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Research Paper

Exploring The Possibility Of Using MODIS AOD Data For PM2.5 Monitoring

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ABSTRACT: *Satellite-based remote sensing could serve as an alternative to station-based PM 2.5 monitoring because of its large spatial coverage. The purpose of this study was to explore the possibility of using MODIS AOD data for PM2.5 monitoring in the state of North Carolina (NC), United States. In this study, spatial-temporal correlation between MODIS AOD and ground PM2.5 was examined at daily, monthly and seasonal levels after corresponding values were matched for AOD and PM2.5. Temporal AOD-PM2.5 correlation was also examined for each Air Now PM2.5 station in NC. Results revealed that there was no statistically significant spatial correlation between the MODIS AOD and ground PM2.5 in NC at daily level in 2011. The temporal correlation between MODIS AOD and ground PM2.5 was statistically significant for every station in NC in 2011. This significant correlation will help develop a practical method for statewide PM2.5 monitoring using MODIS AOD in the U.S.*

Keywords - *AOD-PM2.5, correlation, spatial, spatial-temporal, temporal*

I. INTRODUCTION

Air quality is of high importance in the United States due to the fact that long-term exposure to high concentrations of fine particulate matter (particles with aerodynamic radius less than 2.5 micrometers, or PM2.5) results in asthma, respiratory infections, lung cancer, and cardiovascular problems (Zanobetti et al. 2009, Smart et al. 2011). Traditional station-based PM2.5 monitoring is costly and has a limited spatial coverage. Satellite-based remote sensing could serve as an alternative because of a large spatial coverage and reliable repeated measurements.

Moderate Resolution Imaging Spectrometer (MODIS) Aerosol Optical Depth (AOD) product (10km spatial resolution) derived from the imagery of NASA Terra satellite has been widely used as a tool for regional PM2.5 studies for many years. Numerous studies have suggested that there is a positive relationship between MODIS AOD data and ground-level PM2.5 observations. For example, Slater et al. (2004) found higher (~0.76) coefficients of determination (R^2) between aerosol optical thickness (AOT) and PM2.5 concentration; Wang & Christopher (2003) and Engle-Cox et al. (2004) analyzed the satellite-retrieved AOT with hourly mean PM2.5 concentrations and reported that R^2 were ~ 0.49 and ~ 0.40 respectively; Gupta et al. (2006) concluded there was an excellent correlation between the bin-averaged daily mean satellite and ground-based PM2.5 values with a linear correlation coefficient of 0.96 for 26 global cities. All these studies indicated high potential of using MODIS AOD data as an alternative to particular matter monitoring. Contrary to the research mentioned above, poor correlations were found between MODIS AOD and ground PM2.5 for the western United States (Engel-Cox et al. 2004; Rush et al. 2004). Hu (2009) revealed that the average correlation AOD to PM2.5 was 0.67 in the Eastern U.S. but 0.22 in the Western U.S. Paciorek and Yang (2009) suggested that there was a limited spatial correlation (0.35) between MODIS AOD and ground PM2.5 in the eastern U.S. Alston et al. (2011) discovered that correlation coefficients varied between 0.25 – 0.76 in Atlanta, GA.

There have been several published studies on the evaluation of the new 3km MODIS AOD product after it was publicly available. Munchak et al. (2013) evaluated the 3km MODIS AOD product using aerosol data collected by airborne High Spectral Resolution Lidar (HSRL) and a network of 44 sunphotometers (SP) and they concluded that the 3km product better characterized aerosol spatial distributions than the 10 km product but it tended to be noisier, especially in urban areas. Strandgren et al. (2014) investigated the impact of spatial resolution of AOD on the linear correlation between satellite-retrieved AOD and PM2.5 using AOD at different spatial resolutions (1, 3 and 10 km) and for different spatial scales (urban scale, meso-scale and continental scale) in the United States. They found that the correlation between PM2.5 and AOD was improved significantly with increasing spatial resolution of the AOD and the correlation between PM2.5 and AOD was much more stable and higher in the eastern U.S than the western U.S. Li et al. (2015) examined the correlation between MODIS AOD value and the ground-level PM2.5 concentration in Beijing, China and discovered that the 3 km AOD had nearly the same correlation with the PM2.5 as the 10 km AOD but it could show better spatial details in urban areas.

