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Impact of Long-Distance Transport of $PM_{2.5}$ from the 2023 Canadian Wildfires on COVID-19 Hospitalizations in the Eastern U.S.

Alexandra Parker

Department of Atmospheric Science
The University of North Carolina Asheville
One University Heights
Asheville, North Carolina 28804 USA

Faculty Mentor(s): Dr. Elaine Godfrey

Abstract

The United States has seen an increase in the intensity and frequency of wildfires, and emissions from wildfires may impact health in negative ways that society does not entirely understand. The consequent increase in $PM_{2.5}$ levels often leads to respiratory and cardiovascular problems for those nearby; these conditions also present most commonly in those hospitalized with COVID-19. Consequently, $PM_{2.5}$ exposure from wildfire smoke correlates to increased COVID-19 hospitalizations near the fires—this connection remains understudied for long-distance transport of wildfire smoke. The analysis investigates the height of the Canadian wildfires in June and July of 2023 and considers eight counties with varying distances from active fires: four valley locations and four flat terrain locations. In these locations, this study examines $PM_{2.5}$ levels, COVID-19 hospitalizations, and viral gene copies of SARS-CoV-2 in wastewater. A calculation of correlation coefficients between COVID-19 hospitalizations and both $PM_{2.5}$ and viral gene copies of SARS-CoV-2 in wastewater determined the greatest correlation at each location—either a spike in $PM_{2.5}$ levels or a wave of the SARS-CoV-2 virus in the region associated with increased hospitalizations. A comparison of $PM_{2.5}$ levels and COVID-19 hospitalizations at three locations suggests a spike in the latter due to the former. At the distances considered, no increase in hospitalizations exists due to smoke resting in valleys longer than in flat areas. Past 2000 miles from the wildfire epicenter in Fort Smith, Northwest Territories, the correlation between COVID-19 hospitalizations and wastewater gene copies was stronger than with hospitalizations and $PM_{2.5}$—indicating that poor air quality did not impact COVID-19 hospitalizations in these regions. As wildfire frequency and intensity increase, and COVID-19 becomes a part of the new normal, understanding the effects of the changing environment on human health remains an important goal.

Introduction

As wildfire frequency and intensity continue to increase in the United States (Westerling et al. 2006), researchers estimate that at least 82 million people in the western U.S. will see an increase in the regularity and severity of exposure to wildfire pollutants (Liu et al. 2016). Small particulate matter released by wildfires harms human health (California 2023)—leading to respiratory and cardiovascular problems for those near active wildfires (Delfino et al. 2009; Liu et al. 2014; Alman et al. 2016; Reid et al. 2016; Cascio 2017). Those hospitalized with COVID-19 commonly exhibit these health issues—resulting in the connection between wildfire smoke exposure and COVID-19 hospitalizations. Exposure to particulate matter smaller than 2.5 microns in diameter from wildfire smoke correlates to increased COVID-19 infections in the vicinity of the fire (Zhou et al. 2021; Cortez-Ramirez et al. 2022; Schwarz et al. 2022; Yu and Hsueh 2022), but unknown factors and effects exist regarding the long-distance transport of wildfire smoke and its impact on COVID-19 hospitalizations.

a. Fire, air quality, and health

Wildfires in the United States have increased in frequency and severity in recent years (Westerling et al. 2006). This increase leads to higher concentrations of particulate matter and other harmful pollutants in the atmosphere (Westerling et al. 2006). Because diameter defines particulate matter, $PM_{2.5}$ describes particles that are 2.5 microns in diameter or smaller, and PM_{10} describes particles that are about 10 microns in diameter. The former harms humans more than the latter because the small size allows particles to penetrate the deeper parts of the lung (California 2023). Exposure to $PM_{2.5}$ from wildfires is associated with respiratory diseases, morbidity, and cardiovascular dysfunction (Delfino et al. 2009; Liu et al. 2014; Alman et al. 2016; Reid et al. 2016; Cascio 2017); the risk of hospitalization due to respiratory disease from exposure to wildfire smoke increases for the elderly (Liu et al. 2017). Exposure, and the severity of the body's response, to wildfire smoke depends on several variables—distance, terrain, and preventative measures most significantly.

