Texas 2013 Air Pollution Interpolation and Clustering

Abstract: Air Quality around the world has been in decline since the advent of fossil fuels and the ability for these hydrocarbons to power countries and economies. This article examines the predicted spatial extent of several air pollutants in the southern United States. Only a few studies have been conducted on this matter regarding the location, economic importance and environmental impacts of oil production and refining, automobile usage, and the urban heat island effect on Ozone creation in the southern states of the USA. Three statistical analysis methods (IDW Interpolation, Kriging, and Cluster Analysis) were conducted on the annual pollution data of 2013 from the United States Environmental Protection Agency regarding ground level ozone, Particulate Matter 2.5, and Nitrogen Dioxide in areas around the five states. The results indicate a prediction of $PM_{2.5}$ as high as 0.05683 PPM in areas specializing in oil refining activities as well as ozone readings of 9.879 micrograms in arid climate areas like New Mexico and urban cities. Results also interpolate a similar Nitrogen Dioxide reading across the 5 states at a level of 14.45 - 17.63 PPB or a logged value of 2.558-2.777 PPB from the Kriging interpolation.

Keywords: Particulate Matter 2.5; Ozone; Nitrogen Dioxide

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1. Introduction

Air pollution is a serious problem that has affected the world over. In America, this exact situation of air pollution is getting worse every year [1]. The cause of air pollution is due to the human footprints that results in contaminative particles entering the atmosphere and many of these particles are harmful to living organisms on Earth. In this project, the focusing study areas are 5 of the southern states in the United States which are Texas, Arkansas, Louisiana, Oklahoma, and New Mexico. Texas has the highest population among these states. According to the statistics of the census, the population share of the southern states was around 37.5% in 2013 and 38.3% in 2019 [2]. Texas had around 26 million people in 2013 and around 28 million in 2017 [3]. These numbers can show that the increase in population growth is happening every year. In research, the increase of the population could affect the overall quality of the atmosphere. More people mean more urban life which would increase the emission of greenhouse gases and particles [4]. Further, regarding economic activities, Texas, Louisiana, and Oklahoma are the 3 of the top five states that produce natural gases. Among the states, Texas accounted for 23.9% of natural gas production in 2019 which is the most [5]. In Louisiana, other than producing natural gas, they are reserving and producing crude oil [6]. The more natural gas and oil a state or region produced the greater the pollution released into the atmosphere, due to the inherently polluting way of refining these products. Moreover, more air pollutants are created by using the oil as fuel for vehicles, natural gases for home heating, etc. [7]. The process of consumption and production creates a lot of harmful particles and greenhouse gases which is affecting the overall air quality. It is very important to understand the situation of the environment, and air quality because it can have a huge impact on human health. This research project aims to understand the pollution pattern in Texas and the 4 bordering states by analyzing the pollution data from the United States Environmental Protection Agency. Along with the topic of overall air pollution, this project is going to conduct the interpolation and clustering of the annual average of 3 pollutants of interest, nitrogen dioxide, ozone, and $PM_{2.5}$ in the study area (Texas and 4 contiguous states).

2. Methods

2.1 Study Area

The study for this publication is focusing on 5 states from the United States of America (Arkansas, Texas, Louisiana, Oklahoma, and New Mexico). Texas is the major state of interest and the others are the bordering states. Texas is the second-largest state in the United States. The area size is around 268,580 square miles [8]. The overall population of these states is around 43 million [9]. These states are in the southern region of America. The climate of the states in the study region is diverse. The western areas of the region are dry while the land close to the coast (east) is subtropical (eastern Texas and Louisiana) [10]. Moreover, the geography of the states is also diverse; there is higher elevation and mountainous terrain in the eastern portion (New Mexico and eastern Texas) while the land gradually becomes flatter and closer to sea level westward (Arkansas, western Texas, Louisiana, and Oklahoma). The reasons that the states are chosen are due to the fact that they have first order continuity to the major state of interest Texas and the similarities they have in terms of economies. All the states have a high production of natural gas, oil and a high population which contributed a significant amount to air pollutants [5-7]. Hence, understanding patterns of pollutants is critical; there are potentially 43 million of people who may be impacted by it.

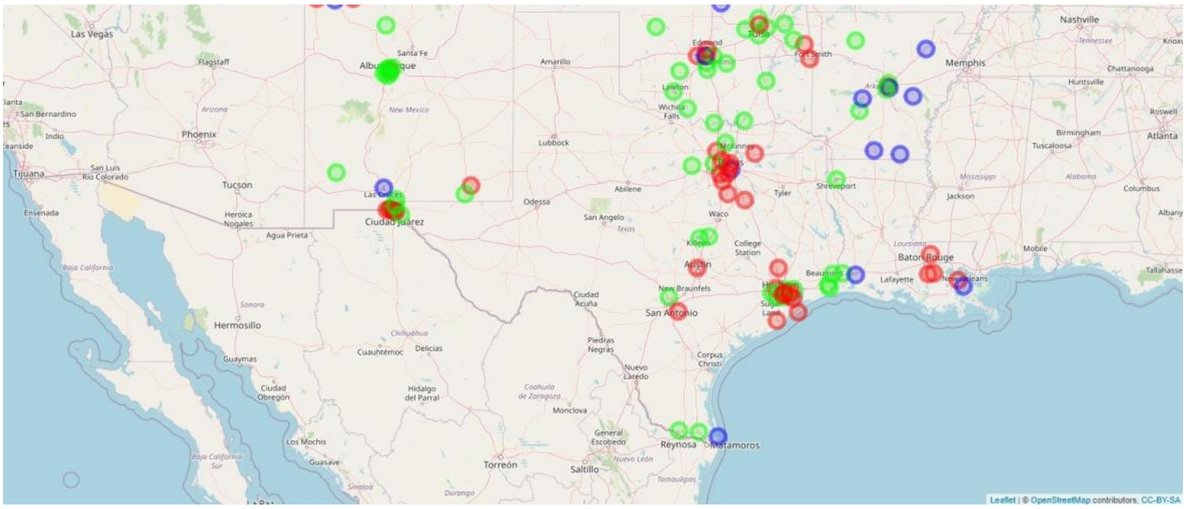

Figure 1. Pollutant Observation Sensors in Study Area.

