9 Estimates of Wildland Fire Emissions

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Abstract Wildland fire missions can significantly affect regional and global air quality, radiation, climate, and the carbon cycle. A fundamental and yet challenging prerequisite to understanding the environmental effects is to accurately estimate fire emissions. This chapter describes and analyzes fire emission calculations. Various techniques (field measurements, empirical relations, modeling, and remote sensing) to obtain fuel and fire properties are first reviewed. A calculation of fire emissions across the continental U.S. is then illustrated. In this calculation, an approach recently developed based on high-resolution fuel types from satellite remote sensing is used for fuel loading factors. The burning information is obtained from a historical fire dataset collected by multiple U.S. governmental agencies. The U.S. fire emissions show large spatial and temporal variability. Finally, uncertainties in fire emission estimates are examined by comparing with another method using the traditional AP-42 Table approach for fuel loading. Emissions with the satellite remote sensing approach are mostly reduced in the western U.S., but increased in the eastern coastal regions. A perspective on future fire emission research is given.

Keywords Wildland fire, emission calculation, emission factors, fuel loading, U.S. fire emission results and analyses

9.1 Introduction

Wildlfire is one of the major natural disasters in the United States that threaten human life and property. Millions of acres of forest and other ecosystems are

burned annually. In 2000, for example, more than 100 thousand fires consumed 8.4 million acres (3.4 million ha) (NIFC, 2002). Nearly 30 thousand people were involved in wildland firefighting efforts, costing the federal agency fire suppression about $1.4 billion. Prescribed burning, on the other hand, 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. The areas burned by prescribed fires have the same order as those by wildfires (Stanturf et al., 2002).

Emissions from wildland fires can cause severe environmental consequences. Fires release large amount of particulate matter (PM) and ozone precursors, adversely affecting regional air quality (Sandberg et al., 1999; Riebau and Fox, 2001). PM and ozone, as well as some other trace gas emissions, are criteria air pollutants subject to the national ambient air quality standards (NAAQS) established by the U.S. Environmental Protection Agency (EPA, 2003a). EPA recently established air quality standards for $PM_{2.5}$ (PM with a diameter of 2.5 μm or smaller) and revised standards for ground-level O_3 and PM_{10} (PM with a diameter of 10 μm or smaller) as an effort to reduce regional haze and smog and to improve visibility. EPA also 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.

Smoke particles are one of the atmospheric aerosol sources, which can affect global and regional radiation (e.g., Penner et al., 1992). They can modify earth radiation balance by scattering and absorbing solar radiation (direct radiative forcing) (Charlson et al., 1992), and by changing droplet size and life time of clouds, which are one of the most important factors for atmospheric radiative transfers (indirect radiative forcing) (Twomey et al., 1984). The radiative forcing can further change regional climate, monsoon, and drought (Hansen et al., 1997; Ackerman et al., 2000; Menon et al., 2002; Koren et al., 2004; Liu, 2005a and b).

Fires also affect the carbon cycles. Carbon emissions due to fire increase atmospheric CO_2 concentration. The perturbation of atmospheric chemistry induced by biomass burning is comparable in magnitude to the effect of fossil fuel burning (Lindesay et al., 1996). The 1997 Indonesia Fires emitted as much carbon into the atmosphere as Europe's annual carbon emissions from burning fossil fuel (Page et al., 2002). Thus, biomass burning is an important source for regional atmospheric carbon. On the other hand, fires affect the ecosystem uptake of atmospheric carbon. Biomass accumulates by consuming atmospheric carbon through photosynthetic reaction. The terrestrial ecosystem, therefore, acts as a sink of atmospheric carbon during this process. Fire disturbance will alter the magnitude of this sink.

A fundamental and yet challenging prerequisite to understanding the environmental effects of smoke is to accurately estimate fire emissions. Fire emissions can be

calculated using fire and fuel properties such as area burned, fuel loading or consumption factors, and emission factors. Various techniques for calculating these properties have been developed. This Chapter describes calculation and analysis of fire emissions. Fire emission calculation formula and techniques for obtaining fuel and fire properties are reviewed in Section 9.2. A calculation of fire emission in the continental U.S. is presented in Section 9.3. Uncertainty in fire emission estimates is discussed in Section 9.4. Summary and a perspective on future fire emission research are given in Section 9.5.

