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Effects of Independence Day fireworks on atmospheric concentrations of fine particulate matter in the United States

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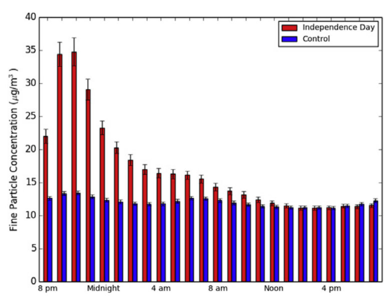
HIGHLIGHTS

- We report early-July hourly particulate (PM2.5) levels at 315 US monitoring sites.
- PM2.5 concentrations are elevated on July 4 evening and July 5 morning.
- Increases are largest at 9–10 pm on July 4 and diminish by noon on July 5.
- On national average, holiday 24-hr PM2.5 levels are elevated by 5 μg/m^3 (42%).
- A site adjacent to fireworks shows 48 μg/m^3 (370%) increases in 24-hr PM2.5.

GRAPHICAL ABSTRACT



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ABSTRACT

Previous case studies have documented increases in air pollutants, including particulate matter (PM), during and following fireworks displays associated with various holidays and celebrations around the world. But no study to date has explored fireworks effects on air quality over large regions using systematic observations over multiple years to estimate typical regional PM increases. This study uses observations of fine PM (with particle diameters < 2.5 μm, PM2.5) from 315 air quality monitoring sites across the United States to estimate the effects of Independence Day fireworks on hourly and 24-hr average concentrations. Hourly PM2.5 concentrations during the evening of July 4 and morning of July 5 are higher than on the two preceding and following days in July, considered as control days. On national average, the increases are largest (21 μg/m^3) at 9–10 pm on July 4 and drop to zero by noon on July 5. Average concentrations for the 24-hr period beginning 8 pm on July 4 are 5 μg/m^3 (42%) greater than on control days, on national average. The magnitude and timing of the Independence Day increases vary from site to site and from year to year, as would be expected given variations in factors such as PM2.5 emissions from fireworks, local meteorological conditions, and distances between fireworks displays and monitoring sites. At one site adjacent to fireworks, hourly PM2.5 levels climb to ~500 μg/m^3, and 24-hr average concentrations increase by 48 μg/m^3 (370%). These results have implications for potential improvements in air quality models and their predictions, which currently do not account for this emissions source.

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1. Introduction

Around the world, celebrations of public holidays, religious festivals, sporting events, political and military victories, and other occasions often include pyrotechnic displays, or fireworks (Plimpton, 1984). Festivities such as Bastille Day in France, Guy Fawkes Night in the U.K., Diwali in India, the Lantern Festival in Taiwan and China, Canada Day, and, in many countries, New Year's Eve often involve aerial fireworks. In the United States, Independence Day (July 4) is particularly associated with fireworks, a custom that dates back to the founding of the nation. Shortly after the drafting of the Declaration of Independence, in a July 3, 1776, letter to his wife Abigail, John Adams predicted:

> "The Second Day of July 1776, will be the most memorable Epocha, in the History of America. I am apt to believe that it will be celebrated, by succeeding Generations, as the great anniversary Festival. It ought to be commemorated, as the Day of Deliverance by solemn Acts of Devotion to G-d Almighty. It ought to be solemnized with Pomp and Parade, with Shews, Games, Sports, Guns, Bells, Bonfires and Illuminations from one End of this Continent to the other from this Time forward forever more."

More than two centuries later, in a 2013 press release, the American Pyrotechnics Association (APA), an industry organization, estimated that "(a)nnually the skies over the nation are graced with over 14,000 Independence Day fireworks displays." Organized aerial displays are only part of the story. APA reports that consumer use of fireworks accounted for 88% of the total 2013 US fireworks consumption (Source: APA website http://www.americanpyro.com/).

The Federal Hazardous Substances Act classifies fireworks as hazardous, because the explosives can have dangerous side effects, including fires, injury, and death. Air pollution is another potentially harmful effect of fireworks (Wang et al., 2007), which release gaseous sulfur dioxide, carbon dioxide and carbon monoxide; hazardous trace elements such as aluminum, manganese, and cadmium; and particulate matter (PM), evidenced by visible clouds of smoke during displays.

