COMPARISON OF DEEP BLUE AND LAND SURFACE REFLECTANCE IN THE SAN JOAQUIN VALLEY

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ABSTRACT

Air quality in the San Joaquin Valley (SJV) has failed to meet federal and state particulate matter (PM) regulation standards for the past several years. While previous studies show strong correlations between the Moderate Resolution Imaging Spectroradiometer (MODIS) derived Aerosol Optical Thickness (AOT) and surface PM measurements on the East Coast of the United States, weak correlations have been found on the West Coast. Specific causes for this discrepancy have not been identified, nor has a solution been found. The Deep Blue algorithm was created in order to correct AOT calculations over arid, non-vegetated regions. Although slight improvements were seen, numbers over California remained problematic. This study aims to understand the poor correlation on the West Coast, specifically in the SJV, by targeting surface reflectance as a factor for the inaccuracy. This will be done by comparing land surface reflectances derived from MODIS Aqua to ground reflectance measurements for the region, in order to examine their correlation. Presumably, an undesirable effect on AOT calculations would occur if these surface reflectance values are imprecise. Results show that there is little correlation between the data sets. MODIS Land Surface Reflectance matched closest to the mixed ground measurements. In all products, the red band (0.620 – 0.670 µm) values vary more than the blue band (0.459 – 0.479 µm) values. Most data seem to fall in a horizontal linear trend line, not the expected 1:1 line.

INTRODUCTION

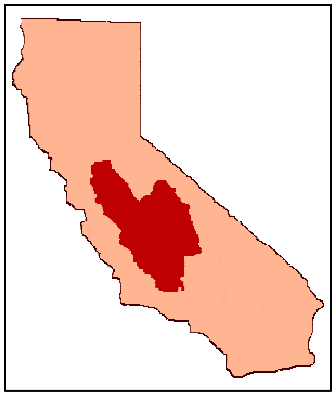

Figure 1. California's San Joaquin Valley Air Pollution Control District shaded in red.

Located in central California, the San Joaquin Valley (SJV, Figure 1) displays some of the poorest air quality in the United States. Since 1999, the Valley's levels of $PM_{2.5}$ (particulate matter with a diameter of 2.5 µm or less) have exceeded federal and state regulation levels. Particulate matter is a "mixture of solid particles and liquid droplets" that can be comprised of a number of chemical compounds, some visible to the naked eye and others that are not (EPA a, 2008). Federal standards require $PM_{2.5}$ levels to be below 15 $\mu g/m^2$ and California state standards require $PM_{2.5}$ levels to be below 12 $\mu g/m^2$ as set by the California Air Resources Board (CARB). The SJV average $PM_{2.5}$ levels have ranged from 18 to 25 $\mu g/m^2$ over the last 10 years. Contributors to the area's air pollution include local agriculture, vehicle emissions, and atmospheric drift from nearby urban populations as well as industrial drift from East Asia (Yu et al., 2008; SJV APCD, 2007). The United States Environmental Protection Agency (EPA), in cooperation with CARB and the San Joaquin Valley Air Pollution Control District (SJV APCD), works to regulate the PM levels in the Valley's Air Basin. The EPA categorizes the Valley Air Basin as a serious nonattainment area for $PM_{2.5}$, or extremely above federal regulation levels for PM (EPA b, 2008). In the

Valley, 66 percent of the population is exposed to health-endangering concentrations of this fine PM (Hall et al., 2008). This high exposure to fine particles can cause a variety of respiratory illnesses, including chronic bronchitis, as well as an increase in cardiovascular problems (Hall et al., 2008). Additionally, since the SJV has been a leading contributor to the United States agriculture industry, the fact that pollution significantly reduces crop yield is cause for even greater concern (Chameides et al., 1999). Due to the fact that the SJV air basin has exceeded federal and state regulation levels of $PM_{2.5}$ for nearly a decade, having accurate measurements of air pollution in the Valley is critical (CARB 2009).

Although federal, state, and local agencies use ground sensors to regulate SJV air quality, there are only a few sensors in the valley and the measurements taken are representative of the conditions for only a limited range surrounding the ground sites. For a better overall understanding of the Valley's air quality, a data source not limited by specific ground sites is necessary. Satellites provide a continuous synoptic coverage of the entire region. Many NASA satellites collect aerosol optical thickness (AOT) data, which is a measurement of the aerosol content in an atmospheric column. Solar radiation enters the Earth's atmosphere and may be interrupted by a variety of particles of matter, such as dust and smog. A clear sky provides the sunlight a direct path to the surface of the Earth, allowing it to reflect back from the land increasing the amount of light that is reflected back from the surface. In an aerosol filled or cloudy sky, sunlight is reflected off the surface of the particulate matter or cloud, decreasing the amount of sunlight that actually reaches the Earth's surface, thus reducing the amount of sunlight that is reflected back. Other factors that impact the reflectance of surfaces such as soil are moisture and organic matter content, as well as the mineralogy and texture (Sharma et al., 2009) The Moderate Resolution Imaging Spectroradiometer (MODIS) one such instrument that is used to get daily AOT coverage.

