Analysis of Short Term $PM_{2.5}$ Measurements for Sensor Scale and Messages
U.S. Environmental Protection Agency
DRAFT
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Low-cost air quality sensors are becoming increasingly available to the public and there is a need to help people interpret air quality concentrations that are collected and reported in increments as short as one minute. However, health studies do not support linking 1-minute fine particulate matter ($PM_{2.5}$) exposures to adverse health effects. In addition, the relationship between 1-minute ambient $PM_{2.5}$ concentrations and ambient concentrations with longer averaging periods, for which health information is available, is variable. Consequently, the potential health implications of 1-minute $PM_{2.5}$ sensor readings are not clear.

Consistent with the available health evidence, the US Environmental Protection Agency's (EPA) existing air quality standards and tools to interpret air quality (i.e., the national ambient air quality standards (NAAQS) and the Air Quality Index (AQI), respectively) are based on longer averaging periods. It is not appropriate to directly compare a 1-minute $PM_{2.5}$ sensor reading to the level of the $PM_{2.5}$ NAAQS or to the $PM_{2.5}$ AQI breakpoints (both of which are based on 24-hour average $PM_{2.5}$ concentrations). However, it is appropriate to set 1-minute sensor breakpoints such that, to the extent possible, $PM_{2.5}$ sensor messages received over a given time period are consistent with concurrent messaging based on 24-hour average $PM_{2.5}$ concentrations (e.g., messaging related to the AQI).

Given the above considerations, to inform the identification of $PM_{2.5}$ sensor breakpoints and messages we investigated the relationships between 1-hour and 24-hour average $PM_{2.5}$ concentrations. While 1-minute $PM_{2.5}$ readings would reflect an averaging period closer to that provided by sensors, important limitations in the available 1-minute $PM_{2.5}$ data led us to focus our analyses on the relationship between 1-hour and 24-hour $PM_{2.5}$ average concentrations in order to gain insight into how sensor readings could relate to the $PM_{2.5}$ NAAQS and to the $PM_{2.5}$ AQI categories. As discussed in "Interpretation and Communication of Short-term Air Sensor Data: A Pilot Project," available at http://bit.ly/SensorScalePilot, sensor messages for $PM_{2.5}$ reflect the use of 1-hour average, rather than 1-minute, $PM_{2.5}$ concentrations. The primary objective of this analysis is to inform the identification of breakpoints for sensor messaging that are based on probabilistic properties relating to the NAAQS and the AQI, and to the underlying human health considerations. Final breakpoints and the corresponding messages are outlined in "Interpretation and Communication of Short-term Air Sensor Data: A Pilot Project."

$PM_{2.5}$ Data

$PM_{2.5}$ data utilized were from 386 monitoring stations across the United States for the years 2012-2014. There were just under 7 million 1-hour averages across 1096 total days, with 31.4% missing, and the data were quality assured. In order to best mimic instantaneous values corresponding to readings that the public might observe, no completeness criterion was implemented for 1-hour averages in the calculation of 24-hour averages. A preliminary analysis considered 1-minute $PM_{2.5}$ data utilizing observations from the four Village Green Benches in DC, KS, PA, and NC and available Federal Reference Monitor (FRM) data. The results from the 1-minute analysis are not presented here, as limitations in the available data prohibited a full analysis. Thus the 1-minute data were used primarily as case study examples and to provide insight into the variability of 1-minute concentrations over 1-hour and 24-hour periods.