Exposure to PM is associated with a broad range of adverse human health effects, mainly affecting the respiratory and cardiovascular systems (WHO, 2003). The US Environmental Protection Agency sets National Ambient Air Quality Standards (NAAQS) for PM (PM2.5 and PM10, with particle diameters less than 2.5 and 10 μm, respectively) under the Clean Air Act. Current NAAQS for PM2.5 pertain to annual and 24-hr averages and are 12 and 35 $\mu g/m^3$, respectively (EPA, 2013a). The latter threshold is used both to determine if an area is in compliance with the NAAQS and to trigger "Action Days," when air quality is forecast to be unhealthy for sensitive groups.

To understand the potential impact of holiday fireworks on compliance, it is important to appreciate the structure of the NAAQS. The 24-hr NAAQS require that the 3-yr average of annual 98th percentile values of 24-hr-average concentrations not exceed 35 $\mu g/m^3$. Thus about six days per year may have PM2.5 exceeding the 24-hr standard, considered in a 3-yr-average context. Furthermore, state, local, and tribal agencies may flag an exceedance of the NAAQS as an "exceptional event," an unusual or natural event, such as a wildfire or volcanic eruption, affecting air quality that is not reasonably controllable by the relevant jurisdiction. Designated exceptional events are not included in determining compliance. Some fireworks events have been allowed exceptional event designation (EPA, 2007).

Previous studies of the air pollution effects of fireworks, summarized below, have demonstrated elevated concentrations of various pollutants, including PM, in association with particular fireworks displays or in particular locations. Examples of some recent findings include:

- Increase in sub-micron particle mass concentration by a factor of 10 or greater for about an hour following the 2005 New Year's celebration fireworks in Mainz, Germany, and a daily average concentration on January 1 exceeding the European Union PM10 air quality standard of 50 $\mu g/m^3$ (Drewnick et al., 2006)
- Increases in daytime and nighttime PM10, SO_2, and NO_x, by factors of 2–7, during Diwali in Lucknow City, India (Barman et al., 2008)
- Increase in PM10 concentrations by up to a factor of 5 during Diwali in Kolkata, India (Chatterjee et al., 2013)
- Increase in PM2.5 concentrations by a factor of 6 during the 2006 Lantern Day in Beijing (Wang et al., 2007).
- Increase in PM2.5 by up to a factor of 50 within the fireworks plume and within 2 km of the launch site during the 2007 Montreal International Fireworks Competition (Joly et al., 2010)
- Increase in PM10 of about 50% during fireworks for World Cup celebrations in Milan in July 2006 (Vecchi et al., 2008)

In the US, Liu et al. (1997) and Carranza et al. (2001) have compared the chemical composition of atmospheric aerosols on July 4 to background levels during single years at single locations in California and Florida, respectively. Other investigators (e.g., Lee et al., 2006; Larson et al., 2006; Hallar et al., 2013) have noted elevated PM levels on Independence Day, deemed them unrepresentative samples, and excluded those data from their analyses of ambient air quality.

To our knowledge, no published studies to date report fireworks effects on air quality over large regions based on systematic observations over multiple years. These are important issues because local topographic and meteorological conditions may cause pollutant concentrations that are not representative of larger domains or different weather patterns. The present study addresses these gaps by taking a national perspective and examining several years of observations, in an effort to characterize PM2.5 exposure in the US associated with Independence Day fireworks.

2. Methods

This analysis is based on hourly, early July observations of PM2.5 at 315 sites across the US during 1999–2013, obtained from the Air Quality System (AQS), a database maintained by the US Environmental Protection Agency (EPA, 2013b). Although the AQS includes observations from more than 4000 sites operated by state, local, and tribal agencies, most do not provide hourly PM2.5 measurements, because they use a filter-based measurement method whereby particles are collected over a 24-hr period. The newer, continuous monitoring method is used at a subset of sites in the network.

