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A statistical model for determining impact of wildland fires on Particulate Matter ($PM_{2.5}$) in Central California aided by satellite imagery of smoke

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ABSTRACT

As the climate in California warms and wildfires become larger and more severe, satellite-based observational tools are frequently used for studying impact of those fires on air quality. However little objective work has been done to quantify the skill these satellite observations of smoke plumes have in predicting impacts to $PM_{2.5}$ concentrations at ground level monitors, especially those monitors used to determine attainment values for air quality under the Clean Air Act. Using $PM_{2.5}$ monitoring data from a suite of monitors throughout the Central California area, we found a significant, but weak relationship between satellite-observed smoke plumes and $PM_{2.5}$ concentrations measured at the surface. However, when combined with an autoregressive statistical model that uses weather and seasonal factors to identify thresholds for flagging unusual events at these sites, we found that the presence of smoke plumes could reliably identify periods of wildfire influence with 95% accuracy.

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1. Introduction

As California's climate warms and wildfires increase in frequency and severity (Miller and Safford, 2012), air regulators and policy makers for land management agencies are becoming increasingly interested in understanding the impacts and spatial extent of smoke from wildland fire on air quality. Of particular interest are regions such as Central California where densely populated areas are adjacent to forest lands that were pre-historically adapted to frequent fire and the smoke that results from those fires (Stephens et al., 2007). After 100 or more years of successful fire suppression (Williams and Baker, 2012; Stevens et al., 2014), those fires, and their associated smoke impacts are returning and likely to increase substantially in the next 50–100 years, exacerbated by a warming climate and increasing tree mortality (van Mantgem et al., 2009; Hurteau et al., 2014). Thus, there is an urgent need for strategies that integrate and reconcile the Federal Land Managers' (FLM) need to protect fire-adapted forests with the regulatory requirements to minimize impact to human health (Rappold et al., 2014; Schweizer and Cisneros, 2014; North et al., 2012), within the existing air quality regulatory framework.

There is an existing regulatory mechanism that provides guidelines to help regulators focus enforcement actions on anthropogenic sources that affect air pollution, rather than on natural sources. The 2007 Exceptional Events Rule (EER) by the Environmental Protection Agency (72 FR 13560), pursuant to the 2005 amendment of section 319 of the Clean Air Act states that, to qualify as an "exceptional event," six key criteria have to be met before data from a given site can be excluded from the calculations that determine non-attainment for the area represented by the monitor. First, the event in question had to (1) have actually affected air quality, and not have been (2) "reasonably preventable," like emissions from fire-adapted forests. In addition, the event (3)

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had to have come from a human activity that is unlikely to recur in the same place or be a natural event (4) that there exists a "clear causal relationship" between the [fire] in question and the monitored concentration, (5) the event is "associated with a measured concentration in excess of normal historical fluctuations, including background, and (6) there "would have been no exceedances but for the event." The last three are problematic from the standpoint of a local air regulator trying to demonstrate a fire's effects, because the science of how to demonstrate causal relationships, quantify "normal historical fluctuations", and prove there would be no exceedances but for the event in questions is still nascent. Though one exceptional event study for impacts in the Sacramento Area during the 2008 summer wildfires has been accepted, specific guidance on the recommended techniques for such demonstrations for $PM_{2.5}$ has not been available from the EPA. This EER policy and its implementation is particularly important in the California Central Valley where currently air quality is in "non-attainment" of state and federal standards for several air pollutants, including $PM_{2.5}$, due to the California's unique topography (Lin and Jao, 1995) and many large-scale urban areas providing a constant source of anthropogenic $PM_{2.5}$.

A variety of dispersion modeling tools has been developed over the years to help understand smoke transport and impacts (Goodrick et al., 2013). One method used to quantify contribution of fire to air quality is to define a circle of a given radius around each PM monitor and assume that all fires within the circle have an effect at the monitoring site (Elliott et al., 2013). However, meteorological conditions such as wind speed and direction also need to be taken into account (Preisler et al., 2005; Preisler et al., 2010; Moeltner, 2013) in order to assess contribution from a particular fire. An alternative method is to develop a statistical relationship between surface $PM_{2.5}$ concentrations and satellite derived aerosol optical thickness (Wang and Christopher, 2003; Hoff and Christopher, 2009; Zhang et al., 2009; Toth et al., 2014), with satellite imagery being used to determine smoke extent and impacts (Rolph et al., 2009; Yao and Henderson, 2014) and to verify smoke model sensitivity (Stein et al., 2009). The present study utilizes real time smoke data, as observed by satellites above particulate monitoring sites, as an aid to assess the contribution of smoke to surface $PM_{2.5}$ levels. Our study attempts to quantify the sensitivity of surface $PM_{2.5}$ values at monitoring sites throughout central California to various levels of smoke as observed by the National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System (HMS). This is done by developing site specific statistical models that take into account various factors including weather, fire, and seasonal patterns of $PM_{2.5}$ at that site.

