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The Analysis of Relationships Between Lightning Strikes and Particulate Matter 2.5 Utilizing Statistical and Numerical Modeling Methods Applied to the 2020 Wildfire Season

Megan Schiede

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The Analysis of Relationships Between Lightning Strikes and Particulate Matter 2.5

Utilizing Statistical and Numerical Modeling Methods Applied to the 2020 Wildfire Season

An honors thesis presented to the
Department of Atmospheric and Environmental Sciences,
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Megan Schiede

Research Advisor: Kristen Corbosiero, Ph.D.

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Abstract

Throughout 2020, ambient air pollution was reduced as a result from limiting anthropogenic activities to mitigate the spread of COVID-19. Not all air pollution is created the same as measurements of particulate matter 2.5 (PM2.5) were generally unaffected by this reduction due to PM2.5’s source from wildfires. Despite influences from COVID-19 lockdowns, rises in PM2.5 concentrations can be attributed to the anomalously active wildfire season of 2020. As climate change progresses, these extraordinarily active seasons can be classified as the “new normal”; thus, comprehension of such events are vital.

Given the ability of lightning to naturally cause wildfires, there exists a positive feedback loop that exists as convection can be influenced by aerosols. To understand this feedback loop, a proper analysis of the interactions between lightning and wildfires is necessary. Data from the Environmental Protection Agency (EPA) Air Quality System, National Lightning Detection Network (NLDN), and the ERA5 Reanalysis was utilized for a statistical analysis. Airports were carefully chosen to result in 132 correlation coefficients for either PM2.5 concentration or lightning strikes to meteorological variables and month. Planetary boundary layer height (PBLH) had the strongest negative correlation with all but one calculated correlation being negative on the East Coast.

Numerical modeling methods were implemented to understand aerosol behavior beyond a statistical scope. Two Weather Research and Forecasting (WRF) model simulations were conducted surrounding the Detroit Metropolitan Wayne County Airport (KDTW) using a 3-km High Resolution Rapid Refresh (HRRR) initialization at 0000 UTC 7 September 2020 to compare model runs with and without the inclusion of NASA’s Goddard Earth Observing System (GEOS) model aerosol data. The difference between the simulations including aerosols to no aerosols showed that PBLH mimicked the frontal structure associated with convection for the case. Positive values indicated that WRF simulations that included aerosols had higher PBLH that were observed behind the cold front. Additional cases must be examined to draw adequate conclusions regarding numerical model output to further confirm the existence of a frontal-based relationship surrounding PBLH.

Keywords: Atmospheric chemistry, Wildfires, Numerical modeling
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Introduction

The University at Albany currently serves as the host of the National Thunderstorm Forecast Contest, providing meteorologists the opportunity to predict thunderstorm occurrences across the continental United States. Since 1983, the contest has the participants forecast the probability of thunderstorm occurrence in METeorological Terminal Air Reports (METAR) for ten cities. A comprehensive climatology of thunderstorm days has been managed by the Department of Atmospheric and Environmental Sciences at the University. Prior to this investigation, the climatology was last updated in 2015 in order to check the verification accuracy of the National Lightning Detection Network (NLDN). NLDN data is used as a backup verification of data when METAR data is unavailable. The network collects data through ground sensors that detect electromagnetic pulses that are detected when lightning strikes the ground (NASA 2022). The NLDN is an excellent source to access precise lightning data in the context of this study.

The discharge of lightning occurs as collisions between ice crystals and graupel particles form charged regions. These charged regions have developed in the presence of supercooled liquid water embedded within a strong updraft (Ren et al. 2018). This process is highly contingent on the microphysical attributes present at the time of a thunderstorm. Aerosols have the ability to alter these microphysical elements, creating modifications to precipitation formation and how charge separation occurs, resulting in lightning (Lynn et al. 2020).

There are always aerosols present in our atmosphere, however, their ability to influence convective activity is highly variable. Enhanced aerosol concentrations reduce rainfall processes while simultaneously increasing the amount of water present in a cloud as ice formation is modified (Chowdhuri et al. 2020). Aerosols possess the ability to act as cloud condensation nuclei (CCN). For clouds to form, CCN must be present as moisture within the atmosphere needs
to latch onto a physical particle in order to form a cloud. Therefore, aerosols have a crucial role in the formation of a cloud. The influence of aerosols in cloud behavior does not end there. Wang et al. (2018) uncovered that ultrafine aerosol can enhance the strength of convection under supersaturated environmental conditions through the activation of cloud droplets. Further supporting the concept of how sensitive convection is to fluctuations of aerosol type and concentration.

Dynamics, thermodynamics, and aerosols are the major factors in the behavior of lightning (Wang et al. 2018). This relationship implies that lightning is not only influenced by a meteorological component, but additionally an atmospheric chemistry component. As lightning is influenced by atmospheric chemistry, lightning, in turn, influences atmospheric chemistry. Lightning is known to emit large amounts of ozone ($O_3$) as well as nitrogen oxides ($NO_x$) (Chowduri et al. 2020; Shi et al., 2020). The chemical impacts from lightning extend far past the local level resulting in global impacts on atmospheric chemistry (Shi et al. 2020). While lightning occurs in a highly localized area, the resulting chemicals linger in the atmosphere following the flash.

