UNDERSTANDING THE CORRELATION OF SAN JOAQUIN AIR QUALITY MONITORING WITH AEROSOL OPTICAL THICKNESS SATELLITE MEASUREMENTS

Marshall Ballard, San Jose State University
Michelle Newcomer, San Francisco State University
Jacqueline Rudy, California Polytechnic State University, SLO
Sachi Lake, Princeton University
Sivakami Sambasivam, Massachusetts Institute of Technology
Anthony W. Strawa, NASA Ames Research Center
Cindy Schmidt, NASA Ames Research Center
J.W. Skiles, NASA Ames Research Center
DEVELOP NASA Ames Research Center
M.S. 242-4
Moffett Field, California 94035
Marshall.Ballard@gmail.com
astrawa@mail.arc.nasa.gov
cschmidt@mail.arc.nasa.gov
Joseph.W.Skiles@nasa.gov

ABSTRACT

Air quality in the San Joaquin Valley has failed to meet state and federal attainment standards for Particulate Matter (PM) for several years. This is attributed to anthropogenic and natural sources. The Environmental Protection Agency (EPA) and California Air Resources Board (CARB) continuously monitor San Joaquin Valley air quality from selected ground sites, and these efforts can be enhanced by the broad spatial coverage provided by satellites. While previous studies show good correlations between satellite derived Aerosol Optical Thickness (AOT) and PM data on the East Coast, this is not the case in the San Joaquin Valley. This paper compares $PM_{2.5}$ ground data from CARB and Interagency Monitoring of Protected Environments (IMPROVE) sites with satellite data in an effort to understand the reason behind this discrepancy. AOT values from the Aerosol Robotic Network (AERONET) offer an opportunity to verify satellite accuracy to coincide the AOT and $PM_{2.5}$ comparison. Fieldwork was conducted using the MicroTops II Sun Photometer to measure AOT values in the city of Fresno and correlate with satellite data. Good correlation between Moderate Resolution Imaging Spectroradiometer (MODIS), Multiangle Imaging Spectroradiometer (MISR) and AERONET are shown. Statistical and spatial analysis of satellite and ground data, demonstrated weak correlations between AOT and $PM_{2.5}$, and consideration of aerosol speciation did not improve the correlations. Further investigation into the effects of meteorological conditions or aerosol layers aloft is needed to determine the causes of the poor correlation.

INTRODUCTION

The future of air quality monitoring will include satellite remote sensing to assist with the ground remote sensors that are already in place. Satellite aerosol observations can overcome the spatial and temporal limitations of surface monitoring networks and enhance daily air quality forecasts (Al-Saadi et al., 2005). The first step in rectifying the problem of poor correlation between ground sensors and satellite sensors is to provide the regulatory agencies with quality satellite data pertaining to the situation. This study was conducted in conjunction with the needs of our partner organizations, United States Environmental Protection Agency (EPA), the California Air Resources Board (CARB), and the San Joaquin Valley Air Pollution Control District (SJVAPCD).

Particulate Matter (PM), or aerosols, are airborne particles in the planetary boundary layer (PBL). PM was brought to the forefront of policy when the United States Environmental Protection Agency (EPA) first issued standards for PM values in 1971 and most recently revised PM standards in 2006. The San Joaquin Valley, (Figure 1) “the nation’s salad bowl,” is home to some of the worst air quality in the nation. The valley is classified as a non-attainment area for state and federal $PM_{2.5}$ and PM $_{10}$ annual standards. $PM_{2.5}$ are particles that are smaller than2.5

microns in diameter and PM_{10} are particles that are smaller than 10 microns in diameter and are "inhalable fine particles and coarse particles" respectively (ARB Almanac, 2005). Aerosol Optical Thickness (AOT) are measurements of atmosphere extinction which typically correlate well with the amount of aerosols in the atmosphere. By understanding where aerosols are, how they circulate, and the meteorological conditions in the PBL, we can better determine relationships between ground measurements of PM and AOT and satellite AOT.

