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DEVELOPING A HIGH-SPATIAL-RESOLUTION AEROSOL OPTICAL DEPTH PRODUCT USING MODIS DATA FOR EVALUATING AEROSOL DURING LARGE WILDFIRE EVENTS

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1. INTRODUCTION

During the summer of 2008, dry conditions, heavy fuel loads in forested areas, and numerous lightning strikes resulted in a large number of wildfires in northern California. The fires burned between 1.5 and 2 million acres and produced approximately 600,000 to 800,000 tons of fine particulate matter ($PM_{2.5}$) (Reid et al., 2009), resulting in harmful air pollution and numerous exceedances of the National Ambient Air Quality Standards (NAAQS) (California Air Resources Board, 2012). Metropolitan areas including Sacramento, Fresno, and the San Francisco Bay Area were impacted by smoke (see Figure 1), and hourly $PM_{2.5}$ observations routinely exceeded 100 $\mu g/m^3$ on June 23-27 and July 9-10, 2008.

Smoke from biomass burning can cause significant health risks (Delfino et al., 2009; Kuenzli et al., 2006) and decrease visibility in nearby areas; therefore, an accurate representation of aerosol emitted during wildfires is important for characterizing visibility impacts and exposure.

Satellite-derived aerosol optical depth (AOD), a measure of atmospheric aerosol loading determined by satellite-based measurement, is often used to determine spatial variations in aerosol concentrations that are not well represented by ground-based monitoring. Remotely sensed AOD can be useful during wildfire events, when aerosol levels can vary widely over small spatial scales depending on the smoke plume location, vertical mixing, and prevailing winds. However, the standard Collection 5 AOD product provided by the National Aeronautics and Space Administration's (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) has a number of limitations: (1) the spatial resolution (10 x 10 km) may be insufficient to capture variations in aerosol loading near smoke plumes; (2) the assumed aerosol optical properties are not representative of biomass burning aerosol; (3) AOD data are often missing due to failed retrievals over the bright land surfaces of the western United States; and (4) the cloud-masking algorithm can incorrectly label heavy smoke as clouds.

To improve the usefulness of the AOD information, we developed a localized AOD product covering northern California at 500-meter spatial resolution, using raw MODIS data for the summer of 2008. The improved algorithm uses local biomass burning aerosol optical properties, local surface reflectance data, and a "relaxed" cloud filter. The methodology can be used to develop an AOD product that can better characterize visibility and haze during smoke events.

Fig. 1. Visible smoke in downtown Sacramento during the summer of 2008.

2. METHODS

A high-spatial-resolution AOD data product was developed to cover northern California during the summer of 2008, when multiple large and

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lengthy wildfires were burning in the region. AOD quantifies the total scattering and absorption of light by aerosols in a column of the atmosphere. AOD can be calculated from ground-based instruments such as sun photometers, as well as from satellite-based instruments that can provide global spatial coverage.

2.1 Data Acquisition and Preparation

The MODIS sensor, aboard the Terra and Aqua satellites, measures top-of-the-atmosphere radiance in 36 spectral bands. Terra and Aqua provide near-daily global coverage of the earth's surface, with daytime overpasses at approximately 10:30 AM (Terra) and 1:30 PM (Aqua) local time at mid-latitudes. MODIS-calibrated radiances (Level 1b) at native spatial resolution (250 m, 500 m, 1 km), as well as geo-location data, were obtained for June and July 2008 from the NASA Goddard Space Flight Center Level 1 and Atmosphere Archive and Distribution System (LAADS). In addition, data from the same months of 2009 were acquired to provide additional clean atmosphere days for developing surface reflectance maps.

MODIS reflectance data contain atmospheric trace gas signals due to absorption by water vapor, ozone, and carbon dioxide. Corrections for these gases were applied to the raw Level 1 MODIS radiance data using the same method applied by Remer et al. (2009). Gas-corrected MODIS reflectance data swaths were then merged and geo-referenced to a standard analysis grid at 500-m resolution covering the northern California region impacted by smoke during the 2008 fires.

The high-spatial-resolution AOD product was developed according to the algorithm used for the global NASA MODIS standard AOD product (Remer et al., 2009). However, several significant modifications to this methodology were made to achieve high spatial resolution and improve local AOD estimates during smoke events: (1) localized seasonal surface reflectance ratios; (2) aerosol optical properties for typical California biomass burning aerosol; and (3) a relaxed cloud filter to better distinguish clouds from smoke pixels.