This study attempts to answer the following questions using the latter approach: 1) What is the relationship between the HMS smoke data and surface $PM_{2.5}$ at monitoring sites? 2) Do total atmospheric column observations of smoke from visible satellite imagery have skill in predicting $PM_{2.5}$ concentrations at the surface? 3) Can the statistical models developed in this study reliably identify potential 'exceptional events', i.e., days when the increase in $PM_{2.5}$ can be attributed to wildland fire with some certainty? 4) Does removing these days affect non-attainment status for $PM_{2.5}$ at the sites in question? Answering these questions will help in understanding whether a combination of the HMS smoke data and a statistical model can provide sensitive and objective demonstrations that satisfy criteria 4–6 of the EER, especially at highly polluted sites where the "but for" and "clear causal" are particularly difficult to satisfy. These tools if proven sensitive enough, can provide a relatively simple method for air regulators and land managers to quickly and objectively satisfy EER criteria and focus more effort and time on addressing anthropogenic rather than natural source issues.

2. Methods

2.1. Study area

Our analysis of ground based monitoring of $PM_{2.5}$ levels focused on the Sierra Nevada and adjacent areas from 2007 to 2013. Included are 13 ground level $PM_{2.5}$ monitors with year round data (Table 1). Ground based particulate monitors were chosen to represent the California Central Valley, various elevations on the western slope of the Sierra Nevada, and areas east of the Sierra Nevada from the Lake Tahoe area south to the Owens Valley (Fig. 1). Included in Fig. 1 are representative HMS smoke density plumes. HMS detected smoke plume is shown during the Rim Fire (a high intensity wildfire) on 8/30/2013 and during the Lion Fire (a managed fire) on 7/23/2011.

2.2. $PM_{2.5}$ and weather data

Ground monitoring hourly values of $PM_{2.5}$ and meteorological data (wind speed and direction, temperature, relative humidity) were compiled from each monitoring site in Table 1. Data was obtained from the U.S. Forest Service for each of these sites.

2.3. HMS data

Since this study is focused on surface smoke effects there are several satellites that seem to be well suited for providing this information. Two candidates for determining the height of the smoke are the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite or the Multi-angle Imaging Spectro-Radiometer (MISR) instrument on NASA's Terra satellite. However, they have their limitations. CALIPSO only provides 2 orbits per day and it is along a pencil thin area of the suborbital track. The MISR provides estimates for the height of smoke plumes but it has a narrow swath width and the revisit period at the latitude of the ground monitoring sites is only once every 2–3 days. For broad areas of moderate or dense smoke it generally would not be able to detect the presence of smoke on the ground. Since this study required the study of many fire events and smoke plumes, the limited temporal coverage of these two instruments precluded them from our use.

The HMS fire and smoke analysis is a daily product generated by NOAA's National Environmental Satellite, Data and Information Service's Office of Satellite and Product Operations over North America using over 100 satellite images per day from multiple geostationary and polar orbiting satellites. The HMS smoke plume data set is manually generated by satellite analysts (Ruminski et al., 2008) and the smoke is identified exclusively in visible wavelength satellite imagery which precludes detection at night. Cloud cover is another limiting factor in smoke detection. For smoke that is observed, HMS data provides the spatial extent, an estimate of smoke concentration (light, medium or heavy), and the time interval over which the smoke was observed for each polygon for smoke plumes over North America. Because of the constant daily daytime monitoring of smoke it was felt that the HMS analysis would be best to use to relate smoke impacts from wildland fires for the years 2007–2013 to ground based $PM_{2.5}$ concentrations.

As indicated above, there is a smoke concentration associated with each of the HMS smoke plumes which is assigned by the analyst and therefore introduces a level of subjectivity to the process. There are automated products which provide estimates of smoke concentration (e.g., GOES Aerosol and Smoke Product (GASP) and the MODIS AOD). While these products provide a certain level of objectivity they have their own issues including the fact that they do not speciate (i.e. aerosol dust, smoke, sulfate, etc)