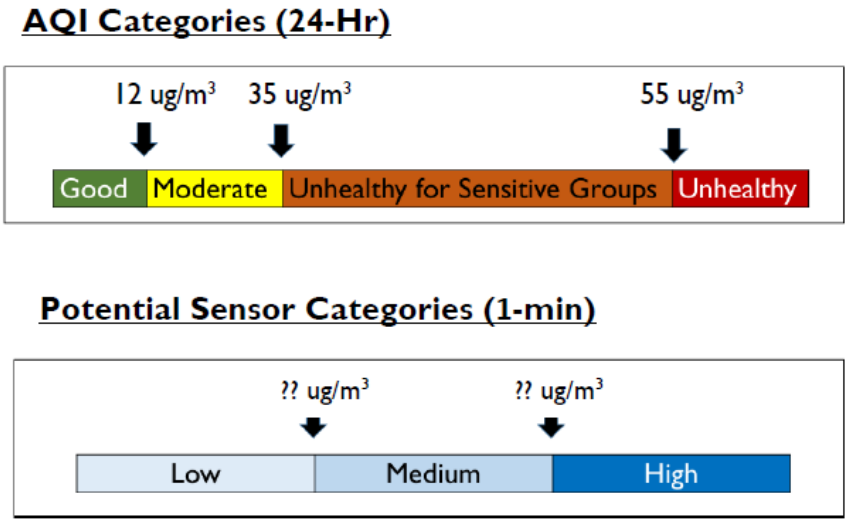
The time series of $PM_{2.5}$ 1-hour averages and corresponding 24-hour averages can be seen in Figure S1 of the Supporting Figures. The level of 35ug/m^3 is of interest as it divides the AQI categories "Moderate" and "Unhealthy for Sensitive Groups" (as seen in Figure 1 below). There were approximately 82,687 1-hour averages that

exceeded 35ug/m^3 that were observed across 375 sites and all 1096 days. 467 days (24-hour averages) exceeded 35ug/m^3 across 205 sites. Figure S2 shows the distribution of the maximum 24-hour average across all sites over time. Figure S3 shows the spatial distribution of the maximum 1-hour average and the maximum 24-hour average, respectively, across the 3 years at each site. Figure S4 shows the distribution of 1-hour averages versus 24-hour averages across all 386 monitoring stations.

Methodology

We consider how 1-hour averages and the distribution of their corresponding 24-hour averages relate to the breakpoints for the AQI categories for "Good", "Moderate", "Unhealthy for Sensitive Groups", and "Unhealthy". Sensor public messaging will be grouped into corresponding "Low," "Medium," and "High" categories.

Figure 1: AQI breakpoints and sensor messaging categories



The breakpoint probabilities for the messaging categories represent the empirical probability of the 24-hour average exceeding specific AQI breakpoints given that the 1-hour average falls within a specified range. The specified ranges correspond to considerations for the possible Low, Medium, and High messaging categories. The distribution of corresponding 24-hour averages is examined to determine the probability that the 24-hour average exceeds the various AQI breakpoint ranges. These are conditional probabilities, conditioned on the observance of a given 1-hour value within a specified Low/Medium/High messaging category. No distributional or modeling assumptions are made about the underlying characteristics of the data and its corresponding behavior and/or distributional properties. This allows for a robust, empirical comparison of events that occur relatively infrequently, i.e., in the tails of the distribution, which is the area of interest for air quality exceedances and public health concerns. Final breakpoints and the corresponding messages are outlined in "Interpretation and Communication of Short-term Air Sensor Data: A Pilot Project," available at http://bit.ly/SensorScalePilot. The breakpoint for the "Very High" category was determined by 1-minute readings that could indicate either a nearby emission source or that the sensor is not working properly. A "Very High" $PM_{2.5}$ concentration is expected to be a very rare occurrence, but could occur at times in extreme situations such as a wildfire