We use two types of PM2.5 data, as categorized in the AQS database. The first is "PM2.5 Local Conditions" measurements obtained with filter-based instruments using Federal Reference Methods (FRM), Federal Equivalence Methods (FEM), and Approved Regional Methods (ARM); such data can be used in NAAQS decisions. The FRM label applies only to daily measurements – the filter is weighed after 24 h of sampling. Continuous PM2.5 data collected via ARM that agree within specified limits with FRM measurements are labeled FEM and are EPA-approved for use by state, local, and tribal agencies to meet air quality objectives. The second category is "Acceptable PM2.5 AQI & Speciation Mass" (where AQI is Air Quality Index). These are continuous PM2.5 data

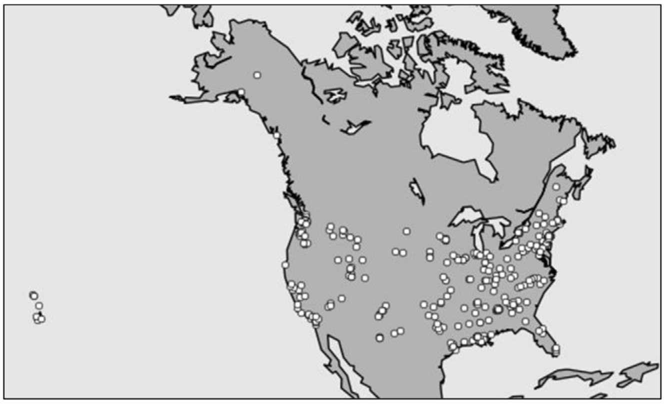

Fig. 1. Locations of 315 PM2.5 monitoring stations used in this study. Station names and locations are included as Supplementary Data.

that reasonably match the FRM but are not used for regulatory purposes. These data are either uncorrected or statistically corrected hourly data that agree within 10% with FRM data, on seasonal or annual average, and show a correlation with FRM of at least 0.9.

To compare PM2.5 on Independence Day with similar control[1] days, we define the holiday as the 24-hr period beginning at 8 pm (20 Local Standard Time, LST) on July 4 and ending at 7 pm (19 LST) on July 5. Defining the Independence Day holiday as starting at 8 pm for the purposes of this study is supported by two important considerations. First, July 4 fireworks displays traditionally and typically begin after sunset, which occurs around 8 pm on July 4. Second, sensitivity tests, varying the starting hour on the evening of July 4, clearly revealed evidence for PM2.5 increases on Independence Day starting at 8 pm.

The four control days, spanning the same hours, begin at 8 pm on July 2, 3, 5, and 6. We include any particular year for a given station only if data are available for every hour of every day in the analysis period for that year, and we require at least three such years for each station. These requirements are designed to minimize the influence of year-to-year variations in background PM2.5, allow a fair comparison of results for different hours of the day, and balance the desire for a large set of stations with the desire for a large sample of years. Of the 315 sites meeting these criteria, 61 have "PM2.5 Local Conditions" data and the other 254 have "Acceptable PM2.5 AQI & Speciation Mass" data. In 14 instances, both data types are available, and, although each is categorized as a separate station, we consider them co-located and compare results from the two data types. The spatial distribution of sites (Fig. 1) reasonably covers the US but is biased toward population centers and shows clustering of sites in some urban areas.

For each station, we compare PM2.5 on Independence Day and control days, using both daily-average and hourly-average PM2.5 data. In both cases, we have n values for Independence Day, where n is the number of years of data available, and 4n values for control days. To test the null hypothesis that average PM2.5 concentrations are not significantly greater on Independence Day than during the control period, we employ a one-tailed t-test, assuming unequal variances and unequal sample sizes, and requiring $p < 0.05$ to reject the null hypothesis.

[1] The term "control" is used here in the standard scientific sense of a set of observations against which another set may be compared and not in the sense of air quality regulatory control.

3. Results

Here we present a summary of observed hourly and 24-hr-average PM2.5 concentrations on Independence Days and control days averaged over all sites across the US, where results for each site represent multi-year averages. Results for two specific locations, Ogden, Utah, and Washington, DC, are then used to illustrate particular points. Comparable results for all 315 sites analyzed are included in Supplementary Data. The impact of the day of the week on which Independence Day occurs is also explored.

