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Chapter 7

Effects of Forest Fires on Visibility and Air Quality

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Abstract

The U.S. Clean Air Act establishes the goal of preventing future and remedying existing visibility impairment in 156 Class I areas (national parks, wilderness areas, and wildlife refuges). A key element in implementing this goal is the Regional Haze Regulation (RHR). RHR is based on relating impaired visibility, using metrics of extinction (inverse megameters and/or "deciviews"), to concentration of ambient particulate matter (PM), especially the chemical components of particulates smaller than 2.5 μm in diameter, collectively known as $PM_{2.5}$. $PM_{2.5}$ itself is also subject to national ambient air quality standards. Forest, rangeland, and agricultural fires, both natural and human caused emit both primary and secondary (formed in the atmosphere from gaseous organic carbon (OC) emissions) $PM_{2.5}$. This chapter will review the RHR and what we know about relationships between fire emissions, their fate in the atmosphere, and their contribution to regional haze and $PM_{2.5}$.

7.1. Introduction

Since the implementation of the Clean Air Act in 1977, the United States has been using visibility in selected special federally managed rural areas—national parks, wilderness and wildlife reserves, designated as Class I areas—as a measure of air quality. In fact, the Act establishes a national goal of the "… prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I federal areas in which impairment results from manmade air pollution." This goal, while simply stated, has proven difficult to quantify and to accomplish.

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(For further explanation see: http://vista.cira.colostate.edu/improve/Overview/hazeRegsOverview_files/frame.htm.)

In response, the U.S. Environmental Protection Agency (EPA) has promulgated a Regional Haze Program, providing States the responsibility to develop plans to reduce visibility impairment at federal Class I areas in their state. (http://www.epa.gov/ttn/oarpg/t1/fact_sheets/rh_girhp_fs.pdf). The Regional Haze Program has established a Regional Haze Regulation (RHR) stating that the appropriate measure of visibility is the haze index: a measure of visibility derived from calculated light extinction measurements that is designed so that uniform changes in the haze index correspond to uniform incremental changes in visual perception, across the entire range of conditions from pristine to highly impaired. The haze index (HI) is calculated in units of deciviews (dv) directly from the total light extinction (b_{ext} expressed in inverse megameters (Mm^{-1})] as follows (http://vista.cira.colostate.edu/IMPROVE):

$$\mathrm{HI} = 10\ \ln\,(b_{\mathrm{ext}}/10)$$

In turn light extinction, b_{ext}, is caused by light being absorbed and scattered by both gases and aerosol particles. Atmospheric scattering by the gases and particles present in clean air is called Rayleigh scattering and is been assumed to have a constant value of $10\,\mathrm{Mm}^{-1}$ by the RHP. Atmospheric gases absorb light, primarily by nitrogen dioxide, which is negligible in rural settings. Most atmospheric absorption is done by aerosols, primarily by their "elemental" carbon (EC or also called black carbon) component. Atmospheric scattering done by aerosols is complex. In the RHP, aerosol scattering is approximated by relating it to the concentrations of aerosol particles smaller than 2.5 μm in diameter ($\mathrm{PM}_{2.5}$) because these particles are most effective in scattering visible light. $\mathrm{PM}_{2.5}$ mostly consists of ammonium sulfate, ammonium nitrate, organic carbon (OC), EC, soil, and the total mass of "coarse" particles (those between 2.5 and 10 μm, $\mathrm{PM}_{2.5-10}$). There are also effects of ambient humidity that must be included in this relationship because many of the aerosols, especially sulfates, are hygroscopic and scatter more light at higher humidity.

In the next section of this chapter, we will discuss the Clean Air Act and the Regional Haze Program. The third section will discuss how pollution is related to visibility degradation including how it is monitored by the IMPROVE network (Interagency Monitoring of PROtected Visual Environments). The fourth section will address the current understanding of contributions from various fire sources to U.S. regional visibility and specifically to $\mathrm{PM}_{2.5}$ aerosol concentrations, especially the OC component of those aerosols. Developing an emissions inventory (EI) and some of the modeling steps needed to utilize the EI in a regional modeling context are discussed. The fifth section addresses the state of knowledge in assessing fire impacts on regional visibility and briefly reviews results to date from a variety of modeling efforts, including both source apportionment modeling and simulation modeling. The final section briefly reviews ongoing research needed in this area recommending next steps.

7.2. The U.S. Clean Air Act and regional haze regulations

The Clean Air Act authorizes regulations to protect visibility in Class I areas, specifically 156 federal wilderness and national park locations. The law and regulations require that all States and tribes:

- Develop implementation plans to achieve RHR goals by limiting emissions of visibility degrading aerosols (and their chemical precursors) from sources that contribute to impaired visibility at each of the 156 designated Class I areas.
- Formalize for each area where open burning is anticipated to make a significant contribution to air quality, a formal Smoke Management Program.

The regulations are based on data taken from the IMPROVE monitoring network. Since forest fire smoke is recognized as a significant contributor to regional haze but one that is different from other pollution sources (e.g., industrial and transportation activities), the States are also mandated in the regulations to implement Smoke Management Programs. The regulations specifically require States to identify for each Class I area the natural background for visibility and the mean of the 20% haziest and 20% cleanest days (based on a 5-year average), and to establish a program of emissions limitations to reduce the haziest days to natural background conditions (whilst not reducing the cleanest days) over the next half century, measuring progress in 10-year increments.

Natural background is a complex determination, but it is specifically identified in the regulations to be reflective of contemporary conditions and land use patterns (not historical or pre-European conditions); a long-term average condition analogous to the 5-year average best-and worst-day conditions that are tracked under the regional haze program; and estimated for each Class I area in the absence of human-caused impairment.

Specifically, the RHR require that natural background be developed as follows:

> derive regional estimates of natural visibility conditions by using estimates of natural levels of visibility-impairing pollutants in conjunction with the IMPROVE

> methodology for calculating light extinction from measurements of the five main components of fine particle mass (sulfate, nitrate, organic carbon, elemental carbon, and crustal material). (EPA Regional Haze Regulations 40 CFR 51.300-309.)

Default values of each of these components have already been established for the eastern and the western United States in the literature (Trijonis et al., 1990).

The EPA recommends natural background be determined by using default values for each of the aerosol components in the IMPROVE equation. The recommendation for OC mass (in micrograms per cubic meter) is 1.4 in the east and 0.47 in the west. Higher values in the east reflect hydrocarbon emissions from trees that can generate secondary organic aerosol (SOA).

EPA guidance also allows States to develop a refined approach essentially allowing different aerosol component values that the state can show more appropriately represent natural conditions. For example, this might include adding OC contributions from such an infrequent natural event as a wildfire, as long as the state can appropriately document the frequency and magnitude of its visibility impact (i.e., its contribution to OC and other aerosol components).