Wildfire smoke can affect people living hundreds of miles away from the fire (Chow et al. 2022), and smoke easily travels long distances in free air, or conversely, gets trapped in valleys for longer durations (Mallia 2020). Synoptic-scale patterns typically drive this process in the eastern U.S. by importing polluted air from the northwest (Nauth 2023). For example, Shrestha et al. (2021) state that New York's air quality can be affected by wildfire activity in the Western U.S. and Canada. This occurs after wildfire smoke from Canada travels from the northwest to the eastern U.S.; the vertical mixing process brings polluted air from aloft to the surface and boundary layer entrainment keeps the polluted air trapped, thereby increasing the concentration of particulate matter at the surface (Shrestha et al. 2021). Though citizens of the western U.S. may see a more significant increase in the regularity and severity of $PM_{2.5}$ exposure (Liu et al. 2016), exposure may increase for many Americans in the central and eastern part of the country since synoptic-scale patterns typically move from west to east. Increased air pollution in lower levels of the atmosphere due to wildfires would negatively impact human health. Socioeconomic factors also impact the vulnerability of a community to wildfire smoke (Rappold et al. 2012). The likelihood of exposure to poor air quality increases for those with lower socioeconomic status (Rappold et al. 2012).

b. COVID-19 and wildfires

As of May 2023, the cumulative number of confirmed COVID-19 cases in the United States was 103.44 million (Mathieu et al. 2023). Of these confirmed cases, most people hospitalized with COVID-19 had underlying medical conditions—particularly hypertension, chronic lung disease, and cardiovascular disease (Garg et al. 2020); wildfire pollutants give rise to and/or worsen all these conditions. Poor respiratory and cardiovascular health most commonly present in those hospitalized with COVID-19 (Garg et al. 2020). Given that wildfire smoke leads to poor respiratory and cardiovascular health and severe COVID-19 primarily presents in people with these conditions, exposure to high levels of $PM_{2.5}$ in wildfire smoke leads to increased vulnerability to COVID-19 infection and death for those near active wildfires (Zhou et al. 2021; Cortez-Ramirez et al. 2022; Schwarz et al. 2022; Yu and Hsueh 2022).

One theory for the association between wildfire smoke exposure and COVID-19 infections involves simultaneous transport of the SARS-CoV-2 virus and angiotensin-converting enzyme II (ACE-2); a study investigating the effects of wildfire smoke on the transmission of COVID-19 between wildland firefighters determined that the SARS-CoV-2 virus is transported with an enzyme that makes one's cells more sensitive to the virus (Navarro et al. 2021). A possibility remains that measures taken to reduce wildfire smoke exposure potentially act to increase or decrease exposure to COVID-19 (Henderson 2020). The presence of wildfire smoke may force people to spend more time indoors, thereby propagating the spread of the SARS-CoV-2 virus. Conversely, poor air quality may encourage those who go out in public during a wildfire event to wear a mask—subsequently preventing the spread of sickness.

c. Investigating the connection

Most sources came to the same conclusion that increased wildfire smoke exposure leads to increased COVID-19 hospitalizations—though they differ in techniques and parameters. Five sources state that exposure to $PM_{2.5}$ from wildfires is associated with respiratory diseases, morbidity, and cardiovascular dysfunction (Delfino et al. 2009; Liu et al. 2014; Alman et al. 016; Reid et al. 2016; Cascio 2017). Liu et al. (2014), Reid et al. (2016), and Cascio (2017) have all written critical or systematic reviews on the effects of wildfire smoke on human health. Alman et al. (2016) use modeling to investigate the relationship between atmospheric $PM_{2.5}$ and respiratory and cardiovascular hospitalizations during the 2012 Colorado wildfires; they found a positive correlation between wildfire smoke exposure and poor respiratory function. Delfino et al. (2009) use a Poisson distribution to investigate a similar relationship for the California wildfires of 2003. However, they adjust for socioeconomic differences of those hospitalized and take fungal spores into consideration due to their association with asthma. Four sources state that exposure to $PM_{2.5}$ in wildfire smoke leads to increased vulnerability to COVID-19 infection and death for those near active wildfires (Zhou et al. 2021; Cortez-Ramirez et al. 2022; Schwarz et al. 2022; Yu and Hsueh 2022). Of these sources, only Cortez-Ramirez et al. (2022) consider PM_{10} rather than $PM_{2.5}$ and adjust for sociodemographic risk factors. Zhou et al. (2021) use a statistical model, Yu and Hsueh (2022) use panel fixed effects models, Cortez-Ramirez et al. (2022) use a Bayesian mixed-effect regression, and Schwarz et al. (2022) use synthetic control models. Though differing in techniques, they all found a positive correlation between $PM_{2.5}$ exposure and COVID-19 hospitalizations.

