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$PM_{2.5}$ Pollution and Temperature Inversions: A Case Study in St. Louis, MO

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ABSTRACT

Wintertime temperature inversions are partially responsible for some of the worst historical air pollution events as cold air pools are favorable for prolonged poor air quality episodes. The St. Louis metropolitan area in Missouri-Illinois has relevant problems with particulate pollution yet is under-studied. This case study examines the characteristics of an inversion layer along with additional meteorological parameters and their effects on $PM_{2.5}$ air quality in St. Louis from November 22 to December 3, 2015. During the selected period, November 26 to December 1 $PM_{2.5}$ Air Quality Index (AQI) daily values often exceeded levels the Environmental Protection Agency classifies as unhealthy for sensitive groups. Shallow surface temperature inversions were most common on less polluted days while strong temperature inversions with a base height around 950 mb persisted on more heavily polluted days. Variability in surface wind speed, wind direction, and relative humidity occurred mostly on less polluted days while values were consistent on more heavily polluted days. Precipitation only happened on the most heavily polluted days but showed no great impact of reducing pollution. Winds from the south on November 26 suggested transport of excess particulate pollutant was the cause of unhealthy $PM_{2.5}$ levels that day, not temperature inversions. Strong temperature inversions contained these pollutants in St. Louis on November 27 to November 30. A surface pressure minimum north of St. Louis on December 1 produced a substantial change in wind direction on November 30, influencing eventual dispersion of pollutants. Further research is necessary to help fill in the knowledge gaps about air quality in the Midwest.

1. Introduction

Air pollution is an interdisciplinary problem that poses a severe threat to Earth's climate, biodiversity, and human health. In 2016, 91% of the world population was living in places where the World Health

Organization's (WHO) air quality guideline levels were not met, with an estimated 4.2 million premature deaths due to ambient air pollution in both urban and rural areas during the same year (WHO 2018).

Mortality is caused by exposure to ambient air particles with an aerodynamic diameter of 2.5 micrometers or less, known as fine particulate matter ($PM_{2.5}$). These particles can be emitted directly from a local source or as combustion particles from industrial emissions (EPA 2018). With penetration to the lung barrier, particulate matter can enter the blood system to cause cardiovascular and respiratory distress, both acute and chronic (EPA 2010, WHO 2018). The WHO 2005 air quality guideline limits are aimed to achieve the lowest concentrations of particulate matter as possible as there is no measured threshold where no damage to human health occurs (WHO 2018).

The stability of the atmosphere is a critical component for understanding the severity of air quality. A stable atmosphere occurs when a layer of warm air is above cooler air, forming a temperature inversion as air temperature increases with height (NWS 2018). Vertical motion of an air parcel is inhibited, trapping air pollutants close to Earth's surface.

Temperature inversions are not the only meteorological influence on air quality. The atmosphere warms, dries and stabilizes because of large-scale downward vertical motion in the presence of an upper-level ridge of high pressure, typically at 500 millibars (mb). Cloud formation is restricted in a temperature inversion layer, allowing an increase in photochemistry for air pollutants to form. When an area of high surface pressure develops, wind speeds are low enough for recirculation and stagnant air, increasing the longevity of a poor air quality episode.

China is a commonly studied place for air pollution meteorology due to its complex geographical terrain and influence from high anthropogenic emissions. Wang et al. (2018) found that observation stations in China have higher $PM_{2.5}$ concentrations during air stagnation events, defined as days without precipitation and daily $PM_{2.5}$ concentrations higher than its monthly average, occurring most frequently during autumn and winter. The study used a quantitative threshold based on 10-meter (m) wind speed, boundary layer height and amount of precipitation to account for the effect of terrain on meteorological conditions as the National Oceanic and Atmospheric Administration's (NOAA) threshold does not.

Taking the inversion layer into account, Enzhong et al. (2015) focused their study on Xingtai City, a Chinese urban area surrounded by mountains. Results showed a positive correlation between air quality and the thickness of the inversion layer and a negative correlation between air quality and temperature, dew point and wind speed within the inversion layer from 2013-2014. The strongest inversions occurred in the winter with the weakest during the summer. Bahari et al. (2014) also noted the importance of the strength of temperature inversions' impact on air quality as this addition indicated a well-fitting model for the prediction of $PM_{2.5}$ concentrations in Iran.