No specific study has been conducted in the San Joaquin Valley to determine whether there is a relationship between satellite measured AOT and ground monitoring PM values. Although, in a previous study, (Engel-Cox et al. 2004) found a poor correlation between MODIS AOT and PM values on the West Coast compared with a good correlation on the East Coast and Midwest. This poor correlation had no clear reason but speculation implied the nitrate / sulfate ratio, increased presence of black carbon and variable conditions in the PBL. AOT has no relation to $PM_{2.5}$ when aerosol is entirely aloft, but has some relation when there is aerosol near the surface and aloft (Al-Saadi et al., 2005; Watson and Chow, 2002). Current studies being conducted by EPA region 9, NASA and CARB are using aerial lidar to study vertical distribution of aerosols (Rosen et al. 2006). This study is building on aerial lidar data that was collected in 2004 to investigate aerosol layers aloft in the SJV (DeYoung et al. 2005). Studies have shown that MODIS and MISR may complement each other with regard to measurement accuracy and spatial coverage (Liu et al. 2006). We used AERONET, CARB, and IMPROVE ground-monitoring data along with measurements gathered from handheld MicroTops II Sun Photometers to correlate with the satellite-derived AOT values from MODIS and MISR satellite sensors.

Data from January through August for the years of 2005 through 2007 were gathered to document seasonal variations in aerosol concentrations and in PM speciation. January through August partially coincided with the current research being conducted by EPA, NASA and CARB. Our focus is the city of Fresno which contains ground monitoring stations from the Aerosol Robotic Network (AERONET), Interagency Monitoring of Protected Visual Environments (IMPROVE), and CARB. The EPA classified Fresno as a PM Supersite in 1999 to research ambient air quality in relation to atmospheric sciences and human health. EPA data show that Fresno $PM_{2.5}$ weighted annual averages have been above the national standards since 1999. We conducted our field work in Fresno on July 15th and July 16th, coincident with the overpass of the Terra spacecraft which carries the MODIS and MISR instruments.

METHODOLOGY

Our project utilized a total of six datasets; four ground based instruments and two satellite sensors. IMPROVE, CARB, and AERONET measurements are available with a high degree of accuracy covering a wide spatial distribution for the San Joaquin Valley. MICROTOPS II was used as an in situ fieldwork survey around the City of Fresno. The accuracy of MISR and MODIS AOT values were compared to PM and AOT ground measurements to determine any correlation.

Ground Data

IMPROVE is a long-term monitoring program to determine visibility and aerosol conditions, and to identify anthropogenic factors that contribute to visibility impairment. The IMPROVE Monitoring network is run by a steering committee consisting of representatives from federal, state and regional organizations. There are 110 monitoring sites in the U.S., including 20 in California. The IMPROVE monitoring network consists of samplers that measure speciated aerosol and optical properties such as $PM_{2.5}$, PM_{10}, and aerosols such as dust, sulfur, and carbon. The IMPROVE sampler has four modules that collect fine particles (d < 2.5 microns) and coarse particles (d < 10 microns) which are collected for 24 hours every three days. University of California at Davis conducts 3 levels of quality assurance by validating sampling equipment, performing analysis on derived data, and through comparing species between samplers (http://vista.cira.colostate.edu/improve/Overview/IMPROVEProgram_files/frame.htm). IMPROVE $PM_{2.5}$ data were obtained for five sites in and adjacent to the San Joaquin Valley, including, Yosemite National Park, Sequoia National Park, Kaiser, Dome Lands Wilderness Preserve, and Fresno (Figure 2). These values were available for 2005 and 2006 with a temporal frequency of every three days. The IMPROVE data were retrieved from the Visibility Information Exchange Web System (VIEWS). It is an online exchange of air quality data, research, and ideas designed to understand the effects of air pollution on visibility and support the EPA regulations (http://vista.cira.colostate.edu/views/).

Figure 1. State of California Air Basin Districts and the San Joaquin Valley Unified Air District.

