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Atmospheric Measurement Techniques Discussions

Where do we need additional in situ aerosol and sun photometer data?: a critical examination of spatial biases between MODIS and MISR aerosol products

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Abstract

AErosol RObotic NETwork (AERONET) data are the primary benchmark for evaluating satellite retrieved aerosol properties. However, despite its extensive coverage, the representativeness of the AERONET data is rarely discussed. Indeed, many studies have shown that satellite retrieval biases have a significant degree of spatial correlation that may be problematic for higher-level processes or inverse-emissions-modeling studies. To consider these issues and evaluate relative performance in regions of few surface observations, cross-comparisons between the aerosol optical depth (AOD) products of operational MODIS Collection 5.1 Dark Target (DT) and operational MODIS Collection 5.1 Deep Blue (DB) with MISR version 22 were conducted. Through such comparisons, we can observe coherent spatial features of the AOD bias while sidestepping the full analysis required for determining when or where either retrieval is more correct. We identify regions where MODIS to MISR AOD ratios were found to be above 1.3 or below 0.75. Regions where lower boundary condition uncertainty is likely to be a dominant factor include portions of Western North America, the Andes Mountains, Saharan Africa, the Arabian Peninsula, and Central Asia. Similarly, microphysical biases may be an issue in greater South America, and specific parts of Southern Africa, India Asia, East Asia, and Indonesia. These results help identify high-priority locations for possible future deployments of both in situ and ground-based remote sensing measurements. Supplement include GeoTIFF and kml files.

1 Introduction

The AErosol RObotic NETwork (AERONET), a global scale sun photometer network, has been providing robust aerosol optical property measurements for nearly two decades. As such, it is often used as the primary standard for validating satellite aerosol products (e.g., Holben et al., 1998; Kahn et al., 2010; Levy, et al., 2010; Hsu et al., 2006). AERONET has included 443 sites globally at various times. Only 11 sites have data records that are longer than seven years, and 39 sites have data records that are longer than five years. Field campaigns, which extensively measure the environment in support of verification, target specific areas of interest but are sporadic and short lived. This ephemeral nature of observations suitable for satellite product characterization leads to fundamental questions about the representativeness of available validation data sets. For example, is the distribution of AERONET sites sufficient to cover the spatial and temporal variations of the aerosol state globally? Are there any surface-observation-data-poor regions that clearly require future deployments of sun photometer instruments and/or in situ measurements, especially for the purpose of validating satellite observations?

Complicating matters further is the spatial correlation of bias. Typically, retrievals are underdetermined and some assumptions must be made, most typically through the lower boundary condition model, the assumed particle microphysics, or optical properties. As land features and particle properties have spatial coherence, we would expect satellite retrievals of aerosol products to share similar patterns in their biases.

Recently Shi et al. (2011), Hyer et al. (2011) and Levy et al. (2010) published evaluations of the over water and land MODIS Dark Target (DT) Collection 5 aerosol products. Over water, low and high biases are quite clear for fine and coarse mode aerosol particles, respectively. Wind and cloud related biases are visible as well. Uncertainties are also shown over coastal regions, where runoff and/or biological activity create issues for the surface boundary conditionS (e.g., Kahn et al., 2010). Biases in the over-water Aerosol Optical Depth (AOD) product were found to be largely correctable through model data and information contained in the retrieval (e.g., Zhang and Reid, 2006). The over-land problem, however, is much more complicated. The lower boundary condition for MODIS DT Collection 5 is empirical and cannot cope with all land forms everywhere. The more complicated land surface also reduces the degrees of freedom in available microphysical models that can be utilized by the retrievals. As a consequence, Hyer et al. (2011) reported many cases where correlations between satellite and AERONET AOD are good within regions, but slopes are vastly different. Such regionally correlated biases are particularly problematic for higher-level investigations

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that require consistent data over large areas, such as inverse modeling or lifecycle studies. Also, Kahn et al. (2010) identified MISR-MODIS DT AOD differences over India, Eastern China, and Southeastern Asia that they attributed, in part, to dark particles absent from the current algorithm particle climatologies. They noted that a lack of mixtures containing dust and smoke optical analogs in the algorithms create AOD discrepancies over Sub-Saharan Africa and several other locations (also see Eck et al. (2010) regarding mixtures).

One way to approach spatially correlated bias is through cross-comparisons between satellite aerosol products, not only over the AERONET sites, but also over regions that may lack ground-based observations. Such methods do not specifically resolve global issues related to quantitative error characterization, but are beneficial in determining the overall scientific uncertainty of aerosol properties. Indeed, in regions with large differences among products, the data need to be understood and the causes of the discrepancies should be collected. This need motivates the current study, which aims to help direct future deployments of surface measurements to support the refinement of future generations of algorithms.