The results of the methods above come together to lay a foundation for an investigation of the long-distance transport of wildfire smoke and its effects on COVID-19 hospitalizations. Canada saw an increase in the size of wildfires during their 2023 wildfire season (Voiland and Garrison 2023). Naturally, a larger fire produces more smoke and pollutes the air more. Prolonged wildfire smoke exposure leads to respiratory and cardiovascular distress (Delfino et al. 2009; Liu et al. 2014; Alman et al. 016; Reid et al. 2016; Cascio 2017)—both of which correlate to increased risk of COVID-19 hospitalization (Garg et al. 2020). This means that exposure to $PM_{2.5}$ in wildfire smoke leads to increased vulnerability to COVID-19 infection and death for those near active wildfires (Zhou et al. 2021; Cortez-Ramirez et al. 2022; Schwarz et al.

2022; Yu and Hsueh 2022). For those farther from the fire, this correlation remains uninvestigated. The importance of understanding this connection lies in the lack of knowledge surrounding COVID-19 as a relatively new virus and in building on the current understanding of wildfire smoke transportation. Understanding the connection between long-distance transport of wildfire smoke and COVID-19 hospitalizations, and taking the proper steps to mitigate the effects, ensures a safe and healthy environment for future generations. Wildfire smoke can travel hundreds of miles away from the fire (Nauth et al. 2023), thereby impacting the health of those far from the fire itself. As a resident of North Carolina, the author noticed that the air quality in the region was negatively affected due to the fires in Québec, Saskatchewan, British Columbia, and the Northwest Territories, Canada in 2023. Uncertainty remains about whether this transport of particulate matter impacts COVID-19 hospitalizations. This paper purports to investigate the correlation between COVID-19 hospitalizations and exposure to wildfire smoke transported into the eastern U.S. from the 2023 Canadian wildfires.

Based on the findings above from past literature, the author hypothesizes that COVID-19 hospitalizations will spike shortly after $PM_{2.5}$ levels in each chosen location. Comparison with viral gene copies per liter of wastewater allows for analysis of the greatest correlation: COVID-19 hospitalizations with the SARS-CoV-2 viral copies in wastewater or $PM_{2.5}$ levels. Consideration of topography and socioeconomic variations will narrow down the factors potentially contributing to greater correlation. Eight counties across the eastern U.S., four valley locations and four plains locations, will demonstrate a possible connection between COVID-19 hospitalizations and smoke settling in valleys for long durations; the author expects a larger spike in COVID-19 hospitalizations in the valley location for this reason. The comparison of counties' median income and ranking in education within the state to the results will determine if socioeconomic factors influence a spike in COVID-19 hospitalizations in the county. The author expects a larger spike in COVID-19 hospitalizations in the county with lower income and poorly ranked education. Research parameters will also neglect some socioeconomic factors, including hospital resources and race. Hospitalizations due to the lasting effects of the COVID-19 virus were also not considered.