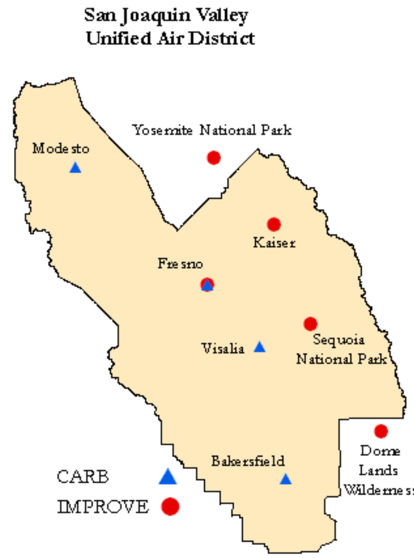

Figure 2. Locations of IMPROVE and CARB data collection locations in the San Joaquin Valley.

It is the responsibility of the EPA and CARB to create air quality standards and enforce emission regulations. Natural sources such as wind blown dust, wildfires, biogenic and geogenic hydrocarbons mix with anthropogenic sources to contribute to PM pollution (ARB Almanac, 2005; NARSTO, 2004). CARB standards are more stringent than the EPA for air quality levels (ARB, Almanac, 2005). The emission sources are estimated by CARB personnel based on information retrieved from districts and government agencies regarding anthropogenic and natural causes (ARB Almanac, 2005; NARSTO, 2004). CARB provided the $PM_{2.5}$ and PM_{10} data with speciation from January 2005 through March 2007 for the following locations, Modesto, Fresno, Visalia, and Bakersfield (Figure 2). Detailed speciation studies have been conducted and correlated to the Federal Reference Methods which determine compliance with U.S. National Ambient Air Quality Standards for PM data (Chow et al., 2006).

Aerosol Robotic Network (AERONET) level 2 data were downloaded from the AERONET data archive for April through August of 2005 and January through August for 2006. AERONET sun photometer stations are located all over the world, including one in Fresno. It is a NASA product that provides AOT values recorded every 15 minutes utilizing seven spectral bands (340, 380, 440, 500, 670, 870, and 1020 nanometers). This study attempted correlating to the 500 band AOT values since MODIS measures AOT at a comparable 550 nanometers (Jiang et al., 2006). The fifteen minute interval readings were averaged per day so that they could easily be compared with the daily values for the satellite and ground data. Multiple spectral and angular measurements allows for excellent retrieval of aerosol parameters with fewer assumptions about aerosol properties than are used in satellite remote sensing (Sinyuk et al., 2006). Past studies in the Mojave Desert and Northeast Asia found an impressive R^2 values of 0.83 and 0.90 respectively on a basic regression comparing spatially averaged MISR AOT and MODIS AOT respectively against temporally averaged AERONET AOT, a validation that we attempted to duplicate (Frank et al., 2006; Lee et al., 2007). MISR was also shown to have a favorable comparison to AERONET, overestimating by 10% with a bias of 0.02 in southern Africa for the first comparison conducted between the two data sources (Diner et al 2001).

Satellite Data

Our primary satellite data source was the MODIS sensor, which is aboard the Terra and Aqua satellites. We chose to use Terra MODIS which passes over Fresno in the late morning. Terra MODIS views the entire surface of the Earth every one to two days, and has 36 spectral bands. Errors in the MODIS aerosol retrievals can be attributed to diverse surface reflectance, snow or ice, sub-pixel cloud, and AOT properties that are not considered in the product's algorithms (Chu et al, 2002). MOD04 Level two Aerosol Product includes AOT values contained in the variable Corrected_Optical_Depth_Land in a 10 kilometer resolution. Since the San Joaquin Valley is considered a dry land study area it was advised to use Corrected_Optical_Depth_Land data (Remer personal communication, Remer et al., 2005). Validation of MODIS products are based on AERONET ground station measurements (Chu et al., 2002). We acquired this data from the NASA Laads web site which allows one to query the spatial and temporal characteristics and the specific field of processed data from the MODIS sensor. We obtained data from January through August 2005, 2006, and until mid July of 2007 (http://ladsweb.nascom.nasa.gov/data/search.html).

