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Do State Fairs with Firework Displays Impact PM2.5 Levels in Nearby Communities?

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by

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ABSTRACT

DO STATE FAIRS WITH FIREWORK DISPLAYS IMPACT PM2.5 LEVELS IN NEARBY COMMUNITIES?

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Under the Supervision of Professor Jon Kahl

This study identified state fairs with known firework displays to evaluate whether they impact local air quality. Previous research has shown firework displays are linked with the short-term degradation of local air quality due to increased concentrations of fine particulate matter (PM2.5) as a result of the display. These studies observed increased PM2.5 concentrations associated with widespread firework displays such as the Lantern Festival in China, Diwali Festival in India, and Independence Day in the United States. However, it has not been investigated whether a signal of increased PM2.5 concentrations from firework displays during a state fair could be observed to degrade air quality in nearby neighborhoods.

Air quality and meteorological data were collected for five state fairs, with the fairs ranging 10 –14 days in duration, over 2 – 7 years. Statistical analysis performed on multi-year aggregated data for each state fair found that festival day concentrations were not larger than non-festival day concentrations. However, results from individual years identified several hours for the Delaware, Iowa, and Minnesota State Fairs where hourly festival day concentrations were larger than non-festival day. These hours occurred in the afternoon (Minnesota State Fair) and in the overnight early morning hours (Delaware and Iowa State Fairs). Statistical analysis was then

performed on multi-year aggregated data during hours in which wind was blowing from the direction of the state fair to air monitoring site (within plus or minus 30˚) and wind speeds were non-zero. The results continued to identify several hours where hourly festival day concentrations were larger during the Iowa State Fair. Once again, these hours occurred overnight, and festival day mean concentrations were generally 3 – 8 μg/m3 larger than control. Possible explanations of the results include (a) the distance of the air quality monitoring site from the fairgrounds being too far to detect firework emissions, (b) other emission sources provided too much noise to discern a clear signal, or (c) emissions from firework displays were smaller than expected.

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LIST OF ABBREVIATIONS

PM2.5	Particulate Matter 2.5
NAAQS	National Ambient Air Quality Standards
EPA	Environmental Protection Agency
WHO	World Health Organization
AQS	Air Quality System
FRM	Federal Reference Method
FEM	Federal Equivalent Method
ASOS	Automated Surface Observing Systems
CMV	Cooperating Meteorological Variables
LST	Local Standard Time

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1. Introduction and Background

The first state fair in United States history dates back to 1841 in Syracuse, New York. 180 years later, state fairs are still an annual event celebrated across the county in nearly every state. Typically lasting for ten days to two weeks, state fairs consist of amusement park rides, concerts, firework displays, food vendors, games, and livestock exhibitions spread throughout acres of fairground. In some instances, fairs can exceed daily attendance of a hundred thousand people from across the country (Grant et al. 2010). The Minnesota State Fair alone sees over two million attendees annually in its twelve-day duration (Sanstead et al. 2018). Although it varies from state to state, fairgrounds are typically located outside large cities in suburban communities. Due to the proximity to substantial residential populations, it is important to identify possible environmental impacts fairs may have on local air quality.

It has been well documented that firework displays are linked to short-term degradation of local air quality due to the high levels of fine particulate matter associated with the display (Perry 1999; Moreno et al. 2007; Barman et al. 2008; Camilleri and Vella 2010; Joly et al. 2010; Thakur et al. 2010; Seidel and Birnbaum 2015; Lin 2016; Joshi et al. 2019; Singh and Sonwani 2019) that can remain suspended in the area for up to a week or more after the display (Lin 2016). One study observed a pyrotechnic display at a soccer game and air pollution measured inside the stadium increased by 1200 percent shortly after (Pirker et al. 2020). Compounds found in firework particulates have also been linked with various health concerns. Perchlorate, found in firework aerosols, has been shown to increase neurodevelopment deficits and thyroid conditions in infants and children (Shi et al. 2011). In addition, poor air quality has also been correlated to outdoor events due to food vendors and environmental tobacco smoke (Collins et al. 2014; Tsai et al. 2015; Chen et al. 2020). Cooking smoke from the use of biomass fuels or gas can increase particulate matter concentrations to unhealthy levels in the areas near food stalls (Collins et al. 2014).

Exposure to air pollution has consequential impacts on human health. Particulate matter with an equivalent diameter less than 2.5 microns (PM2.5) is small enough to be inhaled, absorbed by the lungs, and passed into the bloodstream. As a result, PM2.5 is known to negatively affect both respiratory and cardiovascular systems (WHO 2003).

To mitigate health risk, under authority of the Clean Air Act, the Environmental Protection Agency (EPA) sets National Ambient Air Quality Standards (NAAQS) for PM2.5. In 2013, NAAQS reduced the PM2.5 standards for PM2.5 24-hour average to 35 $\mu g/m^3$ and the annual mean to 12 $\mu g/m^3$ (EPA 2013b). Despite the NAAQS reduction, the annual standard is higher than the World Health Organization (WHO) air quality guideline of 10 $\mu g/m^3$ for PM2.5. The WHO lowered this standard from 35 $\mu g/m^3$ in 2005, citing that the decrease would reduce air pollution related deaths by 15 percent (Ballester et al. 2008; Krzyzanowski and Cohen 2008).

Although this decrease in the PM2.5 annual mean standard by WHO was significant, it should also be noted that experts have not agreed upon a set lower limit of PM2.5 concentration that does not have health consequences (Krzyzanowski and Cohen 2008). Unfortunately, even short-term exposure to elevated PM2.5 can cause systematic inflammation (Li et al. 2017). One study found PM2.5 measurements as low as 4.0 $\mu g/m^3$ to 7.06 $\mu g/m^3$ increases asthma symptoms and within this range, each increase of 1 $\mu g/m^3$ in PM2.5, asthma symptoms rise 3.4 percent (Mirabelli et al. 2016). This limits the effectiveness of the NAAQS 24-hour average to communicate hazardous conditions as PM2.5 can be temporarily increased to unhealthy levels without raising the 24-hour average above the set standard to alert the public. In addition, the 24-hr PM2.5 standard of 35 $\mu g/m^3$ prohibits, specifically, exceeding the 98th percentile of daily values averaged over three years. This means that that over a three-year period, 24-hr concentration can exceed 35 $\mu g/m^3$ twenty-one times without local air quality violating the standard.

While literature is rich with research of impacts and increased emissions of firework displays from large festivals like that of the Lantern Festival in China, Diwali Festival in India, or Independence Day in the United States (Wang et al. 2007; Barman et al. 2008; Seidel and Birnbaum 2015), there is a void of studies that observe local air quality impacts as a result of state fairs with firework displays in the United States. State fairs introduce a mix of prolonged aerosol sources from fugitive dust related to large numbers of vehicles, food vendors, livestock, and firework displays. This study identified state fairs with known firework displays to determine their impacts on local air quality and to what extent air pollutants can be detected at various distances from the source. It was hypothesized emissions associated with state fairs with known firework displays leads to measurable increases in PM2.5 in neighborhoods surrounding state fairs, degrading local air quality for communities surrounding the fairgrounds.

2. Data

To administer this study, multiple state fairs known to include firework displays were identified. The state fairs were required to have available air quality and meteorological parameters measured near the fairgrounds. Once these data were collected, it was compared to data from days absent of known fairs or fireworks to determine potential impacts of the quantity of PM2.5 in the area.

2.1 Identification of State Fairs with Fireworks

Event selection was conducted by first identifying state fairs in which there are known firework displays. Local newspaper articles from various state fair locations were used to determine the presence or absence of firework displays, the timing and duration of firework displays, and the fair's event schedule. Next, a determination was made as to whether the firework display was sizable enough to have the potential to affect local air quality. Unfortunately, this is not a straightforward task.

Throughout the numerous studies regarding elevated particulate matter following firework displays (e.g., Perry 1999; Moreno et al. 2007; Barman et al. 2008; Camilleri and Vella 2010; Joly et al. 2010; Thakur et al. 2010; Seidel and Birnbaum 2015; Lin 2016; Joshi et al. 2019; Singh and Sonwani 2019), a relationship between the firework display parameters and emission strength has not been discerned. This is due to the lack of openly available data to quantify the size of a firework display. In order to accurately define the emissions of a firework display, the mass of pyrotechnic content must be known. Pyrotechnic content within a firework consists of a lift charge (such as gunpowder) and the burst charge which contains an oxidizer, fuel, varying chemical combinations for color, and a binder. Depending on the desired visual effect, the mass and chemical composition of pyrotechnic ingredients will vary (Russell 2009). When transferring fireworks to display sites, pyrotechnic companies are required to share the weight of explosive content with the Bureau of Alcohol, Tobacco, Firearms and Explosives Agency and Department of Transportation (Federal Register 2004). Despite this, pyrotechnic content weight is considered proprietary information of the pyrotechnic group and is not openly available. Firework display parameters that are publicly available include cost and duration of the display. However, cost is an imperfect proxy for firework emissions because several factors unrelated to emissions are often included in reported firework cost, including personnel, transportation, storage, insurance, and taxes. Duration is similarly of limited usefulness. While longer displays would certainly be expected to involve higher emissions, other key factors remain unknown such as the types of fireworks used, and the number of fireworks launched per minute. Accurate characterization of firework emission strength is thus impossible without proprietary knowledge of the pyrotechnic content (C. Helfrich, Premier Pyro, personal communication, November 11, 2020).

Given the unavailability of proprietary pyrotechnic content, after reviewing the literature on firework emissions and consulting with pyrotechnic professionals it was decided to utilize display duration combined with fair attendance as a qualitative proxy. State fair events were thus included in the study if they were known to have a firework display of longer than five minutes or an average daily attendance of over 30,000 people. By limiting the time duration of a display to over five minutes, short displays that likely do not produce enough emissions to be measured were omitted. Average daily attendance was considered because data suggests fairs with a larger attendance may have greater spending power designated for firework displays, as well as displays of longer duration. For example, a budget from the 2018 Minnesota State Fair, which sees over two million attendees annually, allocated 32,500 dollars for fireworks while the 2019 Michigan State Fair, which sees 92,000 attendees annually, budgeted 10,000 dollars for firework displays (Minnesota State Fair 2018; City of Novi Council 2019). After the selection criteria was applied, four state fairs with known firework displays were selected for use in this study: Delaware State Fair, Iowa State Fair, Minnesota State Fair, and Tennessee Valley Fair. Wisconsin State Fair was also included, despite lack of fireworks, for local interest and to compare with state fairs with known firework displays.

2.2 Air Quality and Meteorological Measurement Selection

To determine the impacts of fireworks on air quality, this study compared local air quality on firework days to that on control days. Firework days were defined as state fair festival days with known firework displays. Control days, i.e., days without a fair or known municipal firework events, were determined to be the five days before and after each event. Overall, five fairs met the conditions over a variety of years due to availability and completeness of data (Table 1). None of the festival days or control days align with Independence Day events. This reduced the possibility of additional firework display emissions outside the fairgrounds.

Several types of air quality and meteorological measurements were needed to analyze the environmental impacts of state fairs with firework displays. This study used hourly PM2.5 measurements from the EPA's Air Quality System (AQS) database (EPA 2013a). Measurements were obtained by the Federal Reference Method (FRM) and Federal Equivalent Method (FEM) from the AQS. Due to rigorous requirements, FRM data is the standard for regulatory purposes when regarding daily measurements. FEM consist of other methods that have passed rigorous field tests and the EPA has deemed satisfactory to perform equivalent to the reference method and is widely and legally used in the same ways as FRM data (Noble et al. 2001). Regarding the distance from AQS sampler to fairground, Lin (2016) reviewed 49 studies measuring particulate matter from firework displays and concluded sites sampling data beyond 10 km of the source makes quantifying the impacts of fireworks on particulate matter difficult (Lin 2016). As a result, this study required that AQS samples must be located within 10 km of each event.

Hourly meteorological variables such as precipitation and wind are collected from National Weather Service's Automated Surface Observing Systems (ASOS) (NOAA National Center for Environmental Information 2001). From the state fairs selected, the associated ASOS locations are located within 31 km of the events. In the most ideal conditions, ASOS stations would be located within a short distance of the event to eliminate error in wind and precipitation measurements caused by topography, sea breeze, single cell pop-up storms and other mesoscale phenomena. However, due to the reality of irregularly located ASOS stations, the furthest distance considered for this study to minimize the number of errors produced by the aforementioned phenomena was determined to be 31 km. Four of the five state fairs are located within 13 km of the event site, making the median ASOS distance of all sites 11 km. Figure 1a-e depict maps denoting the location of each state fair, air quality monitoring site and ASOS.

Due to the short duration of state fairs (typically lasting 10-14 days, Table 1), it was critical to ensure data quality and completeness for the events identified in the site selection. ASOS data were subjected to quality control methods where data were filtered for records that were repeated or out of chronological order. In addition, erroneous values such as unrealistically large or negative wind speeds were eliminated. Air quality monitoring data were subjected to similar quality control procedures, removing pollutant concentrations that were negative, out of chronological order or repeated. In order to ensure data completeness, the requirement of a minimum 21 hourly measurements in a 24-hr cycle was required for both air quality and ASOS data, as well as the condition that 90% of hourly measurements be available for the entire duration of an event.

3. Methods

Once data were collected, the next step was to determine if state fairs had any impact on local air quality, and if so, of what magnitude.

3.1 Data Filtering by Cooperating Meteorological Variables

In order to consider periods where air was moving from the festival sites toward the air quality monitors, hourly PM2.5 concentrations were filtered by wind direction and speed. Hourly measurements that met the determined wind direction and wind speed criteria, described below, were deemed to have “cooperating meteorological variables” (CMV). Analysis was performed both with and without CMV filtering.

PM2.5 concentrations were first filtered by wind direction in order to identify times at which pollutants could be moving from source (fair) to receptor (air quality monitoring site). To establish when an air quality monitoring site was downwind from a state fair, hourly wind measurements collected from the nearest ASOS site were used. Air quality monitoring sites were considered to be downwind from a state fair when wind direction occurred within plus or minus 30˚ from the direction of the air quality monitoring site in relation to the state fair location. This directional criterion is referred to as the delta azimuth. The decision to use a wind direction within a plus or minus 30˚ delta azimuth was arbitrary and motivated by a desire to identify times when wind was blowing generally from the festival to the monitor, but not be so restrictive to severely reduce the number of hours available for analysis. Of data filtered for the delta azimuth criterion, wind speeds of zero ms^{-1} were then removed. These criterions identify hourly observations in which state fair emissions may be transported downwind towards the air quality monitoring sites. Table 2 shows, for each hour, the number of festival days (multi-year) meeting the CMV criteria at that hour.

3.1.1 Gaussian Plume Modeling Component

A Gaussian plume dispersion model was utilized to evaluate how emissions from state fairs would disperse downwind of the fairgrounds. The Gaussian plume dispersion model describes how a pollutant concentration downwind from a point source spreads outward from the centerline of a plume following a normal distribution under idealized circumstances (Abdel-Rahman 2008). The Gaussian plume dispersion was calculated according to the formula

$$\chi(x, y, z, t) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right]$$

where $\chi(x, y, z, t)$ is estimated hourly-averaged concentration at a particular location, Q is emission rate of the pollutant source, u is mean wind speed, σ_y is the standard deviation of horizontal pollution distribution, σ_z is the standard deviation of vertical pollution distribution, and h is the effective plume height. Standard deviation of vertical and horizontal pollution distributions (σ_y and σ_z) were calculated using the Briggs-urban model (Hanna 1982).

Figure 2 demonstrates how modeled ground-level pollutant concentrations behave downwind from a pollutant source given (1) an effective plume height of 45m, (2) nominal emission rate of 1 g/s, (3) environment stability of slightly unstable urban conditions, (4) “z” is the altitude at which pollutant concentrations are simulated at 2 m (representing near surface observations), and (5) mean wind speed of 2 ms-1. The largest pollutant concentrations for this set up occurs 150 m from the pollutant source, then decrease at distances further downwind. The relative concentration (the ratio of pollutant concentration to max concentration) decreases logarithmically until it reaches a value just above .001 at the distance of 10,000 m downwind from the pollutant source. This application of the Guassian plume model suggests that emissions, which can be sizeable near the source, may be observable downwind at distances utilized in this study.

3.2 Time Series Analysis

A time series graph visually depicts the change in PM2.5 concentrations with time throughout the duration of control and festival days in relation to the timing and quantities of measured precipitation. Precipitation can act as a sink for air pollutants, effectively cleansing the air of particulates. Precipitation can further inhibit suspension of dust by wind and vehicles by moistening the ground. It is important to identify the timing and influence of precipitation on PM2.5 concentrations to better interpret results. By including precipitation information and also the timing of firework events alongside PM2.5 concentrations in a time series chart, it may be easier to distinguish the influence of precipitation on PM2.5 concentrations as well as identify case study events where concentrations appear to be higher in the hours after a firework display.

3.3 Diurnal Concentration Profile

For this study, composite (over multiple years) diurnal concentration profiles were considered for control and festival days for each fair. To produce composite diurnal concentration profiles for festival and control days, all hourly PM2.5 measurements from a fair were analyzed utilizing box and whisker charts. Box and whisker graphs for both control and festival days were plotted side by side to compare results. This study looked to examine the timing of peak concentrations, mean hourly concentrations, range of hourly concentration measurements, and how these differed between control and festival days. Composite diurnal profile box and whisker charts were recreated for each individual year and for hourly concentrations where CMV were observed.

3.4 Air Pollution Rose Analysis

To further investigate the possible relationships between state fair emissions and observed PM2.5 concentrations, an air pollution rose analysis was utilized. An air pollution rose depicts the frequency in which wind blows from a direction (binned at 10˚) and the PM2.5 concentrations associated with the direction by using both hourly ASOS and air quality monitoring site data. Air pollution rose analysis also calculates the frequency of wind speeds being "calm" or less than .5 ms^{-1}, which can provide insight as to how often a state fair experienced stagnant air during either festival or control days. Air pollution rose analysis was performed on each fair for all years where data were available for both control and festival days.

3.5 Bootstrap Sampling and Statistical Analysis

A bootstrap with replacement sampling was used to obtain a distribution of differences between festival and control day concentrations. To conduct the bootstrap method, hourly PM2.5 measurements from different festival days were combined to create a sampling dataset for each of the 24 hours of a state fair's annual festival days. For example, all measurements from 0600 LST over the course of all festival days were prepared for the subsequent bootstrap sampling. This process was repeated for all 24 hours. Similarly for control days, for each state fair an annual sampling dataset for each of the 24 hours was created. Ten control day and, depending on the duration of the state fair, 10-12 festival day PM2.5 measurements were randomly selected with replacement from the previously mentioned sampling dataset for each hour. These new randomly selected measurements represent synthetic distributions of festival and control day concentrations. Next, of the synthetic festival day samples, a mean PM2.5 concentration was calculated and repeated for the synthetic control day sample. The difference was then found between the synthetic festival and control day mean (festival day mean minus control day mean). The bootstrap sampling with replacement and difference in synthetic mean calculation was conducted 1000 times for each of the 24 hours, resulting in a distribution of concentration differences with 1000 members for each hour. The null hypothesis, that festival day concentrations are not larger than control day concentrations, was rejected at the 5% confidence level if the fifth percentile of the 1000 differences was less than zero.

Due to sample size constraints, once data were filtered by CMV a minimum sample size of five was required each hour for the duration of festival days to be included in the bootstrap analysis. Table 2, which shows the number of hours available for the bootstrap sampling, highlights hours in green that did not meet the sample size criterion for CMV and was not considered for statistical testing. Control day samples were not filtered for CMV and were calculated the same as previously outlined. The bootstrap sampling with replacement and difference in synthetic mean calculation was then conducted for data filtered for CMV during festival days and unfiltered data for control days.

4. Results and Discussion

Once data were collected, the next step was to determine if state fair emissions could be detected by the air quality monitoring sites' observed concentrations, and if not, investigate explanations as to why.

4.1 Comparison of Control and Festival Day Concentrations

Box and whisker charts of the five-state fairs' hourly PM2.5 concentrations during control and festival days, for all years available, are shown in Figure 3a-e. The festival concentrations are unfiltered for CMV.

4.1.1 Diurnal variation in mean hourly control and festival day concentrations

From the multi-year results for control days (blue) in Figure 3a-e, PM2.5 concentrations at all state fairs were observed to have peaked within 2 – 3 hours after noon, with a secondary peak in the evening (6pm – 12am), except for Minnesota and Wisconsin State Fair. The Minnesota State Fair control day concentrations peaked only once in the evening hours (6pm – 12am) (Figure 3c). Control day concentrations for the Wisconsin State Fair also peaked in overnight, but elevated concentrations continued through the early morning hours (11pm – 6am) (Figure 3e).

Festival days (orange) generally followed a similar diurnal pattern in Figure 3a-e, with a slight increase in concentrations in the early afternoon and peak concentrations occurring in the overnight hours (9pm – 6am). Festival day mean concentrations were similar to control days for the Delaware and Minnesota State Fairs, with mean concentrations ranging between 5 – 10 $\mu g/m^3$ (Figure 3a & 3c). The Minnesota State Fair also observed the largest hourly PM2.5 measurements of all the state fairs, with several hourly observations exceeding 30 $\mu g/m^3$ (Figure 3c). Control day mean hourly concentrations are generally larger than festival day concentrations by 2 – 5 $\mu g/m^3$ during Tennessee and Wisconsin fairs throughout the entire day (Figure 3d & 3e). The Iowa State Fair results show several overnight hours between 12am – 9am where mean hourly festival day concentrations were larger than control (Figure 3b). Overall, individual hourly concentrations during festival days rarely exceed the standard of 35 $\mu g/m^3$ and mean hourly concentrations, of either festival or control days, never exceed the standard.