3.1. National average PM2.5 increases

Fig. 2(a) shows the US-average mean hourly PM2.5 values (starting at 8 pm, 20 LST) on Independence Days and control days. On early July control days, hourly values vary between ~11 and 14 $\mu g/m^3$, with standard errors <1 $\mu g/m^3$. There is a suggestion of a diurnal variation with two concentration peaks per day, one before midnight and the other just after sunrise. The 24-hr average is 12.0 $\mu g/m^3$, about one-third of the NAAQS daily standard of 35 $\mu g/m^3$. In contrast, during the 6-hr period beginning 20 LST on July 4, hourly PM2.5 values are elevated to between 20 and 35 $\mu g/m^3$. The national-average, 24-hr-average Independence Day concentration is 17.0 $\mu g/m^3$, or 5 $\mu g/m^3$ (42%) higher than on control days and about one-half of the NAAQS value.

Fig. 2(b) shows these same data expressed as differences (Independence Days minus control days), with largest differences (21 $\mu g/m^3$) at 21 and 22 LST, and differences falling to near zero by noon on July 5. Fig. 2(c) shows the number of stations, of the total 315, at which hourly-average PM2.5 concentrations on Independence Days are statistically significantly greater than on control days. At 21 LST, 109 stations, or 35% of the total, showed significant increases, with smaller fractions for other times of day.

3.2. PM2.5 at all sites

Multi-year-average 24-hr-average PM2.5 concentrations at all 315 sites on Independence Days and control days are shown in Fig. 3. The positive correlation ($r = 0.57$) indicates that typical July 4 concentrations reflect typical concentrations on other early July days. On average, the 35 $\mu g/m^3$ NAAQS for PM2.5 is not exceeded at any of the 315 sites on control days, but it is on Independence Days at 10 sites. They include three sites in Cook County, Illinois, and single sites in St. Joseph County, Indiana; Clark County, Nevada; Weber County, Utah; Los Angeles County, Riverside County, and San Bernardino County, California; and King County, Washington.

Most sites experience higher PM2.5 concentrations on Independence Days than control days. The intercept of the regression line in Fig. 3 is 3.4 $\mu g/m^3$, which we may interpret as the typical increase for the post-fireworks 24-hr average daily value at sites with relatively low background PM2.5. Since the regression slope is 1.14:1, the increase is typically slightly larger at sites with higher background levels, consistent with the national average difference of 5 $\mu g/m^3$ reported above.

The national average patterns of hourly PM2.5 increases on Independence Days, shown in Fig. 2, mask considerable variability among the 315 sites. Many factors might contribute to that variability, including: the magnitude of local fireworks displays and associated emission of PM to the atmosphere; prevailing meteorological conditions (including wind speed and direction and atmospheric stability); distances between the displays and the local monitoring site; and differences in measurement methods from site to site. These last two issues are explored in Section 3.3. Unfortunately, information about the location and magnitude of fireworks displays is not readily available, in part because no national