MISR, the Multi-angle Imaging SpectroRadiometer, is also aboard NASA's Terra satellite. It has cameras with nine different angles to view Earth in various directions. In addition, each of these cameras has four wavelengths (blue, green, red, and near-infrared). Every 275 meters, it acquires spatial samples, and every seven minutes it captures a 360 km wide swath of Earth at all nine angles. MISR has a spatial resolution of 17.6 km and every 9 days achieves global coverage, however, MISR repeats its path number every 16 days (Diner et al., 1998). MISR paths 42, 43, and 44 had the best coverage of the entire San Joaquin Valley; therefore we chose to download all days for those paths from January – August 2005, 2006 and January - May 2007 due to availability. We used Level two Aerosol data MIL2ASAE, ordered from the NASA MISR order and customization tool, (http://l0dup05.larc.nasa.gov/MISR/cgi-bin/MISR/main.cgi). We extracted MISR AOT at 558 nm using the field name RegBestEstimateSpectralOptDepth as suggested by Liu, (Liu et al., 2006).

Processing Data

MODIS data were used as our primary satellite data source because of its higher temporal resolution, its frequency, and because its wider swath width covers a greater part of the valley. This provided us with more data overall to use when conducting our statistical analysis of the correlation between ground monitoring and satellite derived AOT. We first acquired GeoTiff Images of the MODIS swaths over the San Joaquin Valley. We extracted all the AOT values from the satellite data in ArcGIS. We extracted information surrounding the locations of nine sites at eight ground monitoring locations in three ways using the pixel inspector in ArcGIS. We extracted the centroid pixel a 3x3 group of pixels and a 5x5 group of pixels surrounding the sites. These extracted grid values were then averaged to achieve a spatial and temporal value to compare to other data. Centroids and 3x3 grids were extracted for the same locations using MISR Extracting a 5 by 5 grid of pixel values for the MODIS 10 km data and a 3 by 3 grid of pixel values for the MISR 17.6 km data makes the two resolutions relatively comparable (Liu et al., 2006).

Field Work

Our field work was conducted using the MICROTOPS II sun photometer with the objective of collecting aerosol optical depth measurements in various sites centered on the Fresno Super-site. We conducted our field work on July 15 and 16, in the late morning synchronized with the Terra spacecraft overpass. Our center and most important point was at the Fresno First Street Super-site where CARB, IMPROVE and AERONET all have data collection equipment. We collected data from six additional sites within five kilometers and two additional sites at a 10 kilometer radius (Figure 3). The idea of collecting field data is fundamental to the DEVELOP program, however in the case of our project it was impractical to collect enough data to demonstrate relationships to satellite data over a long time period. We found that the MICROTOPS II is a very practical handheld sun photometer and can be applied in aerosol optical depth measurements in areas that do not have ground monitoring stations. Using spatial analysis we provided a visible relationship of the field data that we collected. This demonstrates how the aerosol gradient varies throughout a city.

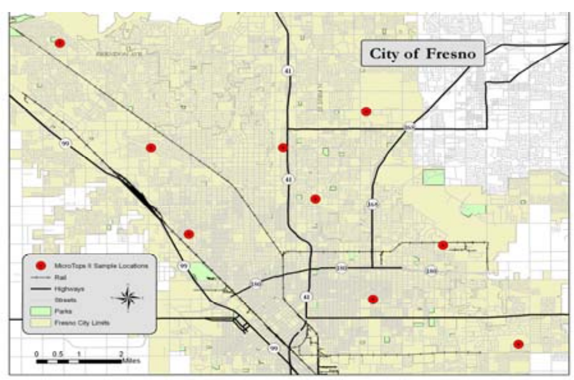

Figure 3. MicroTops II Field Data Collection Sites, July 15 and 16, 2007.

RESULTS

MODIS data showed a correlation to MISR data, as previously noted. A regression was run to verify this and although the data were limited, there was a very high correlation after the removal of outliers with a $R^2 = 0.9414$. In fact, due to different paths and overcast days, there were only 48 days in three years when MODIS and MISR had corresponding 5 by 5 and 3 by 3 extracted data. The best realistic correlation between ground data and satellite data was between the MODIS AOT and the AERONET AOT. These two datasets were the most readily available for a reasonable temporal comparison. MISR AOT and AERONET did have a very impressive R^2 value but out of a three year sample, only 32 days were available for union (Table 1). It is understood that these 32 days coincide because of the ideal atmospheric conditions. After the removal of outliers there is a good correlation between MODIS, MISR and AERONET.