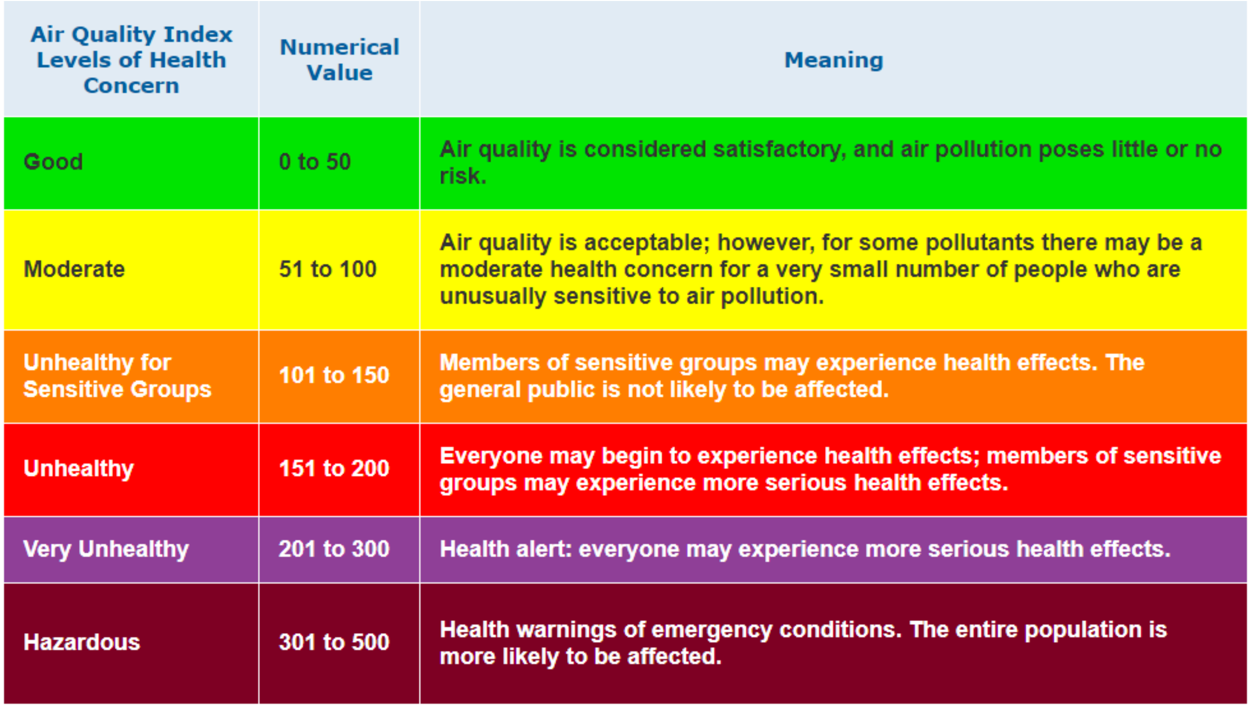
In the United States, the West Coast is a commonly studied area for air pollution due to the complex terrain of the Rocky Mountains and transport of Asian anthropogenic aerosols. The most frequent air stagnation events occur in the summer and autumn using an adjusted quantitative threshold to account for terrain (Wang et al. 2018). A case study in Cache Valley, a narrow area, surrounded by tall mountains located in northern Utah and southern Idaho, showed an increased probability of temperature inversions during cold days during the winter, with a daily mean air temperature below -15℃ indicating certainty for the occurrence (Wang et al. 2015). A regression model was developed to estimate past $PM_{2.5}$ concentrations to account for missing upper-air measurements. Though the model was merely a function of temperature and did not include chemical kinetics, it indicated increased concentration from the early 1980s through the early 1990s, the same period with an increase of the frequency of temperature inversions (Wang et al. 2015).

The effects of prolonged wintertime temperature inversions on air quality have occurred outside of the West Coast, but there is a lack of research in these areas with historical problems of air pollution. For instance, the St. Louis metropolitan area in Missouri-Illinois was plagued with a thick layer of smog for over a month during the cold-weather season in 1939 due to the region’s heavy reliance on cheap, high sulfur coal and continuous urban population increase (O’Neil 2016).

The Clean Air Act was established in the United States by the Environmental Protection Agency in 1970 to address public health issues and welfare risks posed by certain widespread air pollutants by implementing National Ambient Air Quality Standards (NAAQS) for each state to attain (EPA 2018). Regulations of anthropogenic emissions correlate with a negative trend in the annual mean of total ambient air particles from 1975-1986, though health risks from fine ambient air particles persisted, ranking St. Louis as the city with the 2nd highest mortality rate to due ambient air pollution compared to 5 other U.S. cities (Dockery et al. 1993). The health risks from inhaling particulate matter in the 1980s and a decrease in $PM_{2.5}$ concentrations (Dockery et al. 1993) are comparable to current identifiable health risks and a 41% decrease in the national $PM_{2.5}$ air quality trend from 2000 to 2017 (EPA 2018). The St. Louis metropolitan area was an exception, specified as nonattainment for annual $PM_{2.5}$ NAAQS in 2005 (EPA 2010).