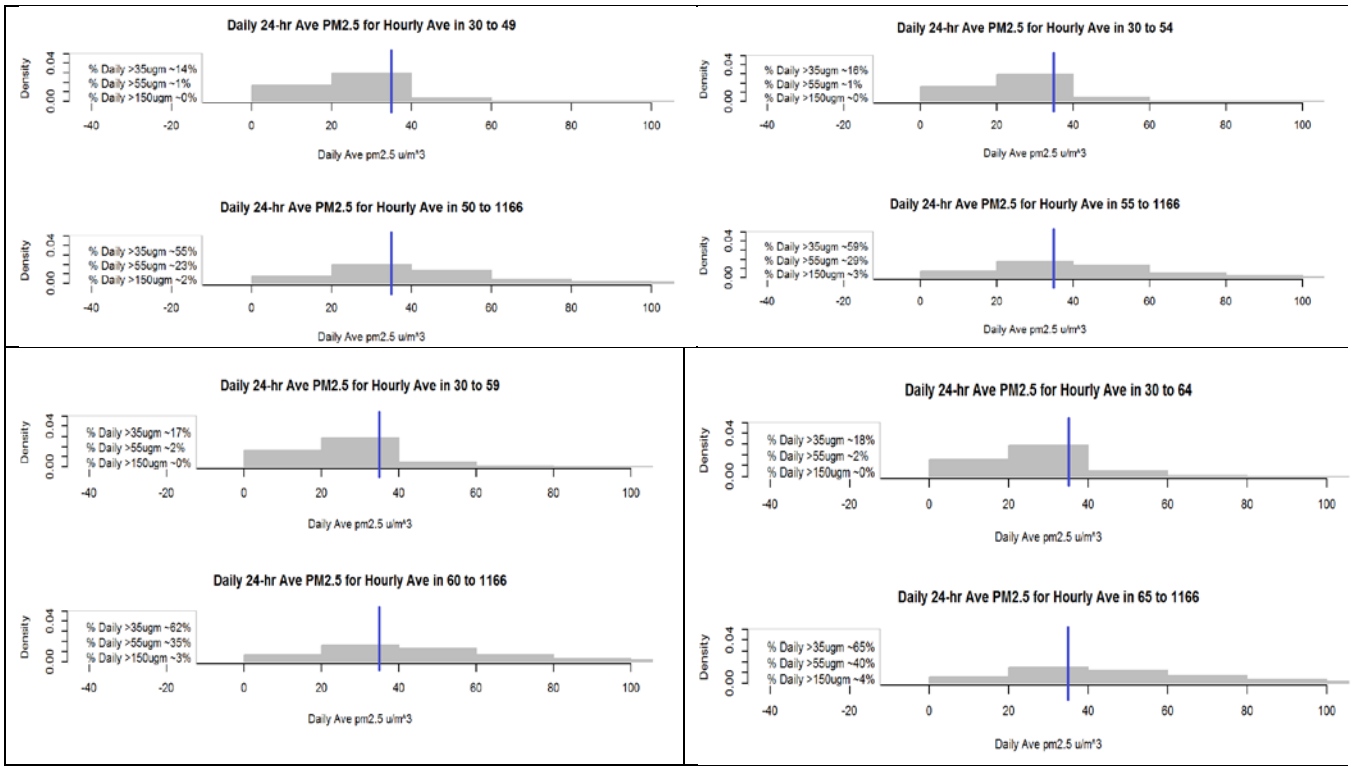
Breakpoint Considerations: Conditional Distributions

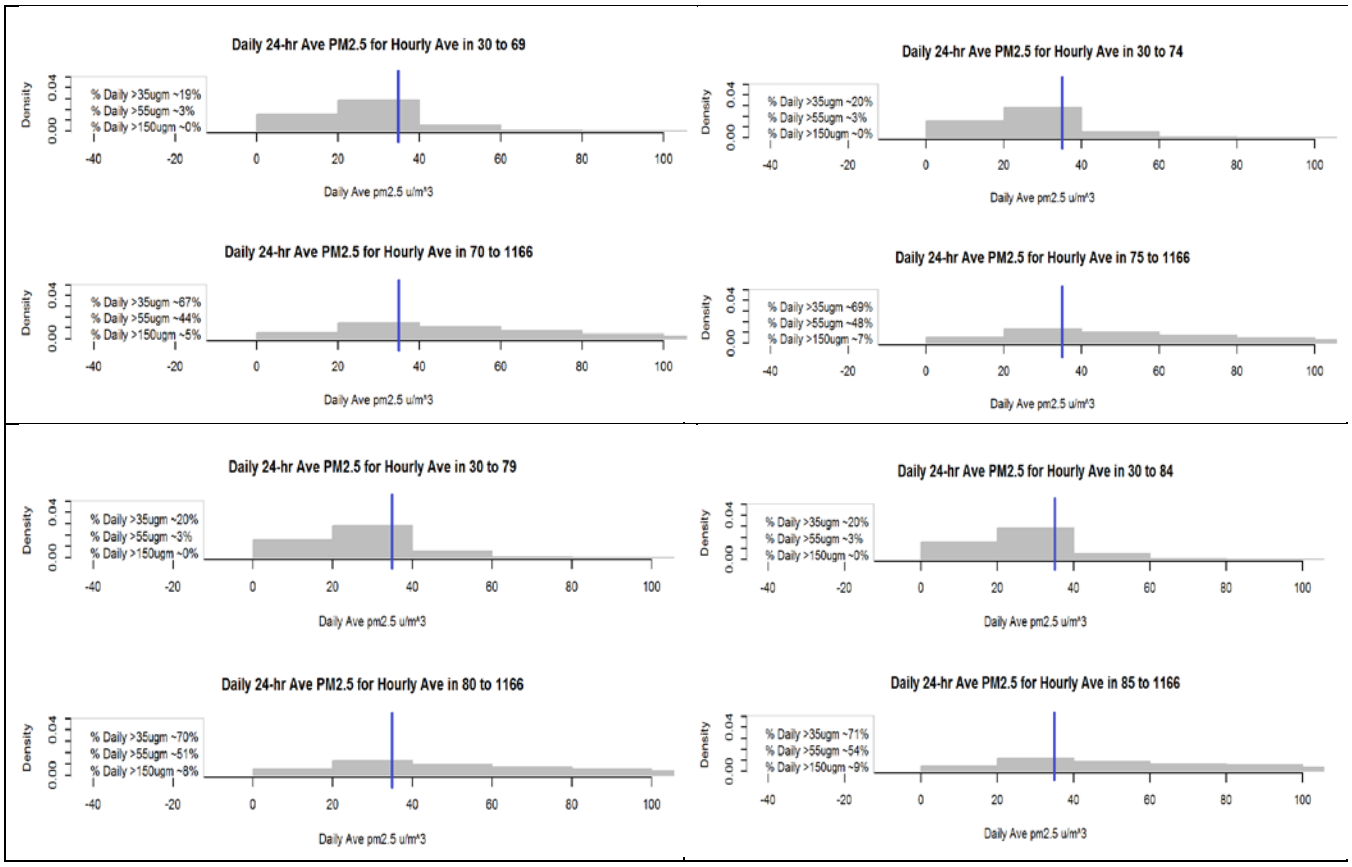
We investigated the relationships between 1-hour and 24-hour average $PM_{2.5}$ concentrations to inform the identification of $PM_{2.5}$ sensor breakpoints and messages for a range of possible breakpoints. Lower breakpoints of