All days that did not contain both MODIS values and either AERONET, IMPROVE, or CARB values were excluded. This limited our available data because ground data is only recorded every three days and even that availability is limited to equipment functionality. We had more days available for MODIS than any of our other datasets. The MODIS swath makes it possible to download images for every day, but the quantity of data available for a particular day is dependent on atmospheric conditions. We were able to download 687 days of MODIS data, compared to 116 days of MISR data. However, satellite data that coincides with ground data was limited to 120 days of MODIS and only 12 for MISR (Table 2). Both satellite sensors are limited by cloud cover, therefore it is impossible to retrieve a substantial amount of data for the winter months in California. To avoid a biased dataset, we removed these days.

Table 1. MODIS AOT, MISR AOT, and AERONET AOT R^2 Values

MODIS - MISR - AERONET				
R Squared Values	MISR 3x3	MISR Centroid	AERONET	# of days
	No Standard Deviations			
MODIS 5x5	0.59		0.6006	32
MODIS 3x3	0.3252		0.3872	32
MODIS Centroid		0.3194	0.1056	28
AERONET	0.6006	0.3872		32
	2 Standard Deviations			
MODIS 5x5	0.9595		0.9728	27
MODIS 3x3	0.9207		0.9101	25
MODIS Centroid		0.8834	0.8168	19
AERONET	0.9752	0.9427		31

Table 2. Days of Data available from data sources collected

Days of Data				
Data Source	Total Downloaded	Total with Data	Days Coincident with MODIS	Days Coincident with MISR
MODIS	687	479		48
MISR	116	49	48	
AERONET	357	357	226	33
CARB	267	255	120	12
IMPROVE	162	155	120	12

A basic regression was run comparing the MODIS AOT value retrieved three different ways to the three types of ground data. The centroid regressions had the worst correlation $R^2 = 0.096$, thus the 3 by 3 pixel and 5 by 5 pixel were used to try to improve the R^2 values. A regression was also run on the $PM_{2.5}$ values for the corresponding days. The initial regression between MODIS and AERONET showed a poor relationship $R^2 = 0.3304$.

The regressions for the 5 by 5 and 3 by 3 MODIS values were analyzed and excluded if more than 50% of the pixel values did not have data. Statistics were run again on this new dataset. The correlation was still poor with an

R^2 = 0.4791, therefore we removed any outliers by using standard deviations for both the thresholded and non-thresholded images. All days outside of two standard deviations and then one standard deviation were excluded for all regressions comparing the three types of ground data to the three MODIS extraction methods. The regressions were improved slightly after removing the data without at 50% representation, however not as good after eliminating outliers, R^2 = 0.3059, when limiting the data to the 50% threshold and two standard deviations. This is most likely due to the elimination of outliers and also because many days were discarded because of no data or cloudy weather. Another reason for this may have been that the days that remain after the 50% threshold have better meteorological conditions. Despite removal of outliers and limiting the data to a 50% threshold, this study was unable to find any correlation between AOT and PM measurements. Post-processed regressions between MODIS and IMPROVE or CARB did not yield an R^2 value higher than 0.26 (Table 3).