2.2 Data

Table 1. Number of Sensors per Pollutant.

Pollutant	Monitors
Particulate Matter 2.5	48

Ozone	102
Nitrogen Dioxide NO_2	53

The data that was used to conduct this study was acquired from the United States Environmental Protection Agency and it consists of readings from observation stations around the USA that capture levels of a specific type of air pollutants present. As this study is looking at 3 types of air pollutants: Particulate Matter 2.5, Ground Level Ozone (O3) and Nitrogen Dioxide, there are three types of monitors spread out across the 5 states being surveyed in this study. In addition, due to the specificity of observation stations, there are varying numbers of monitors for each type of pollutant and some monitors are spatially dispersed or concentrated in comparison with others of the same type. Although some of the areas in Figure 1 appear to have a lack of observations regarding one type of pollutant, there are some sensors that do not appear on the plot that do remotely sense pollution (e.g., Figure 1 shows a lack of NO_2 observation stations in Arkansas, however there is data present in the data frame regarding the pollutant in the area during the interpolations).

2.3 Statistical Analysis

2.3.1 Data Wrangling

1. Acquire Data from EPA website. The data files concerning this study period are the 2013 annual summary datasets.
2. Edit the dataset files so there are no spaces in column names using the built-in "replace" function in Excel.
3. Filter by state code for data relating to the five contiguous states, stemming from the state of Texas in R.
4. Filter data by pollutant type Ozone, $PM_{2.5}$ and NO_2.
5. Remove duplicated locations (this will help later with Kriging) and if applicable remove any rows with NA data from the column ArithmeticMean (the variable we use for the study). ArithmeticMean was chosen because it represents the annual pollution average which is what we want to study.
6. Visualize the point dataset using leaflet and the EPA dataset.
7. Filter the dataset for the appropriate individual pollutant (setting up for interpolation and clustering).

2.3.2 IDW Interpolation

1. Transform Filtered EPA Dataset into a SpatialPointsDataFrame (SPDF).
2. Build a polygon using the outer points of the dataset. Build a raster grid and then impose the previously created polygon on the grid to make a grid shaped as the polygon.
3. Perform LOOCV cross validation on the ArithmeticMean from the EPA dataset. Construct 3 tests using 3 different exponents (1, 2 and 3).
4. Determine the Root Mean Squared Error of each of the 3 LOOCV models. Choose the model with the lowest output value and use the corresponding exponent for the final IDW model.
5. Construct an IDW interpolation model using the identified exponent value and the Arithmetic mean from that filtered EPA dataset.
6. Plot the predicted values resulting from the IDW dataset using spplot.

2.3.3 Kriging

1. Construct a SpatialPointsDataFrame (SPDF) using the filtered EPA dataset using latitude and longitude.
2. Test the data by checking if it is normally distributed and if there is Stationarity to ensure the assumptions for Kriging are met.
    a. Check if the raw data is normally distributed.
    b. If the raw data is not normally distributed run a log transformation on the variable.
    c. Check the logged data to ensure the transformed data is normally distributed.
    d. Verify Stationarity by calculating the mean/variance for the points and then plotting it using spplot. Manually check the visualization/plot to ensure assumption is not broken.
3. Build an empirical variogram.
    a. Build a variogram/plot the data of interest and examine the result graph/chart to understand the general shape of the data.
    b. Look at the various Variograms available and then choose/fit a suitable model that matches the general shape of the data of interest (plotted earlier in step a).
    c. Build a polygon using the outer points of the dataset. Build a vector grid and then impose the polygon on the grid to make a grid shaped as a polygon that contains values from the original EPA dataset.
    d. Create a Kriging model using the ArithmeticMean (variable used for the model due to it representing the annual pollution average), EPA dataset (as a SPDF) and the polygon grid.
4. Plot the Kriging dataset using spplot.
5. Run LOOCV on the Kriging model to cross validate.
6. Perform a root mean squared error test on the cross-validation residuals to further verify the model.

2.3.4 Clustering

1. Remove any duplicated locations or any rows in ArithmeticMean that contain NA values.
2. Construct a SpatialPolygonsDataFrame with the refined EPA dataset.
3. Construct Voronoi polygons to enable running a contiguity-based skater algorithm.
4. Convert the Voronoi dataset into a format suitable to run the skater algorithm using poly2nb, nbcosts, nb2listw and mstree.
5. Run the skater algorithm using the formatted Voronoi polygons and the ArithmeticMean.
6. Plot the output results from the skater algorithm using spplot.

