Using MODIS Satellite Imagery to Estimate
Particulate Matter (PM$_{2.5}$)

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Abstract

With air pollution increasingly becoming one of the most deadly environmental issues worldwide, this study looks to observe a specific type of air pollution called particulate matter (PM$_{2.5}$). PM$_{2.5}$ consists of inhalable particles, less than 2.5 microns or 0.0025 millimeters in size and is a leading environmental cause for cardiovascular diseases and mortality. Since many places in the world, especially in developing countries that are rapidly industrializing and urbanizing, do not have adequate access to PM$_{2.5}$ ground monitors, or even normal weather stations to directly observe and measure high concentration rates, this study strives to determine how accurately particulate matter can be estimated using only readily available Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery that has global coverage since 1999 at 1-2 day intervals. To validate the accuracy, the MODIS data was compared with ground monitor stations across the contiguous United States. Correlation trends were observed temporally (period of time), seasonally, and latitudinally. While results did not show significant evidence of any temporal trends, there were significant seasonal patterns with highest correlations in the summer, followed closely by the fall. The model also showed that higher latitudes tend to produce higher correlations, but generate less satellite data, especially during the winter months. Although satellite imagery passover cannot solely estimate particulate matter, using the trends observed in this study along with meteorological variables and land use could prove to be useful in countries without ground monitors.

Introduction

Air quality issues throughout the world have continued to increase drastically over the last few decades as cities experience greater industrial waste and automobile usage. One of the most harmful air pollutants for the environment is particulate matter 2.5, which is produced by many different types of gases and liquid particles but is less than 2.5 microns in size. These particulates have been shown to reduce visibility in high concentrations and are heavily correlated with cardiopulmonary (heart and lungs) problems and even mortality. In order to control this harmful pollutant, countries such as the United States have set up an extensive network of ground monitor stations to observe and measure local concentrations. In this study, the Environmental Protection
Agency’s (EPA) ground monitor data is used for the contiguous United States, along with MODIS satellite imagery data, in order to investigate the possibility and accuracy of using remotely sensed imagery to estimate these deadly PM$_{2.5}$ particles. This is most valuable in countries which do not currently have adequate access to direct ground monitor data due to absence or lack of ground stations.

**Problem Statement**

Currently, particulate matter levels are extremely high in many countries across the world. Some of the most extreme cases include Saudi Arabia, Egypt and Qatar, which all reach up to 100 μg/m$^3$ in particulate matter concentration, whereas the United States, which monitors and controls PM$_{2.5}$, set its standards at a maximum of 15 μg/m$^3$ (EPA 2018). Some cities have gotten so polluted that their Air Quality Standard has shown that the air is hazardous. Studies have shown that many developing countries have not been attempting to control their air quality and are harming their surrounding environment and the people in them. Ground monitor sensors for observing particulate matter are sparsely distributed in developing countries as well, so being able to use remote sensing imagery data to monitor air quality may prove valuable for finding the hotspots of high pollution and controlling these concentrations to help lower death rates and adverse health effects. If recent trends continue, cities will experience hazardous health side effects that may last generations if they are not controlled soon.

**Literature Review**

**Particulate Matter 2.5 and Air Pollution**

Particulate matter refers to the mixture of harmful solid and liquid particles that can be found within the air. These particles contribute towards a large portion of the
Earth’s overall air pollution and are derived from hundreds of different chemicals. The most dangerous particulate matter is less than 2.5 micrometers in size, or four hundred times smaller than the length of a millimeter (EPA 2018). A particle of that size may seem harmless, but it can actually cause serious negative effects on the human body and the surrounding environment. Studies have shown that particulate matter is strongly correlated to asthma, lung cancer, heart disease and mortality (Pope et al. 2002). In 2012 alone, air pollution, including particulate matter, contributed to over 3.7 million deaths worldwide (Chu et al. 2016).

