Environmental Pollution 205 (2015) 340–349

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

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

Haiganoush K. Preisler [a], [*], Donald Schweizer [b], Ricardo Cisneros [c], Trent Procter [d], Mark Ruminski [e], Leland Tarnay [f]

[a] USDA Forest Service, Pacific Southwest Research Station, 800 Buchanan St., WAB, Albany, CA 94706, USA
[b] Environmental Systems Graduate Group, University of California, Merced, 5200 N. Lake Road, Merced, CA 95343, USA
[c] School of Social Sciences, Humanities and Arts, University of California, Merced, 5200 N. Lake Road, Merced, CA 95343, USA
[d] USDA Forest Service, 1839 S. Newcomb, Porterville, CA 93257, USA
[e] NOAA/NESDIS, Satellite Analysis Branch, 5830 University Research Ct Suite 4035, College Park, MD 20740, USA
[f] USDA Forest Service, Pacific Southwest Research Station, Truckee Ranger District, 10811 Stockrest Springs Road, Truckee, CA 96161, USA

ARTICLE INFO

Article history:
Received 15 March 2015
Received in revised form
9 June 2015
Accepted 13 June 2015
Available online xxx

Keywords:
Air pollution standards
Autoregressive model
Exceptional events
NOAA Hazard Mapping System

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.

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)

---

[*] Corresponding author.

E-mail addresses: hpreisler@fs.fed.us (H.K. Preisler), dschweizer@ucmerced.edu (D. Schweizer), rcisneros@ucmerced.edu (R. Cisneros), tprocter@fs.fed.us (T. Procter), mark.ruminski@noaa.gov (M. Ruminski), ltarnay@nps.gov (L. Tarnay).

http://dx.doi.org/10.1016/j.envpol.2015.06.018
0269-7491/Published by Elsevier Ltd.

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)

Table 1
$PM_{2.5}$ ground based monitoring station location, elevation, and description.

Station	Longitude	Latitude	Elevation (m a.s.l)	Location description
Ash Mountain[d]	−118.827	36.4894	519	western slope
Bakersfield[a]	−119.063	35.35667	117	Central Valley south
Bishop[b]	−118.417	37.36667	1288	East side; Owens Valley
Clovis[a]	−119.716	36.819	86	Central Valley central
Fresno[a]	−119.773	36.78194	98	Central Valley central
Kernville[e]	−118.417	35.75506	842	Southern
Lone Pine[b]	−118.049	36.59556	1128	East side; Owens Valley
Pinehurst[e]	−119.019	36.69731	1246	western slope
Ranchos[c] (Gardnerville)	119.732	38.8989	1488	East side; Nevada
Sacramento[a]	−121.368	38.6136	38	Central Valley north
Springville[e]	−118.811	36.13625	321	Western slope
Visalia[a]	−119.291	36.3325	97	Central Valley central
Yosemite Village[d]	−119.587	37.7486	1216	Western slope

[a] Data from the California Air Resources Board Air Quality and Meteorological Information System (2014).
[b] Data from the Tribal Environmental Exchange Network (2014).
[c] Data from the State of Nevada Division of Environmental Protection Bureau of Air Quality Planning (2014).
[d] Data from the U.S. Department of the Interior National Park Service (2014).
[e] Data from monitors operated by the U.S. Forest Service.

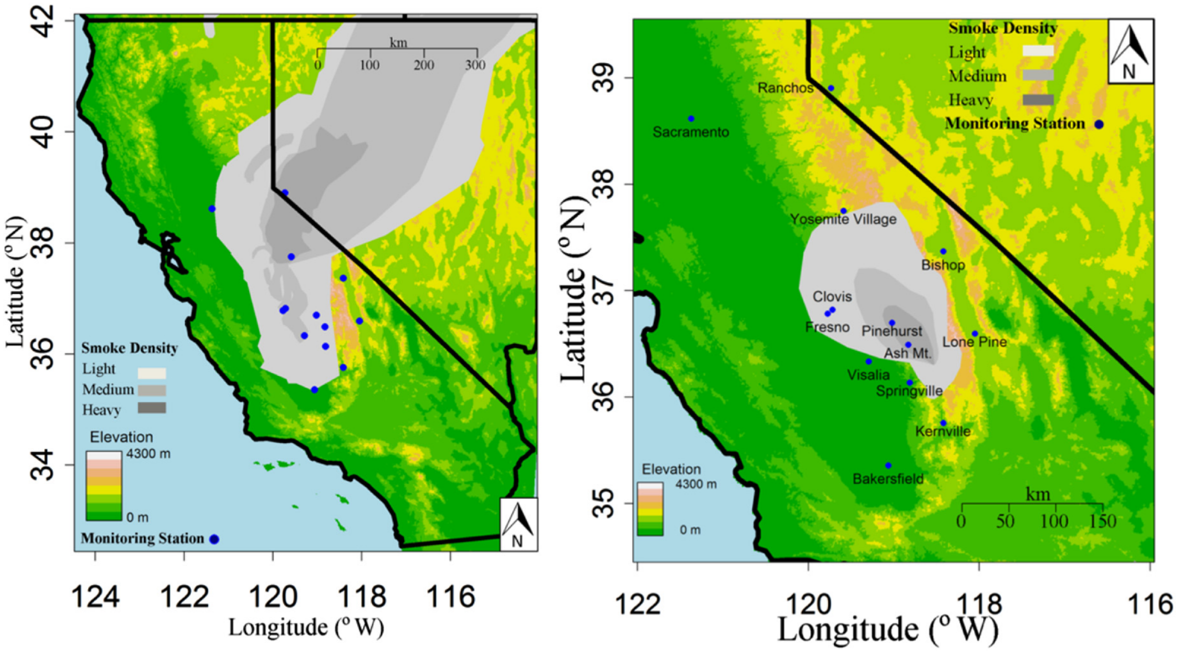

Fig. 1. Station locations and typical HMS smoke density plumes during (left) a high intensity full suppression wildfire (Rim Fire on 8/30/2013) and (right) a managed landscape level wildland fire (Lion Fire on 7/23/2011).

which is what the HMS analyst needs to determine. We feel that the use of the human analyst HMS product – which can incorporate information from the automated products – is preferred for this study. Another possible concern with using the subjective HMS analysis is that there could be a bias toward detecting smoke from known fires. Overall the HMS analysis incorporates a broad situational awareness that is felt to minimize any smoke detection bias.