A reduction in anthropogenic activities as a response to COVID-19 lockdown policies resulted in a reduction in air pollution. Carbon dioxide ($CO_2$) observed an 8.8% decline, while particulate matter 10 (PM10), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), and $O_3$ saw between a 40 to 68% decline in observational measurements (Chowdhuri et al. 2020; Yusfiandika et al. 2021). With this reduction of additional pollutants resulting from anthropogenic sources, there exists a unique opportunity to examine more natural sources of such pollution with minimal human influence on aerosol concentrations.

The reduction in pollution resulting from COVID-19 lockdowns received was counteracted by the abnormally active 2020 wildfire season. The 2020 wildfire season was responsible
for five out of the top ten largest wildfires in California based on the acres burned (CALFIRE 2022), with nearly 2.5 million acres burned in 2020. Lightning is known to be a natural igniter of wildfires. The largest wildfire that occurred in 2020, the August Complex Fire, was ignited by lightning. In addition, all except one of these five wildfires from the 2020 season were ignited by lightning (CALFIRE 2022). Therefore, a positive feedback system exists where lightning causes wildfires, while wildfires produce aerosols that aid in the formation of convective activity resulting in wildfires.

As wildfires burn, particulate matter 2.5 (PM2.5) is the main pollutant that is emitted into the atmosphere. PM2.5 is composed of fine particles that measure a diameter of less than 2.5 μm (EPA 2022). Many scientists including environmental scientists, biologists, and even doctors take interest in the behavior of PM2.5 in our atmosphere. Particulate matter has been determined to have detrimental effects on human health (Koelemeijer et al. 2006). Further implying the importance of understanding the behavior of wildfires, not only to reduce loss of property, but to mitigate effects on human health. This human health impact is widespread; approximately 1 in 20 deaths that occur in the United States can be linked back to PM2.5 and O₃ exposure (Peel et al. 2013). PM2.5 will result from wildfires and O₃ is a by-product of lightning. Recent massive wildfire events contributed to excessive amounts of pollution, further jeopardizing human health; thus, this trend of increasing frequency is alarming to monitor.

Scientists strive to understand how various natural phenomena will behave in order to adapt to climate change, including both wildfires and lightning. As alluded to beforehand, greater amounts of lightning will result in increased frequency of naturally ignited wildfires. An understanding of this feedback loop is vital in order to mitigate risks associated with wildfires and lightning. As surface temperatures continue to warm, the climate becomes more conducive for extreme wildfire events. Significant wildfire events will emit mass amounts of aerosols; thus,
suggesting a need to grow our understanding of the interactions between aerosols and meteorological phenomena.
Methodology

This study required the inclusion of atmospheric chemistry and meteorological data to assess the entirety of the relationship between lightning strikes and PM2.5 that was released from wildfires in 2020. Multiple datasets were utilized in order to adequately assess PM2.5, lightning strikes, meteorological variables of interest, and additional aerosol information. For PM2.5 concentrations, surface observational data from the Air Quality System (AQS) repository was used based on the county location for each airport. If multiple observations were taken within one county for a given day, the average value was calculated. Observational issues exist for collecting data as highly affected states tend to lack the necessary amounts of ground stations to accurately capture smoke (Xue et al. 2021). This tends to be a limitation of ground-based data; however, it was chosen for this study given the ease of access. Meteorological observations were gathered from the ERA5 Reanalysis (on a 0.25º latitude–longitude grid). Lightning strike data was gathered from the National Lightning Detection Network (NLDN) and filtered to focus on 2020. Each of these datasets were incorporated into various calculations to analyze the relations of interest.

The NLDN dataset contained each lightning strike that had occurred on a particular date across the United States. According to the National Weather Service (NWS) Office in Melbourne Florida, approximately 20 million lightning strikes occur across the United States per year; that is approximately 54,800 strikes a day (NWS 2022). This study aimed to mimic the 20-km radius utilized in Verification of Daily Thunderstorm Occurrence using the NLDN (Corbosiero et al. 2022). A 20 km by 20 km grid was established around each airport investigated. This is not consistent with the radius set in place with the Thunderstorm Game, but rather establishes a buffer beyond the radius.
Originally, all airports used in Verification of Daily Thunderstorm Occurrence using the NLDN were intended to be used in this study. Given this, the climatology of thunderstorm days (TS days) was updated to include the year 2020. Initially, data from 20 airports were considered. Through further analysis, six airports were chosen to be the focal points for this investigation. The criteria for elimination included geographic location, as well as results from initial correlation calculations. The following airports were further considered in this study: Albany International Airport (KALB), Billings–Logan International Airport (KBIL), Bismarck Municipal Airport (KBIS), Denver International Airport (KDEN), Detroit Metropolitan Wayne County Airport (KDTW), and Reno-Tahoe International Airport (KRNO). From these resulting airports, three are part of the Thunderstorm Game (KALB, KBIS, and KDEN), one is an additional airport used in Verification of Daily Thunderstorm Occurrence using the NLDN (KDTW), and two are airports located in optimal locations based on wildfire location (KBIL and KRNO). A map of these airports is shown in Figure 1.