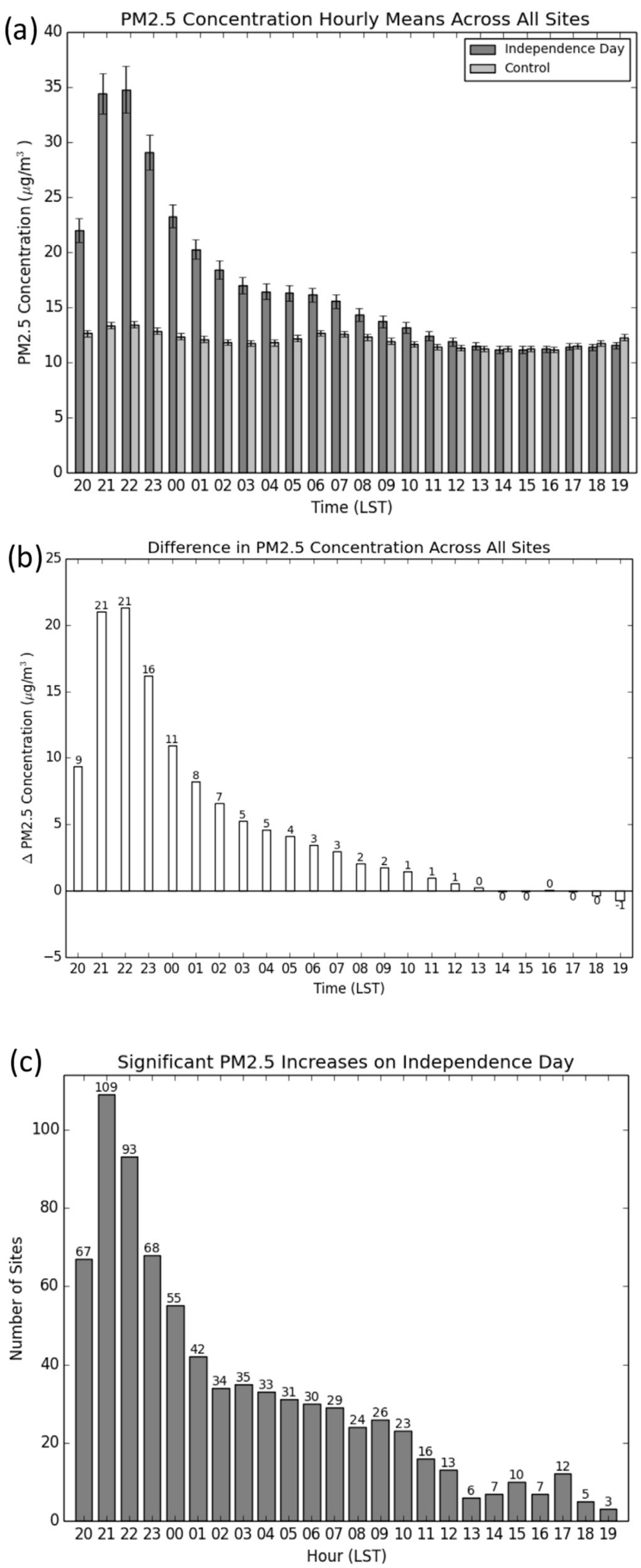

Fig. 2. (a) Hourly averages, ± one standard error, of PM2.5 concentrations (μg/m^3) averaged across all 315 sites during Independence Days (July 4) and control days (July 2, 3, 5, and 6), where each day begins at 20 Local Standard Time (8 pm). (b) Differences between July 4 and control day PM2.5 concentrations, averaged across all sites. (c) Number of sites (of the total 315) showing statistically significantly greater PM2.5 on Independence Days than on control days, for each hour of the day, where statistical significance is based on one-tailed t-tests having $p < 0.05$.

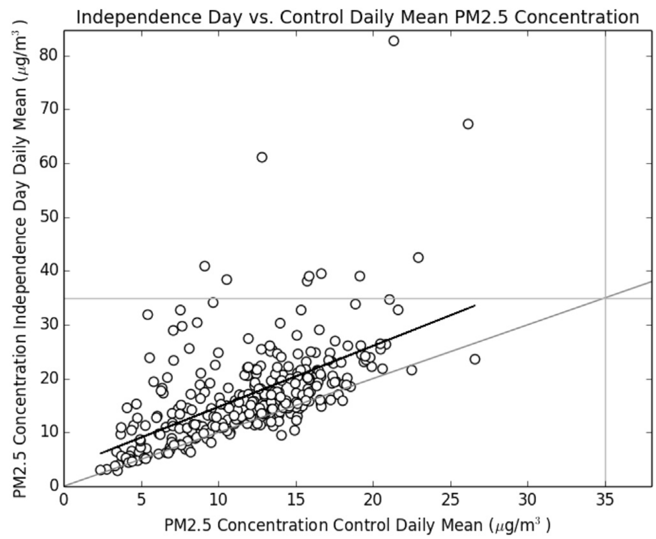

Fig. 3. Comparison of 24-hr-average PM2.5 concentration at each of 315 sites for Independence Days and control days, where Independence Day is defined as beginning July 4 at 20 Local Standard Time. Each point represents a multi-year-average concentration. Grey vertical and horizontal lines allow comparison of observed averages with the NAAQS daily standard of 35 μg/m^3, and grey diagonal shows 1:1 correspondence. Regression line (black) has slope of 1.14 and intercept of 3.4 μg/m^3. Linear correlation coefficient is 0.57.