With historical problems of particulate pollution in St. Louis and the enormous influence of meteorological conditions for deviation in a region's air quality trend, the need for research persists in this underrepresented geographic area. This case study focused on a period during the wintertime when the St. Louis metropolitan area was experiencing persistent $PM_{2.5}$ pollution to answer these questions:

1) How frequently did temperature inversions occur during this period?
2) How did the base height and strength of a temperature inversion on a



Air Quality Index Levels of Health Concern	Numerical Value	Meaning
Good	0 to 50	Air quality is considered satisfactory, and air pollution poses little or no risk.
Moderate	51 to 100	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is not likely to be affected.
Unhealthy	151 to 200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
Very Unhealthy	201 to 300	Health alert: everyone may experience more serious health effects.
Hazardous	301 to 500	Health warnings of emergency conditions. The entire population is more likely to be affected.

Figure 1. EPA classification of Air Quality Index (AQI) values and its implication. Retrieved from https://airnow.gov/index.cfm?action=aqibasics.aqi.

heavily polluted day differ from a less polluted day?

3) What were the meteorological parameters that made this poor air quality event so extreme?

2. Data and Methods

a. Air quality

Case selection came from the EPA's Air Quality Index Daily Values Report. The Air Quality Index (AQI) is a unitless measurement of ambient air pollutants and the severity of its impact on human health (Figure 1).

The air pollutant with the highest daily AQI is used for the combined daily AQI and listed as the primary pollutant. We searched for a case where this is true for $PM_{2.5}$ during a period extending seven days with values exceeding 51 AQI, indicating at least a moderate concern for health. Preference went to a period with at least two days exceeding 101 AQI for thorough analysis regarding the research questions. Dates were chosen near or within meteorological winter months from 2013-2018 to account for the extension of Missouri and Illinois's plan to attain the 2009 $PM_{2.5}$ standard by 2012 (EPA 2010). St. Louis MO-IL (Figure 2) was the selected geographic region for the most accurate representation of measurements across the area available to the EPA from both state agencies. If data were retrieved from individual counties instead, there would have been an issue with missing particulate matter data in Illinois counties due to errors in data processing (ALA 2016).

b. Meteorological parameters

Vertical temperature profiles for the selected AQI days (November 22 at 06Z to November 4 at 06Z) were obtained from the BUFKIT

Figure 2. Counties and cities defined as the Core Based Statistical Area (CBSA) for St. Louis, MO-IL. The AQI daily values report uses CBSA when the selected geographic location is a city. The St. Louis Lambert International Airport, marked with a brown star, is in St. Louis County. Retrieved from https://commons.wikimedia.org/wiki/File:St_Louis_MSA.png.

archive through the Iowa Environmental Mesonet at the St. Louis Lambert International Airport (KSTL), where its location is further away from the city of St. Louis to reduce heat-island effects (Figure 2). Soundings from the Rapid Refresh (RAP) model were utilized, being the only meteorological model available through BUFKIT that recorded data every hour. Data analysis occurred at 00Z, 06Z, 12Z and 18Z for each day.

If any inversions took place in the sounding, defined in BUFKIT as a change of 0.5 degrees Celsius (°C) in the layer, the following equation calculated its strength:

$$dT = T_{top} - T_{bottom} \quad (1)$$

where dT is the difference of temperature from the top to the base of the inversion layer in °C. The strength of the temperature inversion indicates confidence in the impact on air quality.

The base height of each inversion layer in mb, surface pressure in mb, relative humidity (%), wind speed in meters per second (m/s), wind direction in degrees, and precipitation in inches per hour (in/hr) were also recorded at the 0^{th} hour of each sounding at the surface for additional analysis of air quality. Archived daily surface weather maps, 500 mb height contour maps, and twenty-four-hour total precipitation accumulation maps at 12Z from the NOAA Weather Prediction Center were used for further synoptic analysis.

3. Results and Analysis

a. Overview of AQI days

The dates selected for this study was from November 22 to December 3, 2015. These dates were a part of a period of daily $PM_{2.5}$ AQI values exceeding the “Moderate” threshold for 24 consecutive days, indicating possible influence of persistent wintertime inversions. Eight days during the selected period were classified as "Moderate." Two consecutive days were classified as "Unhealthy for Sensitive Groups" with another two consecutive days classified as "Unhealthy."