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was utilized to determine the location of airports that likely experience PM2.5 from wildfire activity. A forward trajectory model was run using North American Mesoscale Forecast System (NAM) model data to simulate how air parcels travel in response to the August Complex Wildfire (CALFIRE 2022). The model was run on 17 August 2020 with an initial location of the source of the fire. The resulting HYSPLIT trajectory is shown in Figure 2. As exhibited in the trajectory output, KBIL and KRNO are both located in the trajectory path of the air parcels on this date. Therefore, these airports serve as a beneficial addition to this study to better understand wildfire behavior in the west. Similar to the issue mentioned prior, as AQS data is lacking in areas out west, the Thunderstorm Game fails to incorporate any West Coast cities with the furthest west being Salt Lake City, UT. KBIL and KRNO are a great addition to fill in this gap.
A. Calculations

Statistical analyses were performed to quantify key relationships that have the potential to promote lightning activity. Data was sectioned into two fragments: data from June and July were grouped together as the pre-wildfire season, and data from August and September were grouped together as the wildfire season. While the wildfire season does extend into the months following September, the data that this study considers stops in September for two reasons. First, convective activity is greatly reduced past September and second, that the Thunderstorm Game only continues into August.

The correlation coefficient was calculated for PM2.5 concentration and frequency of lightning strikes to understand their relationships for each month. Equation (1) below was used to calculate the correlation coefficient

\[ R_{ij} = \frac{c_{ij}}{\sqrt{c_{ii}c_{jj}}} \]  

This process was repeated to investigate PM2.5 concentration and meteorological variables of interest. The definition for bounds of the correlation coefficient used in this investigation is shown in Table 1. This interpretation of the correlation coefficient calculations remains constant for each case presented throughout this study.

The meteorological variables chosen to investigate were based on the three major factors discussed prior in Wang et al. (2018): dynamics, thermodynamics, and aerosols. Convective available potential energy (CAPE) was considered to represent the dynamics/thermodynamics. CAPE plays a vital role in producing convection as significant amounts of energy must be present in order for convection to form. Additionally, planetary boundary layer height (PBLH) was included to represent aerosols. PBLH aids in helping to diagnose aerosol interactions in the atmosphere as the most intense interactions occur within the boundary layer (Li et al. 2017);
therefore, the height can be used as a proxy for how concentrated aerosols may be. If there is a lower PBLH, aerosols will be more concentrated. Lastly, Total column water (TCW) was incorporated to serve as a moisture variable given moisture’s influence on convention. Following the calculations of the correlations, analysis and eliminations of airports were done.

B. Model analysis

Following the broad calculations of correlations conducted, model data was utilized to focus on specific convective events. To pick the convective events of interest, the date of maximum lightning strikes for both the pre-wildfire and wildfire time frames were considered for each airport. To determine the timing of these convective events, the National Centers for Environmental Information (NCEI) Interactive Radar Map was used to examine past radar images to obtain a sense of the start and end time of these events.

A specific case was selected in order to conduct further numerical modeling. To begin, the Weather Research and Forecasting (WRF) Model was utilized initialized with High-Resolution Rapid Refresh (HRRR) data at 3-km resolution with a 400 by 400 grid point, 3-km grid spacing domain looking at KDTW from 0600–0900 UTC 7 September 2020. Two separate simulations were run with varying microphysics schemes to account for the inclusion of aerosols. The first simulation was run as a control; the second simulation incorporated aerosols from NASA’s Goddard Earth Observing System (GEOS) model. Total Aerosol Extinction AOT [550 nm] and Total Aerosol Angstrom parameter [470-870 nm] data were inputted into the WRF Model for the second simulation. Two meteorological variables were examined with the intention to understand the behavior of aerosols in these simulations. Wind speed and PBLH were selected given their influence on the distribution of aerosols within the troposphere (Eun et al. 2020). The model output was analyzed to investigate the change in model behavior resulting from the inclusion of the aerosol model. Therefore, the output was analyzed as the difference
between the simulation with aerosols and the simulation without aerosols. Where positive
changes were observed, the simulation with aerosols showed higher values of either wind speed
or PBLH. Equation (2) below is indicative of the relationship between the two simulations

\[ \Delta WRF = \text{model output with aerosols} - \text{model output without aerosols}. \]  

(2)

This equation was applied to wind speed (wpsd) and PBLH in Equations (3) and (4) shown below

\[ \Delta \text{wspd} = \text{wspd[aerosols]} - \text{wspd[no aerosols]} \]  

(3)

\[ \Delta \text{PBLH} = \text{PBLH[aerosols]} - \text{PBLH[no aerosols]}. \]  

(4)

If there were negative changes observed, the simulation without aerosols showed higher values
of either wind or PBLH. The difference between the simulations was calculated for each time
step utilizing these equations and were plotted for the purpose of analysis.
Results

To reflect more current trends, an initial analysis of the dates added to the TS Days contest was conducted by updating the TS Days Climatology. This new dataset extends from 2015 through 2020. For the sake of this investigation, the 2020 data was prioritized, however, basic comparisons between the new data were made. Examining the dataset on a year-to-year basis, it was found that TS days had generally decreased from 2019 to 2020 in most regions of the United States. The only outlier was the southeastern United States where positive percent changes in frequency were observed. Overall, 13 cities in the Verification of Daily Thunderstorm Occurrence using the NLDN observed a below-average number of TS days. This was not the only instance of observed decline in TS days. For the cities listed in Verification of Daily Thunderstorm Occurrence using the NLDN, 2020 had the second-lowest number of TS days spanned over the five-year period of 2015–2020 with the average number per city being 28.95 days. When this decline is examined using percent changes, it amounts to an average percent change of the ten cities included in the TS Contest of 19.4% from 2019 to 2020.