7.3. Relating pollution to visibility

The IMPROVE equation has been developed over a period of years based on radiation theory and empirical measurements from the IMPROVE network. The relationship that has been applied until 2006 is:

$$\begin{aligned} b_{\mathrm{ext}} = {} & (e_{\mathrm{sf}})f_{\mathrm{s}}(\mathrm{RH})[(\mathrm{NH_4})_2\mathrm{SO_4}] + (e_{\mathrm{nf}})f_{\mathrm{n}}(\mathrm{RH})[\mathrm{NH_4NO_3}] \\ & + (e_{\mathrm{ocmf}})f_{\mathrm{ocm}}(\mathrm{RH})[\mathrm{OMC}] + (e_{\mathrm{soilf}})[\mathrm{SOIL}] \\ & (e_{\mathrm{c}})[\mathrm{Coarse\ Mass}] + (e_{\mathrm{lacf}})[\mathrm{lacf}] \end{aligned}$$

where: b_{ext} is the extinction coefficient, e the extinction efficiencies, $f(\mathrm{RH})$ a relative humidity enhancement factor (bwet(RH)/bdry), [- - - -] the concentrations of species (24-hr averages), OMC the 1.4 × measured carbon mass, and lacf the light absorbing fraction of the aerosol or black carbon.

The IMPROVE network monitoring program measures mass concentrations of major aerosol species using filter-based measurement technologies. Estimates of extinction are made using this IMROVE equation. Dry mass scattering efficiencies are based on Trijonis et al. (1990). The $f(\mathrm{RH})$ function represents the ability of the chemical aerosol in question to take up water, thus increasing its ability to scatter light.

Recently, Hand and Malm (2005) have reviewed and suggested slight alterations to the IMPROVE equation. The revised equation is:

$$\begin{aligned}b_{\text{ext}} = {} & 2.2 \times f_{\text{S}}(\text{RH}) \times [\text{small sulfate}] + 4.8 \times f_{\text{L}}(\text{RH}) \times [\text{large sulfate}] \\ & + 2.4 \times f_{\text{S}}(\text{RH}) \times [\text{small nitrate}] + 5.1 \times f_{\text{L}}(\text{RH}) \times [\text{large nitrate}] \\ & + 2.8 \times [\text{small organic mass}] + 6.1 \times [\text{large organic mass}] \\ & + 10 \times [\text{elemental carbon}] + [\text{fine soil}] + 1.7 \times f_{\text{SS}}(\text{RH}) \times [\text{sea salt}] \\ & + 0.6 \times [\text{coarse mass}] + \text{Rayleigh scattering (site-specific)} \\ & + 0.33 \times [\text{NO}_2 \text{ (ppb)}]\end{aligned}$$

where,

$$[\text{large sulfate}] = ([\text{total sulfate}]/20\ \mu\text{g m}^{-3}) \times [\text{total sulfate}], \quad \text{for } [\text{total sulfate}] < 20\ \mu\ \text{gm}^{-3}.$$

$$[\text{large sulfate}] = [\text{total sulfate}], \ \text{for } [\text{total sulfate}] \geq 20\ \mu\text{g m}^{-3}$$

$$[\text{small sulfate}] = [\text{total sulfate}] - [\text{large sulfate}]$$

Currently, there are 165 sites around the U.S. where parameters for the IMPROVE equation are measured. At some of these sites there are also direct measurement of extinction and scattering to assure the validity of the aerosol component values and their relationship to visibility.

Figure 7.1 presents IMPROVE monitoring network results for the western United States, based on the original IMPROVE equation being used to estimate the worst 20% visibility days measured between 2000 and 2004, the baseline period for the RHRs.

7.4. How does fire contribute to regional visibility and aerosol loading?

Fire contributes to visibility in two fundamental ways: through direct emission of fine organic particles (PM2.5 emissions) and through gaseous emissions of organic hydrocarbons which in turn form SOA in the atmosphere.

In order to quantify the contributions of forest fire to regional air quality, the first step is to develop a fire EI. For retrospective analyses, since it varies much from year to year, the EI must be generated for a specified period of time (e.g., for 2002.) For real-time analyses or forecasts, the EI requires continuing input or a model forecast of fire activity and resulting emissions. Fire EIs are not trivial to develop; they

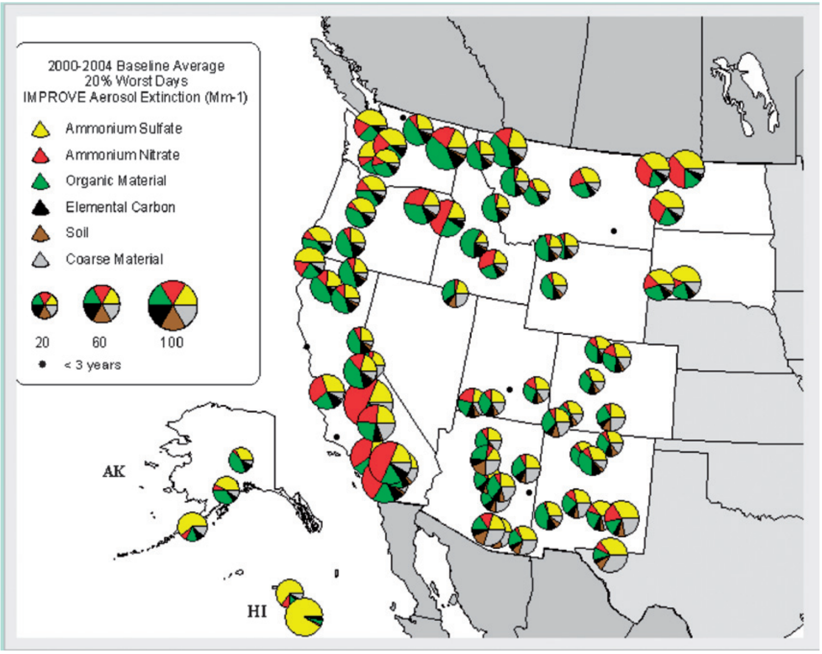


Figure 7.1. IMPROVE results for the Regional Haze Rule baseline period, 2000–2004. (http://vista.cira.colostate.edu/TSS/LinkBrowser/LinkBrowser.aspx?action = baseline)

require large data sets and complex analysis. Quality assurance of such large efforts is always a concern as well.

To create either type of fire EI, three fundamental types of data are needed: fire activity (location, start and end time, and area burned), fuel loadings (the nature of and amounts of fuels involved), and fire type (i.e., wildfire, different types of prescribed burning, agricultural burning.). Fire activity and fuel loadings then can be converted into a numerical estimate of emissions of the various chemical species that affect visibility, as follows:

$$\text{Emissions}_i = A \times B \times \text{CE} \times e_i$$

where emissions$_i$ is the emission of chemical species i (in mass units), A the area burned, B the fuel loading (biomass per area), CE the combustion efficiency, or fraction of biomass fuel burned, and e_i is an emission factor for species i (mass of species per mass of biomass burned.)

In practice there is great uncertainty associated with all the data used for this calculation. A, B, and CE are variables associated with fire activity. Fire activity is subject to significant uncertainty. In the

United States, there are different agencies involved in monitoring and recording fire activity, including federal land managers, state forestry agencies, and local firefighting resources. There are no standards for reporting fire activity: some agencies report total blackened acres and others report fire perimeters each using their own definitions. In addition, *A* depends on determining the actual area combusted, *B* depends upon quantifying the actual biomass complex engaged in the fire, a daunting task, and CE is likely a function of weather, fuel moisture, and a host of other fire dependent variables.