Table 3. R^2 Values of MODIS AOT and $PM_{2.5}$ Values from CARB and IMPROVE

R Squared Values	5x5 Pixels	3x3 Pixels	Centroid	5x5 **50%** Threshold	3x3 **50%** Threshold
Sites PM Values	**No Standard Deviations**			**No Standard Deviations**	
Fresno - CARB	0.0121	0.0121	0.0003	0.0276	0.0197
Modesto - CARB	0.0009	0.0021	0.0028	0.0167	0.0265
Visalia - CARB	0.0153	0.0538	0.0375	0.0243	0.049
Bakersfield - CARB	0.0278	0.0156	0.002	0.0111	
Fresno - IMPROVE	0.0062	0.0176	0.018	0.0614	0.018
Yosemite - IMPROVE	0.023	0.16	0.0978	0.1882	0.1694
Kaiser - IMPROVE	0.0563	0.0079	0.0017	0.0785	0.1022
Sequoia - IMPROVE	0.0479	0.0571	0.0536	0.1255	0.1266
Domelands - IMPROVE	0.1961	0.2914	0.1984	0.1644	0.1705
	One Standard Deviation			**One Standard Deviation**	
Fresno - CARB	0.0005	0.0005		0.0106	0.0041
Modesto - CARB	0.0254	0.0857	0.0423	0.2584	0.2878
Visalia - CARB	0.1154	0.1428	0.0946	0.0243	0.0816
Bakersfield - CARB	0.1498	0.0092	0.047	0.0939	
Fresno - IMPROVE	0.1658	0.1462	0.018	0.2274	0.0334
Yosemite - IMPROVE	0.0023	0.0056	0.1041	0.0022	0.0067
Kaiser - IMPROVE	0.0264	0.0366	0.003	0.0021	
Sequoia - IMPROVE	0.0024	0.0055		0.0088	0.02026
Domelands - IMPROVE	0.1322	0.093	0.9948	0.033	0.1884
	Two Standard Deviations			**Two Standard Deviations**	
Fresno - CARB	0.0022	0.0287	0.001	0.002	
Modesto - CARB	0.0009	0.1205	0.1172	0.1514	0.1914
Visalia - CARB	0.0545	0.0885	0.0877	0.0116	0.0404
Bakersfield - CARB	0.0216		0.0606	0.0657	
Fresno - IMPROVE	0.001	0.1	0.0808	0.2465	0.1899
Yosemite - IMPROVE	0.0898	0.0919	0.0455	0.1012	0.0777
Kaiser - IMPROVE	0.0968	0.0316	0.0029	0.0415	0.0976
Sequoia - IMPROVE	0.0345	0.0334	0.0247	0.0254	0.08727
Domelands - IMPROVE	0.0155	0.1473			

The MICROTOPS II ground data were analyzed using an Interpolated Distance Weighting (IDW) to demonstrate distribution of aerosol levels in Fresno on our fieldwork day. The Fremont and Sequoia sites had the greatest aerosol optical thickness while Hamilton and Skypark had the lowest (Figure 4). However, reasons for this spatial variation are yet to be determined.

Using CARB and IMPROVE $PM_{2.5}$ speciation data we were able to statistically analyze the major constituents of the PM data (Figure 5). We found that there were major differences between the winter and summer months regarding nitrates and sulfates. In the winter the nitrate levels were higher than in the summer and vice versa for the sulfate levels. Our study corroborates the findings of other California speciation reports and NARSTO (a public private organization in North America devoted to improving air quality) reports where it is also stated that Black Carbon and Soil are constituents of aerosols in the air of the western United States. (NARSTO, 2004; Chow et al., 2006)

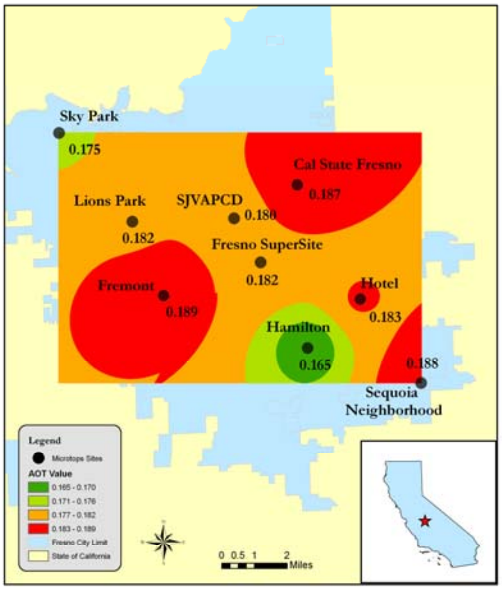

Figure 4. MicroTops II AOT spatial analysis of July 16, 2007.