3. Results

3.1 Descriptive Statistics

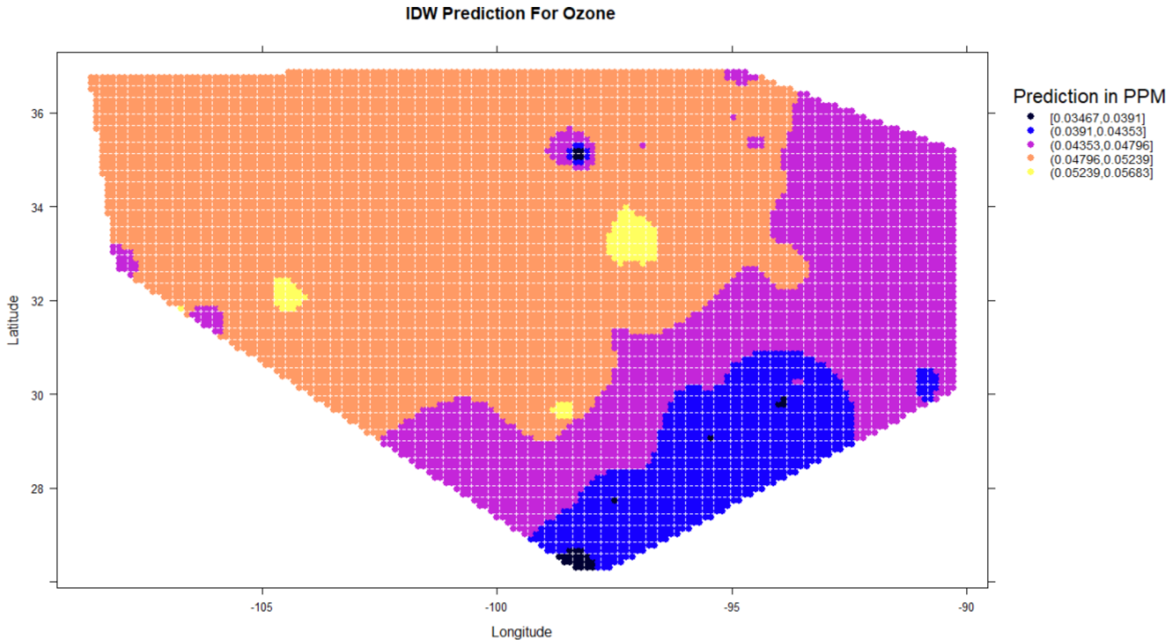

Figure 2. IDW Interpolation for Ozone.

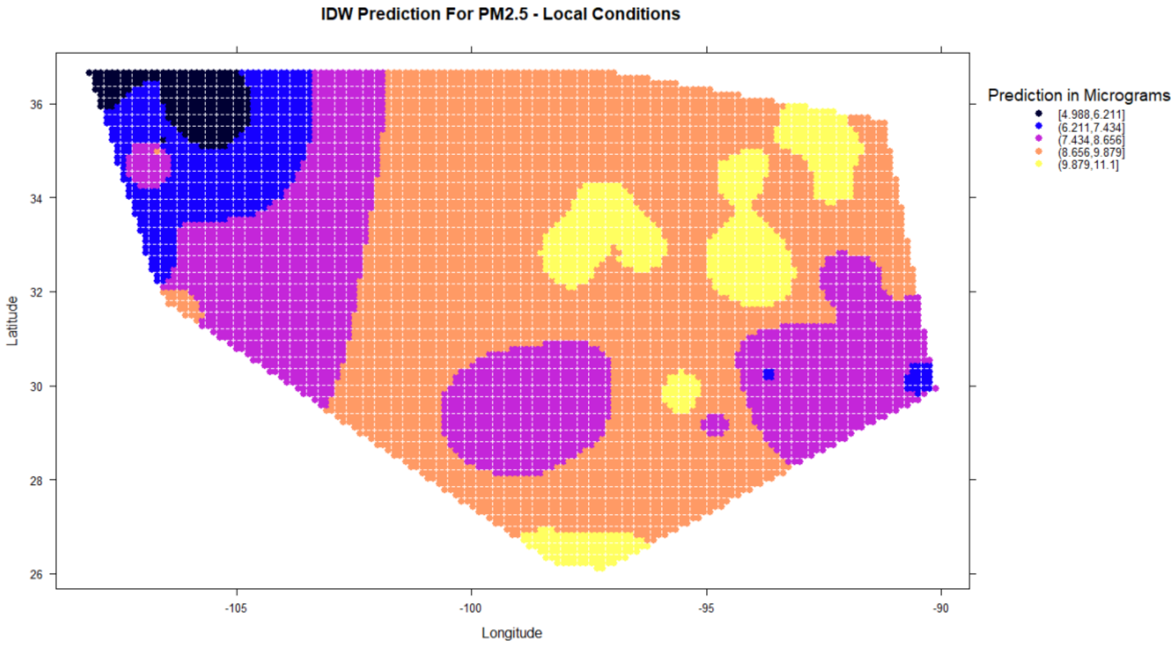

Figure 3. IDW Interpolation for $PM_{2.5}$.