To better understand wildfire behavior, an initial HYSPLIT forward trajectory was run given the source information from the August Complex Fire. A simulated trajectory is shown in Figure 2. The purpose to incorporate this model is to understand the path of air parcels during a specific event. The August Complex Fire was chosen as it was the most destructive wildfire in both the 2020 wildfire season and in the history of California (CALFIRE 2022). From this path, we can see there were three main motion clusters that a parcel would take. The first cluster shows the air moving to the northeast from the source point, making its way over Oregon to Idaho and arriving through Montana over the 72 hours of this simulation. The second cluster appears to take parcels over northwestern Nevada; however, this path is much shorter when compared to that of the first cluster. The last cluster of path trajectories takes parcels south into the Central
Valley of California. From these paths, it became clear that it was vital to incorporate airports that had a close proximity to the wildfires regardless of if they were mentioned in the inspirational study. KBIL and KGTF are both located in Montana and the data from these airports can be used to evaluate the behavior along path one. KRNO was added to the list of airports considered in order to be representative of air parcels that would travel westerly from the source. An airport was not selected to be representative of the air parcels that were funneled through the valley as there are potential for other pollution sources in this region due to various agriculture activities that the region is infamous for.

A. Correlation calculations for PM2.5 and lightning activity

The results for the calculation of correlation coefficient between PM2.5 and lightning activity are shown in Table 2. For this case, the correlation coefficient has been calculated in two subgroups: pre-wildfire season and wildfire season. After first glance at this table, it becomes evident that for most airports there is one time group when there is a correlation, and the other time period has negligible correlation. What is particularly interesting is that there does not appear to be a trend that is consistent at each airport. One observation is that East Coast airports have typically negative correlations, yet the strength of their correlation appears to be random. For example, at KDTW for pre-wildfire, the correlation was strong negative; meanwhile, once it became wildfire season, the correlation shifted to weak negative. However, when compared to KALB where pre-wildfire is negligible, and wildfire is moderate negative there appears to lack general consistency beyond whether the trend is simply positive or negative.

Such variety can be observed as well in Central and Western U.S. airports to a more varying degree than that of the East Coast airports. Typically, the Central Region had the greatest range among the calculated correlations. If we examine during the wildfire season, KBIS had a moderate positive correlation, KOMA had a strong negative correlation, KOKC had a weak
negative correlation, and KIAH had a negligible correlation. This varying degree of correlation among locations of similar longitude, but ranging latitude, is an interesting observation and further suggests that these correlations may be contingent on more small-scale factors having an influence on the number of lightning strikes.

Given this observation of more nuanced correlations between different airports across the country, a few were selected based on these preliminary results in order to examine those with varying correlations. Primarily, any airport that had any negligible or weak correlations (either positive or negative) were eliminated, as the main focus is to examine those with significant correlations. KRNO was the exception to be kept for its location relative to the trajectory of the August Complex HYSPLIT.

B. Correlation calculations for PM2.5 and select meteorological variables

The calculations of correlation coefficient between PM2.5 and the meteorological variables of interest are shown by region in Tables 3, 4, and 5. These tables each individually break down both the description of the correlation as well as the actual numeric value that was calculated. CAPE, PBLH, and TCW were calculated, and the results were interpreted as follows.

CAPE was the first meteorological variable to be considered, due to the crucial role that it has in thunderstorm development. PM2.5 does not appear to affect the energy available for convection in the atmosphere equally at multiple places. Especially along the East Coast, fluctuations at KALB show how in July PM2.5 and CAPE had a moderate positive correlation that quickly jumped to be a strong negative correlation in August. At all other airports, the fluctuations observed were far more minimal than the stark contrast that was observed at KALB. Generally, the correlations for CAPE, if not negligible, were positive over this four-month period.
Following CAPE, PBLH was examined. Given the focus on aerosols and particulate matter, this is the meteorological variable that was hypothesized to have the strongest trends for correlations. PBLH keys us in on how densely packed aerosols are within the atmosphere. If we have lower PBLH heights, we can anticipate that aerosol concentrations to be higher and vice versa. Therefore, consistent negative correlations were anticipated between PM2.5 and PBLH as highlighted in Su et al. (2020).

Consistency was seen in these calculations. The expected output can be observed in the Eastern Region data as both KALB and KDTW show negative correlations for all but one month in the eight-month time range. These correlations are significant as well. In June, a strong negative correlation of -0.609 was calculated for KALB and a strong negative correlation of -0.526 was calculated for KDTW. Time series plots were created for both KALB and KDTW for the month of June. These plots are shown as Figure 3 and 4. After a glance at these time series, particularly for KDTW, the timeframe from 9 to 11 June does an excellent job illustrating what this negative correlation actually looks like in the data.

Shifting from the Eastern Region to the Central Region, the PBLH correlations become more variable. For KBIS, correlation remains negligible for the summer months of June, July, and August while in September the correlation jumps to have a strong negative correlation. KDEN observed a far different pattern of correlation when compared to KBIS. In July, KDEN observed a strong positive correlation, followed by a weak positive correlation in September. Otherwise, the correlation was negligible.

