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Aerosol optical depth compared to particulate matter in the San Joaquin Valley

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AEROSOL OPTICAL DEPTH COMPARED TO PARTICULATE MATTER IN THE SAN JOAQUIN VALLEY

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ABSTRACT

AEROSOL OPTICAL DEPTH COMPARED TO PARTICULATE MATTER IN THE SAN JOAQUIN VALLEY

by Marshall Wilson Ballard

The San Joaquin Valley in California has some of the worst air quality problems directly attributed to particulate matter in the United States. State and Federal regulatory agencies monitor particulate matter with a network of ground sensors throughout the San Joaquin Valley. Satellite technology provides aerosol optical depth data for the entire world every two days. Varying degrees of correlation have been found worldwide in the research of comparing satellite aerosol optical depth to ground sensor particulate matter. In the San Joaquin Valley comparing $PM_{2.5}$ data to satellite aerosol optical depth data failed to demonstrate a strong correlation. This result warrants additional research into the reasons why there is a poor relationship between particulate matter and aerosol optical depth in the San Joaquin Valley.

DEDICATION and ACKNOWLEDGEMENTS

I dedicate my Master's thesis to my wife Susi. Without her love, support, and patience this work would not have been possible. I would also like to acknowledge the support and assistance of following people, Robert W. Ballard, Renata M. Ballard, Venancio Aguirre, Victoria Aguirre, Christina M. Ballard, Marion J. Legg, and NASA Ames DEVELOP 2007.

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LIST OF ACRONYMS

AERONET	Aerosol Robotic Network
AOD	Aerosol Optical Depth
ArcGIS	GIS software product produced by ESRI
CAD	Computer Aided Drafting
CALIOP	Cloud-Aerosol LIDAR with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CARB	California Air Resources Board
EPA	United States Environmental Protection Agency
GeoTIFF	Geographically Referenced Tagged Image File Format
GIS	Geographic Information Systems
HEG	HDF EOS to GeoTIFF
IMPROVE	The Interagency Monitoring of Protected Visual Environments
LIDAR	Light Detection and Ranging
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautic and Space Administration
OMI	Ozone Monitoring Instrument
PM	Particulate Matter
SJVAPCD	San Joaquin Valley Air Pollution Control District
VMT	Vehicle Miles Traveled

INTRODUCTION

Problem Area

Local, regional, national, and global air quality needs to be safeguarded. Increases in air quality related health issues prompted action to understand the problem, establish monitoring networks, and raise awareness through education programs. Several networks of air quality remote sensing systems exist on the Earth's surface and the Earth's orbit. Many of us are unaware of these systems. Satellite technology is constantly collecting and providing us data about our atmosphere.

Particulate matter (PM) is a significant atmospheric problem and persistently exceeds existing standards in urban areas throughout North America (NARSTO, 2004). Increased anthropogenic pollution due to population growth, energy needs, and increased vehicle miles traveled (VMT) have contributed negatively to our air quality. A considerable and increasing body of evidence shows an association between adverse health effects, primarily of the cardiorespiratory system, and exposure to ambient levels of PM (NARSTO, 2004). Fresno, California was identified as a United States Environmental Protection Agency (EPA) Particulate Matter Supersite in 1999 (Desert Research Institute, 1999). The PM Supersite program began as a result of the uncertainties of the effects, exposure, concentrations, source – receptor relationships, and management alternatives (Desert Research Institute, 1999).

Problem Definition

With growing concern and increased legislation to monitor our air quality, diversified reliable monitoring techniques are important to use. This thesis explores whether ground sensor particulate matter data correlates to satellite and sun photometer aerosol optical depth data (AOD) in Fresno and the San Joaquin Valley. A variety of data sources were considered: ground sensors of particulate matter, ground sensors of aerosol optical depth and National Aeronautic and Space Administration (NASA) satellite sensors of aerosol optical depth. Satellite technology provides an unequaled ability to monitor spatially what a ground sensor network cannot. Satellite technology needs to demonstrate its reliability and compatibility with current ground sensors before regulatory agencies can rely on satellite data sources for consistent measurements of air quality.

The temporal and spatial resolution of satellite data is critical to ensuring data quality and reliability. Temporal correlation is the first consideration; the satellite data needs to be available when the ground sensors' data are available. Spatial correlation is the second consideration; the satellite data needs to demonstrate the diversity of its coverage that ground sensors are incapable of. Spectral correlation is not really feasible; however regressions correlating the data sources' measurements are significant to understanding their relationship.

BACKGROUND

Political Geography

This research was focused on the San Joaquin Valley of California and in particular, the City of Fresno. The San Joaquin Valley is comprised of eight counties and more than 3 million residents; the counties include from north to south, San Joaquin, Stanislaus, Merced, Madera, Fresno, Kings, Tulare and Kern (San Joaquin Valley Air Pollution Control District, (SJVAPCD)). The largest city in the San Joaquin Valley is Fresno, with a growing population of over 480,000 residents. Fresno is located at the center of the San Joaquin Valley (Figure 1). Other cities such as Bakersfield, Visalia, and Modesto also have growing populations and economies.

Physical Geography

The San Joaquin Valley is 250 miles long, bordered to the north by the Sacramento Valley, to the west by the Coastal Mountain ranges, to the east by the Sierra Nevada Mountains and to the south by the Tehachapi Mountains (Figure 2). The valley acts as a natural collector and repository of particulate matter. The San Joaquin River is the largest river in the valley and is the primary watershed. The California aqueduct spans the entire length of San Joaquin Valley, beginning at the San Joaquin River delta in the north end of the valley. Both the river and the aqueduct serve as the potable water supply and serve to irrigate the agricultural lands of San Joaquin Valley.