Figure 3 shows the evolution of daily $PM_{2.5}$ AQI values for the selected case. November 22 through November 25 showed AQI values classified as "Moderate." AQI doubled its value from November 25 through November 26, staying above the "Unhealthy" threshold for two consecutive days. November 28 and November 29 were only up to a few units below the "Unhealthy for Sensitive Groups"

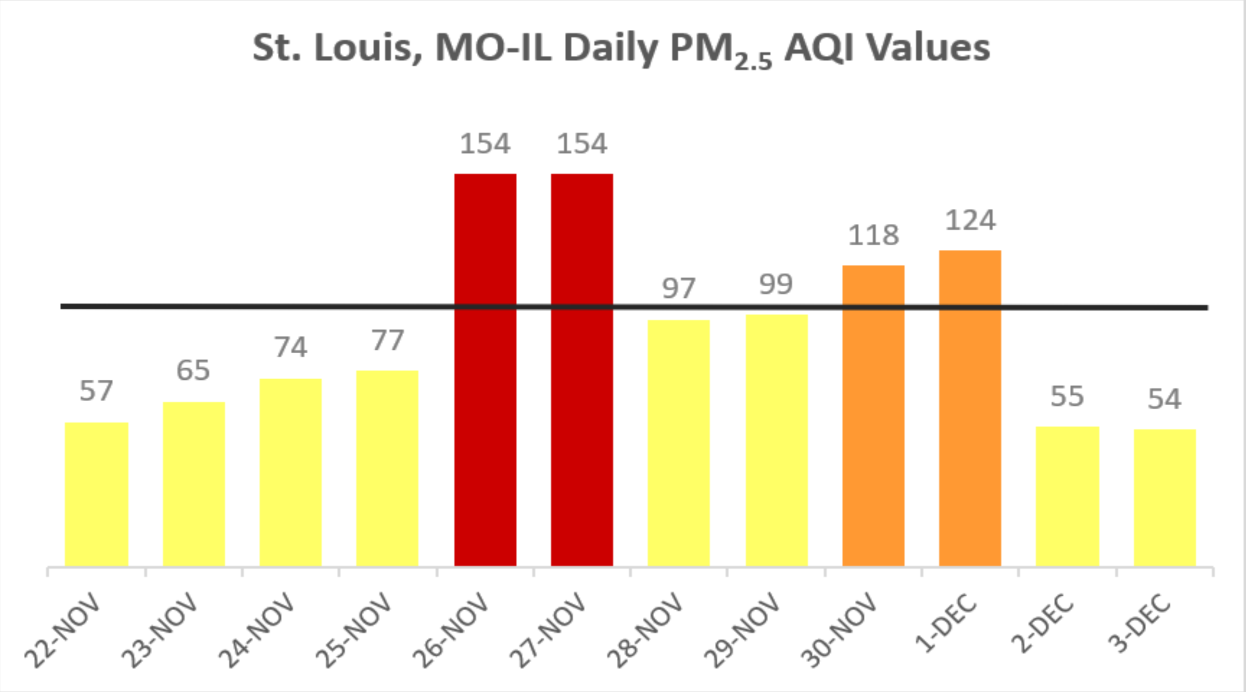


Figure 3. $PM_{2.5}$ AQI values in St. Louis, MO-IL for the selected days in the case study and their classification in regards its impact on human health. The yellow, orange and red bars are classified as “Moderate,” “Unhealthy for Sensitive Groups” and “Unhealthy,” respectively. The solid black line intersecting data has an AQI value of 101, the minimum value needed to be classified as “Unhealthy for Sensitive Groups.”

threshold, while the AQI values exceeded this threshold on November 30 and December 1. AQI values substantially decreased in comparison on December 2 and December 3. Six consecutive days with AQI values exceeding or merely exceeding the “Unhealthy for sensitive groups” threshold generated interest for this study.

b. Inversion layer characteristics

At least one inversion layer appeared for each observed sounding except for November 27 at 12Z. One inversion occurred during nineteen soundings, while two inversions occurred at nineteen soundings, and eight soundings had three inversions. Continuous multiple inversions happened from the beginning of the observed period to November 27 at 06Z and from November 30 at 18Z to the end of the observed period. Apart from a few soundings, November 27 at 18Z to November 30 at 12Z had persistent singular inversion layers.