The Western Region observed a very peculiar trend in correlation between PM2.5 and PBLH. For both KBIL and KRNO, the airports recorded a strong positive correlation between the two variables in June. These strong positive correlations were significant as a correlation coefficient value of 0.660 was calculated for KBIL and 0.579 for KRNO. Meanwhile, in July,
the correlations begin to vary significantly. KRNO retains its strong positive correlation as KBIL shifts to a moderate negative correlation. August and September saw negligible correlations for the most part with a weak positive correlation calculated for KRNO. It is fascinating to see this trend exist, especially this close to a common source of wildfires.

The correlation between PBLH and PM2.5 is expected to be negative as depicted in Su et al. (2020). However, it is observed that close to the source of the wildfires, this may not necessarily be the case. Time series of each month for KRNO were examined in further detail to determine if there happened to be any changes in the variable. These time series, shown in Figure 5, clearly show that as PM2.5 begins to spike as a result of wildfires, the correlation between PM2.5 and PBLH becomes negligible. This does not necessarily mean that the relationship between PM2.5 and PBLH becomes unimportant, but rather it becomes closer to zero, thus making it more negative than compared to the strong positive correlations seen prior. This, therefore, reflects more of the results that were initially anticipated as it is expected that the greater number of aerosols, the lower the PBLH. In Figure 5, lower PBLHs can be seen best in September. One can observe a large spike in PM2.5 values while the values for PBLH are lower than the local maximum recorded towards the beginning of the month; thus, demonstrating this relationship well.

Lastly, the correlations between PM2.5 and total column water (TCW) were calculated in order to evaluate the role of a moisture meteorological variable. Given that the focus of this study pertains to wildfires, it is anticipated that TCW would tend to have a negative correlation in western regions and a more variable pattern in the eastern region. Dry conditions are a necessary ingredient for wildfires; thus, it is reasonable to assume that when there are higher concentrations of PM2.5, the values for TCW will be less. The correlations calculated, however, reflect the opposite. In eastern regions, computations resulted in negative correlations,
particularly in September. Additionally, negative correlations were calculated for KDEN; meanwhile, a strong positive correlation was calculated for KBIS during August, further amplifying the variation of behavior in the Central Region. The Western Region also saw extensive variability in TCW. KBIL saw a quick switch from a strong negative correlation in June to a weak positive correlation in July. KRNO observed even greater fluctuations than KBIL. In June and July, strong positive correlations were calculated followed by a negligible correlation in August as well as a strong negative correlation in September. Therefore, this September setup alludes to the possibility that more wildfires had occurred in this month given that when enhanced PM2.5 concentrations are present, we have lower amounts of total column water.

C. Correlation calculations for lightning activity and select meteorological variables

Correlations between the aforementioned meteorological variables and lightning activity were also calculated to see if any thought-provoking trends would reveal themselves. The calculations for these correlation coefficients are listed in Tables 6–8. Following a similar process as discussed prior, CAPE was calculated first. Given how critical CAPE is for the development of thunderstorms, it is expected that there will be strong positive correlations when compared. As observed from these tables, strength may not always represent a true one-to-one relationship. At some airports, CAPE was more strongly correlated than at others. Airports such as KDTW, KBIS, and KRNO showed persistent positive correlation between CAPE and the number of lightning strikes. The other airports, KALB, KDEN, and KBIL, showed consistently negligible correlations. There were no negative correlations following all the calculations of CAPE. Such an observation is not surprising as the connection between CAPE and convective systems that produce lightning is well known.

Additionally, PBLH correlations were calculated. Interestingly, PBLH had completely negligible correlations for KALB, KDTW, and KBIS. KDEN only observed a moderate positive
correlated relationship in September, otherwise, the variables were negligible. Interesting correlations were observed in the Western Region. KRNO went back and forth between a moderate positive correlation in June to a then weak negative correlation in July. KBIL followed a different pattern as it had a weak negative correlation in both June and August. Regardless, in the Western Region, the negative correlation never exceeded -0.297, so while there may be an observed negative correlation, it was relatively weak and inconsistent to draw conclusive statements.

Lastly, TCW correlations were calculated. It is anticipated that TCW should be positively correlated with lightning strikes. Moisture is a necessary ingredient for producing convection and from this convection, lightning can be produced. In the East, we see generally weak positive correlations, with mostly negligible correlations observed at KALB. Moving to the Central Region, TCW has a weak positive correlation for each month except for June. Meanwhile, at KBIS, strong and moderate positive correlations were calculated. The Western Region has a greater mix of strong positive and weak positive correlations that were calculated. Similar to CAPE, no negative correlations were calculated. The correlation coefficient revealed fascinating relationships that exist between PM2.5, lightning, and selected meteorological variables.

D. Analysis of NASA GEOS Atmospheric Model

The utilization of the NASA GEOS atmospheric model was incorporated into numerical weather prediction models to be able to better understand aerosol behavior. Differences between one WRF simulation run without aerosols and one incorporating aerosols from the NASA GEOS model were plotted. These simulations were run for one particular case. KDTW on 7 September 2020 was chosen as the ideal case to model as lightning was most frequent at this location during the wildfire season. The first lightning strike captured by the NLDN was at 0635 UTC 7 September 2020 and the last occurred at 0842 UTC 7 September 2020. Therefore, this case was
modeled particularly for the time period between 0600–0900 UTC 7 September 2020. An overview of the Total Aerosol Extinction AOT is shown in Figure 6. In this figure, maximum values of AOT are observed in areas of northern California and into portions of California’s Central Valley. The maxima along the coast was associated with the August Complex Fire which continued to burn at the time of these simulations. The plume of smoke is easily recognizable from this plot as seen in the elevated values of AOT just east of the fire. In addition, there are slightly enhanced values of AOT just west of the location of KDTW. Several past studies indicated significant temporal correlations between satellite-derived AOT and PM2.5 surface concentrations (Koelemeijer et al. 2006). Therefore, this signifies that AOT is a good proxy for PM2.5 for this case.