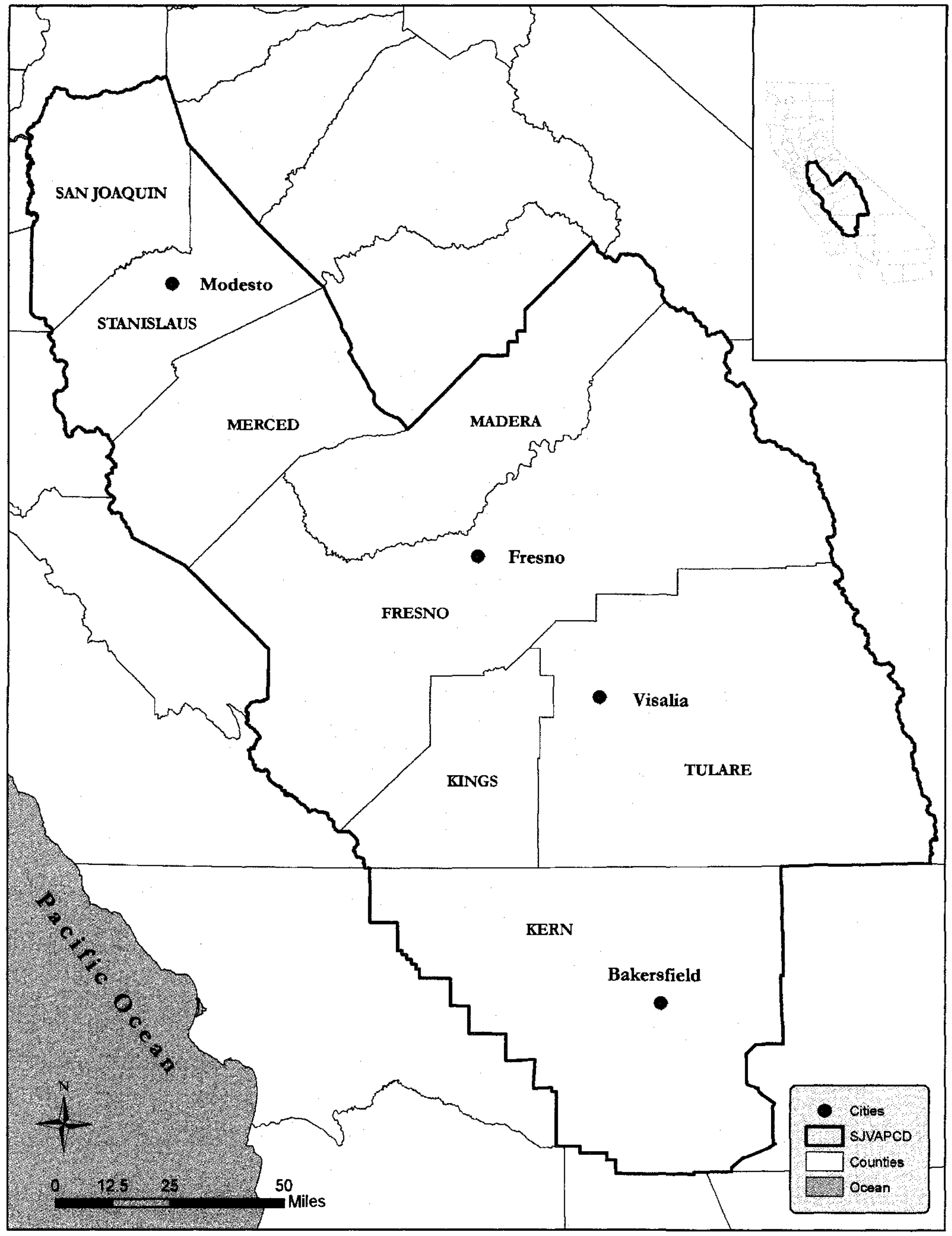

Figure 1: San Joaquin Valley Air Pollution Control District Boundary

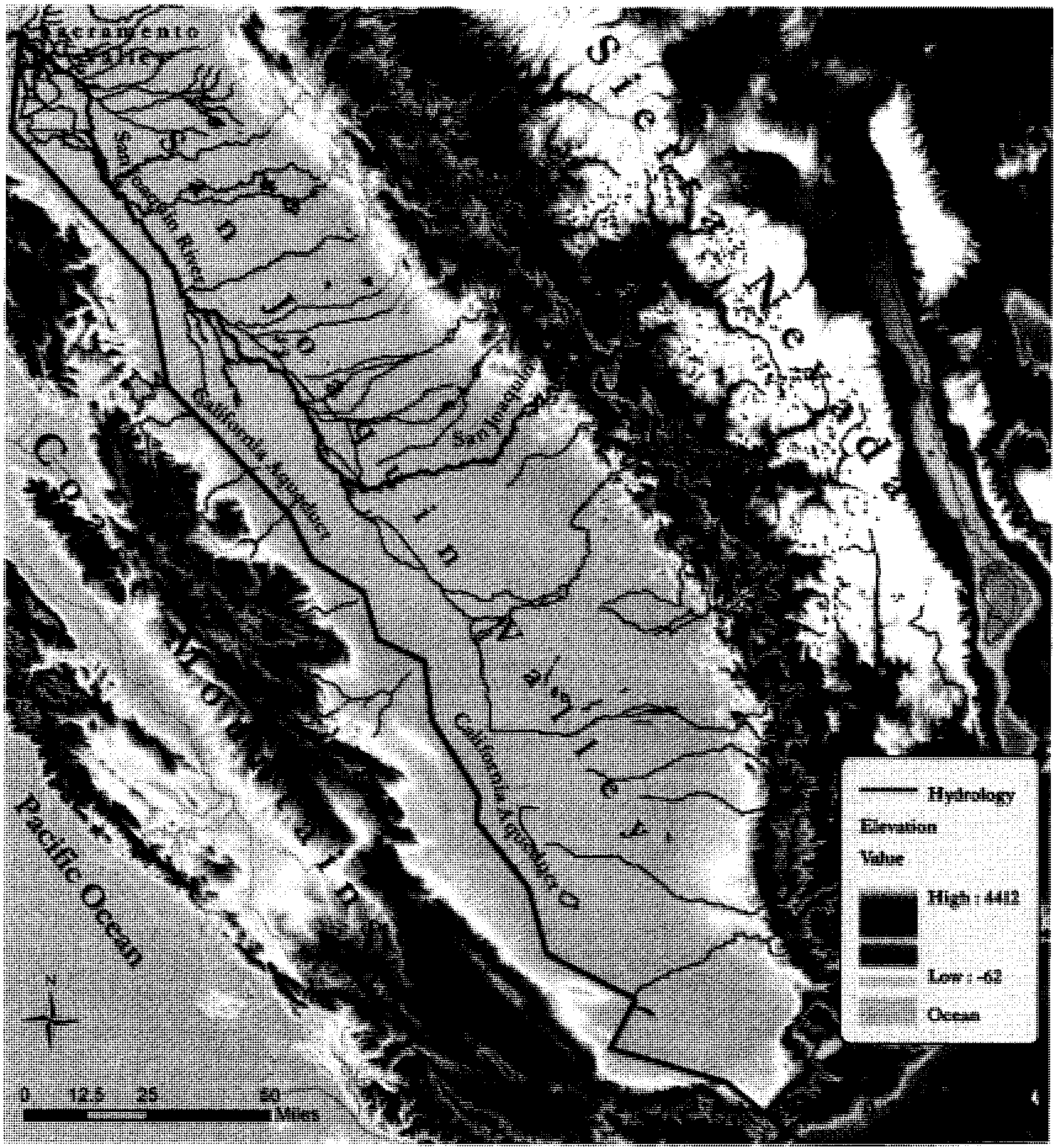

Figure 2: San Joaquin Valley Physical Geography

Site Geography

Sites were selected from two air quality monitoring networks (Figure 3). Both networks have ground sensors located inside the San Joaquin Valley Air Pollution Control District. California Air Resources Board (CARB) data from four cities in the San Joaquin Valley provided a relationship between communities along the trade corridor with very similar topography, economies, and pollution sources. The cities are as follows from north to south: Modesto, Fresno, Visalia, and Bakersfield.

The Interagency Monitoring of Protected Visual Environments (IMPROVE) sites provided an alternative view at sites located primarily in National Parks and Wilderness areas as well as the central location of Fresno. The IMPROVE sites are as follows from north to south: Yosemite National Park, Kaiser Wilderness Area, Fresno, Sequoia National Park, and Dome Lands Wilderness Area. The only common location for both monitoring networks is in Fresno. The NASA Aerosol Robotic Network (AERONET) is also located in Fresno with the CARB and IMPROVE sensors.

Infrastructure Geography

State Highway 99 connects the cities of the San Joaquin Valley (Figure 4). Interstate 5 is the main corridor for commerce between the San Francisco Bay Area, the Sacramento Valley, and Los Angeles (SJVAPCD, 2007). Truck traffic averages one quarter of all traffic traveling on State Highway 99 and traveling on Interstate 5 through the entire San Joaquin Valley (Caltrans, 2006). VMT have steadily increased through the San Joaquin Valley. VMT directly causes emission produced particulate matter. VMT has been monitored as an early indicator of worsening air quality and is a large reason air quality monitoring began. According to CARB data in 1940, annual VMT was about 24 billion miles traveled and in 2000, annual VMT was 280 billion miles traveled. In sixty years that is more than a 1000% increase.

Economic Geography

Agriculture is the main industry in the San Joaquin Valley: fruits, vegetables, grains, nuts, livestock and fibers. The San Joaquin Valley (Figure 5) is the nation's top agricultural producing region. The soils and dust from the agriculture fields contribute to the PM problem in the valley. Fertilizers and pesticides often chemically react with the atmosphere and produce harmful particulate matter. The transportation of the agriculture products out of the valley to urban centers is also a major contributor in particulate matter.

Oil production in the San Joaquin Valley accounts for more than two thirds of California's total oil production (Sheridan, 2006). The majority of the oil production is in the southern third of the valley, predominately around Bakersfield. The oil is also refined in Bakersfield and in the San Francisco Bay area where the ambient particulate matter from the refining processes drift into the valley and the Sierra Nevada.

Tourism is a large and growing part of the economy and contributes to the ailing air quality. The San Joaquin Valley is the gateway to Yosemite, Sequoia and Kings Canyon National Parks. The natural areas suffer from forest fires that often worsen the Valley's air quality and are major contributors to particulate matter.

