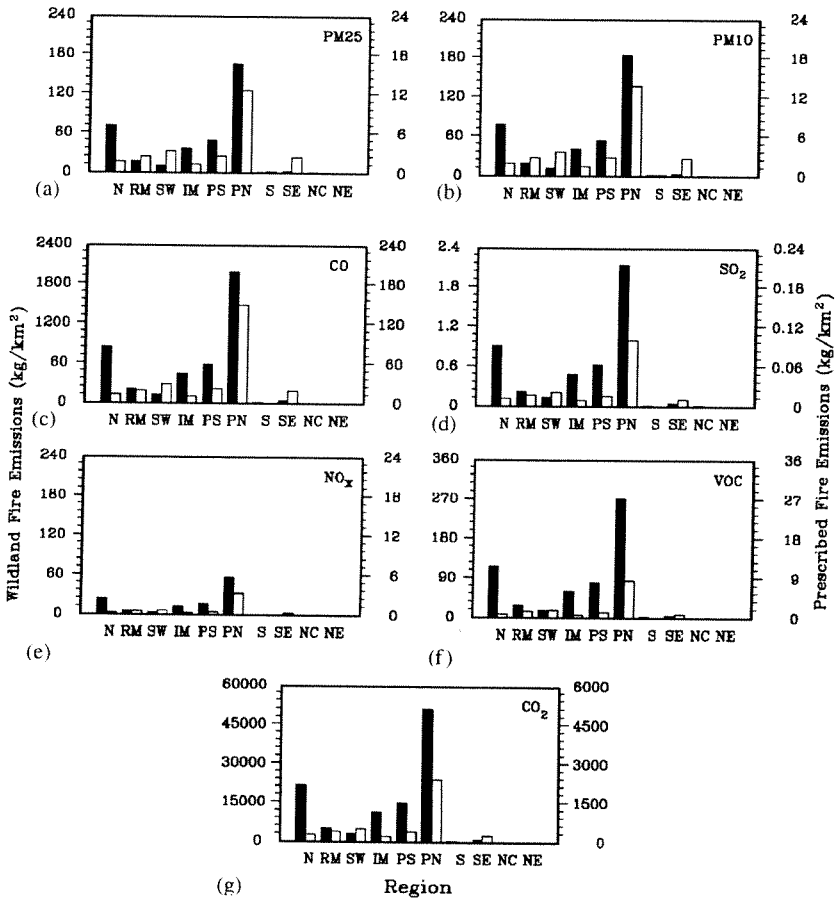

Fig. 4. Regional emissions of various PM and gases from wildland fires (a–g). The solid and void bars represent wildfire and prescribed fire emissions, respectively.

region with the RM never recording a multi-year event while the Southern region has experienced a 7-year episode lasting from 1994 through 2000 and a 5-year episode from 1987 through 1991. No region has had more than two such positive episodes and all except the South have had several multi-year negative departures from the norm.

Prescribed fire emissions vary in a totally different way than wildfire emissions for all regions except the SE. The N, SW, IM, Pacific Northwest, NC, and NE did not exceed the average until 1990 or later and remained small until at least 1995 which is simply a reflection of the lack of prescribed fire in those regions. Since the late 1990s, however, emissions across all regions except the SE and NE have greatly exceeded the average most years, many more than 2.5 times as large as the SD. The below average prescribed fire emissions in the SE between 1998 and 2001 reflect the severe drought that gripped this region during that time.

The wildfire emission SD (figure not shown) is twice as large as the average for the Northern region and almost the same for the Pacific Northwest and Pacific Southwest regions. The prescribed fire emission SD is also twice as large as the average for the Pacific Northwest region. This result indicates large variability over time in some regions.

