ASSESSING SATELLITE-BASED AEROSOL RETRIEVALS AND GROUND TRUTH VALIDATION FOR TERRA'S MODIS SENSOR OVER URBAN AREAS USING THE GLOBE PROGRAM'S HANDHELD SUN PHOTOMETERS

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Abstract

The Edmund Burke School collected numerous GLOBE measurements from 2002 to the present. Working with David Brooks in his scientist, teacher, student partnership concept, Gianna D'Emilio, a Burke ninth grade student, expanded her 9th grade science fair project into a much larger undertaking. Gianna and three other students took aerosol measurements coinciding with the times of overflights of the Earth-observing spacecraft TERRA because "ground truth validation" is an essential component of any program that attempts to use space-based measurements to study Earth's atmosphere. The MODIS measurements collected on TERRA were used to calculate aerosol optical thickness (AOT) at several wavelengths. The team of students completed nine months of AOT measurements, refined the GLOBE *Aerosol Protocol* and has established a data analysis protocol to be used by another team of trained students as part of their long-term science education. The results presented in this paper are inconclusive due to a number of unknown variables. Although GLOBE's ground validation yielded values 0.64 - 4.08 standard deviations below the MODIS AOT values, we cannot be sure whether this is due to procedural (systematic), or random discrepancies.

Research Question

Can the accuracy of MODIS' Aerosol Optical Thickness observations be validated over urban areas by GLOBE's ground validation techniques?

Background

Aerosols have both natural and man-made sources. Volcanoes, dust storms, agricultural activity, marine spray, air pollution from industrial activity, fossil fuel burning, and forest fires all contribute, influencing both weather and climate. The details of their effect on climate (and, in particular, on models for

Diagram 1: Landsat image of Washington DC, 2001

forecasting future climate) are not well known, although aerosols are generally believed to have an overall cooling affect on the atmosphere. Aerosol concentrations are typically determined by measuring the amount of direct sunlight at a particular wavelength that reaches the ground, and the concentrations are expressed as aerosol optical thickness. Put in perspective, an aerosol optical depth of 1 means that only 37 percent of the direct sunlight is getting through the aerosols in the atmosphere. Satellite-based observations of aerosols compare the amount of light coming up from the atmosphere with the amount of sunlight entering the top of the atmosphere. The light must pass down through the atmosphere, reflect off the surface, and then pass back up through the atmosphere to the satellite detector. The data analysis techniques work well over dark and homogeneous surfaces, especially open ocean. When MODIS takes AOT measurements over oceans, because of its homogeneity, the albedo (the percentage of light reflected from the surface) remains uniform over large areas, and the differences are caused by variations in aerosol optical thickness. However, land surfaces, such as urban areas, are usually non-uniform and vary in albedo causing random and systematic errors in AOT calculations. For example, in a single pixel over an urban area, surfaces such as snow, vegetation, tarmac, or glass and building materials can present a wide range in albedo. This variation in surface reflection induces error in the interpretation of the satellite data. According to Yoram J. Kaufman and Didier Tanre the estimated uncertainty of MODIS sensor in calculating AOT over land can be modeled as +/- 0.01 to +/- 0.005(Kaufman et al, 1998**).** The algorithm used to calculate the AOT using MODIS data over the land is very different from that over oceans. Over land the aerosol concentrations are calculated by comparing the "relationship between the measured radiance at the top of the atmosphere and the surface bi-directional reflectance properties"(Kaufman et al, 1998**).**

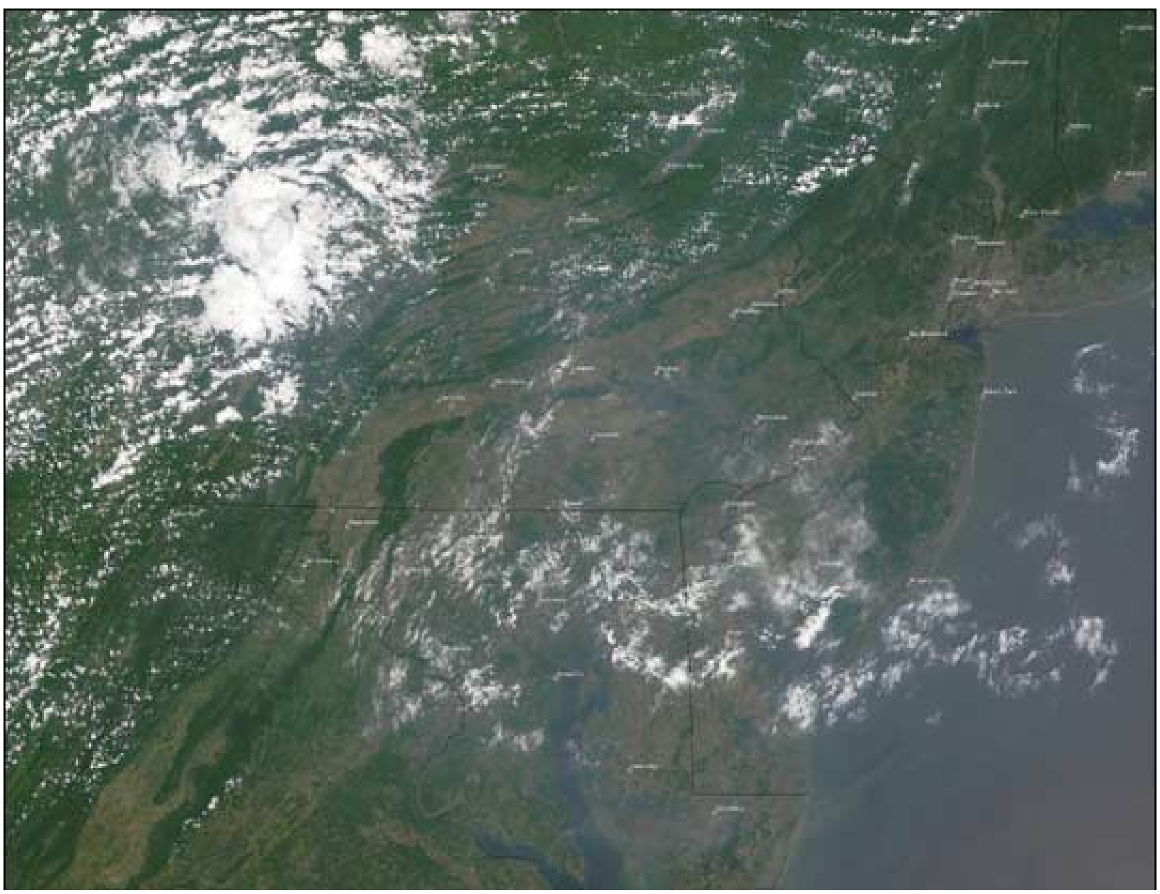


Diagram 2: MODIS Image. Code Red Air over Mid-Atlantic States. Mar 18, 2003

A potential means of assessing the accuracy of the MODIS AOT data product over urban areas is to compare it with reliable ground-based data, in this case collected through the GLOBE *Aerosol Protocol* (Brooks, 2001). This paper presents a series of such measurements made during spring, summer, and fall, 2002, in Washington, DC. The measurements are timed to coincide with overflights of NASA's TERRA spacecraft, which is in a mid-morning sun-synchronous orbit. Comparisons between the GLOBE measurements and MODIS aerosol retrievals are shown, based on the most up-to-date MODIS data available at the time of the presentation.

We believe that the accuracy of MODIS' Aerosol Optical Thickness measurements can be evaluated by comparing with ground validation measurements taken using the GLOBE Protocol. The original ground based observational data is presented as follows.

Hypothesis

The accuracy of MODIS' Aerosol Optical Thickness measurements can be evaluated by comparing them to GLOBE measurements.

