Introduction

There is a perception among many people both in the scientific community as well as the general population that lives within the Mojave Desert of southern California that air quality has increasingly worsened as a result of rapid population growth\(^1\) (Hunter et al., 2003) and land use activities that tend to generate dust. The Mojave Desert has long been a retreat for off-highway enthusiasts, and the desert has been used historically by the military for training with tracked vehicles (Anderson, et al., 2005), and grazing by cattle on public rangelands (Fleischner, 1994). These activities disturb fragile vegetation communities, exposing soils to the wind which then creates dust devils that carry particles into the atmosphere (Koch and Renno, 2005). Dust in the atmosphere may have deleterious affects on health and climate.

Solid or liquid droplets that are small enough to remain suspended in the air (dust, soot and smoke) are referred to as particulate matter. Williamson (1972) suggested that natural sources, such as dust storms, desert and soil erosion, biogenic emissions, forest and grassland fires, and sea spray accounted for about 90% of this aerosol, with the rest resulting from anthropogenic activity. However, the amount of dust and other particulate matter in the atmosphere has been shown to be increasing because of human activity (e.g., Erickson, et al., 1995, Andreae, 1996, Lovich, 1999). Miller and Tegen (1998) even suggested that roughly half of the current atmospheric dust is estimated to be anthropogenic in origin, a result of soil degradation by agriculture, overgrazing, and deforestation.

As stated in the Mojave General Management Plan (2002):

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\(^1\) http://www.npca.org/
“Visibility is probably the most important air quality resource in the desert region, and it is the most easily affected by activities that generate dust, especially fine particulates, and sulfur dioxide. Visibility impacts occur from long-range transport of pollutants from as far away as the San Joaquin Valley and the Los Angeles basin. Local pollution sources in the desert consist primarily of particulate matter from off-highway vehicles, windblown soil, mining operations, livestock grazing, and agricultural activities. These sources have left certain areas denuded or sparsely vegetated, allowing wind erosion to occur and air quality to suffer, occasionally causing violations of particulate standards at many locations.”

Particulate matter is measured for two sizes of particles, PM$_{10}$ and PM$_{2.5}$. PM$_{10}$ are particulates that are ten microns in diameter or smaller. They consist of both direct particulates (e.g., smoke from factories and fugitive dust from farms, dirt roads, desert soils and playas), and secondary particulates (e.g., ammonium nitrate and ammonium sulfate) that are formed in the atmosphere from reactions of precursor gases. PM$_{2.5}$ are the smaller particles in the atmosphere (e.g., toxic organic compounds and heavy metals from automobiles), which can be particularly unhealthy for sensitive groups of people. The U. S. Environmental Protection (EPA) agency provides data for sites operated by a number of state and federal agencies through the Visibility Information Exchange Web System$^3$. However, most of the sites are within urban or suburban locations, while many rural areas are not monitored. Urban sites are generally within spatially heterogeneous locations that contain diverse anthropogenic activities that affect particulate types and temporal concentrations. Such is the case for most sites in the Mojave Desert of southern California. The objective of our research has been to examine whether satellite observations could be used to predict PM$_{10}$ and PM$_{2.5}$ in the Mojave Desert, thus

$^2$ http://www.airinfnow.org/html/ed_particulate.html

$^3$ http://vista.cira.colostate.edu/views/
providing complete spatial enumeration of particulate matter concentrations, rather than relying on just point observations, primarily in the urban regions of the desert.

The Multiangle Imaging SpectroRadiometer (MISR) provides several aerosol products, but in particular, aerosol optical depth (AOD) has been shown to be related to particulate matter concentrations. One non-urban site located at Death Valley National Park has a long period of PM$_{2.5}$ and PM$_{10}$ measurements. This site has been selected to compare field measurements of particulate matter with satellite observations of AOD. If a strong relationship exists between satellite AOD and PM$_{10}$ and PM$_{2.5}$, then the regions between PM$_{10}$ and PM$_{2.5}$ sites could be estimated directly from satellite AOD observations. We examined the relationship between AOD, and PM$_{10}$ and PM$_{2.5}$ for each month from March 2000 to November 2004, for mean monthly averages from January to December, and for four seasons (spring, summer, fall and winter).