The diurnal concentration variation during individual years at each state often deviated from their multi-year aggregate pattern. For the Delaware State Fair, a larger peak in control day concentrations occurred in the early afternoon hours (10am – 4pm) in 2018 and 2019, whereas in 2015 hourly concentrations peak in the overnight hours (1am – 5am) (Figure 4). The Delaware State Fair generally had two nights out of the ten-day fair with known firework displays around 10 pm, except for 2019 which had eight nights with known firework displays over the course of the ten-day fair (Delaware Online 2014; 47abc 2016; Festivals Fairs Fun 2019, Table 1). Festival day concentrations generally peaked in the afternoon and overnight hours, except for 2014 and 2015 where concentrations only peaked in the overnight hours. For all years other than 2016 and 2017, mean hourly PM2.5 concentrations were generally larger for control day concentrations, most notably in the afternoon hours. Hourly control day concentrations reached their largest magnitudes in 2016 and 2018, with hourly concentrations reaching between 20 and 30 $\mu g/m^3$. The only year in which festival day mean concentrations exceeded that of control was in 2016. Hourly festival day concentrations reached their largest magnitudes in 2016 and 2017 of 15 – 25 $\mu g/m^3$.

For the Iowa State Fair control day concentrations generally peaked in the afternoon (Figure 5). An exception to this occurred in 2018 where concentrations peaked in the evenings (6pm – 12am). Iowa festival day concentrations, which has known nightly fireworks after grandstand performances generally between 9 pm and 11pm (The Register 2019), also generally peaked in the afternoons and again in the evening hours. In 2019, festival day concentrations peaked in the evening and overnight hours opposed to the afternoon. Mean hourly PM2.5 concentrations during festival days were generally larger than control for 2017 and 2018, whereas control day mean concentrations were generally larger in 2019. The largest magnitude of hourly control day concentrations reached between 20 – 25 μg/m^3 in 2018 and 2019. The highest festival day hourly concentrations observed had magnitudes of 20 – 30 μg/m^3 which occurred most frequently in 2018 and 2019. Hourly concentrations of PM2.5 for both control and festival day were likely larger in 2018 due to wildfire smoke from British Columbia. This will be addressed later when presenting results for MN this will be addressed later when presenting results for the Minnesota State Fair.

For the Minnesota State Fair (which has known nightly firework displays after the grandstand performance (Minnesota State Fair 2021, Table 1) control and festival day concentrations consistently peaked in the evening hours for most years (Figure 6). Control and festival day mean concentrations were generally similar in 2014, 2016 and 2019. In 2018, control day mean concentrations were larger than festival days. Elevated mean hourly PM2.5 concentrations in 2018 are likely due to wildfires in British Columbia and Washington state, transporting smoke downwind to the area during the control days. Upper-level smoke can be seen from satellite imagery on August 17th, 2018, a control day included in the 2018 for the Minnesota State Fair dataset, in Figure 7. A Hysplit backward trajectory analysis from 500 m above ground level shows that air parcels near the Minnesota State Fair location on August 16th (blue) and 17th (red), 2018, were transported from the northwest days prior (Figure 8). As a result, the largest hourly concentrations for control days were measured to be 30 – 48 μg/m^3 during 2018. Festival day concentrations also observed the largest magnitude of hourly concentrations in 2018, ranging from 30 – 40 μg/m^3. In 2015 and 2017, festival day mean concentrations were generally larger than control, with the largest difference in mean concentrations occurring in the afternoon hours. For these years, a high frequency of hourly concentrations during festival days reached 20 – 40 μg/m^3. In 2015, the largest control day hourly concentrations reached 30 – 50 μg/m^3. The Minnesota State Fair was the only state fair observed in this study where hourly PM2.5 concentrations exceeded the standard of 35 μg/m^3.

For the Tennessee Valley Fair, which has known nightly fireworks (Knox News 2018; The WLAF 2019), control and festival day concentrations peaked in the afternoon (11am – 2pm) and evening (8pm – 10am) in 2019 (Figure 9). In 2018, control day concentrations peaked only in the evenings (10pm – 12am) and festival day concentrations peaked in the morning (8am – 10am). In 2019, festival day mean concentrations were slightly larger than control by up to 2 μg/m^3, but in 2018 control day mean concentrations were larger than festival day by 3 – 7 μg/m^3. While festival day concentrations were observed to be higher than control days, this was not the case in 2018. The largest hourly concentration for control days was between 15 – 21 μg/m^3 in 2019 and for festival days between 20 – 28 μg/m^3 during 2018 and 2019.

Control day concentrations for the Wisconsin State Fair generally peaked in the evening and overnight hours, and a secondary peak in the afternoon in 2019 (Figure 10). Festival day concentrations observed two peaks, once in the afternoon and again in the evening hours. In both 2018 and 2019, mean hourly PM2.5 concentrations were generally larger for control days, compared to festival day hourly concentrations. In 2018 however, festival day mean concentrations were slightly larger than control by 1–2 μg/m^3 in the afternoon hours. The largest hourly concentrations observed during control days were 20 – 27 μg/m^3 in 2018. Similar to results for the Iowa and Minnesota State Fairs, hourly concentrations in 2018 were likely larger due to smoke from wildfires in the British Columbia region. For festival days, the largest hourly concentrations were observed in 2017 and ranged from 20 – 25 μg/m^3.

4.1.2 Consideration of the highest hourly concentrations

Next, interquartile range for both control and festival days was considered. Generally, Iowa, Tennessee, and Wisconsin fairs experienced the largest range in festival day concentration values, with an interquartile range for hourly concentrations generally between of 4 – 20 μg/m^3 occurring in the late evening to overnight hours (6pm – 5am) (Figure 3a-e). Control day concentrations for the Minnesota State Fair experienced the smallest interquartile range of 5 – 10 μg/m^3 during the day, increasing to 10 – 15 μg/m^3 in the evening.

In Figure 3a-e, several state fairs observe higher hourly PM2.5 concentrations which represent upper outliers. Table 3 shows the number of hourly PM2.5 concentrations greater than 20 μg/m^3 for both control and festival days at each state fair. Hourly PM2.5 concentrations greater than 20 μg/m^3 occur most frequently in the overnight hours from 8pm – 1am for all state fairs. The Wisconsin State Fair control days experienced the highest frequency of hourly PM2.5 measurements greater than 20 μg/m^3 over the three years of data observed in the study. This is notable as it is three times larger than the frequency of elevated concentrations during festival days. The Minnesota State Fair festival days observed the second highest frequency of elevated PM2.5 concentrations over the six years of data observed in this study. Several of these instances occurred in 2018 for both Wisconsin and Minnesota State Fairs which was likely influenced by wildfires in British Columbia (Figure 7 & 8). Festival day concentrations greater than 20 μg/m^3 were observed more frequently in the afternoon hours when compared with control days for the Minnesota State Fair. The Iowa State Fair festival days also observed a higher frequency of hourly PM2.5 concentrations greater than 20 μg/m^3 than control days. Overall, Table 4 depicts no straightforward evidence of a signal being detected from nearby firework displays because control day hourly concentrations are similar to that of festival day concentrations. Additionally, hourly festival day concentrations rarely increased over 20 $\mu g/m^3$ near the timing of, or just after, known firework displays.

4.1.3 Festival versus control concentration differences

Statistical significance testing using bootstrap with resampling for multi-year data for each state fair determined that the null hypothesis could not be rejected at any fair location. This indicates that when considering multi-year data, festival day PM2.5 concentrations were not significantly larger than control for any of the state fairs included in the study.

When analyzing results for each state fair annually, the null hypothesis could be rejected for several hours in individual years for the Delaware, Iowa, and Minnesota State Fairs (Figure 11a, 11b, & 11c). Figure 11a-e shows the fifth percentiles from synthetic distributions of festival and control day mean differences for each fair, both for multiyear aggregates and for individual years from data unfiltered for meteorology. Results for the Delaware State Fair shows a positive fifth percentile difference for seven hours in 2015, indicating festival concentrations exceeded control concentrations at these hours (Figure 11a). The Iowa State Fair measured 9 and 4 hours where festival concentrations were significantly larger than control for years 2017 and 2018, respectively (Figure 11b). The Minnesota State Fair data depicts four years in which 1 to 12 hours had concentrations significantly larger than the control (Figure 11c).

The timing of the individual hours where mean hourly festival concentrations were larger than control concentrations (and the null hypothesis could not be rejected) varied. Hours that saw higher festival day concentrations, when compared to control, were generally during the afternoon or overnight. The Minnesota State Fair observed multiple years in which afternoon hourly concentrations were significantly larger for festival days. An increase in afternoon concentrations could be due to an increase in urban traffic due to the state fair. The elevated overnight hourly concentrations observed by the Delaware and Iowa State Fairs could be the result of remaining particulates from the previous night's firework display. One instance for Iowa in 2018 shows a positive fifth percentile at 2000 LST, corresponding to the timing of known firework displays for the fair.

Overall, hourly festival concentrations rarely exceeded hourly control concentrations. Additionally, statistical analysis showed that the timing of these occurrences rarely coincided with the timing of known firework displays but the timing may provide insight for potential causes or reasons for increased concentrations being observed on festival days. It is yet to be seen if the elevated concentrations observed during those hours were due to emissions from the state fair.

4.2 Comparison of Control and CMV Festival Day Concentrations

Box and whisker charts of the multi-year aggregate hourly PM2.5 concentration distributions for all years of fairs hourly PM2.5 concentrations during control and festival days which have been filtered for CMV are shown in Figure 12a-e. When controlled for CMV, box and whisker charts were only produced for festival day hourly concentrations of cumulative years for each state fair because sample sizes were too small to depict annually (Table 2). Due to the sample size restriction requiring a minimum of five hourly observations with CMV present to be included in the analysis, results for the Iowa State Fair and Tennessee Valley Fair were reduced to only 12 and 6 hours, respectively.

Looking at results filtered for CMV for each state fair, the magnitude of concentrations was generally similar to the data unfiltered for CMV, with the largest magnitude of concentrations occurring overnight and early morning.

The Delaware and Minnesota State Fairs both observed similar magnitude in hourly PM2.5 concentrations during both control and festival days, except late morning and early afternoon hours when control day concentrations were larger (Figure 12a & 12c). Mean hourly concentrations generally ranged from 4 – 10 $\mu g/m^3$ in Delaware and 5 – 12 $\mu g/m^3$ in Minnesota. The largest hourly concentrations for both control and festival day ranged from 20 – 30 $\mu g/m^3$ in Delaware. The Minnesota State Fair control day concentrations saw the highest values of PM2.5, ranging from 20 – 50 $\mu g/m^3$, with the largest festival day concentrations only reaching 25 $\mu g/m^3$. The air quality monitoring site for the Tennessee Valley Fair generally measured lower concentrations of PM2.5 during festival days when data was filtered for CMV. Mean festival day concentrations ranged from 7 – 13 $\mu g/m^3$. The largest hourly festival day concentrations measured 15 – 20 $\mu g/m^3$ during the afternoon hours.

The Iowa State Fair measured larger mean hourly festival day concentrations for nearly all hours where sample size was large enough to be considered (Figure 12b). Mean hourly concentrations for festival days were often larger than control by 5 $\mu g/m^3$. The largest control day concentrations measured 20 – 25 $\mu g/m^3$ and the largest festival day concentrations measured 15 – 20 $\mu g/m^3$, with a higher frequency of control day concentrations occurring in this upper-end range.

On the other hand, the Wisconsin State Fair control day mean hourly PM2.5 concentrations were observed to be larger than festival day for all hours (Figure 12e). The largest difference between hourly control and festival day mean concentrations occur generally overnight, with a difference in concentrations of 3 – 8 $\mu g/m^3$. The largest hourly festival day concentrations range from 15 μg/m^3 to just under 20 μg/m^3.

Statistical significance testing using bootstrap with resampling determined that the null hypothesis could be rejected for several hours during the Iowa State Fair. The Iowa State Fair recorded five hours in which festival day concentrations filtered for CMV were significantly higher than control days (Figure 13). These hours generally occurred in the early morning (2:00 – 7:00am LST). These results do not identify a clear signal of increased emissions associated with the timing of known firework displays for each of the state fairs. However, these results indicate festival day concentrations for Iowa's State Fair were significantly larger than control day in the overnight hours, which could be a result of residual particulates from the previous night's firework display. On the other hand, Wisconsin observed 18 hours where control concentrations were significantly larger than festival days when filtered for CMV, suggesting Wisconsin State Fair emissions are less important to local air quality than other local emission sources.

4.3 Air Pollution Rose Analysis

Previous literature reported increased concentrations of PM2.5 on fair grounds caused by nearby firework or pyrotechnic displays (e.g., Perry 1999; Moreno et al. 2007; Barman et al. 2008; Camilleri and Vella 2010; Joly et al. 2010; Thakur et al. 2010; Seidel and Birnbaum 2015; Lin 2016; Joshi et al. 2019; Singh and Sonwani 2019). However, in this study, air quality monitoring sites revealed no significant differences between multi-year aggregate festival and control day concentrations for all state fairs with known firework displays, except for the Iowa State Fair when data were filtered for when CMV are present. To investigate reasons why no significant differences were observed at most sites, further analysis of meteorological variables of wind direction and was conducted using air pollution rose

Air pollution rose results for the Delaware State Fair show that wind blew from the general direction of the state fair at a higher frequency during control days compared to festival days (Figure 14). Additionally, the largest PM2.5 concentrations were measured from the south, southwest and west for both control and festival days. These directions include the direction of the Delaware State Fair relative to the air quality monitoring site (indicated by the red arrow in Figure 14). PM2.5 concentrations associated with winds from the direction of the fairgrounds are similar for both control and festival days, which supports the findings from the box and whisker analysis in Figure 3a that festival day concentrations did not exceed that of control. This indicates that regardless of whether a state fair is taking place, the highest PM2.5 concentrations tend to be observed from the south-southwest direction. These findings could also suggest the 9 km distance between the fairgrounds and air quality monitoring site may be too large to identify a clear signal from the state fair. It is also possible that the state fairs emissions are too small to be detected 9 km away, as the Delaware State Fair often only has two firework displays throughout the duration of the ten-day fair.

For the Tennessee Valley Fair, the air pollution rose plots also reveal wind blowing from the direction of the state fair at a similar frequency for both control and festival days (Figure 15). The Tennessee Valley Fair experienced “calm” winds (wind speeds less than .5 ms^{-1}) 32 – 33% of the time during control and festival days. Generally larger PM2.5 concentrations were measured during control days, with the highest concentrations of 25 – 30 $\mu g/m^3$ observed out of the southwest. Wind most frequently blew from the north and northeast during festival days, which includes the general direction of the fairgrounds. The largest concentrations of 15 – 20 μg/m^3 observed during festival days came from no singular direction, however a higher frequency of these concentrations was observed downwind from the fairgrounds during compared to control. This finding suggests that a higher frequency of concentrations measuring 15 – 20 μg/m^3 were observed from the direction of that state fair, but previous analysis determined it was not statistically significant.

For the Iowa State Fair, the wind blew less frequently from the direction of the state fair during festival days than for control days (Figure 16). Similar to findings in Figure 3b, festival day hourly concentrations were found to be larger than control. The largest measured PM2.5 concentrations during festival days were associated with winds from the north and west, opposite the direction of the state fair. This finding indicates the higher hourly concentrations measured at the air quality site were often not from the state fair, but from other local or distant emission sources. Nevertheless, PM2.5 concentrations associated with wind coming from the direction of the state fair were 5 – 10 μg/m^3 larger for festival days compared to control days. These results suggest a signal of increased PM2.5 concentrations may be detected from the Iowa State Fair during festival days, however more data would be required in order to confirm this signal. The air quality monitoring site is approximately 7 km from the fairgrounds, which at this distance could introduce other emission sources as the cause for elevated PM2.5 concentrations from the general direction of the state fair.

The Wisconsin State Fair experienced a higher frequency of wind blowing from the general direction of the fair towards the air quality monitoring site for festival days. Similar to findings in Figure 3e, the Wisconsin State Fair's control days observed larger concentrations of PM2.5 (Figure 17). The largest PM2.5 concentrations of 15 – 20 μg/m^3 were associated with winds out of the southwest on control days. The magnitude of hourly concentrations is similar when the air quality monitor was downwind from the fairgrounds, despite the higher frequency of wind blowing from the direction of the fair on festival days. This finding suggests that a clear signal of increased concentrations from the state fair could not be identified from the direction of the fairgrounds, in spite of meteorological variables supporting the detection of one. Wisconsin State Fair did not have any known firework displays, but other fair emissions may have been too small to detect 7 km downwind from the fairgrounds.

The Minnesota State Fair also experienced a higher frequency of the air quality monitoring site being downwind from the fairgrounds during festival days (Figure 18). For control and festival days, the largest PM2.5 concentrations were associated with winds from the northwest and west-northwest direction (the general direction of the state fair). Recall that the multi-year aggregate of hourly concentration distributions the Minnesota State Fair were similar for both control and festival days (Figure 3c). From the air pollution rose analysis, the results indicate that PM2.5 concentrations from the northwest appear to be high, regardless of if there is a state fair present. These results explain why diurnal profiles of festival and control day concentrations in Figure 3c are similar.

4.4 Rainfall Incidence

Time series of PM2.5 concentrations and precipitation were investigated to determine if and to what magnitude rain could have dampened measured PM2.5 concentrations. Detectable precipitation was observed for all state fairs, with the Minnesota State Fair receiving the largest hourly rainfall amount (over 30 mm) (Figure 19) and Tennessee Valley Fair seeing the smallest (less than 5mm) (not shown). Often hourly concentrations decreased just after precipitation was measured. One instance for the Delaware State Fair in year 2016, hourly PM2.5 concentrations just under 20 μg/m^3 decreased to below 5 μg/m^3 within hours, after a measured rainfall of 20mm occurred (not shown). Information could not be found to determine if firework displays may have been canceled due to precipitation. Overall, highest PM2.5 concentrations were rarely observed when a nonzero rainfall amount was measured.

4.5 Timing of Peak Concentrations

The hourly time series plots of PM2.5 concentrations and precipitation were also examined to determine if nearby air quality monitoring sites experienced a brief peak in concentrations due to fireworks. Generally, PM2.5 concentrations did not appear to peak within the time of, or just after, known firework displays for most sites. However, there were multiple cases from the Minnesota State Fair (Figure 19) in which hourly measurements of elevated PM2.5 concentrations were observed during, or just after a known firework display when CMV were present. The first instance was on August 30, 2019, in which concentrations at 6pm measured 7 μg/m^3 and increased to 25 μg/m^3 by 10pm (Figure 19a). At this time winds were coming from within 5˚ – 25˚ of the direction of the fair (delta azimuth) and wind speeds of 4.6 to 5.7 ms^{-1}, A second case from the Minnesota State Fair occurred on September 2nd, 2018. Observations from this day measured PM2.5 concentrations of 3 μg/m^3 at 6pm, which increased to 16 μg/m^3 aby 10pm (Figure 19b). At this time delta azimuth ranged between 5˚ and 15˚ and wind speeds were 5.1 ms^{-1}. For either case, PM2.5 concentrations did not exceed that of the NAAQS 24-hour average. Recall the Gaussian plume model calculations presented in Figure 2, which depicted ground-level concentrations downwind of a pollutant source. If the increased concentrations observed in these case studies were a result of emissions from the Minnesota State Fair 10 at km away, concentrations closer to fairgrounds may have been much larger. These findings suggest that a signal of increased PM2.5 concentrations during, or just after, the timing of known firework displays may be detected if sampled closer to the source.

5. Summary and Recommendations

5.1 Summary

Previous research has shown firework displays are linked with the short-term degradation of local air quality due to increased concentrations of fine particulate matter as a result of the display. These studies observed increased PM2.5 concentrations associated with widespread firework displays such as Lantern Festival in China, Diwali Festival in India, or Independence Day in the United States. However, it has not been investigated whether a signal of increased PM2.5 concentrations from firework displays during a state fair could be observed to degrade nearby neighborhood's air quality.

Five state fairs were identified, four of which have known firework displays (Delaware, Iowa, Minnesota, Tennessee) and one that is known not to have fireworks for local interest (Wisconsin). Air quality and meteorological observations were then used to determine the impacts of firework on air quality. Meteorological observations were used to filter data by wind speed (non-zero wind speeds) and direction (wind direction plus or minus 30˚ from direction of state fair). Hourly measurements that met both of these conditions were deemed to have "cooperating meteorological variables" (CMV).

Statistical analysis performed on multi-year aggregated data for each state fair found that the null hypothesis that festival day concentrations were not larger than control concentrations could not be rejected. However, results from individual years identified several hours for the Delaware, Iowa, and Minnesota State Fairs where the null hypothesis could be rejected, and festival day concentrations were larger than control. These hours occurred in the afternoon (Minnesota) and in the overnight early morning hours (Delaware and Iowa). When statistical analysis was performed on multi-year aggregated data filtered for CMV, the results continued to identify several hours where the null hypothesis could be rejected for the Iowa State Fair. Once again, these hours occurred overnight, and festival day mean concentrations were generally 3 – 8 $\mu g/m^3$ larger than control. The larger overnight festival day concentrations could be a result of residual particulates from firework displays the previous night, however the overnight concentrations never exceeded the NAAQS 24-hour average of 35 $\mu g/m^3$. Air pollution rose analysis for the Iowa State Fair further supports those larger concentrations of PM2.5 were measured downwind from the fairgrounds during festival days. The air quality monitoring site is located 7 km from the Iowa State Fair location. Due to this, other emission sources other than the state fair may have contributed to the increased festival day concentrations. More data regarding the composition of the particulate matter would be required to discern if the observed PM2.5 was from firework displays.

It was hypothesized that, given previous studies observing increased PM2.5 concentrations after firework displays and on fair grounds, a signal of increased emissions due to fireworks at state fairs could be detected within 10 km of the fairgrounds. Although several hours for the Iowa State Fair were identified to measure larger hourly PM2.5 concentrations on festival days when CMV were present, higher concentrations were not observed for most state fairs during festival days. Possible explanations of the results include (a) the distance of the air quality monitoring site from the fairgrounds being too far to detect firework emissions, (b) other emission sources provided too much noise to discern a clear signal, or (c) emissions from firework displays were smaller than expected. In the next section, these possible explanations are discussed, and recommendations are suggested to better capture a signal of increased emissions from state fairs in future research.

5.2 Discussion of Possible Reasons for Principal Results

5.2.1 Other Emission Sources Surrounding the Air Quality Monitoring Site

The fairs included in this study occurred in urban areas, which introduce additional sources of nearby emissions that could add noise when trying to identify a clear signal of increase emissions due to a state fair. Generally, the largest PM2.5 concentrations observed at air quality monitoring sites were associated with winds coming from directions other than that of the fairgrounds. For example, statistical analysis conducted for individual years shows several hours during festival days being significantly larger than the control during the Minnesota State Fair. However, larger PM2.5 concentrations were observed from the general direction of the state fair during both control and festival days. This suggest that concentrations from the direction of the state fair are generally high regardless the presence of a state fair due to other local emissions.