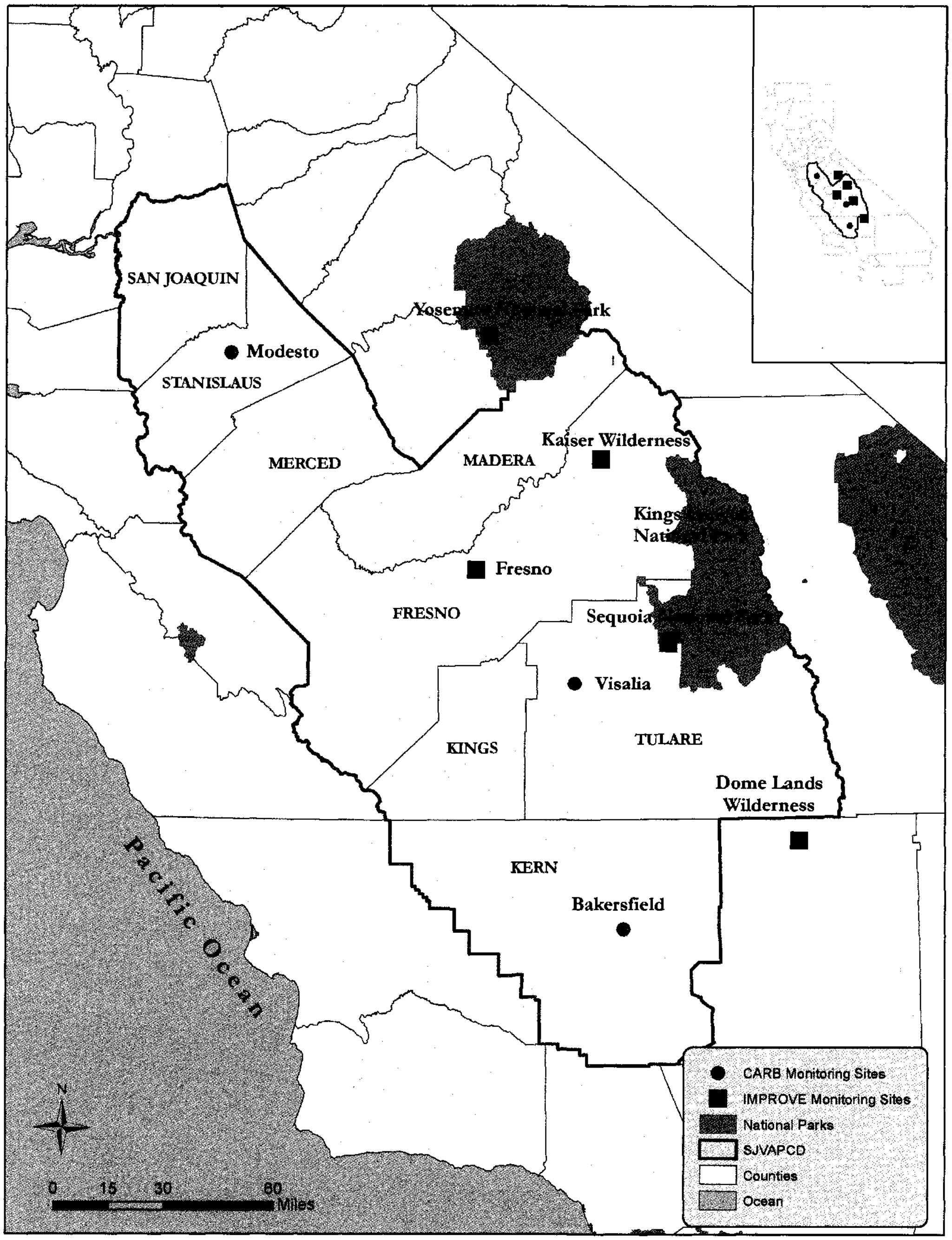

Figure 3: CARB and IMPROVE Monitoring Site Locations

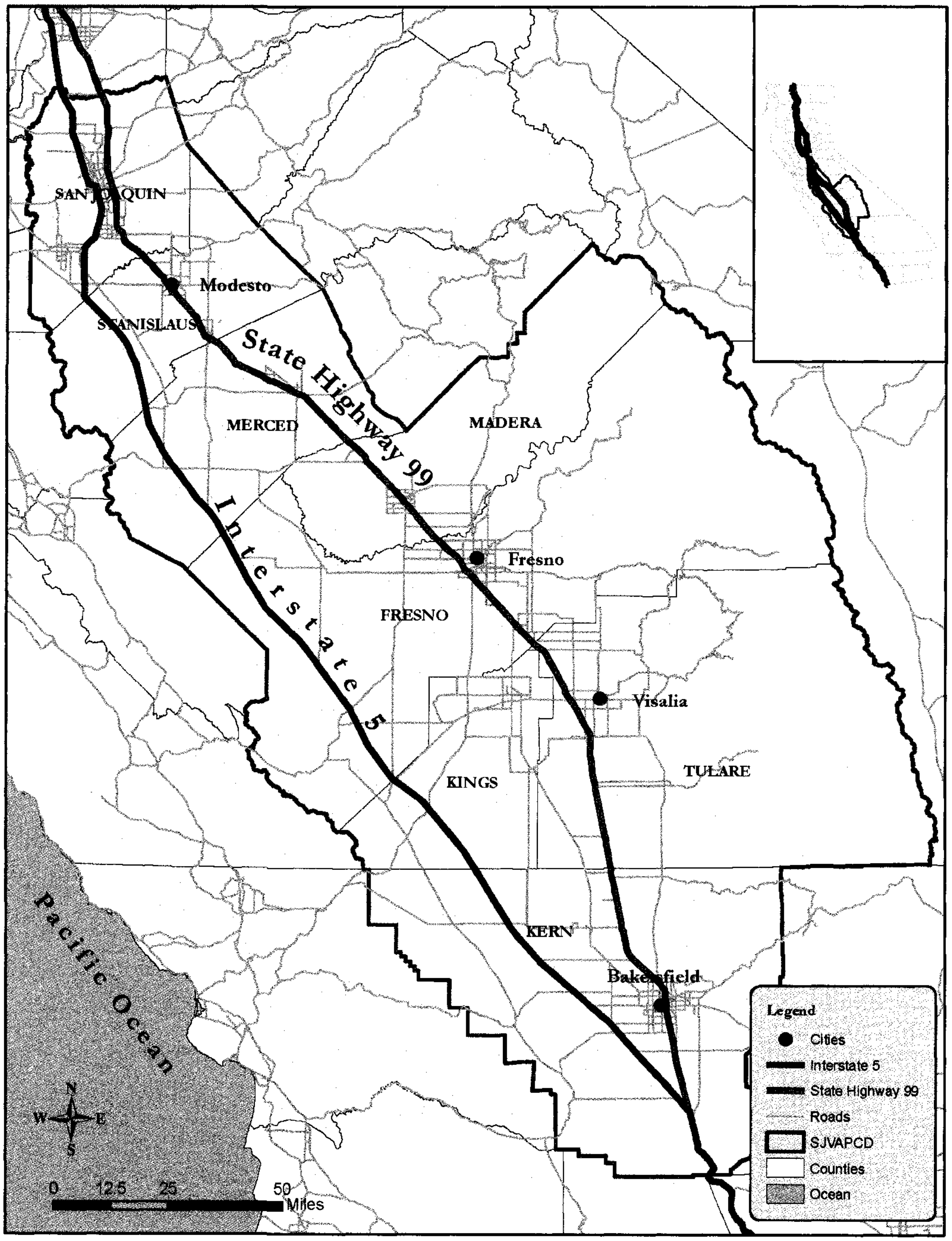

Figure 4: Highway Infrastructure in the San Joaquin Valley

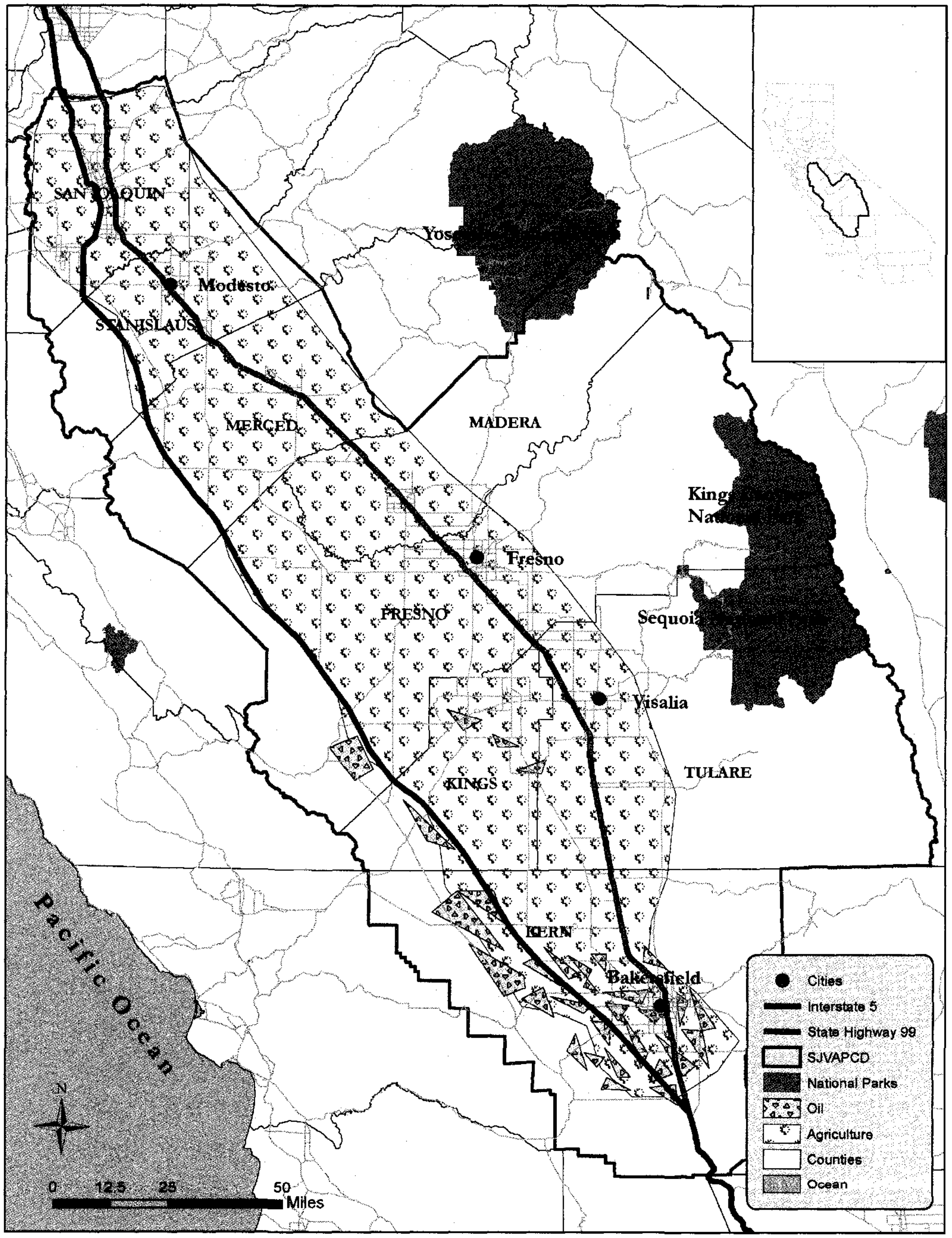

Figure 5: Areas of Economic Importance

Air Quality Control Agencies

Air quality in the San Joaquin Valley is monitored by the San Joaquin Valley Air Pollution Control District (SJVAPCD), CARB and the United States Environmental Protection Agency (EPA). The EPA oversees state and local actions and implements programs for toxic air pollutants, heavy-duty trucks, locomotives, ships, aircraft, off-road diesel equipment, and some types of industrial equipment (SJVAPCD, 2007). The EPA has an extensive network of real-time air quality information available to the public through the program AIRNow; found online at (EPA, 2008). The AIRNow program provides daily and next day air quality forecasts across the country for particulate matter and ozone (Al-Saadi et al., 2005). The AIRNow website provides detailed point information about PM levels and maps with color coded severity levels for monitoring locations (Figure 6).

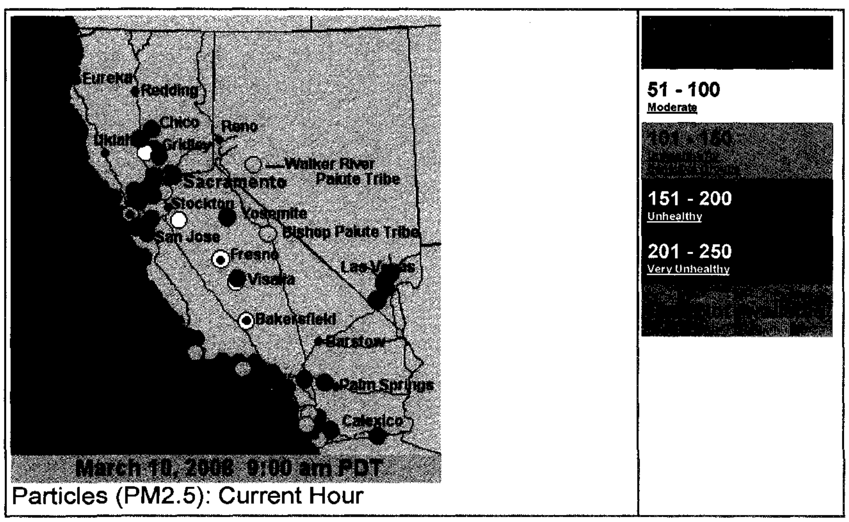

Figure 6: US EPA AIR Now $PM_{2.5}$ Current hour measurements (EPA AIRNow, 2008)

The state Air Resources Board and Bureau of Automotive Repair, sets more stringent standards than the federal government, oversees local actions, and implements programs for motor vehicle emissions, fuels, and smog checks (SJVAPCD, 2007). CARB has extensive data available online from the statewide air quality monitoring network. Many of their programs are approved at the federal level and implemented at the local level.

The SJVAPCD is coordinating efficient and effective air quality management strategies with CARB and EPA. The SJVAPCD develops plans and implements control measures throughout the valley. These controls primarily affect stationary sources such as factories. The air district also provides public education and outreach efforts to raise awareness and cooperation from industry and the public (SJVAPCD, 2007).

Particulate Matter

The EPA classifies "particulate matter, (PM)" (also known as aerosols or particle pollution), as a complex mixture of extremely small particles and liquid droplets. PM_{10} is 10 microns in diameter also called "inhalable coarse particles" and $PM_{2.5}$ is 2.5 microns in diameter also called "fine particles" which can easily be inhaled causing health problems in the lungs and heart (EPA, 2007). PM is a major concern in public health, because of the ease with which the particles can be inhaled and cause health problems. The sources of the PM range from dirt roads, construction sites, smokestacks, fires, to the many chemical reactions in our atmosphere from various vehicle and industrial emissions.

Particulate matter includes a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles (EPA, 2007).

Additional sources can be monitored and to some degree prevented, including wind blown dust and wildfires; biogenic and geogenic hydrocarbons that mix with anthropogenic sources to contribute to PM pollution (ARB 2006; NARSTO, 2004). Particulate matter is the cause of reduced visibility or haze in our neighborhoods and our national parks. Particulate matter also influences regional climate by altering cloud properties, suppressing rainfall and absorbing solar energy.

California Air Quality Standards

It is the responsibility of the EPA and CARB to create air quality standards and enforce emission regulations. CARB standards are more stringent than the EPA for air quality levels for annual arithmetic mean and PM_{10} 24 hour, but $PM_{2.5}$ 24 hour is the same for both, 35 ug/m^3 (Table 1) (ARB, 2006). The emission sources are estimated by CARB personnel based on information retrieved from districts and government agencies regarding anthropogenic and natural causes (ARB 2006; NARSTO, 2004).

Table 1: CARB Ambient Air Quality Standards (ARB, 2006)

Ambient Air Quality Standards						
Pollutant	Averaging Time	California Standards [1]		Federal Standards [2]		
		Concentration [3]	Method [4]	Primary [3,5]	Secondary [3,6]	Method [7]
Ozone (O_3)	1 Hour	0.09 ppm (180 µg/m^3)	Ultraviolet Photometry	—	Same as Primary Standard	Ultraviolet Photometry
	8 Hour	0.070 ppm (137 µg/m^3)		0.08 ppm (157 µg/m^3)		
Respirable Particulate Matter (PM10)	24 Hour	50 µg/m^3	Gravimetric or Beta Attenuation	150 µg/m^3	Same as Primary Standard	Inertial Separation and Gravimetric Analysis
	Annual Arithmetic Mean	20 µg/m^3		—		
Fine Particulate Matter (PM2.5)	24 Hour	No Separate State Standard		35 µg/m^3	Same as Primary Standard	Inertial Separation and Gravimetric Analysis
	Annual Arithmetic Mean	12 µg/m^3	Gravimetric or Beta Attenuation	15 µg/m^3		

Related Work

In recent years a great deal of work has been conducted in atmospheric sciences using satellite technology. With the launch of the Terra Satellite in 1999 a new era began in remote sensing of the Earth. 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). A great deal is at stake for science in using remote sensing from Earth's orbit in addition to the current network of ground based remote sensors. Data and images collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) sensors (Figures 7 and 8) have been used to demonstrate the effects of various types of aerosols, from forest fires, to haze to volcanic eruptions.