Research Method

Our project began when a ninth grader, Gianna D'Emilio, and her science teacher, Frank Niepold, were searching for a science topic for her ninth grade science class project. Around that time, a representative of the GLOBE Program contacted Frank Niepold and asked if he and some students could develop a satellite-based project using a GLOBE protocol to present at the 2002 International Space Congress in Houston, Texas. Frank and Gianna selected a measurement in the *Aerosol Protocol* and expanded it to include ground validation of satellite based Aerosol Optical Thickness (AOT). As the task grew out of the scope of one student's reach, three additional students, Melanie Benetato, Jordan Glist, and Chris Hanawalt, joined the project, to meet the growing workload. There were multiple steps in this project. Students were assigned separate roles based on their availability and talents. Three students were in charge of collecting the daily voltage observations and atmospheric conditions, while another was responsible for entering the data into the email spreadsheet form and compiling the other corresponding values (barometric pressure and temperature.) To accommodate schedules, we alternated the responsibility of data collection for weekends and holidays, while individuals who had a free period during the school day at the overflight time arranged to collect the data. Over the summer (June 9th-August 27th, 2002) data collectors took shifts of two weeks at a time. In the new school year, while this team collected the data through January 10th, 2003, a new team of 9th graders trained in the process of taking measurements.

As soon as the team had collected a sufficient amount of data, we began to analyze our findings. We consulted with Dr. David Brooks on data analysis techniques. Even though part of the project was completed as a long-term project in one class, the majority of the work was extracurricular. The size and duration of this project required the team to work beyond the scope of any academic requirement.

Materials

- GLOBE sun photometer with marked rear alignment bracket with a built-in digital voltmeter
- hand-held GPS receiver: (GPS, the Global Positioning System)

  Note the GPS is used as our most accurate timepiece
- *Sun Photometer Data Sheet*
- pencil or pen
- Celsius calibration thermometer (+/- 0.5 degrees C)
- an accurate barometric pressure and temperature source (web page or automated weather station)
- GLOBE Cloud Chart
- protective cooler, large enough to hold the cloud chart, thermometer, GPS and photometer
- Davis VantagePro weather station (used to obtain the temperature and barometric pressure within 15 minutes of the voltage measurement)

Procedure

a. We downloaded the overflight predictions from the Satellite Overpass Predictor, which tells you what time to take your measurements. The measurements were taken as close to the given time as possible. Even if we were about 10 minutes late or early compared to the time of MODIS overpass, we still took measurements. Thorough metadata was taken.

http://earthobservatory.nasa.gov/MissionControl/overpass.html

b. We took data following the GLOBE *Aerosol Protocol*.

Photos of students collecting the AOT data from our Aerosol site. Note the blue cooler used to keep the instrument at near room temperature.

c. We did not take all of our measurement at a single site. However, all were within 3 kilometers of the registered site and the site used was indicated at the top of the data sheet each day.

d. In order to get the most accurate time reading for our measurements, we used a GPS receiver to tell the time.

e. To keep the photometer as close to room temperature (about 20 degrees Celsius) as possible, we kept it in a food cooler so it would not get too hot when we took it outside.

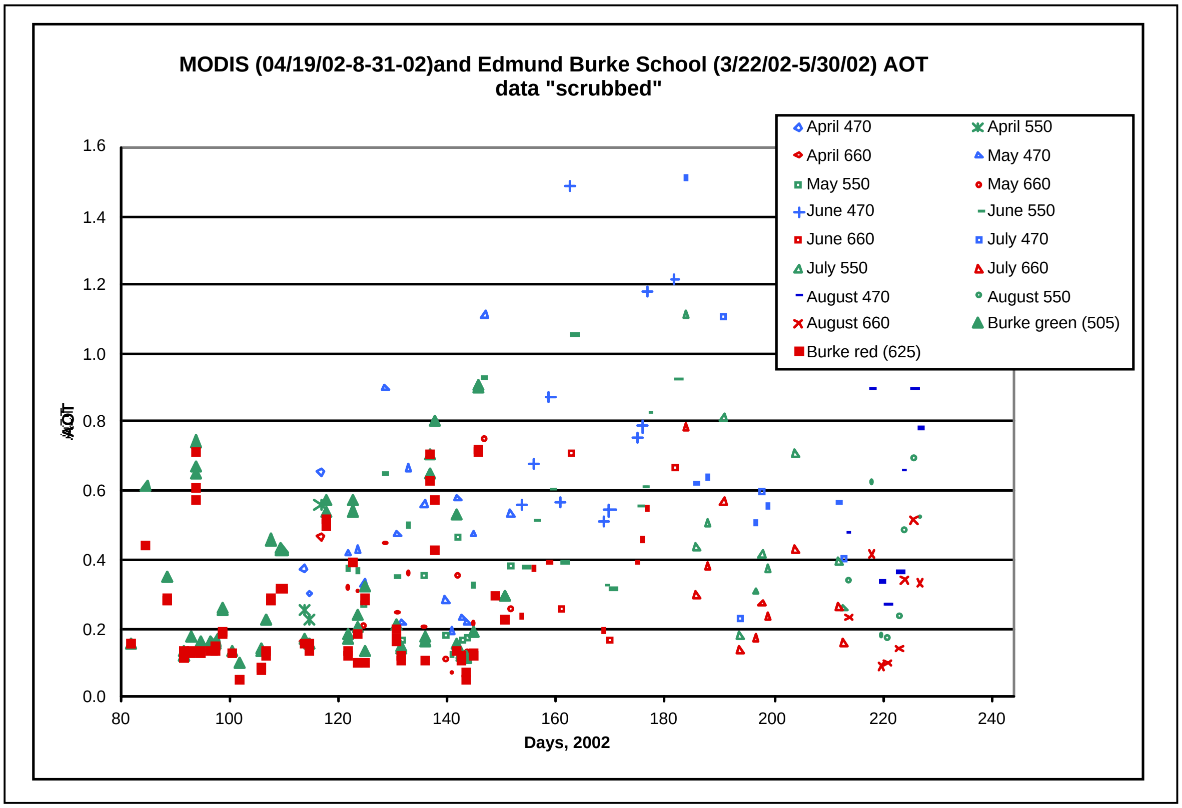
f. We used barometric pressure and temperature data from our school's weather station located about 1 kilometer from the observation site.

g. We entered the data using the GLOBE program's Email Data Entry spreadsheet form for Aerosols (http://www.globe.gov/hq/templ.cgi?emaildatanew&lang=en&nav=1#AZ) and sent the data to Dr. David Brooks. Dr. Brooks processed the data to calculate the AOT values.

h. MODIS AOT data products for our registered site were downloaded.