Aerosol Optical Depth

Aerosols are solid or liquid airborne particulates of various compositions, frequently found in stratified layers. Generally, they are defined as atmospheric particles with sizes between about 0.1 µm and 10 µm, with an average size of 1.0 µm. Under normal conditions, most of the atmospheric aerosol resides in the troposphere, where up to eighty percent of total aerosol particle mass is thought to be within the lowest kilometer of the atmosphere. Aerosols are an important problem in the Mojave Desert because of activities that occur on sparsely vegetated or denuded soils, and the abundance of naturally occurring dry lakes. Dust can be transported to the atmosphere naturally by wind erosion and convection (Koch and Renno, 2005). Convection generally has a
maximum in the spring or early summer which causes a seasonal cycle of atmospheric aerosols (Frank, et al, 2007).

The theory of radiation transfer provides a description of the accumulated effects of all processes as light is transferred from one volume of atmosphere to another along a path through the atmosphere (Stephens, 1994). Lambert’s law of extinction accounts for radiation lost from incidence by extinction along this path. Retrieval of atmospheric constituents integrated along the path can be made with Beer’s law. Optical depth represents the extinction of light.

Multiangle Imaging SpectroRadiometer

NASA launched the Terra platform, which carries MISR, in 1999. MISR was designed to assess atmospheric distributions of solid particulate matter over relatively large regions from multiple spectral and spatial resolutions. MISR uses nine cameras to observe the Earth in four spectral bands at nine fixed view angles; one nadir, and four aft and four forward (26.1°, 45.6°, 60.0° and 70.5°).

Level 2 aerosol products derived from MISR include aerosol optical depth, aerosol composition and size, and other related parameters (Diner, et al., 2001). The Terra orbit and MISR camera configuration allows for repeat of orbit paths that are ~300 miles wide, approximately four times per month. Actual number of monthly products depends upon cloud cover and other environmental factors, so scene availability will range from 0 to 4 scenes per month. The aerosol optical depth images are provided with a spatial resolution of 17.6 sq km. Individual scenes can be used, however, mean monthly and mean seasonal composites are frequently used to study the spatial and temporal variability of aerosols and their relationship to PM ground measurements since the

4 http://www-misr.jpl.nasa.gov/
ground measurements are made more frequently (e.g., every three days), and AOD imagery may be sparse because of cloud contamination.

MISR AOD has been shown to agree with ground measurements of AOD collected through the aeronet aerosol robotic network\(^5\) (Holben et al., 1998, Kahn et al., 2005), and specifically for desert environments throughout the world (Marthonchik, et al., 2004). Frank, et al (2006) demonstrated that MISR can be used to assess the spatial and temporal variability of AOD in the Mojave Desert of southern California. In a study of the relationship between PM\(_{2.5}\) and MISR AOD over the continental United States, Liu et al, (2004) found a strong relationship in the eastern part of the country, but a weaker relationship in the west; and especially poor in southern California as a whole. Van Donkelaar et al, (2006) concurred that excluding California from their analysis significantly increased the correlation between PM\(_{2.5}\) and MISR AOD.

Comparing PM data collected at a point with MISR 17.6 sq km may not be practical if the landscape covered by the pixel exhibits spatial heterogeneity and varied anthropogenic activities. AOD is affected by the type and vertical distribution of aerosols in the atmosphere. A site that has a uniform particle type should have a more consistent vertical distribution than a site that is spatially heterogeneous about the point of the measurement device. Therefore, this study has focused on one non-urban site located at Death Valley National Park, California in order to help minimize the effects of spatial heterogeneity and anthropogenic activity.