Soundings with multiple inversions generally had the base height of their first inversion layer at the surface (Figure 4), comparable to surface pressures at this time. This was especially true from the beginning of the observed period to November 26 at 18Z. As a result, these inversions were unable to cap any pollutants beneath them, correlating with the "Moderate" daily AQI values but contradicting the "Unhealthy" AQI value on November 26. High variability with the base height of a second or third inversion in a

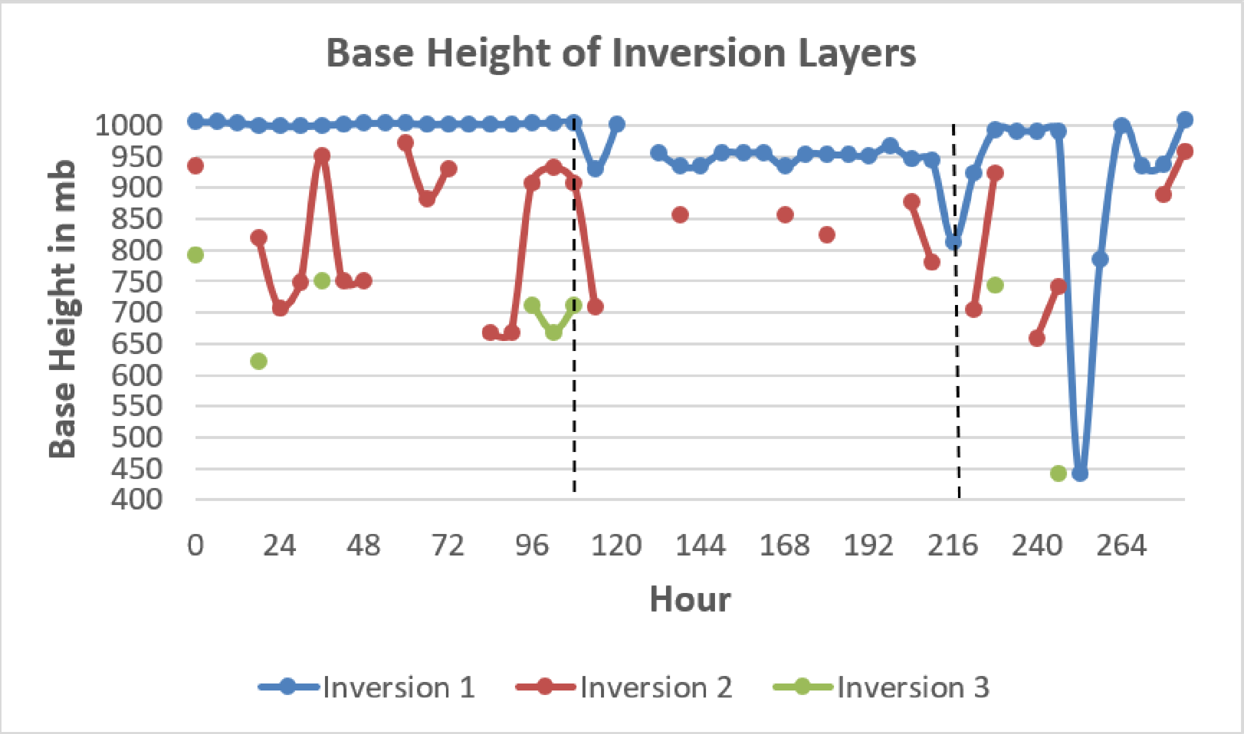


Figure 4. The base height of inversion layers (mb) measured every six hours from the St. Louis Lambert International Airport. Hour 0 is November 22 at 06Z, and every twenty-four hours is equivalent to one measured $PM_{2.5}$ AQI day. 12 pm CST on November 26 is Hour 108, and 6 am CST on December 1 is Hour 216, designated by the black dashed lines. The blue, red, and green data points represent Inversion 1 (the inversion closest to the surface in each sounding), Inversion 2 (the inversion second closest to the surface in each sounding), and Inversion 3 (the inversion third closest the surface in each sounding), respectively.

sounding showed no importance in capping pollutants. In contrast, soundings with single inversion layers from November 27 at 18Z to November 30 at 18Z had persistent base heights around 950 mb. This indicated a favorable environment for capping pollutants close to the surface to produce constant high daily AQI values. December 1 at 00Z through the end of the observed period showed high variability of base height regardless of the number of inversions present in a sounding. The absence of a strong capping layer helped with the vertical dispersion of pollutants and the decrease in AQI values on December 2 and December 3 but did not explain the “Unhealthy for Sensitive Groups” value on December 1.