Until now, despite much progress being made, the use of MODIS AOD in monitoring of PM2.5 is still challenging due to poor correlations in certain regions and time periods. The new 3 km product seems promising but its performance needs to be tested in more regions in order to be effective in PM2.5 monitoring. It was also noticed that a large region was covered in most aforementioned studies in which spatial-temporal AOD-PM2.5 correlation was examined. Seldom has there been any study conducted at a local level, which is essential and required to test the relationship of MODIS AOD and ground PM2.5 for real applications of MODIS AOD products. The purpose of this study is to examine the possibility of using MODIS AOD data (3km) for PM2.5 monitoring in the state of North Carolina at a station level in order to develop a cost-effective method to measure PM2.5 using satellite-based remote sensing in the United States.

II. MATERIAL AND METHODS

In this study, Terra MODIS AOD 3km data (Atmosphere level 2 Aerosol Product in HDF format, Collection 6) collected in 2011 were ordered and downloaded from the Unites States Geological Survey (USGS) web site. HDF data processing procedures include the reprojection of MODIS AOD data to a universal traverse Mercator (UTM) projection and conversion of file format to Geo TIFF. Hourly PM2.5 data for each PM2.5 station in North Carolina was downloaded from the U.S EPA AirNow web site. AirNow is a U.S EPA program that provides public with easy access to national air quality information online. There were seventeen AirNow stations providing hourly PM2.5 measurements in NC in 2011(Figure 1). The latitude and longitude of each AirNow PM2.5 station was used to create a shape file containing all hourly PM2.5 monitoring stations in North Carolina. To match overpass time of Terra satellite (10:30-12:30 pm local time), the average of PM2.5 concentration measured at 11 am and 12 pm for each day was selected for the correlation testing.