Figure 7 displays the difference in wind speed between these two simulations. The change in wind speed for these two simulations varies on local scales. It becomes difficult to distinguish an exact pattern as areas where the wind speed in the aerosol model output is greater are seemingly intertwined with areas where the wind speed is greater without the presence of aerosols. The distribution of these positive and negative changes in wind speed implies that for this case the role of aerosols in the outcome of the meteorological simulation is minimal. This may be attributed to how aerosol distribution is more dependent on wind speed than wind speed is on aerosols; however, it is interesting to note how the difference is not uniform across this domain.

Figure 8 displays the difference in PBLH between the aerosols and the no aerosols simulations. Figure 9 is the 0600 UTC 7 September 2020 surface analysis from the National Weather Service’s Weather Prediction Center Surface Analysis Archive. The general pattern that can be observed is that in the region right ahead of the cold front the simulation with no aerosols had higher values for PBLH; however, behind the cold front, the values with the aerosols had
greater PBLH as well as further into the warm sector of the cyclone. At 0600 UTC, this pattern is unorganized and only noticeable along the tail of the convection in northeastern Illinois. In the following hour at 0700 UTC, the distinction between the areas where the output either PBLH is higher in the aerosols, or no aerosols simulation becomes clear. The gradient between changes in PBLH across central Michigan resembles the cold front spanning across the region seen in Figure 9. As the cold front and the convection propagates eastward across Michigan into 0800 UTC, the differences between the PBLHs for each simulation begin to weaken. Additionally, a greater span of the area appears to have the aerosol simulation having a higher value for boundary layer height. This pattern continues into 0900 UTC as the convection associated with this cyclone exits the KDTW region and weakens. The differences in PBLH between these two simulations echo the behavior of the cold front. The outcome presented can be interpreted to be somewhat surprising. Given the use of AOT as a proxy for PM2.5, the enhanced measurements of AOT that were observed to the west of KDTW would result in lower PBLH due to the existing negative correlation between the two variables; however, this relation was not observed as PBLH behaves exactly the opposite. An exact source for this relation would require additional simulations to be concluded which is supported by the highly variable nature of the correlations calculated for PBLH prior.
Conclusions

In this study, various methods were employed to investigate how variations in PM2.5 caused by wildfires can be related to a range of meteorological variables. A statistical analysis and numerical weather prediction simulations were conducted to varying degrees of success.

A. Statistical conclusions

The calculation of 132 different combinations of correlations resulted in a variety of outcomes based on a variety of parameters. Trends in correlations appear to be somewhat regional. KALB and KDTW from the Eastern Region showed relatively similar correlations between most variables when comparing either PM2.5 or lightning. This is not necessarily the same case for the Central U.S. and West Coast airports. While the Central Region airports, KBIS and KDEN, had variations between correlations for PM2.5 and the meteorological variables, the correlations remained relatively consistent for lightning and meteorological variables. The greatest inconsistencies can be seen between the west coast airports, KBIL and KRNO; however, unsurprising as convective events tend to be uncommon in this region.

If we switch perspective to a by-variable view, PBLH showed the most variation when correlating PM2.5 and the meteorological variables analyzed. It is well accepted in the field of atmospheric chemistry that PBLH is anticipated to have a negative correlation with PM2.5. The surprising result is how in the Western Region, closest to wildfires, the PBLH was first calculated to have a strong positive correlation between PM2.5 in the pre-wildfire season while this correlation became negligible during the wildfire season; thus, the resulting relation strays from the anticipated result. In regard to the other meteorological variables investigated, both CAPE and TCW did not display any consistent trends in correlation.

Lastly, examining correlations between lightning and the meteorological variables reveal correlations that behave in a different manner than discussed prior. Unlike with PM2.5, PBLH
only has an impact on West Coast airports; for the other regions, all but one correlation was negligible. For lightning correlations, CAPE has the strongest correlations, which is expected due to the role that energy plays in the production of lightning. For a storm to be convective and produce lightning, a great amount of energy must be present. Lastly, TCW still has a notable positive correlation for most cases that were calculated, however, this correlation is not as strong as that of CAPE.