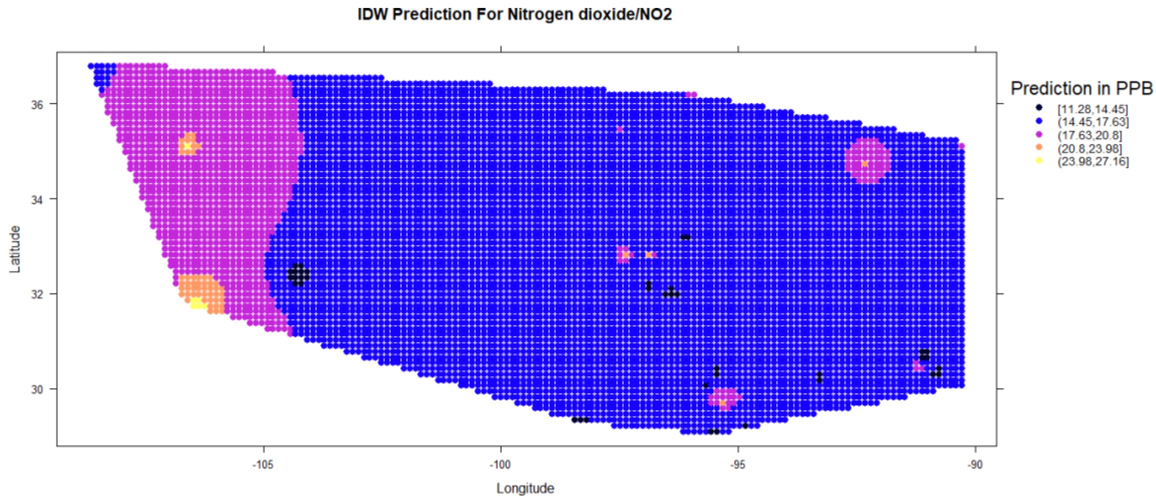

Figure 4. IDW Interpolation for Nitrogen Dioxide.

3.1.2 Kriging Results

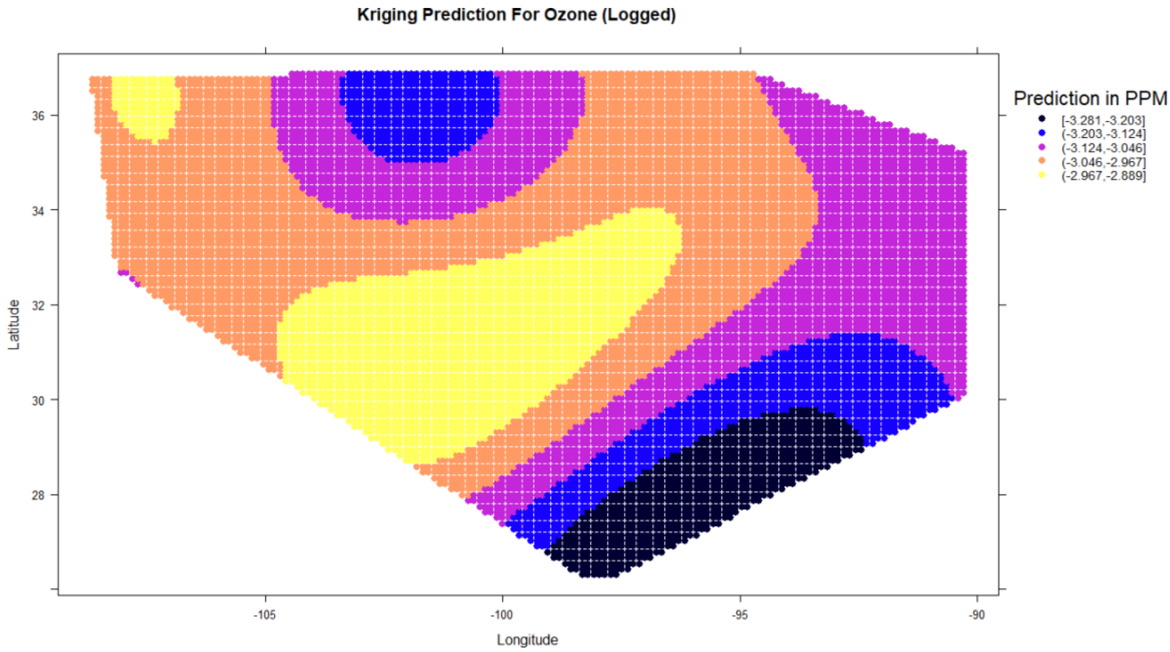

Figure 5. Logged Kriging Prediction – Ozone.

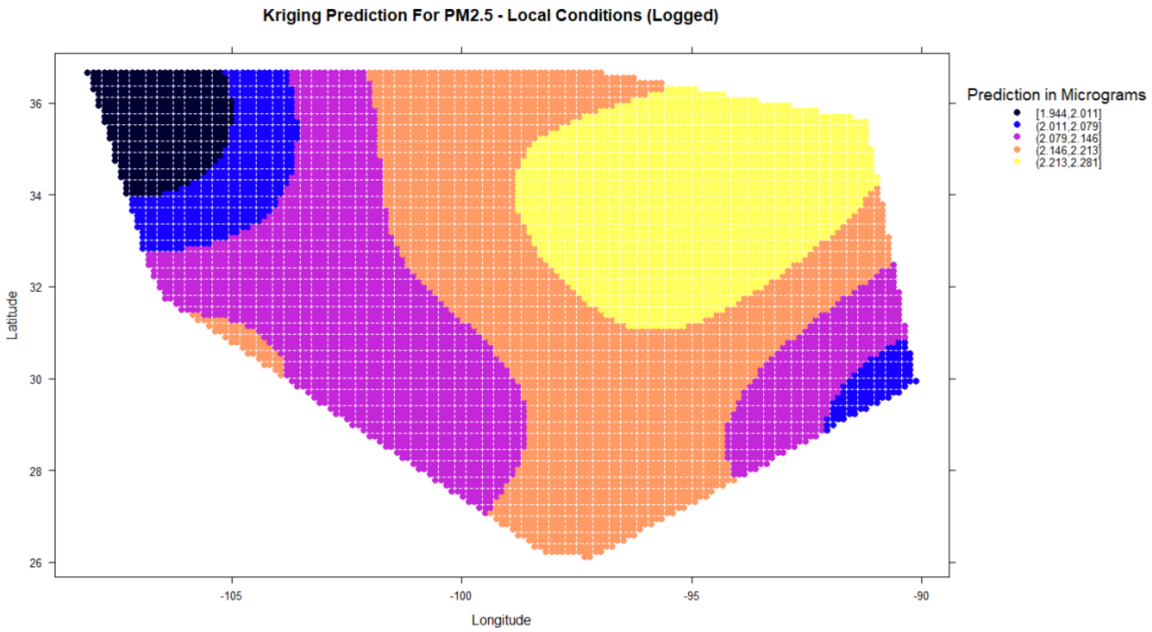

Figure 6. Logged Kriging Prediction – $PM_{2.5}$.