database of large aerial displays exists (to our knowledge) but more importantly because of the prevalence of consumer use of fireworks, which are highly dispersed in time and space. Thus fireworks emissions are probably more usefully thought of as an area source of PM than as a point source. Therefore we are not able to quantitatively assess how PM2.5 increases vary with distance from fireworks.

3.3. Illustrative results from two locations

The Utah Department of Environmental Quality (2013) reports that the air quality monitoring station at Ogden (Weber County) is adjacent to the Ogden Community Action Center, the site of public fireworks displays and consumer fireworks use on Independence Day. Results from this station may exemplify PM2.5 exposures to spectators in close proximity to fireworks displays.

At Ogden, daily average PM2.5 concentrations on Independence Day average 61 μg/m^3, 4.7 times greater than the 13 μg/m^3 average on control days. Fig. 4(a) shows hourly PM2.5 concentration patterns at Ogden, where average concentrations peak at 22 LST on Independence Days and reach values near 500 μg/m^3. By 07 LST, they drop to background levels. The year-to-year variability of the impact is summarized in Fig. 4(b), which shows almost a factor of 6 difference between the minimum and maximum Independence Day 24-hr average PM2.5 concentrations. Highest 24-hr average concentrations, 96 μg/m^3, occurred on Independence Day 2003. But even the lowest Independence Day value, 17 μg/m^3, exceeds the 13 μg/m^3 average for control days at this site.

Comparable results for the other 314 sites are included in Supplementary Data. Readers with detailed knowledge of where and when fireworks are used in the vicinity of a particular monitoring site, and the location of the site relative to population centers, may be able to interpret the representativeness of the observations for estimating human exposure to PM.

To evaluate the impact of measurement method on our results, we examine data from Washington, DC, well known for July 4 fireworks displays near the National Mall (although nearby jurisdictions and private organizations also sponsor displays, on July 4