Data and Methods

The analysis consists of data of varying types and locations: daily $PM_{2.5}$ Air Quality Index (AQI) values come from the U.S. Environmental Protection Agency (EPA) (United States Environmental Protection Agency 2023), data of bi-weekly COVID-19 hospitalizations per 100 000 people comes from Covid Act Now (Covid Act Now 2023), and data of viral gene copies per liter of wastewater comes from the North Carolina Department of Health and Human Services (North Carolina Department of Health and Human Services COVID-19 Response 2023). The data range spans from 11 May 2023 to 8 August 2023; the span of three months allows for consideration of the average duration of the viral incubation period. Data on income and education comes from the U.S. Census Bureau (United States Census Bureau 2023).

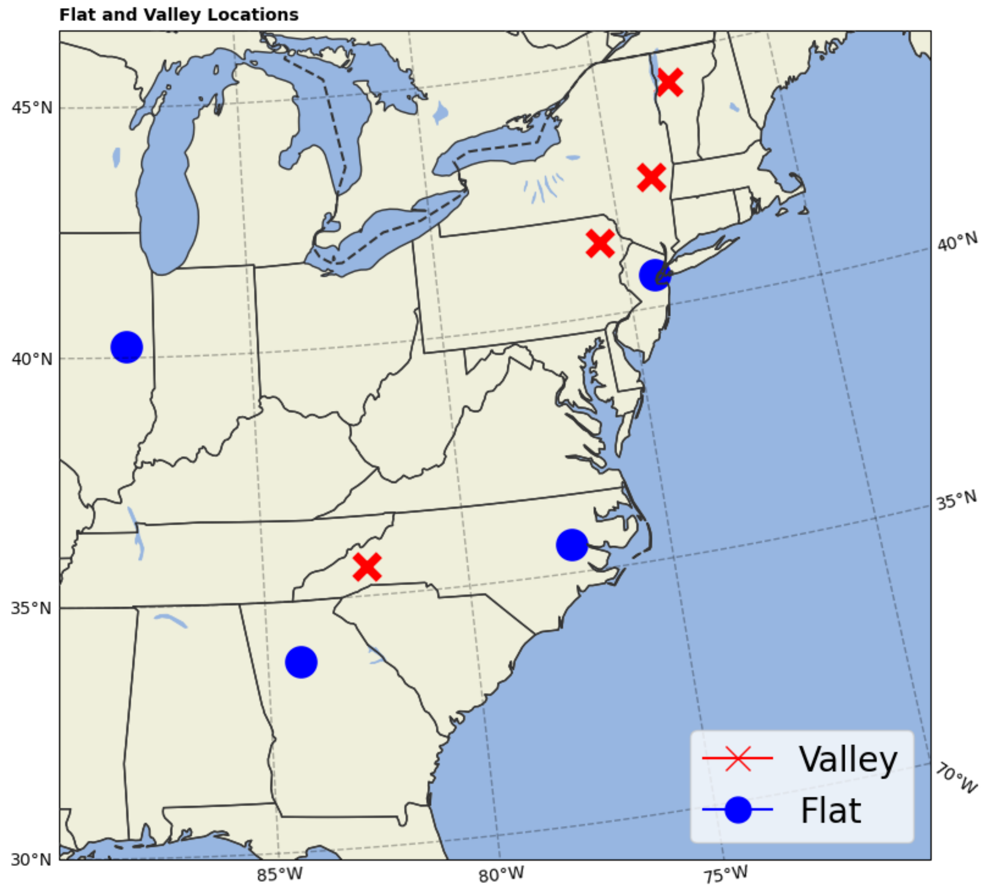

FIG. 1 Valley locations, marked with red ‘X’, and flat-land locations, marked with blue ‘O’.