Three satellite aerosol products were selected for this study: the Terra operational Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 5.1 Dark Target (DT) aerosol product, the Terra MODIS Collection 5.1 Deep Blue (DB) aerosol product, which retrieves aerosol properties, especially but not limited to, over bright surfaces, and the Multiangle Imaging SpectroRadiometer (MISR) version 22 aerosol product. Note that these three products were chosen because they are widely used by the community for various applications ranging from climate to air quality to real-time operational forecasts (Zhang et al., 2001, 2008a,b; Kaufman et al., 2002; Remer et al., 2009; Kahn et al., 2009; Reid et al., 2009; Hsu et al., 2006; Zhang and Reid, 2006). All three products were spatially and temporally collocated, and were used for evaluating the existing aerosol observation system. We conclude with a discussion of regions showing clear heterogeneity between sensor retrieval results, proposing areas that have an urgent need for additional, suborbital measurements.

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2 Datasets

Onboard both Terra and Aqua satellites, MODIS has 36 spectral channels with spatial resolutions ranging from 250 m to 1 km that can be very effectively used in studying aerosol and clouds. Using seven near UV, visible, and near IR channels, AOD over land and water, as well as fine mode to total AOD fraction over water are retrieved (Remer et al., 2005, Remer et al., 2009; Levy et al., 2010). The reported uncertainty for the over-ocean MODIS DT AOD retrieval is $0.03 \pm 0.15 \times$ AOD, and is $0.05 \pm 0.20 \times$ AOD for the over-land cases (Remer et al., 2005). Recent studies (e.g., Shi et al., 2011; Zhang et al., 2006; Kahn et al., 2007) suggest that uncertainties in the operational over-ocean MODIS DT AOD products could be related to cloud contamination, aerosol microphysical biases, and uncertainties in low boundary conditions due to the use of a fixed near surface ocean wind speed of $6\,\mathrm{m\,s^{-1}}$. In the next release (version 6) of the MODIS DT aerosol products, variable near surface ocean wind speeds will be included in the retrieving process (personal communication with Rob Levy, 2010). Over land, Hyer et al. (2011) suggested that complex surface features and regional biases in aerosol microphysical properties are the main sources of uncertainties for the operational MODIS DT aerosol products, whereas uncertainties due to viewing geometry and snow contamination are also noticeable. For the MODIS DT aerosol products, no retrieval is attempted over bright surfaces, such as the Saharan Desert (Remer et al., 2005; Levy et al., 2010). To fill the data gaps, the MODIS DB product was developed, which has the capability of retrieving aerosols over high surface albedo areas with the use of MODIS near UV channels (Hsu et al., 2006). The Collection 5.1 MODIS DB AOD has reported uncertainties on the order of 20–30 %.

MISR, which is onboard the Terra satellite, provides near-simultaneous observations at nine viewing angles (nadir, ±26.1, ±45.6, ±60.0, and ±70.5 degrees) in four spectral bands at 446.4 nm, 557.5 nm, 671.7 nm, and 866.4 nm. It has a much narrower swath of ∼360 km compared with 2330 km of MODIS, providing global coverage about once per week. MISR has been successfully used to retrieve aerosol properties

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globally, including over bright desert surfaces, though not snow and ice (Kahn et al., 2010). Kahn et al. (2005, 2010) showed that the uncertainty in MISR retrieved AOD is on the order of 0.05 or 0.2 × AOD, whichever is larger. Biases and uncertainties in MISR AOD values are associated with cloud contamination, and lower boundary conditions in some locations (Kahn et al., 2010). Uncertainties are also found over regions that have mixtures of dust and smoke aerosol types, as only limited numbers of aerosol models are used in the retrieval process. Specific biases have been identified for retrievals with AOD values lower than 0.025 or higher than 0.5 (Kahn et al., 2010). Besides AOD, constraints on particle shape, size, and absorption, are also reported by the MISR aerosol product.

Different sensors have different spatial coverage and overpass times. For fair comparisons, pairs of observations from different instruments need to be collocated spatially and temporally. Since both MISR and MODIS are onboard the Terra satellite, it is possible to have near simultaneous observations overlapping the same location from both instruments. However, the two aerosol products have different spatial resolutions (10 km for MODIS DT and DB, and 17.6 km for MISR). Therefore, to spatially collocate the MODIS DT (MODIS DB) products with MISR, all three products were averaged into $0.5^\circ \times 0.5^\circ$ (Lat/Lon) gridded products for every six hours. At the second step, the six hours gridded aerosol products were collocated in both space and time, and pairs of data points with valid AOD values from both MODIS DT (or MODIS DB) and MISR aerosol products were chosen for the tests described in the following section. Two comparison datasets were used in this study: (1) spatially and temporally collocated Terra Collection 5.1 MODIS DT and MISR Version 22 aerosol products from 2005–2007 and (2) spatially and temporally collocated Terra Collection 5.1 MODIS DB and MISR Version 22 aerosol products from 2005–2007.