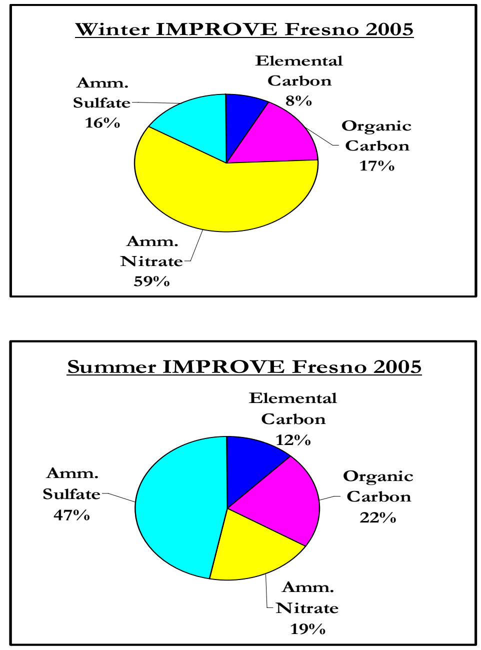

Figure 5. Speciation Percentage from IMPROVE $PM_{2.5}$ data 2005.

DISCUSSION AND CONCLUSIONS

Utilizing NASA satellite AOT data, NASA ground AOT data, PM data from two sources and an example of how a handheld AOT measurement device a new approach to monitoring regional air quality was demonstrated for regulatory agencies. The PM data sources from CARB and IMPROVE showed a good correlation $R^2 = 0.8546$, thus leading us to be confident in using additional locations from both sources. MODIS, MISR and AERONET all showed a good correlation with one another $R^2 > 0.95$ that was exceptional after the removal of outliers past the second standard deviation.

The composition of particulate matter in the air of the Western United States may hold the key in determining the relationship between satellite AOT and PM data. Our study showed that there was a poor relationship between $PM_{2.5}$ data and satellite AOT data from MODIS and MISR sensors. Our speciation analysis corroborated what CARB reports, that nitrate levels are higher in the winter than summer and sulfate levels are higher in the summer than the winter. PM speciation and monitoring is limited to a 24 hour sample every three days, while satellite observations are daily and sometimes multiple times per day. Thus diurnal variations in PM could contribute to poor correlation. PM speciations measurements with finer temporal resolution are required to investigate this. Better collaboration of ground data monitoring with clear skies can improve the number of data days that satellite sensors are able to collect data. In addition to collecting the PM data perhaps regulatory agencies can use a MicroTops II unit to collect AOT measurements to coincide with the PM data and assist in corroborating satellite data.

Had we included additional analysis of the meteorological conditions of the PBL such as speciation, relative humidity, temperature, and PBL height similar to (Liu et al., 2004) we may have improved our regression values and shown a better correlation. There are factors in the California skies whether it be aerosols layers aloft, varied speciation or meteorological attributes that are causing the poor relationship between PM and AOT. Further investigation into layers aloft will demonstrate whether there are significant findings from using airborne LiDAR and satellite LiDAR to assist in identifying the locations and concentrations of aerosols (De Young et al., 2005). Another method of using AOT to determine air quality is simply to create AOT standards to determine the air quality; this would be similar to the existing PM standards.

ACKNOWLEDGEMENTS

We are grateful to the DEVELOP program at NASA for providing all the funding and support for this project. In addition we would like to thank our partner organizations for providing data and consultations: CARB; Ajith Kaduwela and Kasia Turkiewicz; EPA Region 9 Air Division; Rebecca Rosen and Carol Bohnenkamp, SJVAPCD; Gary Arcemont and Evan Shipp, IMPROVE / UC Davis; Chuck McDade In support of our research analysis we would like to thank Richard Brill for assistance with the MicroTops II Sunphotometer, Marion Legg for assistance with IDL software, Gary Pereira, Joshua Ingham and Casey Teske for assistance with GIS troubleshooting and Ken Weinstock for administrative network support.

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