12, 15, 20, 25, 30, 35, 40, and 45ug/m^3 were considered for the break between the "Low" and "Medium" categories along with "Medium" category upper breakpoints of 50, 55, 60, and 65ug/m^3. Additional consideration was given to the upper range 70, 75, 70, and 85ug/m^3 for a "Low" breakpoint of 30ug/m^3. Thus thirty six total sets of possible breakpoint messaging ranges were explored. The example detailed in the figures and tables expands upon the considerations for the "Medium" category with the "Low" range from 0- 29ug/m^3.

We consider the empirical distribution of the 24-hour averages given the corresponding 1-hour averages used in the calculation of the 24-hour averages. The 24-hour averages are considered for 1-hour averages that fall within a specified range under consideration for messaging breakpoints. Figure 2 shows the distribution of 24-hour averages for the 1-hour average in the ranges 30-49ug/m^3, 30-54ug/m^3, and 30-59ug/m^3, up through 30-84ug/m^3. The general trend shows that lower 24-hour averages are associated with lower 1-hour averages. For example it is shown in the top left plot in Figure 2 that for 1-hour averages in the range 30-49ug/m^3, only 14% of the corresponding 24-hour averages are above 35ug/m^3 and only 1% are above 55ug/m^3. Analogously, the trend among the higher values is that higher 24-hour averages are associated with higher 1-hour averages. The bottom right plot in Figure 2 indicates that for 1-hour averages above 85ug/m^3, 71% of the corresponding 24-hour averages are above 35ug/m^3 and 54% are above 55ug/m^3. Each set of histograms considers the implementation of possible "Medium" and "High" breakpoints for the "Low" range 0-29ug/m^3.

Figure 2: Conditional distribution of 24-hour averages for the possible sensor messaging categories and the corresponding AQI breakpoint ranges for the "Medium" category considerations with a low breakpoint of 29ug/m^3. The vertical blue line represents 35ug/m^3. Note: While the analysis includes the full range of data, for display purposes only the x-axis is truncated to 100ug/m^3.





Breakpoint Considerations: Empirical Messaging Frequencies

The empirical frequencies (%) for the messaging categories Low, Medium, and High were also considered. Messaging frequencies are not conditional probabilities – they simply represent the frequency with which the range of values corresponding to a given message (i.e., "High") is observed at the corresponding breakpoint. Note that these frequencies are based on 1-hour readings, which are correlated – i.e., high values of $PM_{2.5}$ likely occur near other high values. Final breakpoints and the corresponding messages are outlined in "Interpretation and Communication of Short-term Air Sensor Data: A Pilot Project," available at http://bit.ly/SensorScalePilot, with selected messaging ranges indicated by shading in the following tables.