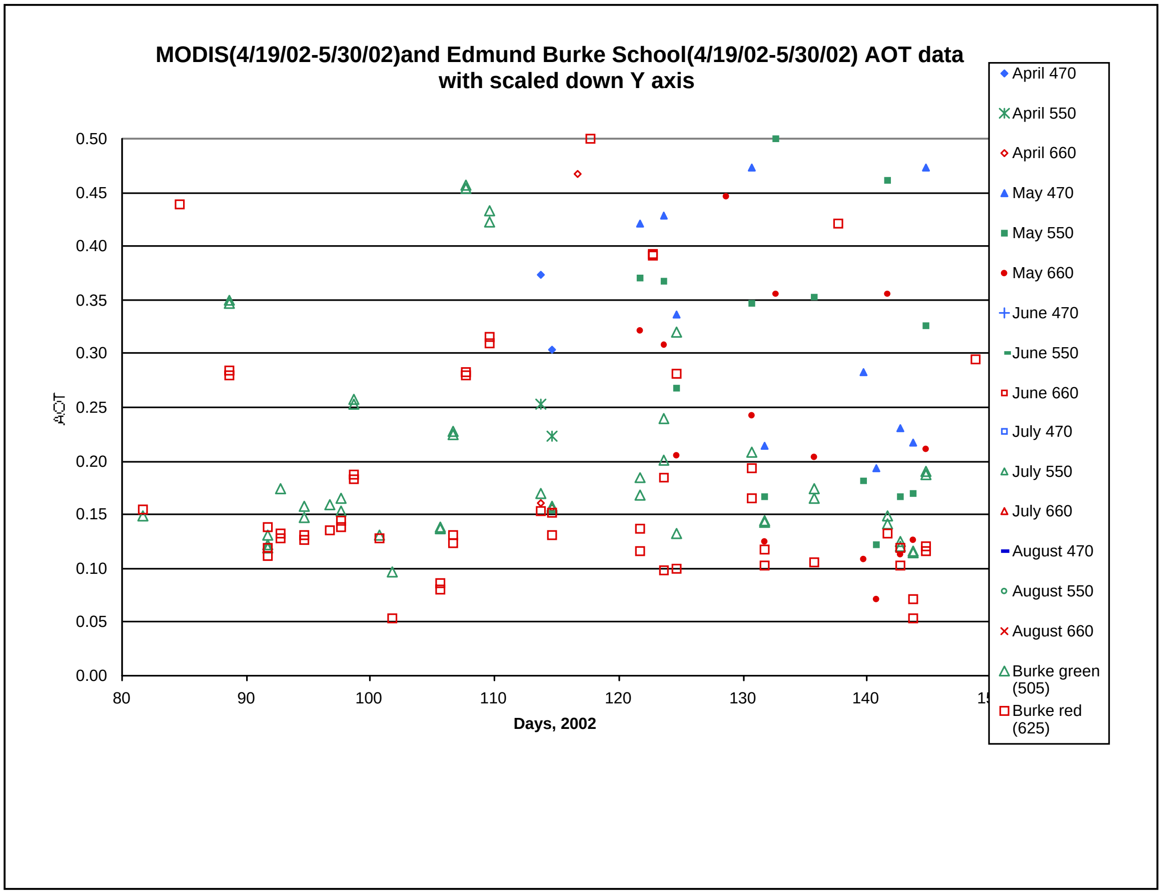
"Scrubbing" the Data:

Due to various problems that occurred when taking measurements, some of the data entries that we collected were not useful and therefore needed to be taken out of the dataset to be analyzed. Because AOT values increase as obstruction of the sky increases, we wanted to delete the highest AOT values that we collected. Since the Edmund Burke School is close to the Goddard Space Flight Center's Aeronet station, we used the highest recorded AOT as an indicator of the top end of acceptable AOT values. The highest aerosol readings ever recorded in the eastern U.S. (at NASA's Goddard Space Flight Center) have approached values of 1.5 to 2. Our measurements that have an AOT over 1 are likely to have had a cloud or some other error that made the voltage reading lower than it should have been, resulting in a very high AOT. We chose to delete all data



Graph 1: All data that had been collected at the Edmund Burke School, processed to calculate the AOT by Dr. David Brooks, and the MODIS AOT values calculated for the Edmund Burke Schools registered ground validation site are shown in this graph. The Burke data stops at May 30th, 2002, while the MODIS data continues to August 31st, 2002. This is due to a processing delay. In the second data analysis, all the data for both Burke and MODIS will be scatter plotted. The center is approximately 15 kilometers from the school.

points with AOT's greater than 1, and keep only those with AOT's less than 1. For example, within the period of April 27th to May 30th, we found 7 days where the AOT value exceeded 1. We deleted these days because in each case the value was high and the readings were taken under cloudy conditions (sky was overcast or broken clouds; a cloud obstructed one reading). Next, we checked back to the Data Sheets for days with any abnormal cloud cover or error. If there was a significant error, we removed these measurements from the dataset.



Graph 2: The same data that is presented in graph 1 is shown here in an expanded form due to the scaled down Y-axis. All cloud cover conditions are shown.

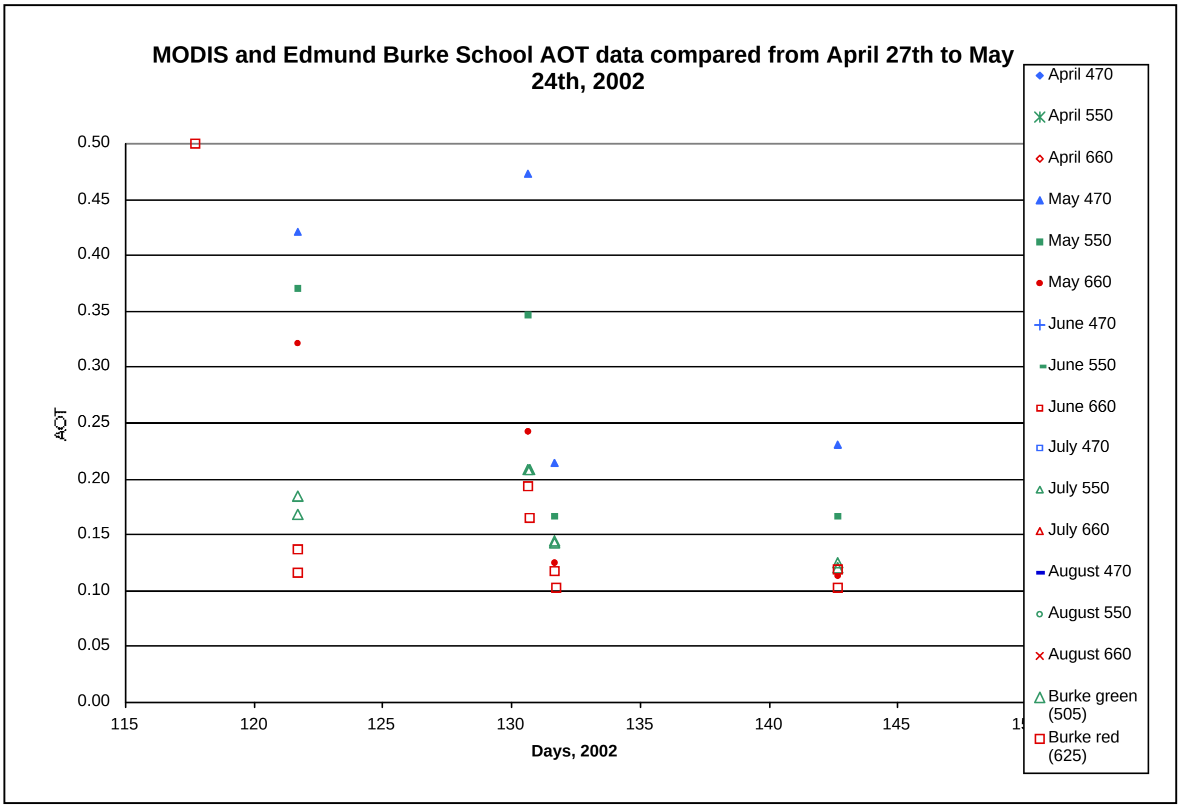
After deleting the least accurate days in the data set, we isolated the "ideal" days from our data. Days that have the least haze, clouds or other obstructions give the most accurate readings, therefore making them the ideal for comparing to the MODIS data. We then removed the questionable data from our dataset and isolated the days that were clear or had isolated cloud cover. We also identified the days where the sky condition was either somewhat hazy, clear or unusually clear.

Table 1: For the period April 20th to May 28th, we found 6 days where the AOT value exceeded an AOT of 1.