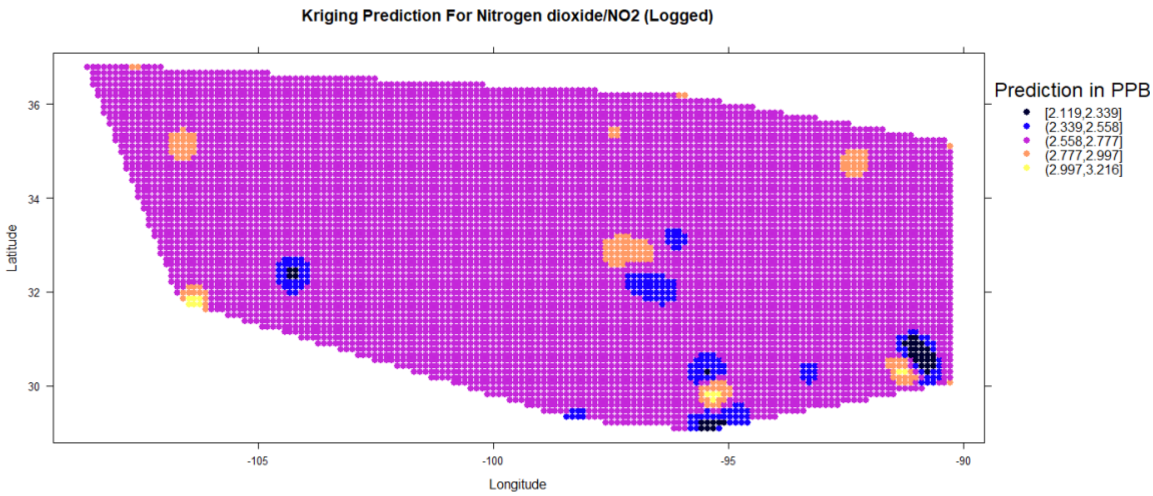

Figure 7. Logged Kriging Prediction – Nitrogen Dioxide.

3.1.3 Clustering Analysis Results

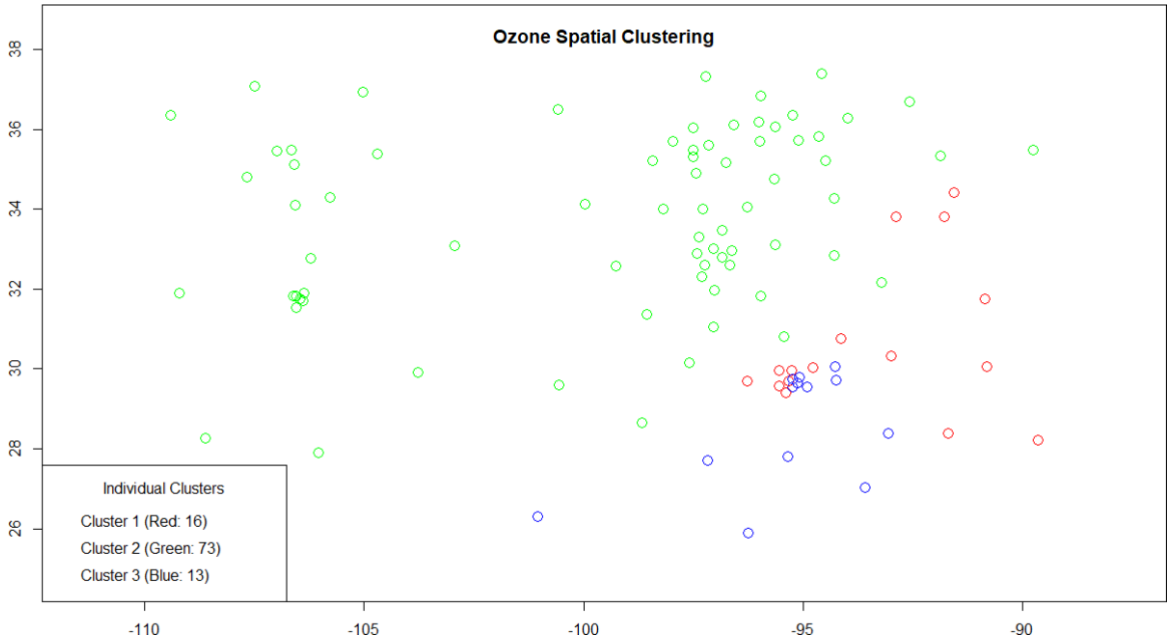

Figure 8. Clustering Analysis – Ozone.