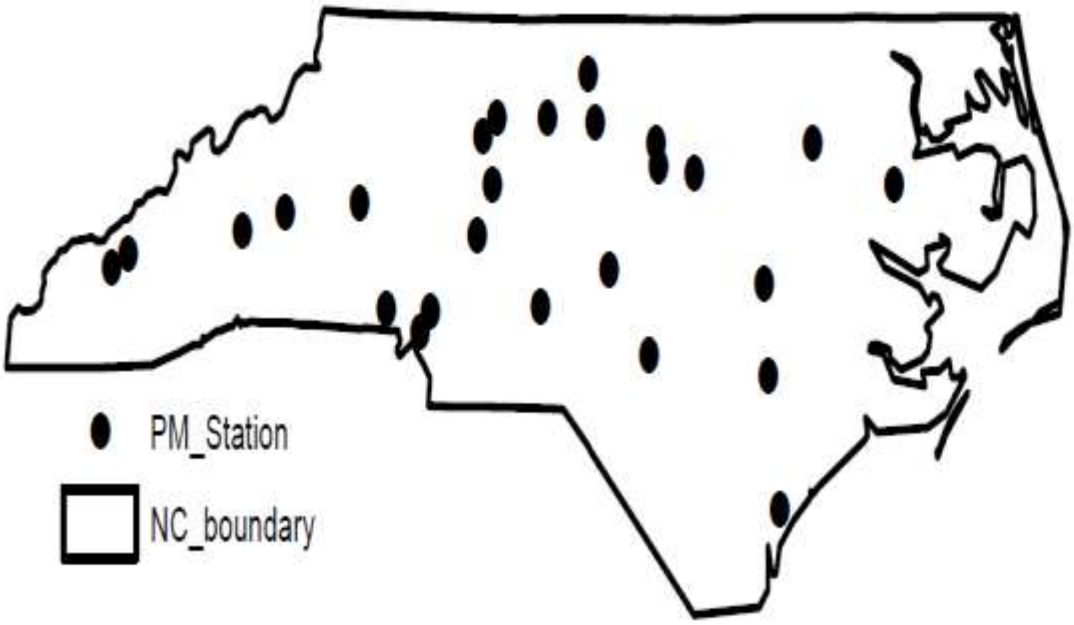

Figure 1. Map of study area and PM2.5 stations

In software ArcMap (ESRI Inc.) both the shape file of all PM2.5 stations in NC and downloaded MODIS AOD images were overlaid. AOD value at each PM2.5 station was extracted using a function tool entitled as “Extract values to points” in ArcTool Box. The attribute table of each newly generated shape file was exported as a txt file and then transferred into Microsoft Excel format. The spatial correlation between MODIS AOD value and ground PM2.5 concentration was examined for the day in which both data existed. The spatial-temporal correlation of AOD-PM2.5 was tested for each month and season in 2011 after paired AOD and PM2.5 data were grouped by month and season. Next, temporal AOD-PM2.5 correlation was examined for each AirNow PM2.5 station in NC in 2011. The significance of all correlations was tested at 95% confidence level for all correlations.

III. RESULTS AND DISCUSSION

3.1 Spatial and Spatial-temporal correlations

It is necessary to check how MODIS AOD was sampled daily at all stations since ground PM2.5 is sampled almost 365 days except the time for maintenance. The number of AirNow stations sampled for AOD was summarized in Table 1. It can be seen that there were very few days in which both AOD and ground PM2.5 data existed for at least three stations (for statistical purpose) from January to September in 2011. Even for those days there were only 3-12 stations per day where both AOD data and ground PM2.5 concentrations existed. In 2011, there was no single day in which both AOD and ground PM2.5 data existed for all seventeen PM2.5 stations while ground PM2.5 concentration is measured hourly for almost every day at all seventeen AirNow PM2.5 stations in NC, U.S. This is a well-known "low sampling" problem mentioned in the literature (Gupta and Christopher 2008; Christopher and Gupta 2010). Satellite-based remote sensing such as MODIS tends to have a lower sampling frequency compared to routine ground PM2.5 measurements. It was caused by the lower number of cloud-free days in the state of North Carolina in those months since MODIS AOD values are only available in cloud-free days. On the average, AOD was sampled once a week over most AirNow PM2.5 stations in 2011. In November and December, this situation was changed significantly and AOD was sampled for approximately half of the month. In addition, the State of North Carolina runs from 75^{o} 30 W to 84^{o}15 W for about 800 km long. Cloud-free days occur at different locations at different times. It is less likely that one cloud-free MODIS AOD image can cover all PM2.5 stations in NC for the same day. In general, not all PM2.5 stations in NC can be sampled for MODIS AOD for majority of days in any year. Therefore, it is challenging to use MODIS AOD data for statewide PM2.5 monitoring in NC at a daily level.

Table 1. Spatial correlations for days both AOD data and ground PM2.5 existed in 2011

Month	#Days with at least three matching pairs	Range of daily correlation coefficient	Significance at 95% confidence level
January	**5**	**-0.3526 to 0.5575**	**insignificant**
February	**3**	**0.1320 to 0.6707**	**insignificant**
March	**3**	**0.2206 to 0.4839**	**insignificant**
April	**5**	**0.1797 to 0.9189**	**insignificant**
May	**4**	**-0.7835 to 0.7135**	**insignificant**
June	**5**	**-0.2644 to 0.9547***	**significant for one day in June**
July	**2**	**-0.7341 to 0.5160**	**insignificant**
August	**5**	**-0.1629 to 0.2802**	**insignificant**
September	**4**	**-0.4066 to 0.4961**	**insignificant**
October	**8**	**-0.3410 to 0.8643**	**insignificant**
November	**13**	**-0.9571 to 0.4838**	**insignificant**
December	**18**	**-0.9499 to 0.7236**	**insignificant**

#Days with at least three matching pairs: the number of days in which at least three stations were sampled for both AOD and PM2.5; *: significant at 95% confidence level