In this study daily HMS data was converted to hourly values to determine smoke over a given station. Following are the steps used to calculate the hourly smoke level data over each site:

Step 1. Ground based monitoring site location (latitude and longitude) were overlaid on HMS daily spatial polygons to determine all daily polygons directly over a given site.

Step 2. Total polygon area over a given site was calculated.

Step 3. HMS polygon data for all smoke density levels over a given site were estimated to occur from the Start time to the End times associated with the individual polygon.

Step 4. Days with HMS data that did not have a polygon over a station were considered clear (no smoke) for that station, although it is possible that smoke may have been present but obscured by clouds. Since these observations are based on visible light, hours between sunset and sunrise were necessarily invalid for smoke detection.

Each station with any smoke polygon over a site in a given day had a number of hours of each smoke density level (low, medium, and heavy) along with hours where no smoke was detected over the given site.

Smoke from wildland fire will often result in smoke being present in significantly different locations which can be highly associated with the time of day. Diurnal transport of smoke fluctuates as smoke often is pulled into the steep river canyons of the Sierra Nevada during the night and remains until lifting in late morning or early afternoon. In our analysis, we were attempting to capture these fluctuations in the smoke plumes as they evolve over the day. Likely some of the hours in a given day saw smoke over the site that was not included in the HMS start and end time. This is particularly true if smoke was present in both the morning and evening because the satellite image derived smoke plumes take advantage of favorable viewing angles for smoke detection employing both GOES-West and GOES-East imagery. Statistical analysis used in this paper focused on concentrations 24 h in advance and after a given hourly surface monitoring concentration; thus gaps in hourly smoke density data were largely irrelevant for overall patterns and probability of exceedance. For days when there was no polygon directly over a station, the nearest polygon was determined. Distance to the nearest polygon and the area of this polygon was calculated from each monitoring station for each smoke density level with hourly values determined the same as explained above. Polygon area was calculated to determine the spatial extent of smoke impacts over a given site to understand if HMS data was indicating a large or small smoke plume over or near a given site. This area was used in conjunction with fire size and location data to help inform us of individual fires size and potential emissions impacting a given site on a given day. The smoke metric used in the statistical analysis below was evaluated by first obtaining the maximum observed level over the site in the past 24 h and the maximum level at distances of 1–1000 m and 1–10 km from the site in the past 48 h. Next the maximum of those values over a given day was evaluated and used in the statistical analysis as the HMS smoke level on a given day. A thorough check was done for each day with HMS analyzed smoke to ascertain that there were no potential sources of smoke other than fires.

2.4. Wildland fire

Data for wildland fire on federal and state land in California were retrieved from the National Wildfire Coordinating Group (NWCG, 2014). Validation for localized smoke impacts was determined by compiling all wildland fires less than 10 km from each site and fires over 4046 ha within 100 km.

2.5. Statistical models

Estimation was done in two steps. In the first step we estimate the expected 96th percentile $PM_{2.5}$ value for days with no observed HMS smoke above the site. In the second step we compare the distributions of departure from the 'norm' for days with various levels of smoke (including no smoke).

Step 1: Our metric for the amount of $PM_{2.5}$ at a given site was the daily 96th percentile value (Y96) calculated from the observed hourly $PM_{2.5}$ values recorded at each site. Using the 96th percentile of 24 hourly $PM_{2.5}$ values as the response variable implies that there was only one hour with a value greater than Y96. The statistical methods described next also apply if the response variable is the median (Y50) or the mean or any other quantile. Because different sites have their unique, characteristic, seasonal patterns (Cisneros