Figure 1 shows a map of the chosen locations. The four valley locations were designated as Lackawanna County, PA, Buncombe County, NC, Albany County, NY, and Chittenden County, VT. The author designated the four plains locations as Pitt County, NC, DeKalb County, GA, Champaign County, IL, and Union County, NJ. Given the two-to-fourteen-day incubation period of the SARS-CoV-2 virus (European 2023), the author calculated the correlation coefficient between $PM_{2.5}$ AQI and COVID-19 hospitalizations per 100 000 (hereafter referred to as CCPM) for five-, seven-, ten-, and fourteen-day lag times in all counties. The author also calculated correlation coefficients between viral gene copies per liter and COVID-19 hospitalizations per 100 000 (hereafter referred to as CCWW) for each county with the same lag times. The author substituted data for the previous or following day for missing or unavailable values of viral gene copies per liter due to a lack of publicly available data. If there was no data for the previous or following day, the author averaged values for the two nearest days before and after the target day. If there was no data for the nearest day before or after the target day, the day in question was omitted from calculations of correlation coefficient. Several CCWW were omitted due to a lack of data; these include the five- and ten-day lag times for Lackawanna, DeKalb, Chittenden, and Union counties, and the fourteen-day lag time for Champaign and Chittenden counties. The 0-day lag times were disregarded from analysis since symptoms would not appear on the same day as exposure—let alone hospitalization.

Results

Tables 1 and 2 depict the correlation coefficients for each county. Table 3 outlines the socioeconomic status of each county, as well as population and distance from the epicenter of the wildfires in Fort Smith, Northwest Territories. In each table, the first four locations listed are the valley locations and the last four locations are the plains locations.

TABLE 1. Correlation coefficients calculated between COVID-19 hospitalizations per 100 000 people and $PM_{2.5}$ AQI (CCPM) for five different lag-times.

	0-day	5-day	7-day	10-day	14-day
Buncombe, NC	-0.45	-0.29	-0.37	0.21	-0.16
Chittenden, VT	0.70	0.59	0.45	0.85	0.33
Albany, NY	0.61	0.51	0.41	0.50	0.34
Lackawanna, PA	0.64	0.57	0.61	0.20	0.32
Champaign, IL	0.48	0.69	0.54	0.63	0.57
Union, NJ	0.87	0.89	0.66	0.70	0.79
Pitt, NC	-0.45	0.15	-0.23	0.33	0.09
DeKalb, GA	0.79	0.60	0.67	0.83	0.86

TABLE 2. Correlation coefficients calculated between COVID-19 hospitalizations per 100 000 people and SARS-CoV-2 viral gene copies per liter of wastewater (CCWW) for five different lag-times. Some locations have missing values due to a lack of available data.

	0-day	5-day	7-day	10-day	14-day
Buncombe, NC	0.50	-0.23	0.45	0.53	0.57
Chittenden, VT	0.93	——	0.92	——	0.91
Albany, NY	0.47	0.27	0.39	0.41	0.76
Lackawanna, PA	0.22	——	0.63	——	0.69
Champaign, IL	——	0.66	——	0.60	——
Union, NJ	0.87	——	0.93	——	0.98
Pitt, NC	0.91	0.91	0.84	0.91	——
DeKalb, GA	0.97	——	0.94	——	0.96

TABLE 3. Median household income (in 2022 dollars), percent of people age 25 years or older with a high school degree, percent of people age 25 years or older with a Bachelor's degree, from 2017–2022, the population of each county in 2022, and the distance of each county from the epicenter of the wildfires in Fort Smith, Northwest Territories.

County	Median Income	High School Diploma	Bachelor's Degree	Population	Distance from Epicenter
Buncombe, NC	$66,531	92.1%	43%	273,589	2135 mi (3435 km)
Chittenden, VT	$89,494	95.3%	55.7%	169,301	1931 mi (3107 km)
Albany, NY	$78,829	92.6%	44.4%	315,811	1995 mi (3210 km)
Lackawanna, PA	$63,739	91.6%	29.9%	215,615	2003 mi (3223 km)
Champaign, IL	$61,090	94.7%	45.6%	206,542	1706 mi (2746 km)
Union, NJ	$95,000	86.8%	38.3%	569,815	2087 mi (3358 km)
Pitt, NC	$54,915	90.2%	33.1%	173,542	2281 mi (3670 km)
DeKalb, GA	$76,044	91.1%	46.7%	762,820	2201 mi (3541 km)