9.2 Fire Emission Calculation

As indicated in the following formula (Seiler and Crutzen, 1980),

$$E = A\,f\,L\,S \tag{9.1}$$

fire emission E (in mass) is determined by four fuel and fire properties: area burned A, consumption efficiency f (fraction of fuel consumed), fuel loading L (mass of forest fuel per unit area), and emission factor S (mass of the species per unit mass of forest fuel consumed). The product of f and L is also called effective fuel consumption or fuel loading factor (mass of forest fuel per unit area burned). These properties can be obtained using the techniques briefly described below.

9.2.1 Measurements

Burned area has been traditionally obtained from ground measurement and reporting systems. There are a number of regional and national datasets available, in the format of either individual burnings or total burnings of a county or state. The examples are the nation-wide prescribed fires in 1989 (Peterson and Ward, 1993; Ward et al., 1993), wildfires over 11 Western states (Hardy et al., 1998), the data used for developing the EPA the national emission inventory (NEI) for three base years of 1996, 1999, and 2002 (EPA, 2003a), and the federal fire historic dataset (BLM, 2003). The dataset developed by the department of interior bureau of land management (BLM) collects individual fires over the lands owned by five U.S. federal agencies (BLM, Bureau of Indian Affairs, Fish and Wildlife Service, National Park Service, and USDA Forest Service). Besides area burned, this dataset also includes fire information on number, date, location, type, and causes. Figure 9.1 shows wildfire burned areas in each of the contiguous U.S. states.

9.2.2 Empirical relations

Empirical relations have been used extensively to obtain fire emission factors and

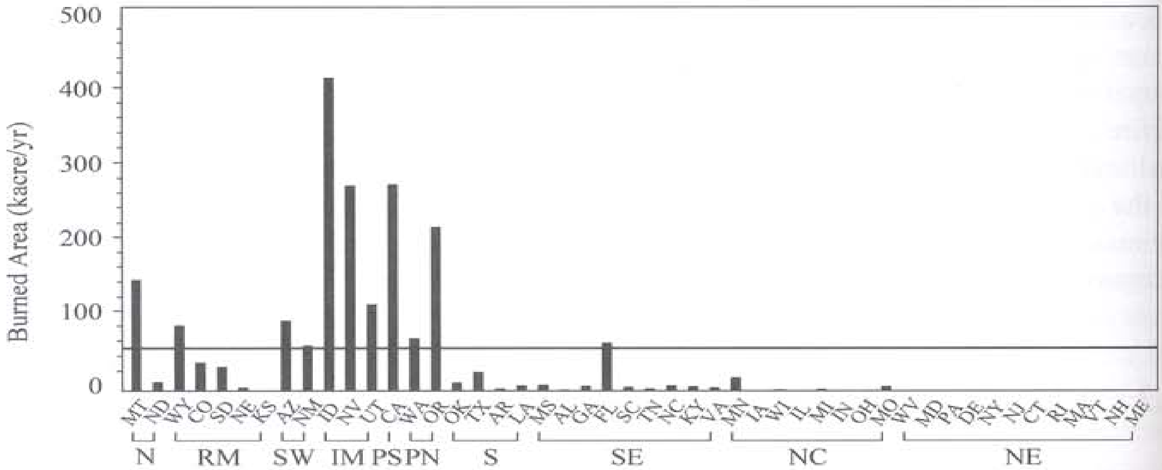

Figure 9.1 Annual burned area by wildfires in the contiguous U.S. states during 1980 – 2002. The horizontal line represents the average over all states. Below the state names are forest service regions (see Fig. 9.2) (redrawn from Fig. 1 in Liu, 2004)

fuel consumption factors. EPA (1995) has formed a table of default values (AP-42 Table) for emission factors of major species. Emission factors in Table 9.1 are adopted from the AP-42 Table for all species except CO_2, which is derived based on the flaming fire emission factor (Battye and Battye, 2002, Table 39) and Hao et al. (2002). The emission factors are geographically independent. Fuel loading factors for the USDA forest service regions (Fig. 9.2) from the AP-42 Table are listed in Table 9.2.