1-minute observations in the range 0-29ug/m^3 were observed with relative frequency 97.9%. Therefore a "Low" message would be observed approximately 97.9% of the time if the "Low" range was 0-29ug/m^3. Given a "Low" range of 0-29ug/m^3, Table 1 shows the messaging frequencies for a variety of "Medium" to "High" breakpoints.

Table 1: Messaging frequencies for the "Medium" and "High" categories

Medium	%	High	%
30-49	1.7	50+	0.4
30-54	1.8	55+	0.3
30-59	1.8	60+	0.2
30-64	1.9	65+	0.2
30-69	**1.9**	**70+**	**0.1**
30-74	2.0	75+	0.1
30-79	2.0	80+	0.1

30-84	2.0	85+	0.1

For example, given a "Medium" range of 30-69ug/m^3, the "Medium" message would be seen with a relative frequency of 1.9%. Table 1 indicates that "High" would be observed 0.4% to 0.1% across the increasing options (49 – 84ug/m^3) for the upper Medium breakpoint.

Breakpoint Considerations: AQI breakpoint ranges and corresponding messaging categories

Tables 2-4 display the empirical probabilities of 24-hour averages falling in the corresponding AQI breakpoint ranges for the possible sensor messaging categories. Displayed for the possible "Low" range 0-29ug/m^3.

Table 2: 24-hour Average for 1-hour Average PM in **Low** Category

AQI breakpoints (Category)	0 to 11	0 to 19	**0 to 29**	0 to 44
% Ave > 35 (Above Moderate)	0	0	**0**	0
% Ave 35 to 55 (Unhealthy for Sensitive Groups)	0	0	**0**	0
% Ave > 55 (Unhealthy)	0	0	**0**	0
% Ave > 150ug/m^3	0	0	**0**	0

If Low was set at 0-29ugm^3, 0% of the time the 24-hour average would be above 35 ugm^3 into the "Unhealthy for Sensitive Groups" and above AQI categories, with a 0% chance of being "Unhealthy" (55ug/m^3) or above.

The example for the "Medium" range is for the lower breakpoint of 30ug/m^3 and each of the upper range points 49, 54, 59, 64, 69, 74, 79, and 84ug/m^3 respectively.

Table 3: 24-hour averages for 1-hour $PM_{2.5}$ averages in **Medium** Category

AQI breakpoints (Category)	30-49	30-54	30-59	30-64	**30-69**	30-74	30-79	30-84
% Ave > 35 (Above Moderate)	14	16	17	18	**19**	20	20	20
% Ave 35 to 55 (Unhealthy for Sensitive Groups)	13	15	15	16	**16**	17	17	17
% Ave > 55 (Above USG)	1	1	2	2	**3**	3	3	3
% Ave > 150ug/m^3	0	0	0	0	**0**	0	0	0

If Medium was set at 30ug/m^3 to 49ug/m^3, 14% would be above the "Moderate" category (35 ug/m^3), with 13% in the "Unhealthy for Sensitive Groups" AQI category, and 1% in "Unhealthy" and above. If Medium was set at 30-69ug/m^3, 19% would be above "Moderate", with 16% in the "Unhealthy for Sensitive Groups" AQI category, and 3% in "Unhealthy" and above.

Table 4: 24-hour Averages for 1-hour Averages PM in **High** Category

AQI breakpoints (Category)	50+	55+	60+	65+	**70+**	75+	80+
% Ave > 35 (Above Moderate)	55	59	62	65	**67**	69	70
% Ave 35 to 55 (Unhealthy for Sensitive Groups)	32	30	27	25	**23**	21	19
% Ave > 55 (Unhealthy)	23	29	35	40	**44**	48	51
% Ave > 150ug/m^3	2	3	3	4	**5**	7	8

If High was set at $\geq$50ug/m^3, 55% of the time the 24-hour average would be above 35ug/m^3 into the "Unhealthy for Sensitive Groups" and above AQI categories, with a 23% chance of being "Unhealthy" (55ug/m^3) or above. If High was set at $\geq$70ug/m^3, 23% would be in the "Unhealthy for Sensitive Groups" category and 44% of the time the 24-hour average would be above 55ug/m^3 in the "Unhealthy" AQI category.