7.4.1. Area burned, **A**

Determining A, the area of the burn, is complicated by the fact that natural forest fires do not burn uniformly across the fuel bed. There are two different ways to determine the area burned: by ground observations from fire management personnel and from remote sensing, especially by satellite. Inaccuracies of the ground-based approach result from human errors and the priority of this data compared to other responsibilities. Satellite observations have the capability of indicating the actual fire boundaries if the fire is large enough to be resolved by the satellite A recent paper suggests that fires larger than on the order of $6\,\text{km}^2$ can be reliably detected by satellite sensors (about 92%), while those below this size cannot reasonably be detected accurately (Soja et al., 2006). A recent west wide demonstration project of the BlueSky smoke management tool suggested that there were significant errors in the ground-based reporting data associated with wildfires, the IS 209 reports (AirFire, 2006; BlueSky, 2006).

7.4.2. Fuel loading, **B**

The fuel loading or biomass is neither easily nor accurately estimated. In the United States, the National Fire Danger Rating System (NFDR) fuel models are often utilized to estimate fuel loading because they have been mapped based on data from satellite observation and a large ground-truth measurement program for the U.S. (Burgan et al., 1998; Cohen and Deeming, 1985).

Recently, USDA Forest Service researchers at the Pacific Northwest Research Station have refined the NFDR fuel models by developing a nationally mapped Fuel Characteristics Classification System (FCCS) (McKenzie et al., 2006; Sandberg et al., 2001), which is generated using a rule-based fuzzy classification system that is effectively a landscape fuel succession model allowing a default fuel loading to be approximated anywhere in the U.S.

7.4.3. Combustion efficiency, CE

Determining the specific amount of available fuel actually combusted is difficult. To date, most fire EIs have used the Emissions Production Model (EPM) (Ottmar et al., 1993; Sandberg & Peterson, 1984) which is an empirical relationship based on data collected from prescribed fire activities in the 1970s and 1980s as well as weather and fuel moisture. It has recently been updated with a more user-friendly system known as the Fire Emissions Production System (FEPS) (Sandberg et al., 2004).

7.4.4. Emission factor, e_i

An emission factor is a ratio of the mass of a chemical species released and the total mass of fuel consumed in a combustion process. It can be different for each chemical species and may also depend on the nature of the combustion process.

Table 7.1 summarizes the latest estimates of emissions factors for forest fires (Battye & Battye, 2002; U.S. EPA, 2003b). It is based largely on the research of the fire chemistry research group at the Forest Service's Fire laboratory in Missoula, Montana. Of course, there are added emission factors that are not included in this table, especially for primary and SOA emissions.

Table 7.1. Estimates of emission factors for forest fires in Montana, 2006

CO_2	1833∗CE
CO	961—(984∗CE)
CH_4	42.7—(43.2∗CE)
$PM_{2.5}$	67.4—(66.8∗CE)
PM_{10}	1.18∗$PM_{2.5}$
EC	0.072∗$PM_{2.5}$
OC	0.54∗$PM_{2.5}$
NO_x	16.8∗MCE—13.1
NH_4	0.012∗CE
VOC	0.085∗CO

Notes: Combustion Efficiency (CE) is defined as the difference of (CO_2) in the plume—[CO_2] outside the plume divided by the sum of the differences (between in and outside the plume) of CO+CO_2+CH_4+other organics. Modified Combustion Efficiency (MCE) is defined by the following equation: MCE = 0.15+0.86 CE.

7.5. Modeling fire emissions

The Community Smoke Emissions Model (CSEM) was developed to convert fire activity anywhere in the contiguous U.S. into emissions (Sestak et al., 2002; http://www.wrapair.org/forums/fejf/documents/emissions/JFEFWRAP_CSEM.ppt). Since its initial development, CSEM has been refined and improved by the BlueSky development team and others. The BlueSky emissions generator has been further developed to incorporate alternative fuel models, improved fuel consumption modeling (BlueSky, 2006).

7.5.1. Generating fire emissions inventories

Fire contributes to the $PM_{2.5}$ load in the atmosphere as well as to the specific burden of the various chemical species that make up regional air quality. In order to quantify the specific contribution that fire makes to regional visibility as well as other regional air pollution, it is necessary to use the tools described above to generate specific emissions inventories that can be used in an air quality simulation model. This activity is generally conducted by air quality regulators and managers seeking to estimate relative contributions from various pollution sources. For this purpose, it is helpful to recognize the differences between what, for lack of a better term, might be called natural and human caused fire emissions. Natural fire emissions are, of course, wildfire and prescribed fire done for the purpose of maintaining natural ecological conditions. Prescribed fire conducted to increase production or alter natural landscapes and agricultural burning clearly represents an example of human activities. Although the distinctions can become rather muddled when management practices have suppressed natural fire for decades, for the purpose here, inventories have been constructed based on distinguishing wildfire, wildland fire use (a conceptual category where a wildfire is not suppressed while accomplishing certain management objectives), prescribed fire, and agricultural burning.

A few recent projects have applied these concepts and the modeling approaches and other tools to develop specific fire emissions inventories. The most comprehensive fire EIs have been constructed for the Regional Haze Program's Regional Planning Organizations (RPOs) (http://www.epa.gov/oar/visibility/regional.html).

A national wildfire EI for 2002 for the entire United States has been developed by the RPOs. It is the best and the most comprehensive wildfire EI yet developed from a quality control standpoint. (The RPO inventory is available for download from the Western Regional Air Partnership

Web site at Inter-RPO National 2002 Wildfire Emissions Inventory, Final Work Plan, and the data can be found at http://www.wrapair.org/forums/fejf/tasks/FEJFtask7InterRPO.html.)

In addition to the national RPO wildfire EI, the Western Regional Air Partnership (WRAP) has generated more detailed fire emissions inventories for different types of fire (wildfire, wildland fire use fire, prescribed fire, and agricultural burning) for the western United States for the year 2002. WRAP has also generated hypothetical "baseline" or average-year fire emissions inventories and future average year fire emissions projections for the year 2018, assuming differing levels of prescribed fire and smoke management activities. (All of these fire emissions inventories are available from the WRAP Web site at http://www.wrapair.org/forums/fejf/tasks/FEJFtask7PhaseII.html for the 2002 inventory, and at http://www.wrapair.org/forums/fejf/tasks/FEJFtask7Phase3-4.html for the baseline and 2018 projection data.)

There have also been a few efforts to develop emissions inventories using satellite observations (Soja et al., 2004, 2006; Wiedinmyer et al., 2006). Alternative estimates of emissions such as these are useful in helping to bound EI uncertainties and improve the confidence one might wish to take in fire emissions estimates. These and related efforts have indicated that satellites are increasing in their ability to identify fire location and area burned. As new sensors are flown on satellites, more accurate determinations of smaller and smaller areas are possible.

Some of the results from these emissions inventories are informative. Figure 7.2a summarizes the emissions from all sources, including the contribution made by fire, to the total $PM_{2.5}$ emissions in the western United States. Clearly fire is a significant source in this region.

Figure 7.2b provides an illustration of the relative contribution made by fire (estimated from the 2002 inter-RPO fireEI) to the total $PM_{2.5}$ emissions in the United States from fuel combustion, transportation, and industrial process. Again, it is apparent that on a national basis, fire represents a major contribution to the total $PM_{2.5}$ loading in the U.S. atmosphere.