Figure 7: MODIS images of Forest Fires in Southern California
(NASA, October 29, 2007)

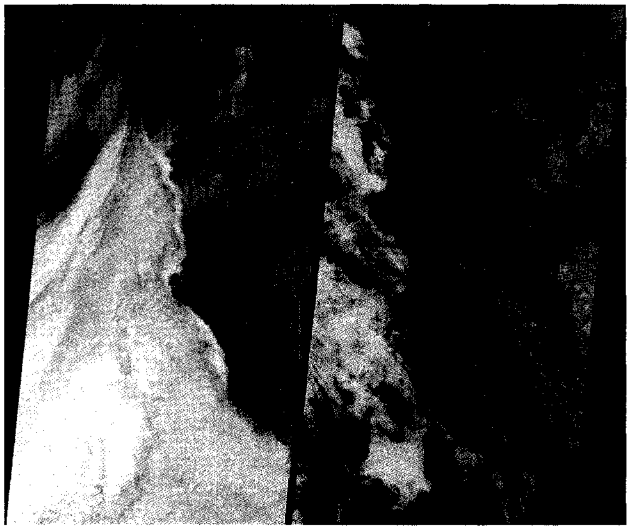

Figure 8: MISR images of Forest fires in Oregon,
(NASA, July 29, 2002 and October 29, 2002)

Validation of MODIS AOD over land was conducted using AERONET measurements to corroborate the MODIS AOD levels (Chu et al., 2002). The validation focused on continental inland and coastal areas with similar industrial/urban pollution and biomass burning aerosols (Chu et al., 2002). The validation was successful for MODIS, however several factors including water contamination, uncertainties in surface reflectance and variable aerosol properties reinforced that the MODIS sensor is not applicable globally (Chu et al., 2002). Errors in the MODIS aerosol retrievals can be attributed to diverse surface reflectance, snow or ice, sub-pixel clouds, and AOD properties that are not considered in the product's algorithms (Chu et al, 2002).

MODIS and MISR sensors are both capable of detecting AOD, however they vary in their temporal, spatial and spectral abilities. Studies have shown that MODIS and MISR complement each other with regard to measurement accuracy and spatial coverage (Liu et al. 2006). Past studies in the Mojave Desert and Northeast Asia found an impressive R^2

values of 0.83 and 0.90 on a basic regression comparing spatially averaged MISR AOD and MODIS AOD respectively against temporally averaged AERONET AOD (Frank et al., 2006; Lee et al., 2007).

No specific study has been conducted solely in the San Joaquin Valley to determine whether there is a relationship between satellite-measured AOD and ground monitoring PM values. A previous study of the continental United States, found a poor correlation between MODIS AOD and PM values in the western United States compared with a good correlation in the midwestern and eastern United States (Engel-Cox et al. 2004; Von-Donkellar et al., 2006). Several factors could be the underlying causes of the weak relationship between the two data sources. Low correlations occurring in the Los Angeles area are due to large hourly and daily variability of very local emission sources (Al-Saadi et al., 2005).

$PM_{2.5}$ and satellite AOD represent two different but related atmospheric loadings of pollutants. The $PM_{2.5}$ is the dry mass of aerosols measured at the ground level and the satellite AOD represents the total columnar loading of all aerosol particles from the surface to the top of the atmosphere (Gupta et al, 2006). Using airborne LIDAR, a vertical distribution was recorded in the southern part of the San Joaquin Valley near Bakersfield. The aerosol layers aloft were pinned against the Tehachapi Mountains and experienced some venting into the free troposphere (DeYoung, 2005). A current study being conducted by EPA region 9, NASA and CARB are using aerial lidar to study vertical distribution of aerosols, along with MODIS, AOD and ground based $PM_{2.5}$ data (Rosen, personal communication, 2007).

AERONET sun photometer stations are located all over the world; including one in the San Joaquin Valley in Fresno. AERONET is a NASA product that provides AOD values recorded every 15 minutes utilizing seven spectral bands (340, 380, 440, 500, 670, 870, and 1020 nanometers). Multiple spectral and angular measurements allow for excellent retrieval of aerosol parameters with fewer assumptions about aerosol properties than are used in satellite remote sensing (Sinyuk et al., 2006). MISR has shown to have a favorable comparison to AERONET, (Diner et al 2001).

AIR QUALITY MONITORING

Remote Sensing of Air Quality

Air quality monitoring equipment is more diverse today than ever before. The majority of monitoring equipment operates remotely; measuring air quality through light backscatter, and filter samples of the local air. As technology advances our monitoring equipment changes and the data collected varies in form. Aerial technology has led the way for satellite technology to be an applicable and legitimate atmospheric remote sensing data source.

$PM_{2.5}$ Ground Sensors

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. The IMPROVE monitoring network consists of samplers (Figure 9) 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 (diameter < 2.5 microns) and coarse particles (diameter < 10 microns), which are collected for 24 hours every three days (IMPROVE, 1995).

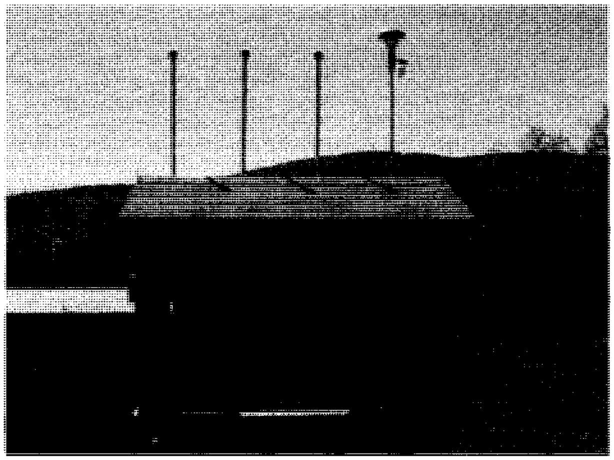

Figure 9: IMPROVE $PM_{2.5}$ Monitoring Equipment (IMPROVE, 2008)

CARB uses Federal Reference Monitors (Figure 10) that collect particulate samples on filters that are later weighed and analyzed in a laboratory (ARB, 2006). IMPROVE collects particulate samples on Teflon filters that are later weighed and optically analyzed for absorption levels (IMPROVE, 1995). The data collected by these sensors are publicly available through data downloading from their respective web sites. There is a degree of lag time for the data to be available from its time of collection to its availability.

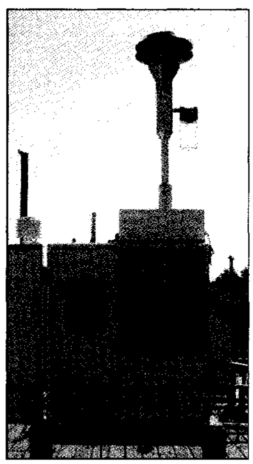

Figure 10: CARB $PM_{2.5}$ Monitoring Equipment (ARB, 2006)

Sun Photometers

AERONET is a worldwide network of sun photometers (Figure 11) established by NASA and partner agencies to primarily measure aerosol optical depth. Aerosol optical depth is calculated by the spectral extinction of the sunlight at specific wavelengths (Giles, 2007). AERONET data is available by download through the NASA AERONET web-site. The data is updated daily for a near fluid collection to processing procedure.

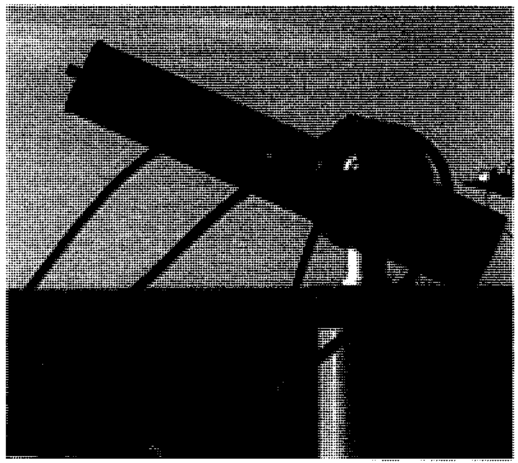

Figure 11: AERONET Sun Photometer (Chambers, 2008)

Satellite Sensors

Using the MODIS and MISR sensors', data from the Terra satellite allowed precise data corroboration every 16 days. The Terra satellite orbits the earth with an approximate 10:30 am equatorial crossing time, allowing for late morning measurements in the northern hemisphere. The Terra satellite was the first Earth Observing System satellite, launched on December 18, 1999.

The MODIS sensor, which is aboard the Terra and Aqua satellites, measures aerosol optical depth (AOD), (Hubanks, 2007). MODIS has a swath width of 2330 km with a spatial resolution of 10 km with a near complete daily global coverage (Remer et-al., 2005). MODIS' 500nm spectral resolution is most comparable to MISR's 558 nm and AERONET's 550nm (Liu et al., 2006).

The MISR sensor is also aboard NASA's Terra satellite. MISR has a unique approach of data collection, viewing the earth with nine different angles and four wavelengths (blue, green, red, and near-infrared) (Diner et al., 1998). MISR has a swath width of 360 km with a spatial resolution of 17.6 km and every 9 days achieves global coverage, however, MISR repeats its path every 16 days (Diner et al., 1998).

METHODOLOGY

Ground Sensors Data

Using the two types of ground sensors from three data sources, PM measurements from CARB and IMPROVE and AOD measurements from AERONET provided stable consistent data to compare with satellite data. The current network of PM ground sensors provides a wide spatial distribution for the San Joaquin Valley, while AERONET will provide a basis for the centralized location of Fresno.

IMPROVE data were obtained with $PM_{2.5}$ for five sites in and adjacent to the San Joaquin Valley; Yosemite National Park, Sequoia National Park, Kaiser Wilderness Preserve, Dome Lands Wilderness Preserve, and the city of Fresno. 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); 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 (IMPROVE, 2007). CARB provided $PM_{2.5}$ and PM_{10} data, from January 2005, 2006 through August 2005, 2006 respectively for the following cities; Modesto, Fresno, Visalia, and Bakersfield.

AERONET level 2 data were downloaded from the AERONET data archive for April 2005 through August 2005 and January 2006 through August for 2006 for the Fresno AERONET station. Prior to April in 2005, the Fresno AERONET sun photometer was out of operation for calibration. This study correlated to the AERONET 500 nanometers band AOD values since MODIS measures AOD at a comparable 550 nanometers (Jiang et al., 2006). The fifteen minute interval readings were averaged per day to allow easy comparison with the daily values of the satellite and ground data.

Satellite Sensors Data

MODIS data were from Terra MODIS which passes over Fresno in the late morning. MOD04 Level Two Aerosol Product includes AOD values contained in the variable Corrected_Optical_Depth_Land in a 10 kilometer resolution. Due to quality assurance and a dry-land study area, the best data field to use is the Corrected_Optical_Depth_Land (Remer et al., 2005). All MODIS data were downloaded from the NASA Laads web site (Horrocks, 2008). NASA Laads web site allowed queries of the spatial, temporal, spectral characteristics and conversion of the data to GeoTiff format. The option to download the original Hierarchical Data Format (HDF) files were also available. Data were downloaded from January through August 2005 and 2006, respectively.

The MISR sensor is also aboard the Terra satellite. MISR paths 42, 43, and 44 had the best coverage of the entire San Joaquin Valley; therefore data were downloaded for all days on those paths from January – August 2005 and 2006 respectively. Level two Aerosol data MIL2ASAE, were ordered from the NASA Langley ASDC MISR order and customization tool, (Krusterer, 2008). MISR AOD data were extracted at 558 nm using the field name RegBestEstimateSpectralOptDepth as was demonstrated in "Liu et al. 2006." MISR files were only available as HDF files.

Satellite Sensor HDF Files

Hierarchical Data Format (HDF), were created to be a standard method of data storage for large amount of data collected. HDF files are easy to share and can be used with an assortment of software and programming languages. HDF format is the official data format for the NASA Earth Observing System, which includes MODIS and MISR products.

GeoTIFF Files

GeoTIFF files are becoming increasingly popular in remote sensing. They allow more users access to remotely sensed data including satellite imagery. GeoTIFF files are simply TIFF images with geographic metadata embedded in one or more forms, including but not limited to, projection, georeferencing, and can be used in any GIS, CAD or image processing software (Ruth, 2005). If all the NASA satellite products could be easily converted into GeoTIFF format then the data would be much more accessible to the general public and researchers.