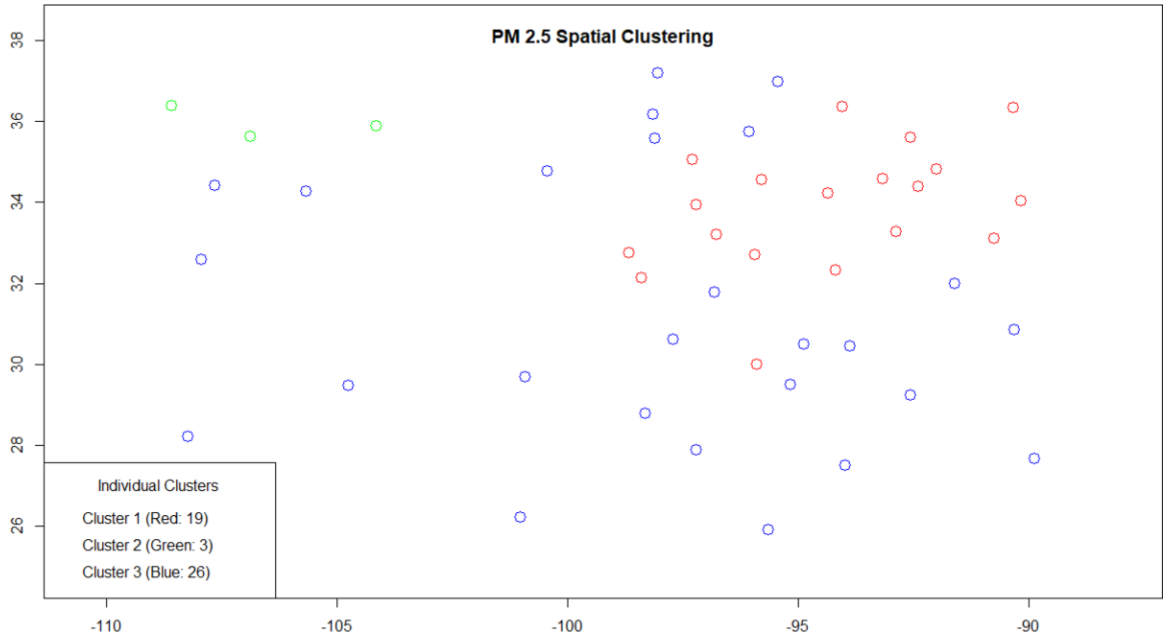

Figure 9. Clustering Analysis – $PM_{2.5}$.

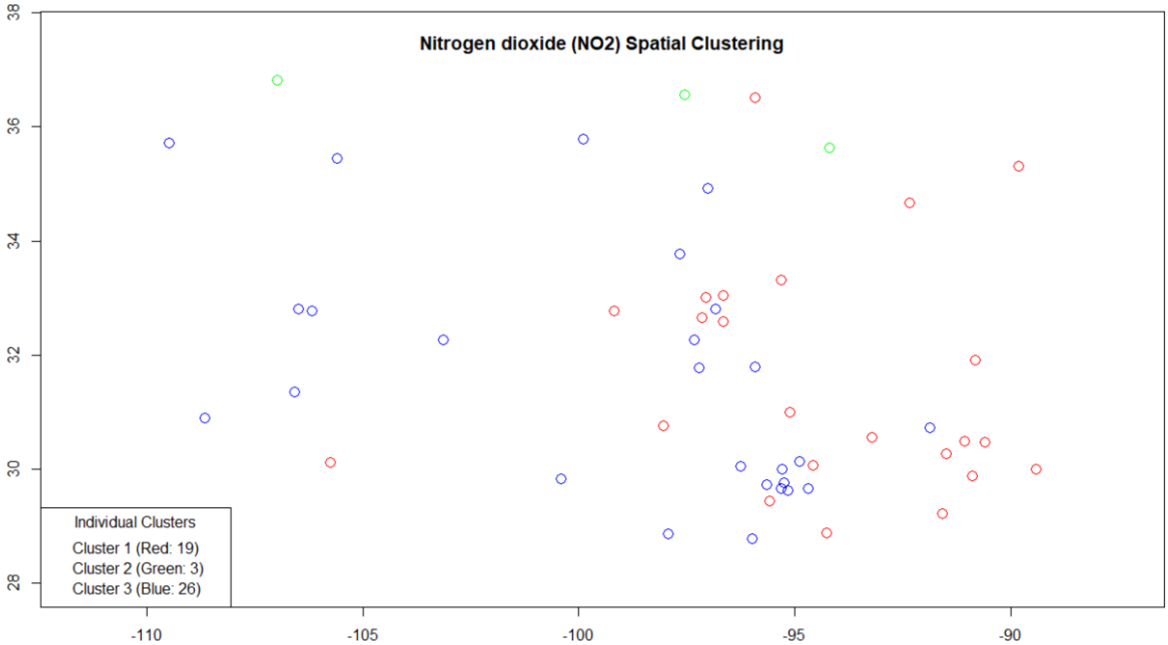

Figure 10. Clustering Analysis – Nitrogen Dioxide.

3.2 IDW Interpolation Results

Table 2. Maximum Values for Pollutant Type (IDW) in corresponding state alongside refining capacity.