2.2 Surface Reflectance Ratios

The raw MODIS data, measured at the top of the atmosphere, include the signal from light reflected by the ground as well as light reflected by aerosols in the atmospheric column. Therefore, an AOD retrieval method must distinguish the surface reflectance component in order to derive the reflectance of atmospheric aerosols and optical depth.

Surface reflectance at 0.66 µm was calculated using the principles of Kaufman et al. (1997) and the methods of Drury et al. (2008). As described by Kaufman, in principle, the top-of-atmosphere reflectance is equal to the surface reflectance in the near-infrared, such as the 2.13 µm MODIS channel, and the surface reflectance in the near-infrared is related to the surface reflectance in the visible, such as the 0.66 µm MODIS channel, by a simple ratio of the 0.66/2.13 channels.

The NASA AOD algorithm uses a dynamic 0.66/2.13 surface reflectance ratio, varying between 0.39 and 0.67, based on locally retrieved Normalized Difference Vegetation Index (NDVI) values (Drury et al., 2008); however, the algorithm was found to underestimate the 0.66/2.13 ratio in certain areas (Oo et al., 2010). Therefore, monthly localized 0.66/2.13 ratios were developed for each grid cell in our analysis grid using the method described by Drury et al. (2008). The ratios ranged from 0.3 to near 1, with the lowest values occurring in areas of sparse vegetation and the highest values in coastal forests and the Sierra Nevada (see Figure 2). Urban areas have 0.66/2.13 ratios between 0.65 and 0.9.

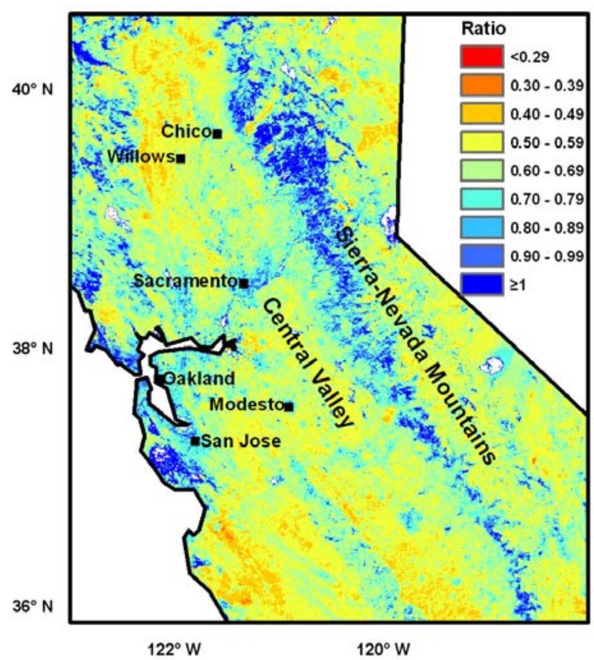

Fig. 2. Average clean-day surface reflectance ratios calculated using Terra satellite data from June-August 2009.

2.3 Aerosol Optical Properties

Further enhancement to the NASA AOD algorithm was made to develop localized aerosol optical properties, such as size distribution, complex index of refraction, single scattering albedo, and phase functions typical of smoky conditions. The NASA AOD product uses a single aerosol model, representative of rural/background aerosol properties, for the entire western United States. Instead, aerosol optical properties for biomass burning conditions were developed for northern California summers through a cluster analysis of AErosol RObotic NETwork (AERONET) measurements at five California sites between 2003 and 2007 (Omar et al., 2005).

A lookup table was generated using the localized aerosol optical properties, a range of satellite geometries, surface reflectances, and AOD; a radiative transfer model (6S RTM version 1.1) was used to define relationships between top-of-atmosphere reflectance and AOD according to the methods described in Castanho et al. (2008). The pre-computed lookup table was used to derive AOD at 0.55 µm.

2.4 Cloud Filter

Identifying cloud-contaminated pixels is an important part of the AOD retrieval; however, we analyzed false AOD retrievals and found that they were often triggered by false cloud contamination, even in clean, cloudless conditions. We also found that the current cloud mask mistakes thick aerosol plumes for clouds.