The daily spatial correlations are shown for days in which both AOD data and ground PM2.5 concentrations existed in 2011 in Table 1. Except one day in June, all daily spatial correlation coefficients in each month were lower than the critical value (at 95% confidence level). Thus there was no statistically significant spatial correlation between MODIS AOD value and ground PM2.5 concentration at a daily level in 2011. This indicates it is not practical to use MODIS AOD value as a surrogate of ground PM2.5 concentration in the state of North Carolina at a daily level. It appears that MODIS AOD data failed to capture the spatial variability of ground PM2.5 concentration for all NC stations at a daily level. It is well known that AOD is a measure of light extinction by aerosols in an atmospheric column but ground PM2.5 is a measure of aerosol (less than 2.5 μm) concentration on the ground. There might be a significant difference in spatial variability between these two kinds of aerosol measurements at daily level in NC.

Spatial-temporal AOD-PM2.5 correlation was improved at monthly and seasonal level (Table 2). With the exception of May, July and October, there was statistically significant correlation (low to medium) between MODIS AOD value and ground PM2.5 concentration in every month in 2011. The highest and lowest correlation occurred in June and May respectively. Table 2 shows that there was statistically significant correlation between MODIS AOD value and ground PM2.5 concentration in 2011 for each season. It can be also seen that seasonal AOD-PM2.5 correlation was higher in summer and spring than in winter and fall in 2011. Although more AOD-PM2.5 matching pairs were observed in the fall season in 2011, the AOD-PM2.5 correlation was the lowest. This indicates the lower number of cloud-free days in North Carolina may not be the only obstacle to use MODIS AOD as a surrogate of ground PM2.5. All results above show that when more temporal data was added from daily to monthly and seasonal level, AOD-PM2.5 correlation was gradually improved. This may be because the difference in spatial-temporal variability between columnar AOD and ground PM2.5 for all AirNow stations was reduced with the increased amount of temporal data. This also suggests that it is possible to use MODIS AOD value as a surrogate of ground PM2.5 concentration in the state of North Carolina at a monthly and seasonal level.

Table 2. Spatial-temporal correlations of AOD-PM2.5 in North Carolina in 2011

Month	**# Matching AOD and PM2.5 pairs**	**Correlation coefficient**	**Significance at 95% confidence level**
January	**33**	**0.3508**	**significant**
February	**16**	**0.5324**	**significant**
March	**28**	**0.4368**	**significant**
April	**26**	**0.4789**	**significant**
May	**22**	**-0.1297**	**insignificant**
June	**33**	**0.6794**	**significant**
July	**21**	**0.2313**	**insignificant**
August	**34**	**0.4598**	**significant**
September	**31**	**0.6351**	**significant**
October	**45**	**0.2877**	**insignificant**
November	**92**	**0.2898**	**significant**
December	**140**	**0.2399**	**significant**
WINTER	**55**	**0.3153**	**significant**
SPRING	**68**	**0.4585**	**significant**
SUMMER	**77**	**0.5371**	**significant**
FALL	**264**	**0.2526**	**significant**

 # Matching AOD and PM2.5 pairs: the number of coexisting AOD and PM2.5 data pairs in a month or a season

Based on monthly and seasonal correlation, it is possible to use MODIS AOD value as a surrogate of ground PM2.5 concentration in North Carolina at a monthly and seasonal level. However, in some months, there were no significant correlations. It means it is not good to use MODIS AOD value as surrogate of ground PM2.5 for those months. Thus there will be some missing months in the application of MODIS AOD. Also, seasonal correlations were not strong (the highest is 0.5371 in summer). This indicates that there might be a large bias when MODIS AOD value is used as a surrogate of ground PM2.5 concentration in NC, U.S. for some seasons such as fall. In a word, it is not very promising to develop an effective tool to use MODIS AOD for PM2.5 monitoring using the popular spatial-temporal AOD-PM2.5 correlation approach. It is necessary to seek an alternative approach.