State	IDW Maximum $PM_{2.5}$ in Micrograms	IDW Maximum Ozone in PPM	IDW Maximum Nitrogen Dioxide in PPB	Largest Refinery Capacity (Oil)
Texas	9.879 - 11.1	0.05239 - 0.05683	20.8 - 23.98	250 + [11]
Oklahoma	9.879 - 11.1	0.04796 - 0.05239	17.63 - 20.8	110 - 250 [11]
Louisiana	7.434 - 8.656	0.04353 - 0.04796	17.63 - 20.8	110 - 250 [11]
Arkansas	9.879 - 11.1	0.04353 - 0.04796	20.8 - 23.98	110 - 250 [11]
New Mexico	8.656 - 9.879	0.04796 - 0.05239	23.96 - 27.16	50 - 110 [11]

Ozone (Figure 2):

The results of the interpolation on the Ozone levels are the further the distance is from New Mexico and Texas the less ozone pollution there is. The reason for this is the arid and sunny climate of the desert biome featured in the states of Texas and New Mexico where ozone readings are predicted to be around 0.04796 - 0.05239 PPM, and even feature levels as high as 0.05239 - 0.05683 PPM. Ground level ozone is produced at a faster rate in these climate conditions in comparison to humid areas where the increased moisture levels would act as a restriction on ozone production [13]. Therefore, the predicted ground level ozone values are shown to be lower in southern Texas and Louisiana ranging from 0.04353 - 0.04796 PPM due to the proximity of these areas to the coast and the presence of wetland areas in south-eastern USA. Hence, a more arid state sees an increase in ozone pollution which can be observed in Table 2.

Particulate Matter 2.5 (Figure 3):

The results from the interpolation predict a spatial distribution of $PM_{2.5}$ whereby higher concentrations of the particulate matter would be seen in certain areas (cities) across the 5 states. The IDW interpolation is more precise compared to Kriging and as a result it highlighted certain cities that have elevated $PM_{2.5}$ pollution levels. The cities highlighted with the highest values (9.879 - 11.1 micrograms) are Dallas Texas, Houston Texas, McAllen Texas, Texarkana Texas, and Little Rock/El Dorado Arkansas. Further Texas, Oklahoma and Arkansas are the states with the highest PM pollution levels overall (8.656 - 9.879 micrograms). The common thing the most polluted cities have is the large population, rising above 1 million. As a result, increased car activity (gas and diesel) from the large population would contribute to the predicted high levels of $PM_{2.5}$ [14]. These areas are also located near oil fields and their respective refineries which contributes to the pollution seen in the local clusters of $PM_{2.5}$ [11]

Nitrogen Dioxide (NO_2) (Figure 4):

It is predicted that NO_2 levels are generally the same across the states, however, NO_2 hotspots are to be predicted in urban areas, with both Houston Texas, El Paso Texas and Albuquerque New Mexico having the highest concentration (2.997 - 3.216 PPB). The specific cities with second highest concentration (2.777 - 2.997 PPB) are Dallas, New Orleans, and Tulsa. Once again, the common element these cities all share is, they have a large population and are involved in oil/energy production. Each of these cities have 1 or more refineries either within the city or in surrounding areas [11]. Refining oil leads to NO_2 output into the air as pollution and all the cities mentioned are large hence, they have a large car population which further contributed to the pollution [15]. Finally, the cities mentioned with the most pollution also contain natural gas production/refineries [12] and the production of this gas leads to more NO_2 pollution [16], further explaining why these cities/regions have the highest pollution levels.

3.3 Kriging Results

Ozone (Figure 5):

Deserts are known to increase ozone pollution and the Kriging results highlight the driest regions that contain the most ozone levels within the selected 5 states (mostly located in the westernmost areas). What makes Kriging different from IDW in this case is the deserts/areas that are hot/arid are highlighted distinctly (separate from the other zones in the study area). This once again makes sense because these areas are extremely hot and dry and are prone to higher ozone production/levels [13]. The Chihuahuan desert (In Texas and New Mexico) and the Colorado Plateau (another desert in New Mexico) are highlighted by the Kriging map along with their surrounding areas for increased ozone levels which is as expected due to the hot and sunny conditions.

Particulate Matter 2.5 (Figure 6):

The major source of $PM_{2.5}$ is generally considered to be gas/diesel engines [14] and it is also known to be an unwanted pollutant from the processing of crude oil [11]. This makes sense because the region with the highest $PM_{2.5}$ pollution based on the Kriging results is Arkansas, northeastern portions of Texas and Oklahoma. The Kriging results unlike IDW do not pinpoint individual cities but highlights large areas in this instance. The result makes sense because cities/areas that contain a lot of refineries [11]and people [17] are highlighted to have the highest $PM_{2.5}$ pollution.

Table 3. Most impacted cities based on Kriging predictions for Nitrogen Dioxide (measured in PPB) and their corresponding hydrocarbon refining capacities.

City	State	Capacity of Oil Refineries (Barrels Per Day)	Capacity of Natural Gas Facilities Close to or in the City Measured in Million Ft^2 Per Day	Peak Nitrogen Dioxide Prediction in PPB (Logged)
Houston	Texas	250 + [11]	1050 [12]	2.997-3.216
El Paso	Texas	110 - 250 [11]	210 [12]	2.997-3.216
Albuquerque	New Mexico	Under 50 [11]	1050 [12]	2.777-2.997
Dallas	Texas	50 - 110 [11]	1050 [12]	2.777-2.997
New Orleans	Louisiana	250 + [11]	2100 [12]	2.997-3.216
Tulsa	Oklahoma	50 - 110 [11]	210 [12]	2.777-2.997
Average for Kriging Prediction	All 5 in Study	N/A	N/A	2.558-2.777

Nitrogen Dioxide (NO_2) (Figure 7):

Nitrogen Dioxide (NO_2) is primarily emitted by cars, trucks, and oil production. The highest concentrations are found in areas that feature a high population or regions with natural gas or oil refining. The Kriging map in this case highlighted the same cities as the IDW interpolation and emphasized them a lot more. This once again makes sense because these cities Houston (Texas), Little Rock (Arkansas), El Paso (Texas), Albuquerque (New Mexico), Dallas (Texas), New Orleans (Louisiana) and Tulsa (Oklahoma) have a high concentration of refineries (for oil and gas) [11]. Further looking at Table 3 the higher the oil/gas production in a city/region the greater the NO_2 pollution predicted values. These cities/regions also have large populations leading to more cars further increasing the NO_2 pollution in these areas.