Therefore, a relaxed cloud filter algorithm (van Donkelaar et al., 2011) was implemented to better distinguish clouds from smoke in each analysis grid cell. As with the NASA AOD product (Remer et al., 2009), brightness and variability tests were implemented to mask clouds. However, the maximum allowed spatial variability at 0.47 µm was relaxed from 0.0025 to 0.005 to reduce the number of heavy aerosol pixels masked as clouds. In addition, a new spatial variability test at 2.12 µm was added to preserve cloud-free aerosol pixels declared cloudy by the relaxed 0.47 µm spatial variability test, because fine mode aerosol is transparent at 2.12 µm relative to clouds or dust (Kaufman et al., 1997).

This relaxed cloud mask improved the coverage of our AOD retrievals for California wildfire events, while reducing spurious cloud retrievals over highly textured land surfaces.

3. RESULTS

The high-resolution AOD product provides high spatially resolved information about variations in aerosol in the areas surrounding active fire and smoke plumes. As shown in Figure 3, on June 27, 2008, several large smoke plumes near Sacramento and Chico are visible in the true-color imagery available from Terra and Aqua. The high-resolution product estimates AOD values that range from 1.0 to more than 5 (unit-less), with greater variability than is provided in the standard Collection 5 AOD product available at coarse spatial resolution. Variation in aerosol observed in a high-spatial-resolution product can be used to more accurately inform exposure or visibility estimates.

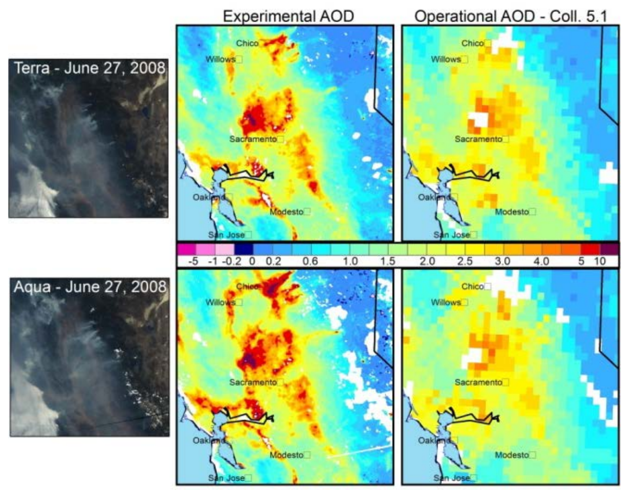

Fig. 3. High-spatial-resolution AOD compared to the NASA standard level 2 product for Terra and Aqua on June 27, 2008; visible imagery included for evaluation of smoke plumes.

AOD values from the high-resolution product and the standard Collection 5 AOD algorithm were compared to observed aerosol optical thickness (AOT) values at three coastal Aerosol Robotic Network (AERONET) sites during June and July 2008. Data from AERONET sites in central and northern California—Trinidad Head, Monterey, and UCSB—were available for comparison. The average of the Terra and Aqua AOD values corresponding to AERONET locations were compared to daily average AERONET AOT values for each available day during the study period; results are shown in Figure 4. The high-resolution AOD product has an R^2 of 0.53 and a slope of 0.63; the standard AOD product has an R^2 of 0.08 and a slope of 0.27. By both measures in this limited data set, the high-resolution AOD is much better at matching observed AOT.

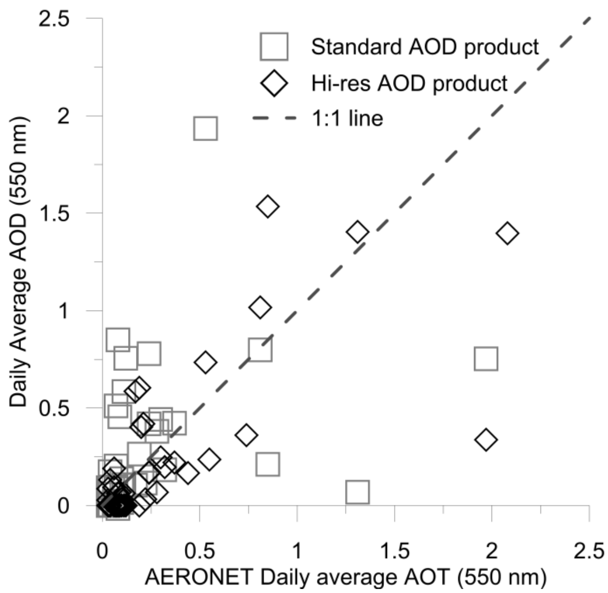

Fig. 4. Comparison of AERONET daily average AOT from the UCSB, Monterey, and Trinidad Head sites to the high-resolution AOD product (open diamonds) and standard AOD product (open squares).