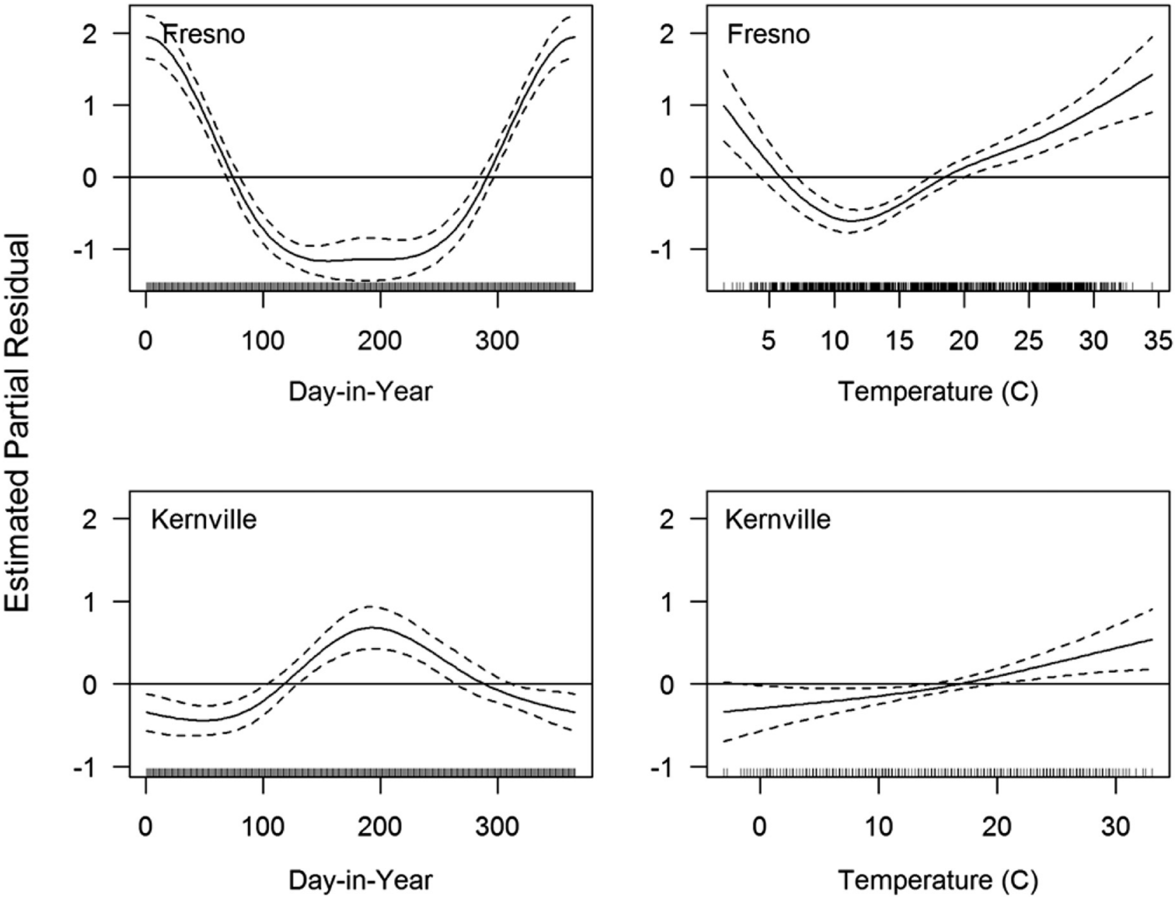

Fig. 2. Estimated effects (smooth spline functions from equation (1)) of day-in-year and temperature on square root of the daily 96th percentile $PM_{2.5}$ values at two sites.

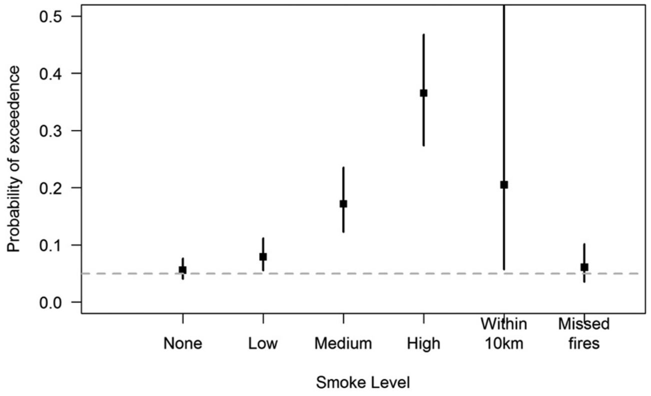

Fig. 3. Estimated probability of $PM_{2.5}$ level significantly exceeds expected (and 95% confidence bars) for days with various levels of HMS smoke over and within 10 km of a site. The missed fires category refers to days with fire nearby but no observed HMS smoke.

et al., 2014) and unique relationships with weather, a separate model was estimated for each site. Following are the specifics of the fitted autoregressive models:

$$Y_i = \beta_o + \gamma_{4i} + sp(day_i) + s(ws_i) + sp(wd_i) + s(temp_i) + s(rh_i) + \varepsilon_i \quad \text{for } i \in NS \tag{1}$$

Where $Y_i = \sqrt{Y96}$ (the square root was used to satisfy a symmetric assumption).

β_o = intercept of the regression line

γ_4 = a categorical variable indicating whether the day is July 4th or not. This variable is used to account for the heavy level of $PM_{2.5}$ at some sites due to fireworks on July 4th.

s(ws), s(temp), s(rh) = are smooth spline functions of the daily median wind speed, temperature and relative humidity (Wood, 2006).

sp(day), sp(wd) = are smooth periodic spline functions of day-in-year and daily median wind direction. The periodic function is used to account for the cyclic nature of the day-in-year and wind direction metrics.

ε_i = autoregressive error of order one used to account for potential serial correlation in the daily PM values.

NS = set of all days with no observed HMS smoke over the site.

Using the above model we were able to estimate expected $PM_{2.5}$ levels for each site on a given day using the observed weather conditions on that day, for days with no smoke observed above the site. This is important because we found that different sites have different seasonal patterns and different relationships with weather. For example, at the Fresno site $PM_{2.5}$ values appear to be characteristically high in the winter and on colder days when, apparently, anthropogenic source emissions dominate, likely attributed to low level temperature inversions which act to trap emissions (Fig. 2). At the Kernville site $PM_{2.5}$ values are characteristically highest during the summer months (July in particular) and $PM_{2.5}$ values seem to increase with increasing temperature, albeit marginally. This may be due to higher inversion levels or the lack of them during the warm season which allows for greater mixing of the boundary layer. Estimation was done within the R-statistical package (R Core Team, 2013).

Step 2: The above model takes into account the variability in $PM_{2.5}$ values due to weather and seasonal patterns. For a good fit, we anticipate approximately 5% of the observed values to be greater than 1.64 standard deviations from the expected (upper 95th percentile). In order to study this we used the following response variable as a measure of exceedance of the norm,

$$\begin{aligned} r &= 1 \quad \text{if } Y96 > (\widehat{\mu} + 1.64\widehat{\sigma})^2 \\ &= 0 \quad \text{otherwise} \end{aligned} \tag{2}$$

where $\widehat{\mu}$ and $\widehat{\sigma}$ are estimates of the expected value and standard deviation, respectively, evaluated for each site and each day-in-year using the model in equation (1). Next we estimate the frequency of times we have departure from the norm, i.e. $p = \Pr[r = 1]$. We used the following random effect logistic regression model

$$logit\left(p_{ijk}\right) = \beta_o + \gamma_{ijk} + \tau_k \tag{3}$$

where

γ_{ijk} ~ categorical variable for site *i*, day *j*, year *k* with the following six categories:

(1) None – no HMS smoke in past 24 h and no fires nearby.