Past studies have shown that on the East Coast, MODIS AOT measurements correlate sufficiently with surface PM measurements (Engel-Cox et al., 2004), but on the West Coast, measurements do not correlate adequately (Ballard et al., 2008 and Engel-Cox et al., 2004). Thus, this study focuses on understanding the reason behind this discrepancy. During the spring of 2009, a group of DEVELOP interns at the NASA Ames Research Center made a comparison of the hourly and daily surface PM measurements to Aqua MODIS Traditional and Deep Blue AOT data as well as analyzed "the effects of relative humidity, and surface reflectance on differences in PM and AOT measurements" (Justice et al., 2009). They found that $PM_{2.5}$ data in the Fresno and Bakersfield area correlated better with MODIS Deep Blue measurements of AOT than with traditional MODIS AOT measurements, but could not make a conclusive statement regarding the effects of surface reflectance and relative humidity.

This study further examines the role of surface reflectance in the calculation of MODIS AOT to determine if it has an adverse affect on the MODIS AOT calculations. In order to do so, this study focused on the comparison between the surface reflectance products of MODIS Deep Blue and MODIS Land Surface to discover if a missing pattern of distortion exists that needs to be factored into the AOT algorithm.

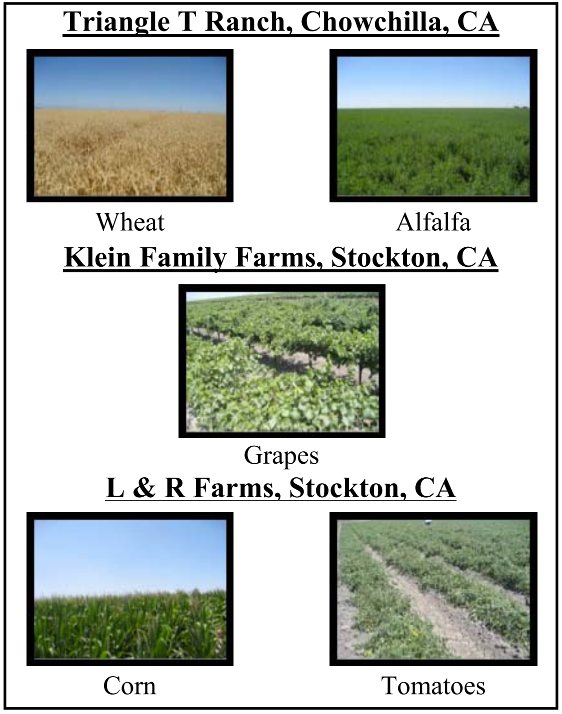

Figure 2. Crop Type and sampling locations.

METHODOLOGY

This study compared ground measurements to three MODIS reflectance products: Deep Blue, Traditional, and Surface Reflectance. All data were concentrated within the SJV. Crop reflectance measurements were taken from a variety of sites: wheat and alfalfa from Triangle T Ranch, Chowchilla, California, grapes from Klein Farms, Stockton, California, and corn and tomatoes from L&R Farms, Stockton, California (Figure 2). All sites were chosen based on the crop field dimensions and commonality of crops being grown within the SJV.

Ground Measurements

In order to validate the surface reflectance product of MODIS for the SJV, it is necessary to compare the satellite data to actual measurements from the region. The current Deep Blue AOT is processed from measurements taken by the MODIS instrument on the Aqua platform and has an ascending equatorial crossing time of 1:30 PM. Knowing this, we set the range of possible sampling times (and acceptable solar angles) within a 5 hour window (11:00 AM to 4:00 PM) on July 7th and 8th, 2009. Wheat, alfalfa, grapes, corn and tomatoes were the crops selected because of their large area of cultivation in the SJV. Reflectance measurements were collected through the use of an Ocean Optics USB4000 spectrometer at a height of 3.20 m from the crop leaf surfaces. A piece of black plastic tubing was placed around the lens to decrease the field of view from 180 º to 55 º. To ensure that the instrumentation was correctly calibrated, the measurements were set with a 99 percent reflectance spectralon panel as the bright target and a covered lens for the dark source. To ensure that the instrument was providing accurate reflectance values we used known reflectance panels to find the percent error. A 1 – 3 percent absolute error was found for the blue wavelengths and a 0 – 3 percent absolute error for the red wavelengths (Figure 3a), which were then used to correct the averages of the ground measurements (Figure 3b). Figure 3b shows that in both wavelengths, alfalfa had the lowest reflectance due to its high chrlorophyll absorption and the wheat had the highest reflectance because it was dry and photsynthetically inactive (de Almedia Castanho et, al., 2007).