4.3. Seasonal cycle

Fire emissions display strong seasonal dependence, in response to the seasonal variations in acreage burned by wildland fires in the US. Fig. 6 shows the seasonal cycle of the percentage of monthly to annual $PM_{2.5}$ emissions (seasonal cycle is the same for all emission components). In the six western regions (a–f), large percentages of 15 or more occur over a period of 2–4 months, which is referred to as wildfire season hereafter. The percentage in one or two summer months during wildfire season can exceed 40. In the remaining four more eastern regions (g–j), on the other hand, the situation is reversed with the largest percentage occurring October through May. The NE and NC regions are strongly bimodal with a

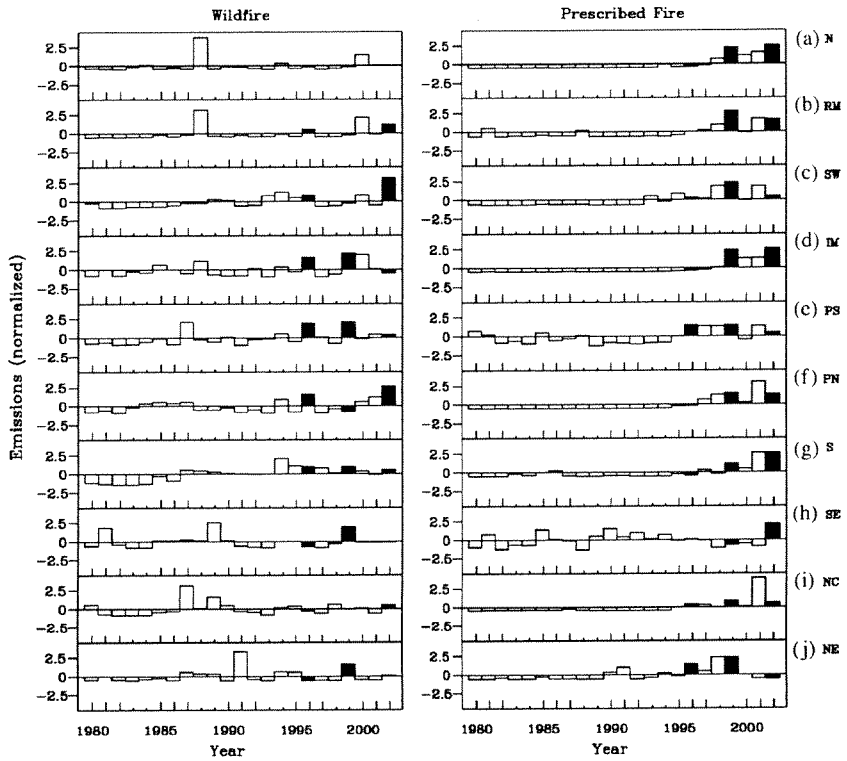

Fig. 5. Temporal variations of normalized $PM_{2.5}$ emissions in various regions (a–j) for wild (left) and prescribed (right) fires. The three NEI base years (1996, 1999, and 2002) are highlighted.

period of large emissions between leaf fall and snow cover (October–November), and the other January through May. In the Southern region, not a single month is found with a percentage over 15, indicating a weak seasonal cycle.

In comparison with wildfire, prescribed fires at the six western regions tend to be more frequent during spring and fall, when the soil moisture tends to be higher. The seasonal cycle in the remaining regions is more or less similar to that of wildfire emissions except that the percentage becomes larger in spring at Southern and NE, and smaller in spring at SE.

5. Atmosphere–emission relations

Weather is the most important among the three major environmental factors (weather, fuel property and topography, Pyne et al., 1996) for interpreting and predicting seasonal and interannual variations in wildfire occurrence and size because of its significant temporal variability. In fact, several researchers have successfully correlated long-term atmospheric anomalies and wildfire activities (e.g., Swetnam and Betancourt, 1990 for Southwest; Brenner, 1991 for Southeast; Chu et al., 2002 for Hawaii). Thus, it is logical to assume that atmospheric variability is a major contributor to the interannual variability of wildfire emissions.