Discussion

While it was hypothesized that valley locations would see higher numbers of COVID-19 hospitalizations and higher correlation coefficients, this was not the case. Distance from the fires' epicenter was a better predictor of high CCPMs than topography. Figures 2 and 3 show the CCPMs and CCWWs plotted by location. The 0-day lag times were disregarded from analysis since symptoms would not appear on the same day as exposure due to the necessary incubation period of the SARS-CoV-2 virus. Dekalb and Union counties have the highest CCPMs, except at the 10-day lag-time, and CCWWs as outlier counties regarding population; while their populations are approximately 763 000 and 570 000 people, respectively, the county with the next highest population is Albany County with approximately 315 000 people. This is likely because increased population density corresponds to a higher transmission rate of viruses. Despite this, not all of the highest correlation coefficients correspond to the highest population regions. Excepting DeKalb and Union Counties, locations closer to the wildfire epicenter generally have higher correlation coefficients for both CCPM and CCWW. The North Carolina locations are the only two that have negative correlation coefficients—meaning that COVID-19 hospitalizations decreased as the $PM_{2.5}$ AQI increased. This could mean that people were more likely to wear their masks or stay indoors due to the poor air quality—but the magnitude of the CCPMs for these locations are too low to draw a conclusive correlation. For many locations, the CCPM peaks at the five- and ten-day lag-times—meaning that COVID-19 hospitalizations due to $PM_{2.5}$ exposure were more likely to happen five and ten days after exposure than seven or fourteen days after exposure.

While some of the CCPMs were high, many of the CCWWs were higher. This indicates that COVID-19 hospitalizations in many locations are more strongly correlated to a wave of the SARS-CoV-2 virus going around, as indicated by viral gene copies in the wastewater, rather than poor air quality due to wildfire smoke transport. Champaign, Albany, and Lackawanna Counties were the only counties with higher CCPMs than CCWWs—indicating that COVID-19 hospitalizations were more strongly correlated to poor air quality from wildfire smoke transport. Champaign County is the closest location to the epicenter of the fires, has the second-lowest median income, and has the third-lowest population. These indicate that socioeconomic factors may make those living in Champaign County more vulnerable to exposure to poor air quality and subsequent transmission of the SARS-CoV-2 virus than counties with higher socioeconomic status. Despite this, the author was required to omit the most CCWWs from this location compared to the others due to a lack of available wastewater data—leading to some discrepancy in the analysis. Albany County has a higher median income, so the population may not be as vulnerable as the population of Champaign County. This location is also the second closest to wildfires burning in Québec at the same time as those burning around Fort Smith, Northwest Territories; this may contribute to a higher $PM_{2.5}$ AQI in the region. The CCWW and CCPM for Lackawanna County are very comparable at the five- and seven-day lag-times. According to Figure 2, poor air quality from wildfire smoke was most likely to hospitalize people with COVID-19 five days after exposure—after which the subsequent spread of the virus may have been detected by viral gene copies in the wastewater. The median income of Lackawanna County is only $2000 greater than that of Champaign County—suggesting that socioeconomic factors may make this population more vulnerable to exposure to poor air quality and COVID-19 than counties with a higher socioeconomic status. Champaign, Albany, Lackawanna, and Chittenden Counties are the four closest locations to the Canadian wildfires. The second closest location is Chittenden County. This location has the lowest population, the highest education rating, and the second highest median income; these socioeconomic factors suggest that Chittenden County is not as vulnerable to exposure to poor air quality and the SARS-CoV-2 virus as the other three closest counties—despite being the closest location to the Québec fires.