7.5.2. Processing the fire emissions inventories for use in air quality simulation models

The University of North Carolina's Environmental Program group has adapted the BlueSky emissions model to generate inputs for regional air quality models based on the SMOKE emissions processor (Pouliot et al., 2005). This code is available for anyone to use from the UNC Web site (http://www.cep.unc.edu/empd/products/smoke/bluesky/).

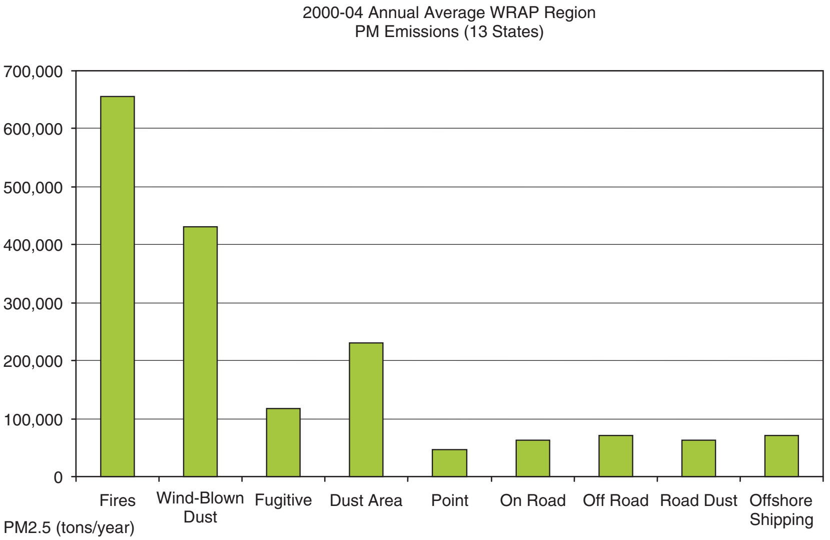


Figure 7.2a. WRAP emissions inventory developed as an annual average for the period from 2000 to 2004. (The inventory does not include out-of-region sources.) (http://wrapair.org/WRAP/meetings/060913m/Board_Tech_Talk_9_14_06_final.ppt)

The inventories have all been processed using the SMOKE model to generate model-ready emissions inventories. Details are available at the WRAP Web site (http://www.wrapair.org/forums/fejf/).

Model-ready fire EI results are detailed in two reports developed by Air Sciences, Inc. (Air Sciences, 2004; Air Sciences, 2005).

7.6. Assessing fire impacts on visibility

7.6.1. Using fire emissions inventory in air quality modeling

The Community Multiscale Air Quality model (CMAQ) is a standard for regional air quality simulation (U.S. EPA, 1999). For this reason, the RPOs have funded its development and application to simulate regional air quality and to realistically portray fire contributions.

Working under contract to the WRAP, the WRAP Regional Modeling Center (RMC) at the University of California, Riverside, conducted a set of simulations that were designed to illustrate the difference between the CMAQ-modeled visibility impacts with and without fire emissions. These model simulations isolate the effects of fire emissions on visibility from

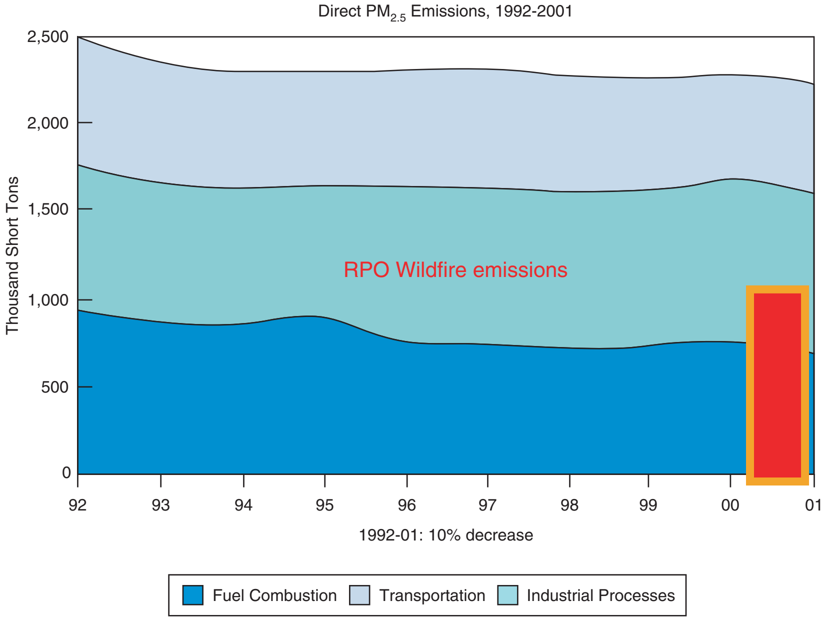


Figure 7.2b. EPA estimate of $PM_{2.5}$ national emissions inventory with the national RPO fire EI added for comparison. (http://www.epa.gov/air/airtrends/aqtrnd03/images/fig-2-45.gif and http://wrapair.org/WRAP/meetings/060913m/Board_Tech_Talk_9_14_06_final.ppt)

the effect of all other emissions sources in the model. It is important to realize that these figures only look at the isolated impact of fires on visibility. There are very large and significant anthropogenic emissions from industrial, mobile, and area sources that make a relatively larger contribution to visibility impact than does fire. However, for our purpose here we have isolated only the various forms of fire and look individually at their impacts. The WRAP RMC conducted three model sensitivity runs considering fire impacts on the WRAP region (Regional Modeling Center (RMC) 2005). These runs used 2002 fire emissions that included prescribed, agricultural and wildfire emissions in the region. The WRAP considers that wildfires, wildland-fire use fires, and prescribed burning used for resource management are natural, while agricultural burning and some prescribed burning are anthropogenic. (For more information regarding the definitions of specific fire activities see http://wrapair.org/forums/fejf/meetings/041208m/FEJF_N-A_EI_Approach_20040903.pdf and http://wrapair.org/forums/fejf/documents/nbtt/FirePolicy.pdf; and for results see http://wrapair.org/forums/aoh/ars1/report.html.)

Figure 7.3a presents the 2002 modeled annual average contribution to light extinction by the full set of emissions, including all fire emissions. However, the extinction values plotted for each grid cell represent modeled extinction due to fire activity only because the extinction due to other species has been subtracted out. Visibility impacts due to all fires are shown to have been generally less than 10 Mm^{-1} across WRAP, although some locations were impacted by as much as 25, 50, or $>100\,\mathrm{Mm}^{-1}$. Geographically, the largest impacts due to fire occur in southern Oregon, much of California, and isolated locations in Utah, Arizona, and Colorado. Figure 7.3b presents the modeled annual average contribution to light extinction by all natural fires for 2002. This map is not significantly different from Fig. 7.3a, indicating that natural fires contribute a large percentage of the impact of both fire categories combined. Figure 7.3c presents the modeled annual average contribution to light extinction by all anthropogenic fires for 2002. This map indicates that the most significant contributions by anthropogenic fires during 2002 occurred in the region around the panhandle of Idaho and California's Central Valley. The maximum modeled impact of anthropogenic fires is less than 5 Mm^{-1} (http://wrapair.org/forums/aoh/ars1/report.html and http://wrapair.org/forums/aoh/ars1/report.html).