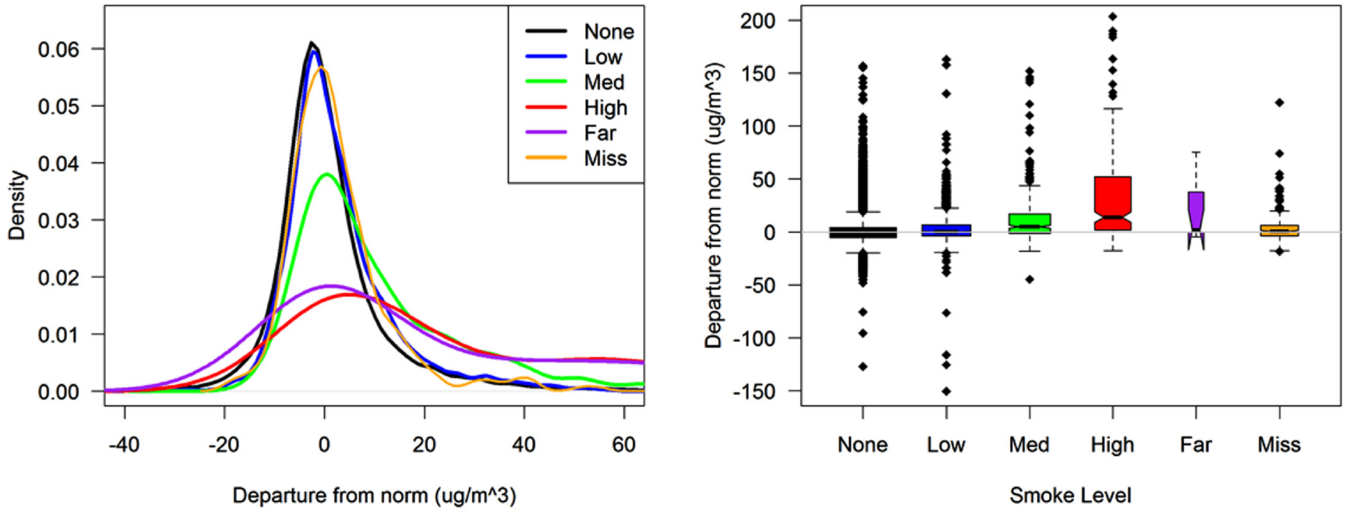

Fig. 4. Distributions (left panel) and boxplots (right panel) of departure from 'norm' (residuals), for days with no smoke over or near a site (black); low smoke level (blue); medium smoke level (green); heavy smoke level (red); medium or heavy smoke level within one to ten km from site (purple) and days with fire within 10 km but no Smoke over site (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

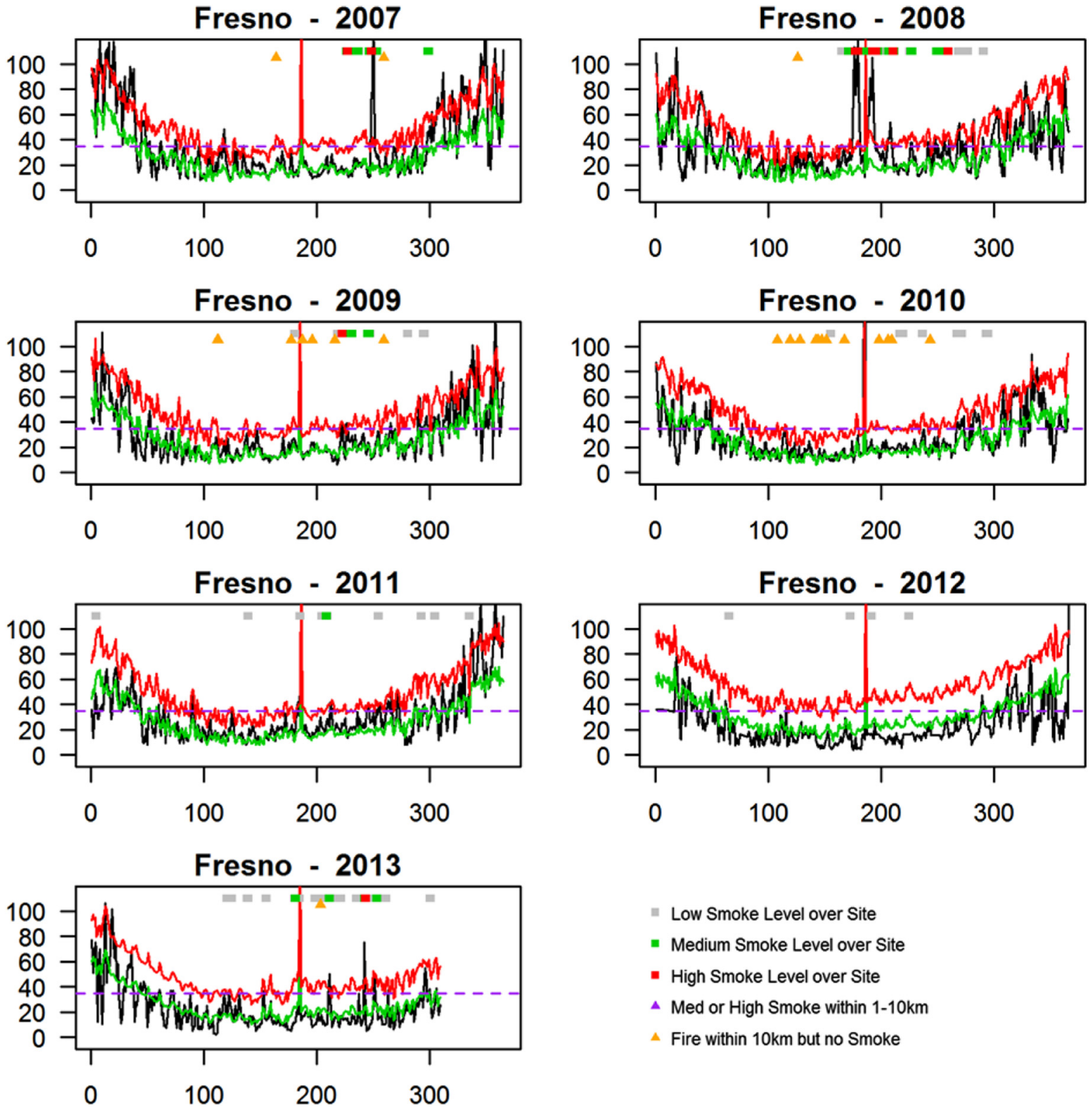

Fig. 5. Observed (black) and expected (green) daily 96th percentile $PM_{2.5}$ values at the Fresno site. The x-axis is day-in-year and the y-axis is $\mu g/m^3$. Red lines are the estimated pointwise upper 95th confidence bounds. The expected (green) and upper 95th percentile (red) were estimated from days with no smoke over the site and consequently are assumed to be the expected norm. The very high observed and expected values each year are on July 4th. Also marked are the days with various levels of smoke observed over and near the site and days with observed fires within 10 km of site but no observed smoke over the site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2) Low – Low level of HMS smoke above site in past 24 h (see Section 2.3).
(3) Med – Medium level of HMS smoke above site in past 24 h.
(4) High – Heavy level of HMS smoke above site in past 24 h.
(5) Far – Med or High within 1 km or High 1–10 km distance from site in past 48 h.
(6) Miss – no HMS smoke above the site but fires within 10 km of site (see Section 2.4 for nearby fires).