Processing Data

Using data-sets from two types of measurement variables establishes multiple data-set and data type analysis. Processing the data was consistent for each data type. AOD data from AERONET and satellite sources allowed for analysis of corroborative conclusions. Comparison is possible for the two sources of particulate matter data: CARB and IMPROVE.

Ground Sensors Data Processing

Both CARB and IMPROVE data were downloaded in comma separated values allowing for easy use and analysis. AERONET was also easily manageable in a comma separated values. However, AERONET data were not provided in fifteen minute intervals as advertised, but a mixture of times, primarily beginning in the early afternoon.

This did not allow for an easy match to the satellite data, which was from the late morning. An average for all the measured AERONET data were used to represent the values for the AERONET data.

Satellite Sensors Data Processing

The primary satellite AOD data source was the MODIS sensor. MODIS was selected for its higher temporal resolution, frequency, and wider swath width covering a greater part of the valley. MODIS provided more data overall to correlate with ground monitoring and satellite derived AOD.

For rapid data processing, GeoTIFF images were acquired of the MODIS data directly from the aforementioned web site. Using the image post processing options the GeoTIFF files were ordered. These images had the applicable AOD data are much easier to manage than their HDF counterpart. Using ArcGIS all the AOD values from the GeoTIFF images were extracted. First an ArcGIS project was created that contained a state boundary layer of California and more importantly the locations of the all the ground sensors. An original shapefile was downloaded from the CARB website that was altered to only contain the interested four sites. IMPROVE sites were located by using the x,y, coordinates provided by the data management agency.

MISR data involved an additional step in processing; the HDF file was first converted into a GeoTIFF using the HDF EOS to GeoTIFF (HEG) converter. The HEG tool allowed HDF files to be converted and projected for use in commercial software that cannot read HDF files. Processing time increased, however the number of MISR files were considerably fewer than MODIS. Since MODIS files were converted to GeoTIFF format prior to download, MISR HDF files were converted to GeoTIFF files to maintain file formats among the satellite data.

Satellite Sensors Data Extraction

For the MODIS and MISR AOD values, information was extracted for the nine sites at eight ground monitoring locations in three ways using the pixel inspector in ArcGIS (Figure 12). First for MODIS, all values in a 5 x 5 pixel square around each site were extracted, and then the median values for the 5 x 5, 3 x 3 and the centroid pixel were calculated. The median values allowed for an easier spatial comparison between data. The same locations were extracted from MISR data using the 3 x 3 method, finally calculating 3 x 3 median and the centroid. Extracting a 5 x 5 median filter of pixel values for the MODIS 10 km data and a 3 x 3 median filter for the MISR 17.6 km data makes the two resolutions relatively comparable (Liu et al., 2006). Median filters allowed for increased accuracy and created acceptable values if some of the measured pixels had no data (Chu, et al. 2002). If the date of the data did not have fifty percent of the pixels present in the median filters the date was eliminated from the statistical analysis.

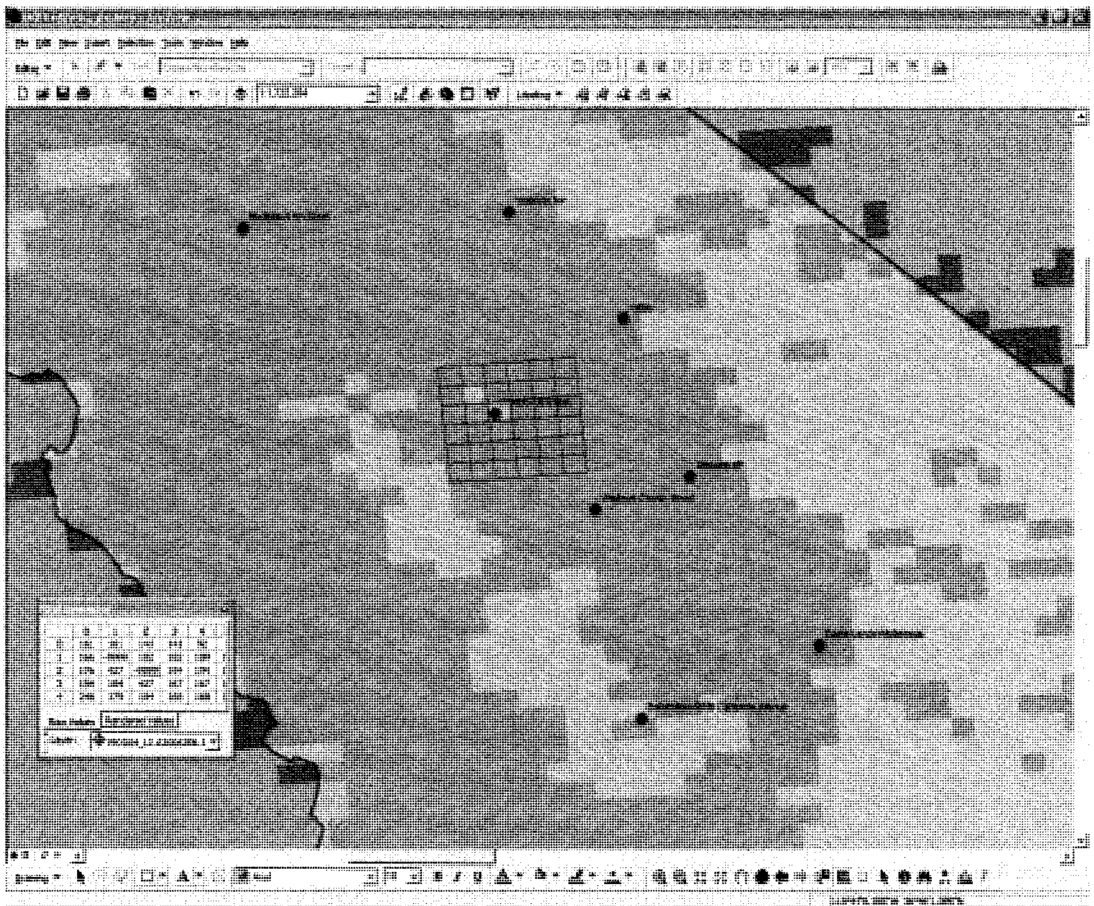

Figure 12: ArcGIS Pixel Inspector and MODIS AOD data

RESULTS

Data availability and coincidence

A significant problem with satellite data is the lack of consistency in availability. When investigating aerosols, cloudy days were no value days. This is a large inhibition for regulators to use satellite data to assist in determining air quality. In Table 2, the number of days of data downloaded compared to the days with values for the MODIS and MISR satellite sensors varied greatly. The ground sensors were uninhibited by the cloudy weather and continued to collect data. Another significant problem was when correlating the data types the days became limited by collection date. The PM ground sensors only collected data every three days and the satellite sensors are limited to atmospheric conditions; this resulted in only 120 days of PM sensors coinciding with MODIS and only 12 days coinciding with MISR. This essentially eliminated MISR from any sort of practicality as a regular measurement monitor.

Table 2: Days of data available from collected data sources

Days of Data				
Data Source	Total Downloaded	Total with Data	Days Coincident with MODIS	Days Coincident with MISR
MODIS	480	379		48
MISR	76	49	48	
AERONET	357	357	87	32
CARB	162	157	120	12
IMPROVE	162	155	120	12

$PM_{2.5}$ Ground sensors

Using two data sets to measure particulate matter, CARB and IMPROVE broadened the spatial area that was investigated. Additionally it allowed for the two data sets to be compared. Within two standard deviations of the mean the regression in Figure 13 shows a very good relationship between CARB $PM_{2.5}$ data and IMPROVE $PM_{2.5}$ data.

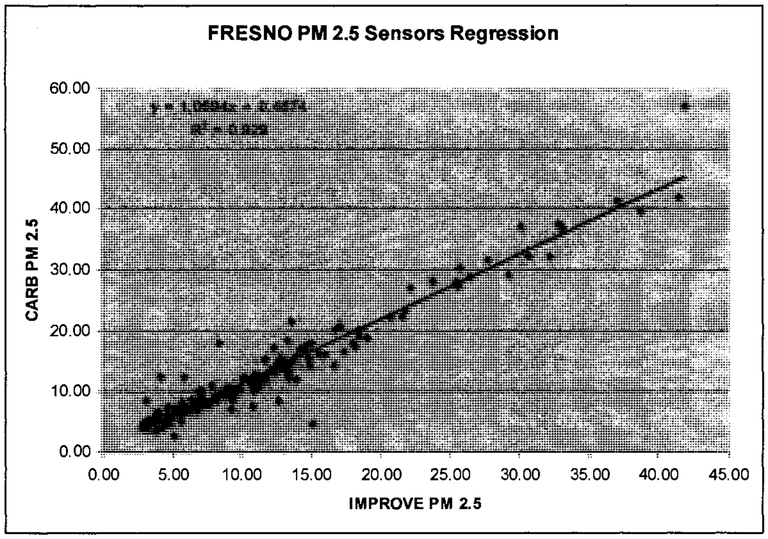

Figure 13: Relationship of CARB and IMPROVE $PM_{2.5}$ data in Fresno

In Fresno, of the 150 coincident days between the datasets, only 7 days from the IMPROVE dataset and 10 days from the CARB dataset exceeded the federal 24 hour standard of 35 ug/m^3 for $PM_{2.5}$. The remaining IMPROVE sites had no days that exceeded the federal standards, however the CARB sites did, Bakersfield with 9 days, Modesto with 5 days and Visalia with 3 days. Days that the $PM_{2.5}$ exceeded federal standards there were relationships between $PM_{2.5}$ and AERONET or satellite AOD.

AOD Sensors

As with the PM ground sensors, to first show a correlation between the different AOD sensors, prior to looking at the correlation between the PM and AOD sensors was important. Temporal deficiencies were further exacerbated by the removal of outliers outside two standard deviations. Figure 14 shows a mediocre relationship between MODIS and AERONET. Data were only from the days that both MODIS and AERONET had values; a total of 87 days.

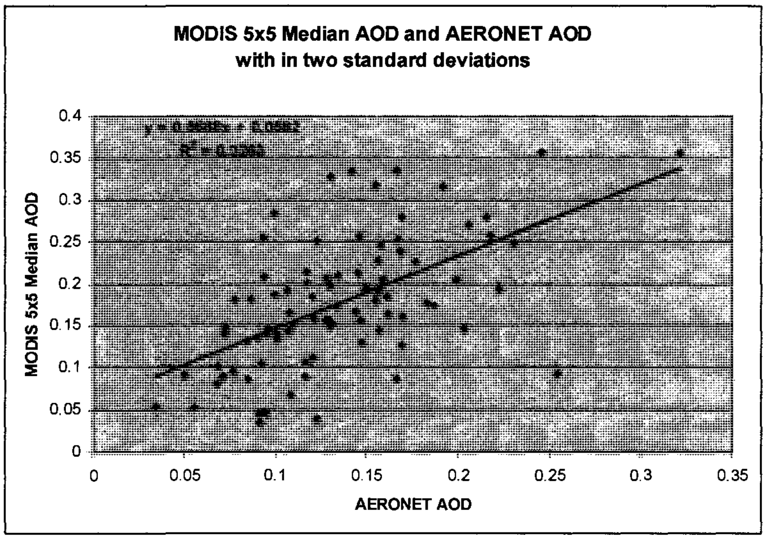

Figure 14: Regression of AOD sensors, MODIS and AERONET

After the poor result of MODIS and AERONET, it was important to verify with MISR. A total of 32 coincident days of data proved beneficial to the three datasets with much higher R squared values. Table 3 shows regression values between MODIS, MISR and AERONET within two standard deviations of the mean. AERONET has an outstanding correlation with both MODIS and MISR. The MODIS 5x5 median pixel filter and the MISR 3x3 median pixel filter improved the correlation significantly with one another compared to their centroid values. MODIS also had a much higher correlation with AERONET using its 5x5 median pixel filter versus the 3x3 or centroid values. The examples below in Figures 15 through 17 show the linear regressions between MODIS 5x5 median AOD with AERONET AOD, MODIS 5x5 median AOD with MISR 3x3 median AOD and MISR 3x3 median AOD with AERONET AOD respectively.