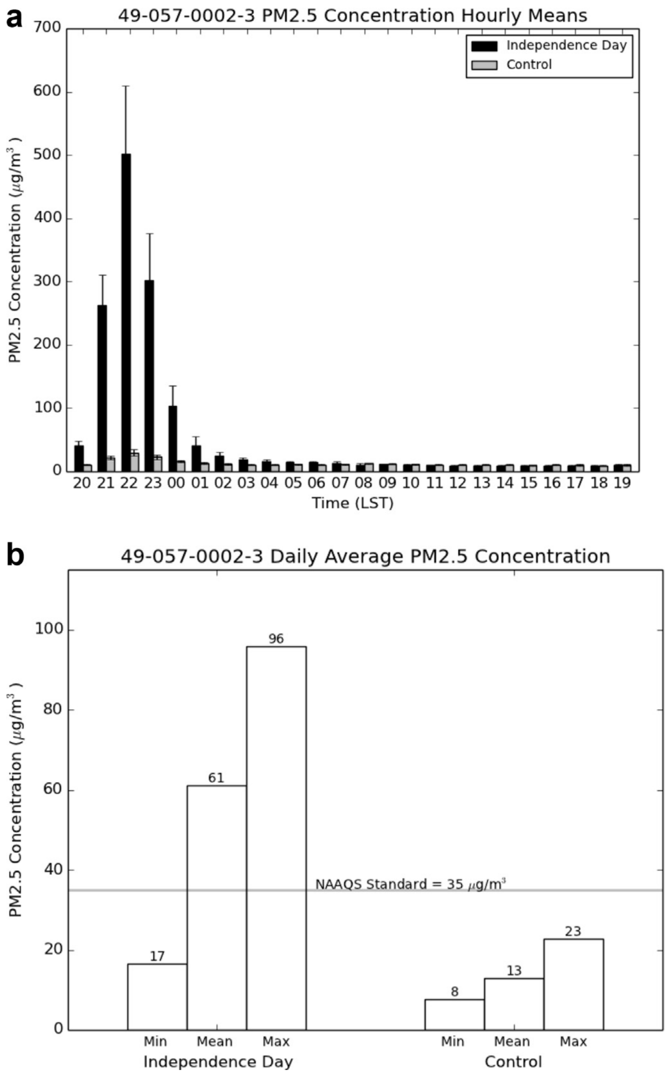

Fig. 4. (a) Average (±1 standard error) hourly PM2.5 concentration at Ogden (Weber County), Utah for Independence Days and control days. Comparable plots for all other sites are in Supplementary Data. (b) Comparison of minimum, mean, and maximum 24-hr average PM2.5 concentration at Ogden, Utah, on Independence Days and control days. Minimum and maximum values represent occurrence for a single day and year, while means represent averages over all relevant days during the period 2006–2013. Comparable plots for all other sites are in Supplementary Data.

and other dates). Air quality data are available from two co-located sites at the McMillan Reservoir in Washington, about 5 km north of the National Mall, where two different measurement techniques are employed. Fig. 5 compares hourly PM2.5 concentrations on control and Independence days using data from the two sites. The site reporting Acceptable PM2.5 AQI & Speciation Mass, for which 7 years of data were available, has average control day concentrations of 16 μg/m^3, and the site reporting PM2.5 Local Conditions, for which 3 years of data were used, has average control day concentrations of 17 μg/m^3. At both sites, Independence Day averages are 23 μg/m^3. These results, and similar findings at 13 other pairs of co-located sites (see Supplementary Data), give confidence in the robustness of the signal. Note, however, that statistical significance tests yield different results; 2 h (20 and 22 LST) showed significant differences at the Washington site with only 3 years of observations, while 4 h (20, 21, 22, and 23 LST) had significantly greater concentrations on Independence Days at the site with 7 years of data.

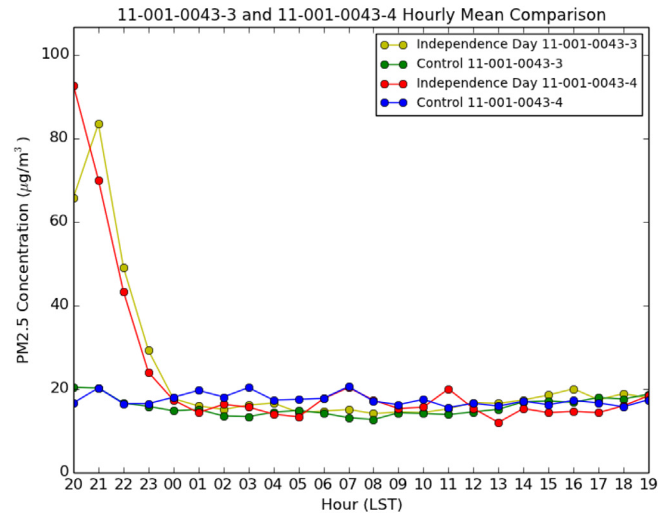

Fig. 5. Average hourly PM2.5 concentrations during Independence Days and control days from two co-located sites at the McMillan Reservoir in Washington, DC, that use different measurement methods and report different parameters. The site ID numbers are 11-001-0043-3 (where data are for the Acceptable PM2.5 AQI & Speciation Mass parameter, and 7 years of data were used) and 11-001-0043-4 (where data are for PM2.5 Local Conditions, and 3 years of data were used). Additional comparisons of results for 13 other co-located site pairs are in Supplementary Data.