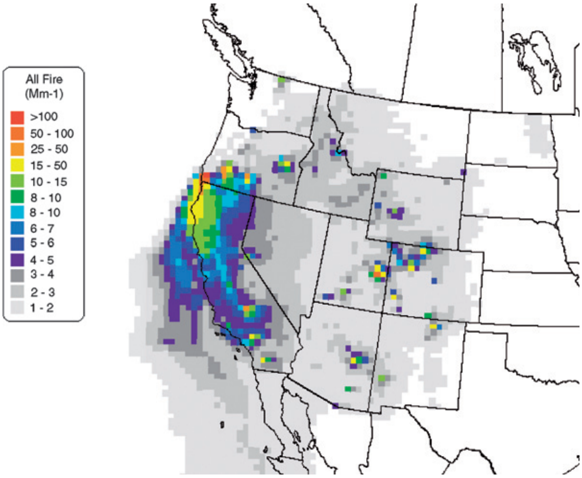


Figure 7.3a. CMAQ model results from a 36 km simulation of all 2002 emissions. However, only the light extinction attributed to fire emissions (all fire emissions, wildfire, wildland fire use fire, prescribed fire and agricultural burning) is presented. (http://www.wrapair.org/forums/aoh/ars1/documents/reports/Section_4.pdf)

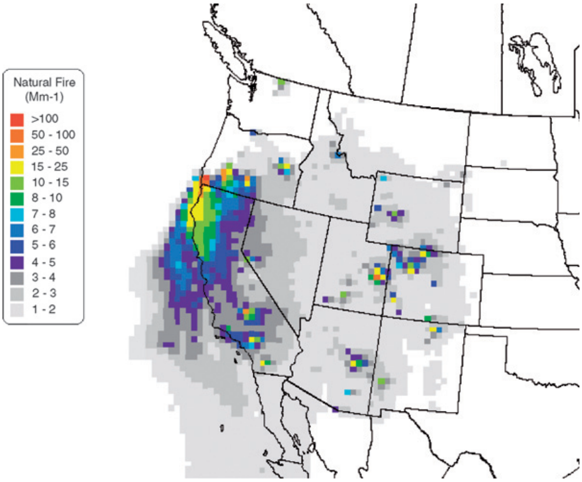


Figure 7.3b. CMAQ model results from a 36 km simulation of all 2002 emissions. However, only the light extinction attributed to "natural" fire emissions (wildfire, wildland fire use fire, and prescribed fire for ecosystem management purposes) is presented. Note this figure is nearly identical to Fig. 7.3a showing results of all fire emissions. (http://www.wrapair.org/forums/aoh/ars1/documents/reports/Section_4.pdf)

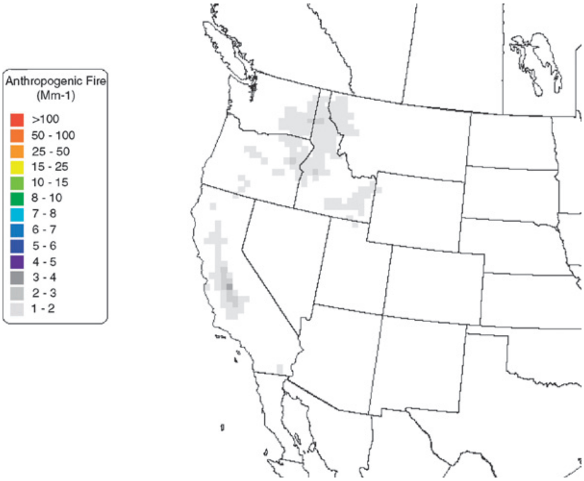


Figure 7.3c. CMAQ model results from a 36 km simulation of all 2002 emissions. However, only the light extinction attributed to "anthropogenic" fire emissions (some prescribed fire and agricultural burning) is presented. Note this figure illustrates that in the western United States, the contribution of this anthropogenic fire to regional haze appears to be quite limited. (http://www.wrapair.org/forums/aoh/ars1/documents/reports/Section_4.pdf)

7.6.2. Use of IMPROVE monitoring with modeling to quantify impacts of fire on regional visibility

In support of the RHR, two key Web sites have been developed: VIEWS presents details of regional air quality data and TSS provides a technical reference to help ascribe causes to impaired visibility in the western U.S. TSS also provides an array of tools that can help to quantify fire's contributions to regional visibility. However, none of these is completely satisfying by itself. Figure 7.1 illustrates the average results from the IMPROVE monitoring from 2000–2004, showing the relative contribution that each of the IMPROVE aerosol species makes to visibility on the 20% worst visibility days in the western United States. Figure 7.4 shows the same information for the entire United States in 2002. Note that the locations where the pie charts are predominantly green are locations where one might expect fire to be a significant contributor to regional visibility degradation.

7.6.3. Statistically apportioning visibility impacts to fire

Among the inferential ways to consider fire's impact are statistical analyses of the IMPROVE and other aerosol data. If there were a unique tracer of fire's contribution, then simply measuring the amount of that unique tracer would be possible. However, there is no such unique tracer, although this is the subject of ongoing research activities.

One approach that has been followed is to look at the ratio of OC to black (or elemental) carbon in the measurements (Malm et al., 2004). Ames et al. (2004) present results of this and an alternative approach aimed at bracketing the influence of fire. The ratio of organic carbon to elemental carbon (OC/EC) can be associated with significantly different forms of combustion. Combustion of fossil fuels (gasoline, diesel, etc.) is generally associated with an internal combustion engine characterized by a relatively efficient combustion. This combustion is enriched in EC such that the OC/EC ratio is on the order of 3. Urban organic fine particulate measurements often display ratios on this order. Open combustion is often less efficient, emitting a higher amount of OC relative to EC. Fine particulate measurements that can otherwise be related to wildland fire display OC/EC ratios on the order of 10 or more. Ames used this ratio to distinguish fire from urban sources in the IMPROVE measurements. However, there are sources of OC not associated with EC at all, namely atmospheric chemical reactions of natural hydrocarbon emissions from vegetation, termed biogenic emissions that generate SOAs. Wherever there is significant vegetative cover, there will be SOA formed. Since this