B. Numerical model output

The incorporation of aerosols using the NASA GEOS model provided a unique insight into how sensitive numerical models and our atmosphere can be to aerosols. The difference between the normal output from the WRF model initialized off the HRRR and that which includes aerosols resulted in an interesting output shown in both Figures 7 and 8. Wind speed and PBLH were plotted due to their well-known influence on the transfer of aerosols through our atmosphere (Eun et al. 2020). Minimal definitive results can be extracted from Figure 7 of wind speed at the time of this event. Higher values of wind speed from both the simulation with and without aerosols are intertwined, making it difficult to draw conclusions. In contrast, the difference of PBLH height among the two simulations displays itself quite well. The difference in PBLH between the aerosols and no aerosols simulation appears to mimic the structure of the cold front passing through with this particular convective case. Behind the cold front, higher values for PBLH from the WRF simulation including aerosols from NASA GEOS can be observed. Immediately ahead of the cold front, the opposite can be observed as higher values for PBLH from the WRF simulation containing no aerosols are higher. A conclusive explanation for the behavior of the PBLH cannot be provided given the small sample size of these simulations. A further exploration of this relationship will be beneficial for the understanding of the connection between pure meteorology and atmospheric chemistry.
References

California Department of Forestry and Fire Protection (CAL FIRE), 2022: Top 20 Largest California Wildfires. [https://www.fire.ca.gov/media/4jandlhh/top20_acres.pdf.]


University at Albany, Department of Atmospheric and Environmental Sciences, 2022: Verification of Daily Thunderstorm Occurrence Using the National Lightning Detection Network (NLDN). [http://www.atmos.albany.edu/facstaff/kristen/tsclimo/tsclimo.html.]


Appendix A

Table 1: Correlation Coefficient Definitions

<table>
<thead>
<tr>
<th>r value</th>
<th>Relationship description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40 to 1.00</td>
<td>Strong positive</td>
</tr>
<tr>
<td>0.30 to 0.39</td>
<td>Moderate positive</td>
</tr>
<tr>
<td>0.20 to 0.29</td>
<td>Weak positive</td>
</tr>
<tr>
<td>-0.19 to 0.19</td>
<td>Negligible</td>
</tr>
<tr>
<td>-0.20 to -0.29</td>
<td>Weak negative</td>
</tr>
<tr>
<td>-0.30 to -0.39</td>
<td>Moderate negative</td>
</tr>
<tr>
<td>-0.40 to -1.00</td>
<td>Strong negative</td>
</tr>
</tbody>
</table>

Description of intervals used to classify relations calculated using the Pearson’s correlation coefficient.

Table 2: PM2.5 and Lightning Frequency Correlation

<table>
<thead>
<tr>
<th>Airport</th>
<th>Correlation between PM2.5 and Lightning Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALB</td>
<td>negligible</td>
</tr>
<tr>
<td>BIL</td>
<td>negligible</td>
</tr>
<tr>
<td>BIS</td>
<td>negligible</td>
</tr>
<tr>
<td>BNA</td>
<td>weak positive</td>
</tr>
<tr>
<td>CHS</td>
<td>negligible</td>
</tr>
<tr>
<td>DEN</td>
<td>moderate positive</td>
</tr>
<tr>
<td>DTW</td>
<td>strong negative</td>
</tr>
<tr>
<td>GSO</td>
<td>negligible</td>
</tr>
<tr>
<td>GTF</td>
<td>strong positive</td>
</tr>
<tr>
<td>IAH</td>
<td>negligible</td>
</tr>
<tr>
<td>MGM</td>
<td>negligible</td>
</tr>
<tr>
<td>MIA</td>
<td>weak positive</td>
</tr>
<tr>
<td>MSP</td>
<td>negligible</td>
</tr>
<tr>
<td>OKC</td>
<td>negligible</td>
</tr>
<tr>
<td>OMA</td>
<td>negligible</td>
</tr>
<tr>
<td>SLC</td>
<td>weak positive</td>
</tr>
<tr>
<td>SPI</td>
<td>negligible</td>
</tr>
<tr>
<td>TPA</td>
<td>negligible</td>
</tr>
<tr>
<td>TUS</td>
<td>weak positive</td>
</tr>
<tr>
<td>RNO</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Correlations between PM2.5 and lightning frequency for all airports considered based on airports used in Verification of Daily Thunderstorm Occurrence Using the National Lightning Detection Network.
Table 3: PM2.5 Correlation for Eastern Region

| Correlation between PM 2.5 and Meteorological Variables in Eastern Region |
|-----------------------------|-----------------------------|
|                            | ALB                        | DTW                       |
|                            | CAPE | BLH | TCW | CAPE | BLH | TCW | CAPE | BLH | TCW | CAPE | BLH | TCW |
| June                       | negligible | strong negative | weak positive | negligible | strong negative | negligible |
| July                       | moderate positive | strong negative | weak negative | negligible | negligible | negligible |
| August                     | strong negative | strong negative | negligible | weak positive | moderate negative | negligible |
| September                  | negligible | moderate negative | weak negative | negligible | moderate negative | weak negative |

Table 4: PM2.5 Correlation for Central Region

| Correlation between PM 2.5 and Meteorological Variables in Central Region |
|-----------------------------|-----------------------------|
|                            | BIS                        | DEN                       |
|                            | CAPE | BLH | TCW | CAPE | BLH | TCW | CAPE | BLH | TCW | CAPE | BLH | TCW |
| June                       | negligible | negligible | negligible | weak positive | negligible | negligible |
| July                       | negligible | negligible | negligible | weak positive | negligible | negligible |
| August                     | strong positive | negligible | strong positive | weak negative | negligible | weak negative |
| September                  | negligible | strong negative | negligible | weak positive | weak negative |

Calculated correlations between PM2.5 and the specified meteorological variables for the Eastern Region. These calculations were conducted for Albany International Airport (KALB) and Detroit Metropolitan Wayne County Airport (KDTW). The table above shows descriptive correlations while the table below shows the numerical values that were calculated for correlations.