3.4 Clustering Results

Ozone (Figure 8):

Bearing similarity to the IDW Interpolation and Kriging predictions, the dispersion of Ozone shown in the clustering analysis is based on the proximity of the location in relation to desert climates. The green cluster contains 73 locations and is limited to areas/regions that have a hot climate (New Mexico, Texas, and Oklahoma) which makes sense as this climate is conducive to ozone production. Moreover, the red cluster (16 locations) is in a more humid region and contains states like Louisiana and eastern regions of Texas. This makes sense due to the different climate in the area. Finally, the blue cluster (13 locations) covers most of Houston and the southernmost regions of Texas which makes sense due to the large oil industry in this area (mostly Houston) coupled with the large population found there as well.

Particulate Matter 2.5 (Figure 9):

The spatial distribution shown in Figure 9 is due to the location of cities and oil production across the study areas. The bottom and topmost areas of the study area feature their own cluster (blue) with 26 locations, this region has a low population and lower economic activity (encompasses most of the study area). Regarding the green cluster (3 locations) located in the top left of the study area in New Mexico; this is an area that features very low economic activity and population due to the harsh hot desert climate seen in the state hence, it has its own cluster. Finally, the red cluster has 19 locations and is centered around major economic (mainly oil production) and high population areas like north-east Texas, south-east Oklahoma, and southern Arkansas.

Nitrogen Dioxide (NO_2) (Figure 10):

Concerning the clustering of Nitrogen Dioxide in the area, multiple hotspots are once again centered on large urban areas or industrial regions like Dallas and Houston Texas (in red) forming a cluster with 19 locations. Tied together with the results from the Kriging and IDW interpolation, we can say that there is a low and somewhat consistent level of NO_2 seen across the study area (in blue) forming another cluster with 26 locations. There also is an insignificant cluster that only has 3 locations tied to it (in green). This cluster is located at the very top of the study area and contains very little economic activities or people in general.

4. Discussion

The results indicate that high $PM_{2.5}$ concentrations are predicted to be in urban areas and the immediate surroundings than in rural areas. This is due to high $PM_{2.5}$ concentrations that occur due to the large amounts of cars and trucks found in cities [18] (p.910). Furthermore, previous research done on $PM_{2.5}$ levels has also predicted heavy amounts of pollution ($PM_{2.5}$) caused by the urban heat island effect in cities [19]. Alongside $PM_{2.5}$, Nitrogen Dioxide is also created through the burning of fossil fuels and the refining of crude and shale oil [20] (p.1). Areas of high NO_2 readings are predicted to be found in urban areas as well, given the large number of automobiles. However, with the similarly low levels of NO_2 being seen across the study area, we can only assume that there is no substantial issue regarding the presence of NO_2 in the overall study area, hence showing that high NO_2 levels would only be seen in areas featuring very high automotive activity coupled with oil/gas production (usually large cities) and this is reflected in the IDW and Kriging results as hotspots are exclusively located in or near cities. Regarding the various levels of ground ozone pollution across the study area, it can be said that higher levels of ozone will be present in areas featuring higher elevations that are greater distances from oceans [21] (p.255). In addition, as mentioned above, ozone is produced at a much faster rate in arid climate conditions, where the near absence of moisture prevents the breaking down of ozone [13] hence, the arid and dry climates in the deserts and surrounding areas located in Texas and New Mexico acts as a medium for ozone production/retention in comparison to the coastal, humid areas in the study region, which is reflected in the IDW and Kriging results showing elevated ozone pollution inland (near deserts) with reduced levels seen closer to the coast.

5. Conclusions

The prediction and cluster models conducted in this study shows both the general locations of polluting activities as well as pollutant hotspots in the southern USA. This paper has also suggested how various conditions and activities combine to actively produce such pollution given the landscapes and economy of this region in the United States. Measures should be taken to protect the population of these states from contracting lifelong respiratory illnesses that are caused by poorer air quality predominantly seen in cities and inland regions that are hot/arid.

Author Contributions: Sajeeth Wimalasuriyan and Parmvir Grewal implemented the code for IDW interpolation, Kriging interpolation, Clustering and generated the various graphs, visualizations and tables seen in the study (primarily in 3.1 Descriptive Statistics). Further, Sajeeth Wimalasuriyan and Parmvir Grewal helped to edit and format the documentation. Moreover, Sajeeth Wimalasuriyan and Parmvir Grewal helped to write out the 2.3.1 IDW, 2.3.2 Kriging, 2.3.3 Clustering and co-wrote results for 3.1 Descriptive Statistics, 3.2 IDW, 3.3 Kriging, and 3.4 Clustering. Additionally, Edward Ang led the analysis on 3.2 IDW Interpolation, 3.4 Clustering Analysis and 4.0 Discussion. Edward Ang also co-wrote results for 3.1 Descriptive Statistics, 3.3 Kriging, 5.0 Conclusions and provided literature review throughout the paper. Lastly, Christy wrote the introduction, 2.1 study area, and formatted the citations.

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Appendix A

Available as Appendix_A.pdf