3.2 Temporal correlations

For effective PM2.5 monitoring by the MODIS imagery in NC, it is essential that AOD is sampled regularly at each PM2.5 station every month. Thus it is necessary to examine the number of days during which MODIS AOD was sampled at each PM2.5 station. The results in 2011 were summarized in Table 3. It can be seen that the low sampling problem was present for almost all stations in NC. In 2011, with the exception of November and December, MODIS AOD was sampled for less than five days per month for every PM2.5 station in 2011. Also, MODIS AOD was sampled for 18 to 56 days per year for all NC AirNow Stations in 2011. Three stations, including Durham Armory and Hickory and Leggett, were not sampled for AOD for six months in 2011. Moreover, every month except November and December, there were 2-7 stations at which AOD values were missed due to a cloud cover problem. In November and December, there was a higher sampling frequency for AOD. But spatial correlations (AOD-PM2.5) were poor in those two months. This presents a significant challenge when considering MODIS AOD value as a PM2.5 surrogate for those stations.

Table 3. Number of days in which AOD was sampled in North Carolina in 2011

Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
BDED	2	1	2	3	1	1	2	1	2	3	4	11	33
Bryson	1	1	4	2	2	3	5	7	3	5	4	6	43
Clemmons Middle	2	2	2	4	5	4	3	4	3	5	8	7	49
Durham Armory	2	0	0	1	0	1	0	0	2	0	3	9	19
Garinger	4	1	3	2	1	3	0	3	2	5	7	4	36
Grier Middle School	2	1	1	1	2	2	2	2	1	4	4	6	28
Hattieaven	2	2	1	3	3	3	1	3	3	1	7	8	39
Hickory	0	2	1	0	0	1	0	0	0	1	5	6	18
Hopedale	3	0	2	1	0	3	0	1	2	2	9	10	35
Leggett	0	0	0	0	0	0	2	0	3	4	7	13	30
Lwattowr	0	0	1	0	2	1	0	1	1	1	4	8	19
Marion	2	1	3	1	0	4	0	1	2	5	2	9	31
Mendnhal	2	1	2	2	2	0	1	3	1	0	4	11	27
Millbrook NCore	3	0	1	1	0	0	1	1	3	0	5	7	22
Montclaire	1	0	2	2	0	1	1	3	1	2	5	7	25
Rockwell	4	1	3	5	2	4	3	4	3	6	9	11	56
W Owen school	3	1	0	0	2	1	0	0	0	3	10	10	25

Temporal AOD-PM2.5 correlation was examined for each AirNow PM2.5 station in 2011. The results are shown on Table 4 including one linear equation for each AirNow PM2.5 station. It can be seen that the temporal correlation between MODIS AOD value and ground PM2.5 concentration was positive and statistically significant for every AirNow PM2.5 station in the state of North Carolina in 2011. In most stations, except BDED, Millbrook- NCore and W Owen Sch, there were medium to strong AOD-PM2.5 correlations at a station level. This is promising since it opens an opportunity to address the "low sampling" problem mentioned above. When a station is not sampled for AOD for one day due to the cloud cover problem, AOD value for this station in the missing day can be retrieved using the equation and corresponding PM2.5 concentration which is usually available for that PM2.5 station. It also brings a hope to fill spatial PM2.5 concentration gaps for locations near current AirNow PM2.5 stations. In this case, PM2.5 concentrations at those locations could be retrieved from their corresponding AOD values using the linear equation for a nearby AirNow PM2.5 station once AOD values are available during cloud-free days from MODIS AOD data. For a location which is far from any existing AirNow PM2.5 station, its PM2.5 concentration could be interpolated from retrieved PM2.5 concentrations from surrounding locations using various spatial interpolation techniques such as Kriging..

It is noted that each PM2.5 station had different correlation coefficients for AOD-PM2.5 relationship while they were statistically significant (Table 4.). Also, the slope and intercept of linear equations ranged 0.0067-0.0433 and 1.4523-5.3659 respectively for PM2.5 stations in NC. Additionally, no spatial pattern was observed in the correlation coefficient, slope and intercept. Thus each PM2.5 station may have its own unique AOD-PM2.5 correlation in NC. This explains why a spatial correlation between AOD and PM2.5 was not significant for almost all days in which both AOD and PM2.5 data existed. It is likely that mixed AOD values from different PM2.5 stations would lead to a failure in building up significant spatial AOD-PM2.5 correlations in NC.