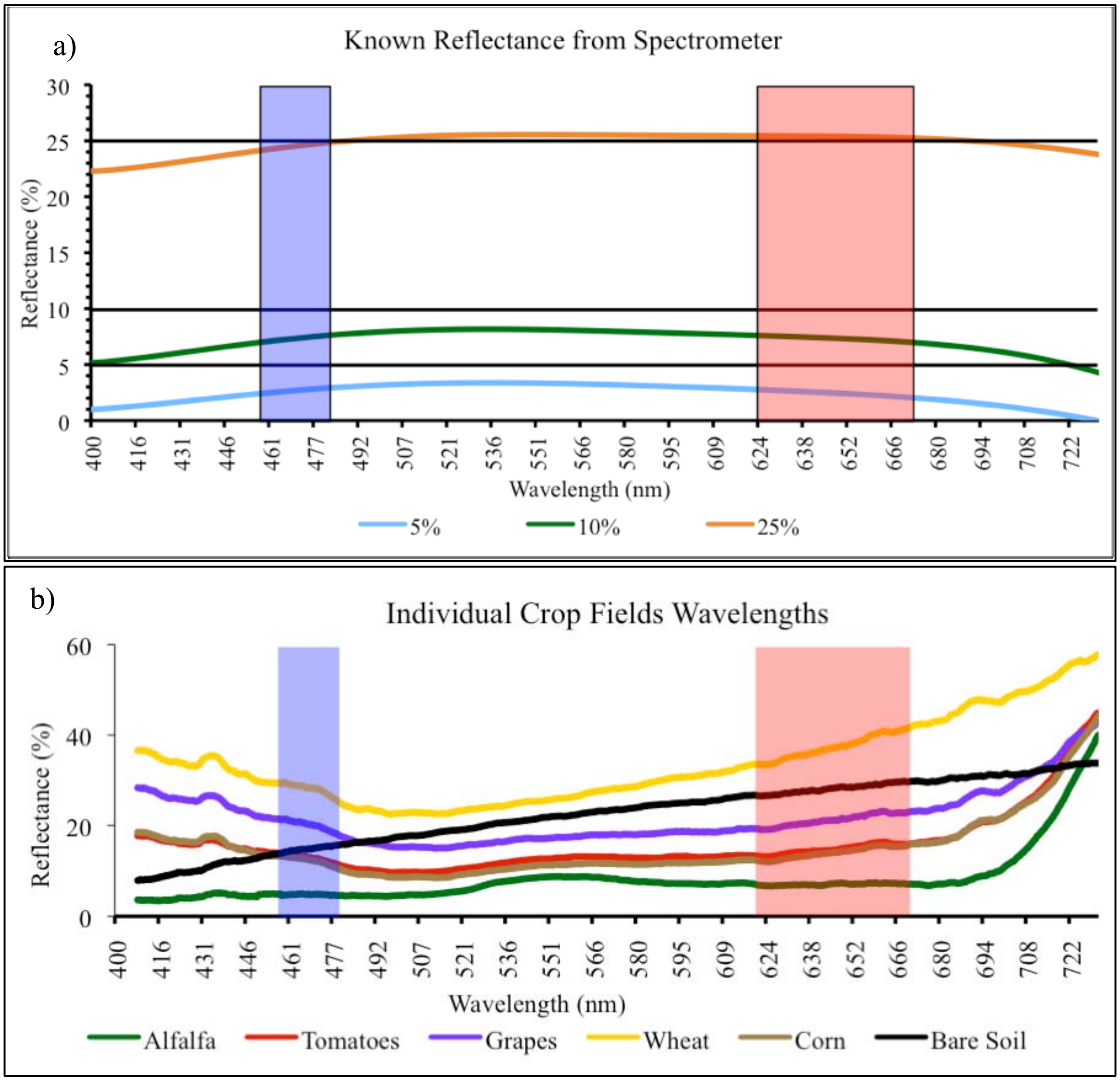

Figure 3. a) Reflectance data for standard reflectance panels used to calibrate the ground data. b) The average of the five crops and bare soil with the blue and red wavelengths highlighted.

Each crop field was at least 500 m x 500 m in size to compare with both MODIS pixel resolutions. A 6 x 6 array of points spaced 10 meters apart was collected for each crop field to efficiently and effectively take measurements in large fields, thus providing a total of 36 measurements for each crop. The fields were sampled so that the proportions of thickly to thinly vegetated regions, as well as plant to soil ratios, were taken into account. Since most fields are uniformly planted, it can be assumed that the small sample taken will accurately represent any field of its type. For both data collection days, conditions were similar in nature: no clouds present, temperatures were in the mid-90s, and the evapotranspiration (ETo) was 0.29 to 0.31 inches (CIMIS, 2009).

MODIS

MODIS (Figure 4), aboard both Terra and Aqua NASA satellites, continuously acquire daily global measurements at 36 spectral bands (0.41 – 14µm) and at three different spatial resolutions (250 m, 500 m, and 1 km) (Salomonson et al., 1989) within a 10 km by 10 km area for atmospheric products and 500 m x 500 m area for land products. The spatial and temporal resolutions from MODIS are well suited for evaluating air quality on local, regional and global scales.

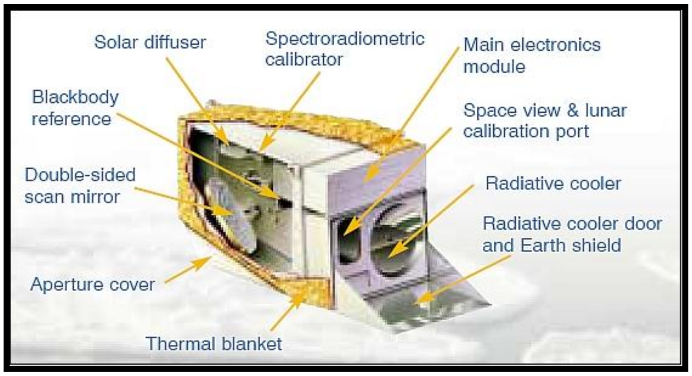

Figure 4. MODIS Instrument .