The high-spatial-resolution AOD product was also validated using measurements of $PM_{2.5}$ at monitoring stations throughout northern California and the central valley. $PM_{2.5}$ values were averaged for the hours surrounding satellite overpass (10 AM to 2 PM) and compared to coincident high-resolution AOD data averaged for Terra and Aqua. Figure 5 shows an overall R^2 value of 0.422 when all monitors are included for June 24 to July 31, 2008. The relationship is an improvement over previous comparisons between the standard NASA MODIS AOD product and $PM_{2.5}$ in the western United States where correlations to ground monitors in California had regression coefficients between 0.1 and 0.2 (Hu, 2009).

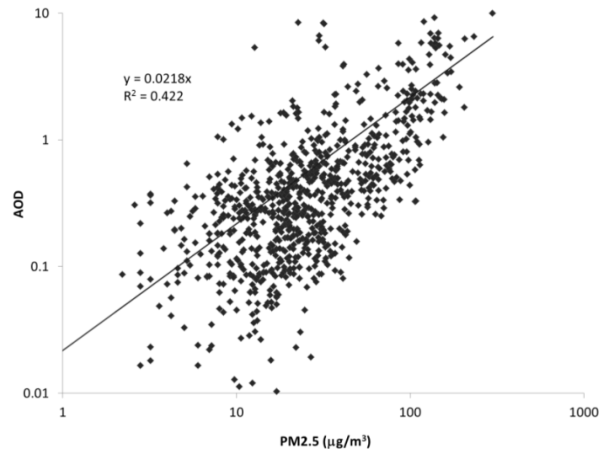

Fig. 5. Relationship between ground-based $PM_{2.5}$ concentrations averaged from 10 AM to 2 PM and daily mean high-spatial-resolution AOD that overlaps the ground monitors for June 24 to July 31, 2008.

Figure 6 shows time series of $PM_{2.5}$ surface observations and midday average $PM_{2.5}$ predicted concentrations based on our high-resolution AOD product for four surface sites in Chico, Willows, downtown Sacramento, and downtown San Jose. Concentrations at the northernmost sites (Chico and Willows) were highly variable, with concentrations changing by over 100 $\mu g/m^3$ within a few hours of major smokes plumes impacting sites. Overall, the AOD-predicted $PM_{2.5}$ concentrations track the midday concentrations relatively well at all of these sites. And, while there were multiple days when surface $PM_{2.5}$ concentrations were significantly overpredicted, it is clear that the general shape of the pollution episodes is captured well by this method.

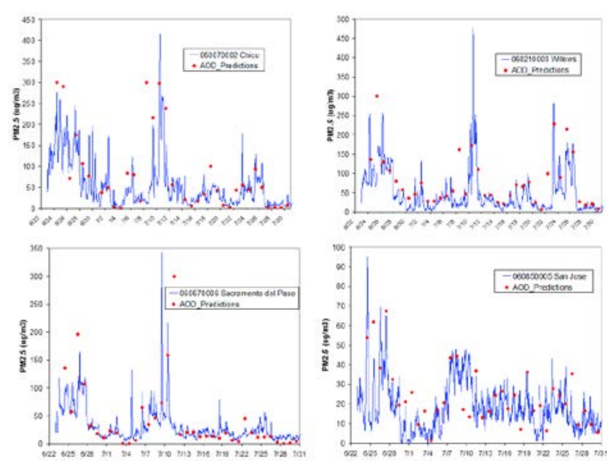

Fig. 6. Time series of surface $PM_{2.5}$ observations and AOD-predicted midday $PM_{2.5}$ concentrations at Chico (top left), Willows (top right), Sacramento (bottom left), and San Jose (bottom right).

4. CONCLUSIONS AND DISCUSSION

Raw MODIS data were used to develop a high-spatial-resolution AOD product covering northern California and the June to July 2008 time period. Enhancements were made to the methodology for deriving AOD used for the NASA standard AOD product, including (1) localized surface reflectance ratios, (2) aerosol optical properties typical of California biomass burning aerosol, and (3) a relaxed cloud filter to preserve smoke pixels typically classified as clouds. The high-spatial-resolution product showed correlation to ground-based $PM_{2.5}$ concentrations in the study region, which was consistent with earlier findings. The methodology can be used to develop similar high-spatial-resolution data during other fire events, and provide additional details regarding aerosol for use in exposure or visibility analyses.