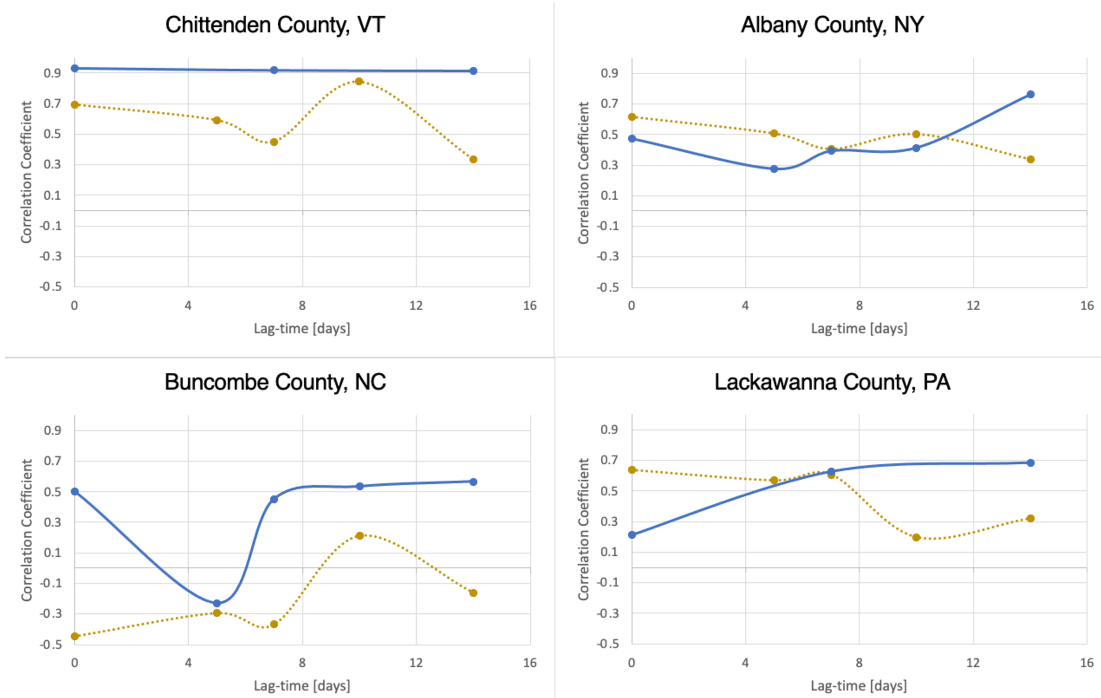

FIG. 2 Correlation coefficients for each lag-time at the valley locations. The solid blue line is the correlation coefficient between COVID-19 hospitalizations per 100 000 people and viral gene copies per liter of wastewater. The dashed orange line is the correlation coefficient between COVID-19 hospitalizations per 100 000 people and $PM_{2.5}$ AQI.