The Traditional Aqua MODIS AOT retrieval algorithm uses the dark-target reflectance method to retrieve AOT values, which assumes the ratio of surface reflectance between 0.47 µm and 2.1 µm is 0.25 and between 0.64 µm and 2.1 µm is 0.5. To calculate the surface reflectance for each 10 km x 10 km area, this particular algorithm, after masking clouds, water, and ice, discards 50 percent of the brightest pixels and 20 percent of the darkest pixels in an area to lessen contamination and balance the darker features. If there are at least 12 good pixels left within a box of 400 pixels, the average is calculated providing the overall surface reflectance for that box. Boxes that have fewer than 12 good pixels, however, receive a value of zero. These values are then placed in a monthly look up table (LUT). The algorithm is useful for collecting data above densely vegetated surfaces, but is not satisfactory over highly reflective surfaces such as cities and deserts (Remer et al., n.d.).

This necessitated the creation of the Deep Blue algorithm, which has been shown to be successful at collecting AOT measurements over such surfaces. Deep Blue uses a set of LUTs based on a polarized radiative transfer model simulating satellite signaling in the solar spectrum vector code (6S code), allowing it to simulate the radiance for "a range of solar and viewing geometries at the top of the atmosphere" (Hsu et al., 2004). According to Clare Salustro from the MODIS Deep Blue team at the NASA Goddard Space Flight Center, for surface reflectance values, Deep Blue uses the minimum reflectivity technique, where the clearest pixel value is chosen out of 0.1° latitude by 0.1° longitude resolution for a three-month period (April – June, August – October and December – February). The pixel value is then placed in a corresponding seasonal LUT (Hsu et al., 2004). For March, July, and November, the LUTs are populated by averaging the pixel value of the two tables it falls between. Upon data retrieval, the pixel value, depending on the day of year and location, is extracted from one of the seasonal LUTs. Both products assume the Lambertian approximation error for surface reflectance within its algorithm (Remer et al., n.d.). However, the traditional algorithm doesn't take into account the cloud-coverage contamination, which has a tendency to overestimate the surface reflectance values (Hsu et al., 2004).

MODIS Land Surface Reflectance, available on both the Terra and Aqua platforms, continuously acquires eight-day global measurements with a RGB-image composed of surface reflectance measured by the red and blue channels. This product is an estimate of the surface reflectance for each band as it would have been measured at ground level if there was no atmospheric scattering or absorption (Vermote, 2008). The surface reflectance is inverted with the help of a radiative transfer model using atmospheric inputs (ozone, pressure) taken from the National Centers for Environmental Predication (NCEP) or directly derived from MODIS data (aerosol, water vapor) and then stored in a LUT (NASA b, 2007). Like the aerosol products, this product takes the 6S code into account as well as the Lambertian approximation error. However, the algorithm utilizes the minimum-blue criterion for surface reflectance, selecting the clearest conditions over a certain amount of time. For example, the 8-day product chooses the three clearest days and records the average of those three days into a LUT for the 8-day period (Vermote, 2008).

The Aqua MODIS Daily Level II Aerosol Product Deep Blue Surface Reflectance (MYD04_L2) and Land Surface Reflectance (MYD04_L2) were taken from the Level 1 and Atmosphere Archive and Distribution System (LAADS), The Aqua MODIS Surface Reflectance 8-Day Level 3 Global 500 m (MYDO9_A1) was extracted from the Land Processes Distributed Active Archive Center (LP DAAC). Although all three data sets use LUTs, this study uses the raw values from each image. All three datasets fell within the time period of July 1st to July 31st, 2007 because the data should be comparable to measurements taken in the same month and the crop file (Landsat 7 imagery) obtained from the USGS was last updated in 2007. This study focused on the red (0.620 – 0.670 µm) and blue (0.459 – 0.479 µm) channels because the Deep Blue algorithm utilizes these for AOT measurement. Days 182 (1 July 2007) and 193 (12 July 2007) provide the best coverage for all imagery products used. These days present roughly the same conditions: no clouds present, temperatures in the high 90s, and the ETo ranged from 0.30 to 0.32 inches (CIMIS, 2009). Elevation for the research area is fairly constant. These conditions are similar to our ground measurement overall.