Fig. 7 depicts temporal variations of normalized regional precipitation and mean surface air temperature, together with that of wildfire emissions of $PM_{2.5}$. For some regions, annual precipitation is not a good index of atmospheric moisture during the wildfire season. For example, the wildfire season in the Pacific Northwest is from July to August, but the rainy season is in winter. For this reason, precipitation and temperature averaged over the fire season are used here instead of their annual values. In most cases, large emissions are accompanied by dry and hot weather. The strong emission event in 1988 in the Northern region was accompanied by a negative precipitation anomaly and positive temperature anomaly. A similar situation is found for the events in 1988 and 2000 in the RM region; 2002 in the SW; 1988, 1996, and 2000 in the IM region; 1996 in the Pacific Southwest; 2002 in the Pacific Northwest; 1999 in the S and SE; and 1987 in the NC. For other events such as those in 1987 and 1999 in the Pacific Southwest and 1996 in the 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 in the SE

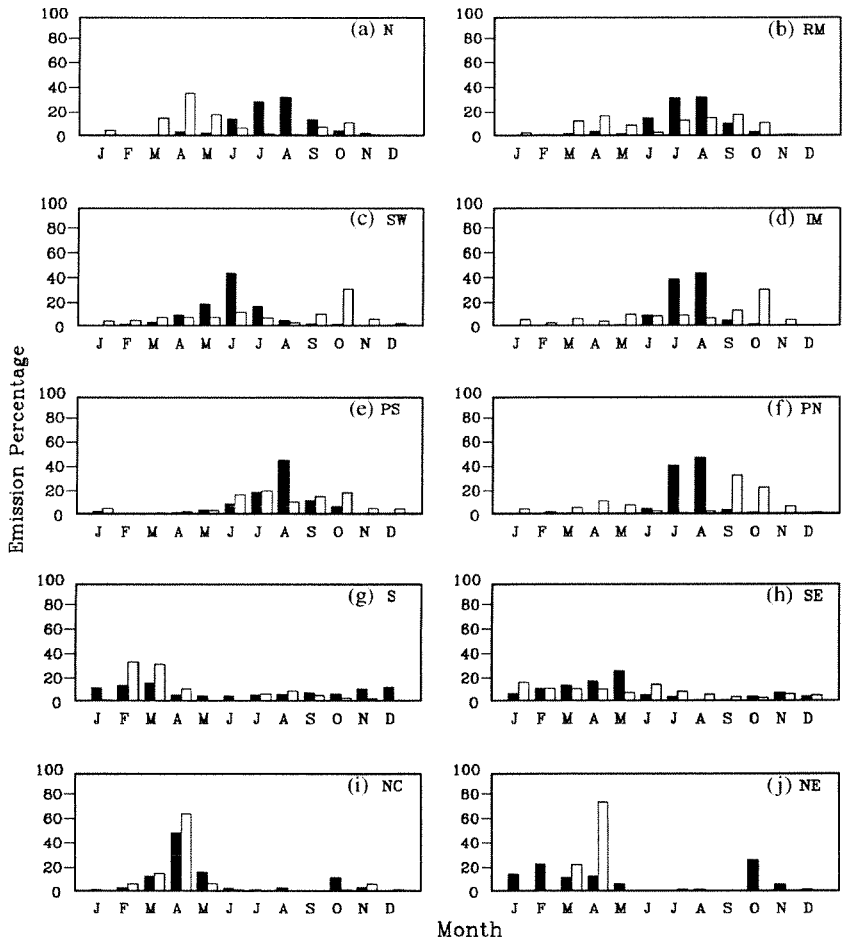

Fig. 6. Seasonal cycles of $PM_{2.5}$ emissions for various regions (a–j). The solid and void bars represent wildfire and prescribed fire emissions, respectively.

accompanied with little anomalies in both precipitation and temperature.