Other nearby events that correspond with the timing of state fairs control and festival days could also impact local emissions. An example of this is for the Wisconsin State Fair where the air quality monitoring site used in this study is located just over 3 km southwest of the American Family Field, a large baseball stadium in Milwaukee. Events held at the stadium could influence local emissions by increasing vehicle traffic to the area. This additional traffic could introduce noise and make it more challenging to discern a clear signal of increased PM2.5 concentrations from the state fair. Another instance of how local emissions can make interpreting results challenging is for the Iowa State Fair. For the Iowa State Fair, the air quality monitoring site measured increased emissions for festival days when data was filtered for CMV. However, at 7 km from the state fair, discerning if PM2.5 concentrations are definitively from state fair fairgrounds is challenging due to the potential noise caused by other local emissions. Because of the urban location of the air quality monitoring site, when the site is considered downwind from the fairgrounds, it is also downwind from a large interstate and north side of Des Moines (Figure 1c). If air quality monitoring sites were closer to fairgrounds, it could potentially reduce the noise from urban emission sources to better detect a signal from state fair firework displays.

5.2.2 Other Emission Sources Within State Fairs

Analysis for this study did not find conclusive evidence of increased PM2.5 concentrations associated with the timing of known firework displays near state fairs, however statistical analysis did identify several hours where hourly PM2.5 concentrations were significantly larger on festival days. The timing of these hours was not consistent between state fairs. For the Minnesota State Fair, significantly larger festival day concentrations occurred in the late morning and into the afternoon, whereas air quality monitoring sites for the Iowa and Delaware State Fair measured hours of larger festival day concentrations in the early morning. One possibility as to why larger concentrations were observed could be due to the other sources of emissions from state fairs besides firework displays, such as increased vehicle traffic, livestock, food vendors, etc. Additionally, many of these hours occurred in the early morning hours, where the environment is typically more stable, and pollutants are not as easily mixed and diluted through the boundary layer. A stable overnight environment could have led to emissions from state fairs to build up and increase locally. It is possible that emissions from state fairs could degrade the local air quality during festival days, particularly in the overnight hours when stable conditions are present.

5.2.3 Distance of Air Quality Monitoring Site and State Fair

Air quality monitoring sites were located within a 10 km radius of the location of the state fair, but 10 km may have been too far to detect a clear signal from the fair's firework displays. The Minnesota State Fair's air quality monitoring site (10 km from fairgrounds) observed two cases where PM2.5 concentrations tripled just after the timing of known firework displays when downwind of the fairgrounds, with winds over 4.6 ms^{-1}. In both cases, the increased concentrations were below that of the NAAQS PM2.5 24-hour average. The timing of increased concentrations suggest it may be possible for emissions due to state fairs firework displays to be measured at distances of 10 km downwind from the fairgrounds, but also that PM2.5 concentrations could be well mixed and at levels considered safe for the local community at that distance. Although concentrations measured at 10 km were below the NAAQS PM2.5 24-hour average of 35 $\mu g/m^3$, calculations from the Gaussian plume model (Figure 2) suggest concentrations may be larger closer to the fairgrounds.

The closest air quality monitoring site to a fairground included in the study was for the Tennessee Valley Fair. However, at a distance of 4 km from the fairgrounds, increased festival day emissions from the Tennessee Valley Fair were not observed at the air quality monitoring site. The Tennessee State Fair's air quality monitoring site observed only 6 hours which met sample size requirements for when CMV were present (Table 2). This finding underscores the importance of meteorology to potentially detect a signal from state fair firework emissions. It is possible that under ideal conditions, such that air quality monitoring sites were closer to a state fair's location and a larger sample of hourly data with CMV present, a signal from state fair firework emissions could be detected.

5.2.4 Firework Emissions Less Than Expected

Another possibility of why there was generally no clear signal of increased concentrations detected from state fair firework displays could be that the firework displays may have been smaller than expected or emitted less PM2.5. For all state fairs, PM2.5 concentrations rarely exceeded the NAAQS 24-hour average during festival days. The decision to include state fairs with known fireworks displays was determined based on the size of daily attendance of the fair or known duration of the firework displays. This decision may not have captured firework displays large enough for a signal to be detected outside of the fairgrounds. For example, the Delaware State Fair (9 km from air quality monitoring site) generally did not observe larger PM2.5 concentrations on festival days, despite winds frequently blowing towards the air quality monitoring site, although distance from the fair could also be the reasoning. These findings for the Delaware State Fair could suggest the emissions from firework displays were too small for a signal to be detected downwind.

5.2.5 CMV Criteria

A Gaussian plume model was used to interpret how pollutants disperse away from the plume centerline downwind from the pollutant source. A ratio was found of concentration to a reference concentration along the plume's centerline ($\chi/\chi ref$) at 1 km, 5 km, and 10 km downwind from a pollutant source. According to the Gaussian plume model, wind directions plus or minus 30˚ from the plume's centerline will reduce the concentrations by over 99 percent when 10 km from the pollutant source, given a mean wind speed of 2 ms^{-1} and slightly unstable urban conditions (Figure 20).

For concentrations observed 1 km downwind of the pollutant source with a delta azimuth of plus or minus 30˚ and stable environmental conditions, the Gaussian plume model again shows concentrations being reduced over 99%. This idealized model displays a delta azimuth of plus or minus 0˚ to 10˚ could better represent measurable concentrations, with concentrations being 5% of that at the plume's centerline at a distance of 10 km from the pollutant source. Although a delta azimuth of plus or minus 0˚ to 10˚ is more stringent of wind direction criterion, it may allow for a better signal to be detected. However, it would also significantly reduce the sample size of hours that met CMV criteria. Due to sample size concerns, the decision to use a larger wind deviation of plus or minus 30˚ wind direction from source to receptor was used in this study. Given a larger dataset, it may be useful to consider a narrower delta azimuth closer to that of plus or minus 0˚ to 10˚.

5.3 Recommendations for Further Research

To further explore the local impacts of state fairs with firework displays, a larger sample of air measurements near state fairs would be required. One way to increase the sample size is to include state fairs without fireworks. Results from this study found increased festival day concentrations during the afternoon and overnight hours, which suggest other sources related to state fairs could contribute to these elevated measurements of PM2.5. Analysis of state fairs without firework displays could determine if increased vehicle traffic, food vendors, and other fugitive dust sources from state fairs could degrade local air quality. By increasing the number of state fairs, a signal of increased emissions during festival days may be better detected.

This study used air quality monitoring sites within 10 km, which may have been too far from the fairgrounds to identify a clear signal of emissions from a state fair. A signal may be more easily detected by air quality monitoring sites closer to the fairgrounds. Additionally, the criterion for CMV could also be adjusted in future research, to reflect a narrower delta azimuth of 0˚ to 15˚ to better capture PM2.5 concentrations closer to the plumes centerline and potentially filter out noise from other local emissions. Ideally, future work could utilize portable air quality monitoring sites placed radially around fairgrounds to measure pollutants. By having a radial network of air quality monitoring sites around the site of a state fair, issues due to distance of the air quality monitoring site and meteorology would be resolved.

Case studies could also investigate local PM2.5 concentrations during and after large, non-Independence Day firework displays such as Aquatennial, Thunder of Louisville, or Harborfest. Often for larger displays, data is more readily available regarding the monetary value spent on fireworks, the duration of the firework display, or the number of fireworks used. Although information regarding the characterization of firework emissions may still be impossible to discern without proprietary knowledge of the pyrotechnic content, it is important to investigate if larger firework displays degrade local air quality.

FIGURES

Figure 1a. Map of the location for the Delaware State Fair, air quality monitoring site, and automated surface observation station (ASOS).

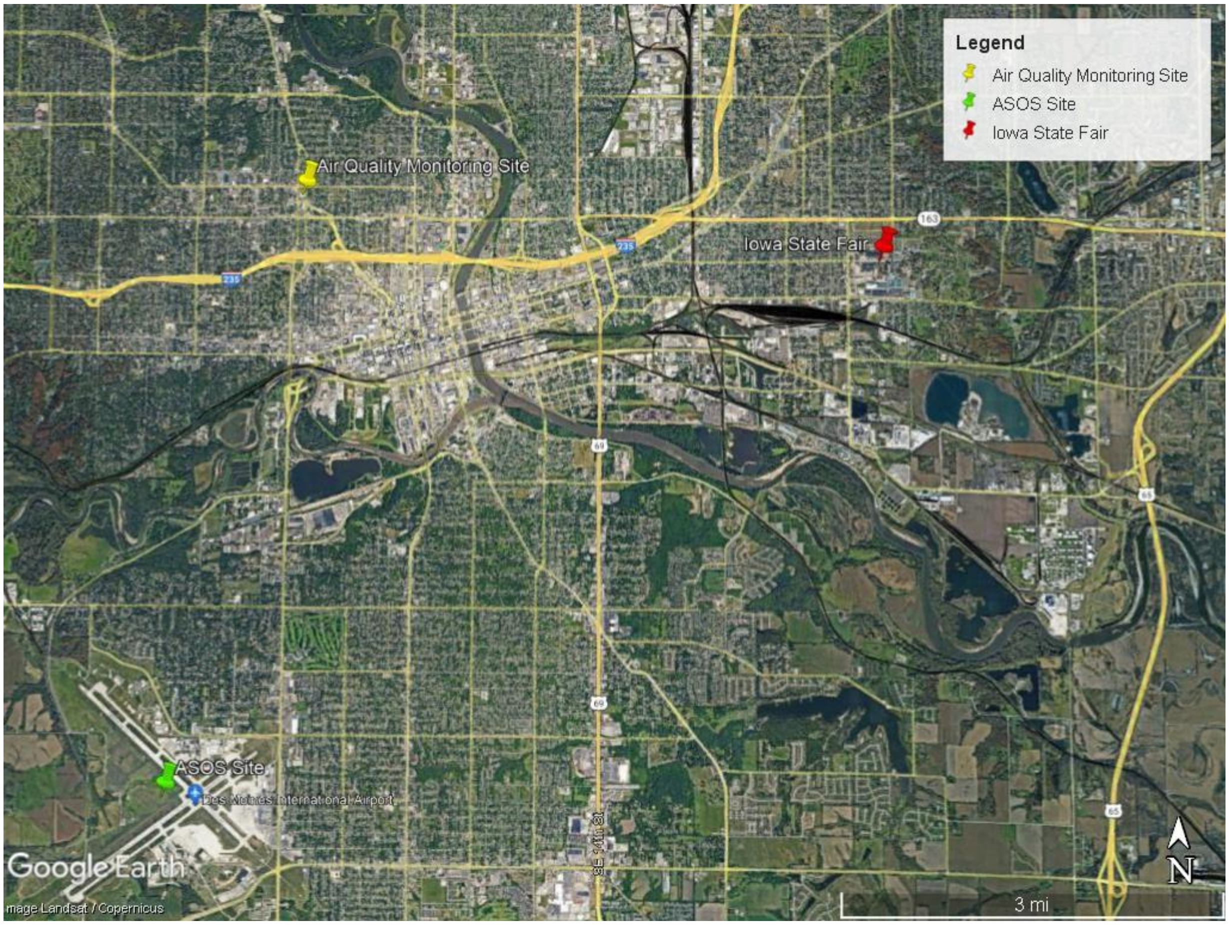

Figure 1b. Map of the location for the Iowa State Fair, air quality monitoring site, and automated surface observation station (ASOS).

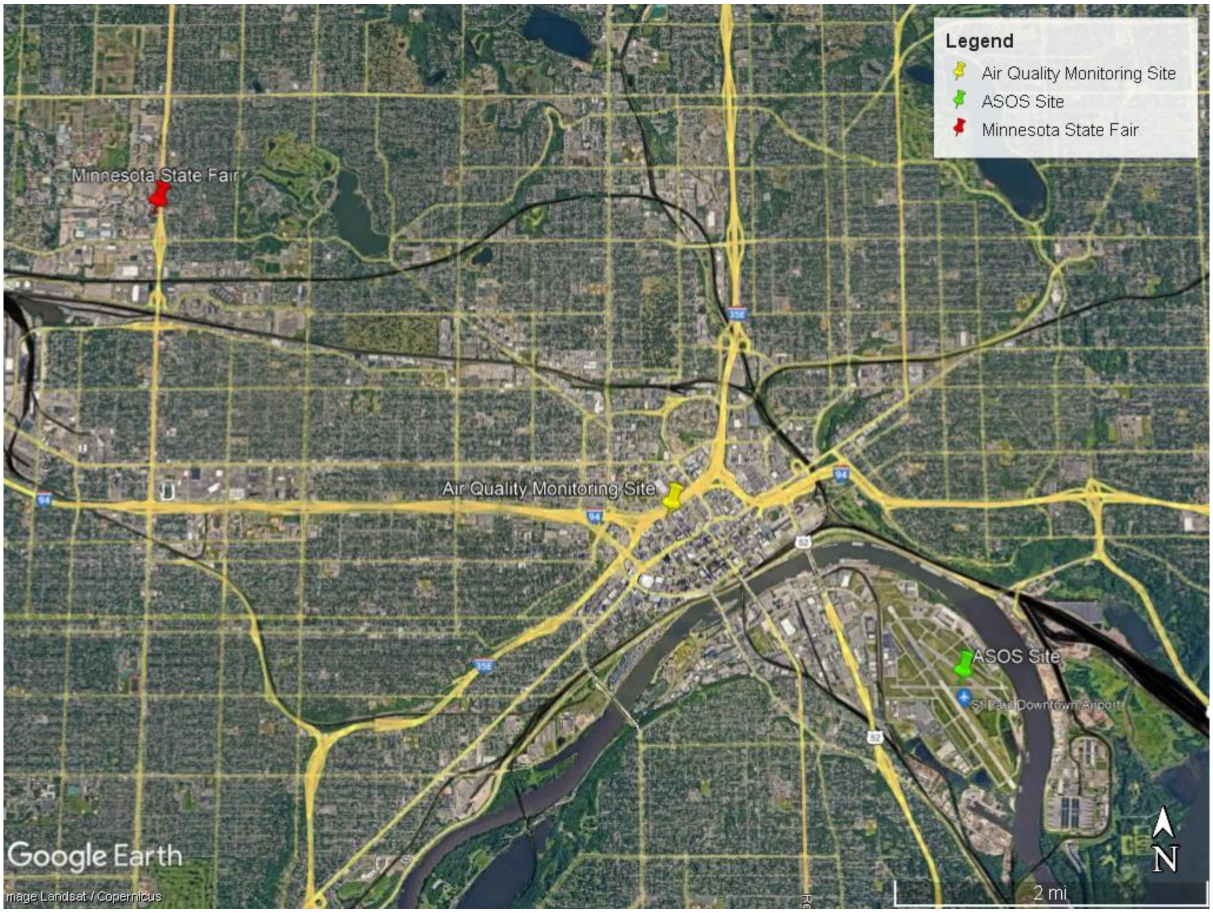

Figure 1c. Map of the location for the Minnesota State Fair, air quality monitoring site, and automated surface observation station (ASOS).

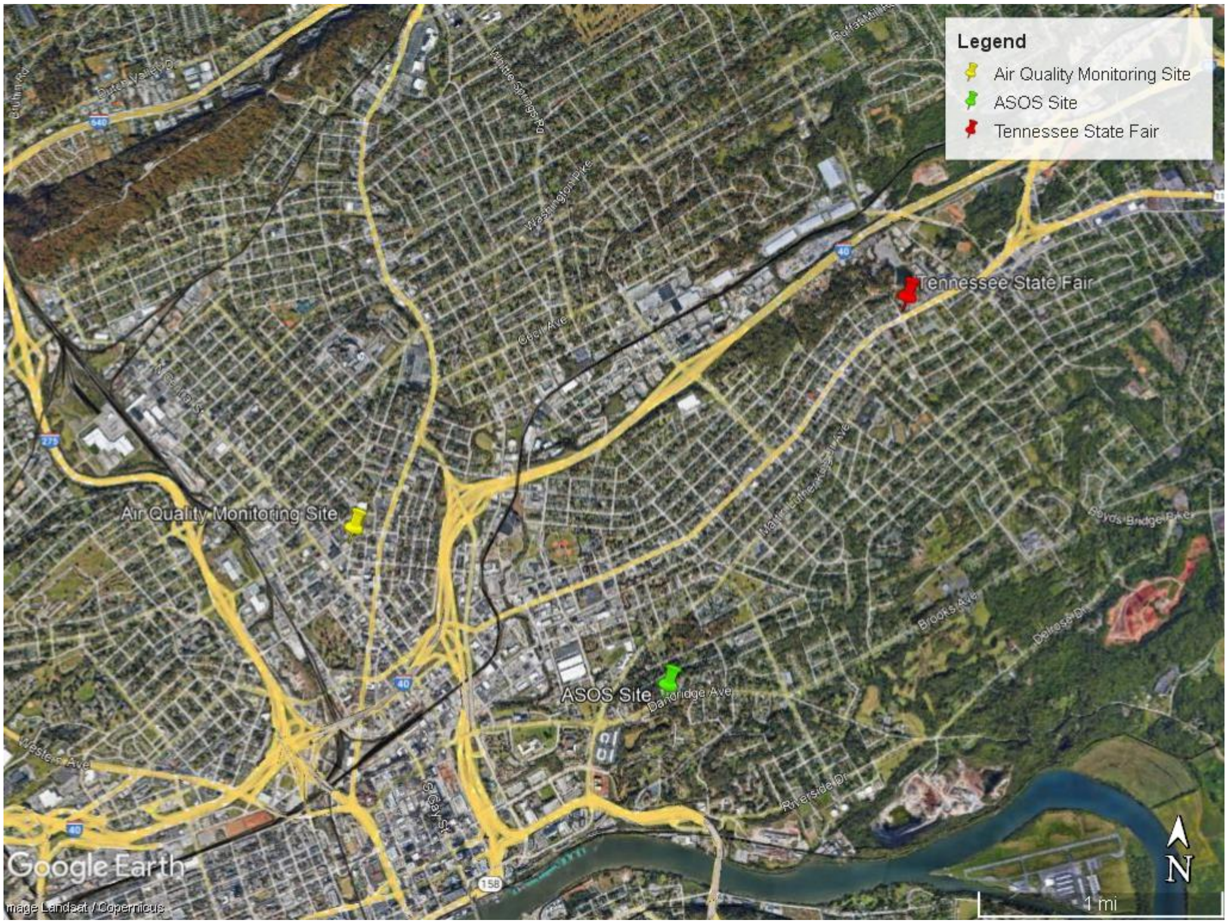

Figure 1d. Map of the location for the Tennessee State Fair, air quality monitoring site, and automated surface observation station (ASOS).

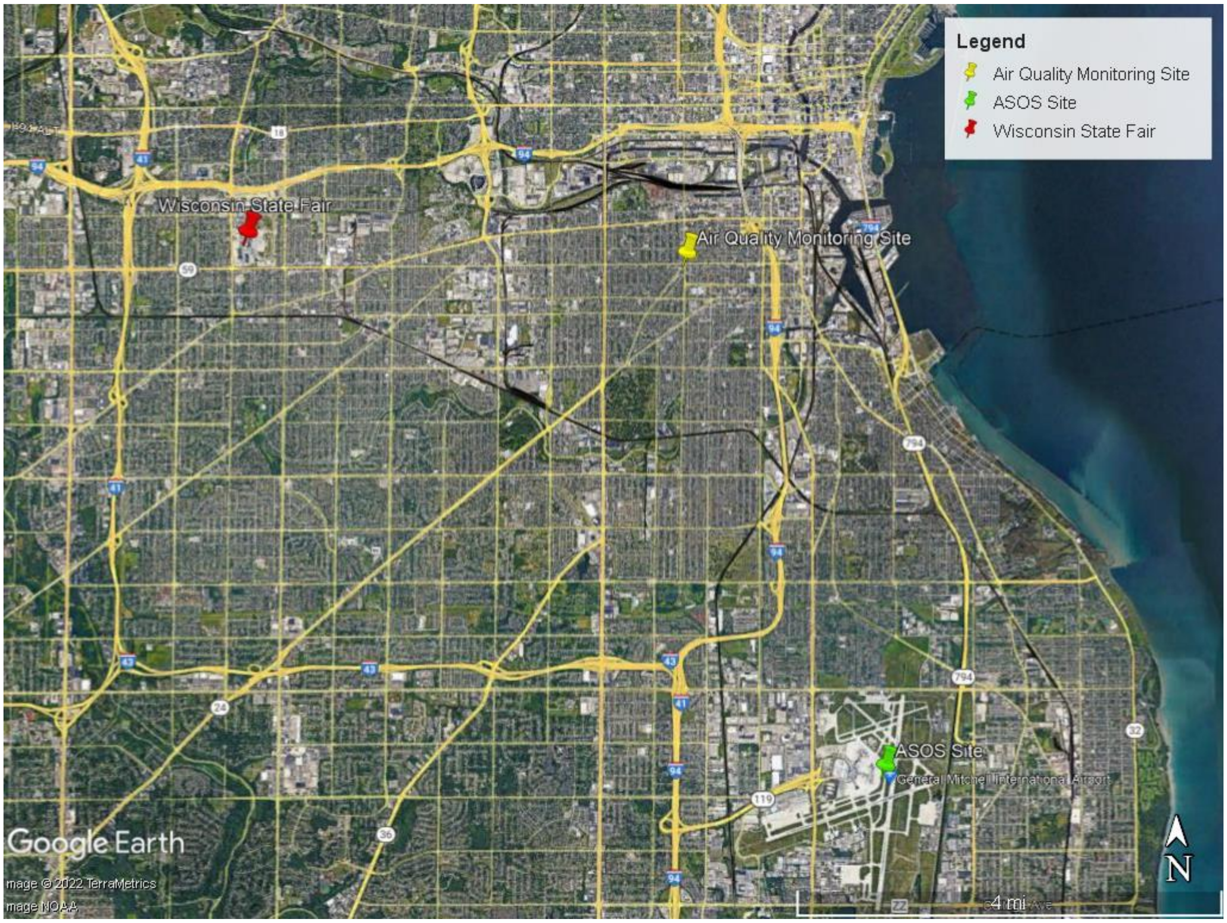

Figure 1e. Map of the location for the Wisconsin State Fair, air quality monitoring site, and automated surface observation station (ASOS).