When these particles are high in concentration, they often produce haze and cause reduced visibility in the lower atmosphere (EPA 2018). The human need to control particulate matter stems from widespread economic development and urbanization (Chen et al. 2018). Some of the particles come from natural sources such as forest fires, volcanic eruptions and dust storms, but a large majority of air pollution can be controlled and avoided in the future (Huang and Kuo 2018). In the United States, the EPA has set up ground monitors all across the country in order to observe trends and to control the total concentration of air pollutants within a specific area. EPA
provides yearly, daily, and even hourly PM$_{2.5}$ data to the public, which have been utilized over the years to create models for predicting high concentrations of air pollution nationwide (Lui et al. 2007).

In 2014, China’s Ministry of Environmental Protection concluded that of the seventy-four cities they monitored for particulate matter, only eight met their healthy annual concentration standards of 35 ug/m$^3$ (Chen et al. 2018). Even though the Chinese government has set up ground monitors, there has still been a nationwide problem in controlling particulate matter (Huang and Kuo 2018). If trends continue in this direction, more people will have cardiopulmonary problems (relating to heart and lungs). Many developed and underdeveloped countries that have even higher PM$_{2.5}$ concentration compared to China still do not have any way to monitor and control their air pollution (Yanosky et al. 2009). Although ground monitors may be helpful if a country is wealthy enough to afford hundreds of monitoring stations, outside of a one hundred-kilometer (62.13 miles) radius, PM$_{2.5}$ data becomes unreliable. (Lee et al. 2012).

Because of this, it is important to rely on other resources such as satellite imagery and remote sensing to make predictions (Xue et al. 2019). Results from 1436 records of predicting concentration data from 116 different articles have shown that using the MODIS and Multi-angle Imaging Spectroradiometer (MISR) instruments on NASA’s Terra Satellite provide the most conclusive data (Chu et al. 2016).
Satellite Imagery - MODIS & MISR

The MODIS satellite instrument was created for various land and ocean applications. It has a variety of distinct features that make it useful for measuring particulate matter, including its one to two day temporal resolution as well as its 36-band spectral resolution (the number of bands which can reflect light at different wavelengths) (Lillesand et al. 2004). This high spectral resolution uses 12-bit radiometric sensitivity which allows for 4096 different shades of colors that can help locate miniscule changes between pixels. These spectral bands play a major role for retrieving aerosol thickness accurately with detailed particle sizes. Seven of the bands are used for aerosol characteristics, while additional wavelengths are used for identifying potential data skewing factors such as cloud cover (Remer et al. 2005). On the other hand, some aerosol concentration data studies have only used MODIS’ blue, red and shortwave infrared bands to calculate aerosol concentration (Lui et al. 2007). MODIS also has a spatial resolution from 250 meters to one kilometer and a 2330 kilometer wide swath (width that a sensor can observe) to give scientists access to geospatial data over large areas of land (Lillesand et al. 2004).
Although the MISR can be found on the same satellite as MODIS, this instrument is very unique because of its nine unique sensors which observe the Earth at all different angles (0° and forward/backward angles of 26.1°, 45.6°, 60°, 70.5°). To keep consistency, all of the sensors have the same spectral resolution with four bands: visible red, green, and blue lights, and near infrared imagery. These different angles make it possible to locate haze and other pollutants that are invisible to see from a zero-degree satellite image. Although all of the sensors are valuable for different purposes, the 45.6° angle sensor has proven to have conclusive results for particulate matter data (Lillesand et al. 2004). MISR’s sensors use top-of-atmosphere and surface reflection signals from these sensors to identify this aerosol concentration data (Lui et al. 2007).

The MISR instrument also has a swath of 360 kilometers and a spatial resolution of 250-275 meters (Lillesand et al. 2004). Because of its smaller swath compared to MODIS, repeat coverage over a specific area can take place between two and nine days depending on a location’s latitude. MISR data is also impacted by the different seasons as well as weather conditions. Because of this, predictions in PM$_{2.5}$ concentration data have often been recorded to be significantly higher in summer compared to the winter (Liu 2004). In order to create a strong model with high predictability, researchers have to take these types of variables into account.