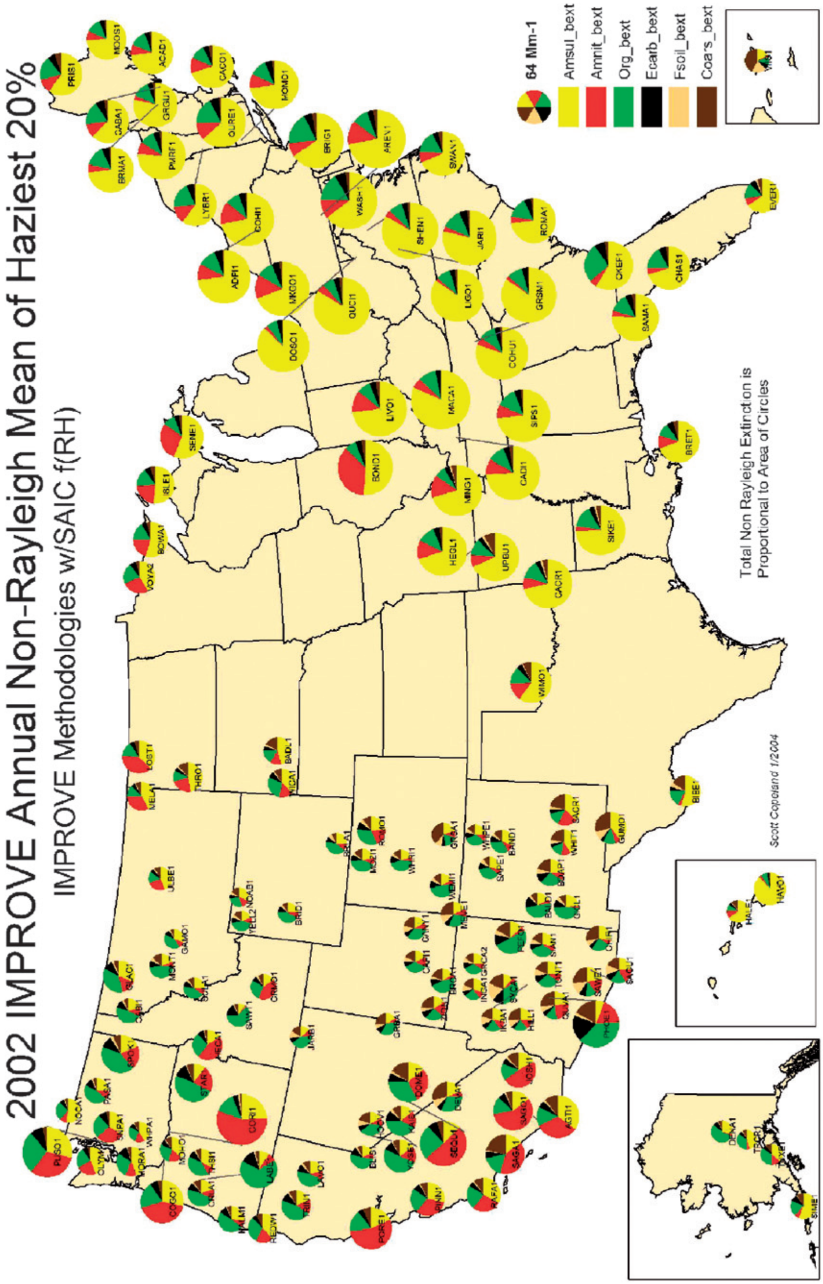


Figure 7.4. IMPROVE monitoring results from 2002 for the 20% worst visibility days. The pie charts illustrate the contribution that each of the IMPROVE aerosol components makes to the extinction. Note the distribution of values of OC (green) suggests locations where fire may have a potentially significant impact on regional visibility. (Unpublished graphic prepared by S. Copeland, CIRA, 2004 based on IMPROVE data from http://vista.cira.colostate.edu/improve/Publications/Reports/2006/PDF/Chapter3.SeasonalPatternsRegionalConcentrations.pdf)

source of OC is not considered in the analysis, the OC/EC ratio will be highly biased by the presence of this added OC; thus, this ratio is likely to overestimate the influence of fire on visibility. To bracket this, Ames considered a second apportionment method, namely using a fire occurrence database (Brown et al., 2002) and then looking at back trajectories (Heffter, 1980) from each IMPROVE monitor for a period of time leading up to and through the measurement and apportioning the fire influence based on the amount of time the air spent over fire locations. This approach has many potential errors, so many in fact, that the Joint Fire Sciences Program (JFSP) recently funded the National Park Service to investigate this and related methodologies further. Due to the facts that the fire activity database used does not include all fire and the inadequacies of trajectories, this method is likely to underestimate the influence of fire on visibility.

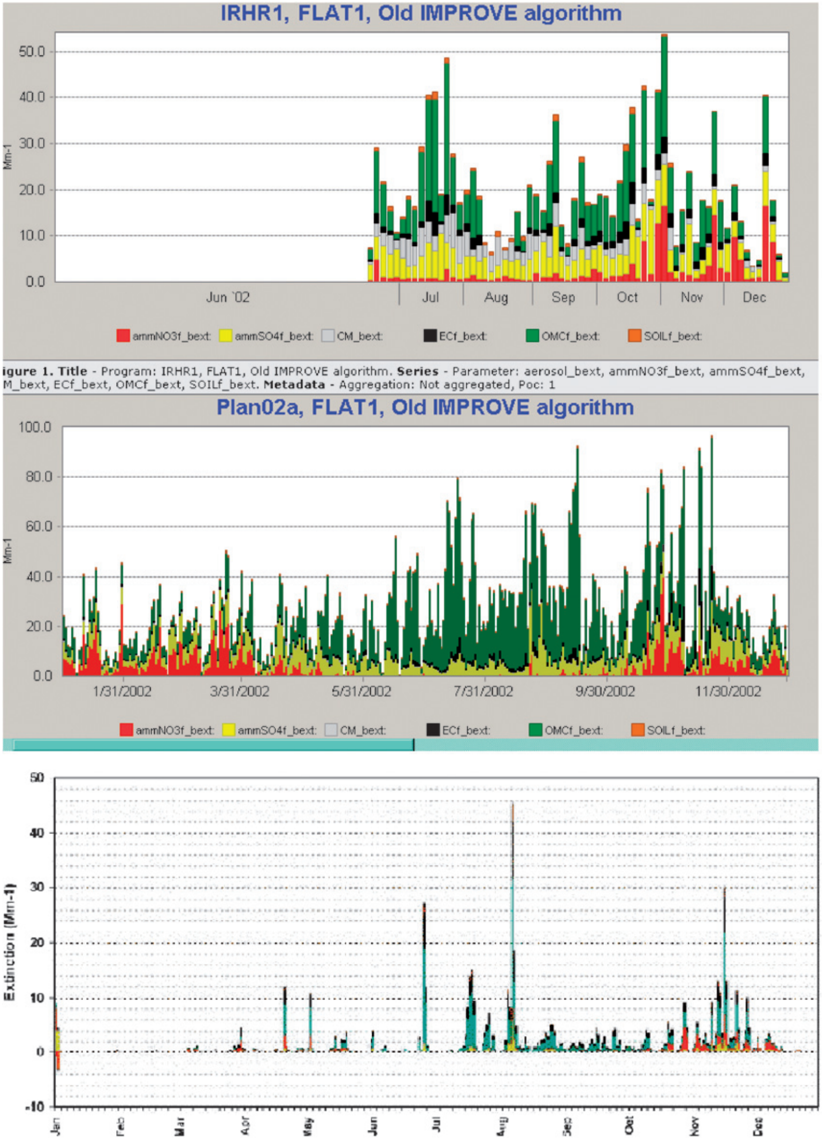
OC concentrations at IMPROVE monitoring sites (2000–2002 OC/EC analysis) are approximately 1.0 $\mu g/m^3$ in the western U.S. and 1.7 $\mu g/m^3$ in the east. Over the same time period and monitoring sites, OC apportioned to fire and SOA using the OC/EC ratio approach is about 0.6 $\mu g/m^3$ in the west, and 0.9 $\mu g/m^3$ in the east, or approximately 60% of observed OC in the west and 55% in the east. OC apportionments to U.S. wildland fires from the fire activity and trajectory method averaged about 0.3 $\mu g/m^3$ in the west and 0.4 $\mu g/m^3$ in the east, or approximately 30% of observed OC in the west and 20% in the east.

For reference, the RHRs assume that natural visibility in the U.S. is characterized by an OC concentration of approximately 1.1 $\mu g/m^3$ in the eastern U.S. and 0.4 $\mu g/m^3$ in the west (U.S. EPA, 2003a).