The sixth category is included to see whether HMS missed any days where a nearby fire may have had an effect on ground level PM even though no smoke was observed above the site by satellite.

τ_k ~ a random year effect included in the model to minimize the potentially unduly effect of a particular year.

We also produced plots of the distributions of the residuals from model [1] (departure from the norm) for each HMS smoke level as another means of showing the impact of HMS smoke on $PM_{2.5}$ levels.

3. Results

Estimated probability of $PM_{2.5}$ exceedance of the norm was on average 5% for days with no observed HMS smoke above the site (Fig. 3). Because of the way we defined exceedance of the norm (equation (2)) we expect to observe exceedance on approximately 5% of days with no smoke and no fire nearby. The probability for days with low smoke level was 7%, and 6% on days with a nearby fire and no HMS smoke above the site. The latter implies that there is little to no difference in surface $PM_{2.5}$ values for days with low

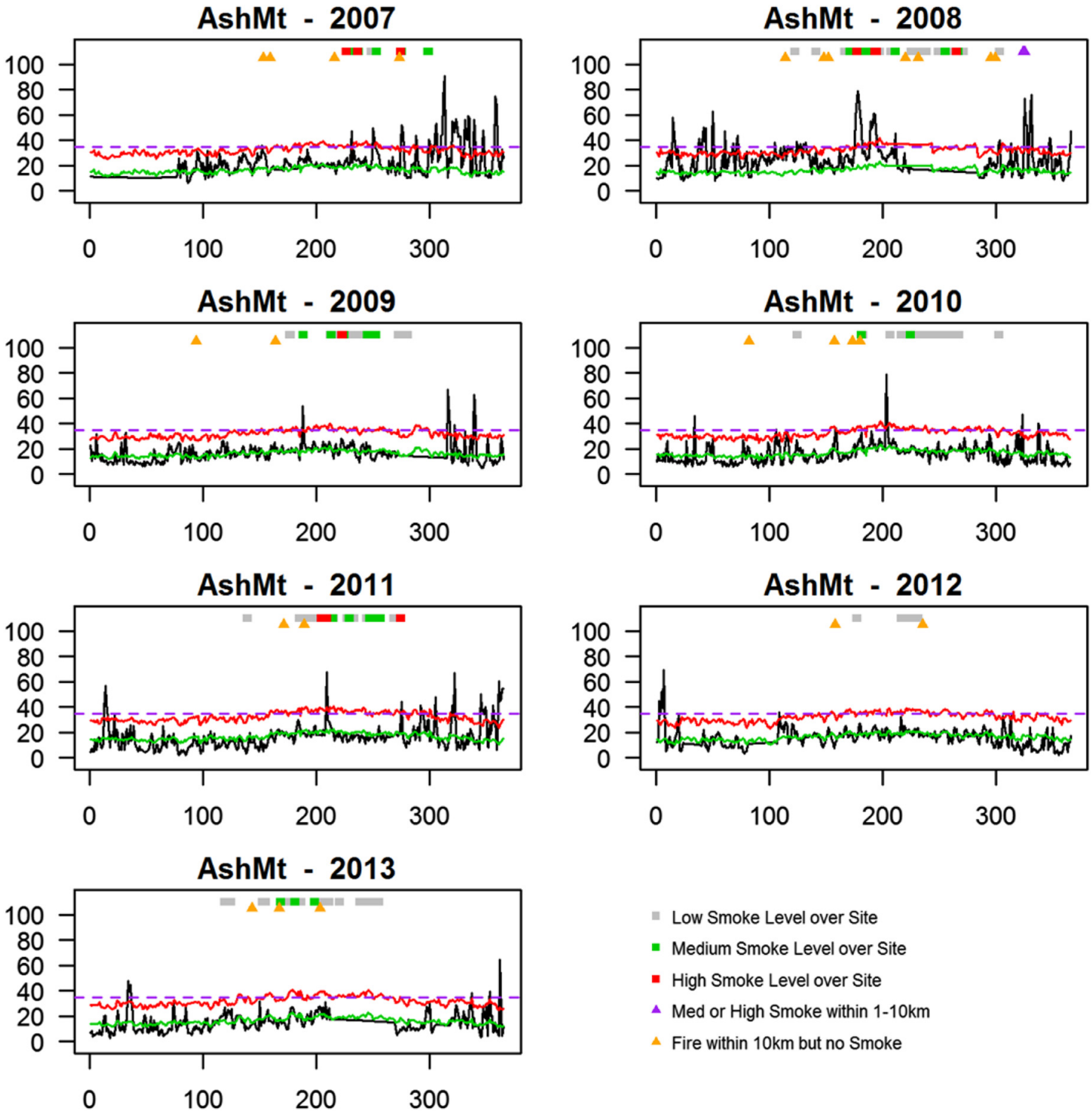

Fig. 6. Observed (black) and expected (green) daily 96th percentile $PM_{2.5}$ values at the Ash Mountain site. The x-axis is day-in-year and the y-axis is $\mu g/m^3$. Red lines are the estimated pointwise upper 95th confidence bounds. Also marked are the days with various levels of smoke observed over and near the site and days with observed fires within 10 km of site but no observed smoke over the site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

level of HMS smoke or days with nearby fire but no HMS smoke, as compared to control days -no HMS smoke and no nearby fire-. We noted however a significant increase in exceedances from norm on days with medium or heavy smoke levels, with the probability of exceedance of 36%, (95% CL between 27 and 47%) on days with heavy levels of observed smoke over the site. The increase in probability of exceedance on days with medium or heavy levels observed within 1 m – 10 km of the site over the past 48 h was also significant; however the standard error was large due to small number of cases. To summarize, medium or heavy levels of observed smoke over a site do show significant impact on surface $PM_{2.5}$ in that the probability of exceeding the expected $PM_{2.5}$ value is significantly increased (Fig. 3). However, observed satellite smoke over a site does not always translate to an increase in surface $PM_{2.5}$. The number of days with an expected increase in surface $PM_{2.5}$ was on average 36% on days with heavy smoke levels. The estimated amount of increase in the daily 96th percentile for days with a heavy level of smoke was 14 $\mu g/m^3$ (95% CL was 9–19 $\mu g/m^3$) and 5 $\mu g/m^3$ for days with medium smoke level (95% CL was 3.6–6.1 $\mu g/m^3$). On average no significant increase was observed on days with a low level of smoke above the site (Fig. 4). These results are also confirmed in the plots of the distributions of the residuals (departure from norm) generated by subtracting the expected $PM_{2.5}$ values – for the given site, day and weather conditions - from the observed (Fig. 4). The heavier tail distribution observed for days with medium or heavy HMS smoke is another indication of the positive impact of HMS smoke levels on surface $PM_{2.5}$ levels.