	4/20/02	5/17/02	5/21/02	5/25/02	5/27/02	5/28/02
CLOUD COVER	Overcast	Broken Overcast	Scattered	Scattered	Overcast	Broken
CLOUD TYPE	Stratus	Stratus Stratocumulus Cumulus	Cirrocumulus Cumulus	Cirrostratus Cirrocumulus Stratocumulus	Cirrostratus Stratocumulus	Altocumulus Stratus
SKY COLOR	Milky	Pale blue	Deep blue	Pale blue	Milky	Light blue
SKY CONDITION	Very hazy	Somewhat hazy	Somewhat hazy	Somewhat hazy	Very/Extremely hazy	Somewhat hazy
ABNORMAL CONDITIONS	"Very cloudy, overcast, only faint shadow"	N/A	"Clouds passing over sun, sometimes really hard to see circle of light	N/A		"Clouds while doing measurements "
MODIS AOT	GN RN IRN	G 0.856 /R 0.589 /IR 0.381	G 0.579 /R 0.462 IR 0.355	G 0.808 R 0.611 IR 0.524	G None R None IR None	G 0 R 0 IR 0.239
BURKE AOT	G 3.740 3.558 R 3.451 3.563 IR None	G 2.024 0.803 R 0.421 0.572 IR None	G 0.525 0.148 0.141 R 1.068 0.133 -1.975 IR None	G 0.711 0.721 1.020 R 0.897 0.904 1.102 IR None	G 1.709 2.109 R 1.536 1.692 IR None	G None R None IR None

Analysis

In order to get the most accurate comparison between the data we collected and the data collected by MODIS, we include only the "ideal" days in our data analysis. The days that we included in our data the days with the least amount of clouds or other obstructions that may contaminate the measurements. We decided to include *only* the days with "no clouds", "clear", or "isolated" cloud cover in our analysis. (See Graph 3 orTable 2) We then excluded the remaining days from both our data and the data collected by MODIS in order to give us the closest comparison possible.



Graph 3: This graph represents the final analysis product of the ground validation of the MODIS measurements over the registered Burke validation site. To visualize the "ideal" conditions for a ground validation point all cloud conditions other than "No Clouds," "Clear" (0%-10% cover) or "Isolated" (10%-25% cover) were removed.

Of the 6 days in May 2002 were we had both MODIS AOT values and "ideal" cloud cover conditions to compare to our observations, we found that there were numerous differences to explain. The MODIS mean and pval calculations had consistently higher AOT values than our observations. The differences displayed in table 3 ranged from 4.08 to 1.36 standard deviations from the green MODIS mean values. The red MODIS mean values on the whole varied less than the green when compared to our observations. They ranged from 3.14 to 0.64 standard deviations.

Year	Month	Day	Time[UT]		Cloud condition	Sky condition	Color
2002	4	27	16	25	Clear	Clear	Light blue
2002	5	1	16	5	Isolated	Clear	Blue/light blue
2002	5	10	15	55	Isolated	Unusually Clear	Light blue
2002	5	11	16	40	Clear	Clear	Deep blue
2002	5	22	16	20	Clear	Clear	Blue
2002	5	23	15	25	No Clouds	Clear	Blue
2002	5	24	16	10	No Clouds	Clear	Blue

Table 2: Seven days selected of the 53 processed days where the cloud cover is either clear, no cloud or isolated. These are the "ideal" days using the parameters established through consultation with Dr. David Brooks. More potential days will be included as we obtain the MODIS AOT values for the remaining 6.5 months of AOT measurements (75 measurements) that were collected at the Burke sites.

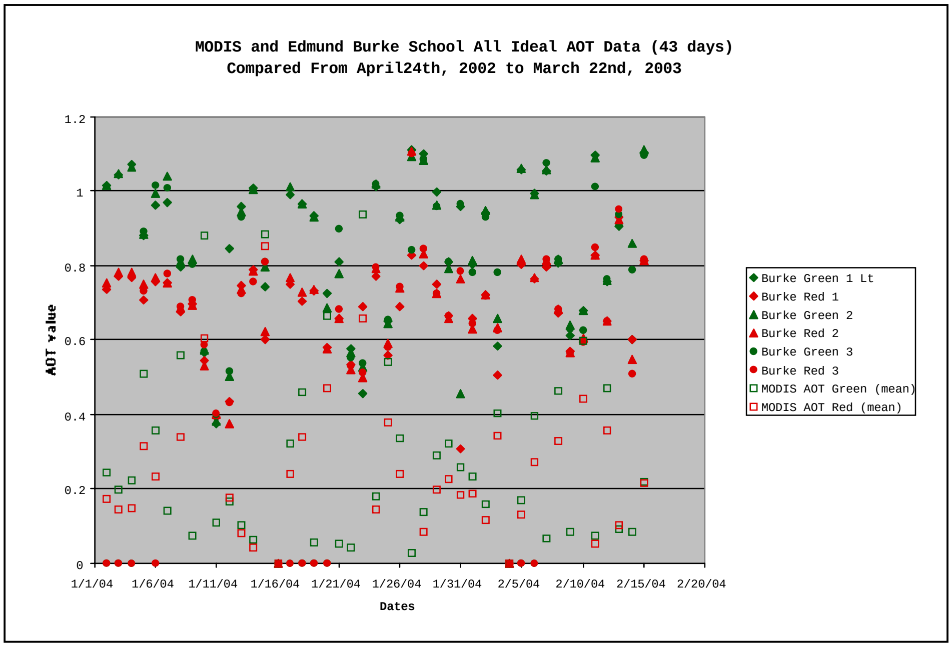
From the second processing of the data, from May 25th, 2002 to March 22nd, 2003, we could not tell whether ground validation helps find errors in the MODIS data analysis as very few values calculated from satellite measurements were similar to the measurements collected at Burke. This could be caused by errors in the processing of the satellite measurements, or in our ground measurements, or both. The MODIS derived values for the first period (March to May of 2002) have consistently higher AOT values than the Burke observations. In a sharp contrast, the second period of the Burke data has constantly lower data than that of the MODIS measurements. This could be caused by cloud formation, which would cause the reading to be unusual, or by other factors in the urban environment. There is yet another factor that could potentially explain this discrepancy. The data processing of our voltages conducted by Dr. Brooks or the data processed by the MODIS science team could have errors that could explain the odd trends demonstrated in graphs 4-7 and graphs 8-13.

Another unexpected finding in the data was MODIS red (550 nm) readings of an AOT up to 50. (As seen in Table 3) An AOT of fifty would imply that the atmosphere contained so many aerosols that they would block out all sunlight from reaching Earth. While clouds can make aerosol readings erroneous, an AOT value this unusually high suggests that there is a processing error in the MODIS calculations.