Table 3: R^2 values for AOD sensors, MODIS, MISR and AERONET

MODIS - MISR - AERONET			
R Squared Values	MISR 3x3	MISR Centroid	AERONET
	No Standard Deviations		
MODIS 5x5	0.59		0.3263
MODIS 3x3	0.3252		0.3872
MODIS Centroid		0.3194	0.1056
AERONET	0.6006	0.3872	
	2 Standard Deviations		
MODIS 5x5	0.9714		0.9728
MODIS 3x3	0.9207		0.9101
MODIS Centroid		0.8834	0.8168
AERONET	0.9752	0.9427	

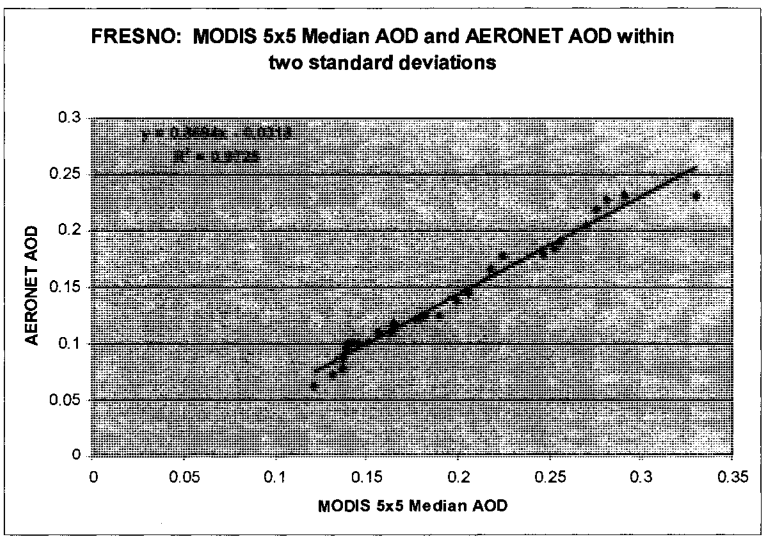

Figure 15: Regression of MODIS AOD and AERONET AOD

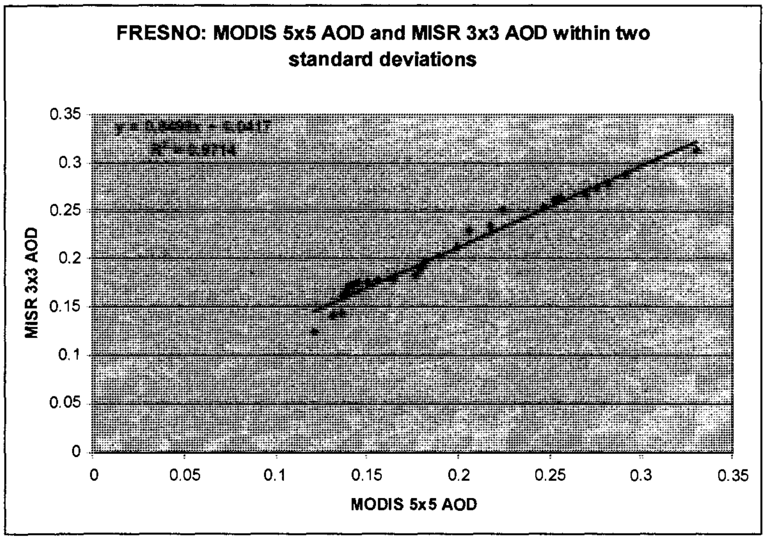

Figure 16: Regression of MODIS AOD and MISR AOD

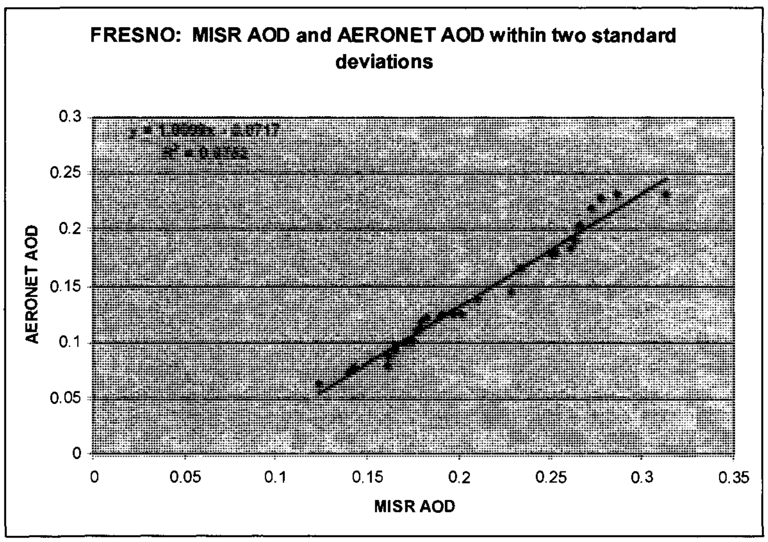

Figure 17: Regression of MISR AOD and AERONET AOD

AOD Sensors and PM 2.5 Sensors

Due to the lack of data for MISR, it was eliminated from the data processing with the PM 2.5 data. This left AERONET data only to correlate in Fresno and MODIS data to compare with all the sites. There were no good correlations between any AOD sensor and PM sensor. In Fresno, neither AERONET nor MODIS showed a correlation through regression. Using a logarithmic scale also did not show a distinct relationship that correlated daily fluctuations of air quality. There were slight improvements comparing the data when applying the 50 percent pixel presence rule. The improvements were not significant enough to show a direct correlation between the two types of data. Using Fresno as an example of the poor relationship, Figures 18 through 21 show the linear regression of MODIS 5x5 and both CARB $PM_{2.5}$ and IMPROVE $PM_{2.5}$ data with and without the 50 percent pixel presence. Table 4 shows the regression values for all sample sites using MODIS 5x5 and $PM_{2.5}$ data.