These results suggest that dry and hot weather, especially large negative precipitation anomalies, would be a good predictor for high emission years. The correlation coefficients (Fig. 8) 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) in the six western regions; The SE and NC come close to reaching this threshold as well. The correlation with mean surface air temperature, on the other hand, exceeds the level only in two regions: the RM and SW. This result suggests different wildfire emission-favorite atmospheric conditions for distinct geographic regions. In general, moist atmospheric conditions are more important than the thermal ones, and atmosphere–emission relationships are more important in the west than east.

6. Summary and discussion

Spatial and temporal variability of wildfire and prescribed fire emissions across the contiguous US has been analyzed using a historical fire dataset developed by the US Bureau of Land Management (BLM). The major findings are: (1) Large wildfire emissions occur only in those states bordering the Pacific Ocean, while prescribed fire emissions are large in these states and in the southeastern coastal area. (2) Wildland fire emissions have significant interannual variability, as demonstrated by the occurrence of some strong wildfire emission events over the past two decades, and the dramatic increase in prescribed fire emissions over all regions except the SE in recent years. (3) The most conducive atmospheric condition for strong wildfire emissions in most regions is dry weather. High temperature also contributes to strong emissions in the RM area. Atmospheric condition plays a less

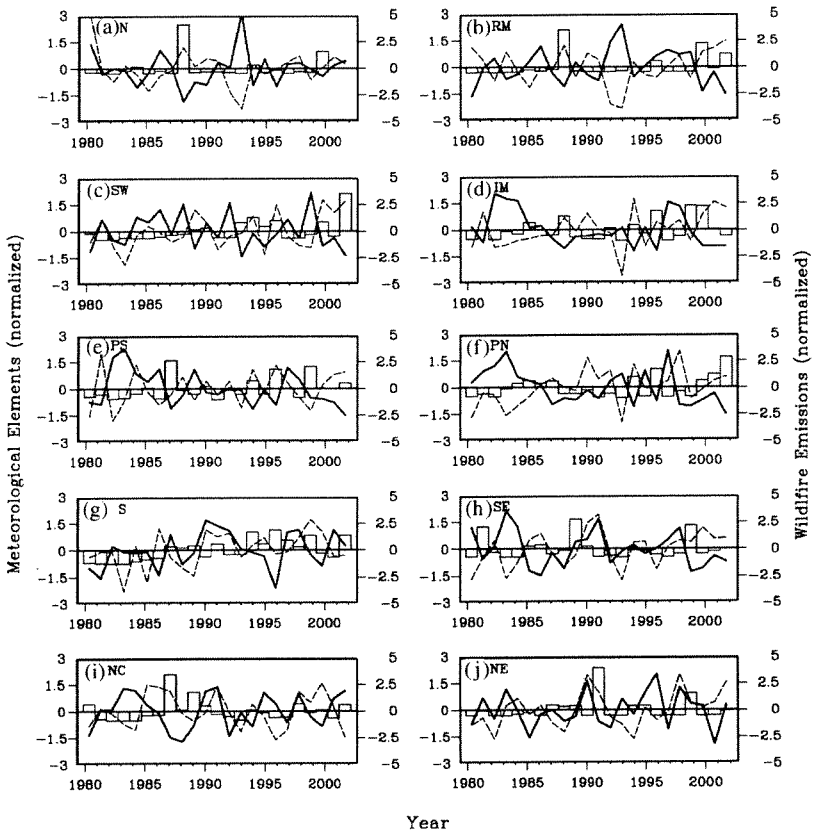

Fig. 7. Temporal variations of normalized precipitation (solid lines) and mean surface air temperature (dashed lines) for various regions (a–j) averaged over the fire seasons. Also shown are the corresponding wildfire emissions of $PM_{2.5}$ (bars).