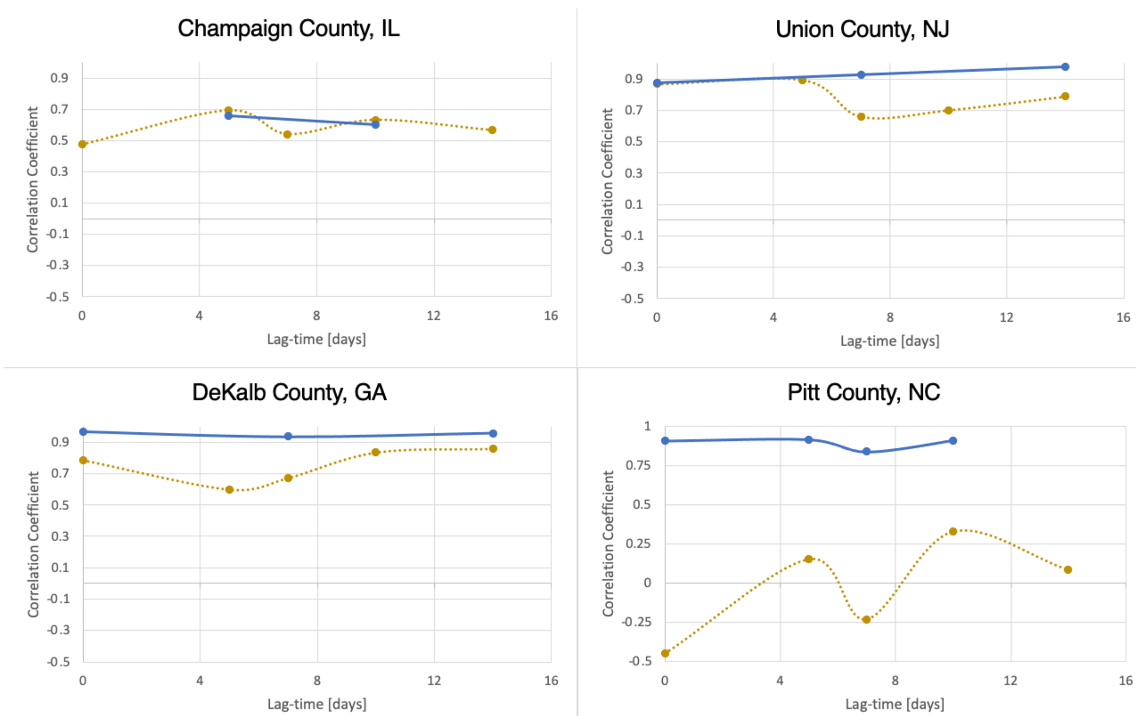

FIG. 3 Correlation coefficients for each lag-time at the plains locations. The solid blue line is the correlation coefficient between COVID-19 hospitalizations per 100 000 people and viral gene copies per liter of wastewater. The dashed orange line is the correlation coefficient between COVID-19 hospitalizations per 100 000 people and $PM_{2.5}$ AQI.

Conclusion

As U.S. wildfires continue to increase in frequency and severity (Westerling et al. 2006) and COVID-19 becomes a part of the new normal, the impact of the former on the latter and on humans is crucial to understand. Exposure to $PM_{2.5}$ in wildfire smoke leads to increased vulnerability to COVID-19 infection and death for those near active wildfires (Zhou et al. 2021; Cortez-Ramirez et al. 2022; Schwarz et al. 2022; Yu and Hsueh 2022). As a resident of North Carolina, the author noticed that the air quality in the region was negatively affected due to the record-breaking 2023 Canadian Wildfires.

The author calculated CCPMs for zero-, five-, seven-, ten-, and fourteen-day lag times and analyzed viral gene copies per liter of wastewater and COVID-19 hospitalizations per 100 000 people (CCWWs) for the same lag times for eight counties: four valley and four plains locations. The time frame of calculations depended on data available at each location but encompasses 11 May 2023 to 8 August 2023.

Correlation between COVID-19 hospitalizations and $PM_{2.5}$ exposure was found at three out of eight locations. These three (Albany, Champaign, and Lackawanna Counties) were some of the closest locations to the wildfire epicenter in Fort Smith, Northwest Territories—excluding Chittenden County. These three locations were all within 2000 mi (3200 km) of the wildfire epicenter. For the remaining five locations, CCWWs were higher than CCPMs. Therefore, 2000 mi (3200 km) may be the longest linear distance that wildfire smoke can travel and affect COVID-19 hospitalizations; farther than this, there is no significant correlation between $PM_{2.5}$ AQI and COVID-19 hospitalizations. Of the three locations that showed a significant connection between COVID-19 hospitalizations and $PM_{2.5}$ AQI, two of these were valley locations and one was a flat-land location. Had more locations closer to the wildfires been examined, a connection might exist between topography and COVID-19 hospitalizations due to $PM_{2.5}$ exposure. Linear distance is also not the best measure for tracking the motion of particulate matter in the atmosphere; it is well-understood that synoptic scale motions do not work this way. The author also only considered distance to the fires surrounding Fort Smith, Northwest Territories, and distance from chosen locations to the fires does not include the fires burning in Québec, Canada at the time. This should be considered in future studies.

A more in-depth comparison of multiple valley and flat-land locations up to 2000 mi (3200 km) from the fire would allow for significant conclusions to be drawn on the impact of topography and consequent valley smoke on COVID-19 hospitalizations. Additional statistical analysis would also prove beneficial to resulting in significant correlations. This study unfortunately does not consider COVID-19 hospitalizations due to lasting effects/complications of the virus that happen after patient is asymptomatic and no longer contagious—causing the hospital not to flag the hospitalization of the patient as due to COVID-19. Future studies can benefit from these things as well as adding other socioeconomic factors for consideration and potentially analyzing these more quantitatively.

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