Calculated correlations between PM2.5 and the specified meteorological variables for the central region. These calculations were conducted for Bismarck Airport (KBIS) and Denver International Airport (KDEN). The table above shows descriptive correlations while the table below shows the numerical values that were calculated for correlations.
### Table 5: PM2.5 Correlation for Western Region

<table>
<thead>
<tr>
<th></th>
<th>BIL</th>
<th>RNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPE</td>
<td>BLH</td>
<td>TCW</td>
</tr>
<tr>
<td>June</td>
<td>negligible</td>
<td>strong positive</td>
</tr>
<tr>
<td>July</td>
<td>weak positive</td>
<td>moderate negative</td>
</tr>
<tr>
<td>August</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>September</td>
<td>weak positive</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Calculated correlations between PM2.5 and the specified meteorological variables for the western region. These calculations were conducted for Billings–Logan International Airport (KBIL) and Reno–Tahoe International Airport (KRNO). The table above shows descriptive correlations while the table below shows the numerical values that were calculated for correlations.

### Table 6: Lightning Frequency Correlation for Eastern Region

<table>
<thead>
<tr>
<th></th>
<th>ALB</th>
<th>DTW</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPE</td>
<td>BLH</td>
<td>TCW</td>
</tr>
<tr>
<td>June</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>July</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>August</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>September</td>
<td>negligible</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Calculated correlations between lightning strike frequency and the specified meteorological variables for the eastern region. These calculations were conducted for Albany International Airport (KALB) and Detroit Metropolitan Wayne County Airport (KDTW). The table above shows descriptive correlations while the table below shows the numerical values that were calculated for correlations.
Table 7: Lightning Frequency Correlation for Central Region

| Correlation between Lightning Strikes and Meteorological Variables in Central Region |
|---------------------------------|----------------|----------------|----------------|
| BIS                             | DEN            |
| CAPE                            | BLH            | TCW            | CAPE | BLH | TCW |
| June strong positive            | negligible     | moderate positive | negligible | negligible | negligible |
| July moderate positive          | negligible     | moderate positive | negligible | negligible | weak positive |
| August strong positive          | negligible     | strong positive | moderate positive | negligible | weak positive |
| September                        | negligible     | moderate positive | weak positive |

Calculated correlations between lightning strike frequency and the specified meteorological variables for the central region. These calculations were conducted for Bismarck Airport (KBIS) and Denver International Airport (KDEN). The table above shows descriptive correlations while the table below shows the numerical values that were calculated for correlations.

Table 8: Lightning Frequency Correlation for Western Region

| Correlation between Lightning Strikes and Meteorological Variables in Western Region |
|---------------------------------|----------------|----------------|----------------|
| BIL                             | RNO            |
| CAPE                            | BLH            | TCW            | CAPE | BLH | TCW |
| June negligible weak negative   | weak positive  | strong positive | moderate positive | weak positive |
| July negligible negligible      | strong positive | weak negative  | weak positive |
| August weak positive weak negative | strong positive | negligible | strong positive |
| September                        |                 |

Calculated correlations between lightning strike frequency and the specified meteorological variables for the western region. These calculations were conducted for Billings–Logan International Airport (KBIL) and Reno–Tahoe International Airport (KRNO). The table above shows descriptive correlations while the table below shows the numerical values that were calculated for correlations.
Appendix B

Figure 1: Airports examined
Map of location of each of the six airports examined in this study. Airports are color coded based on region: yellow is representative of the Eastern Region, magenta is representative of the Central Region, and cyan is representative of the Western Region.
Figure 2: HYSPLIT trajectory for August Complex Fire

Output from NOAA HYSPLIT Forward Trajectory model for 1500 UTC 17 August 2020. The source for this trajectory is the source location of the August Complex Fire.
Figure 3: KALB timeseries

Time series of maximum boundary layer height (m) and scatter plot of PM2.5 (µg/m³) scaled by a factor of 100 for KALB for June 2020. The data is from the ERA-5 Reanalysis.
Figure 4: KDTW timeseries

Time series of maximum boundary layer height (m) and scatter plot of PM2.5 (µg/m³) scaled by a factor of 100 for KDTW for June 2020. The data is from the ERA-5 Reanalysis.
Figure 5: KRNO timeseries
Time series of maximum boundary layer height (m) and scatter plot of PM2.5 (µg/m³) scaled by a factor of 100 for KRNO for each month in the pre-wildfire and wildfire time frames. The data is from the ERA-5 Reanalysis.
Figure 6: NASA GEOS AOT 07 September 2020
Total Aerosol Extinction AOT [550nm] from the NASA GEOS model plotted for 07 September 2020. Location of the Detroit Metropolitan Wayne County Airport is plotted as the area of interest for this case.
Figure 7: Wind speed numerical model output
Plots of the difference in wind speed (m/s) from WRF simulation with aerosols and WRF simulation without aerosols.
Figure 8: PBLH numerical model output
Plots of the difference in boundary layer height (m) from WRF simulation with aerosols and WRF simulation without aerosols.
Figure 9: WPC surface analysis

0600 UTC 07 September 2020 surface analysis issued by NOAA’s Weather Prediction Center (WPC). This product is available at https://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.