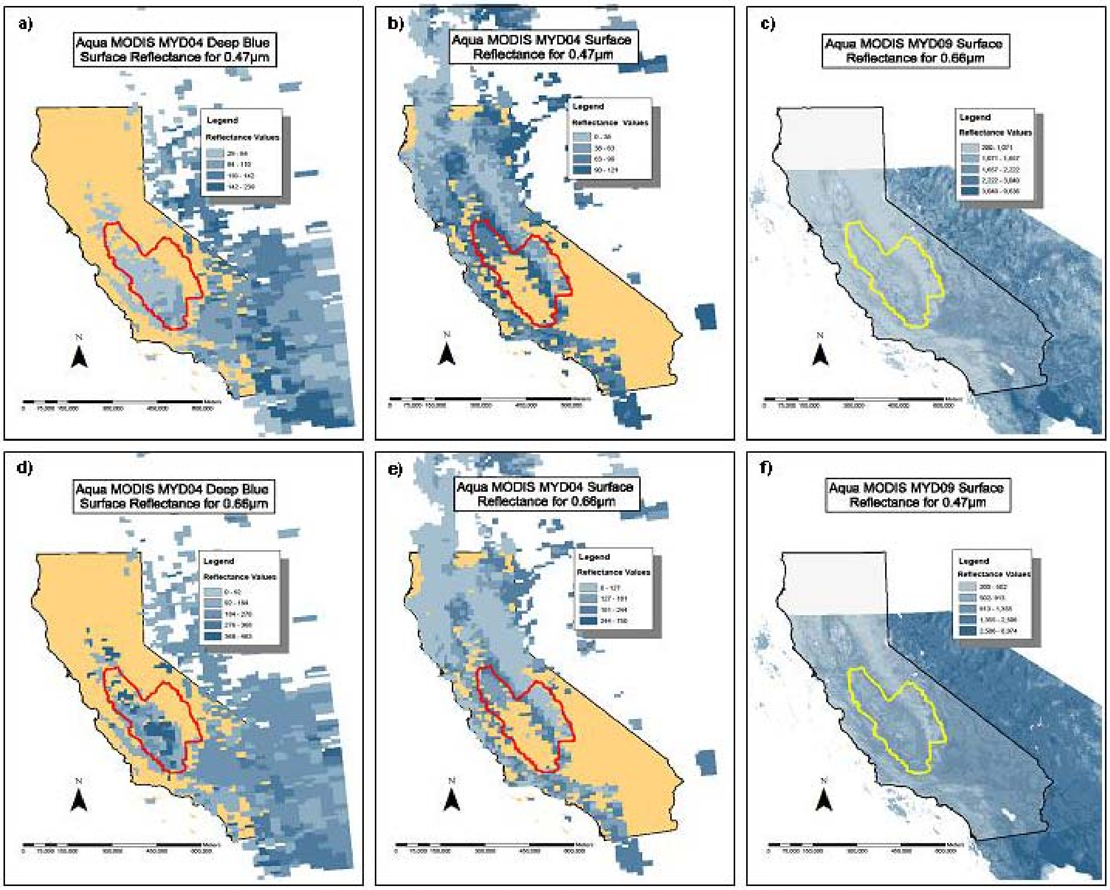

Figure 5. All images are of Day 193 in 2007: a) Aqua MODIS MYD04 Deep Blue .47 µm, b) Aqua MODIS MYD04 Surface Reflectance .47 µm, c) Aqua MODIS MYD09 Surface Reflectance .66 µm, d) Aqua MODIS MYD04 Deep Blue .66 µm, e) Aqua MODIS MYD04 Surface Reflectance .66 µm, f) Aqua MODIS MYD09 Surface Reflectance .47 µm.

Analysis

Once we converted the imagery file formats (Figure 5) and re-sampled all images to a 500 m x 500 m pixel resolution, we selected 50 pixels containing measured crop types in the SJV. Since the Deep Blue and Traditional products account for aerosols and gas content within the atmosphere, zero data values are given where there are no aerosols present, thus comparison is unfeasible. The chosen pixels were then overlaid with the three MODIS surface reflectance products: Deep Blue, Traditional, and Land Surface Reflectance. For ground measurements, values for pixels containing more than one crop type were calculated by taking a weighted average. Data from the MODIS satellite images were extracted for each pixel and scaled accordingly (0.001 for aerosol products and 0.0001 for Land Surface Reflectance products). These numbers were then compared to the ground measurements in order to study the correlation between the four different values for each wavelength (Table 1 for Day 182 and Table 2 for Day 193). Table 3 provides the overall mean averages of all comparable reflectance values for both days. Scatter plots (Figure 6 for 0.47 and Figure 7 for 0.66 µm) were created to compare the MODIS products to our ground measurements as well as to each other. Figures 6a and 7a show the correlation between all MODIS products to ground measurements. Figures 6b and 7b compare the Land Surface Reflectance to both aerosol products. Figures 6c and 7c graph the two aerosol products against each other. The data were evaluated using a linear 1:1 line assuming the values would be equal if they were accurate. A least squares regression, R^2, was also used to further test for correlation.

Table 1. Reflectance data sets at the chosen Valley locations where coverage from MODIS Deep Blue (MYD04 DB), Aerosol Land Surface Reflectance (MYD04 SRL), and Land Surface Reflectance (MYD09 SRL) where aligned for day 182. A missing model filled the ground data using measurements from July 2009.