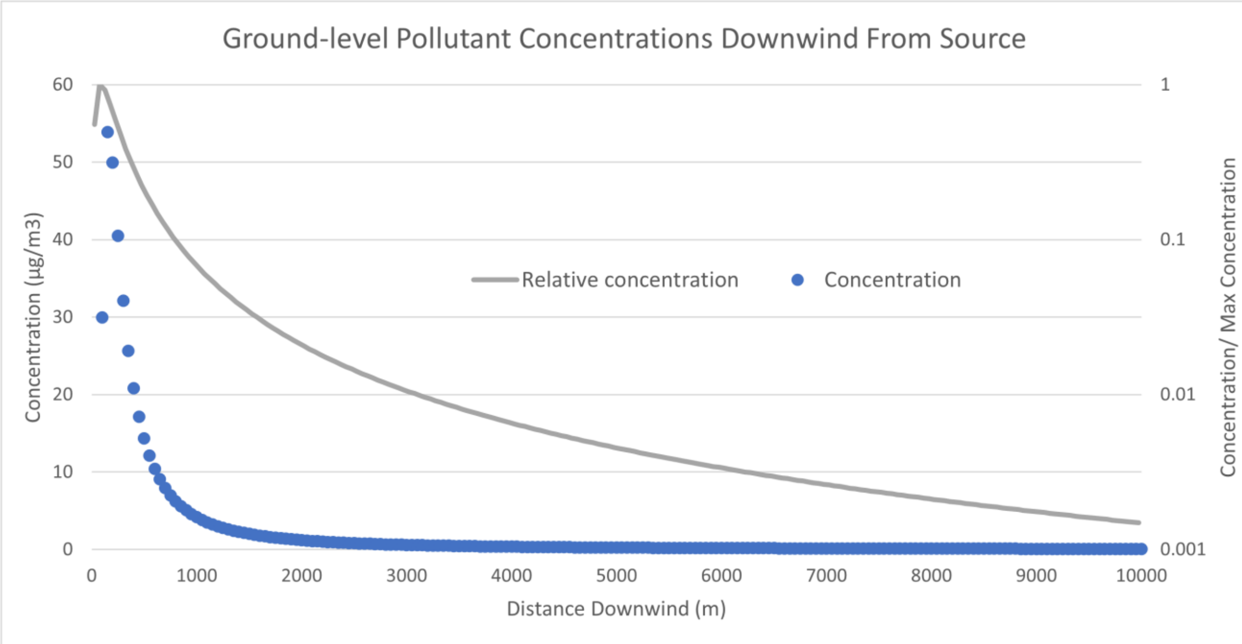

Figure 2. Ground-level pollutant concentrations downwind from source using the Gaussian plume dispersion model. Assumptions made in the model formula are: (1) nominal emission rate of 1 g/s, (2) environment stability of slightly unstable urban conditions, (3) "z" is the altitude at which pollutant concentrations are simulated at 2 m (representing near surface observations), and (4) mean wind speed of 2 ms-1.

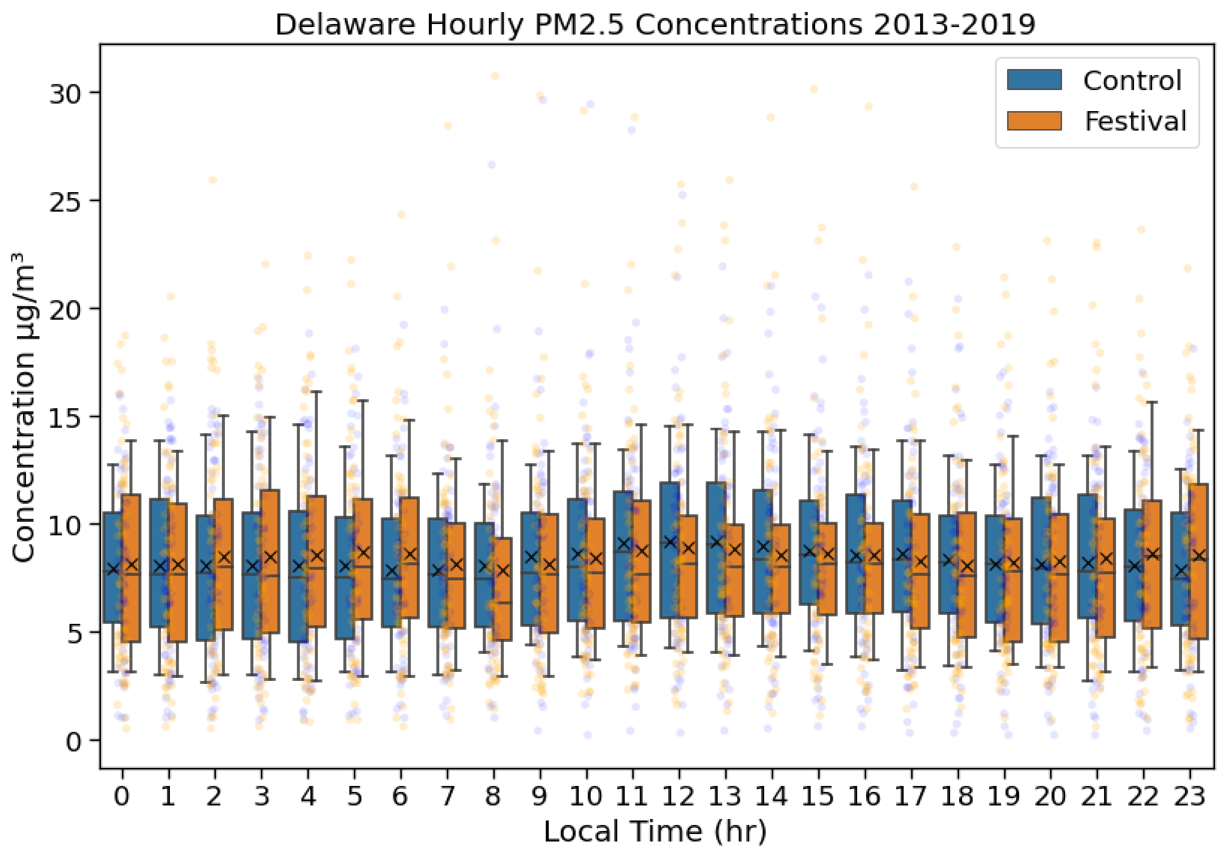

Figure 3a. Box and whisker plots of hourly PM2.5 concentrations for Delaware State Fair (2013-2019) during festival and control days for all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

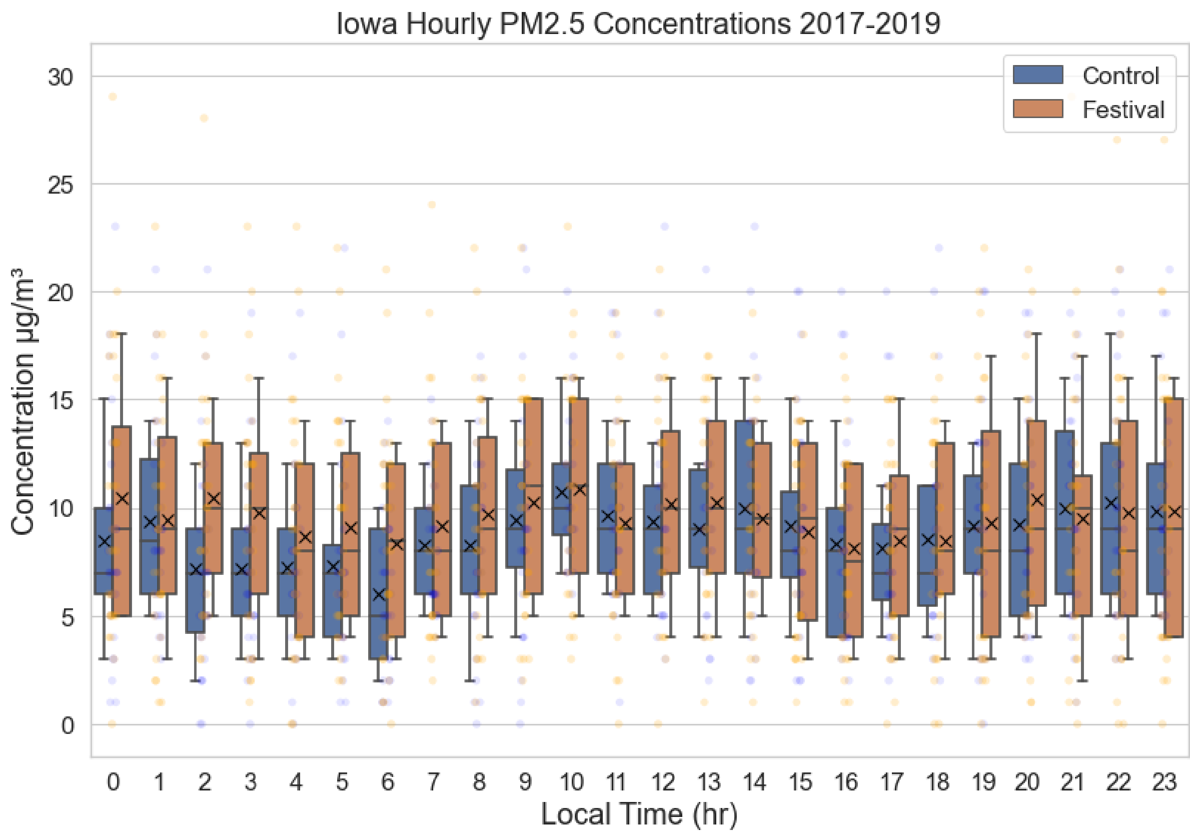

Figure 3b. Box and whisker plots of hourly PM2.5 concentrations for Iowa State Fair (2017-2019) during festival and control days for all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

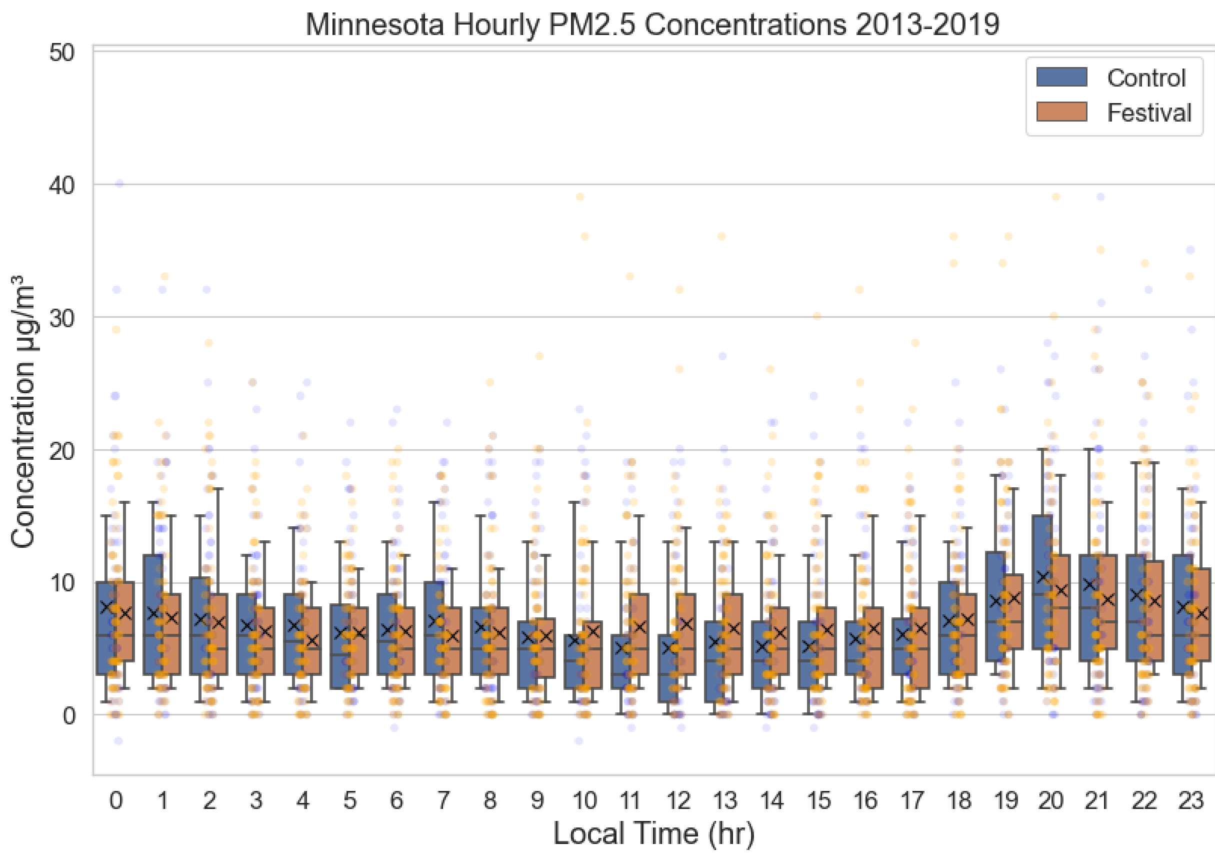

Figure 3c. Box and whisker plots of hourly PM2.5 concentrations for Minnesota State Fair (2013-2019) during festival and control days for all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

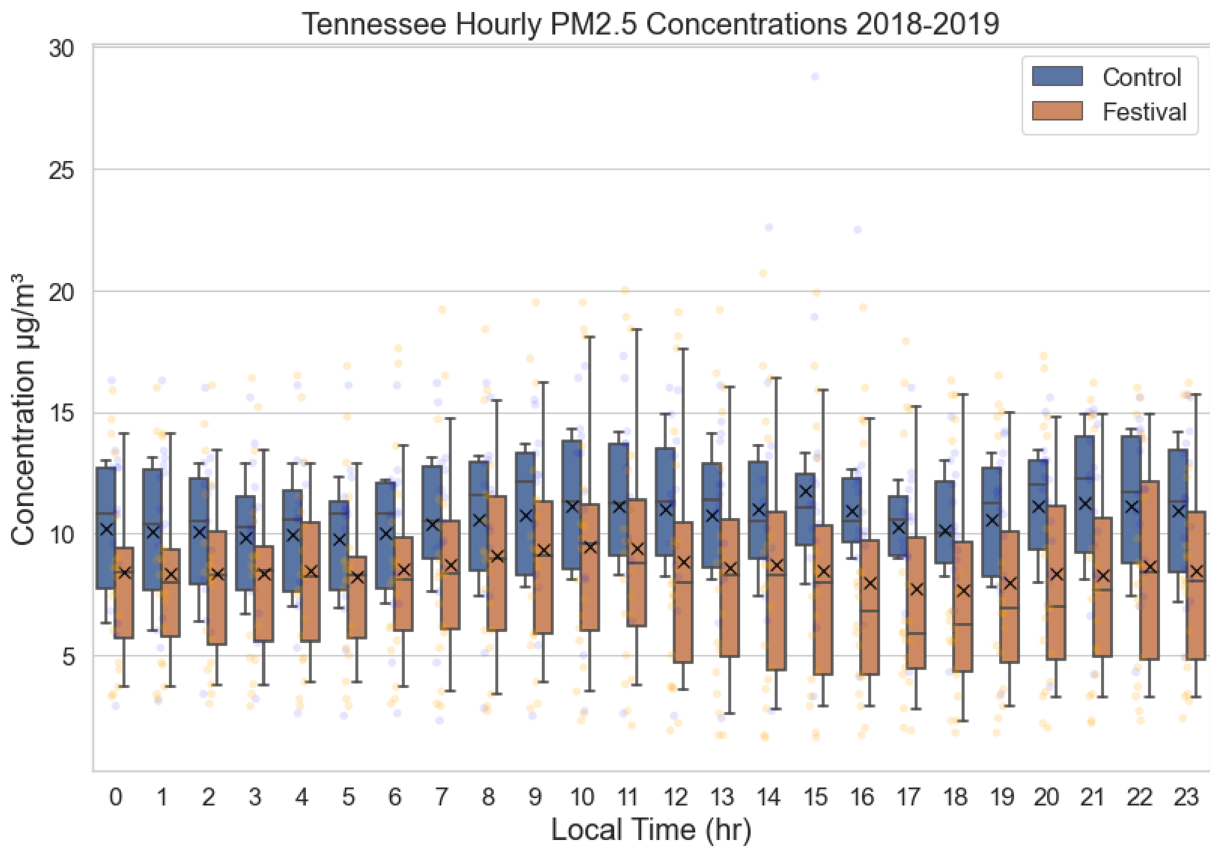

Figure 3d. Box and whisker plots of hourly PM2.5 concentrations for Tennessee Valley Fair (2018-2019) during festival and control days for all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

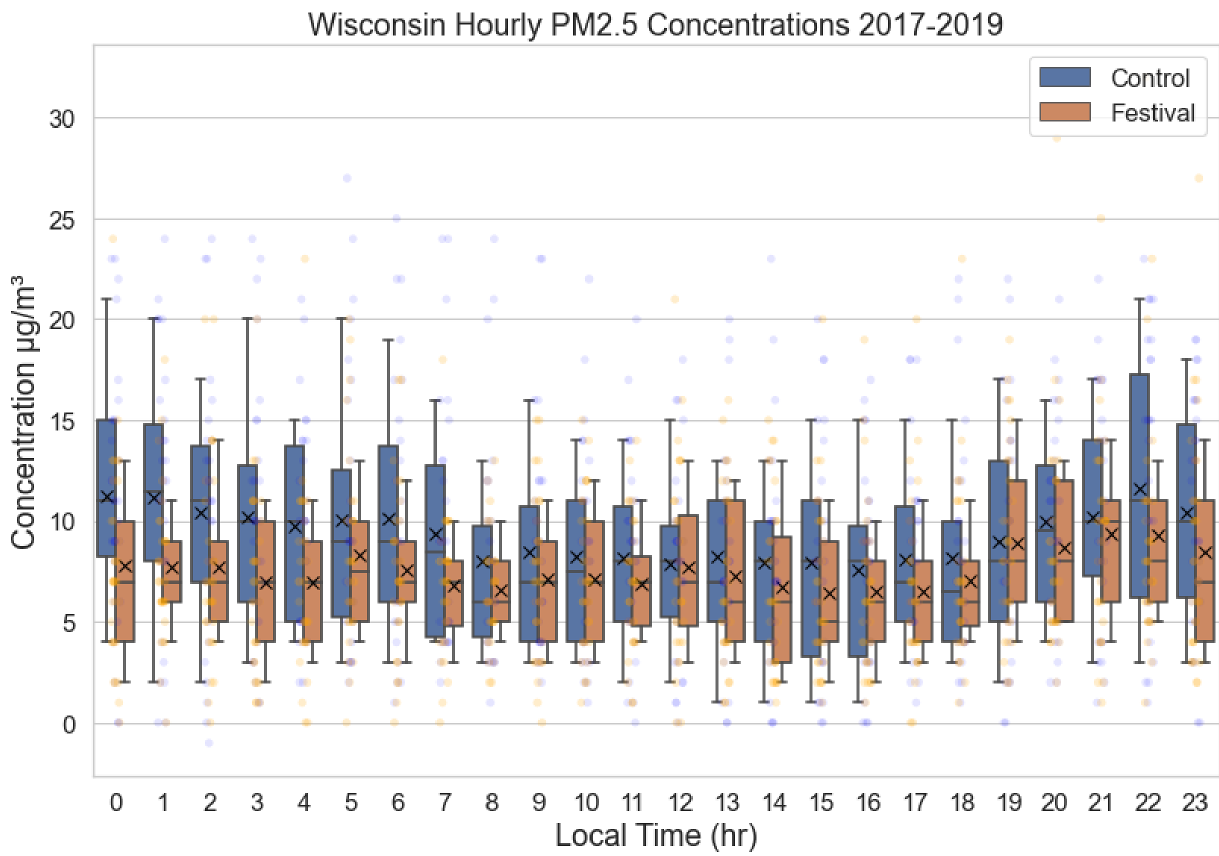

Figure 3e. Box and whisker plots of hourly PM2.5 concentrations for Wisconsin State Fair (2017-2019) during festival and control days for all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

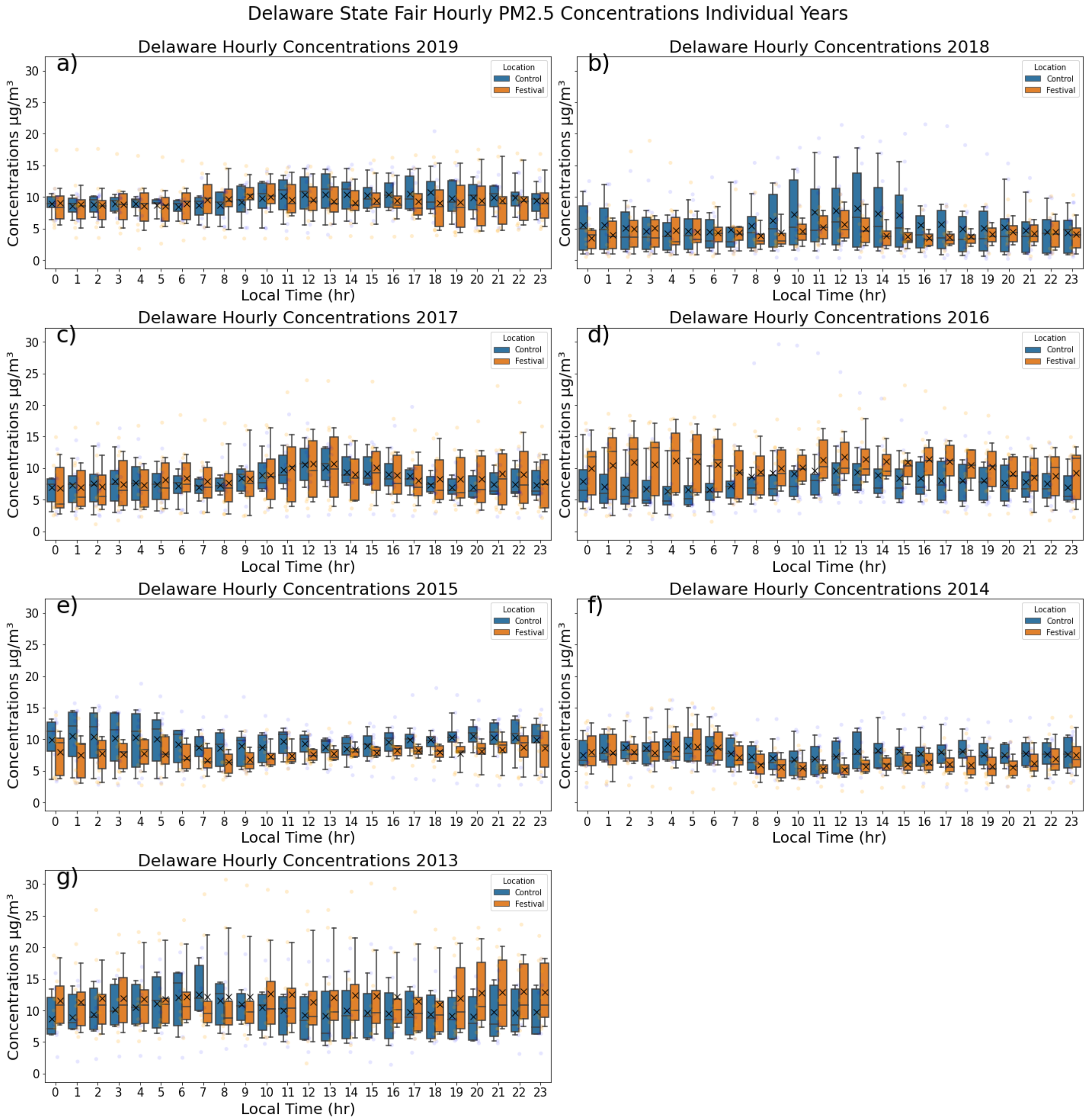

Figure 4. Box and whisker plots of hourly PM2.5 concentrations during festival and control days for Delaware during all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