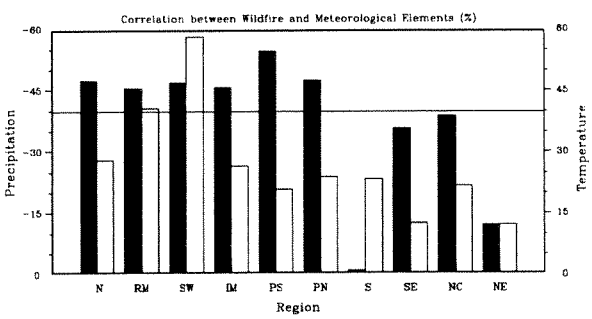

Fig. 8. Correlation coefficients between wildfire $PM_{2.5}$ emissions and precipitation (solid bars), and mean surface air temperature (void bars) of the fire seasons. The horizontal line indicates the critical correlation value at the 95% significance level.

important role in wildfire emissions in the southern and eastern regions.

These results may have important implications for the NEI. In Fig. 5, the emission estimates based on the BLM data corresponding to the three NEI base years are highlighted. Wildfire emissions were above average all 3 NEI base years in the Pacific Southwest and Southern regions and were above average at least one of the base years in all regions except the Northern region. At least one of the base years was a strong event in all regions except the Northern and NC regions and two of the three base years were strong event years in the SE, IM, California, and Pacific Northwest regions. On the other hand, prescribed fire emissions for 1999 and 2002 are much larger than the multi-year averages at most regions, which is due to the increased use of prescribed fire in all regions except the S and SE. The 1996 emissions are mostly close to the averages at all regions except the Pacific Southwest and NE where 1996 was a strong event year. All three base years were above average in the SW, Pacific Northwest, and NC regions.

This analysis suggests that the average of the three NEI emission base years would represent fairly typical wildfire emissions for all regions except the SW and Pacific Southwest. Prescribed fire emissions during the NEI base years, on the other hand, were much higher than the historical average for all regions except the SE. If, however, the number of acres annually treated with prescribed fire continues to expand throughout the contiguous United States, the NEI base years may in fact represent the emerging situation fairly well.

Fire weather elements such as precipitation and temperature have proved to be useful predictors at seasonal and interannual scales (e.g., Klein et al., 1996), which are attributed to atmospheric interactions with, e.g., sea surface temperature (SST) and soil moisture which have longer memory than the atmosphere (e.g., Cane, 1992; Liu, 2003). The close relationship between wildland fire emissions and precipitation for most regions as well as temperature in some regions provides a basis for predicting possible strong emissions during a fire season in these regions based on long-term variations of these two meteorological elements.

A major shortcoming in this analysis is the uncertainty in burning areas. The BLM data include only burnings on federal lands, while those of state and private lands and Department of Defense lands, which together contribute to a substantial portion of the acres burned in the S, are missed. Missing reports and the difference between the acreage planned and that actually burned are other large error sources. It is expected that, however, this shortcoming, as well as the uncertainties to be discussed below, would affect mainly on the magnitude estimates of fire emissions and their spatial distribution, but little on temporal variability.

Uncertainties in fuel loading and emissions factors also cause errors in emission estimates. WRAP (2002) estimated fuel loading factors for the National Fire Danger Rating System (NFDRS) fuel model categories (Cohen and Deeming, 1985). The fuel consumption factors for the contiguous states recently obtained by EC/R (2003) based on the WRAP fuel loading factors and fuel classification map are considerably smaller than those in Table 1 for the western states. Fire emission estimates using the new fuel consumption factors (figure not shown) display a pattern generally similar to what is seen in Fig. 3, but the wildfire emission center is shifted from the Pacific Northwest to Pacific Southwest with a smaller magnitude.

The prescribed fire (flaming fire) emission factors in Battye and Battye (2002) are 16.1, 18.9, and 165 lb ton^{-1} for $PM_{2.5}$, PM_{10}, and CO (independent of geographic regions), which are smaller than the corresponding ones in Table 2. Hao et al. (2002) derived prescribed fire emission factors of 7.9–34.5, and 99–264 lb ton^{-1} for $PM_{2.5}$ and CO from a 1996 field study in the SE US in 1996, that demonstrated the wide range in the amount of pollutant produced.

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