Aerosol optical depth (AOD), which is a measure of aerosols within a column of air in the atmosphere, was used to compare the two spectroradiometers using the same regression models in St. Louis. The biggest takeaways from the results were that MODIS has an 11% less chance of variability compared to MISR, while MODIS underpredicts concentrations more than MISR by 6%. With MODIS providing less
chance of variability due to its higher spatial coverage, and with MISR’s higher predictability accuracy, Liu suggests the possibility of combining the data between the two satellite instruments to get the most developed results (Liu et al. 2007).

Another positive for using MODIS over MISR imagery is its temporal resolution. Although both instruments are on NASA’s Terra Satellite, the MODIS instrument can also be found on NASA’s Aqua Satellite, which increases its temporal resolution (since they cover the same land at different times throughout the day) and allows researchers to observe distinct changes in particulate matter over a short time frame (Lillesand et al. 2004). MODIS’ greater spectral resolution also allows for more options and selectivity when trying to find the correct wavelength bands for a project (Lillesand et al. 2004). Overall, even though both satellite instruments have their own positives and negatives, MODIS has proven to be the clear favorite from past studies across the world. The study of 116 articles concluded that 67 studies used MODIS, only four studies used just MISR, and nineteen articles used both (Chu et al. 2016).

Model Testing

For combining MODIS and MISR data with ground sensors, many different statistical models have been applied over the past thirty years. Results have shown that the Mixed-Effect Model has proven to have the highest prediction accuracy (Chu et al. 2007). A Mixed-Effect Model uses regression and cluster analysis along with an inverse distance weight method to help compensate for missing aerosol optical depth data. This method uses meteorological variables such as temperature, visibility, and wind speed along with land use variables such as elevation, area emission, and distance from major roads to help predict particulate matter accurately (Chu et al. 2007). Another popular
model is called kriging, which uses interpolation and linear regression methods to weigh found samples from ground monitors and predict concentration data in other places within a certain proximity (Lee et al. 2012).

Several studies have shown that using cross-validation techniques are valuable for testing and analyzing the success of a specific machine learning model. Cross-validation splits up testing data into ‘k’ number of folds or samples and uses one of the folds for testing, while the other data folds are used to train the model. This process is used ‘k’ number of times with the same samples, but selecting different folds to represent the testing estimations of the model (Li et al. 2018). The results are averaged in order to use all of your data for both training and testing. This type of model testing may take extra computation time, but it is essential for accurately estimating the effectiveness and skill of a predictive model (Deters et al. 2017). Cross validation has been used in China to test ground monitor PM2.5 data with remote sensing imagery by splitting up historical annual data from 2013-2016 into separate folds and examining the model performance (Xue et al. 2019). Another study was completed in the Wuhan Urban Agglomeration region of China which used two randomly picked data sets and repeated a testing process for up to one hundred times and then averaging the results afterwards (Feng et al. 2015).

**Methods**

**Study Area**

The study area for this project is the contiguous United States. In the United States, the most impactful wind belt for transporting particulate matter comes from the Prevailing Westerlies which move from the west and travel up towards the North Pole. While a majority of land use is composed of forests, pasture, and crop land; urban areas
with high industrial pollution and population density in cities such as New York and Los Angeles tend to be correlated with higher PM$_{2.5}$ concentrations. The southwestern region of the U.S. also has drastically lower humidity compared to the rest of the country. While recognizing all of these underlying factors, the model created in this study focuses on using only satellite imagery data from the United States as the independent variable and observing how effective estimates can be made without any other meteorological data.

**Data Sources**

The EPA, which observes air pollution data across the United States, provides daily concentration across their 1,000+ active PM$_{2.5}$ ground monitors (Figure 3). The data on their website provides in-depth data on the latitude/longitude of the ground monitor, the time and date the concentration was recorded, the recorded air quality index value, along with the specific state and county of the ground monitor. Since the Terra and Aqua satellites (which both use the MODIS instrument) orbit the Earth with a temporal resolution of 1-2 days, EPA’s ground monitor data will only be extracted when a MODIS fly over at that location is on the same day.