**Mojave Desert of southern California**

The Mojave Desert of southern California is a diverse and dynamic arid landscape, enough so that it can be divided into five regions (Rowlands, et. al., 1982).

\(^5\) http://aeronet.gsfc.nasa.gov/index.html
Our research is limited to the Mojave Desert within southern California to minimize inter-region differences in particulate matter concentrations (Figure 1). The western edge of the Mojave Desert of southern California is bounded by the imposing Sierra Nevada, San Gabriel, and San Bernardino Mountains, which alter the prevailing westerly winds. The mountains intercept moisture coming from the Pacific Ocean, creating a rain-shadow downwind. Climate and topography are the primary factors controlling the distribution and abundance of desert plant species, and subsequent control over sources of particulate matter, such as barren or disturbed ground (Rowlands, 1995). Vegetation cover is generally sparse and ranges from desert scrub communities dominated by *Larrea tridentata* (creosote bush) and *Ambrosia dumosa* (white bursage) on lower alluvial slopes, to relatively dense *Yucca* communities at higher elevations (*Yucca brevifolia* and *Yucca Schidigera*).

Hereford et al., (2006) examined the historical record of 52 weather stations in the Mojave (1893-2001) and found that two distinctive patterns of precipitation occur on either side of ~117°W meridian. A bi-seasonal pattern occurs to the east, but winter-dominant precipitation occurs to the west. They then defined two precipitation seasons, warm (July 4 - October 14), and cool (October 15 – April 15). Climate variation is one of the principal factors controlling changes in the contemporary Mojave Desert, as the period from 1976 to 1998 was above average precipitation. However, 1999 to 2004 had been a period of sustained drought.

The number and frequency of dust events in the Mojave Desert are small compared to other deserts of the world. Bach et al., (1996) reported that from 1973 to 1994 the Mojave averaged 1.3 dust storms (defined internationally as a storm that reduces
visibility to 1km) per year, while stations in southeast Asia, China, Mongolia, the Middle East and Africa all average more than 15 events, with some as high as 60 per year. Even the southern high plains of Texas averaged twelve times the number of events as the Mojave Desert of southern California. Smaller dust events (visibility reduced to 11km) were found to occur more frequently, consistent with anthropogenic activities (Bach et al., 1996). They concluded that winter precipitation during the preceding year was a main factor controlling the number of dust events near weather stations in the Mojave. Increased winter precipitation was inversely related to the occurrence of dust events ($r^2 = -.65$)

Death Valley National Park is located in the northern Mojave Desert (Figure 1). Vegetation cover is sparse throughout most of the valley as a result of extremely high temperatures during the spring and summer, high potential evapotranspiration, and low amounts of precipitation. Precipitation at Death Valley is winter dominant.

The valley floor consists of silts and salts that have eroded from the surrounding mountains and precipitated from ancient lakes, respectively, creating abundant sources for dust to enter into the atmosphere. Winds are generally stronger in the summer and come from the southwest, while winter winds are more likely from the west and northwest. These two patterns provide a consistent type of particle and vertical distribution during these seasons. Even though the site is 120 miles from the nearest large metropolitan area, the area has been affected by the inflow of pollutants from cities and agriculture to the southwest and west, respectively.

Particulate matter is recorded on a three day schedule on the eastern side of the valley at Furnace Creek (36.51N, 116.85W). The distribution of particulate matter
stations in the Mojave Desert illustrate that most have been implemented in the western half, with a large extent of the Mojave that contains no stations. Five of the stations contained data collected during the time of the MISR observations, while the others had intermittent data records (Figure 1). The PM$_{2.5}$ and PM$_{10}$ values for Death Valley National Park are affected by pollution generated from industrial plants located in nearby Searles Valley (Trona), and Owens Lake. Off-road vehicles, and consequent vegetation depletion, expose soils which can be carried by wind across Death Valley. Farmland in Owens Valley and Mono Basin also expose barren soil that contributes wind-blown dust throughout the area. Not only do these nearby sources produce pollution that affect the health of the native population, but it results in poor visibility for Death Valley National Park visitors. In fact, pollution and dust from areas as far away as the Los Angeles Basin and the San Joaquin Valley can account for nearly two-thirds visibility loss in the desert region.\footnote{http://www.nps.gov/archive/moja/devplan/affnat.htm#air}