Table 9.1 Emission factor (lbs/ton)

Component	$PM_{2.5}$	PM_{10}	CO	SO_2	NO_x	VOC	CO_2
Factor	11.7	13.0	140.0	0.15	4.0	19.2	3,500.0

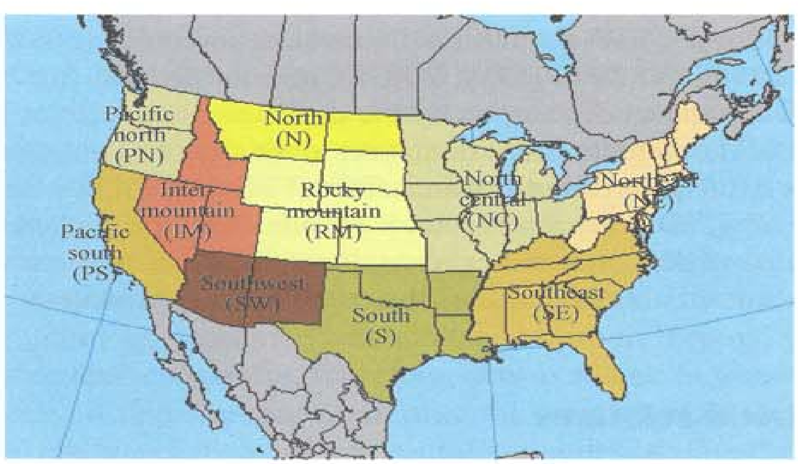

Figure 9.2 The USDA forest service regions (old division)

An effort was recently made to improve the traditionally used AP-42 fuel loading factors. The Western regional air partnership (WRAP, 2002) developed an approach to estimate fuel loading and consumption using the national fire danger rating system (NFDRS) (Cohen and Deeming, 1985) vegetation types for the WRAP states. This approach was extended by EPA (2003b) to the reminder of the contiguous U.S. using the 1999 NFDRS fuel classification map at 1 km resolution derived from a combination of satellite and ground data (Burgen et al., 1998). The state accumulated values from the RS approach are also listed in Table 9.2.

Table 9.2 Fuel loading factor L (ton/acre)

Remote sensing approach		AP-42		Remote sensing approach		AP-42	
State	L	Region*	L	State	L	Region	L
MT	4.7	N	60	TN	4.3		
ND	0.5			NC	9.6		
WY	5.0	RM	30	KY	3.3		
CO	12.6			VA	7.7		
SD	1.3			MN	13.6	NC	11
NE	1.1			IA	2.8		
KS	1.0			WI	7.4		
AZ	17.7	SW	10	IL	3.1		
NM	14.1			MI	10.1		
ID	8.1	IM	8	IN	2.4		
NV	3.0			OH	3.0		
UT	9.6			MO	2.7		
CA	15.5	PS	18	WV	4.8	NE	11
WA	2.6	PN	60	MD	5.4		
OR	12.5			PA	3.3		
OK	2.7	S	9	DE	7.7		
TX	3.5			NY	20.3		
AR	10.1			NJ	11.6		
LA	9.1			CT	3.1		
MS	9.7	SE	9	RI	3.1		
AL	10.1			MA	24.0		
GA	13.2			VT	51.3		
FL	19.7			NH	33.4		
SC	9.6			ME	27.8		

*See Fig. 9.2 for various regions

9.2.3 Modeling

Numerous fuel models have been developed. Fuel types in NFDRS are represented by 20 fuel models, each of which falls into one of four groups that account for fuels composed mainly of grass, shrub, timber, or slash. In consume, a comprehensive fuel model (Ottmar et al., 1993), separate algorithms are used to calculate consumption of different fuels based on fuel loading, slope, wind, and fuel moisture. In the FCCS (Sandberg et al., 2001), live and dead fuel loadings for 16 types of fuels across 6 layers, from canopy to duff, for 150 fuelbed types defined for the continental U.S. are quantified. The system calculates available fuel potential index between 0 – 9 for each FCCS National or customized fuelbed and provides available consumption of fuels. The fire emissions production simulator (FEPS) is developed to calculate fuel consumption efficiency (PNW, 2005). The FEPS model is run for each of the NFDRS fuel models and for each of the six fuel moisture classes in the model. For each of these combinations the model is used to estimate a unique fuel consumption.

Fire emissions can be simulated using modeling tools such as emission production model (EPM) (Sandberg et al., 1984), first order fire effects model (FOFEM) (Reinhardt et al., 1997), and community smoke emissions modeling (CSEM) (Barna and Fox, 2003). In the recently upgraded version of EPM, FEPS (Anderson et al., 2004), fuel loading, fuel moisture, meteorological conditions, and other parameters are used to obtain hourly fire emissions as well fuel consumption, heat release and plume rise. CSEM, specifically designed to provide historical fire emission estimates for use in air quality models, uses consume and EPM and national GIS coverage for developing a fire inventory, locations, time and size.