Supporting Figures

Figure S1: Time series of 1-hour $PM_{2.5}$ averages and corresponding 24-hour average for the 386 monitoring stations.

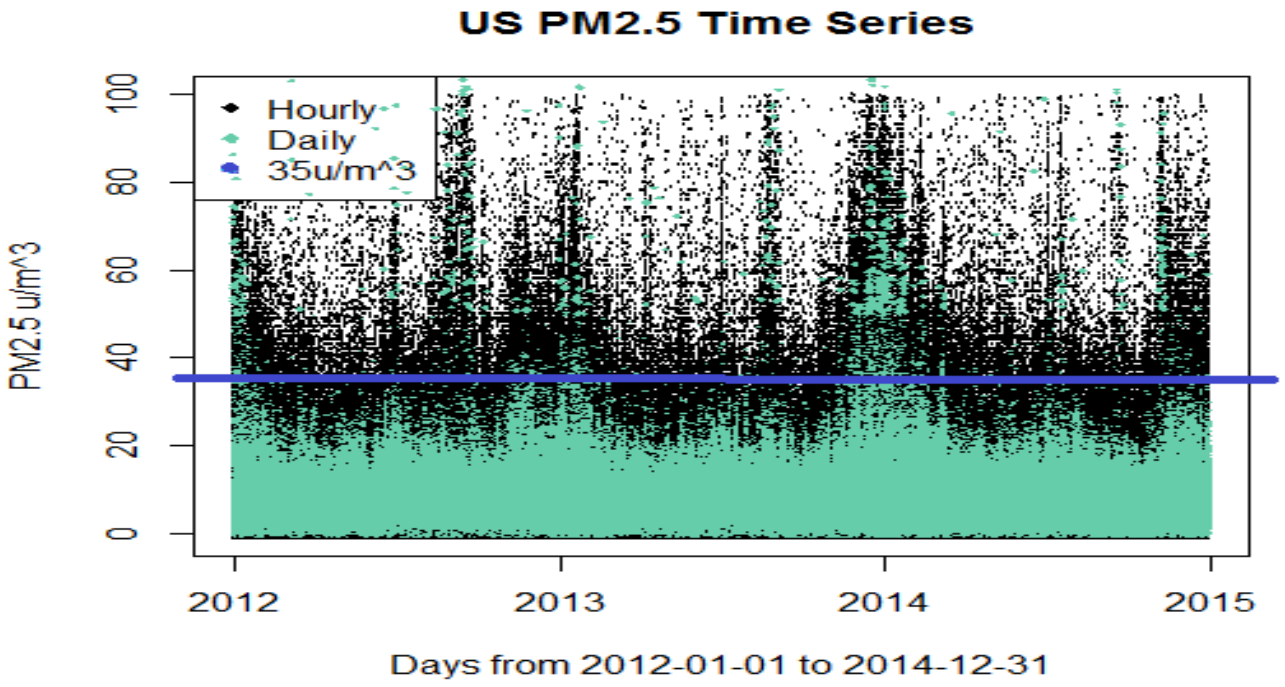


Figure S2: Time series of the daily maximum 24-hour average $PM_{2.5}$ across all 386 monitoring stations. 467 days exhibited an exceedance of 35ug/m^3.