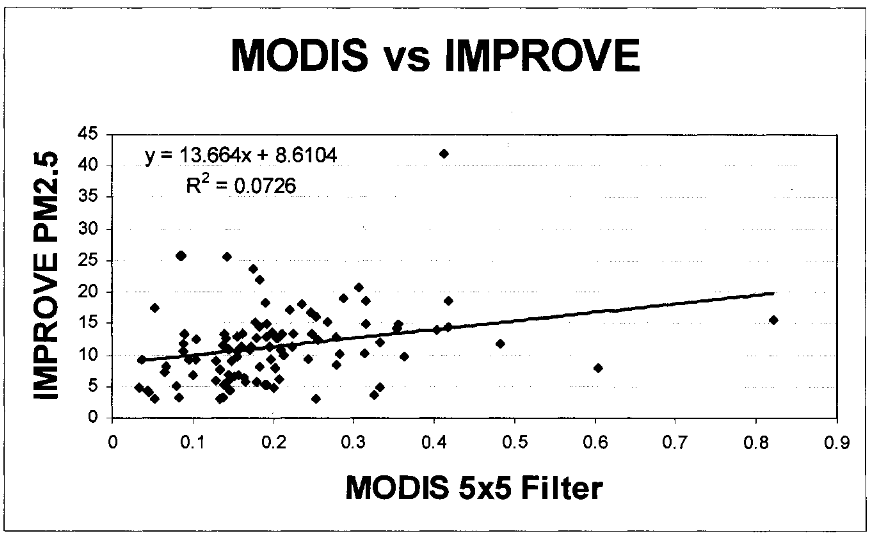

Figure 18: MODIS AOD vs IMPROVE $PM_{2.5}$

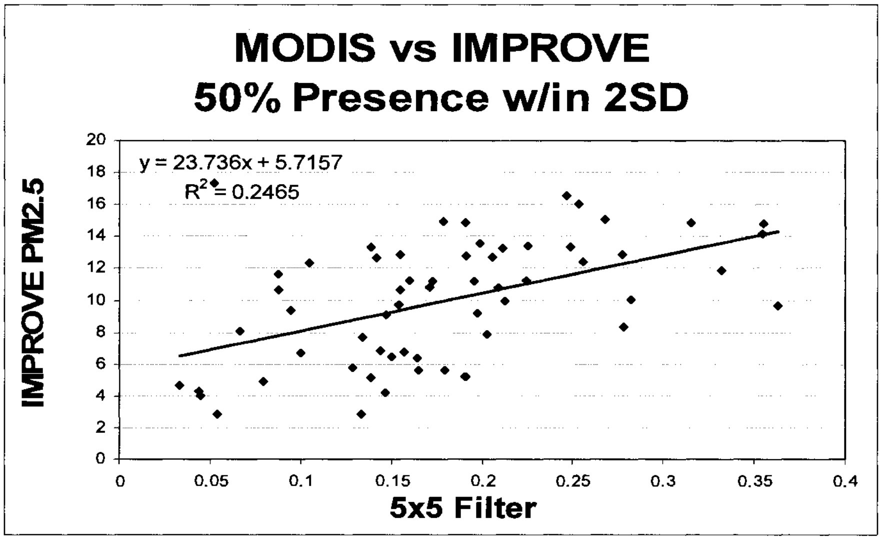

Figure 19: 50% MODIS AOD vs IMPROVE $PM_{2.5}$

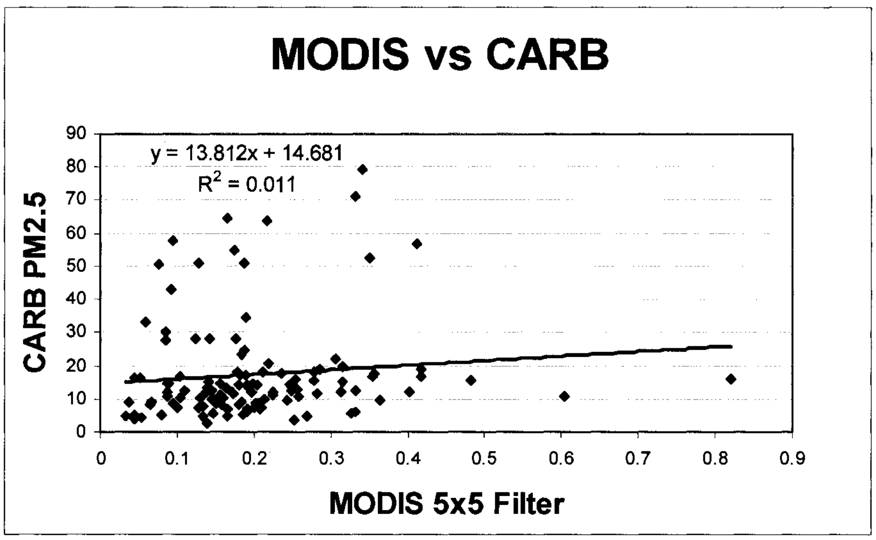

Figure 20: MODIS AOD vs CARB $PM_{2.5}$

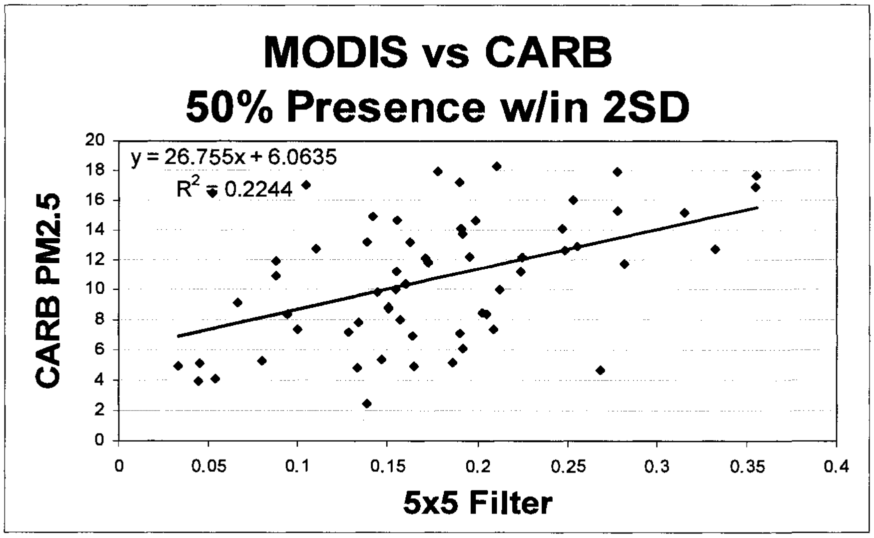

Figure 21: 50% MODIS AOD vs CARB $PM_{2.5}$

Table 4: R^2 values for all sample sites of MODIS AOD and $PM_{2.5}$ sensors

R Squared Values	5x5 Filter	3x3 Filter	5x5 Filter 50%	3x3 Filter 50%
Sites PM Values	No Standard Deviations			
Fresno - CARB	0.0121	0.0121	0.0276	0.0197
Modesto - CARB	0.0009	0.0021	0.0167	0.0265
Visalia - CARB	0.0153	0.0538	0.0243	0.049
Bakersfield - CARB	0.0278	0.0156	0.0111	
Fresno - IMPROVE	0.0062	0.0176	0.0614	0.018
Yosemite - IMPROVE	0.023	0.16	0.1882	0.1694
Kaiser - IMPROVE	0.0563	0.0079	0.0785	0.1022
Sequoia - IMPROVE	0.0479	0.0571	0.1255	0.1266
Domelands - IMPROVE	0.1961	0.2914	0.1644	0.1705
	One Standard Deviation			
Fresno - CARB	0.0005	0.0005	0.0106	0.0041
Modesto - CARB	0.0254	0.0857	0.2584	0.2878
Visalia - CARB	0.1154	0.1428	0.0243	0.0816
Bakersfield - CARB	0.1498	0.0092	0.0939	
Fresno - IMPROVE	0.1658	0.1462	0.2274	0.0334
Yosemite - IMPROVE	0.0023	0.0056	0.0022	0.0067
Kaiser - IMPROVE	0.0264	0.0366	0.0021	
Sequoia - IMPROVE	0.0024	0.0055	0.0088	0.02026
Domelands - IMPROVE	0.1322	0.093	0.033	0.1884
	Two Standard Deviations			
Fresno - CARB	0.0011	0.0287	0.2244	
Modesto - CARB	0.0009	0.1205	0.1514	0.1914
Visalia - CARB	0.0545	0.0885	0.0116	0.0404
Bakersfield - CARB	0.0216		0.0657	
Fresno - IMPROVE	0.2465	0.1	0.2244	0.1899
Yosemite - IMPROVE	0.0898	0.0919	0.1012	0.0777
Kaiser - IMPROVE	0.0968	0.0316	0.0415	0.0976
Sequoia - IMPROVE	0.0345	0.0334	0.0254	0.08727
Domelands - IMPROVE	0.0155	0.1473		

DISCUSSION

Data Availability

A temporal relationship between the AOD and PM data was difficult to establish depending on the time of year. Unless there was system downtime, the ground sensors collected data regardless of the atmospheric conditions. However, the satellite data were dependent not only orbit but also on the weather. If the weather was even partly cloudy, it was likely that the data were unusable and discarded. Pixels are missing data and appear white in Figures 22 and 23. These white areas have no data due to cloud cover, colored pixels represent AOD values. Comparing Figure 22 to Figure 23, the previous being in the winter and the latter being in the summer, the summer date (Figure 23) demonstrates better AOD data availability.

$PM_{2.5}$ Ground Sensors

The particulate matter sensors from CARB and IMPROVE provide a reliable network of sensors along the San Joaquin Valley floor and in the Sierra Nevada, east of the Valley. Comparing the two sensors data at Fresno, their one common location, they showed a great correlation with a $R^2 = 0.929$. This provided the confidence that all the sampling sites could be used as a network to compare to the satellite data.

AOD Sensors

Similar to the $PM_{2.5}$ ground sensors, correlating the AOD sensors was important. After the initial comparison of the data days for all three AOD sensors, MISR data was eliminated from the analysis. However comparison of the MISR data to both AERONET and MODIS for the days they coincided was justified. Excellent correlations were found between MISR, MODIS and AERONET. Though the datasets were limited the R^2 = 0.9714 for MISR and MODIS, and R^2 = 0.9752 for MISR and AERONET. This demonstrates that MISR can be used as ancillary data if needed.

The MODIS and AERONET initial correlation was weak with a R^2 = 0.3263, however during the MISR coincident days and the removal of outliers the relationship strengthened with a R^2 = 0.9728. The initial MODIS and AERONET data compared included more than twice as many days as did the comparison with MISR. A possible reason why the initial correlation was weak could be that MODIS AOD is recorded in the late morning and the AERONET data was averaged daily. The AOD data regressions developed the base to correlate the satellite and ground AOD data with the ground $PM_{2.5}$ data.

$PM_{2.5}$ and AOD relationships

After demonstrating that the PM data-sets compared well with one another and select AOD datasets compared well with one another, comparing AOD and $PM_{2.5}$ was possible. Unfortunately, no relationship was found between the AOD data and the $PM_{2.5}$ data. Regardless of pixel presence or the removal of outliers, the relationship did not improve to a level worth deeming as a legitimate correlation.