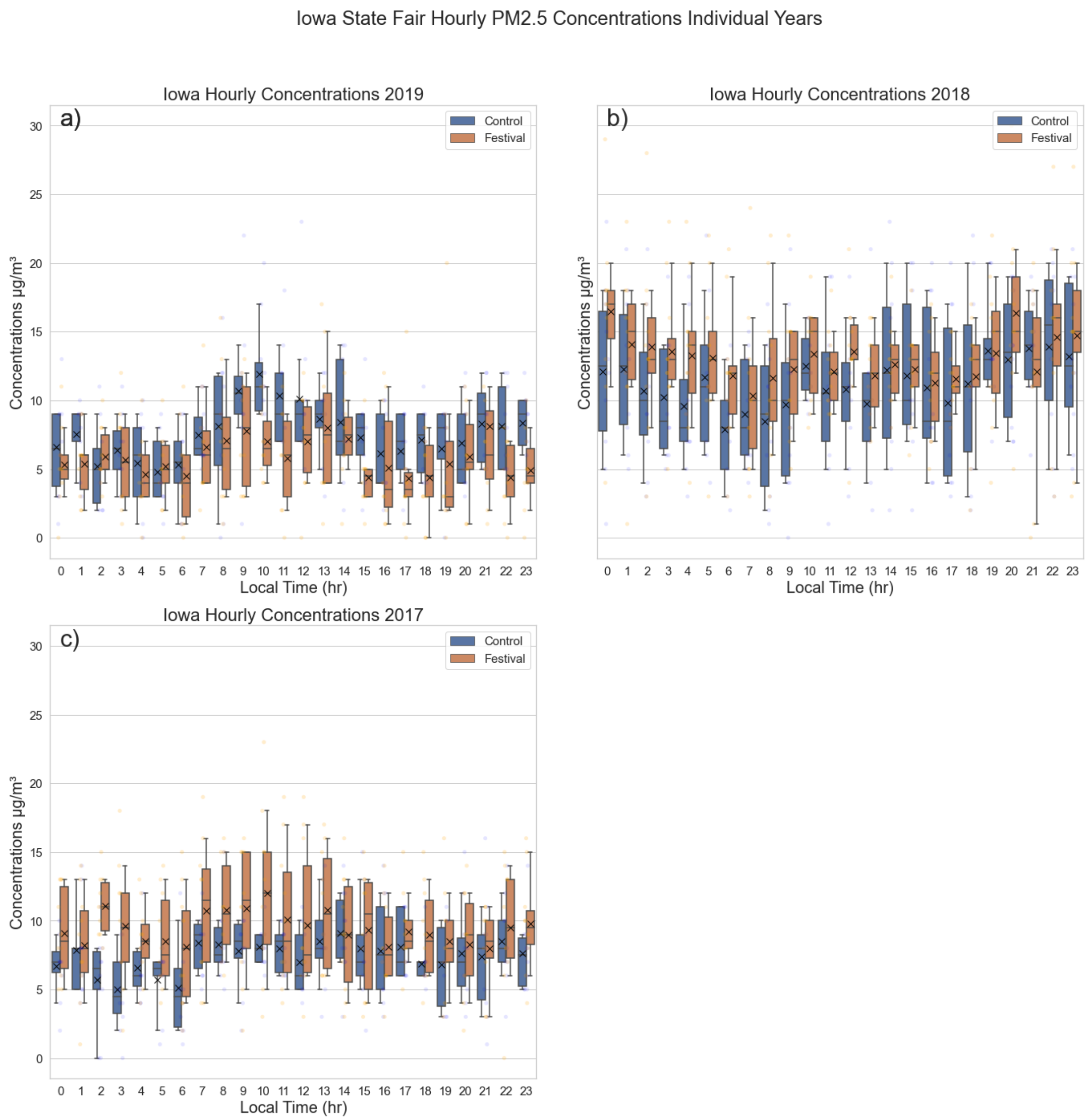

Figure 5. Box and whisker plots of hourly PM2.5 concentrations during festival and control days for Iowa State Fair during all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

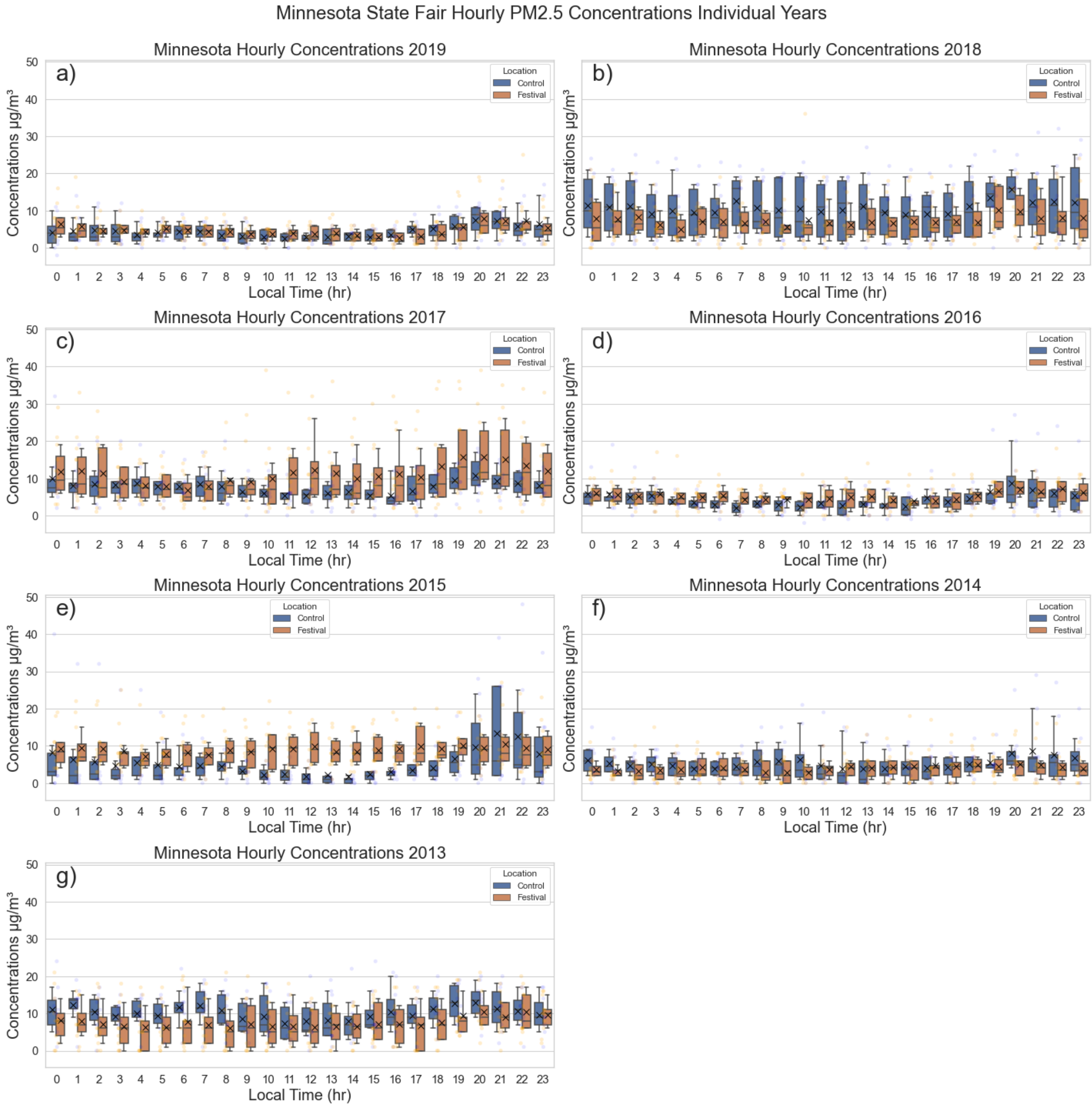

Figure 6. Box and whisker plots of hourly PM2.5 concentrations during festival and control days for Minnesota State Fair during all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

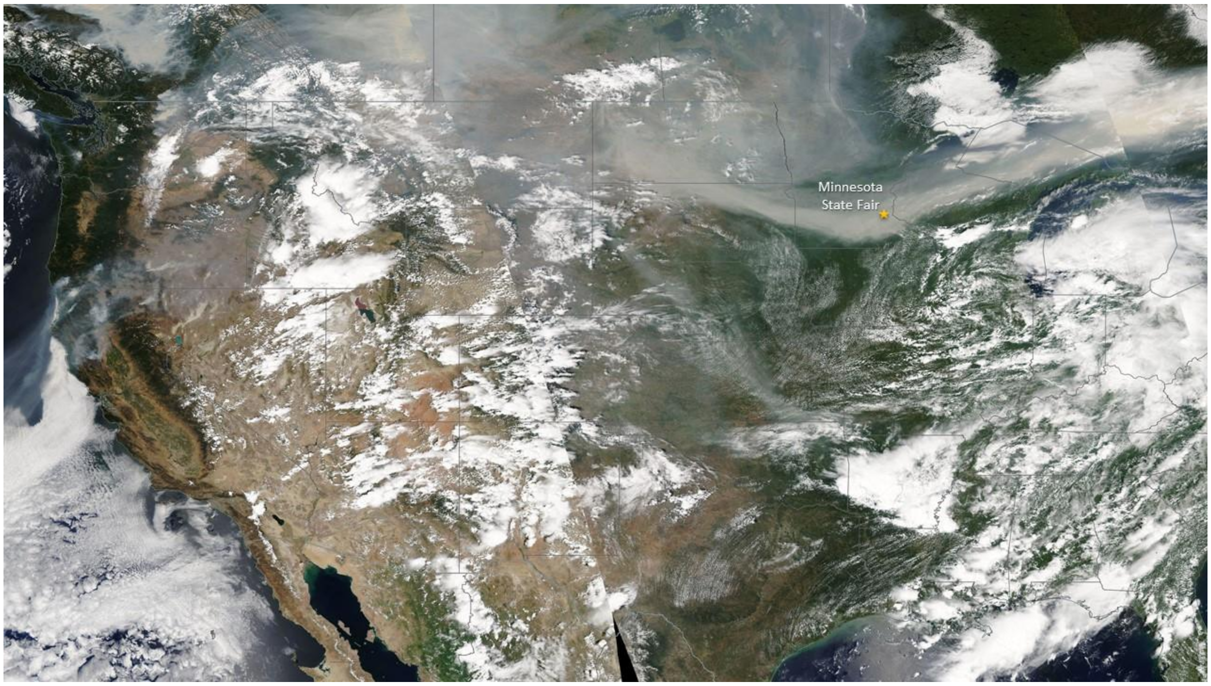

Figure 7. MODIS satellite imagery of wildfire smoke from British Colombia being transported across the United States from NASA Worldview application on August 17, 2018, a control day for the Minnesota State Fair.

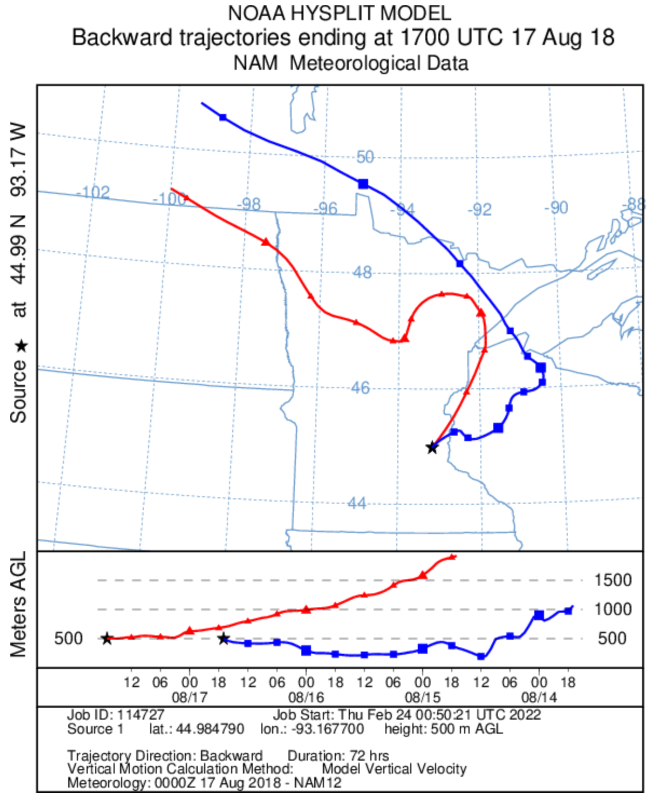

Figure 8. HYSPLIT backwards trajectory model analysis from the Minnesota State Fair on August 17, 2018, at 1700 UTC using the North American Model (NAM) meteorological data.

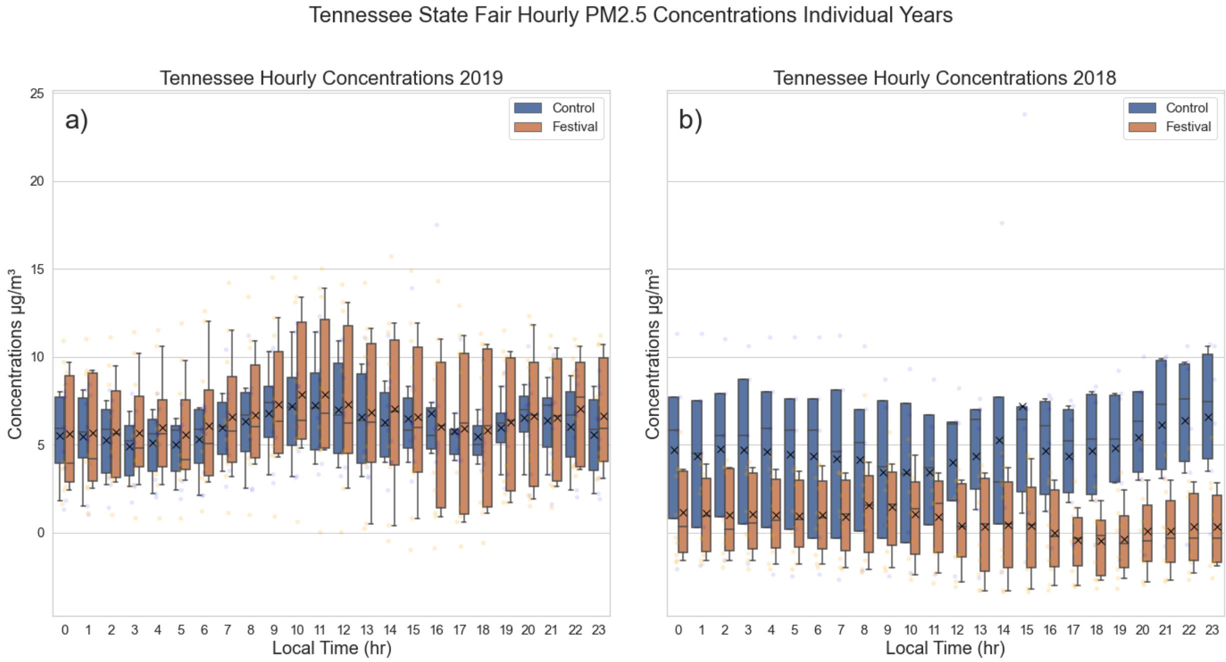

Figure 9. Box and whisker plots of hourly PM2.5 concentrations during festival and control days for Tennessee Valley Fair during all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

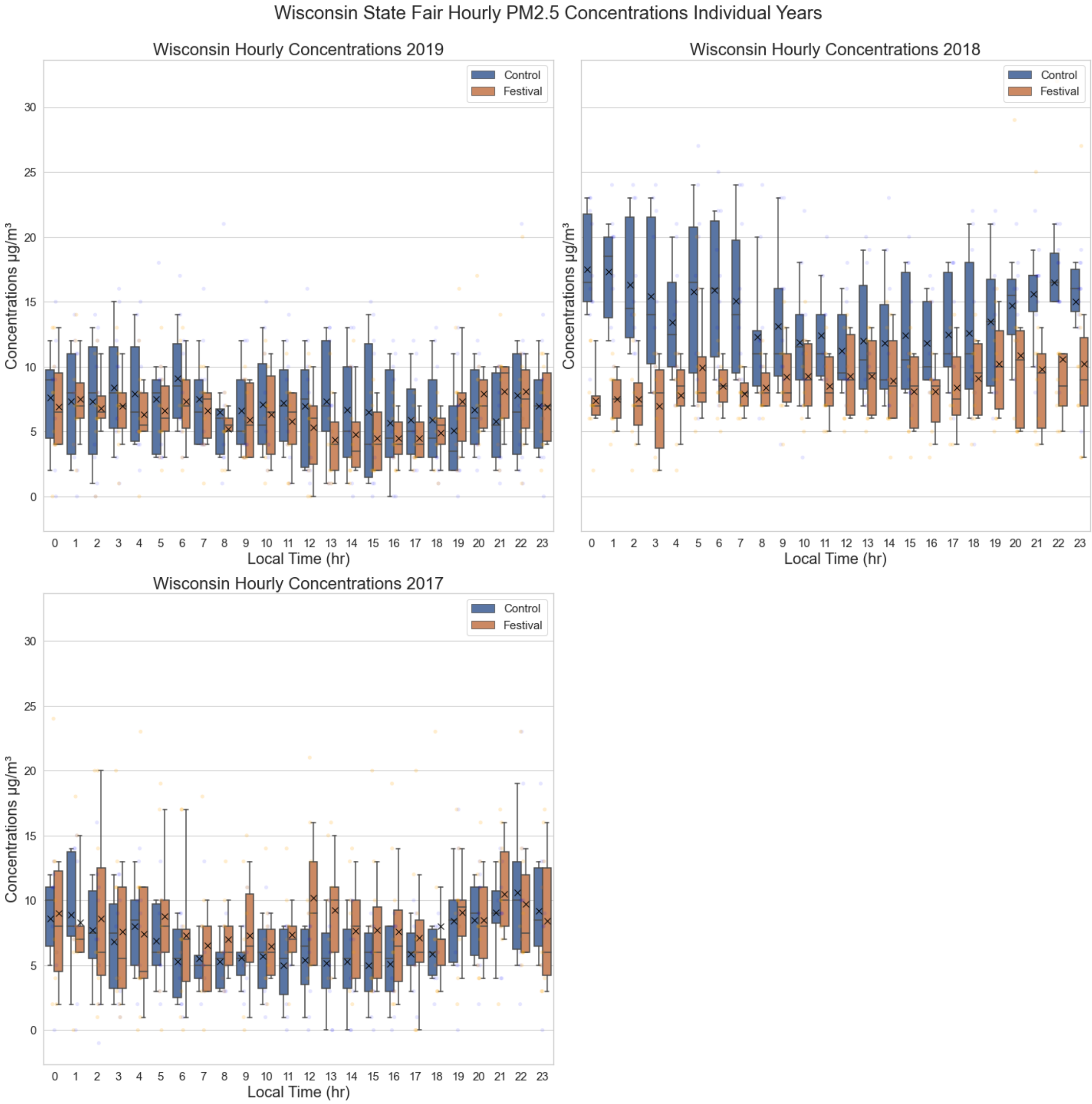

Figure 10. Box and whisker plots of hourly PM2.5 concentrations during festival and control days for Wisconsin State Fair during all years of unfiltered data. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

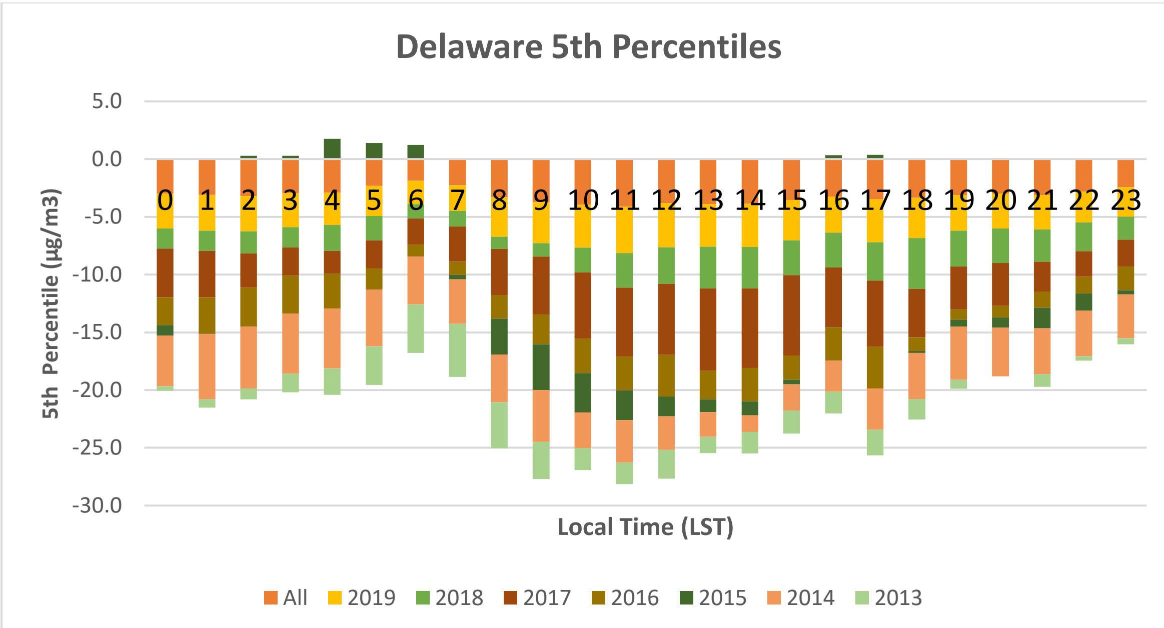

Figure 11a. 5th percentiles from distributions of festival and control day mean difference for Delaware State Fair from data unfiltered for meteorology. When the 5th percentile of the 1000 mean differences was less than zero, the null hypothesis could not be rejected.