We generated plots of the observed and predicted daily 96th quantile $PM_{2.5}$ values with HMS smoke metric and fire occurrence's dates on the same figure. The predicted curves in these plots are 96th percentile PM values expected on days with no smoke above the site. Examples from two sites (Fresno and Ash Mountain) are presented in Figs. 5 and 6. Plots for all the other sites are in Supplemental material (S1 – S11). Some interesting features to

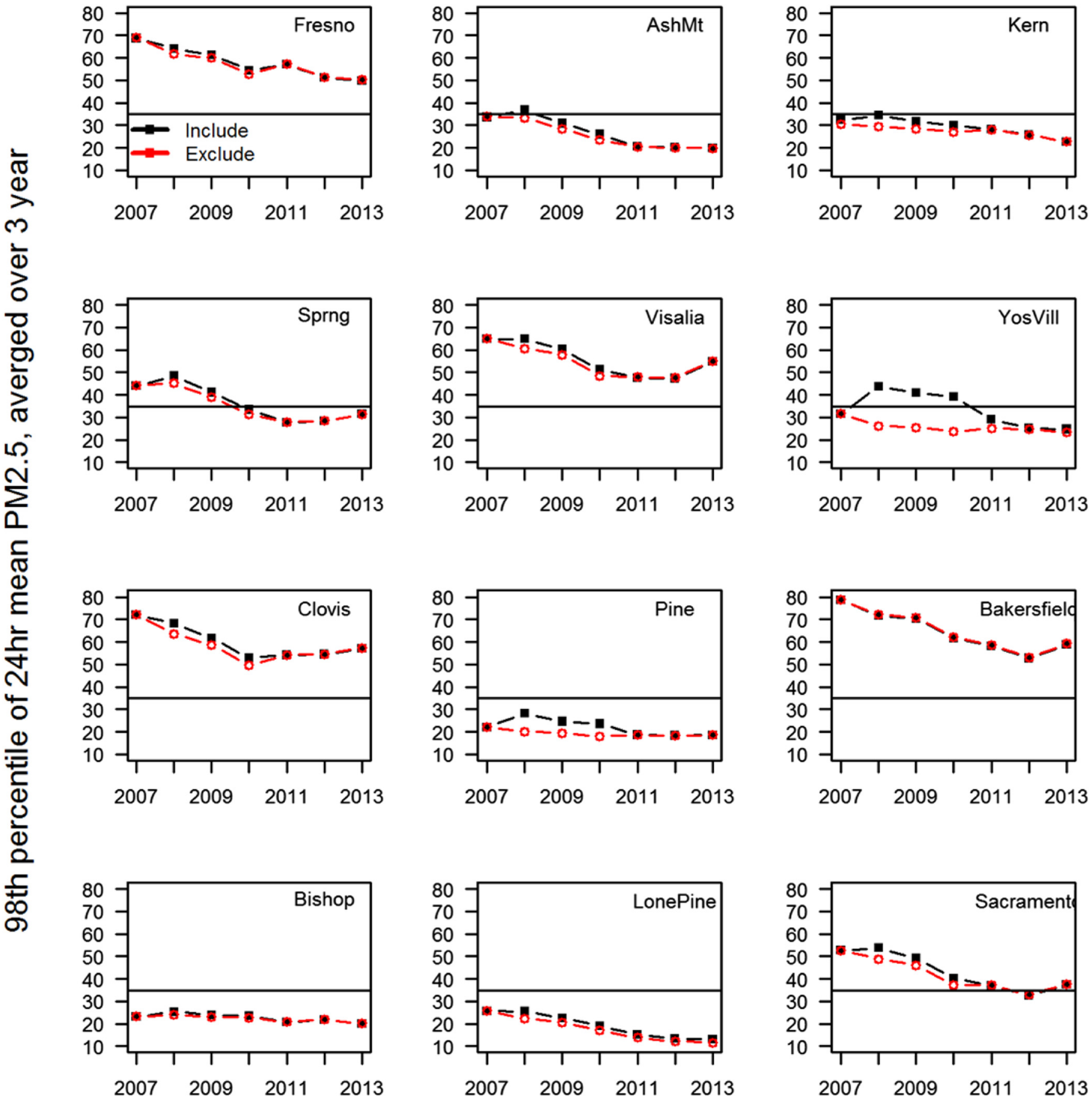

Fig. 7. Ninety eight percentile statistics calculated for each site in two ways: 1) using all days in a given year (black) and 2) using only days not impacted by fire (red). A given day was assumed to be impacted by fire if the HMS smoke metric was at a medium or heavy level (further details in text). All values are three year averages, except for 2007 (one year value) and 2008 (two year average). In almost all years and sites (except for Yosemite village) removal of fire days did not have an effect on the compliance of a site to the National quality standards. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

note are the unique seasonal patterns and the daily variability in the observed and expected values at the various sites. For example, the amounts of fluctuation (wiggles in the observed values) around the seasonal pattern (high in winter, lower in summer months) at the Fresno site appear to be adequately explained by the fluctuations in the daily expected values. The daily fluctuations in the expected values are due to weather, the only explanatory variables in the model that change daily. The few cases of departure from norm (e.g., day-in-year 250 in 2007 and between days 180–200 in 2008 where the observed values are larger than the expected upper 95th percentiles) seem to coincide with observed HMS smoke over or near a site. Note also how each instance of observed HMS smoke above or near a site does not always imply $PM_{2.5}$ exceedance at the surface (e.g., between day-in-year 200–250 in 2009). On the other hand, at the Ash Mountain site there are quite a few instances of departure from norm (in particular in late Fall). These departures do not seem to be accounted for either by weather or fire. And since these above normal $PM_{2.5}$ values in the fall are not consistently observed each year, they are not accounted for by the seasonal pattern as was the case at the Fresno site. Concentrations of $PM_{2.5}$ at

Ash Mountain are typically lower than the more urban Fresno site particularly during fall and winter when $PM_{2.5}$ concentrations are highest in the adjacent Central Valley (Cisneros et al., 2014). Although the sources of higher than expected $PM_{2.5}$ values at Ash Mountain on those days are unknown, we can be confident that they are not caused by wildfires because no smoke was observed from the satellites and there were no observed fires in the neighborhood of the site on those days.