	Reflectance Percentage Day 182 (2 July 2007)							
	0.46 µm Band				0.66 µm Band			
	Ground Data	MYD04 DB	MYD04 SRL	MYD09 SRL	Ground Data	MYD04 DB	MYD04 SRL	MYD09 SRL
Point38	4.410	6.2	6.7	7.76	5.519	10.6	13.8	16.31
Point39	7.013	6.2	6.8	4.65	10.620	10.4	13.8	8.43
Point41	4.404	6.2	6.8	5.25	5.448	10.4	13.8	11.89
Point42	2.208	5.3	6.9	6.26	3.508	10.4	14.2	10.83
Point44	2.208	6.2	6.9	4.87	3.508	10.4	14.2	8.99
Point48	10.181	6.3	6.7	9.26	14.354	10.9	15.5	16.84
Point49	4.194	5.3	5.4	8.95	6.448	10.1	10.4	14.7
Point50	2.208	6.2	6.9	8.21	3.508	10.4	14.2	13.46

Table 2. Reflectance data sets at the chosen Valley locations where coverage from MODIS Deep Blue (MYD04 DB), Aerosol Land Surface Reflectance (MYD04 SRL), and Land Surface Reflectance (MYD09 SRL) where aligned for day 193. A missing model filled the ground data using measurements from July 2009.

	Reflectance Percentage Day 193 (15 July 2007)							
	0.46 µm Band				0.66 µm Band			
	Ground Data	MYD04 DB	MYD04 SRL	MYD09 SRL	Ground Data	MYD04 DB	MYD04 SRL	MYD09 SRL
Point1	4.404	6.6	8.7	3.07	5.448	1.3	17.0	5.93
Point2	4.438	6.1	6.6	3.58	5.480	1.4	13.0	5.86
Point3	7.322	6.1	11.6	5.36	8.206	1.4	23.1	11.11
Point4	8.791	6.1	6.6	5.85	12.464	1.4	13.0	12.09
Point5	2.208	6.3	8.6	3.41	3.508	4.3	17.0	6.78
Point6	10.181	6.3	8.2	8.41	14.354	4.3	16.2	15.07
Point9	2.208	6.7	8.8	4.88	3.508	4.6	17.5	9.54
Point11	4.654	6.7	8.2	4.53	5.715	4.0	16.1	9.21
Point12	5.641	6.4	4.8	4.78	6.662	4.5	14.7	9.53
Point13	2.208	6.8	8.4	4.64	3.508	4.5	16.6	9.58
Point14	4.651	6.8	8.4	5.19	5.712	4.5	16.6	10.56
Point15	2.319	7.1	8.4	5.66	3.660	4.6	16.2	9.31
Point16	4.299	7.1	8.4	2.79	5.313	4.6	16.2	4.98
Point22	3.593	6.8	7.7	3.57	4.834	1.6	15.0	7.03
Point37	2.208	7.5	9.6	4.26	3.508	1.3	19.3	8.11
Point39	7.013	7.2	8.5	3.68	10.620	4.5	16.6	9.31
Point40	9.066	6.6	10.0	5.92	13.649	4.4	20.2	10.30
Point49	4.194	7.2	7.0	8.57	6.448	3.7	13.5	8.32
Point50	2.208	6.6	9.7	4.24	3.508	2.3	19.5	6.95

Table 3. Average reflectivity of full data sets for MODIS Deep Blue (MYD04 DB), Aerosol Land Surface Reflectance (MYD04 SRL), and Land Surface Reflectance (MYD09 SRL) at the chosen Valley locations. A mixing model filled in the ground data using measurements from July 2009.

		Mean Reflectance Percentage			
		Ground Data	MYD04 DB	MYD04 SRL	MYD09 SRL
Day 193*	0.47um	5.468	7.244	8.324	5.592
	0.66um	7.285	3.084	16.7	10.842
Day 182^	0.47um	4.659	5.970	6.638	6.8
	0.66um	6.627	10.471	13.738	12.602