A comprehensive modeling tool, BlueSky (O'Neill et al., 2003), was developed as a framework for fire emission and air quality effect simulation and prediction. Regional forecast of smoke concentrations is made using burn information from state and federal agency burn reporting systems, and meteorology, fuel consumption, emission, and dispersion and trajectory models. The southern high-resolution modeling consortium southern smoke simulation system (SHRMC-4S) (Achtemeier et al., 2003) is similar to bluesky but more specifically for prescribed burning in the south. It uses the sparse matrix operator kernel emissions modeling system (SMOKE) (Houyoux et al., 2002) for processing emission data and providing initial and boundary chemical conditions, and the community multiscale air quality (CMAQ) (Byun and Ching, 1999) model for chemical modeling. A unique feature with SHRMC-4S is that it includes a dynamical model (daysmoke) (Achtemeier, 1998) to calcualte smoke plume rise. Figure 9.3 shows a simulation result of SHRMC-4S.

9.2.4 Remote Sensing

Satellite remote sensing (RS) has emerged as a useful technique for fire detection in the past decade. With the unique features of global coverage, high-resolution,

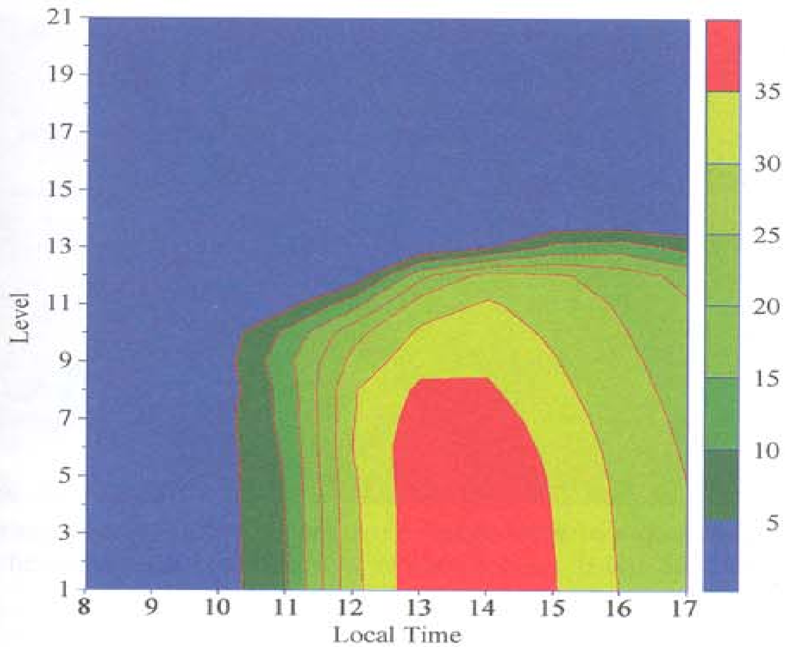

Figure 9.3 Time-height section of $PM_{2.5}$ concentration ($\mu g \cdot m^{-3}$) from prescribed fire emissions in Florida simulated with SHRMC-4S. The horizontal and vertical coordinates represent hour (local time) and height in level (from Liu et al., 2006)

and continuous operation, RS is able to obtain detailed information of fuel type and loading, fire occurrence, extent, structure, and temporal variation (Riebau and Qu, 2004; Qu et al., 2003 and 2005). Satellite instruments such as the advanced very high resolution radiometer (AVHRR) (Kaufman et al., 1990; Justice et al., 1996; Li et al., 1997; Burgan et al., 1998), the geostationary operational environmental satellite (GOES) (Prins and Menzel, 1990), and the moderate resolution imaging spectroradiometer (MODIS) (Kaufman et al., 1998; Justice et al., 2002) have been applied to field experiments and routine monitoring of fuels and wildfires.

AVHRR has daily data over two decades. Algorithms for detecting active fires and mapping burned area (Fraser et al., 2000) have been developed and validated for the fires in North America (Li et al., 2003). With more spectral bands and higher spatial resolution, MODIS measurements can be used to retrieve fire information more accurately (Kaufman et al., 2003). The MODIS rapid response system (MRRS) was recently developed to provide rapid access to MODIS data globally with initial emphasis on 250 m color composite imagery and active fire data. MODIS was found to be able to detect small and cool fires in the South more robustly and accurately (Wang et al., 2005). The Hazard Mapping System (HMS) (NOAA, 2006) was developed to manually integrate data from various automated fire detection algorithms with GOES, AVHRR, MODIS and defense meteorological satellite program/operational linescan system (DMSP/OLS) images. It produces a quality controlled display of the locations of fires and significant smoke plumes detected by meteorological satellites for air quality forecast. Figure 9.4 shows an example of MODIS detection of wildland fires.