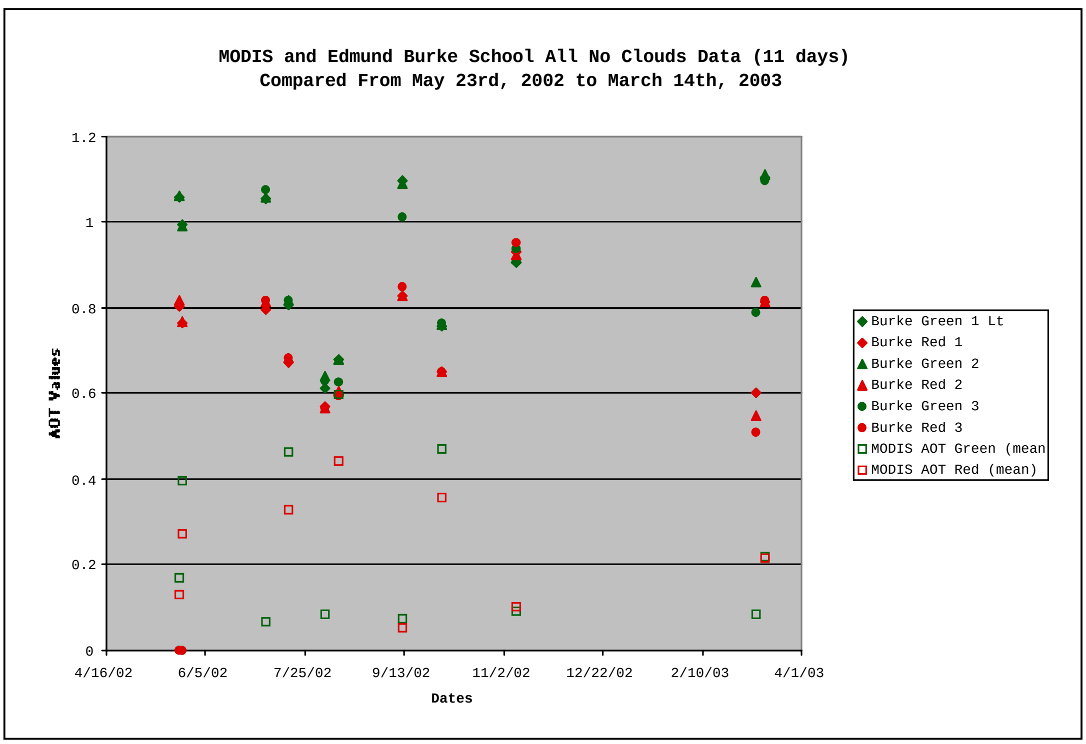
The ideal day for readings is completely clear with no clouds at all (graph 5). Out of all of the "clear" days, there is only one day, March 8, 2003, when the MODIS data matches Burke data (see graph 6). On all other "clear" days, the Burke AOT red values are 0.081-0.403 standard deviations higher than that of MODIS data. In the Isolated days, graph 7, there were not "match points" between the MODIS data and the Burke observations. The general trend is that the MODIS data are lower than the Burke data.

Date	Burke Red #1	Burke Red #2	Burke Red #3	MODIS Mean AOT (550)
5/17/02	0.553	0.47	0	52.567
7/8/02	0.206	0.21	0.211	47.764
6/29/02	0.502	0.505	0.428	36.488
7/16/02	0.696	0.693	0.707	31
5/16/02	0.389	0.425	0	26.568
4/19/02	0.605	0.601	0	22.569
5/25/02	0.382	0.381	0.272	20.042
6/26/02	0.753	0.755	0.777	15.6
9/3/02	0.394	0.4	0.403	12.18
8/4/02	0.569	0.565	0.567	11.866
3/9/03	0.601	0.55	0.509	11.841

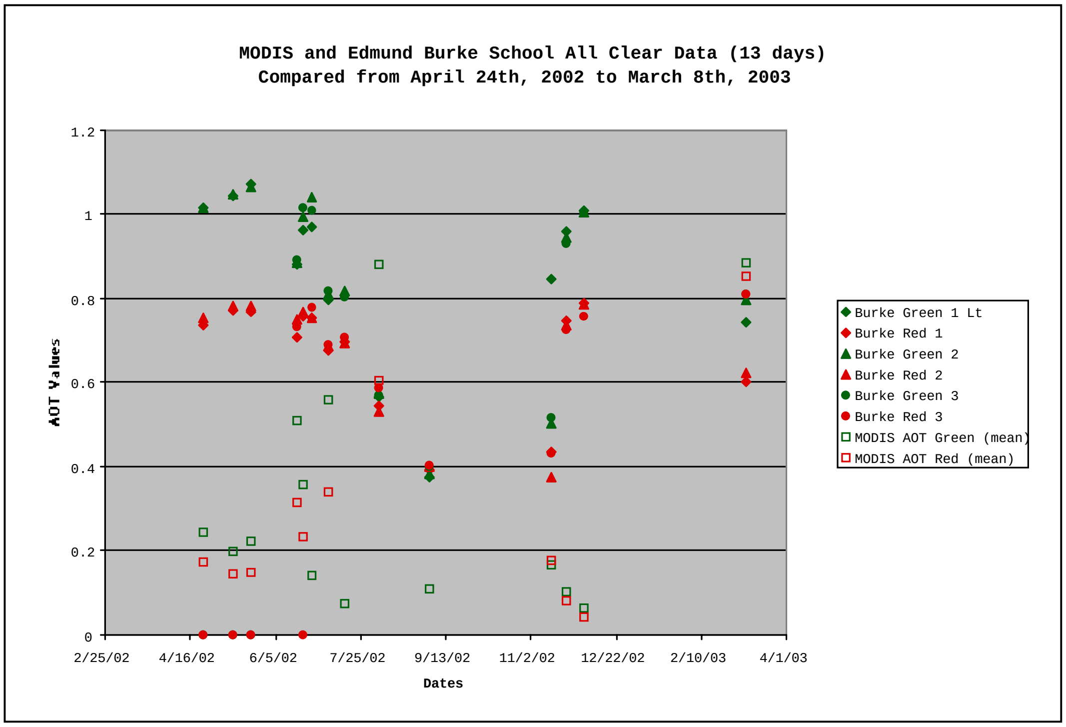
Table 3: In the above table the Edmund Burke school data are compared to the MODIS AOT values for all dates where the MODIS AOT value is over 3.



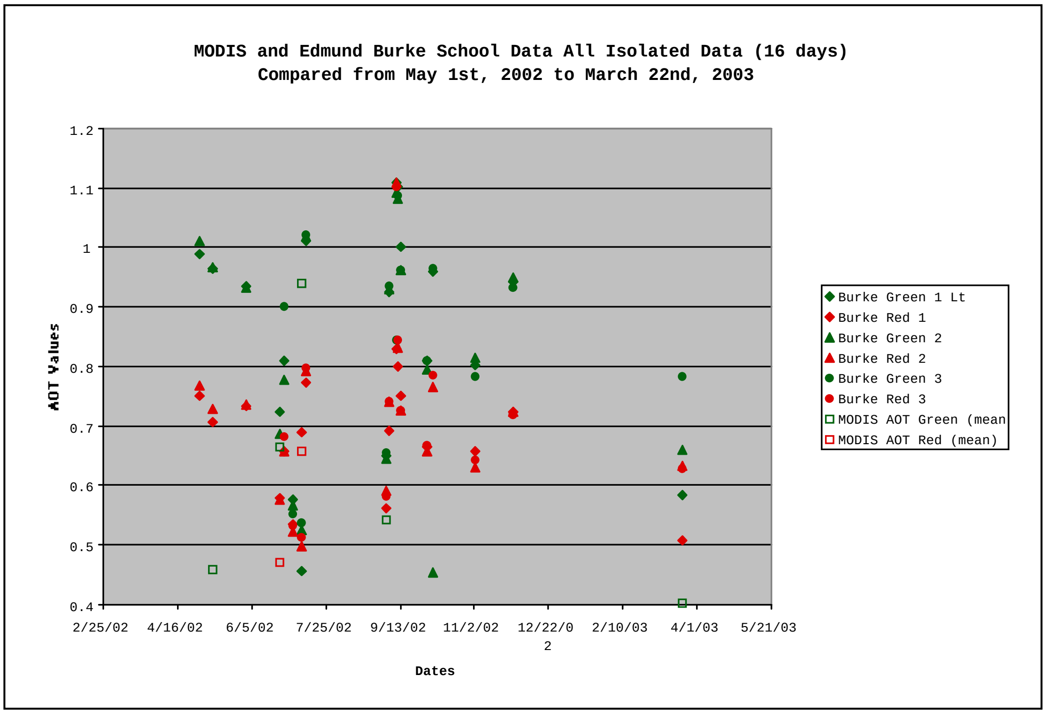
Graph 4: This graph represents the 43 ideal days out of 128 possible days of data collection of MODIS measurements over the registered Burke validation site. "Ideal" conditions for a ground validation point include only cloud conditions of "No Clouds," "Clear" (0%-10% cover) or "Isolated" (10%-25% cover).