![Figure 3: Current PM$_{2.5}$ Ground Monitors Across the Contiguous U.S (EPA 2018).](image)
Along with the ground monitor data, MODIS satellite imagery was gathered from NASA's Land Processes Distributed Active Archive Center (LP DAAC) as an explanatory variable in the model. This archive center provides free access to raw satellite imagery and processes it into a readable and interpretable format. In order to retrieve aerosol optical depth data, the MODIS Multi-Angle Implementation of Atmospheric Correction algorithm was used to create the MCD19A2 daily product. MCD19A2 uses Level-2 sinusoidal grids at a 1-km resolution, contains thirteen separate scientific dataset layers and has Stage-3 validation. For this model, the Optical_Depth_047 layer was used, which is derived from the Aqua & Terra visible blue bands (Lyapustin and Wang 2018).

MODIS data is processed through Hierarchical Data Format - Earth Observing System (HDF-EOS) files, which allow the transfer of scientific data across multiple machines. Each HDF-EOS file represents a single grid tile and can then be formatted into GeoTIFF rasters for use with GIS software. The MCD19A2 derived layers are created as science datasets (SDS) layers with three dimensions. Because of this, each layer may have up to twelve bands depending on the total number of orbit overpasses for a specific HDF-EOS image on a given day (Lyapustin and Wang 2018).
Data Analysis

The particulate matter data was retrieved and downloaded for the years 2000, 2009, and 2018 from the EPA’s pre-generated CSV files. Each ground monitor has a latitude and longitude, so the daily data was georeferenced into an XY layer and then copied over to a feature layer within ArcGIS Pro. Multiple sample durations for a specified day were filtered out to remove inconsistencies. Since the data collected from the EPA included one hour test periods at several stations, those were removed since this study is centered around a 24 hour time period. A separate feature layer was then created for each day of the year using the select-by-attributes and copy features tools through the Python ‘ArcPy’ library to be used later with the daily MCD19A2 data.

The MODIS MCD19A2 data was retrieved through R’s ‘MODIS’ library, which allowed users to send Hypertext Transfer Protocol requests to retrieve daily HDF-EOS files for selected sinusoidal tiles and dates. After downloading between 30-40 GB of data for a given year, the HDF-EOS files were then converted into GeoTIFF images with only the Optical_Depth_47 layer using the Geospatial Data Abstraction Library (GDAL).
The GeoTIFFs were then reprojected to the WGS 84 Web Mercator projected coordinate system to match the ground monitor data.

Using the multi-values-to-points tool, the twelve unique GeoTIFF file paths for a given day were stored in an array and used with their corresponding queried ground monitor feature points. Each GeoTIFF’s band intersection values are stored within separate fields for the queried feature class. If there was no intersection for a specific band, the result displayed a null value. After all of these multi-values-to-points tools are calculated for a specific day, the average aerosol optical depth is calculated, disregarding all null values due to the bands representing multiple orbit passes from the Aqua and Terra satellites. Once all of the average aerosol optical depth calculations are made for each day, ArcGIS Pro’s generalized linear regression tool was used to calculate daily, seasonal, latitudinal, and annual correlation for each year. The explanatory variable was the average Optical_Depth_47 data, while the dependent variable was the air quality index (AQI) for PM2.5 from the ground monitor sensors.

Results

Annual Scatter Plot Data

Results were tracked over the lifespan of the MCD19A2 product starting with the year 2000, and then through observing trends for both 2009 and 2018. Linear regression models were graphed to observe clustering and the value of a single explanatory variable (AOD) model for predicting particulate matter. Although the United States has used between 900-1,100 ground monitors on average, the total number of readings have increased over the years as the United States strives to lower the risk of air pollution. Observing trends from the linear regression data in Table 1 show that 35,460 data points were tested to create the model in the year 2000 (Figure 5), while
2009 analyzed 51,123 data points (Figure 6) and 2018 used 89,330 data points (Figure 7). R² values tracked in succeeding charts below refer to the coefficient of determination, or the percentage of particulate matter variation that can be explained by the specified linear regression model.

Figure 5: Scatter plot relationship between MODIS aerosol optical depth & recorded PM2.5 readings from ground monitors in 2000.

Figure 6: Scatter plot relationship between MODIS aerosol optical depth & recorded PM2.5 readings from ground monitors in 2009.
Figure 7: Scatter plot relationship between MODIS aerosol optical depth & recorded PM$_{2.5}$ readings from ground monitors in 2018.