Figure 9.4 An example of True-color composite MODIS GeoTiff data (Bands 1, 4 and 3) of the Flathead and Bitterroot Valleys in Montana. Image acquired August 19, 2003 (from Quayle et al., 2003)

In spite of not being a parameter in the formula for fire emissions, fuel moisture is an important property for estimating fuel consumption and fire emissions. Forest fuel consists of live and dead vegetation. Meteorological measurements are traditionally used to estimate fuel moisture. The NFDRS monitors fuel moisture of live vegetation for shrub ecosystem using the normalized difference vegetation index (NDVI) and calculates dead fuel moisture with air temperature, humidity, and cloudiness. The Canadian forest fire danger rating system (CFFDRS) calculates live and dead fuel moisture using various algorithms basically based on meteorological measurements. The limitations with the traditional technique include relatively small spatial resolution of observations, unavailability over part of forest regions, and uncertainties in the relationship between meteorological data and fuel moisture. RS technique has been demonstrated as an efficient means to supplement field measurements for monitoring live fuel moisture, especially in locations not readily accessible by forest rangers. In addition to covering extensive regions, RS also provides values closely related to forest vegetation status such as NDVI and Surface Temperature. Thus, RS data can be directly used to estimate fuel moisture (Chuvieco et al., 1999).

9.3 U.S. Fire Emissions

9.3.1 Parameter Specifications

This section describes a calculation of the U.S. fire emissions. The BLM fire dataset (BLM, 2003) is used. The data used are monthly total acres burned by wildfires

for each of the 48 contiguous states during 1980 – 2002. The areas burned by wildfires were about 41,000 acres per year averaged over the contiguous U.S. states (Fig. 9.1). Large emissions occurred in the Western states. Idaho, California, Nevada, Oregon, Montana and Utah had burning areas over hundreds of thousands of acres. Florida was the only state in the East with the emission reaching the national average. A detailed description of the fire statistics is given in Liu (2004). Emission factors are adopted from Table 9.1. Fuel loading factors are adopted from the values for RS approach in Table 9.2.

9.3.2 Spatial Distribution

Figure 9.5 shows geographic distribution of $PM_{2.5}$ emissions from wildfires expressed as emission intensity ($kg \cdot km^{-2}$). Large emissions are found in the West.