3.4. *Weekday vs. weekend effects*

We have also explored the possibility that the Independence Day signal in PM2.5 differs if the holiday falls on a weekend vs. a weekday. Two possible circumstances might cause such a difference. One is that celebratory fireworks might be more likely to occur on days other than July 4 (which we consider non-fireworks control days) if the holiday falls during the weekend. A second is that background hourly PM2.5 concentrations may differ between weekends and weekdays, due to differences in emissions due to industry, traffic, etc. Previous studies have shown a weekend or Monday minimum in atmospheric PM both in urban (e.g., Harley et al., 2005) and rural (Murphy et al., 2008) areas of the US.

The small standard errors of PM2.5 hourly averages during control days (Fig. 2(a)) suggests that the Independence Day signal is larger than the signal of weekday–weekend differences at the monitoring sites used in this analysis. This inference is supported by results obtained by repeating our analysis using data from the 67 stations for which data are available for at least three years when Independence Day fell on a weekend (Friday-Sunday) and at least three years when it fell on a weekday (Monday–Thursday). The resulting plots for both the weekday and weekend samples (included in Supplementary Data) are very similar to each other, and to those in Fig. 2.

4. Discussion

The above analysis demonstrates discernible, and sometimes large, increases in hourly atmospheric PM2.5 in the evening of July 4 and morning of July 5 that account for 24-hr average concentrations that exceed values on control days. Although our analysis of 315 stations across the US, using 3–11 years of observations at each station, is more comprehensive than any prior study, two important caveats are worth mentioning.

Details of the so-called “source–receptor relation” were not explored, because we lack specific information about the locations and timings of fireworks displays, the assumed source of the elevated PM2.5 concentrations. Moreover, we recognize that the air quality monitoring sites may not be located where human "receptors" breathe the PM. It seems very likely that the increased concentrations shown in the observational data underestimate the increases experienced by spectators close to the display, or immediately downwind. In that regard, our analysis provides a conservative estimate of human exposure. The results from Ogden, Utah, where the monitoring site is adjacent to the fireworks display, may be more representative of exposure to spectators than results from other sites.

Another limitation of this study is its focus on PM concentration changes without any attention to PM composition changes. Case studies (Liu et al., 1997; Carranza et al., 2001; Kulshrestha et al., 2004; Drewnick et al., 2006; Moreno et al., 2007; Steinhauser et al., 2008; Vecchi et al., 2008; Camilleri and Vella, 2010; Croteau et al., 2010; Joly et al., 2010; Witt et al., 2010; Shi et al., 2011; Tsai et al., 2012) have demonstrated the different chemical composition of PM following fireworks displays. The national, multi-year set of observations used here did not include hourly chemical species measurements, so this issue could not be addressed.

Nevertheless, the results of this study may have practical applications and suggest other avenues of investigation. Current air quality prediction efforts in the US address PM2.5, but the national prediction models do not currently include fireworks as source of particulate emissions (Pius Lee, NOAA, personal communication), although local forecasters may account for fireworks effects in communications with the public. It may be possible to use the results here as a basis for estimating hourly emissions of total particulate for inclusion in air quality models. Emissions of individual chemical species could potentially be estimated by assuming they scale with PM2.5 in a consistent fashion and as measured by earlier case studies.

5. Conclusion

This study used observations of PM2.5 from 315 sites across the US to estimate the effects of Independence Day fireworks on hourly and 24-hr-average concentrations. The main findings are:

1. Hourly PM2.5 concentrations during the evening of July 4 and morning of July 5 are higher than on the two preceding and following days in July, considered as control days. The national average increase is largest (21 $\mu g/m^3$) at 9–10 pm on July 4 and drops to zero by noon on July 5.
2. On national average, concentrations for the 24-hr period beginning 8 pm on July 4 are 5 $\mu g/m^3$ (42%) greater than on control days.
3. The magnitude and timing of the Independence Day increases vary from site to site and from year to year, as would be expected given variations in PM2.5 emissions from fireworks, distances between fireworks displays and air quality monitoring sites, local meteorological conditions, etc.
4. A site adjacent to fireworks shows 48 $\mu g/m^3$ (370%) increases in 24-hr-average PM2.5.
5. Observations from 67 sites indicate that, on average, PM2.5 increases are similar regardless of whether the holiday falls on a weekday or weekend.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.05.065.

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