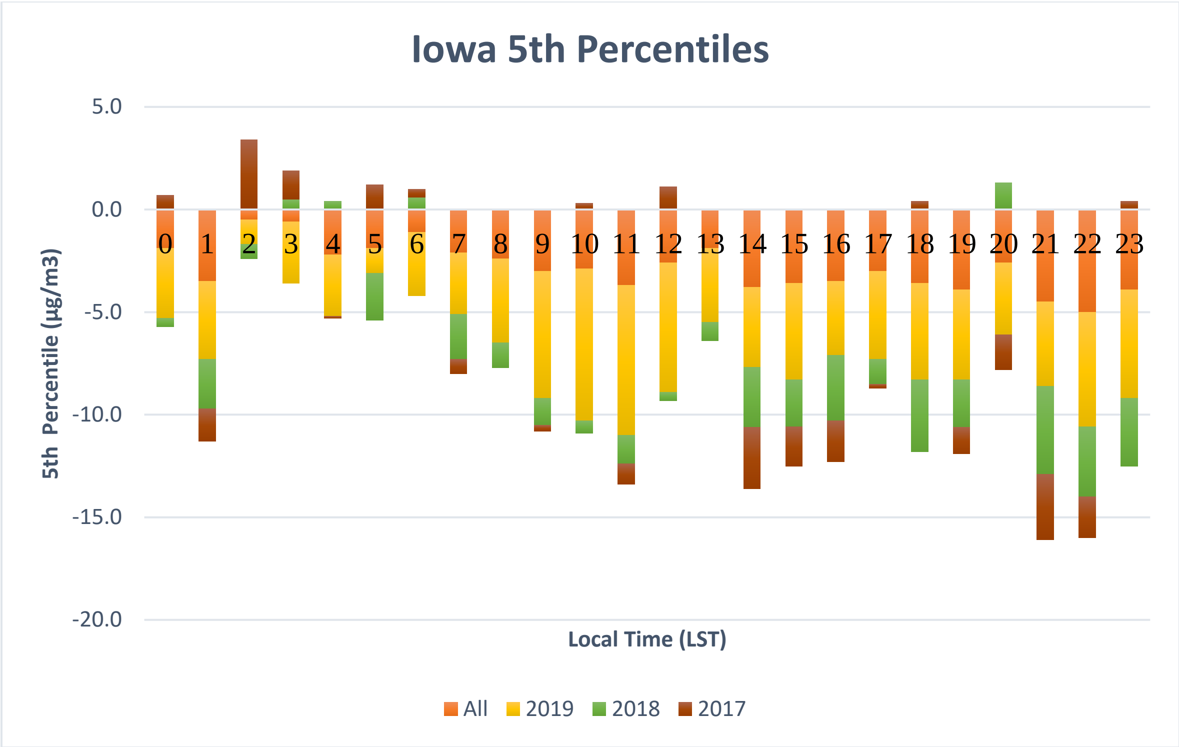

Figure 11b. 5th percentiles from distributions of festival and control day mean difference for Iowa State Fair from data unfiltered for meteorology. When the 5th percentile of the 1000 mean differences was less than zero, the null hypothesis could not be rejected.

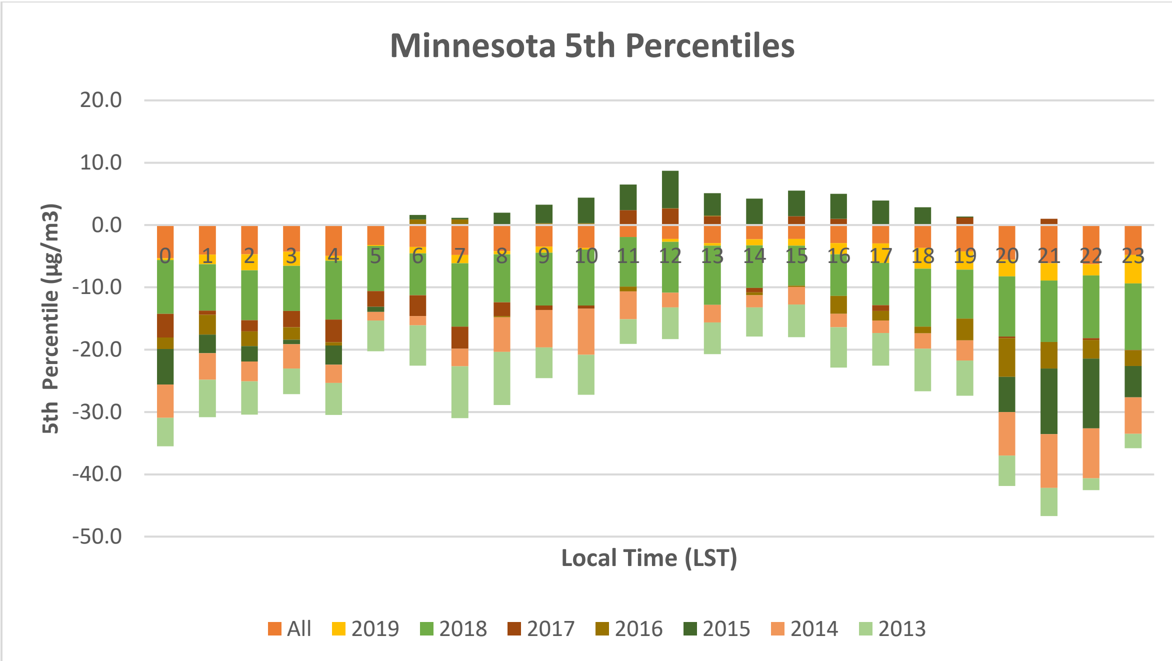

Figure 11c. 5th percentiles from distributions of festival and control day mean difference for Minnesota State Fair from data unfiltered for meteorology. When the 5th percentile of the 1000 mean differences was less than zero, the null hypothesis could not be rejected.

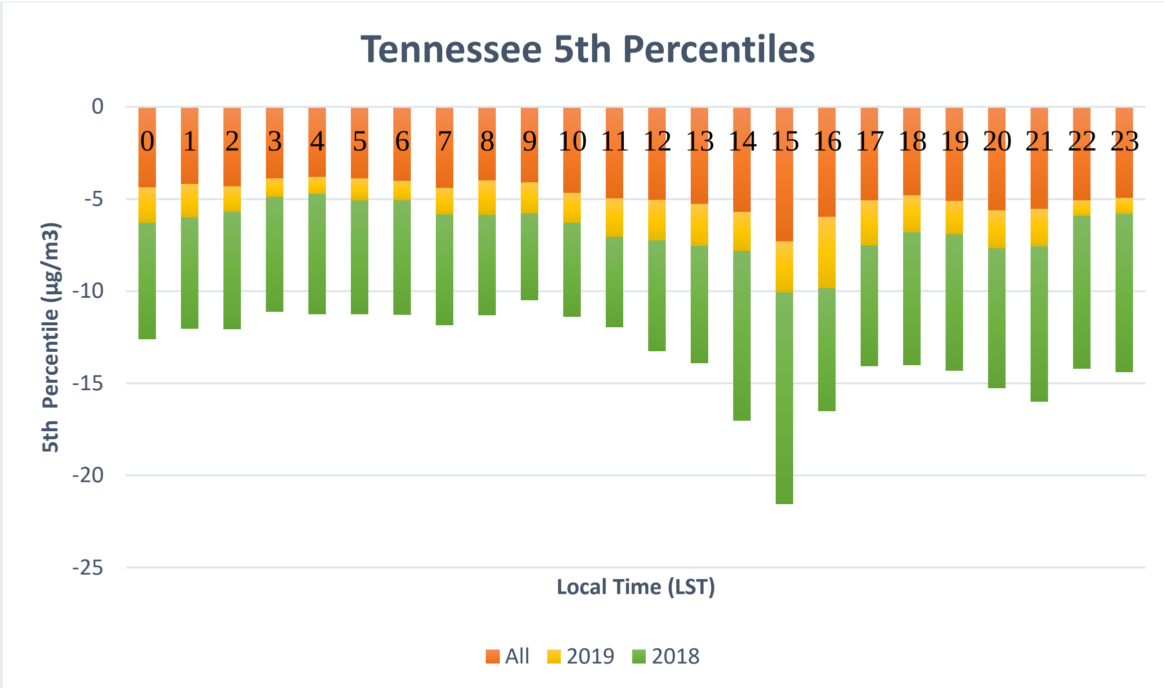

Figure 11d. 5th percentiles from distributions of festival and control day mean difference for Tennessee Valley Fair from data unfiltered for meteorology. When the 5th percentile of the 1000 mean differences was less than zero, the null hypothesis could not be rejected.

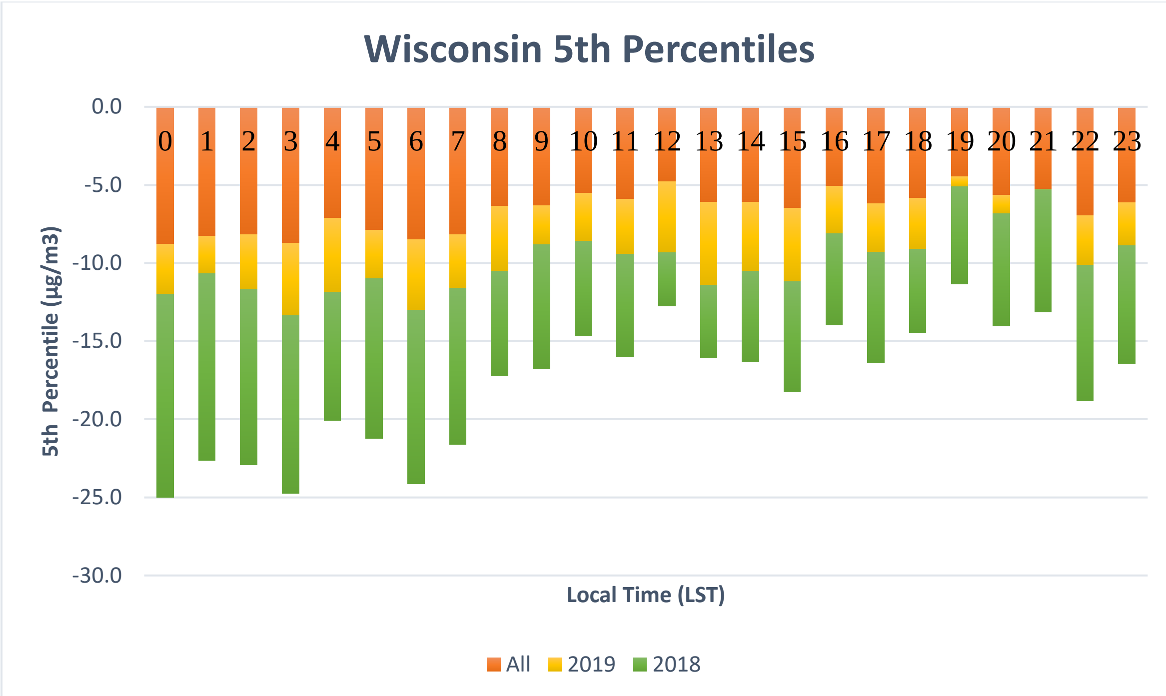

Figure 11e. 5th percentiles from distributions of festival and control day mean difference for Wisconsin State Fair from data unfiltered for meteorology. When the 5th percentile of the 1000 mean differences was less than zero, the null hypothesis could not be rejected.

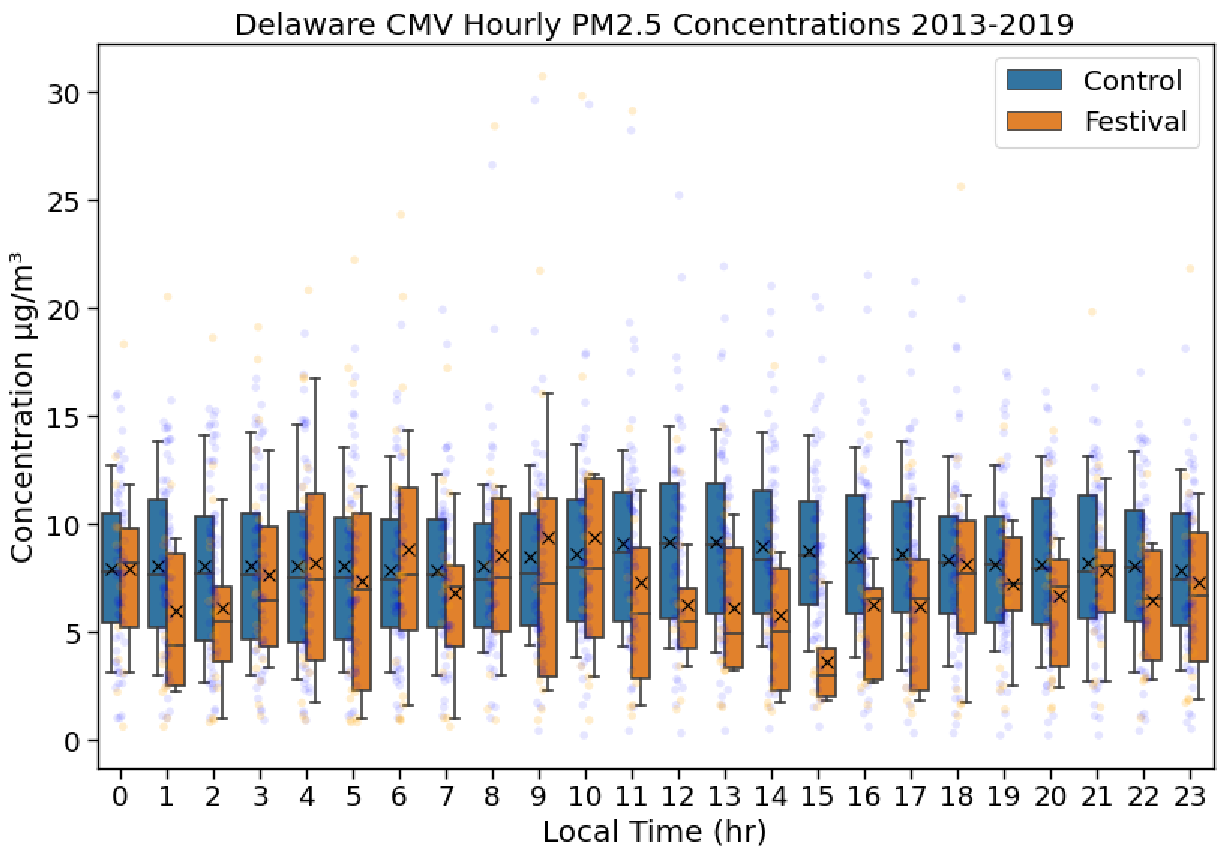

Figure 12a. Box and whisker plots of hourly PM2.5 concentrations for Delaware State Fair (2013-2019) during festival and control days filtered by cooperating meteorological variables (CMV) for all state fairs. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

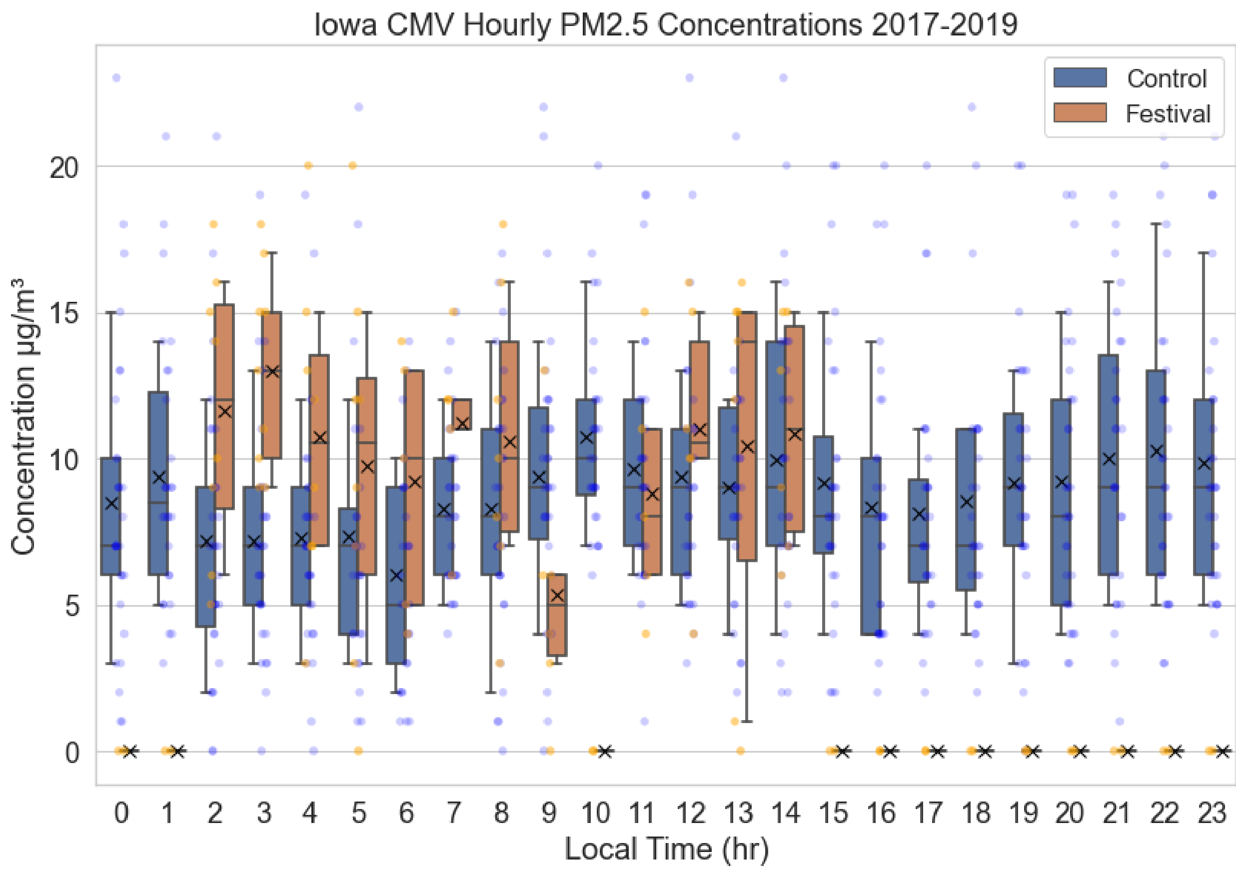

Figure 12b. Box and whisker plots of hourly PM2.5 concentrations for Iowa State Fair (2017-2019) during festival and control days filtered by cooperating meteorological variables (CMV) for all state fairs. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

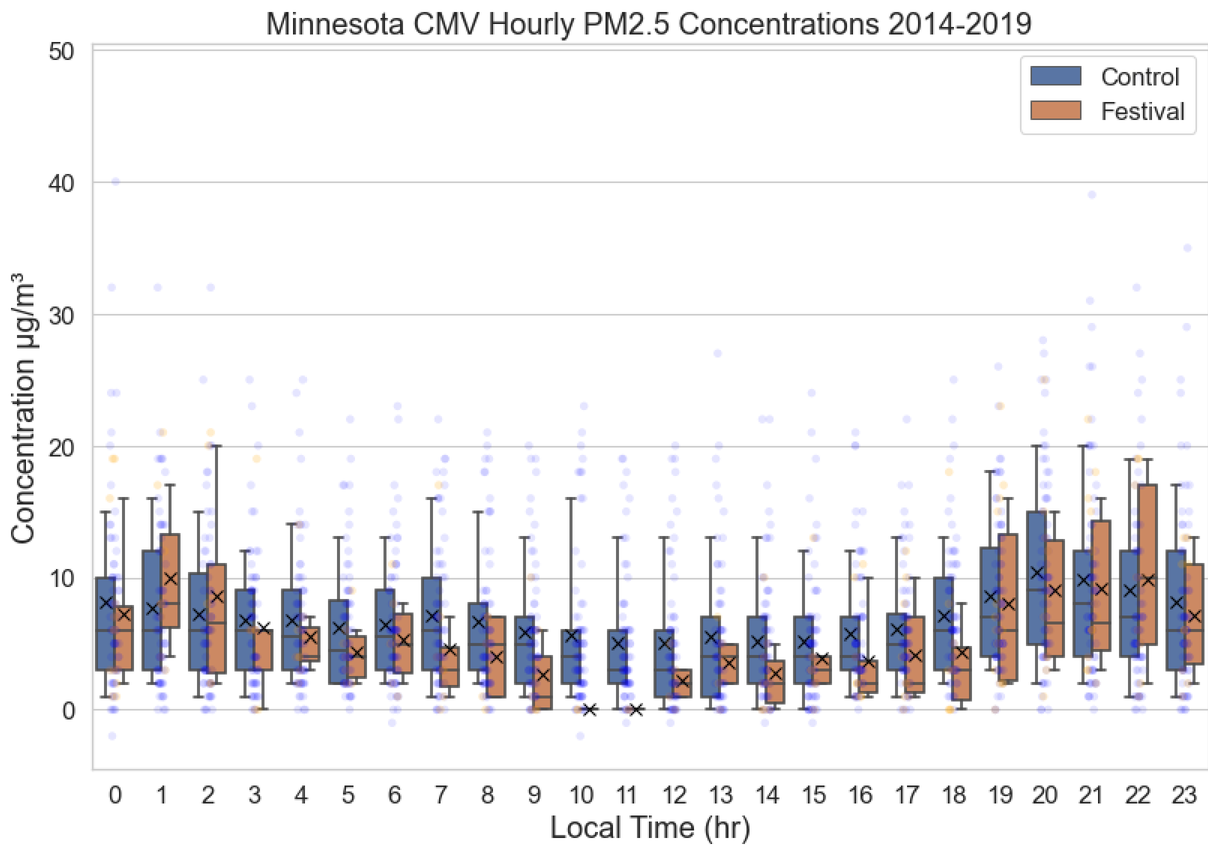

Figure 12c. Box and whisker plots of hourly PM2.5 concentrations for Minnesota State Fair (2013-2019) during festival and control days filtered by cooperating meteorological variables (CMV) for all state fairs. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