Variability of the strength of the temperature difference (dT) in inversion layers had resemblance with the variability of base heights (Figure 5). The beginning of the observed period to November 27 at 06Z had

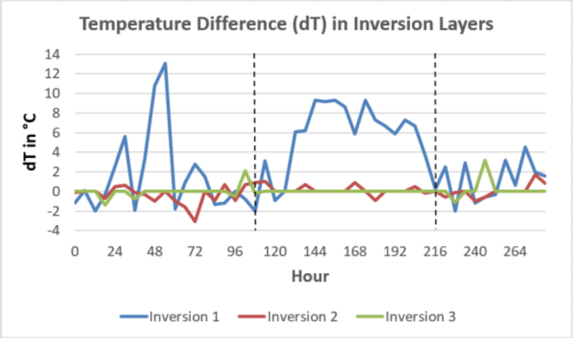


Figure 5. Like Figure 4, but for the strength of an inversion layer measured as the temperature difference (dT) of each sounding (°C). A value of 0 °C means no inversion occurred.

a range of dT values from -3.1 °C to 13.1 °C. The high variability during this period exhibited minimal influence on worsened air quality during this time. dT values of the inversion layer closest to the surface ranged from 5.9 °C to 9.3 °C from November 27 at 18Z to December 1 at 00Z. These persistent strong temperature inversions trapped the cooler air underneath its warm and stabilized layer, keeping AQI values at or near unhealthy levels. High variability with a range of dT values from -2 °C to 4.5 °C was detected from December 1 at 06Z to the end of the observed period. This finding influenced improved air quality on December 2 and December 3 but not on December 1.

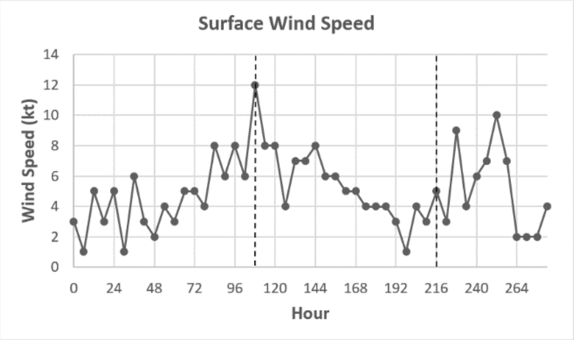


Figure 6. Like Figures 4 and 5, but for surface wind speed (kts).

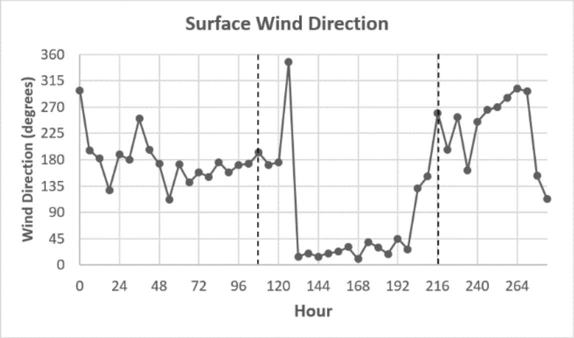


Figure 7. Like Figures 4, 5, and 6, but for surface wind direction (degrees).

c. Wind

Surface wind speeds ranged from 1 to 12 kts during the case study (Figure 6). A general, increasing trend in these values occurred from the beginning of the observed period to November 26 at 18Z. Daily AQI values increased each day during this time, contradicting the theory of wind speeds decreasing with worsened air quality. High variability from November 27 at 00Z to November 28 at 06Z occurred before a general decreasing trend was detected through November 30 at 12Z. Thus, the surface wind speeds had no sole influence on the "Unhealthy" daily AQI levels on November 26 and 27, but the decrease of these values the following couple of days helped with the stagnation of existing pollutants. A general, increasing trend with high variability from November 30 at 12Z through the end of the observed period was detected. This finding contradicted the high daily AQI values on November 30 and December 1 but complemented the sudden decrease in daily AQI values on December 2 and 3 through horizontal dispersion of pollutants.

Wind direction showed more variability than wind speed (Figure 7). Values ranged from 315 to 115 degrees from the beginning of the observed period to November 24 at 12Z. This variability suggested horizontal dispersion of pollutants were a cause for lower daily AQI values during this time. November 24 at 18Z through November 27 at 06Z had wind directions from the south, ranging from 141 to 192 degrees. Horizontal dispersion of pollutants was inhibited, correlating with the increased daily AQI values during this time. This finding also suggested an abundance of PM2.5 could have been advected from the south, explaining the sudden jump to an "Unhealthy" daily AQI value on November 26. A rapid change in wind direction (over 180 degrees) occurred from 06Z to 18Z on November 27. Although this would suggest horizontal dispersion, the daily AQI remained at its highest value of the case study. November 28 at 00Z through November 30 at 12Z had general wind directions from the northeast with values ranging from 10 to 45 degrees, suggesting recirculation of pollutants and constant high daily AQI values. Wind direction values from November 30 at 18Z through the end of the observed period ranged from 113 to 302 degrees, suggesting decreased daily AQI values as a result of horizontal dispersion on December 2 and 3 with disagreement for the “Unhealthy for Sensitive Groups” value on December 1.