* Averaged from 19 data points that had data from every category

^ Averaged from 8 data points that had data from every category

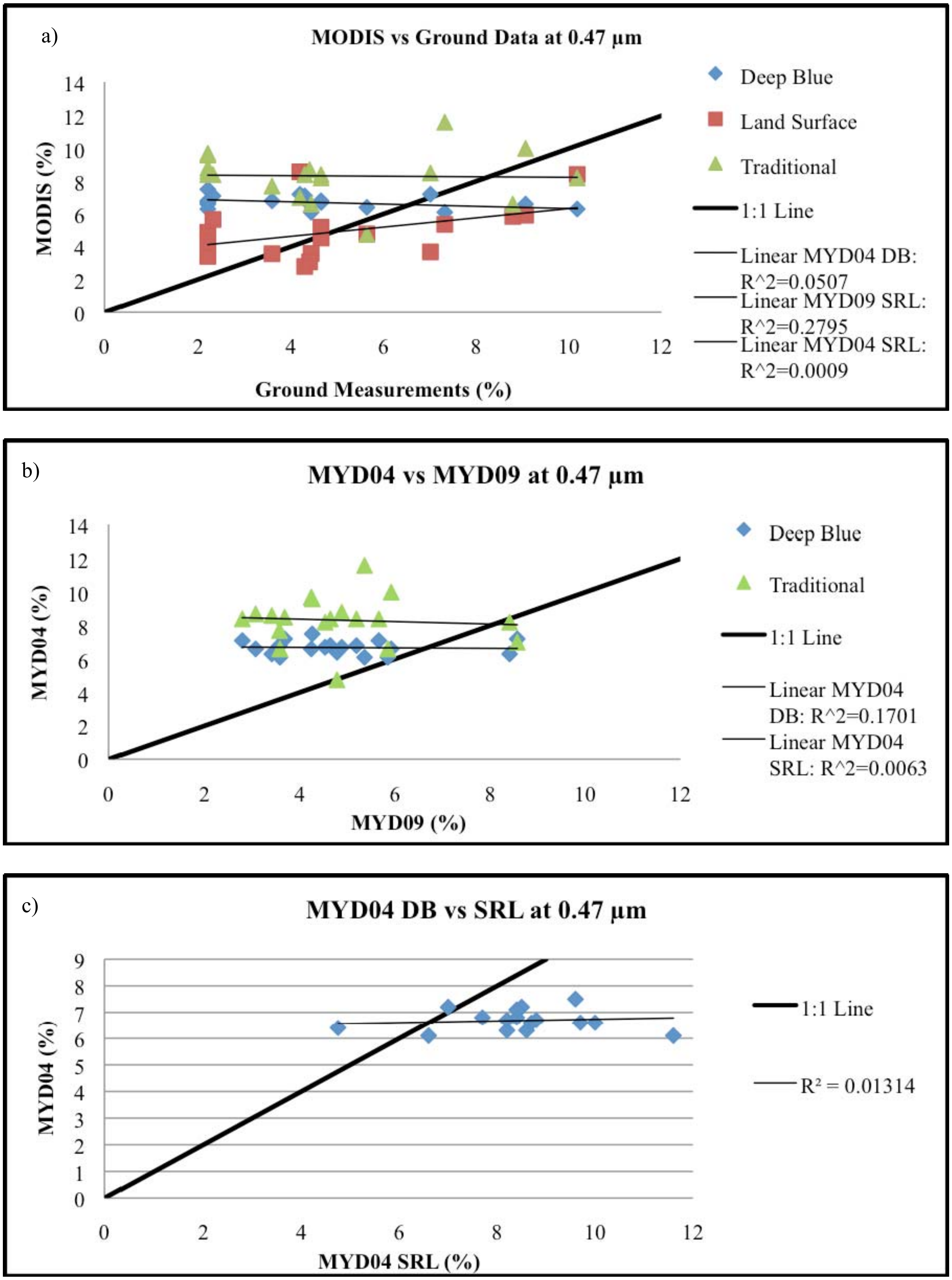

Figure 6. Blue band comparison of Land Surface Reflectances. a) Comparing ground data to three MODIS products. b) Comparing MYD09 Surface Reflectance to MYD04 Surface Reflectance. c) Comparing the MYD04 Deep Blue to Traditional Land Surface Reflectance.