Our analysis demonstrated that HMS is a useful tool for deciding whether the $PM_{2.5}$ values on a given day were impacted by wildland fires or not. When the expected 96th quantile of surface $PM_{2.5}$ is surpassed on a day with a heavy HMS smoke over a site we can conclude with high level of certainty (95% confidence) that smoke (from wildland fires) had an impact on $PM_{2.5}$. Additionally, when the expected 96th quantile of ground level $PM_{2.5}$ is surpassed on a day with no observed HMS smoke we can conclude with 95% certainty that the impact was not caused by a fire.

To recap, the EER criteria require that demonstrations for fires that impact air quality monitoring data related to exceedances or violations of the NAAQS have a clear causal relationship to the fire in question, show that historical fluctuations were exceeded, and that the exceedances would not have occurred but for the presence of the fire. Here we demonstrate a relatively simple, sensitive, and objective way to use the HMS metric developed in this study to assist in the flagging and demonstration process. In particular, the metric may be used to decide whether a given day with an exceedance may be considered an exceptional event day and subsequently whether the $PM_{2.5}$ for that day may be excluded from the calculation of compliance to NAAQS. The latest (2012) national air quality standard for $PM_{2.5}$ requires that the 98th percentile of X −where X is the daily (24hr) average $PM_{2.5}$ − averaged over three years be less than 35 $\mu g/m^3$.

As an exercise to demonstrate this method and its ultimate result, we calculated the above statistic for each of the sites in our study using all days in the year. Then we evaluated the same statistic with all days impacted with smoke removed. We assumed any day that had an observed exceedance (observed $PM_{2.5}$ significantly greater than expected) and observed medium or heavy HMS smoke level (maximum smoke level in the past 48 h within 10 km of site) is an impacted day (Fig. 7).

In almost all the sites the removal of fire-impacted-days from the calculation did not affect the compliance. The exception was the Yosemite site where a drop in the 98th percentile statistic from above 35 $\mu g/m^3$ (no compliance) to below the standard was observed in 2008–2010. Also, we note an effect of fire in almost all the sites during 2008 when smoke from large fires throughout California seems to have been transported to the monitoring sites and had a large impact on the surface $PM_{2.5}$ values (Cisneros et al., 2014; Gyawali et al., 2009). Nonetheless, the impact of fire on compliance was seen only at three of the sites in our study (Ash Mountain, Kernville and Yosemite Village).

4. Discussion & conclusions

Years with large wildland fire emissions (such as 2008 throughout much of California) have been shown to increase surface $PM_{2.5}$ concentrations. These emissions necessarily must be taken into account when considering air quality for both policy and public health considerations, especially where air quality is already poor. While years with large high intensity wildland fire incidents impact $PM_{2.5}$ concentrations in the area around the Sierra Nevada (including the San Joaquin and Owens Valley), the impact from all wildland fires do not appear to be the main driver in terms of $PM_{2.5}$ increases in this area (Fig. 7). The above exercise, using this tool, seems to indicate that wildland fire is not a major driving force in attainment compliance of the federal standard in this area. This is similar to the findings in Cisneros et al. (2014) where the majority of the $PM_{2.5}$ pollution in the Sierra Nevada appears to be driven by the constant anthropogenic emissions, rather than the episodic natural sources, like fire.

NOAA HMS product is a useful tool for corroborating the influence of wildland fires on surface $PM_{2.5}$ values. However, it is not a replacement for monitoring at surface sites because, while the observed plumes are statistically significant predictors of days with fire impact, the strength of the relationships between HMS smoke level and $PM_{2.5}$ level, or even with the change in $PM_{2.5}$ from expected, are weak (~65% of the days with observed heavy smoke levels show no impact on surface values). Furthermore, on days that impacts from observed fire plumes were found, the amount of increase in $PM_{2.5}$ is decidedly imprecise: on average anywhere between 9 and 19 $\mu g/m^3$, with a range between minus 10 to over 200 $\mu g/m^3$. In combination with a statistical model that quantifies thresholds for historical fluctuations however, this HMS product, can provide a powerful, simple, and sensitive diagnostic for finding and flagging days that can be considered 'exceptional events' under the EER (2007). The statistical model is essential for quantifying the distribution of PM levels for days not impacted with fire and characterizing the variability due to factors other than fire, such as weather or other seasonal sources of smoke. Our study found that fires in most years have no significant impact on compliance with current federal regulatory thresholds.

Acknowledgment

We would like to thank Ellen Ramirez, Ton Salemi, and Laura Paulik from NOAA for their help with the HMS data.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2015.06.018.

References

Air Quality and Meteorological Information System, 2014. http://www.arb.ca.gov/aqmis2/aqmis2.php (accessed 14.08.14.).

Cisneros, R., Schweizer, D., Preisler, H.K., Bennett, D.H., Shaw, G., Bytneworicz, A., 2014. Spatial and seasonal patterns of particulate matter less than 2.5 microns in the Sierra Nevada Mountains, California. Atmos. Pollut. Res. 5, 581–590.

Elliott, C.T., Henderson, S.B., Wan, V., 2013. Time series analysis of fine particulate matter and asthma reliever dispensations in populations affected by forest fires. Environ. Health 12, 11–20.

Exceptional Events Rule 40 U.S.C. Sec 50.14, 2007. U.S. Government Printing Office, 2014. http://www.ecfr.gov/cgi-bin/text-idx?SID=c203a60eb1ef06f943b24cdc0944981d&node=40:2.0.1.1.1.0.1.14&rgn=div8 (accessed 11.04.14.).