Methods and Results

MISR AOD, PM$_{2.5}$ and PM$_{10}$ were analyzed using data from March 2000 (the first available MISR products) through November 2004. Linear regression of PM$_{2.5}$ and PM$_{10}$ over the period of time indicated a strong relationship between PM$_{2.5}$ and PM$_{10}$ ($r = .90$), with a stronger relationship during winter months than summer months (Figure 2). Therefore, further discussion will focus on PM$_{2.5}$. A plot of MISR AOD and PM$_{2.5}$ (Figure 3) revealed similarity between the satellite measurements and the ground-based particulate matter, but linear regression resulted in a relatively low $r^2 = .55$. PM$_{2.5}$ was averaged for each month, from the 57 months of data, providing mean daily PM for each calendar month (Table 1). Again, there was a strong relationship between MISR AOD
and PM$_{2.5}$ (Figure 4) with $r^2 = .75$. Four seasonal averages of MISR AOD and PM$_{2.5}$ was computed from the 57 months of data; spring (March - May), summer (June - August), fall (September - November), and winter (December -February). Both the MISR AOD and PM$_{2.5}$ had peak values during summer, and the lowest values during the winter (Table 1). The strengths of the seasonal relationships between MISR AOD and PM$_{2.5}$ (Figure 5) was exceptionally strong ($r^2 = .98$).

Regression analysis between MISR AOD and PM$_{2.5}$ resulted in statistically significant relationships (Table 2), particularly for each calendar month ($r^2 = .75$) and the four seasons ($r^2 = .98$). The strongest relationship was between seasonal AOD and PM$_{2.5}$ and PM$_{10}$. The value of the regression model is that now each MISR AOD could be used to predict the monthly or seasonal value of PM$_{2.5}$ and PM$_{10}$. This approach allowed for the creation of maps of the entire Mojave Desert of southern California to illustrate the spatial variability of the temporal dimensions of particulate matter concentrations in places where PM$_{2.5}$ and PM$_{10}$ are not being collected.

Discussion of Results

The strong statistical relationships between MISR AOD and PM$_{2.5}$ and PM$_{10}$ at Death Valley National Park are most likely the result of the consistent sources of particulate matter (dry lake bed to the southwest of the measurement site) and the seasonal strength of wind and direction. In comparison to other PM sites in the Mojave, averaged from 2000 to 2004 (Figure 6), Death Valley exhibits seasonality (low winter – high summer) in particulate matter concentrations, as does the town of Mojave; while three other more urban sites (Ridgecrest, Victorville and Lancaster) exhibit high winter
values (November - January). The five sites compared in this study also vary in the amount of spatial heterogeneity and amount of anthropogenic activity as illustrated with the Landsat Thematic Mapper images of those cities (Figure 7). Death Valley National Park is essentially rural. Mojave is a small town with 000 population that is located on the Northeast corner of Edwards Air Force Base (EAFB). Frank et al. (2007) demonstrated that EAFB has among the highest aerosol optical depths in the Mojave Desert of southern California. Lancaster is a larger community on the southwest corner of EAFB. Victorville is a large city located northwest of the Marine Corp Air Ground Combat Center. Particulate matter concentrations measured at a point within urban areas may be applicable for reporting locations that are above federal limits, or for identifying long-term trends at a site. Point observations though are not appropriate to evaluate the regions that surround those points.