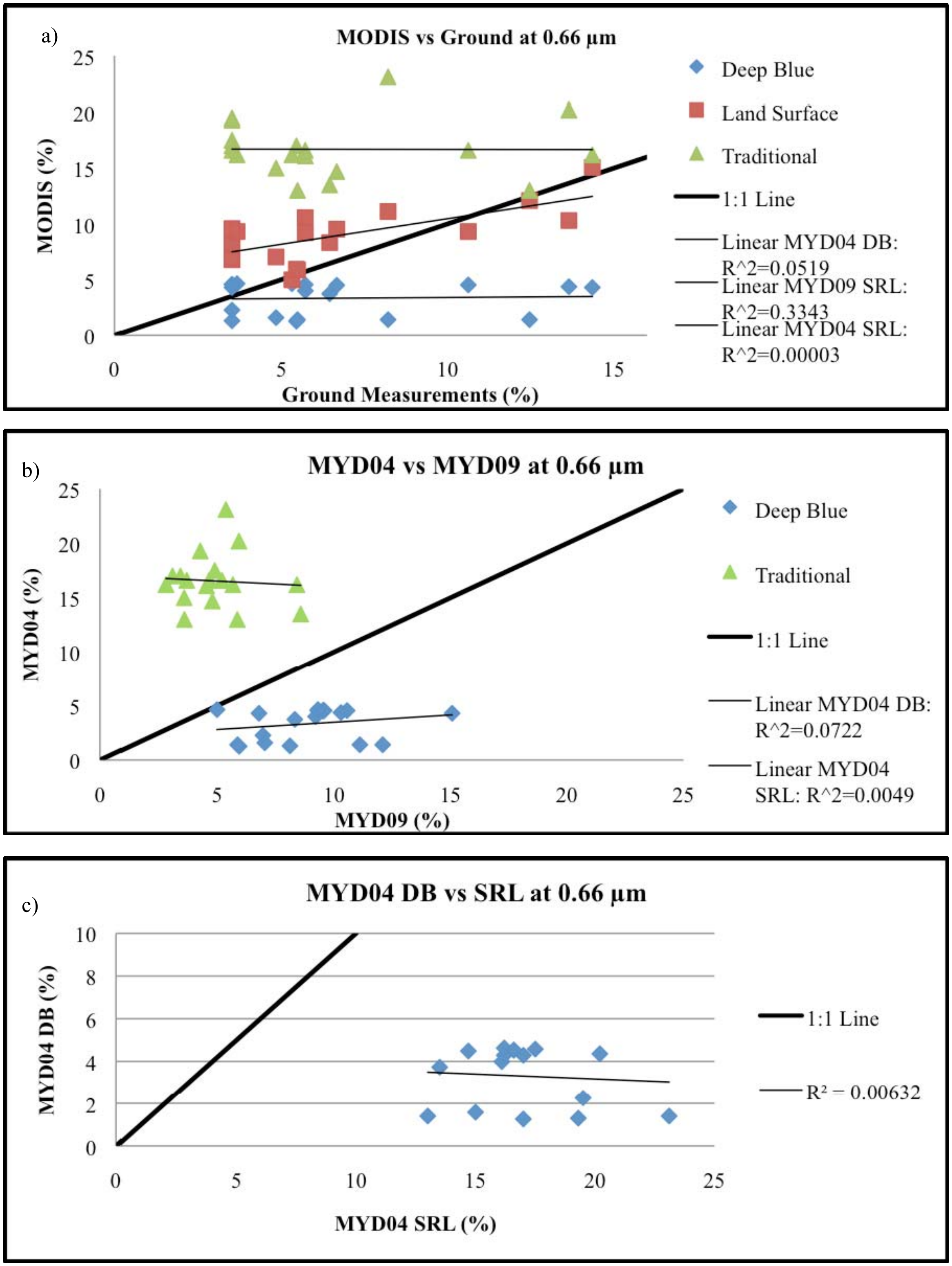

Figure 7. Red band comparison of Land Surface Reflectances. a) Comparing ground data to three MODIS products. b) Comparing MYD09 Surface Reflectance to MYD04 Surface Reflectance. c) Comparing the MYD04 Deep Blue to Traditional Land Surface Reflectance.

RESULTS/DISCUSSION

When viewing Figure 5, an inverted effect is noticeable between the Traditional and Deep Blue MODIS products. According to Figures 6 and 7, there is poor correlation between all data sources. The comparison of Land Surface is the closest matched to the 1:1 line. It exhibits minor correlation with R^2 values of 0.2795 for the 0.47 µm band and 0.3343 for the 0.66 µm band. A horizontal slope regression can be seen between all sources when compared to both aerosol products, indicating that the algorithms may have too much variance, distorting the actual reflectance values. When comparing the individual data points, the 0.47 µm values have a smaller range than the 0.66 µm values. Further investigation of Tables 1 and 2 indicates a relatively stable reflectance value for the Deep Blue 0.47 µm channel for both days. In the 0.66 µm channel, however, the values between the days differ greatly; Day 182 has a reflectance average of 10.471 while Day 193 has an average of 3.084 (Table 3). One explanation for this extreme inconsistency could be that the amount of dust contamination within the region was greater on Day 182 than on Day 193, thus misrepresenting reflectance values for the red channel as dust reflects red wavelengths more than blue wavelengths. This, however, does not explain why the Deep Blue Day 182 average value of 10.471 is closer to the other MODIS products. Due to this substantial variance in data, we cannot conclude if there is a definite distortion factor between ground data and MODIS, but our research does indicate that measurement of surface reflectance is a problem in AOT calculations.

CONCLUSION

The comparisons from our data show a lack of correlation between ground data and MODIS reflectance products, with the aerosol reflectance products being particularly poor, indicating that the lack of PM-AOT correlation may be due to the reflectance inputs. This lack of correlation is probably due to the assumptions made in the algorithms, specifically the process for selecting pixels, the quantity of pixels discarded, the difference in spatial resolution, and temporal resolution. Since the traditional algorithm screens out the lower 20 percent and upper 50 percent of the reflectance values and the Deep Blue algorithm takes only the brightest pixel from the 10 km area, the comparison of surface reflectance is difficult to make since the pixel values are different for the same region. The 10 km area is very large in comparison to the 500 m MODIS pixels and our field sizes, making it very hard to link the two. In farming areas this is difficult because the reflectance values are not homogenous over the large area, especially considering that the aerosol products seem to discard over half the usable pixels in the area. There is also a temporal resolution that needs to be considered. While in the fields, in the middle of July, harvesting had already started on some of the crops, and others continued to grow. The aerosol reflectances are constant for 3 month intervals and cannot be accurate for areas like the SJV where crops leaf area changes drastically over a season. A reason for this may be that the land surface reflectance compares better to our data for the days tested because it is only an 8 day average for the reflectances. Additionally, it is challenging to accurately compare a three month product to a single or eight day product. This is one reason that may explain the lack of correlation between AOT and PM in the SJV.

Furthermore, the Deep Blue LUT is currently being updated to a 250 m resolution, which may help improve the correlation between MODIS AOT and surface PM measurements. Additional research is recommended to examine if surface reflectance correlation between MODIS and ground on the East Coast has similar outcomes, as well as to study what other factors may have an adverse affect on the continental discontinuity. It would also be useful to compare seasonal ground measurements to the recently updated LUT used in Deep Blue calculations. Also, since such an opposite affect was seen between the aerosol products, the development of an algorithm that combines the two would be beneficial.

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