Recently, using a global air quality model, Park et al. (2003) have estimated OC values of approximately 0.7–1.1 $\mu g\,m^{-3}$ may be representative of natural conditions in the west, and OC concentrations of approximately 0.9 $\mu g\,m^{-3}$ to be characteristic of natural conditions in the eastern United States.

7.6.4. Compare model results to IMPROVE monitoring

Figures 7.5a–c present WRAP 2002 fire simulations and IMPROVE data developed from the TSS. Here, we present results at three of the more obviously fire-influenced sites in the western U.S.: the Flathead Lake IMPROVE site in Montana (Fig. 7.5a); Hells Canyon IMPROVE site in Oregon (Fig. 7.5b), and the Sequoia National Park IMPROVE site in California (Fig. 7.5c). The IMPROVE monitoring result is presented in the top panel, the second panel presents WRAP CMAQ modeling results



igure 1. **Title** - Program: IRHR1, FLAT1, Old IMPROVE algorithm. **Series** - Parameter: aerosol_bext, ammNO3f_bext, ammSO4f_bext, M_bext, ECf_bext, OMCf_bext, SOILf_bext. **Metadata** - Aggregation: Not aggregated, Poc: 1

Figure 7.5a. Fire monitoring and modeling compared for the IMPROVE site at Flathead Lake, Montana, for 2002. Top panel represents the IMPROVE observations, the second panel the WRAP full emissions inventory modeling results and the third panel the WRAP fire emissions inventory modeling only. (http://vista.cira.colostate.edu/TSS/Results/HazePlanning.aspx)

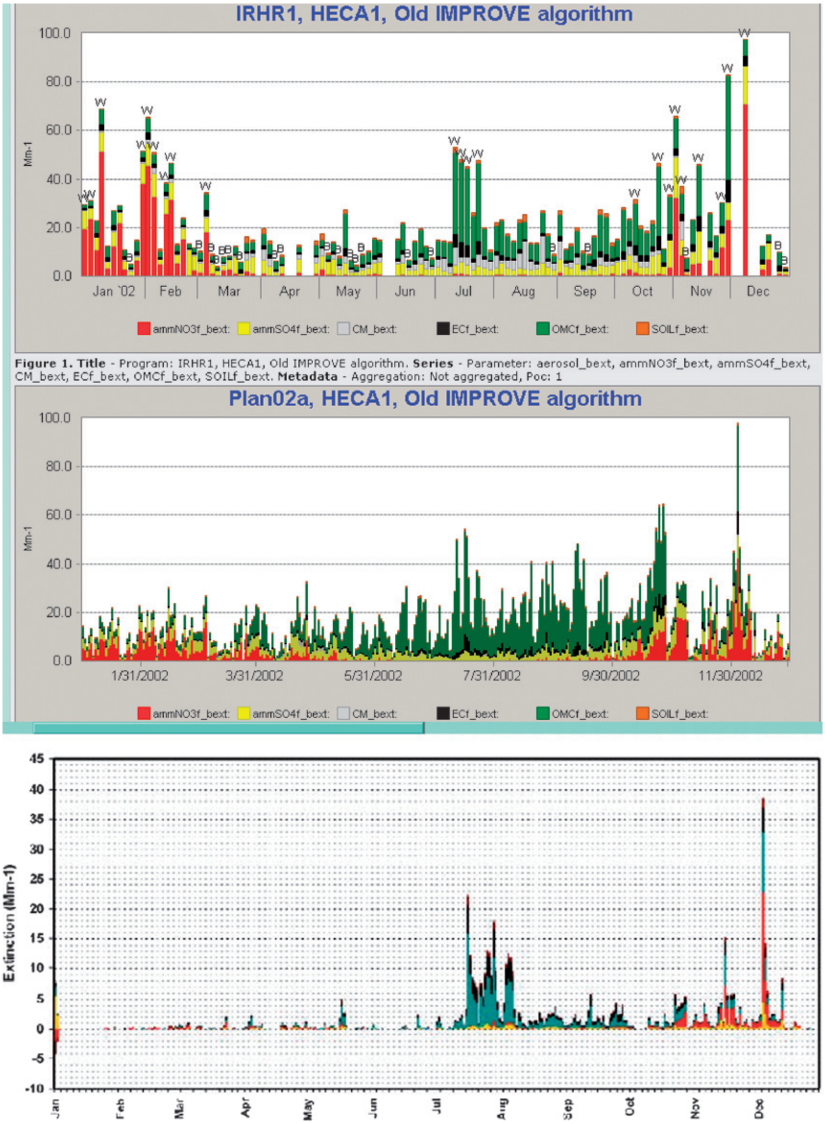


Figure 1. Title - Program: IRHR1, HECA1, Old IMPROVE algorithm. **Series** - Parameter: aerosol_bext, ammNO3f_bext, ammSO4f_bext, CM_bext, ECf_bext, OMCf_bext, SOILf_bext. **Metadata** - Aggregation: Not aggregated, Poc: 1

Figure 7.5b. Fire monitoring and modeling compared for the IMPROVE site at Hells Canyon, Oregon, for 2002. Top panel represents the IMPROVE observations, the second panel the WRAP full emissions inventory modeling results and the third panel the WRAP fire emissions inventory modeling only. (http://vista.cira.colostate.edu/TSS/Results/HazePlanning.aspx)