Since there is wide landscape and anthropogenic diversity between these sites, it wasn’t appropriate to regress PM and AOD using all five sites. However, using data from Death Valley alone allowed for the development of a regression equation for MISR AOD and PM$_{2.5}$ and PM$_{10}$ observations. From this regression equation, it was possible to calculate an estimated PM$_{2.5}$ value from each MISR AOD value for a larger geographic extent. The spatial and temporal variation of PM in unmonitored locations can then be assessed, and comparison of PM estimates for the areas surrounding the four point urban samples could be made with point PM data.

Four seasonal maps of PM$_{2.5}$ are reported and discussed here (Figures 8A-8D). Since there was a strong relationship between PM$_{2.5}$ and PM$_{10}$ as stated earlier, it wasn’t necessary to discuss the maps for both PM$_{2.5}$ and PM$_{10}$. The estimated PM$_{2.5}$ maps should
be interpreted independently for each season. The color scale varies by season as the categories are defined by standard deviation within a season. Therefore the colors illustrate within season spatial variation within the Mojave Desert.

The other four PM sites located in the cities of Mojave, Ridgecrest, Victorville and Lancaster were used for comparison with Death Valley (Figure 6). Death Valley and the city of Mojave demonstrate a seasonal, summer high, particulate matter concentrations, while the other cities demonstrate a more consistent concentration. The four PM sites were compared with the MISR estimated PM$_{2.5}$ for the four seasons (Table 3). These results show that Mojave, which is the least populated of the sites, compares fairly well with MISR estimates of the surrounding particulate matter concentrations (the 17.6 km$^2$ of MISR) during all seasons. Ridgecrest underestimates particulate matter during the spring and summer, and overestimates particulate matter during fall and winter. Victorville and Lancaster report seasonal averages that are approximately two to three times that of the surrounding area during all seasons. Therefore, the point samples collected in urban areas may not be representative of a larger surrounding, heterogeneous region. Since there are few rural PM sites in the Mojave Desert, the MISR estimates of PM$_{2.5}$ provide a valuable look into the spatial and temporal variability of aerosol concentrations throughout the Mojave Desert of southern California.
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Table 1. Mean PM$_{2.5}$, PM$_{10}$, and MISR aerosol optical depth (AOD) for each calendar month and each season averaged over March 2000 to November 2004 at Death Valley National Park, California.

<table>
<thead>
<tr>
<th>Month</th>
<th>PM 2.5</th>
<th>SD</th>
<th>PM 10</th>
<th>SD</th>
<th>AOD</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.69</td>
<td>0.39</td>
<td>6.19</td>
<td>1.23</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>February</td>
<td>2.76</td>
<td>1.53</td>
<td>8.67</td>
<td>5.63</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>March</td>
<td>3.20</td>
<td>0.64</td>
<td>9.14</td>
<td>3.32</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>April</td>
<td>6.11</td>
<td>0.96</td>
<td>14.54</td>
<td>3.47</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>May</td>
<td>7.27</td>
<td>0.17</td>
<td>22.55</td>
<td>6.01</td>
<td>0.15</td>
<td>0.04</td>
</tr>
<tr>
<td>June</td>
<td>7.37</td>
<td>1.89</td>
<td>17.64</td>
<td>3.79</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>July</td>
<td>6.25</td>
<td>1.35</td>
<td>16.80</td>
<td>4.66</td>
<td>0.14</td>
<td>0.02</td>
</tr>
<tr>
<td>August</td>
<td>6.90</td>
<td>2.93</td>
<td>17.34</td>
<td>6.27</td>
<td>0.16</td>
<td>0.06</td>
</tr>
<tr>
<td>September</td>
<td>3.92</td>
<td>0.65</td>
<td>12.64</td>
<td>3.39</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>October</td>
<td>4.94</td>
<td>0.75</td>
<td>12.94</td>
<td>1.63</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>November</td>
<td>2.77</td>
<td>0.24</td>
<td>6.11</td>
<td>1.68</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>December</td>
<td>1.64</td>
<td>0.40</td>
<td>5.50</td>
<td>0.94</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>Season</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring</td>
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<td>14.97</td>
<td>1.78</td>
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<tr>
<td>Summer</td>
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<td>0.01</td>
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<td>Fall</td>
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<td>10.45</td>
<td>0.95</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>Winter</td>
<td>2.05</td>
<td>0.32</td>
<td>6.78</td>
<td>0.97</td>
<td>0.05</td>
<td>0.01</td>
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Table 2. Results of regression between MISR aerosol optical depth (AOD) and PM\textsubscript{2.5} and PM\textsubscript{10} at Death Valley National Park, California.