Table 1: Displays the total number of unique daily PM$_{2.5}$ ground monitor readings for the specified years, along with the number of readings that had a corresponding satellite imagery value.

<table>
<thead>
<tr>
<th></th>
<th>Daily PM 2.5 Readings</th>
<th>PM Readings w/ AOD Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>145349</td>
<td>35460</td>
</tr>
<tr>
<td>2009</td>
<td>148036</td>
<td>51123</td>
</tr>
<tr>
<td>2018</td>
<td>245377</td>
<td>89330</td>
</tr>
</tbody>
</table>

**Temporal and Seasonal Trends**

Looking at the R$^2$ values from Figure 8, there are no significant temporal conclusions that can be determined for this simple linear regression model. While 2018 had the highest R$^2$ value with 0.22, year 2000 had the second lowest with 0.21, and year 2009 had a very low predictability with 0.07. For seasonal trends, the summer had the highest overall R$^2$ values on average, followed closely by the fall, and then the spring (Figure 9). The winter months had significantly lower R$^2$ values for all three years.
and cannot be considered reliable with this current model. These low \( R^2 \) values may be due to snowfall, cloud cover or other weather conditions.

![Figure 8: Bar chart showing \( R^2 \) values for 2000, 2009 & 2018](image)

![Figure 9: Bar chart showing \( R^2 \) values for each season per year](image)

**Latitudinal Trends**

Latitudinal trends were observed by splitting ground monitor data for the contiguous United States at its geographical midpoint of 39°50’N. The trends from
Figure 10 show that on average, the highest northern latitude $R^2$ values occur during the summer with 0.36, while the southern latitudes highest value occurs during the fall with 0.29. Figure 11 reveals the percentage of ground monitor readings that had corresponding aerosol optical depth data from the Aqua or Terra satellites. This data was created for determining the reliability of getting an accurate AOD reading for a certain location and day. Readings show that locations closer to the equator have a significantly higher chance to retrieve AOD data throughout the year. While results also show that the latitudes closer to the equator have higher percentages in the fall and spring, the summer data has proven to be most consistent across the whole contiguous U.S. (overall average among northern and southern latitudes).

Table 2: Linear regression models for each season and split up by locations further & closer to the equator for the United States. ($y = \text{PM}_{2.5}, \ x = \text{AOD}$)

<table>
<thead>
<tr>
<th></th>
<th>Northern Latitudes</th>
<th>Southern Latitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>$y = 26.74165 + 0.06717 \times x$</td>
<td>$y = 29.00447 + 0.07337 \times x$</td>
</tr>
<tr>
<td>Spring</td>
<td>$y = 20.45010 + 0.05924 \times x$</td>
<td>$y = 27.09247 + 0.05948 \times x$</td>
</tr>
<tr>
<td>Summer</td>
<td>$y = 23.83177 + 0.06543 \times x$</td>
<td>$y = 27.89284 + 0.06231 \times x$</td>
</tr>
<tr>
<td>Fall</td>
<td>$y = 25.35945 + 0.09132 \times x$</td>
<td>$y = 24.59295 + 0.13502 \times x$</td>
</tr>
</tbody>
</table>
Figure 10: Bar chart showing $R^2$ values comparing seasonal averaged data to latitudes above or below 39°50’N. (Averaged from 2000, 2009 & 2018)

Table 3: Exact $R^2$ values for calculated latitudes by season.

<table>
<thead>
<tr>
<th></th>
<th>Northern Latitudes</th>
<th>Southern Latitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>0.061032916</td>
<td>0.050727648</td>
</tr>
<tr>
<td>Spring</td>
<td>0.137086766</td>
<td>0.115833761</td>
</tr>
<tr>
<td>Summer</td>
<td>0.355542147</td>
<td>0.156737661</td>
</tr>
<tr>
<td>Fall</td>
<td>0.118404386</td>
<td>0.292975359</td>
</tr>
</tbody>
</table>
Figure 11: Bar chart showing how often MODIS data was recorded at a specific ground monitor during a given season divided based latitudes above or below 39°50’N in the United States. (Averaged From 2000, 2009 & 2018)

Table 4: Exact percentages for total spatial coverage for calculated latitudes by season.