Graph 5: This graph represents the 11 data points out of 128 data collection days where there were no clouds at the time of the ground validation of the MODIS measurements over the registered Burke validtion site. "No clouds" signifies zero percent visible obstructions at the time the reading is taken.



Graph 6: This graph represents the 13 data points out of 71 data collection days when the sky was determined to be clear at the time of the ground validation of the MODIS measurements over the registered Burke validation site. "Clear" represents a zero to ten percent cloud cover over at the time the reading is taken.



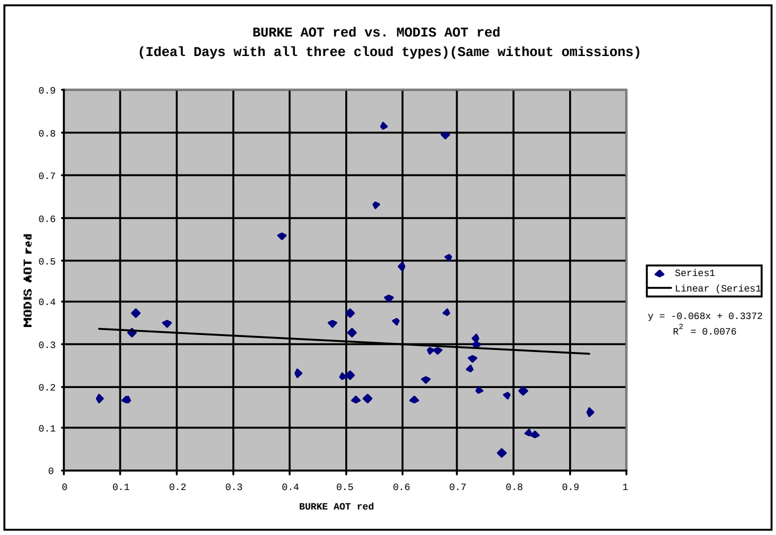
Graph 7: This graph represents the 16 data points out of 71 data collection days where there were isolated clouds at the time of the ground validation of the MODIS measurements over the registered Burke validation site. Isolated denotes a 10% to 25% cloud cover at the time the reading is taken.

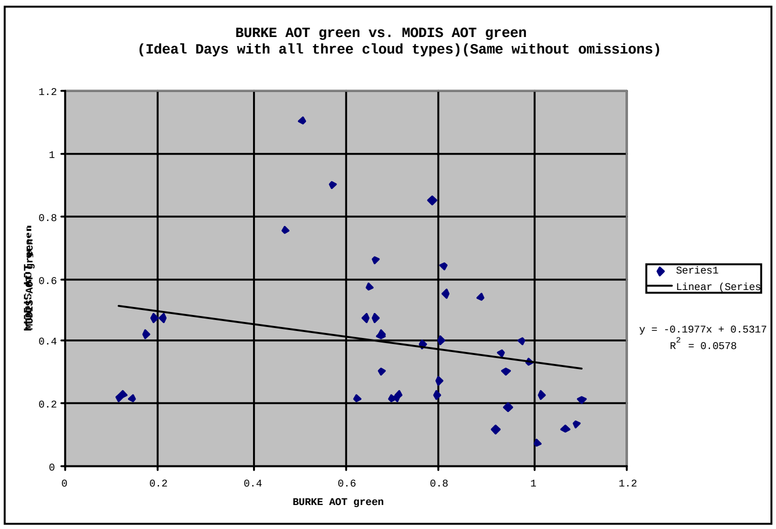
In order to perform a T-test (a recognized statistical test of means), the differences between the Burke AOT values and the MODIS AOT values were calculated for all 39 ideal days (three ideal days were missing data and were not included). The calculations were done independently for green and red wavelengths. Calculations were carried out with the MODIS p-val data, which are the AOT values over a five square kilometers area, centered over our test site. The p-val was used instead of the 50 square kilometer mean because it more closely corresponds to the cloud cover of the measurement site. Since the green AOT values and the red AOT values were handled separately but in an identical fashion and yielded quite similar results, the procedure will be outlined for just the green. The mean and standard deviation of the differences were calculated. A T-test was carried out according to the following formula:

$$t = \frac{(\bar{x} - \mu)}{s / \sqrt{n}}$$

The probability for this t value (with 38 degrees of freedom, since the degree of freedom for a statistic is equal to one less than the sample size) was calculated according to the normal t distribution.

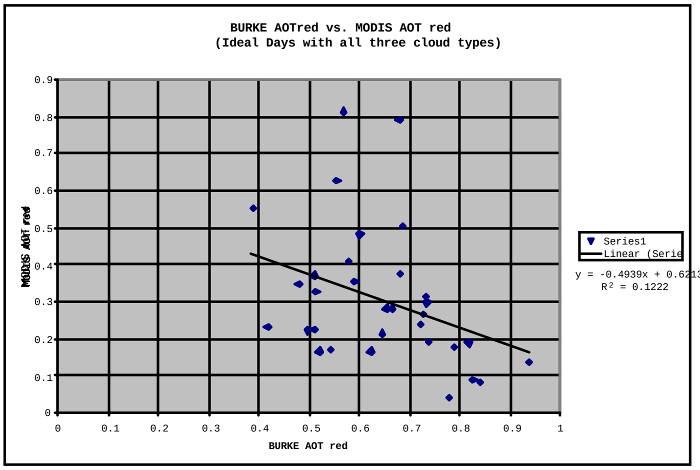
The following graphs of Burke AOT versus MODIS AOT show the same discrepancy. If Burke AOT values corresponded to MODIS AOT values, a positive linear relationship would be expected. However the data, which are highly scattered, show no such relationship. Perplexingly, in fact, an inverse relationship appears to be present. The reason for this is, as of now, unknown.