Spatial variability of PM2.5 at various stations has been demonstrated by many previous studies (Pinto et al. 2005; Tunno et al. 2015). It is common that each sampling station has its own meteorological environment and particular aerosol sources. Thus PM2.5 from each AirNow PM2.5 station may have its special characteristic including optical and physical properties. There might be a unique AOD-PM2.5 relationship for each individual PM2.5 station. The seventeen AirNow PM2.5 stations in North Carolina across different longitudes and are located at different physical environments. It is reasonable that each of those stations has its special temporal correlation with MODIS AOD.

Table 4. Temporal correlations between MODIS AOD and ground PM2.5 in North Carolina in 2011

Name	Correlation coefficient	Significance at 95% confidence level	Linear Equation
BDED	**0.3753**	**Significant**	**PM2.5 = 0.0067*AOD + 5.3659**
BRYSON	**0.6281**	**Significant**	**PM2.5 = 0.026*AOD + 5.0558**
Clemmons Middle	**0.6083**	**Significant**	**PM2.5 = 0.0157*AOD + 4.1755**
Durham Armory	**0.8496**	**Significant**	**PM2.5 = 0.0234*AOD + 2.7948**
Garinger	**0.7949**	**Significant**	**PM2.5 = 0.0222*AOD + 1.9847**
Grier Middle School	**0.7704**	**Significant**	**PM2.5 = 0.0203*AOD + 2.3554**
Hattieaven	**0.5488**	**Significant**	**PM2.5 = 0.0172*AOD + 1.8613**
Hickory	**0.6137**	**Significant**	**PM2.5 = 0.0156*AOD + 4.5604**
Hopedale	**0.7530**	**Significant**	**PM2.5 = 0.03*AOD + 1.4523**
Leggett	**0.7855**	**Significant**	**PM2.5 = 0.0433*AOD + 2.6235**
Lwattowr	**0.5809**	**Significant**	**PM2.5 = 0.0169*AOD + 4.0463**
Marion	**0.8692**	**Significant**	**PM2.5 = 0.0283*AOD + 2.1746**
Mendnhal	**0.7333**	**Significant**	**PM2.5 = 0.0155*AOD + 3.6155**
Millbrook NCore	**0.4570**	**Significant**	**PM2.5 = 0.0172*AOD + 4.5233**
Montclaire	**0.8184**	**Significant**	**PM2.5 = 0.0269*AOD + 1.7902**
Rockwell	**0.7694**	**Significant**	**PM2.5 = 0.0213*AOD + 3.9573**
W Owen School	**0.4558**	**Significant**	**PM2.5 = 0.0078*AOD + 3.552**

PM2.5: ground PM2.5 concentration (ug/m^3); AOD: AOD value from MODIS AOD data

The relationship between ground-level PM2.5 and satellite-based AOD is complex. It depends on optical properties of local aerosols (a function of aerosol type and atmospheric conditions) and their vertical distribution (a function of boundary layer height, transport, production, and loss) (van Donkelaar et al. 2010). If these factors are not taken into consideration, the correlation between the PM2.5 and the MODIS AOD will be poor or not significant. For past years, there have been successful attempts to improve correlations between MODIS AOD and ground PM2.5 by incorporating vertical distribution (Boyouk et al. 2010; Chu et al. 2013) or inclusion of meteorological parameters (Koelemeijer et al. 2006; Gupta and Christopher 2009). These studies demonstrate that the strong relationship between AOD and PM2.5 could be achieved by considering vertical distribution and meteorological parameters. However, large amount of money and time has to be invested in order to develop a reliable method to be used in the real application of MODIS AOD. Also, it is very promising that significant temporal AOD-PM2.5 correlation was present for every station in North Carolina in 2011. This demonstrates that there might be a strong correlation between columnar AOD and ground PM2.5 for each station independent of various meteorological conditions, month and other factors such as aerosol sources. Once environmental factors and other factors are removed, significant correlation between MODIS AOD value and PM2.5 concentration will be revealed.