d. Relative humidity

No direct influence on air quality from relative humidity occurred from the beginning of the observed period to November 25 at 06Z as high variability with recorded values were detected, ranging from 39 to 91 percent (Figure 8). A general, increasing trend on November 25 and 26 signaled a favorable environment for holding atmospheric constituents in place, explaining the sharp increase of daily AQI values for these two days. Values ranged from 86 to 98 percent from November 27 at 12Z to December 1 at 06Z, signifying an indirect indication of air pollutants held in place to keep daily AQI values at or near unhealthy levels. A sudden decrease in relative humidity (96 to 61 percent) on December 1 from 06Z to 18Z implicated a release of these pollutants, leading to decreased AQI values on December 2 and 3.

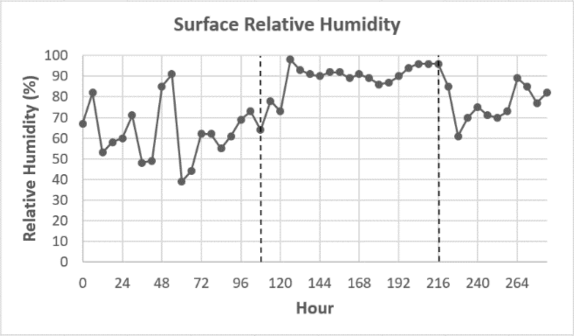


Figure 8. Like Figures 4, 5, 6, and 7, but for surface relative humidity (%).

e. Surface pressure, precipitation, and supplemental synoptic analysis

A 500 mb height trough was over the St. Louis area at the beginning of the observed period. As the wave propagated eastward the following day, the 500 mb height increased from around 5400 to 5640 m in twenty-four hours. Heights steadily increased to a maximum of 5820 m on November 27 at 12Z and steadily decreased back down to 5700m on November 30 at 12Z. A slow-moving closed low at 500 mb over the western United States was the reason for a low range of these heights. Small ridge patterns were seen during this period, indicating a minimal influence on a stable atmosphere and high AQI daily values. The closed low deepened and moved over the southwest corner of Minnesota on December 1 at 12Z and propagated directly eastward to the Wisconsin-Illinois border on December 2 at 12Z. As a result, 500 mb heights decreased from 5700 to 5400 m over St. Louis during the same period, indicating an unstable atmosphere and thus contradicting the “Unhealthy for Sensitive Groups” daily AQI values on November 30 and December 1. The height increased to 5640 m within the next twenty-four hours, influencing a decrease in the daily AQI value on December 2 because of this rapid upper-level movement.

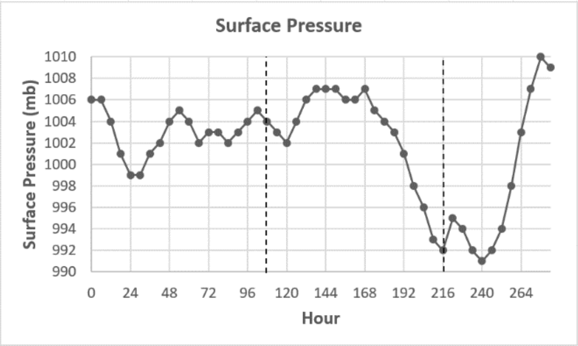


Figure 9. Like Figures 4, 5, 6, 7, and 8, but for surface pressure (mb).

Surface pressure showed a similar pattern to 500 mb height maps throughout the case study (Figure 9). A 7 mb decrease in surface pressure on November 22 kept the daily AQI level low through decreased stability, while a 5 mb increase the following day increased stability and the daily AQI value. Low variability of surface pressure was detected from November 24 at 06Z to November 27 at 06Z after the passage of a cold front on November 24 at 12Z, maintaining a stable atmosphere for trapping air pollutants. A stationary front passed over St. Louis on November 27 at 12Z, which lowered surface pressure. This did not affect the "Unhealthy" daily AQI value on November 26, though instability should have vertically dispersed pollutants. A 5 mb increase in surface pressure over the next twenty-four hours kept the November 27 daily AQI value the same as the previous day. High surface pressures persisted on November 28 at 06Z to keep the daily AQI near the "Unhealthy for Sensitive Groups" threshold. A substantial decrease in surface pressure on November 29 and 30 and December 1 did not hinder increasing daily AQI values during this time. The disagreement continued through the end of the observed period as decreased daily AQI values occurred with increasing surface pressure after the passage of a low-pressure system north of Missouri.