Goodrick, S.L., Achtemeier, G.L., Larkin, N.K., Liu, Y., Strand, T.M., 2013. Modelling smoke transport from wildland fires: a review. Int. J. Wildland Fire 22 (1), 83–94.

Gyawali, M., Arnott, W.P., Lewis, K., Moosmuller, H., 2009. In situ aerosol optics in Reno, NV, USA during and after the summer 2008 California wildfires and the influence of absorbing and non-absorbing organic coatings on spectral light absorption. Atmos. Chem. Phys. 9, 8007–8015.

Hoff, R.M., Christopher, S.A., 2009. Remote sensing of particulate pollution from space: have we reached the promised land? J. Air & Waste Manag. Assoc. 59, 645–675.

Hurteau, M.D., Westerling, A.L., Wiedinmyer, C., Bryant, B.P., 2014. Projected effects of climate and development on California wildfire emissions through 2100. Environ. Sci. Technol. 48, 2298–2304.

Lin, Y.L., Jao, I.C., 1995. A numerical study of flow circulations in the central valley of California and formation mechanisms of the Fresno eddy. Mon. Weather Rev. 123, 3227–3239.

Miller, J.D., Safford, H.D., 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and Southern Cascades, California, USA. Fire Ecol. 8, 41–57.

Moeltner, K., Kim, M.-K., Zhu, E., Yang, W., 2013. Wildfire smoke and health impacts: a closer look at fire attributes and their marginal effects. J. Environ. Econ. Manag. 66, 476–496.

National Wildfire Coordinating Group (NWCG), 2014. http://fam.nwcg.gov/fam-web/weatherfirecd/state_data.htm (accessed 17.11.14.).

North, M.P., Collins, B.M., Stephens, S.L., 2012. Using fire to increase the scale, benefits and future maintenance of fuels treatments. J. For. 110, 392–401.

Preisler, H.K., Grulke, N.E., Bytnerowicz, A., Esperanza, A., 2005. Analyzing effects of forest fires on diurnal patterns of ozone concentrations. Phyt. (Austria) 45, 33–39. Special issue: APGC 2004.

Preisler, H.K., Zhong, S., Esperanza, A., Brown, T.J., Bytnerowicz, A., Tarnay, L., 2010. Estimating contribution of wildland fires to ambient ozone levels in National Parks in the Sierra Nevada, California. Environ. Pollut. 158 (3), 778–787.

R Core Team, 2013. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Rappold, A.G., Fann, N.L., Crooks, J., Huang, J., Cascio, W.E., Devlin, R.B., Diaz-Sanchez, D., 2014. Forecast-based interventions can reduce the health and economic burden of wildfires. Environ. Sci. Technol. 48, 10571–10579.

Rolph, G.D., Draxler, R.R., Stein, A.F., Taylor, A., Ruminski, M.G., Kondragunta, S., Zeng, J., Huang, H.-C., Manikin, G., McQueen, J.T., Davidson, P.M., 2009. Description and verification of the NOAA smoke forecasting system: the 2007 fire season. Weather Forecast. 24, 361–378.

Ruminski, M., Simko, J., Kibler, J., Kondragunta, S., Draxler, R., Davidson, P., Li, P., August 2008. Use of multiple satellite sensors in NOAA's operational near real-time fire and smoke detection and characterization program. In: Presented at SPIE Optics and Photonics Conference, San Diego, CA.

Schweizer, D., Cisneros, R., 2014. Wildland fire management and air quality in the southern Sierra Nevada: using the Lion Fire as a case study with a multi-year perspective on $PM_{2.5}$ impacts and fire policy. J. Environ. Manag. 144, 265–278.

State of Nevada Division of Environmental Protection Bureau of Air Quality Planning, 2014. http://nvair.ndep.nv.gov/ (accessed 21.08.14.).

Stein, A.F., Rolph, G.D., Draxler, R.R., Stunder, B., Ruminski, M., 2009. Verification of the NOAA smoke forecasting system: model sensitivity to the injection height. Weather Forecast. 24, 379–394.

Stephens, S.L., Martin, R.E., Clinton, N.E., 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. For. Ecol. Manag. 251, 205–216.

Stevens, J.T., Safford, H.D., Latimer, A.M., 2014. Wildfire-contingent effects of fuel treatments can promote ecological resilience in seasonally dry conifer forest. Can. J. For. Res. 44, 843–854.

Toth, T.D., Zhang, J., Campbell, J.R., Hyer, E.J., Reid, J.S., Shi, Y., Westphal, D.L., 2014. Impact of data quality and surface-to-column representativeness on the $PM_{2.5}$/satellite AOD relationship for the contiguous United States. Atmos. Chem. Phys. 14, 6049–6062.

Tribal Environmental Exchange Network, 2014. http://trexwww.ucc.nau.edu/ (accessed 21.07.14.).

U.S. Department of the Interior National Park Service, 2014. http://ard-request.air-resource.com/data.aspx (accessed 13.08.14.).

van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fule, P.Z., Harman, M.E., Larson, A.J., Smith, J.M., Taylor, A.H., Veblen, T.T., 2009. Widespread increase of tree mortality rates in the western United States. Science 323, 521–524.

Wang, J., Christopher, S.A., 2003. Intercomparison between satellite-derived aerosol optical thickness and $PM_{2.5}$ mass: implications for air quality studies. Geophys. Res. Lett. 30 (21), 2095.

Williams, M.A., Baker, W.L., 2012. Spatially extensive reconstructions show variable-severity fire and heterogeneous structure in historical western United States dry forest. Glob. Ecol. Biogeogr. 21 (10), 1042–1052.

Wood, S.N., 2006. Generalized Additive Models: an Introduction with R. Chapman and Hall/CRC Press, p. 392.

Yao, J., Henderson, S.B., 2014. An empirical model to estimate daily forest fire smoke exposure over a large geographic area using air quality, meteorological, and remote sensing data. J. Expo. Sci. Environ. Epidemiol. 24, 328–335.

Zhang, H., Hoff, R.M., Engel-Cox, J.A., 2009. The relation between moderate resolution imaging spectradiometer (MODIS) aerosol optical depth and $PM_{2.5}$ over the United States: a geographical comparison by U.S. Environmental Protection Agency regions. J. Air & Waste Manag. Assoc. 59, 1358–1369.