To be practical and cost-effective, the use of station-specific temporal correlation may be an alternative approach to develop the application of MODIS AOD for PM2.5 monitoring. In this case, the major effort will be the development of an equation based on temporal AOD-PM2.5 correlation for each PM2.5 station. This will be a challenging task for a regional AOD application. However, it is applicable at a state level. There are only seventeen AirNow PM2.5 stations in North Carolina. It is practicable to examine the temporal correlation for each PM2.5 station for a certain time period and develop a robust retrieval equation for each station. For the state of North Carolina, seventeen equations are needed to convert AOD value to PM2.5 concentration or vice versa. These equations can be used to address the "low sampling" issue and retrieve missing AOD values for existing PM2.5 stations. When one AOD image that covers a large area and many PM2.5 stations is available, this image could be used to fill PM2.5 concentration gaps for locations which are not covered by existing PM2.5 stations in NC using the aforementioned method. This may be a viable way to conduct a real application of MODIS AOD for monitoring PM2.5 in the state of North Carolina. The similar approach can be applied to other states in the U.S. and other countries as well. Further studies are needed to develop a robust retrieval AOD-PM2.5 equation for each AirNow PM2.5 station in North Carolina for a real application of MODIS AOD products.

IV. CONCLUSIONS

This study developed a methodology to estimate PM2.5 concentration by using MODIS AOD imagery. Our results show that there was no significant spatial correlation between MODIS AOD value and ground PM2.5 concentration at daily level while there was significant spatial-temporal correlation between MODIS AOD value and ground PM2.5 concentration for most months and each season for NC. U.S. in 2011. The temporal correlation between MODIS AOD values and ground PM2.5 concentration was statistically significant for every AirNow PM2.5 station in NC, U.S. in 2011. This significant correlation will help develop a practical method for statewide PM2.5 monitoring using MODIS AOD data in the United States. Despite the limitations of this work, our findings demonstrate that the use of station-specific temporal correlation may be an alternative approach to develop the application of MODIS AOD for PM2.5 monitoring. This new way would help improve the understanding of characteristics of AOD-PM2.5 correlation at various levels and their applications from a new perspective. The similar approach can be applied to other states in the U.S. and other countries as well.

REFERENCES

[1]. Alston, E.J., Sokolik, I.N., and O. V. Kalashnikova. (2011). Characterization of atmospheric aerosol in the US Southeast from ground- and space-based measurements over the past decade. *Atmos. Meas. Tech. Discuss*. 4: 7559–7595.

[2]. Boyouk, N., J. F. Leon, H. Delbarre, T. Podvin and C. Deroo. 2010. Impact of the mixing boundary layer on the relationship between PM2.5 and aerosol optical thickness. *J Atmos. Environ*. 44: 271-277.

[3]. Christopher, S.A. and P. Gupta. 2010. Satellite remote sensing of particulate matter air quality: the cloud-cover problem. *J Air Waste Manag Assoc*. 60(5): 596-602.

[4]. Chu, D. A., T. Tsa, J. Chen, S. Chang, Y. Jeng, W. Chiang. and N. Lin. 2013. Interpreting aerosol Lidar profiles to better estimate surface PM2.5 for columnar AOD measurements. *Atmospheric Environment* 79: 172-187.

[5]. Engle-Cox, J.A., C.H. Holloman, and B.W. Coutant. 2004. Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality. *Atmospheric Environment* 38: 2495–2509.

[6]. Gupta, P., S.A. Christopher, J. Wang, R. Gehrigc, Y. Leed, and N. Kumar. 2006. Satellite remote sensing of particulate matter and air quality assessment over global cities. *Atmospheric Environment* 40:5880–5892.

[7]. Gupta, P. and S.A. Christopher. 2009. Particulate matter air quality assessment using integrated surface, satellite, and meteorological products: multiple regression approach. *J. Geophys. Res.*114, D14205. http://dx.doi.org/10.1029/2008JD011496.