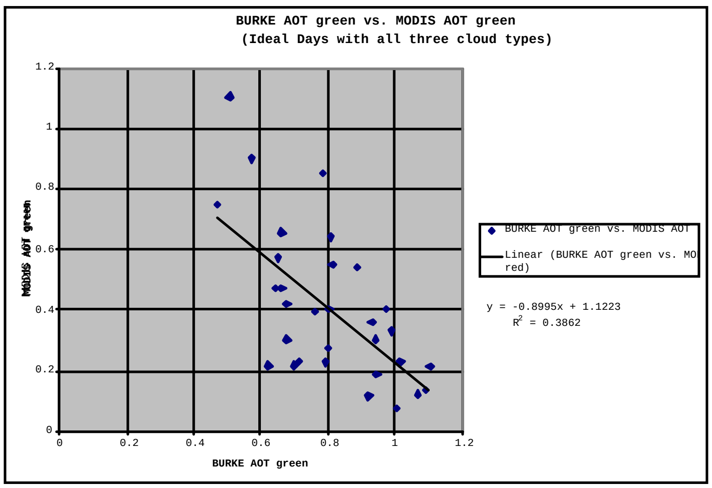




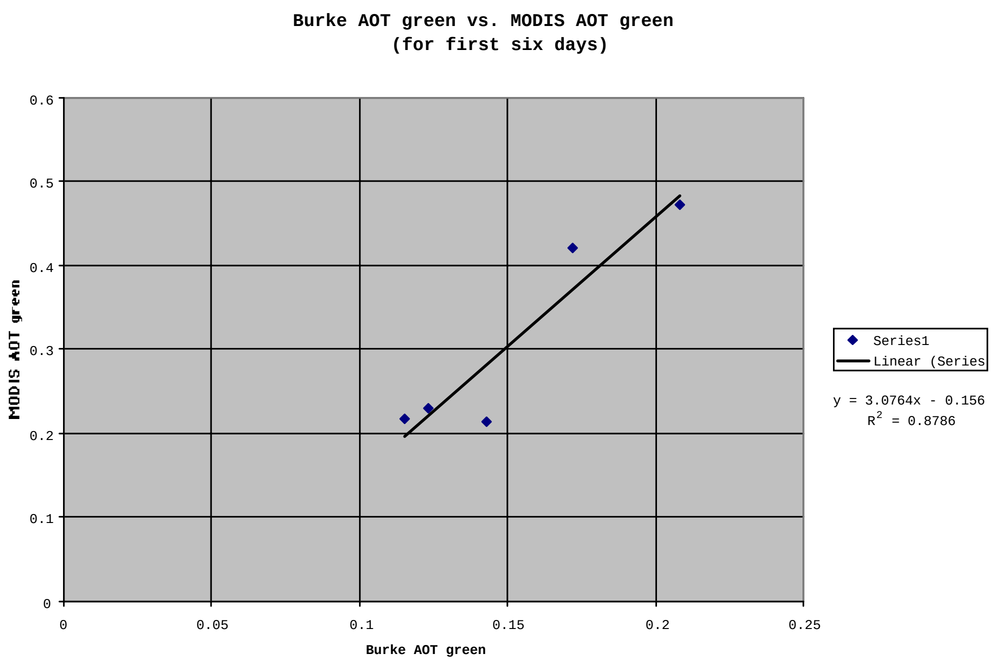
Graphs 8 and 9: "GREEN all days" and "RED all days." These graphs are compiled AOT values for all the ideal days, which we used for data analysis. Each point on the graph corresponds to the Burke AOT value plotted against the MODIS AOT value for the same day. The two clusters of data are evident in each of these graphs. The very low R squared is a result of a linear regression between the two widely scattered clusters of data, which are discussed in greater depth in later graphs.

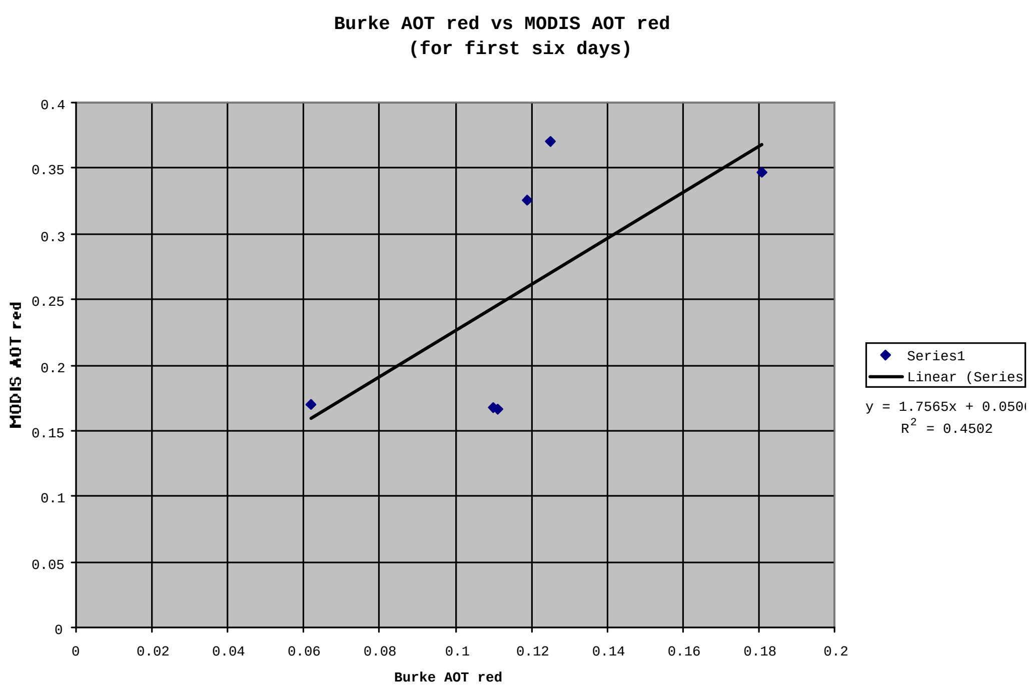
Also it is important to note that the first six ideal days had quite different AOT values than the latter 33. On the first six, Burke AOT tended to be lower than the MODIS AOT and the data showed a more positive trend. However on the latter 33, the opposite is true, as Burke AOT are consistently higher than MODIS AOT and the data showed an inverse trend. Because of this discrepancy three sets of graphs are presented for each wavelength, one with the first six days alone (graphs 12 and 13), one with the last 33 (graphs 10 and 11), and a final set with both sets of days present (graphs 8 and 9). Although there appears to be a positive linear correspondence on the first six days we cannot draw any strong conclusions based upon only six days.





Graphs 10 and 11: “GREEN last 33” and “RED last 33”These graphs contain points which corresponds to Burke AOT values against MODIS AOT values for the last 33 days. In this data the unexplained i0nverse relationship is present. The low R squared is a result of widely scattered data around the regression line.





Graphs 12 and 13: “GREEN first six” and “RED first six.” These graphs show only the first six days Burke AOT values against their corresponding MODIS AOT values. Although a positive regression line was fitted, few conclusions can be drawn from such a small set of data. The R squared for the red data is reasonably high, while the Green data has a lower R squared because it is more scattered. The reason for this is unknown but it is likely to be simply chance variation, which can have a large affect in such a small data set. It is for precisely this that many conclusions can not be drawn from this graph.

Conclusion

When looking at the MODIS green mean AOT (470) or the MODIS red mean AOT (550), and the associated standard deviation, it is important to understand that the mean is calculated from a series of 5 km^2 areas of individual AOT values that are averaged. In table 2, the cloud cover for each day in May is shown. This is relevant when considering there is a high variation in the mean. On May 10th, one of the two days with isolated clouds, there is a high standard deviation for both the green and red values. These variations in the sample could be explained from the 10%-25% cloud cover in the area. However, of the six best days to use for comparison, there were only two. The two days were very similar with no cloud cover whatsoever and also similiar sky condition and color (see Table 2 on page 14). The second day had a higher AOT value in both the Burke and MODIS values. The distance of the reading from the mean was much higher on the second day, May 24th. When we looked at the standard deviation of each day, May 23rd is lower, 0.036 (green) - 0.037 (red). May 24th had a higher deviation, 0.051 (green) – 0.49 (red). Even if we assume that the variability of the atmosphere, through different concentrations of aerosols in the $(50\ KM)^2$ MODIS AOT validation product are the least, on the 23rd of May (our best sampling day) the MODIS AOT value is still, 1.52 deviations for the green and 1.89 deviations for the red, higher than our observations. (See table 4) Through our data analysis, we concluded that we could not validate the accuracy of MODIS' aerosol optical thickness over urban areas by GLOBE's ground validation techniques. Even on days with ideal conditions, such as May 23rd and 24th, the standard deviation of our data was lower, 0.64 to 4.08, than that of MODIS.