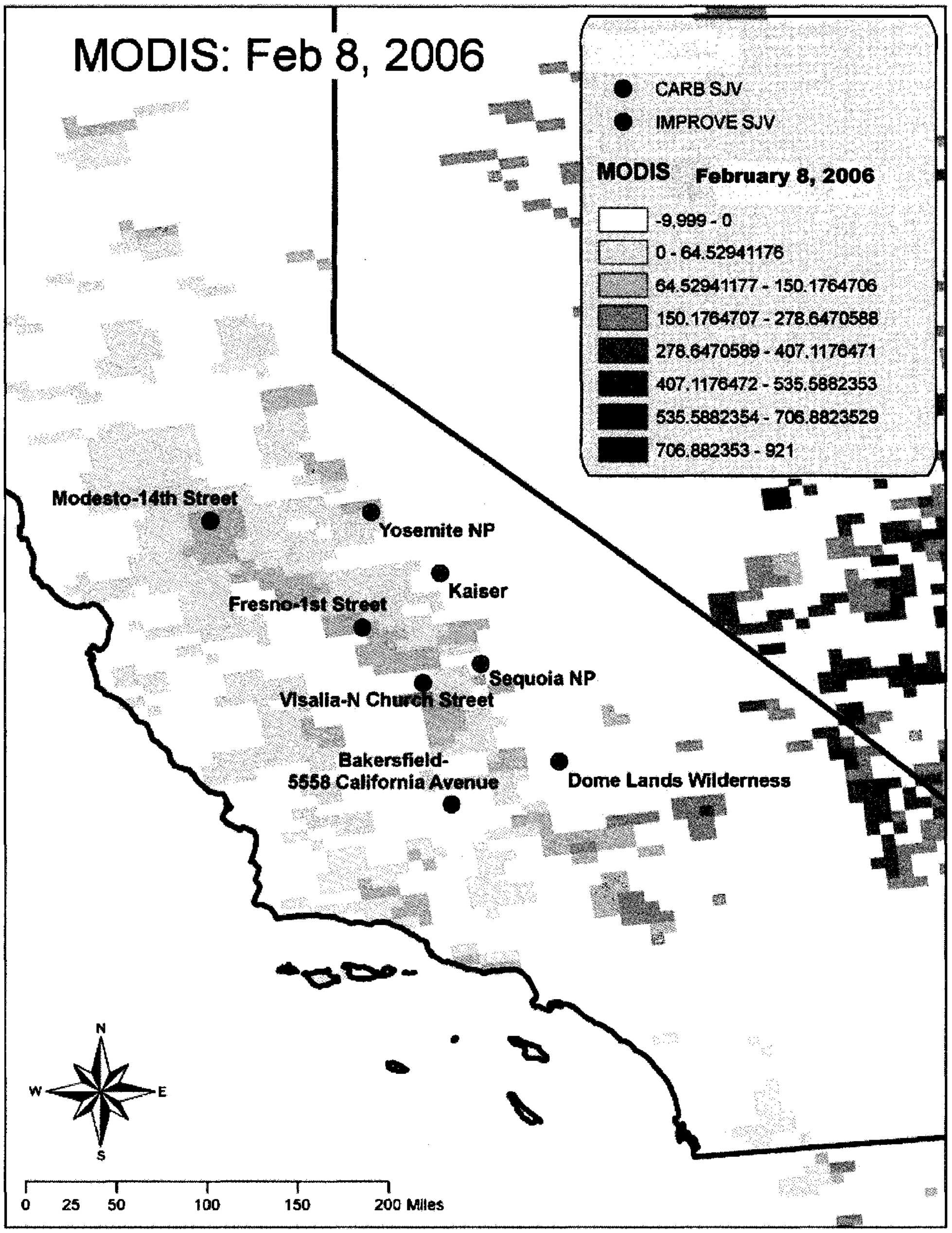

Figure 22: MODIS AOD data partly cloudy day

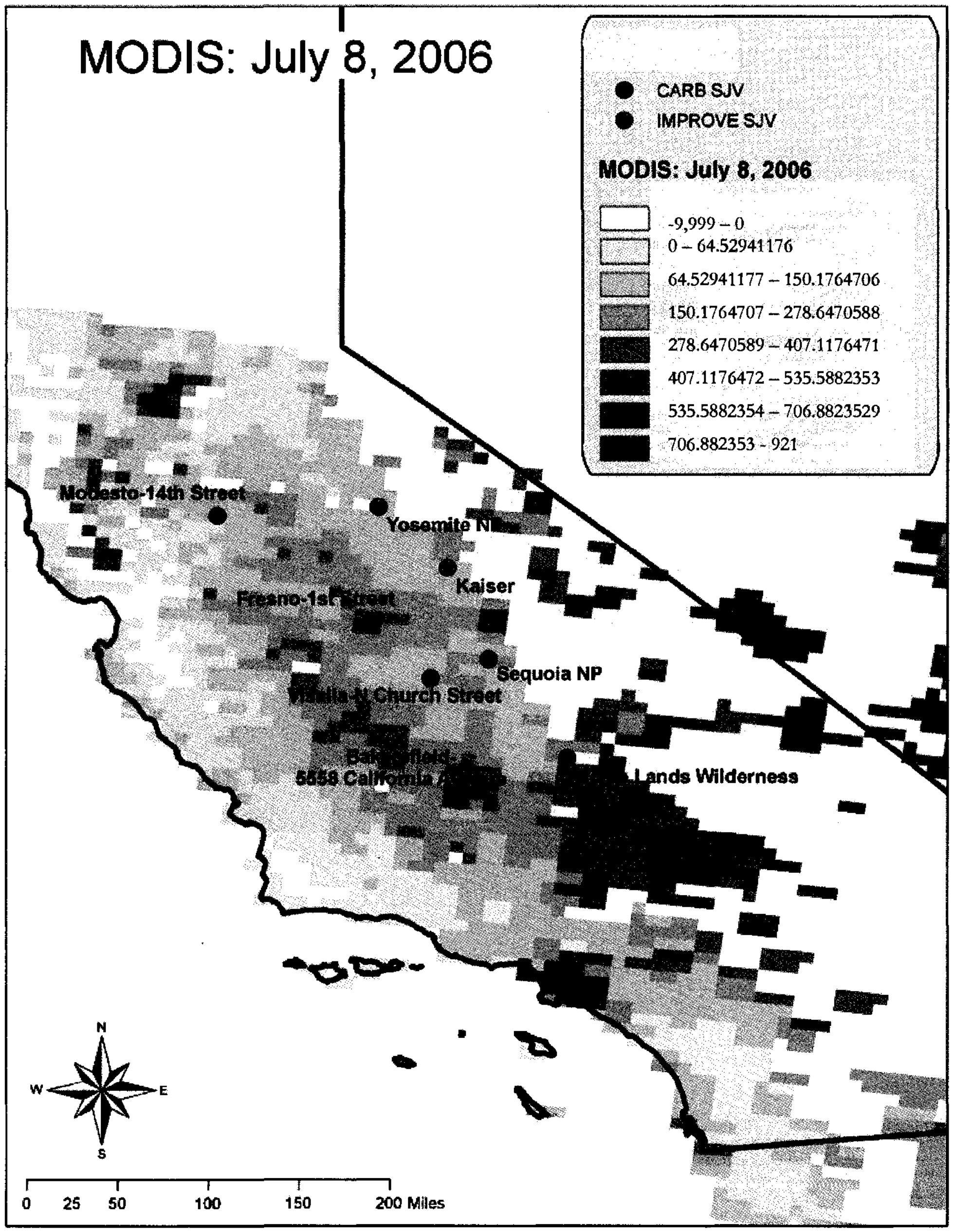

Figure 23: MODIS AOD data partly cloudy day

CONCLUSION

Potential of Satellite Remote Sensing of Air Quality

As direct correlations have worked elsewhere in the world to show a relationship between $PM_{2.5}$ and AOD data, no relationship was found between $PM_{2.5}$ and AOD data in the San Joaquin Valley. The instruments of similar measurements validated one another, which holds potential in developing a better understanding of the reasons why the two differing datasets showed no relationship. The vetted interests in the air quality of the San Joaquin Valley will no doubt help to drive the investigation of how to validate a relationship between $PM_{2.5}$ and AOD. As an enhanced tool for regulators and policy makers, there is great potential for use of satellite data to assist in determining air quality.

Possible causes of the uncertainty

There are several possible causes for the uncertainty of a direct correlation between $PM_{2.5}$ and AOD. Aerosol layers aloft in the troposphere may have impacted the satellite sensors' measurements. The atmospheric conditions in the San Joaquin Valley could be influencing the satellite sensors' measurements. The speciation of the particulate matter may be impacting the satellite sensors' data collection.

Additional data sources and data processing may reveal an improved relationship between $PM_{2.5}$ and AOD in the San Joaquin Valley. Monitoring of backscatter, speciation, relative humidity, and the elevation of the planetary boundary layer would allow for new algorithms to be used with the $PM_{2.5}$ data. Recent additions to the NASA repertoire of satellite sensors of the atmosphere also hold great potential to better understanding aerosols in the troposphere. The Cloud-Aerosol LIDAR with Orthogonal Polarization (CALIOP) sensor aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite is a LIDAR instrument focused on better understanding how clouds and aerosols impact the Earth's climate. The AURA satellite is carrying the Ozone Monitoring Instrument (OMI) sensor that specializes on collecting data about the Earth's atmospheric ozone layer, air quality and impacts to the climate. As analysis techniques are further developed the use of all satellite remote sensing data will enhance our knowledge of our atmosphere.

REFERENCES

ARB. (2006). Annual Report on the Air Resources Board's Fine Particulate Matter Monitoring Program. Retrieved from http://www.arb.ca.gov/pm/pm25_monitor_2006.pdf

Al-Saadi, J., Szykman, J., Pierce, R. B., Kittaka, C., Neil, D., Chu, D. A., et al. (2005). Improving National Air Quality Forecasts with Satellite Aerosol Observations. *Bulletin of the American Meteorological Society* Volume 86, (Issue 9), 1249–1261.

Caltrans. (2006). *Vehicle Miles Traveled Data 1976-2006.* Available from Caltrans Web site: http://traffic-counts.dot.ca.gov/

CARB. (2005). *ARB Almanac* Chapter 1. 2-44. Retrieved from http://www.arb.ca.gov/aqd/almanac/almanac07/almanac07.htm

Chambers, L.H., (2008). *NASA AERONET Aerosol Robotic Network Photo.* Retrieved from http://mynasadata.larc.nasa.gov/images/AERONET_sunphotometer.jpg

Chu, D. A., Kaufman, Y. J., Ichoku, C., Remer, L. A., Tanré, D., & Holben, B. N. (2002). Validation of MODIS aerosol optical depth retrieval over land. *American Meteorological Society* (Vol. 29, pp. 8007).

Desert Research Institute, (1999). Fresno Supersite Installation, Operation, and Data Analysis: A Research Proposal for the Cooperative Institute for Atmospheric Sciences and Terrestrial Applications (CIASTA).

DeYoung, R. J., Grant, W. B., & Severance, K. (2005). Aerosol Transport in the California Central Valley Observed by Airborne Lidar. *Environmental Science and Technology* (Vol. 39, pp. 8351-8357).

Diner, D. J., Abdou, W. A., Bruegge, C. J., Conel, J. E., Crean, K. A., Gaitley, B. J., et al. (2001). MISR aerosol optical depth retrievals over southern Africa during the SAFARI-2000 dry season campaign. *Geophysical Research Letters*, 28(16), 3127-3130.

Diner, D. J., Beckert, J. C., Reilly, T. H., Bruegge, C. J., Conel, J. E., Kahn, R. A., et al. (1998). Multi-angle Imaging SpectroRadiometer (MISR) instrument description and experiment overview *IEEE Transactions on Geoscience and Remote Sensing*, 36(4), 1072-1087.

Engel-Cox, J. A., Holloman, C. H., Coutant, B. W., & Hoff, R. M. (2004). Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality. *Atmospheric Environment*, 38(16), 2495-2509.

EPA. (2007). *Particulate Matter Fast Facts* [Fact sheet]. Retrieved from http://www.epa.gov/air/particlepollution/fastfacts.html

EPA. (2008). [A map of California current levels of $PM_{2.5}$]. *AIRNow California Current* $PM_{2.5}$ *Levels.* Retrieved from http://airnow.gov/index.cfm?action=airnow.displaymaps#map

Frank, T.D., Di Girolamo, L., Geegan, S., (2007). The spatial and temporal variability of aerosol optical depths in the Mojave Desert of southern California. *Remote Sensing of the Environment,* In Press.

Giles, D. & Holben, B. N. (2007). *NASA AERONET Aerosol Robotic Network* [Fact sheet]. Retrieved from http://aeronet.gsfc.nasa.gov/new_web/ system_descriptions_operation.html

Horrocks, K., Masuoka, E., (2008). *NASA MODIS Moderate Resolution Imaging Spectroradiometer* [Data download page]. Available from http://ladsweb.nascom.nasa.gov/

Hubanks, P., King, M., (2007). *NASA MODIS Moderate Resolution Imaging Spectroradiometer, Atmosphere Home Page* [Fact sheet]. Retrieved from http://modis-atmos.gsfc.nasa.gov/index.html

IMPROVE, (1995). *IMPROVE Data Guide* [White paper]. Retrieved from http://vista.cira.colostate.edu/improve/Publications/otherDocs/IMPROVEDataGuide/IMPROVEDataGuide.htm#Sample%20Collection%20and%20Analyses

IMPROVE, (2007). *IMPROVE Views download portal* [Data download page]. Available from http://vista.cira.colostate.edu/views/

IMPROVE, (2008). *IMPROVE equipment photo*. Retrieved from http://vista.cira.colostate.edu/improve/Overview/IMPROVEProgram_files/frame.htm

Jiang, X., Liu, Y., Yu, B., & Jiang, M. (2006). Comparison of MISR aerosol optical thickness with AERONET measurements in Beijing metropolitan area. *Remote Sensing of Environment* (doi:10.1016/j.rse.2006.06.022).

Kusterer, J.M., (2008). *NASA MISR, Multi-angle Imaging Spectroradiometer* [Data download page]. Available from http://l0dup05.larc.nasa.gov/MISR/cgi-bin/MISR/main.cgi

Lee, K. H., Kim, Y. J., Hoyningen-Huene, W. v., & Burrow, J. P. (2007). Spatio-temporal variability of satellite-derived aerosol optical thickness over Northeast Asia in 2004. *Atmospheric Environment*, 41, 3959-3973.

Liu, Y., Franklin, M., Kahn, R., & Koutrakis, P. (2006). Using aerosol optical thickness to predict ground-level PM2.5 concentrations in the St. Louis area: A comparison between MISR and MODIS. *Remote Sensing of Environment*, 107(1-2), 33-44.

NARSTO, McMurry, P., Shepherd, M., & Vickery, J. (2004). Particulate Matter Assessment for Policy Makers: A NARSTO Assessment, *Executive Summary*. Retrieved from http://www.narsto.org/files/files/ExecSum52K.pdf

Remer, L. A., Kaufman, Y. J., Tanré, D., Mattoo S., Chu, D. A., Martins, J. V., Li, R.R., Ichoku, C., Levy, R.C., Kleidman, R.G., Eck, T. F., Vermote, E., Holben, B.N. (2005). The MODIS Aerosol Algorithm, Products, and Validation. *American Meteorological Society*, 947 - 973.

Rosen, R., Szykman, J., Bohnenkamp, C., Chu, D.A., DeYoung, R., Al-Saadi, J.A., Kaduwela, A., (2006). Application of satellite data for three-dimensional monitoring of $PM_{2.5}$ formation and transport in the San Joaquin Valley (SJV), California. *Current Study.*

Ruth, M. & Warmerdam, F., (2005). *GeoTiff FAQ* [Fact sheet]. Retrieved from www.remotesensing.org/geotiff/faq.html

San Joaquin Valley Air Pollution Control District, (SJVAPCD), (2007). *About the District* [Fact sheet]. Retrieved from http://www.valleyair.org/General_info/aboutdist.htm

Sheridan, M., (2006). California Crude Oil Production and Imports. *California Energy Commission, CEC-600-2006-006, 15pp.* [White paper] Retrieved from *http://www.energy.ca.gov/2006publications/CEC-600-2006-006/CEC-600-2006-006.PDF*

Sinyuk, A., Dubovik, O., Holben, B., Eck, T. F., Breon, F.-M., Martonchik, J., et al. (2007). Simultaneous retrieval of aerosol and surface properties from a combination of AERONET and satellite data. *Remote Sensing of Environment*, 107(1-2), 90-108.