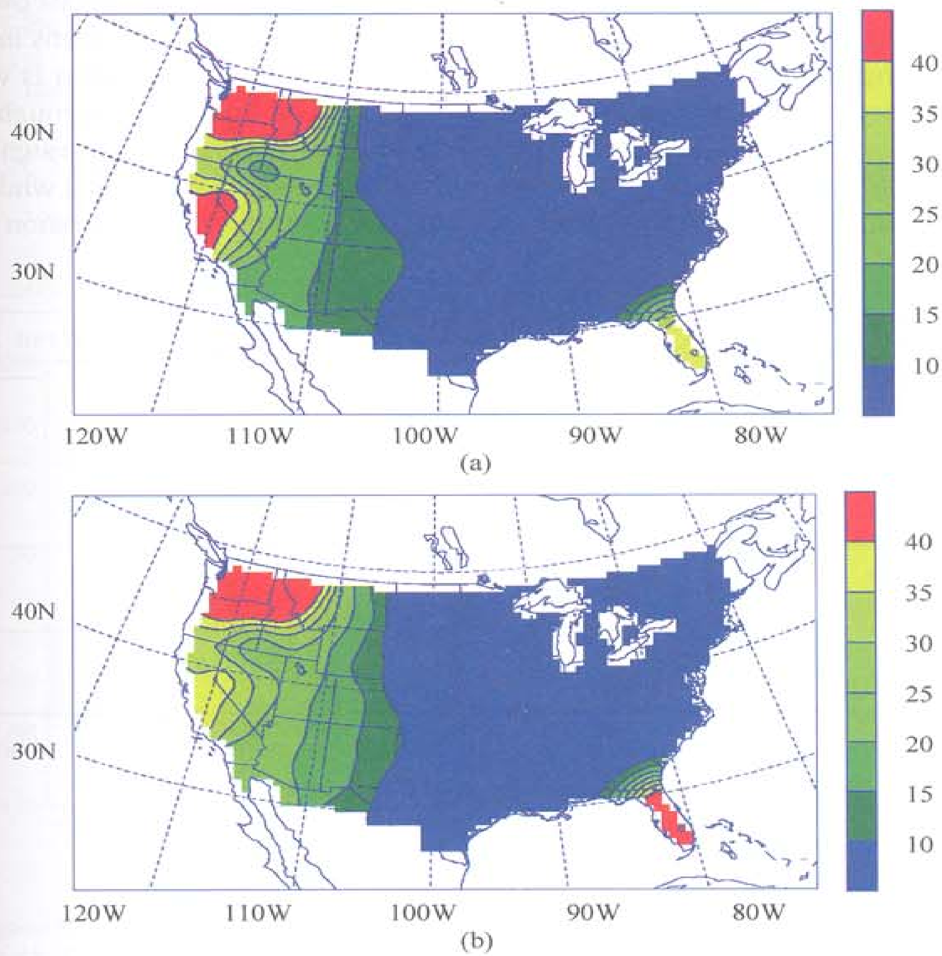

Figure 9.5 Spatial distribution of annual wildfire emissions of $PM_{2.5}$ ($kg \cdot km^{-2}$) (a) and standard deviation (b)

Two centers with a magnitude of over 40 kg·km^{-2} are located in Pacific South and Pacific North, respectively. Emissions gradually decrease to below 10 kg·km^{-2} east of the Rocky Mountains. Emissions, however, have a center in Florida with a magnitude of about 35 kg·km^{-2}. Emissions decrease rapidly to less than 10 kg·km^{-2} in the surrounding states. Standard deviation of annual emission series has the same magnitude as the average in most states, indicating large inter-annual variability. As shown in Liu (2004), wildfire emissions are characterized by a number of strong emission events and a relatively quiet episode up to a decade long between two strong emission events.

9.3.3 Seasonal Distribution

Figure 9.6 shows total annual emissions of $PM_{2.5}$ of each state and each season. In the West, California, Idaho and Oregon have the emissions around 15,000 tons, a majority of which is during summer. In the East, Florida has the emissions over 5,000 tons. Different from the West, a substantial portion of wildfire emissions in Florida and many other southern states occurs during spring, when the weather is warming up but not very moist yet. The emissions of PM_{10}, VOC and NO_x are roughly comparable to those of $PM_{2.5}$, while the emissions of other components are significantly different. CO and CO_2 are about one and two orders larger, respectively, while SO_2 is about two orders smaller. They reflect the differences in the AP-42 emission factors.

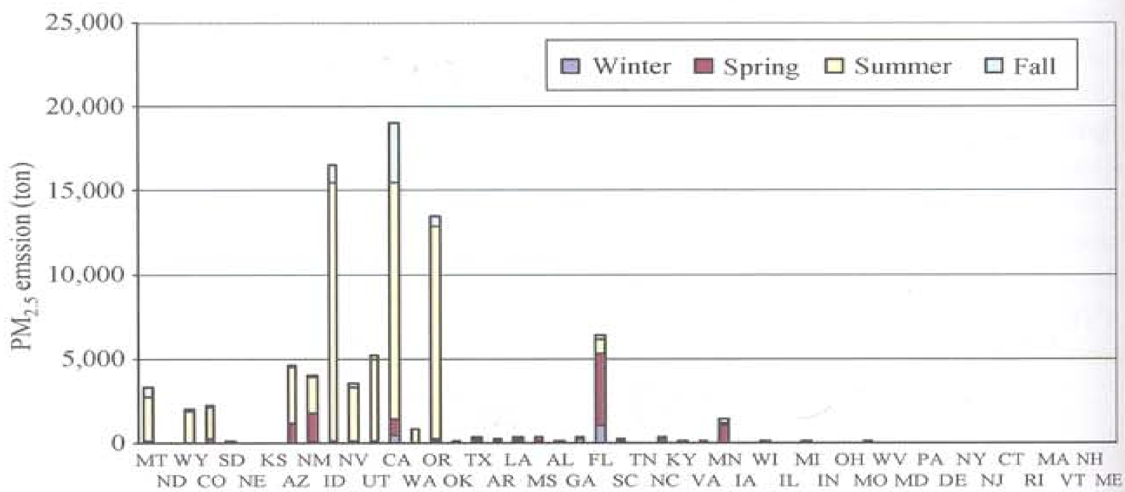

Figure 9.6 Wildfire emissions of $PM_{2.5}$ by state and season

9.4 Uncertainties

Substantial differences in fire emissions are found between the RS and AP-42 Table approaches for fuel loading factors. In general, wildfire emissions from the