In the second processing of the Burke data, from May 25th, 2002 to March 22nd, 2003, a statistical T-test was used to determine the difference in the mean of the MODIS AOT values and the Burke AOT values. The p-value for green is .00002988. For red the p-value is .000003628.

day	Month	Year	BURKE Green AOT	pval_AOT0470corr	mean_AOT0470corr	sdev_AOT0470corr	Percent difference to MODIS pval	Percent difference to MODIS mean	Burke compared tomean sdev (all below)
27	4	2002	0.552	No data	No data	No data	N/A	N/A	N/A
1	5	2002	0.172	0.421	0.321	0.054	59.1%	46.4%	2.76 sdev
10	5	2002	0.208	0.473	0.459	0.068	56.0%	54.6%	3.69 sdev
11	5	2002	0.143	0.215	0.199	0.041	33.4%	28.1%	1.36 sdev
22	5	2002	0.123	0.23	0.224	0.051	46.0%	45.0%	1.98 sdev
23	5	2002	0.115	0.218	0.17	0.036	47.2%	32.3%	1.52 sdev
24	5	2002	0.189	0.473	0.397	0.051	60.0%	52.3%	4.08 sdev
day	Month	Year	BURKE Red AOT	pval_AOT0550corr	mean_AOT0550corr	sdev_AOT0550corr	Percent difference to MODIS pval	Percent difference to MODIS mean	Burke compared tomean sdev
27	4	2002	0.51	No data	No data	No data	N/A	N/A	N/A
1	5	2002	0.125	0.371	0.24	0.054	66.3%	47.9%	2.13 sdev
10	5	2002	0.181	0.347	0.339	0.077	47.8%	46.6%	2.05 sdev
11	5	2002	0.11	0.167	0.144	0.052	34.1%	23.6%	0.65 sdev
22	5	2002	0.111	0.166	0.147	0.056	33.1%	24.4%	0.64 sdev
23	5	2002	0.062	0.17	0.132	0.037	63.5%	53.0%	1.89 sdev
24	5	2002	0.119	0.326	0.273	0.049	63.4%	56.4%	3.14 sdev

Table 4: The above table shows the AOT values for both the Edmund Burke Schools AOT measurements compared to the MODIS AOT values. The MODIS values have been calculated in two ways. The pval AOT, according to Dr. Brooks, is the value for the center $(5\ KM)^2$ of the $(50\ KM)^2$ area. The mean value is calculated using the average of all of the 25 divisions of the 50 KM squared area. The standard deviation is of the MODIS mean value. The individual values used to generate the mean value were not available to us for this analysis.

The probability that the differences between Burke data and MODIS data were due to chance error is .00002988. Therefore we have very strong, significant statistical evidence that the Burke data and the MODIS data are different for reasons other than chance variation. This, again, leads to the final conclusion question, what factor(s) are causing the AOT measurements to be so drastically different?

Discussion: The data has shown that MODIS urban area AOT values cannot be validated by the ground based validation techniques which were used. It may be possible, however, to alter GLOBE's collection procedures in a number of ways (which will be discussed here) so that ground validation may be possible. Currently, GLOBE's ground validation yielded values 0.64 - 4.08 standard deviations below the MODIS AOT values. There are a number of possible explanations for the lack of correlation, but we cannot be sure which is truly the primary confounding factor.

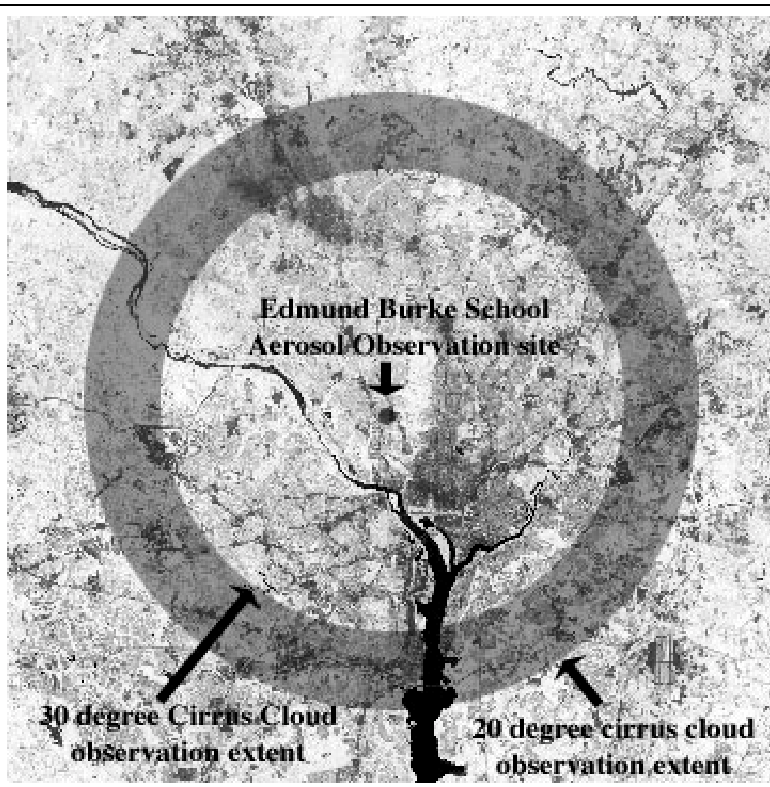


Diagram 1: The Landsat image of the Washington D.C. metropolitan area represents the (50 KM) ^{2} area that MODIS uses to calculate the mean AOT correlation. The potential extent of the geographic area that cirrus clouds, the highest cloud, can cover using a 20º and 30º observation angle is shown by the gray ring in the image. The extent is assuming the cloud heights are 6,000 meters. The area covered by the two observation extents of the MODIS mean area is for the 30-degree observation 13.56% and for the 20-degree observation 34.12%. From these calculations the confidence of the cloud cover measurement are limited.

Procedural (systematic) or actual discrepancies could be explained in part by the way in which MODIS collects its data. As explained earlier, the value calculated by the MODIS algorithms is actually an average of 25 sub areas each measuring 5 square kilometers which total to 100 square kilometers of area. At its best, our GLOBE procedure can only measure 34% of this area. (See Diagram 1) Furthermore, our calculated value is not an average of 25 separate values. This averaging process is likely to have affected the results. However, as we do not know the values of each individual sub area that contributed to the average, we do not have enough information to draw a conclusion about how severely our results are affected. Analyzing these sub area values could help to explain to what degree our results were confounded. Another solution would be to increase the number of current simultaneous ground validations. Not only would this allow for a more reliable comparison, but also a higher sample size would make calculations more accurate. Additionally, the cloud observation extent that can be reliable for identifying an "ideal" validation day is limited when compared to the (100 KM2) MODIS AOT product area. As diagram 1 shows our observations of the sky include at best 34% of the MODIS product area. An improved cloud observation protocol has to be devised. It needs to be able to see a greater portion of the sky and would need to have a lower cloud observation angle, lower than the 20% we relied on consistently. This is higher than the GLOBE cloud protocol specifies.

Our collection technique has been clarified over the past 11 months during which numerous difficulties have arisen. Many days, especially during school weekdays, the students in charge of data collection would have conflicts that prevented them from taking the AOT measurements. For example, sometimes a student would leave the cooler with the instrument at home and an accommodating parent would have to bring it to school, for the measurement to be made. Regardless of the reason, there were several days when the data were not collected. In the coming second round of data collection, we plan to manage the data collection protocol in a more consistent manner. It is likely that there may have been some error in either Burke's or MODIS's AOT calculations. There is a clear discrepancy between sets of days, which were calculated at different times. In order to dispel this discrepancy it would be important to reprocess all of the data, both the Burke voltages and the MODIS processed data, in another attempt to remove the apparent error represented in the MODIS second data set (see table 3). One way to draw a firm conclusion about whether the GLOBE *Aerosol Protocol* could validate the MODIS accuracy over an urban area would be to establish another validation project in an area where the land cover is homogenous in the (100 KM2) MODIS AOT product area. To date, we are unaware of any such project, but we would need to see another set of data to compare the trend of the data relating to ideal days. If the homogenous land cover yielded higher or similar AOT values for the GLOBE AOT measurements, we could more clearly conclude that MODIS' AOT values are consistently higher due to the heterogeneous nature of urban land cover

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