No hourly precipitation accumulation occurred in any of the soundings used for the study. Twenty-four total precipitation accumulation of at least 0.01 inches ending at 12Z occurred on November 27, 28, 30 and December 1. Though precipitation should indicate dispersion of pollutants, these dates equated with the highest daily AQI values. Therefore, there was no critical impact from this meteorological parameter.

f. Discussion of conflicting results

November 26 and December 1 were two of the dates with high daily AQI values (154 and 124, respectively), but the ample variability with meteorological parameters disagreed with common knowledge of air pollution meteorology. In particular, a decreasing trend on surface pressure for both November 26 and December 1 suggested an unstable atmosphere, thus producing the variability seen with temperature inversions and daily precipitation accumulation exceeding 0.01 inches. One explanation is surface wind speeds were low enough for the entirety of the observed period, allowing for recirculation and inhibition of horizontal dispersion of pollutants. Wind direction near 180 degrees on November 26 suggested advection of several particulate pollutants from the south could have also contributed to a high daily AQI value. A sharp change in wind direction due to the passage of a stationary front on November 27 at 12Z kept these pollutants in St. Louis, while another sudden shift in direction on November 30 lead to eventual horizontal dispersion on December 1. Though not the primary reason for poor air quality during the first "Unhealthy" AQI day, strong and persistent temperature inversions the following few days were a robust contributing factor in this prolonged poor air quality episode.

4. Conclusion and Discussion

This case study analyzed the relationship between temperature inversions and persistent $PM_{2.5}$ pollution from November 22 to December 3, 2015, in St. Louis, Missouri, having two consecutive daily $PM_{2.5}$ AQI values. During this period, temperature inversions in all but one sounding, partially the reason for all daily AQI values exceeding the "Moderate" threshold. Variability in the number of inversions, as well as base height and strength of inversions, were most prevalent from November 22 to November 26 and December 1 to December 3. Most of these inversions were shallow and close to the surface, corresponding with daily AQI values much lower than the "Unhealthy for Sensitive Groups" threshold during the period, apart from November 26 and December 1 having values of 154 and 124, respectively. Persistent singular and strong inversion layers ($dT > 5$ °C) with a base height close to 950 mb occurred from November 27 to November 30, equated with persistent daily AQI values near or exceeding 101. Thus, there was mainly a positive linear relationship between the characteristics of an inversion layer and how polluted the air was.

Other meteorological parameters have contributed to this extreme event. Trends in surface wind speeds, wind direction, and relative humidity were like the pattern shown with inversion layer characteristics. Hence, variability with these parameters was also most prevalent from November 22 to November 26 and December 1 to December 3, once again corresponding with daily AQI values much lower than the "Unhealthy for Sensitive Groups" threshold except for November 26 and December 1. Decreased wind speeds from the north and high relative humidity values (over 86%) occurred from November 27 to November 30, relating to persistent daily AQI values near or exceeding 101. Twenty-four-hour precipitation totals ending at 12Z with at least 0.01 in occurred on November 27, 28, 30 and December 1, with high daily AQI values indicating no notable impact on the dispersion of pollutants. Advection of particulate pollutants from the south was thought as the main contribution to the "Unhealthy" AQI value on November 26, whereas strong, persistent temperature inversions preserved poor air quality with the addition of local sources. A closed low-pressure system at 500 mb and the surface to the north of Missouri produced a sharp change in surface wind direction on November 30 along with decreasing surface pressure from November 29 to December 1. This generated variability in inversion layer characteristics and wind direction, leading to both vertical and horizontal dispersion of pollutants and "Moderate" AQI values by December 2.

Extension of this case study would be beneficial as St. Louis is an under-discussed region for air quality. Aerosol optical depth (AOD), the measure of aerosols distributed within a column of air from an instrument at Earth's surface to the top of the atmosphere, is integrated into $PM_{2.5}$ measurements for AQI values. Measurements from a station with AOD data would give insight into the AOD-$PM_{2.5}$ correlation and influence on a temperature inversion layer. The addition of the height of the planetary boundary layer would justify the role of temperature inversions as a definite capping layer for pollutants is known. Furthermore, analysis of $PM_{2.5}$ daily AQI values and low-level winds in stations south of St. Louis at least two days before November 26, 2015, would either accept or reject the conclusion of particulate pollutant transport due to a southerly wind. Another case study concerning the same parameters utilized in this study would also be beneficial in another Midwest metropolitan area to diminish knowledge gaps about air quality in this region further. More research is imperative for advancements in air quality monitoring, modeling and public health practices in preparation for future air quality extremes.

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