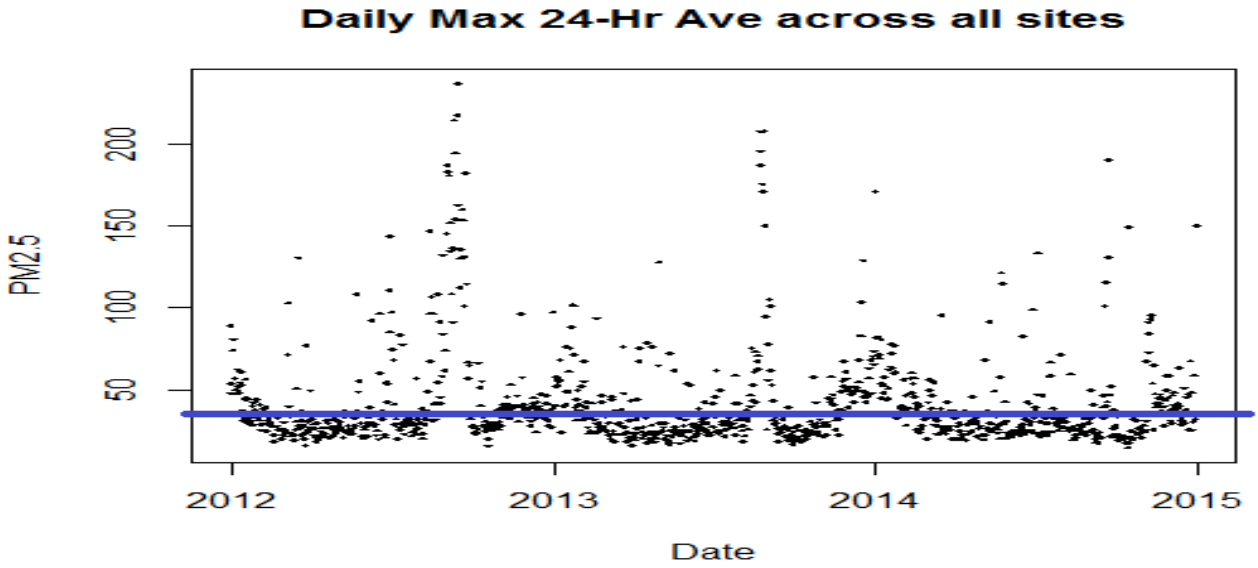


Figure S3 Spatial distribution of the $PM_{2.5}$ maximum 1-hour average and the maximum 24-hour average, respectively, across the 3 years at each site.

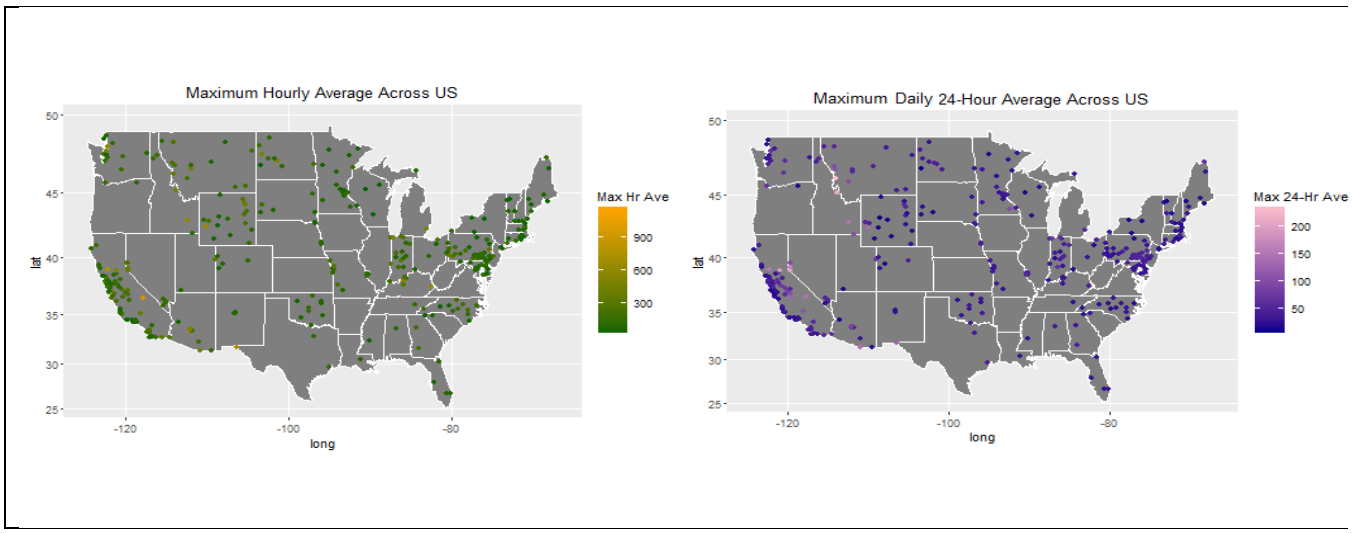


Figure S4: Distribution of the 1-hour averages versus 24-hour average $PM_{2.5}$ across all 386 monitoring stations. The vertical blue line represents 35ug/m^3.