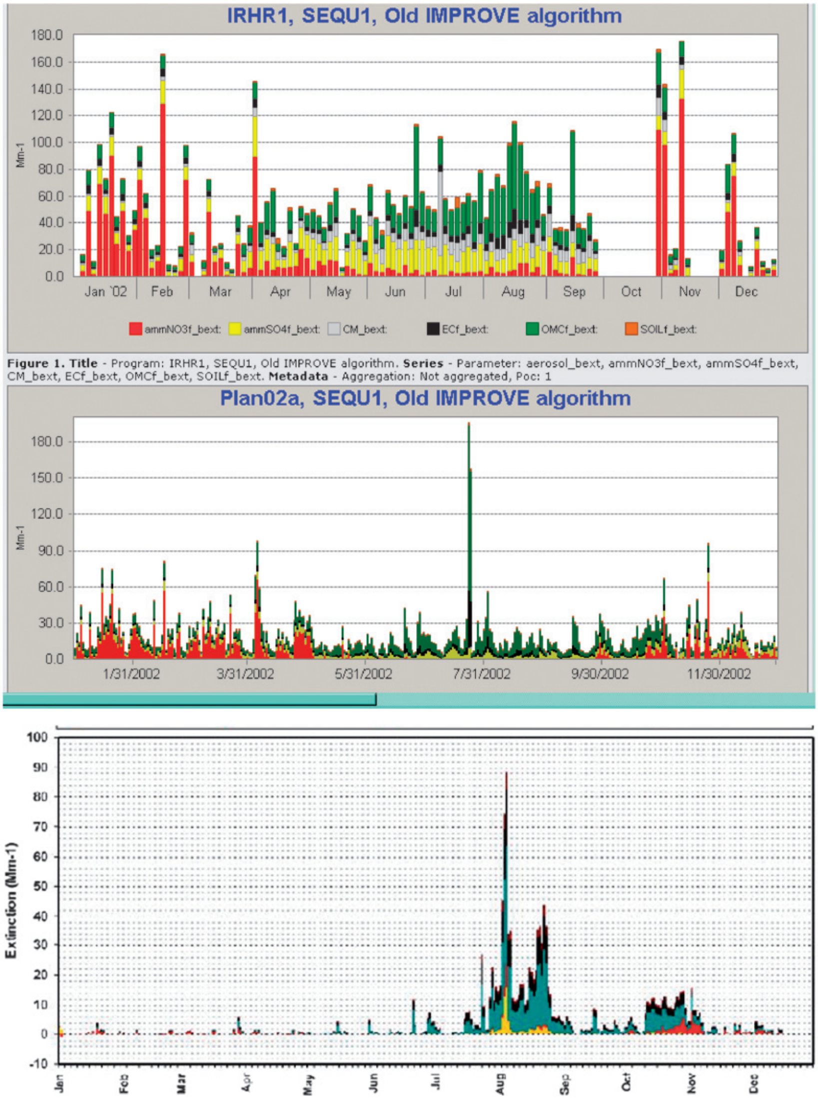


Figure 1. Title - Program: IRHR1, SEQU1, Old IMPROVE algorithm. **Series** - Parameter: aerosol_bext, ammNO3f_bext, ammSO4f_bext, CM_bext, ECf_bext, OMCf_bext, SOILf_bext. **Metadata** - Aggregation: Not aggregated, Poc: 1

Figure 7.5c. Fire monitoring and modeling compared for the IMPROVE site at Sequoia National Park, California, for 2002. Top panel represents the IMPROVE observations, the second panel the WRAP full emissions inventory modeling results and the third panel the WRAP fire emissions inventory modeling only. (http://vista.cira.colostate.edu/TSS/Results/HazePlanning.aspx) based on the full WRAP EI, and the third panel represents the fire only contribution to the extinction as calculated by the simulations.

It is clear from the results that the modeling appears to exhibit at least qualitative skill in simulating the impacts of fire on visibility. However, it is also clear that this represents only the beginning of what will be a continuing investigation into the influences of fire on regional haze (Rodriguez et al., 2006).

In July 2007 the WRAP engaged in an attribution of haze analysis utilizing the capabilities of the TSS (http://wrapair.org/forums/aoh/index.html). This project is scheduled for completion by the end of 2007. Figure 7.6 presents preliminary results illustrating the influences of different emissions types on visibility at the Hells Canyon Class I area. Specifically looking only at the impact of OC aerosol, this analysis involves combining source regions and the trajectories of air flows during the worst visibility conditions experienced in the 2000–2004 5-year baseline period as well as the simulated contributions from these sources in future inventories based on both planned and possible emissions reductions. Details of the analysis are found on the TSS web site (http://vista.cira.colostate.edu/tss). The results show that "anthropogenic fire" has a significant potential impact on this site.

7.7. Conclusions and next steps

By way of a preliminary conclusion, research to date suggests that somewhere between 25% and 60% of the OCM measured in ambient air is a result of smoke from wildfire. In relation to estimated natural background values, this suggests that the vast majority of the natural background of OC aerosol in the western U.S. results from fire and nearly 50% of it in the east may be due to fire. A significant portion of the remainder in the east is likely attributable to secondary aerosol formation from vegetation emissions of reactive hydrocarbons. These results are confounded by the presence of fine mass transported long distances, from Asia and Africa, which occasionally impact the United States. As regional air quality simulation modeling progresses, we should be better able to quantify these impacts.

We feel that the following six activities are among the most significant missing elements in any ongoing attempt to assess fire's contribution to regional air pollution and specifically to visibility degradation:

- *Develop a national fire activity database* system as a single, all-agency, all-area source of quality-assured information about the location, timing, and size of fires. This is the necessary first step in developing an

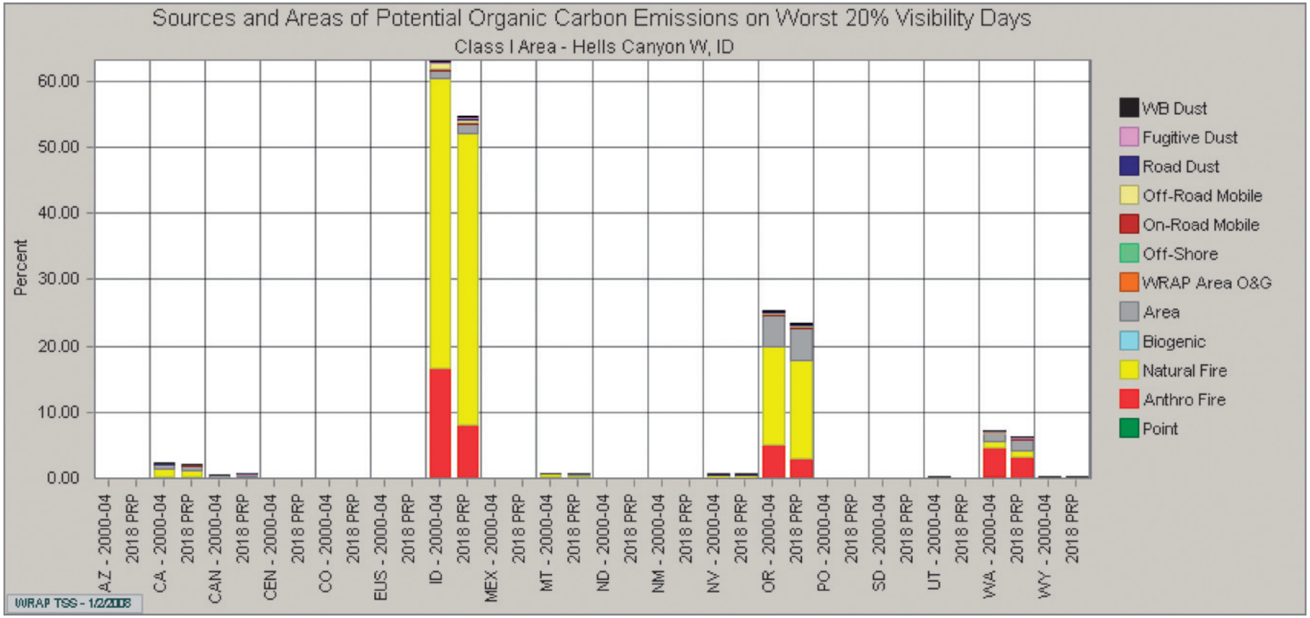


Figure 7.6. TSS results illustrating the influences of different emissions types on visibility at one IMPROVE site. Looking at only organic carbon aerosol, this analysis involves combining source regions and the trajectories of air flows during the worst visibility conditions experienced in the 2000–2004 5-year baseline period as well as planning inventories for future years. (http://vista.cira.colostate.edu/TSS/Results/HazePlanning.aspx)

accurate and continuing EI of fire emissions for not only air pollution but for climate change and CO_2 emissions issues as well.

- *Develop chemical tracers* to distinguish carbon from different types of fire and other sources in the measured regional aerosol mixture.
- *Improve emissions factors and secondary aerosol formation mechanisms* for primary and SOA resulting from different types of fires.
- *Continue apportionment* studies using multiple years of speciated PM data.
- *Apply improved regional scale simulation modeling including fire emissions.*
- *Apply satellite remote sensing* for fire impacts on Class I areas.

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