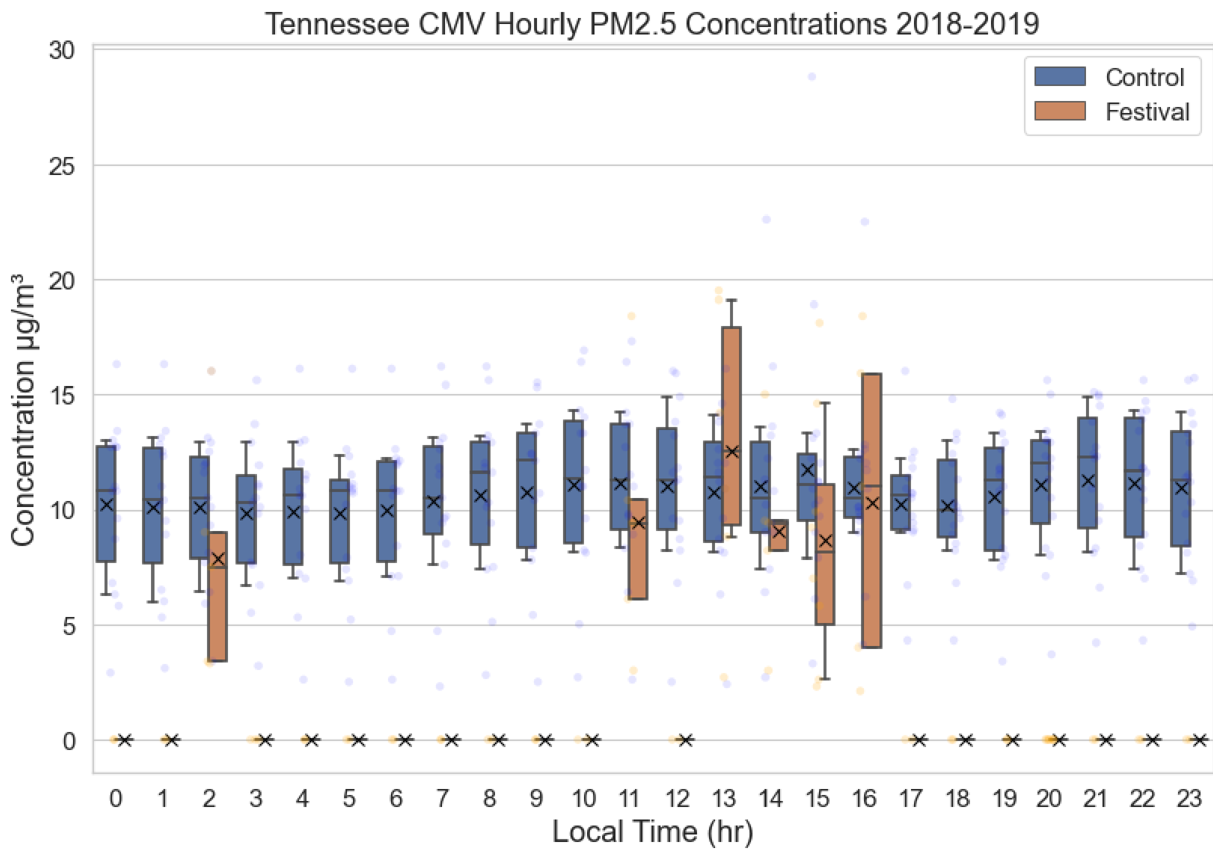

Figure 12d. Box and whisker plots of hourly PM2.5 concentrations for Tennessee Valley Fair (2018-2019) during festival and control days filtered by cooperating meteorological variables (CMV) for all state fairs. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

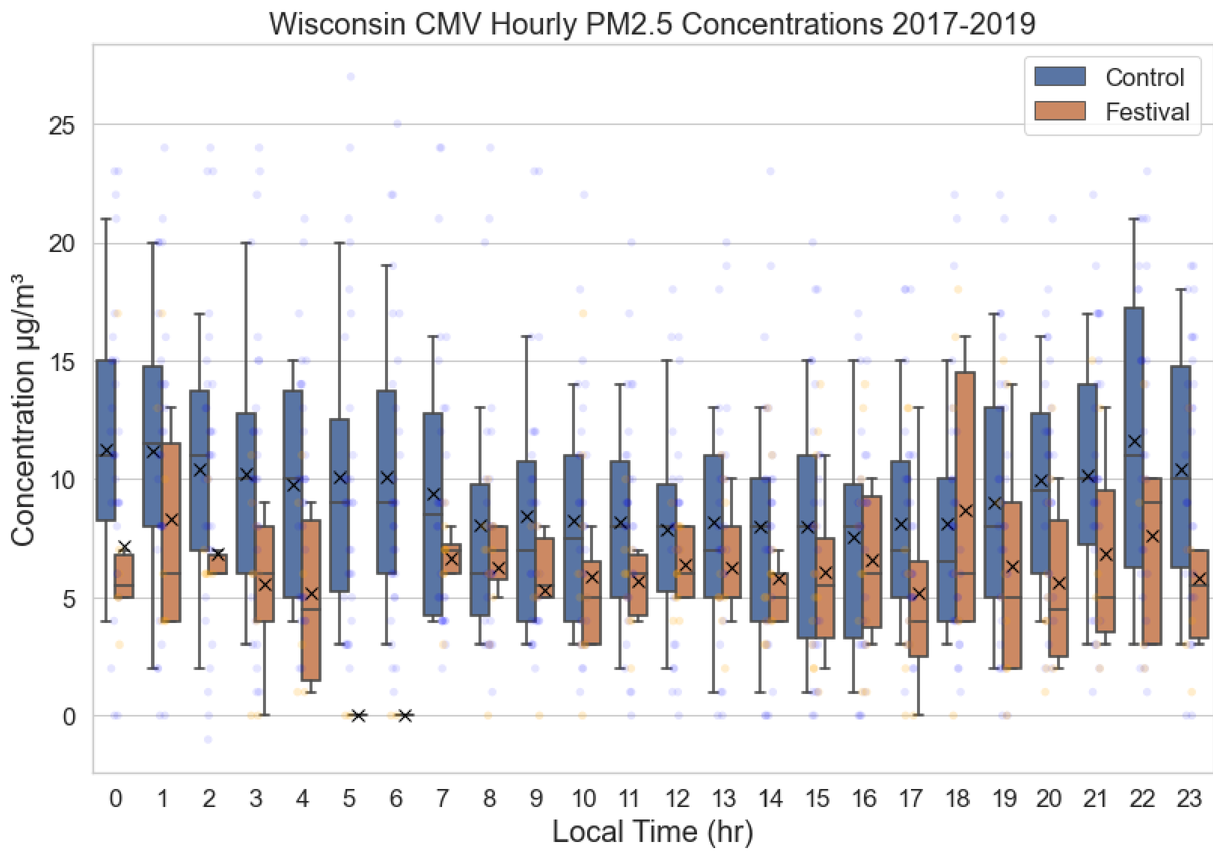

Figure 12e. Box and whisker plots of hourly PM2.5 concentrations for Wisconsin State Fair (2017-2019) during festival and control days filtered by cooperating meteorological variables (CMV) for all state fairs. The lower and upper boundaries of each box show the 25th and 75th percentiles; the lower and upper "whiskers" identify the 10th and 90th percentiles; the horizontal line within the box denotes the median; the 'x' represents the mean; blue and orange circles represent the individual hourly concentrations.

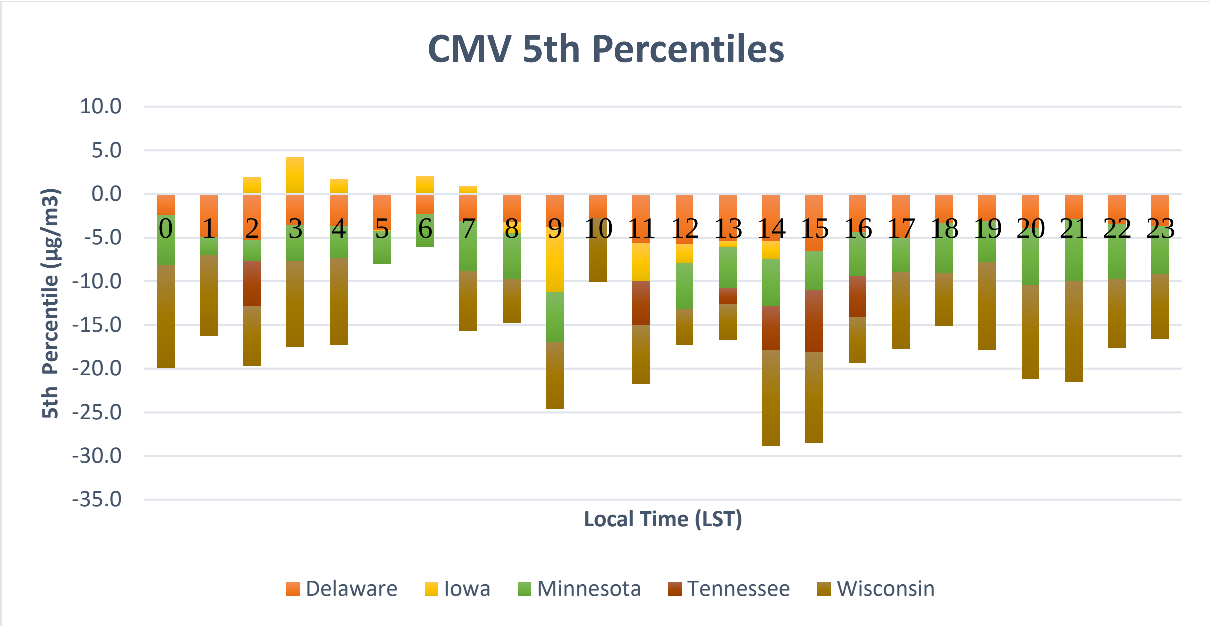

Figure 13. 5th percentiles from distributions of festival and control day mean difference for each fair from data filtered for meteorology. When the 5th percentile of the 1000 mean differences was less than zero, the null hypothesis could not be rejected.

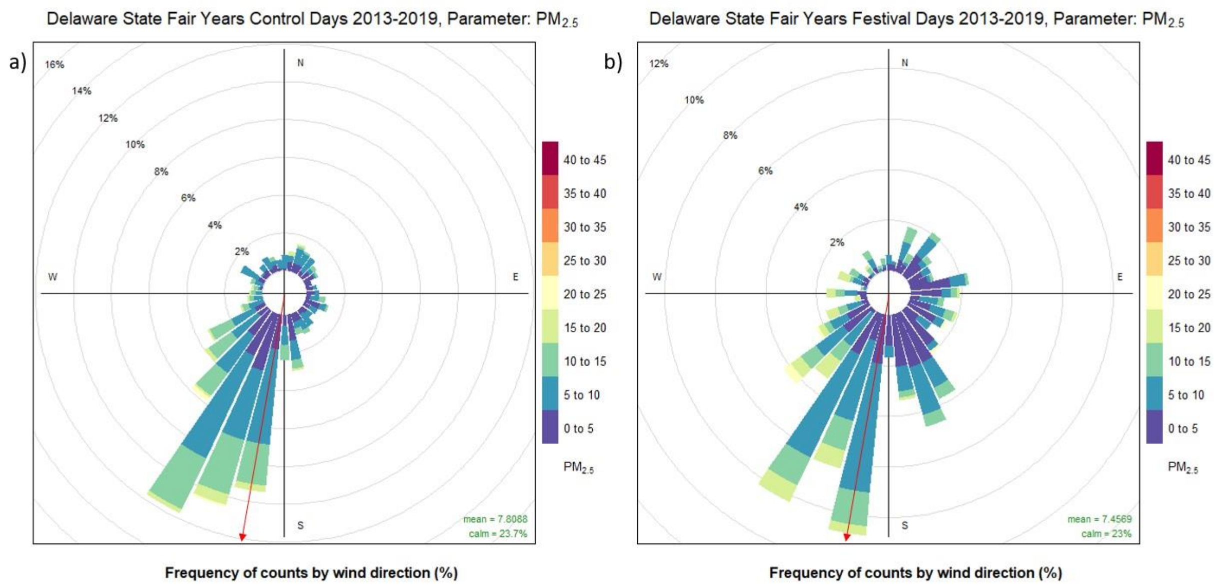

Figure 14. Air pollution rose analysis depicting wind direction and associated PM2.5 concentrations frequencies for control and festival days for accumulative years at the Delaware State Fair. Red arrow denotes direction bearing toward state fair at 189˚.

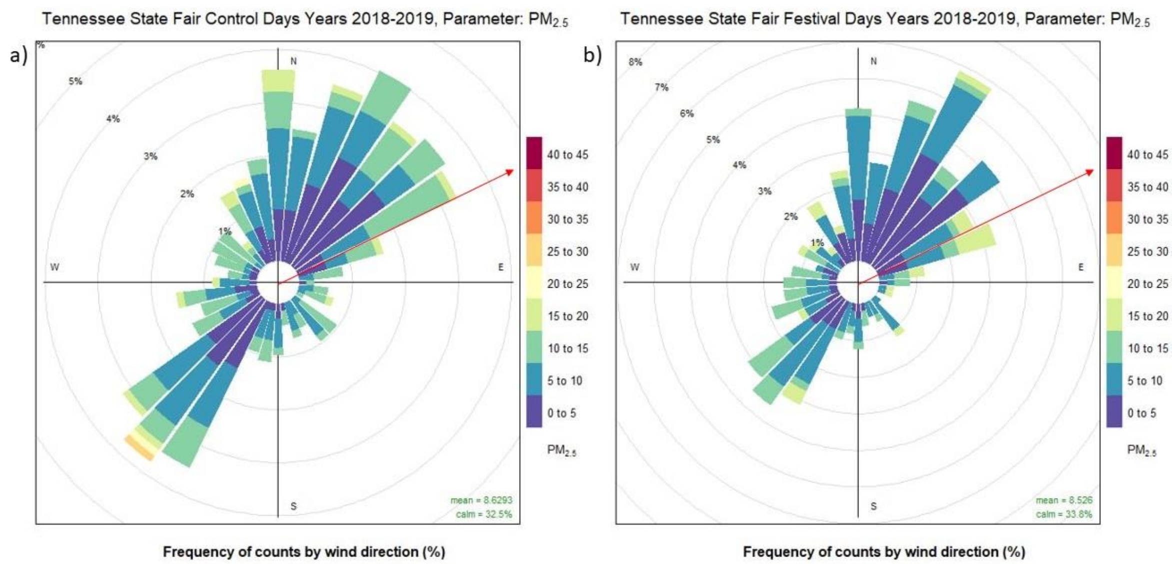

Figure 15. Air pollution rose analysis depicting wind direction and associated PM2.5 concentrations frequencies for control and festival days for accumulative years at the Tennessee Valley Fair. Red arrow denotes direction bearing toward state fair at 65˚.

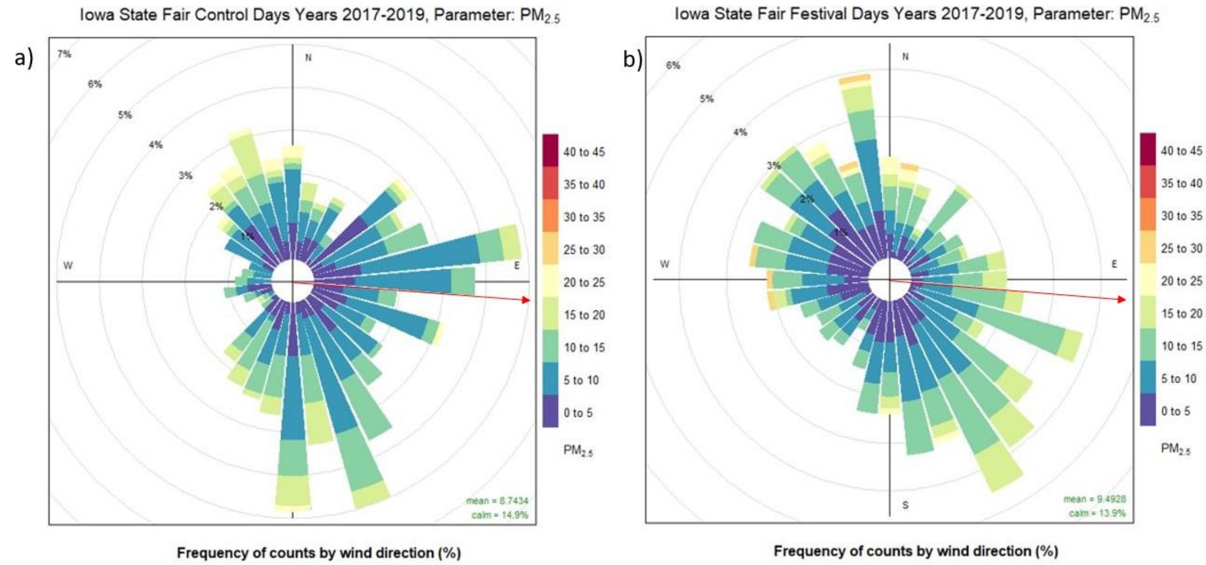

Figure 16. Air pollution rose analysis depicting wind direction and associated PM2.5 concentrations frequencies for control and festival days for accumulative years at the Iowa State Fair. Red arrow denotes direction bearing toward state fair at 96˚.

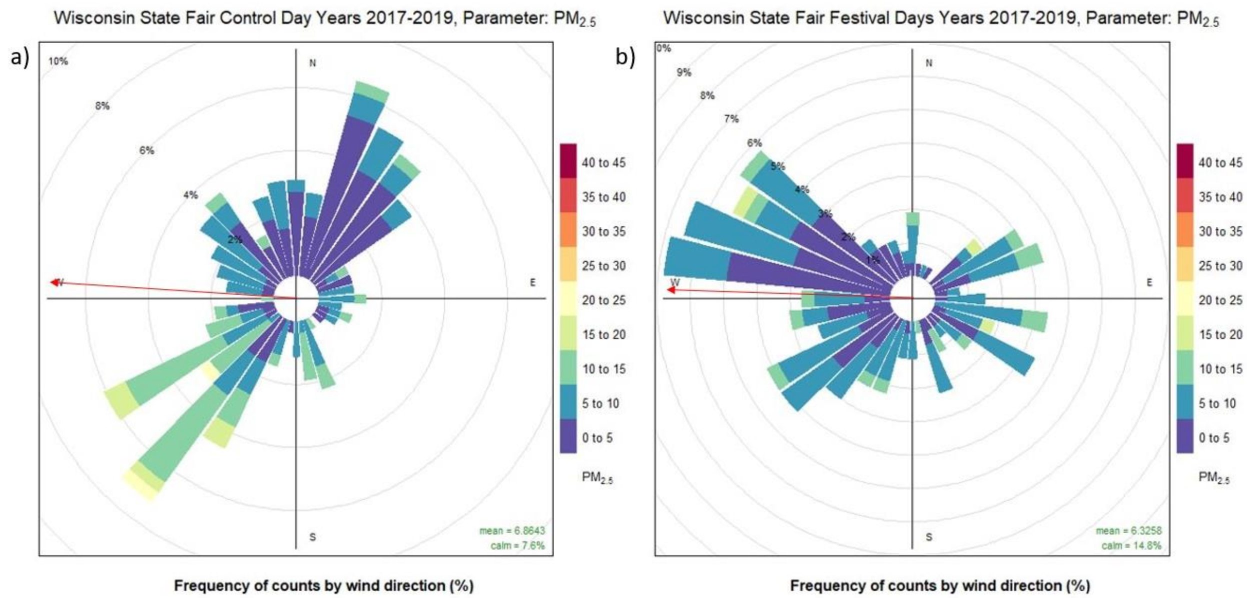

Figure 17. Air pollution rose analysis depicting wind direction and associated PM2.5 concentrations frequencies for control and festival days for accumulative years at the Wisconsin State Fair. Red arrow denotes direction bearing toward state fair at 272˚.

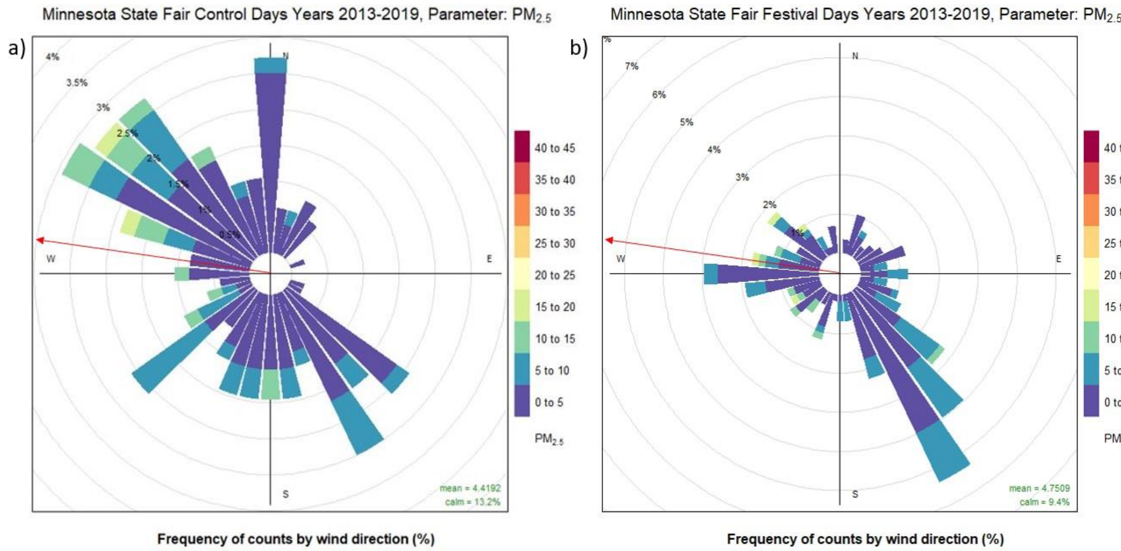

Figure 18. Air pollution rose analysis depicting wind direction and associated PM2.5 concentrations frequencies for control and festival days for accumulative years at the Minnesota State Fair. Red arrow denotes direction bearing toward state fair at 285˚.