RS approach are smaller in the west and larger in Florida than those from the AP-42 Table approach. A quantitative comparison is shown in Fig. 9.7 using the ratio of the difference in emission between the RS and AP-42 Table approaches to emission from the AP-42 Table approach. Remarkable changes ranging from -100%~450% are obtained. The changes display certain geographic patterns. The RS approach leads to overall reduced emissions in the regions from the Pacific coast to Midwest except Southwest. In contrast, overall increased emissions are found in Southeast and Northeast. The largest increase of 200% or more is found in a number of New England states due to the extremely small

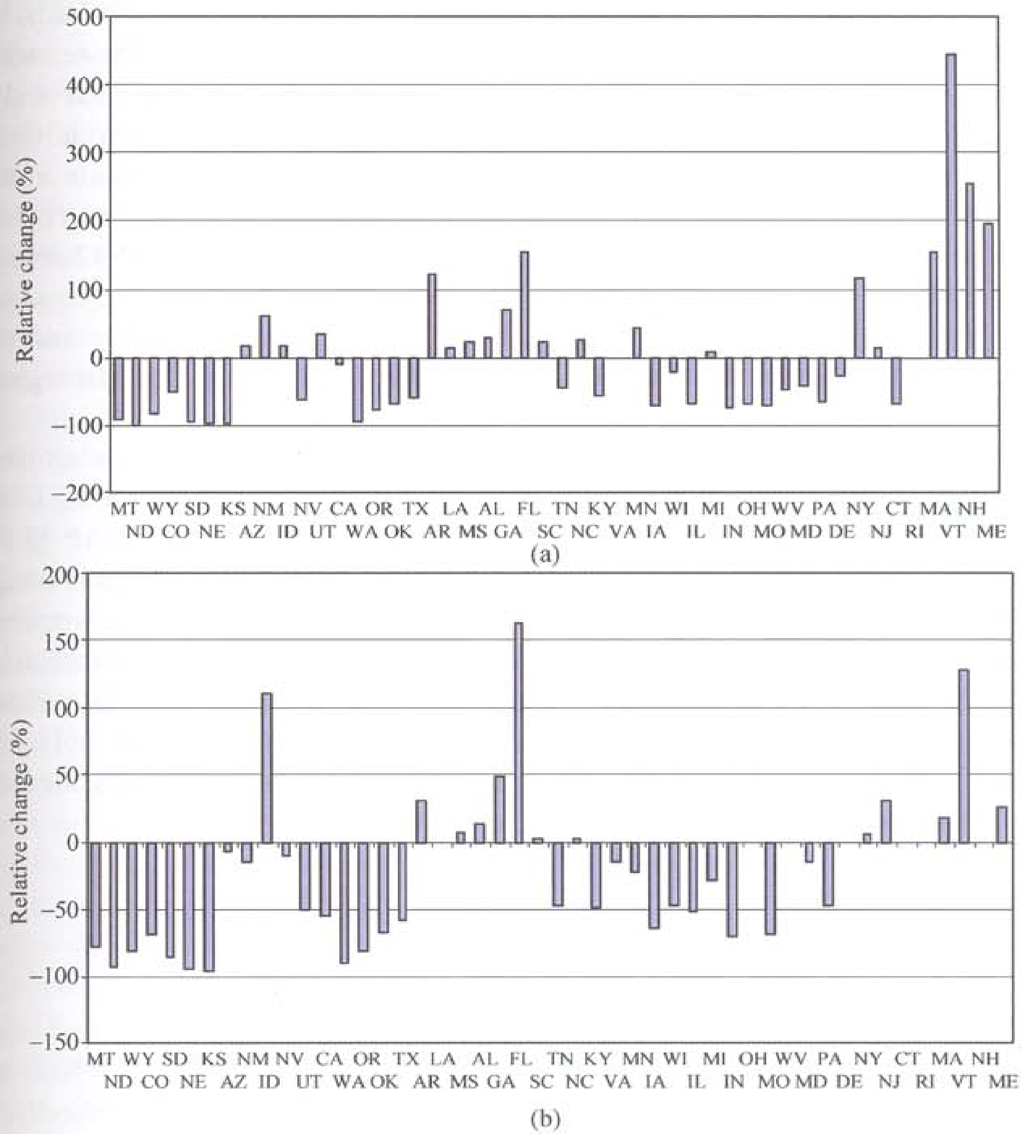

Figure 9.7 Ratio of the difference in fire emissions between RS technique and AP-42 Table to the emission estimated using AP-42 Table for wildfire (a) and prescribed fires (b)

amounts of emission in these states. Among the states with large emissions, the most significant changes happens in Oregon and Florida, where emissions are reduced by about 80% and increased by about 160%, respectively. Changes in California and Idaho are less than 20% in magnitude.