[8]. Hu, Z., (2009). Spatial analysis of MODIS aerosol optical depth, PM2.5, and chronic coronary heart disease. *International Journal of Health Geographics* 8:27.

[9]. Koelemeijer RBA, C.D. Homan, and J. Matthijsen. 2006. Comparison of spatial and temporal variations of aerosol optical thickness and particulate matter over Europe. *Atmos Environ* 40:5304; doi:10.1016/j.atmosenv.2006.04.044

[10]. Li, J., B.E. Carlson, and A. A. Lacis 2015. How well do satellite AOD observations represent the spatial and temporal variability of PM2.5 concentration for the United States? *Atmospheric Environment* 102: 260-273.

[11]. Li, R., J. Gong, L. Chen, and Z. Wang. 2015. Estimating Ground-Level PM2.5 using fine-resolution satellite data in the megacity of Beijing, China. *Aerosol and Air Quality Research* 15 1347–1356.

[12]. Munchak, L. A., R.C. Levy, S. Mattoo, L.A. Remer, B.N. Holben, J.S. Schafer, C. A. Hostetler, and R.A. Ferrare. 2013. MODIS 3 km aerosol product: applications over land in an urban/suburban region, Atmos. Meas. Tech., 6, 1747–1759, doi:10.5194/amt-6-1747-2013.

[13]. Paciorek, C.J., J.D. Yanosky, R.C. Puett, F. Laden, and H.H. Suh.2009. Practical large-scale spatio-temporal modeling of particulate matter concentrations. *Annals of Applied Statistics* 3:370-397.

[14]. Pinto, J. P., A. S. Lefohn, and D. S. Shadwick. 2004. Spatial variability of PM2.5 in urban areas in the United States. *Journal of Air & Waste Management Association* 54(4):440-449.

[15]. Rush, A., J. Dougherty, and J. Engel-Cox. 2004. Correlating seasonal averaged in-situ monitoring of fine PM with satellite remote sensing data using geographic information system (GIS). In: Proceedings of SPIE (Chu A, Szykman J, eds). Vol 5547. Bellingham, WA:SPIE

[16]. Slater, J.F., J.E. Dibb, J.W. Campbell, and T.S. Moore. 2004. Physical and chemical properties of surface and column aerosols at a rural New England site during MODIS overpass. *Remote Sensing of Environment* 92:173–180.

[17]. Smart, J.C.R., K. Hicks, T. Morrissey, A. Heinemeyer,, M.A. Sutton, and M. Ashmore, 2011. Applying the ecosystem service concept to air quality management in the UK: a case study for ammonia. *Environmetrics* 22(5):649-661.

[18]. Strandgren, J., L. Mei, M. Vountas, J.P. Burrows, A. Lyapustin, and Y. Wang. Study of satellite retrieved aerosol optical depth spatial resolution effect on particulate matter concentration prediction. *Atmos. Chem. Phys. Discuss*., 14, 25869-25899, doi:10.5194/acpd-14-25869-2014.

[19]. Tunno,B.J., K.N. Shields, P. Lioy, N. Chu, J.B. Kadane, B. Parmanto, G. Pramana, J. Zora, C. Davidson, F. Holguin, and J.E. Clougherty. 2012. Understanding intra-neighborhood patterns in PM2.5 and PM10 using mobile monitoring in Braddock, PA. *Environ Health*. 11:76. doi: 10.1186/1476-069X-11-76.

[20]. van Donkelaar A, R.V. Martin, M. Braue, R. Kahn, R. Levy, and C. Verduzco, et al. 2010. Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: development and application. *Environ Health Perspect* 118:847–855.

[21]. Wang, J., and A. Christopher. 2003. Intercomparison between satellite-derived aerosol optical thickness and PM2.5 mass: Implications for air quality studies. *Geophysics Research Letters* 30:1–4.

[22]. Zanobetti, A., N. Franklin, P. Koutrakis and J. Schwartz. 2009. Fine particulate air pollution and its components in association with cause-specific emergency admissions. *Environmental Health* 8:58–70.