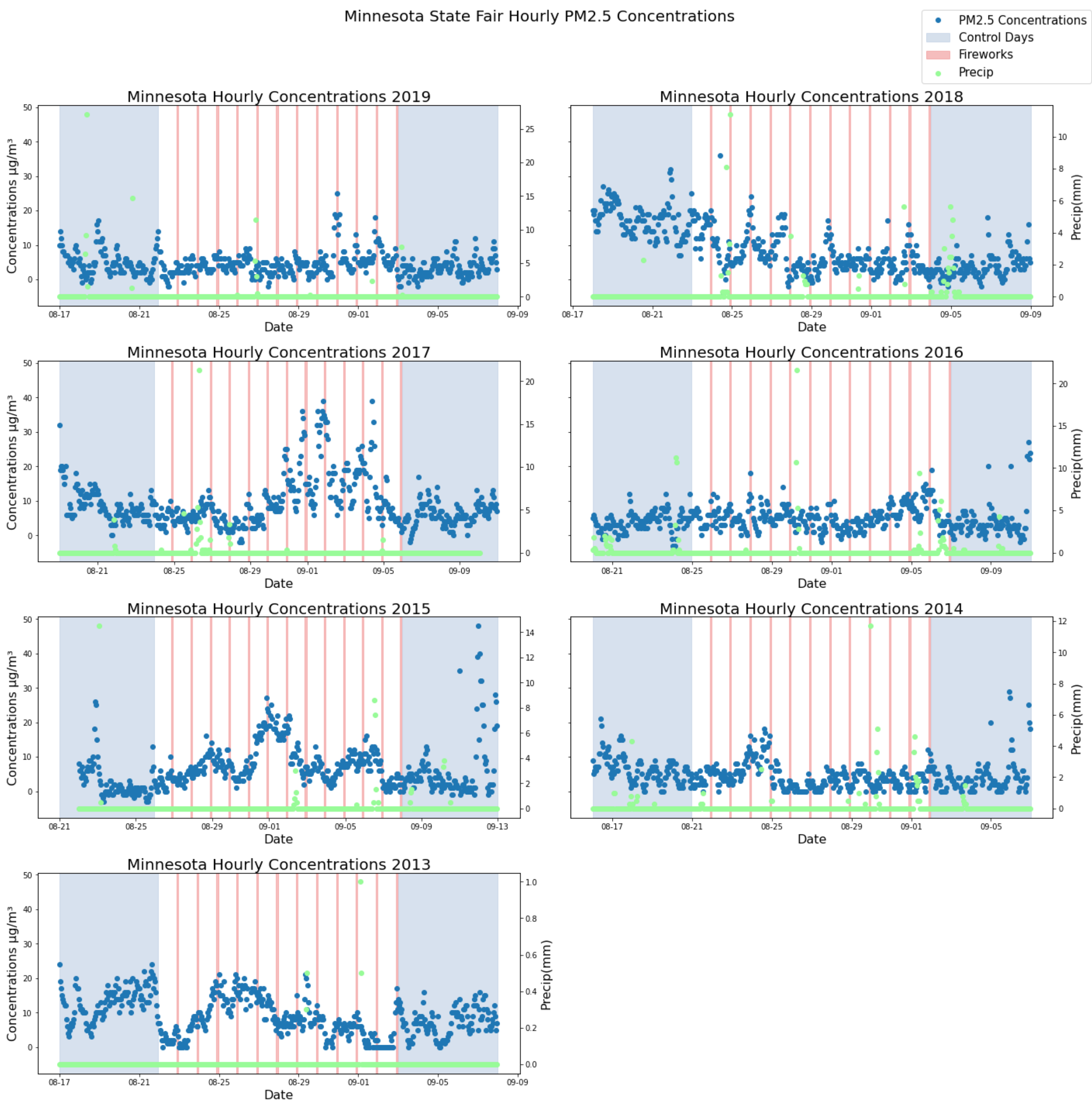

Figure 19 *a-g.* Time series plot of annual hourly PM2.5 concentrations for the Minnesota State Fair. Blue shaded regions represent control days. Red shaded regions represent the timing of known firework displays. Green dots represent measured precipitation from the nearest ASOS location.

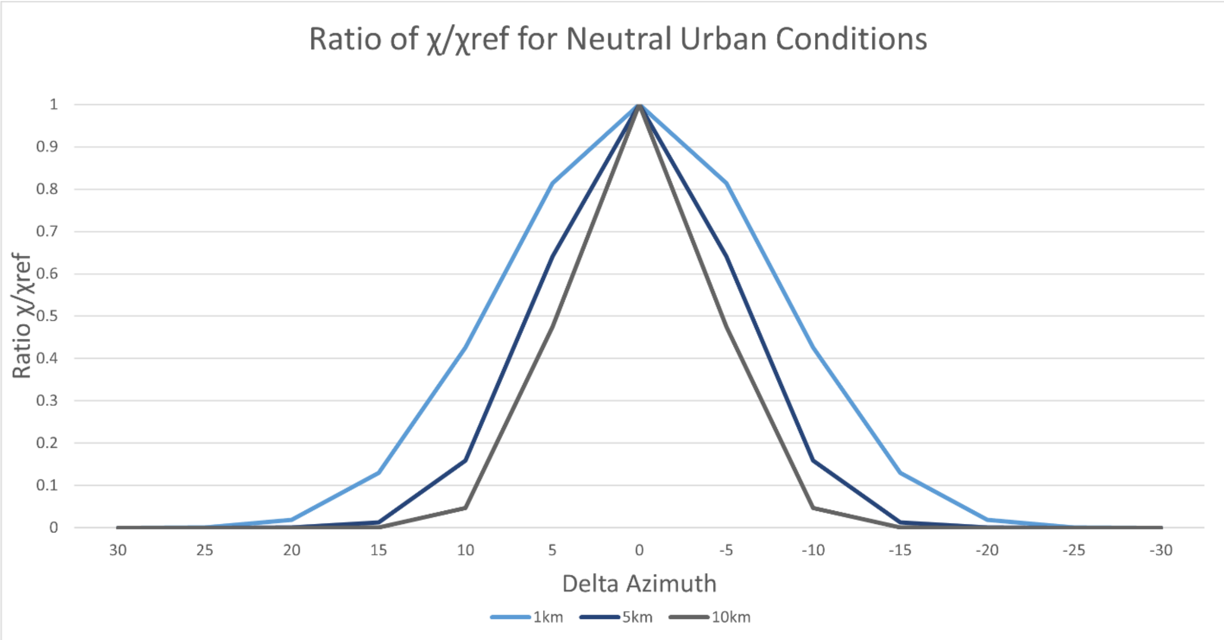

Figure 20. Gaussian Plume model depicting the ratio of concentrations (χ) to centerline concentrations (χ ref) at 1 km, 5 km, and 10 km downwind for slightly unstable urban conditions and mean wind speed of 2 ms^{-1}.

State Fair	Daily Attendance (approximately)	Years	AQS Distance (km)	ASOS Distance (km)	Duration (days)	Fireworks Details
Delaware	50,000[a]	2013-2019	9	31	10	8 Displays in 2019, 2 Displays in 2013-2018 10 pm
Iowa	100,000[b]	2017-2019	7	11	10	Nightly, 9 – 11 pm
Minnesota	70,000[c]	2013-2019	10	10	12	Nightly, 9 – 11 pm
Tennessee	30,000[d]	2018-2019	4	3	10	Nightly
Wisconsin	100,000[e]	2017-2019	7	13	10	None

Table 1. Location and details of state fairs investigated during the study. The distance between state fair location and air quality sites (AQS) and automated surface observation stations (ASOS) are included.

[a] Delaware Public Media 2019, [b] Iowa State Fair 2020, [c] Minnesota State Fair 2020, [d] The Daily Post Athenian 2016, [e] Milwaukee Journal Sentinel 2019.

CMV Sample Size Festival Days

Hour	Delaware (70)	Iowa (30)	Minnesota (84)	Tennessee (20)	Wisconsin (30)
0	17	3	14	3	6
1	17	2	8	3	7
2	20	7	8	5	6
3	22	10	7	4	9
4	19	8	8	3	6
5	24	8	7	3	4
6	23	5	6	1	4
7	18	5	8	2	8
8	13	7	5	4	12
9	14	6	7	2	6
10	15	4	3	1	12
11	15	5	4	5	10
12	12	6	5	4	13
13	14	7	5	6	11
14	13	6	10	5	13
15	9	4	8	8	14
16	13	3	10	5	12
17	16	3	10	1	11
18	16	3	10	1	7
19	17	2	14	3	9
20	18	0	10	3	10
21	20	2	14	2	7
22	16	1	9	2	5
23	16	2	10	2	6

Table 2. Table 2 shows, for each hour, the number of festival days (overall years) meeting the CMV criteria at that hour. Total number of festival days for each state fair is denoted in parenthesis. Highlighted in green are hours that did not meet the sample size requirement (n=5) to be included in bootstrap with resampling or subsequently statistical analysis

Frequency of Concentrations > 20 ug/m3

Local Time

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Total
DE Fest.	0	0	0	0	0	0	0	0	0	0	0	1	2	1	1	2	1	0	0	0	0	1	1	0	10
DE Cont.	0	0	0	0	0	0	0	0	1	1	1	1	2	1	1	0	1	1	1	0	0	0	0	0	11
IA Fest.	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	1	2	1	2	1	19
IA Cont.	1	1	1	0	0	1	0	0	0	2	0	0	1	1	1	0	0	0	1	0	0	0	1	1	12
MN Fest.	4	3	4	1	1	0	0	0	2	1	3	1	2	1	2	1	3	2	2	4	5	7	6	4	59
MN Cont.	5	2	2	2	3	1	2	1	1	0	2	0	0	1	2	2	1	1	2	2	6	6	6	4	54
TN Fest.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
TN Cont.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	3
WI Fest.	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	1	1	2	1	10
WI Cont.	4	2	3	3	1	3	3	3	2	2	1	0	0	0	1	0	0	0	2	2	1	1	4	0	38
Total Fest.	5	4	5	2	2	1	1	1	3	2	4	2	5	2	4	3	4	2	2	5	7	9	9	5	
Total Cont.	10	5	6	5	4	5	5	4	4	5	4	1	3	3	6	3	3	2	6	4	7	7	11	5	

Table 3. Frequency of hourly PM2.5 concentrations measuring larger than 20μg/m^3 during control and festival days during all years for each state fair.

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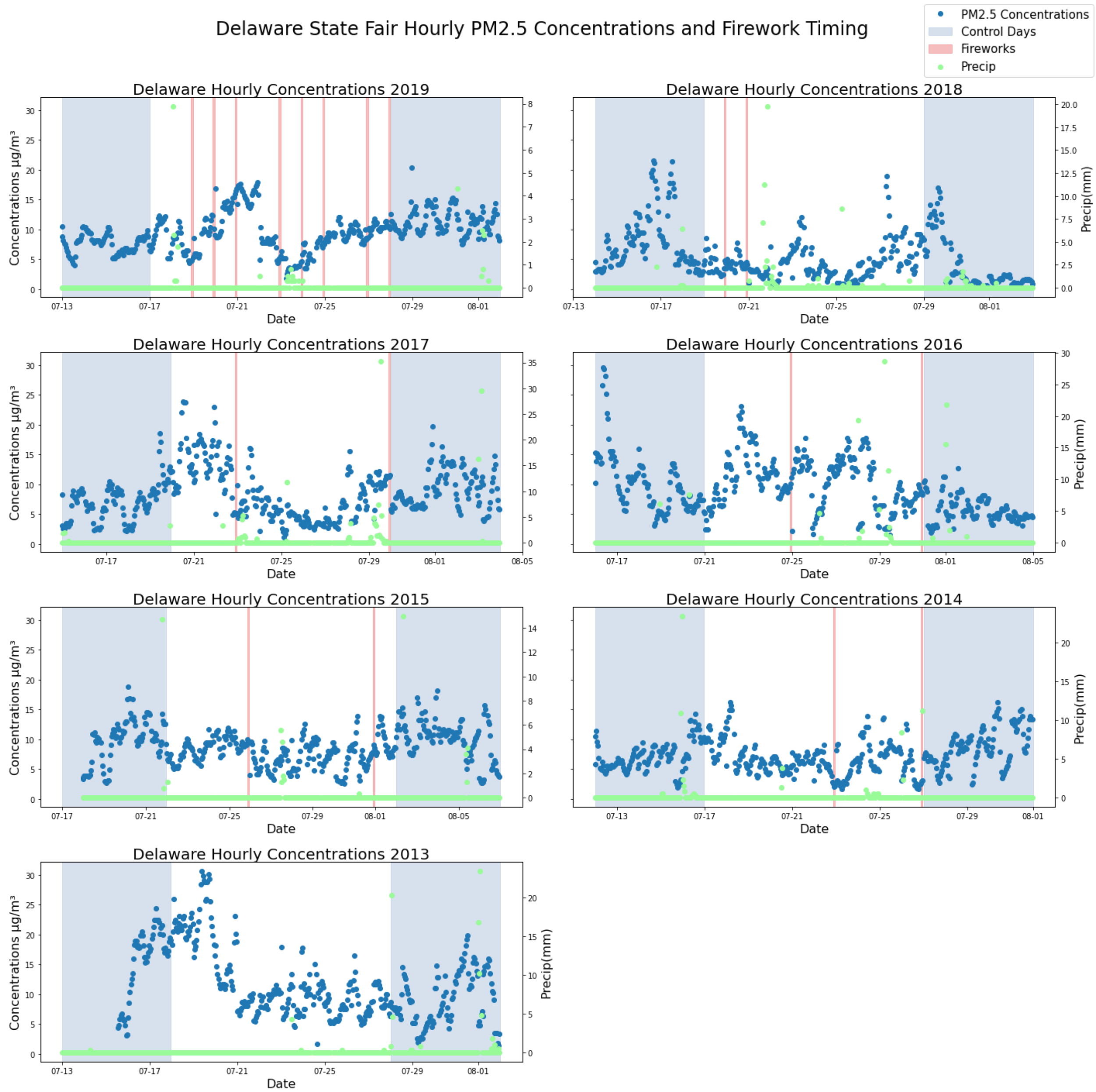
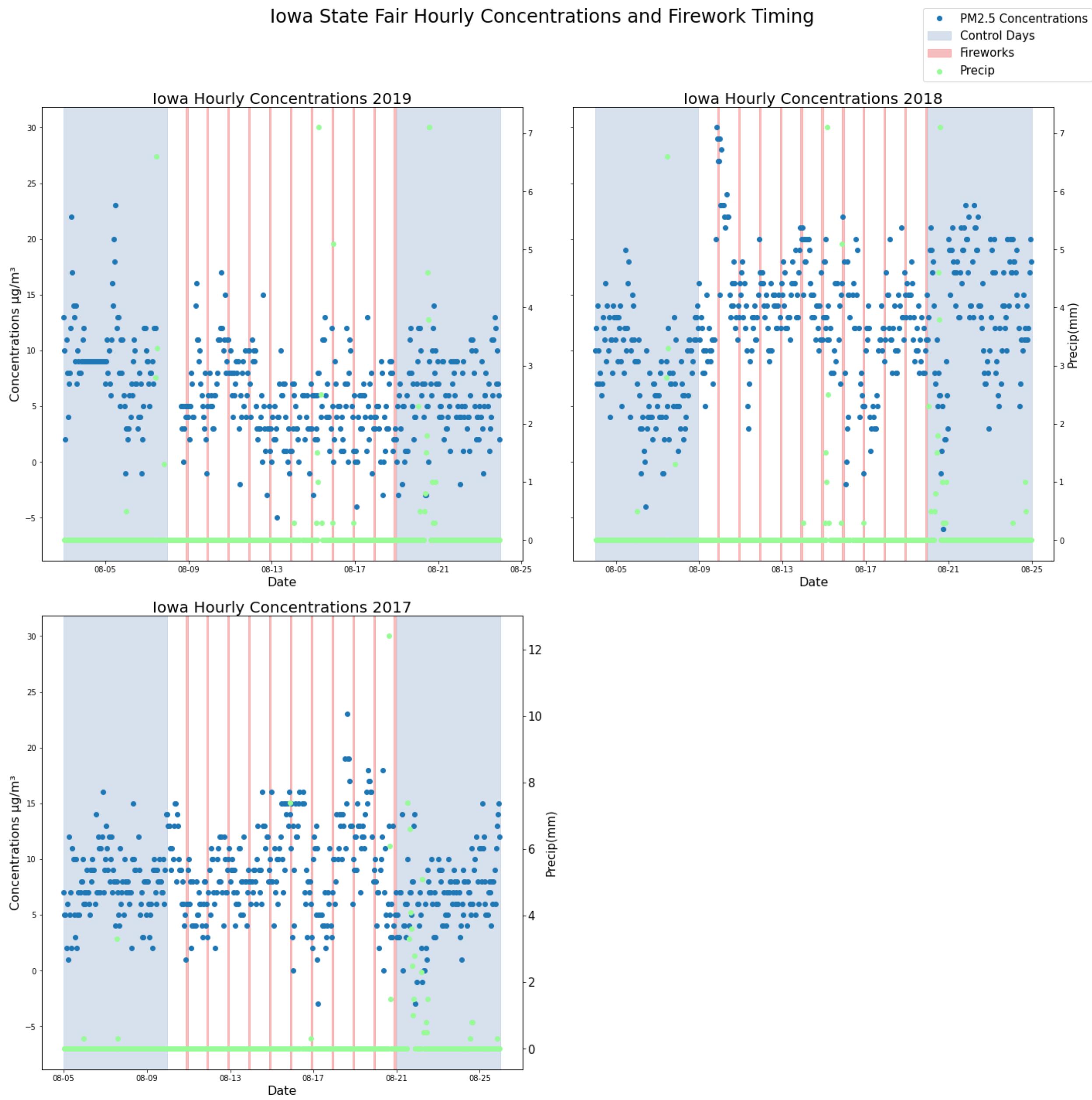
Appendix: Time Series Analysis Full Results

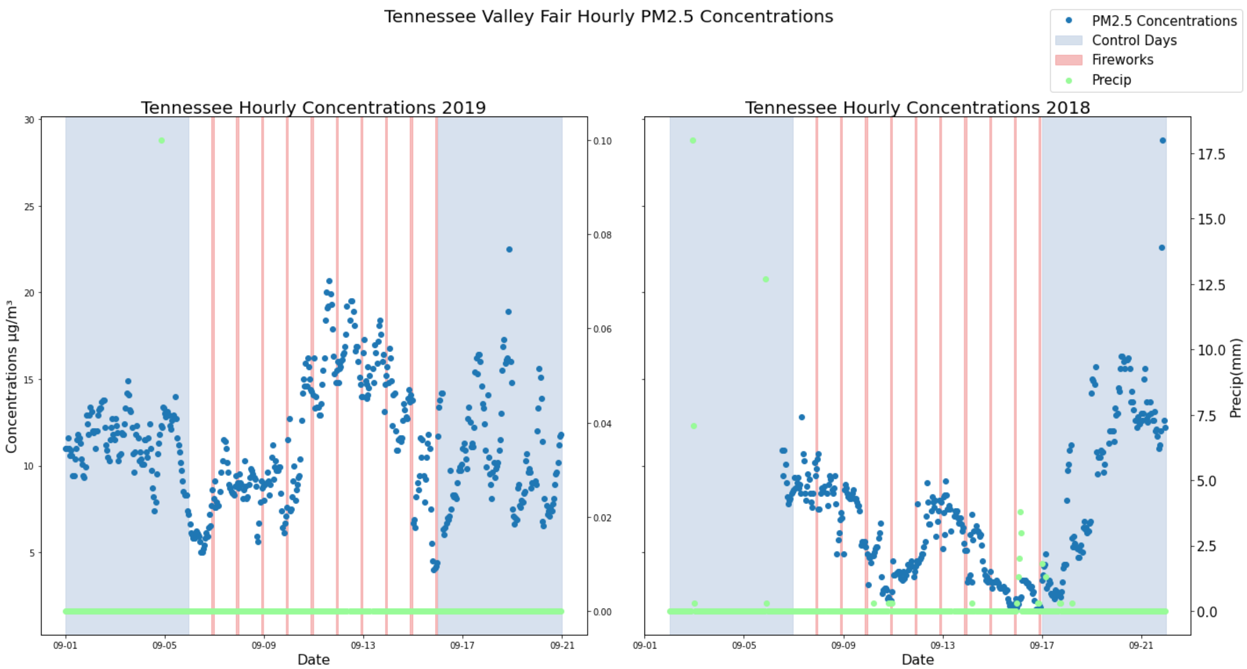
A1 a-g. Time series plot of annual hourly PM2.5 concentrations for the Delaware State Fair. Blue shaded regions represent control days. Red shaded regions represent the timing of known firework displays. Green dots represent measured precipitation from the nearest ASOS location.



A2 a-c. Time series plot of annual hourly PM2.5 concentrations for the Iowa State Fair. Blue shaded regions represent control days. Red shaded regions represent the timing of known firework displays. Green dots represent measured precipitation from the nearest ASOS location.



A3 a-b. Time series plot of annual hourly PM2.5 concentrations for the Tennessee Valley Fair. Blue shaded regions represent control days. Red shaded regions represent the timing of known firework displays. Green dots represent measured precipitation from the nearest ASOS location.



A4 a-c. Time series plot of annual hourly PM2.5 concentrations for the Wisconsin State Fair. Blue shaded regions represent control days. Red shaded regions represent the timing of known firework displays. Green dots represent measured precipitation from the nearest ASOS location.