<table>
<thead>
<tr>
<th></th>
<th>Northern Latitudes</th>
<th>Southern Latitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>11.79%</td>
<td>33.02%</td>
</tr>
<tr>
<td>Spring</td>
<td>28.35%</td>
<td>40.03%</td>
</tr>
<tr>
<td>Summer</td>
<td>37.38%</td>
<td>38.21%</td>
</tr>
<tr>
<td>Fall</td>
<td>26.84%</td>
<td>41.83%</td>
</tr>
</tbody>
</table>

Model Application Example

This applicability of this model worldwide is shown in Figure 12. Since the predicted time period was made for November 8th, 2019, the fall linear regression model near the equator was used to predict China’s particulate matter concentrations. Although results are not 100% accurate, these results reflect the applicability of this model, especially in places with no or too few ground monitors. Since China has over 1,000 ground monitors across the country, a map was created to look at how closely
this model would compare to actual particulate matter readings outside of the United States. Figure 12 shows a map of estimated particulate matter for November 8th, 2019 in China. Although the estimated results show significantly more unhealthy air quality compared to the actual data, the overall spatial pattern and hotspots that need to be monitored more closely are identified. The higher estimated air quality indexes could be the result of the Optical_Depth_47 band tracking pollutants other than PM$_{2.5}$, or possibly due to the estimated model being trained mainly with low AQI values.

![Figure 12: Map of predicted average PM$_{2.5}$ data for November 8th, 2019 in China.](image-url)
Discussion

The results of these linear regression models have shown significance for seasonal and latitudinal trends over the three recorded years: 2000, 2009, and 2018. The summer months’ linear regression model proved to show the highest percentage of particulate matter variation that can be explained solely by the Optical_Depth_47 MCD19A2 layer. The overall spatial coverage in the summer has also proven to be most consistent across the contiguous country, possibly due to less cloud coverage. The winter months’ model, which produced very sporadic and low predictability results, was most likely due to the limited test data that could be collected for these months. With snow and other meteorological factors limiting aerosol optical depth imagery, the $R^2$ values were only between 0.05 - 0.07. For latitudinal trends, the latitudinal model further from the equator produced higher $R^2$ values, but was limited to overall less
spatial coverage, especially during the winter. These trends are valuable to
acknowledge as they allow users to locate when and where they can estimate the most
accurate particulate matter data based on MODIS imagery alone. If, for example, a
researcher wanted to look at PM$_{2.5}$ data in Egypt, the fall model would be most
beneficial as it produces the highest spatial coverage and R$^2$ values for locations near
the equator.

On the other hand, none of the linear regression tests proved to show
significantly high R$^2$ values for estimating particulate matter. This is to be expected as
particulate matter change drastically at any given moment throughout the day, and
cannot be explained solely from a satellite passover with 100% confidence. The 1-2 day
temporal coverage and inconsistent spatial coverage also play a role lower than
expected R$^2$ results. In order to further refine this model, follow up research could be
done by adding more explanatory variables that are easily accessible on a large scale.
Although adding meteorological data is not fully applicable worldwide, most countries
have weather stations to track temperature, air pressure, wind patterns, humidity, and
precipitation. This would prove most beneficial for countries in which particulate matter
concentration is high, but still do not have adequate access to ground monitors. As seen
in Figure 14, many African and Southwest Asian countries have no monitors for
measuring PM$_{2.5}$. Other factors that could be tested are land use and population
density, which both play a role in increasing overall pollution, mainly from power plants,
industrial sites, and automobiles.
While the EPA has taken action to reduce overall particulate matter concentration levels in the United States, many countries and cities are still suffering from hazardous PM$_{2.5}$ levels. Without proper awareness or action, more and more people will continue to be exposed to fatal health conditions. Ecosystems will suffer and haze will continue to reduce visibility if PM$_{2.5}$ is not controlled. Ideally, the trends found in this study can be applied further in the future to increase overall particulate matter predictability on a world-wide scale.
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