Information derived from this high-resolution AOD product could also be useful to the air quality modeling community. AOD observations and corresponding surface $PM_{2.5}$ predictions could be used to evaluate modeled smoke predictions, particularly close to fires where model results are highly sensitive to uncertainties in fire emission rates and plume injections heights. The AOD data could also be assimilated into air quality models to improve $PM_{2.5}$ forecasts.

5. REFERENCES

California Air Resources Board, 2012. 2008 Northern California Wildfires. Available at http://www.arb.ca.gov/desig/excevents/2008wildfires.htm. January 17.

Castanho A.D.A., J.V. Martins, and P. Artaxo, 2008. MODIS aerosol optical depth retrievals with high spatial resolution over an urban area using the critical reflectance. *J. Geophys. Res*, 113(D02201), doi: 10.1029/2007JD008751. Available at http://www.agu.org/pubs/crossref/2008/2007JD008751.shtml.

Delfino R.J., S. Brummel, J. Wu, H. Stern, B.D. Ostro, M.J. Lipsett, A. Winer, D.H. Street, L. Zhang, T. Tjoa, and D.L. Gillen, 2009. The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. *Occupational and Environmental Medicine*, 66(3), 189-197, March.

Drury E., D.J. Jaco , J. Wang, R.J.D. Spurr, and K. Chance, 2008. Improved algorithm for MODIS satellite retrievals of aerosol optical depths over western North America. *Journal of Geophysical Research*, 113(D16204), doi: 10.1029/2007JD009573.

Hu Z,. 2009. Spatial analysis of MODIS aerosol optical depth, $PM_{2.5}$, and chronic coronary heart disease. *International Journal of Health Geographics*, 8(27), doi: 10.1186/1476-072X-8-27, May 12.

Kaufman Y.J., D. Tanre, L.A. Remer, E.F. Vermote, A. Chu, and B.N. Holben, 1997. Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. *J. Geophys. Res.*, 102(D14), 17,051-017,067.

Kuenzli N., E. Avol, J. Wu, W.J. Gauderman, E. Rappaport, J. Millstein, J. Bennion, R. McConnell, F.D. Gilliland, and K. Berhane, 2006. Health effects of the 2003 southern California wildfire on children. *Am. J. Resp. Crit. Care*, 200604.

Omar A.H., J.-G. Won, D.M. Winker, S.-C. Yoon, O. Dubovik, and M.P. McCormick, 2005. Development of global aerosol models using cluster analysis of Aerosol Robotic Network (AERONET) measurements. *Journal of Geophysical Research*, 110(D10S14), doi: 10.1029/2004JD004874.

Oo M.M., M. Jerg, E. Hernandez, A. Picon, B.M. Gross, F. Moshary, and S.A. Ahmed, 2010. Improved MODIS aerosol retrieval using modified VIS/SWIR surface albedo ratio over urban scenes. *IEEE (Institute of Electrical and Electronics Engineers) Transactions on Geoscience and Remote Sensing*, 48(3), doi: 10.1109/TGRS.2009.2028333.

Reid S.B., S. Huang, E.K. Pollard, K.J. Craig, D.C. Sullivan, P.H. Zahn, C.P. MacDonald, and S.M. Raffuse, 2009. An almanac for understanding smoke persistence during the 2008 fire season. Final report prepared for the USDA Forest Service, Pacific Southwest Region by Sonoma Technology, Inc., Petaluma, CA, STI-908045-3747-FR, November 5.

Remer L.A., D. Tanre, Y.J. Kaufman, R.C. Levy, and S. Matoo, 2009. Algorithm for remote sensing of tropospheric aerosol from MODIS: collection 005: revision 2. Algorithm theoretical basis document version 2.0. Prepared for the National Aeronautics and Space Administration.

van Donkelaar A., R.V. Martin, R.C. Levy, A.M. da Silva, M. Krzyzanowski, N. Chubarova, E. Semutnikova, and A.J. Cohen, 2011. Satellite-based estimates of ground-level fine particulate matter during extreme events: A case study of the Moscow fires in 2010. *Atmos. Environ.*, 45, doi: 10.1016/j.atmosenv.2011.07.068.