Besides wildfires, fuel loading factors for prescribed burning have also been developed using satellite remote sensed fuel types and loading and consumption of individual fuel types (EPA, 2003b). In Florida, a state with the most extensive prescribed burning in the nation, for example, fuel loading factor is increased from 9 ton/acre in the AP-42 Table to 19.7 ton/acre estimated by the RS approach for wildfire, comparing from 7.1 – 17.2 ton/acre for prescribed burning.

Most fire emission inventories, including fire emissions in the EPA NEIs, have been developed using the AP-42 Table default fuel loading factors. The remarkable changes in the magnitude of fire emissions between this approach and RS approach, including in some states with large fire emissions such as Oregon and Florida, suggest a large uncertainty in estimating fire emissions in these inventories. The result that the fire emissions are reduced in most Westerns states and increased in most Eastern states with RS approach than the AP-42 approach would lead to a reduced geographic contrast between the two regions. Especially, it suggests larger importance of prescribed burning for air quality and other smoke-related environmental issues in the Southeast, which is a major region of such burning.

The changes in fire emission estimates can have some important implications for the environmental effects of wildland fires. A recent modeling study using CMAQ model (Byun and Ching, 1999) with fire emissions estimated using the AP-42 Table fuel loading factors indicated significant impacts of Florida prescribed burning on regional air quality (Liu et al., 2004). The impacts could more serious considering that emissions are about 1.6 times larger if using the RS approach. In addition, a simulation study with a regional climate model indicated the role of wildfires in enhancing drought with emissions estimated using the AP-42 Table fuel loading factors (Liu, 2005b). A better understanding of the role could be achieved by using the RS approach for fuel loading factors.

9.5 Summary and Perspective

Fire emissions are determined by area burned, consumption efficiency, fuel loading, and emission factor. The ground measurement and recording systems have been traditionally used to obtain burned area and fuel loading information. Satellite RS, a new technique developed rapidly in the past decade, is able to provide high-resolution fire and fuel properties. Actual fuel consumption and fire emissions can be determined using modeling and empirical relations.

The U.S. fire emissions estimated using the fuel loading factors recently developed

based on satellite RS and ground measurements are found large in Pacific South and Pacific North. A majority of fire emissions occur during summer. In addition, there is an emission center in Florida, which is the largest during spring. There are significant differences in wildfire emissions between the RS and AP-42 Table approaches for fuel loading factors. In general, fire emissions are reduced in the Western U.S. except the Southwest, and increased in the Eastern coastal regions by using the RS approach. The magnitude is up to about 80% in the major Western emission regions and 160 % in the Eastern ones.

It appears that the RS approach is able to detect high resolution properties of fuel type and consumption and therefore is useful for understanding more spatial details of wildfire emissions. The EPA Regional Planning Organizations, for example, has recently decided to re-calculate wildfire emissions in the 2002 NEI using the RS approach (WRAP, 2005).

The following studies in the future are critical to improving our understanding of fire emissions and their environmental effects:

(1) Wildfire data is a key to analyzing fire regimes and the spatial and temporal variability. Continuous efforts are needed to develop historical datasets, and improve the capacity to obtain real or near real time fire information. Some existing datasets such as the one developed by BLM (2003) only include burns occurred on the 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 South. Expansions to these datasets will make them more valuable.

(2) The lack in systematic prescribed burning information, especially real time burning information, has been one of the major limitations in estimating fire emissions and environmental consequences. The efforts in developing automated reporting systems will provide a capacity in obtaining such information.

(3) More and more RS applications are expected for fire and fuel detection. Further algorithm development and evaluation are needed to solve some technical issues such as false fire signals and cloud interference. The development of the capacity in detecting prescribed fires is of great value. So is the capacity in measuring atmospheric concentrations of fire emissions.

(4) Fuel and fire properties are under constant disturbances from natural processes. Hurricanes, for example, can increase dead fuel loading, which in turn increases wildfire risks. More studies are needed to understand fuel and fire variations in response to environmental forcing.

(5) Decision making support systems are a useful tool for fire and land managers to understand and predict the effects of fire emissions on air quality, radiation, climate, the carbon cycle, and other environmental processes, and to plan and implement plans to migrate possible diverse consequences. Bridging between measurements and monitoring techniques (e.g., satellite RS) and modeling techniques (e.g., fuel, climate, ecosystem, and air quality models) is critical for the development of the systems.

Acknowledgements

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