<table>
<thead>
<tr>
<th>PM</th>
<th>α</th>
<th>β</th>
<th>( r^2 )</th>
<th>ρ</th>
<th>n</th>
</tr>
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<tbody>
<tr>
<td>AOD\textsubscript{57months}</td>
<td>PM\textsubscript{2.5}</td>
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<td>0.0562</td>
<td>0.55</td>
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<td>PM\textsubscript{10}</td>
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<td>0.00</td>
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<tr>
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Table 3. Average seasonal PM$_{2.5}$ derived from field data at four towns in the Mojave Desert of southern California, and the estimated PM$_{2.5}$ values predicted by MISR for the 17.6 sq. km. area surrounding the towns.

<table>
<thead>
<tr>
<th>Season</th>
<th>Location</th>
<th>Mojave PM 2.5</th>
<th>Ridgecrest PM 2.5</th>
<th>Victorville PM 2.5</th>
<th>Lancaster PM 2.5</th>
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<td>7.07</td>
<td>4.76</td>
<td>10.99</td>
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<td>Summer</td>
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<td>7.91</td>
<td>6.97</td>
<td>12.15</td>
<td>10.08</td>
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<td>6.35</td>
<td>5.93</td>
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<td>5.34</td>
<td>4.95</td>
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<td>4.34</td>
<td>4.04</td>
<td>3.19</td>
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</table>
Figure 1. The Mojave Desert of southern California, illustrating the location of Death Valley National Park, five particulate matter monitoring stations, legacy monitoring stations, national parks and military installations.
Figure 2. Mean monthly particulate matter concentrations at Death Valley National Park, California.
Figure 3. Relationship between monthly PM$_{2.5}$ and MISR aerosol optical depth at Death Valley National Park, California from March 2000 to November 2004. $r^2 = .55$. 
Figure 4. Relationship between mean monthly PM$_{2.5}$ and MISR aerosol optical depth (AOD) at Death Valley National Park, California from March 2000 to November 2004. $r^2 = .75$
Figure 5. The relationship between mean seasonal PM$_{2.5}$ and MISR aerosol optical depths at Death Valley National Park, California from March 2000 to November 2004. Adjusted $r^2 = .98$. 
Figure 6. Mean PM2.5 measured at five sites in the Mojave Desert of southern California from 2000 to 2004.
Figure 7. Landsat Thematic Mapper imagery showing the 17.6 km² area surrounding the particulate matter monitoring site that is also covered by the Multiangle Imaging SpectroRadiometer aerosol optical depth imagery.
Figure 8A-D. Seasonal particulate matter concentrations for the Mojave Desert of southern California derived from the Multiangle Imaging SpectroRadiometer.
Spring PM 2.5 Concentrations Estimated from MISR AOD

Legend
- Mojave Boundary
- National Parks
- DOD Lands
- Playas

PM 2.5 Value
- 0.00 - 1.12
- 1.13 - 3.20
- 3.21 - 5.29
- 5.29 - 7.39
- 7.37 - 9.44
- 9.45 - 11.52
- 11.53 - 12.97
- 5 PM Sites

- Mojave Desert
- California

Joshua Tree National Park
Mojave National Park
DOD

0 55 110 220 Kilometers