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3 Results

In this paper, our results begin by presenting example regressions of satellite AOD to AERONET from eight important geographical regions. Then, to understand the size of the bias features, we ratio the MODIS retrievals to MISR aerosol optical depth retrievals and study the spatial patterns of different products through spatially and temporally collocated comparisons. From these results, we return to our original eight comparisons and discuss limitations in spatial coverage of the current ground-based observations for the problematic regions identified from our results.

3.1 Example AERONET Comparisons

Eight AERONET sites, which have at least five-year data records that provide representative observations to the aerosol state of a given region, were selected: Alta Floresta (for South America), Banizoumbou (for North Africa), GSFC (for the Eastern US), Maricopa (for the Western US), Kanpur (for India), Mongu (for South Africa), Solar Village (for Saudi Arabia) and Shirahama (for East Asia). AERONET direct sun measurements of AOD are highly accurate, with the uncertainties on the order of ~0.01 in the visible and near-infrared wavelengths for the level 2 product (Eck et al., 1999). Using the standard Angstrom (linear) fit, AERONET observations from the 0.50 and 0.67 µm wavelengths were used to estimate AOD values at the 0.55 (for MODIS) and 0.558 (for MISR) µm wavelengths (Shi et al., 2011). Within a 30 min temporal window and 0.1 degree spatial difference, one-to-one collocated operational MODIS/MISR and AERONET AOD were used for the comparisons. Regressions are shown in Fig. 1, with regression line parameters and r^2 values presented in Table 1. Because the behavior of satellite retrievals can change when AODs are large, we provide scores for all data and also for those AODs less than 0.5.

Figure 1 shows that in most regions (the Eastern US, South America, North Africa, South Africa, East Asia and India), retrievals from the operational MODIS DT (MODIS DB) and MISR aerosol products show reasonable correlations with the collocated

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AERONET data. Yet slope differences are clearly noticeable for areas dominated by different aerosol species, indicating that aerosol microphysical properties are among the sources of uncertainties in these aerosol products. Also, although an underestimation is observed for high MISR AOD values (AOD > 0.5), in almost all regions except Mongu (as previously reported in Kahn et al., 2010), the influence of lower boundary conditions (generally manifested in the intercept of the regressions) is less evident in MISR-AERONET than the MODIS-AERONET comparisons. For example, over the Western US, where AERONET reported AOD values are mostly smaller than 0.2, collocated AOD values from the operational MODIS DT aerosol products show a much higher AOD range up to 0.6. Note that the black regression line for MODIS is not provided from the Maricopa plot due to an insufficient number of data points. Also, large intercept values are observed for the comparisons between the MODIS DB and AERONET AOD values at the Kanpur and Mongu sites, showing that uncertainties can exist for the MODIS DB products over low surface albedo regions. In contrast, observations from the Banizoumbou and Solar Village sites suggest that both the MODIS DB and MISR have capability to retrieve aerosols over bright surfaces.

However, point comparisons are not sufficient and may not fully represent the performance of satellite AOD retrievals. For example, the spatial comparisons between MISR and MODIS over South Africa in Sect. 3.2 (Fig. 4) indicate larger differences than what the point comparisons show at the AERONET site. Similar observations are also made over the Arabian Peninsula. Comparisons between satellite AOD products are therefore evaluated globally for the rest of the paper.

3.2 Global Ratios

The regressions shown in the previous section reveal a common observation: satellite products often correlate well, but suffer from slope or Y-intercept biases. Hyer et al. (2001) reported highly variable regression slopes for different sites in the same region. The question now becomes: Over what area do these regressions hold? We begin with an examination of overall AOD for the 2005–2007 timeframe in Fig. 2 keyed

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to data of simultaneous MODIS and MISR retrievals. Also, as part of the Supplement, Fig. 2 is repeated seasonally (DJF, MAM, JJA, SON).

Figure 2 shows three-year averaged spatial plots of AOD from MISR and MODIS Collection 5.1 retrievals. The plots shown were calculated pairwise; only MISR aerosol retrievals with collocated MODIS AOD retrievals (and vice versa) were used to calculate the averages (Sect. 2). Therefore, the sampling biases in Fig. 2a could be different from the three-year averaged MISR AOD plot that used all available MISR data. Shown in Fig. 2a, the commonly acknowledged continental scale aerosol features are visible. Heavy smoke aerosol plumes are found over regions of South America, South Africa and Indonesia; dust aerosol plumes are visible over North Africa and the Middle East (e.g., Husar et al., 1997). Aerosol plumes that originate from multiple aerosol sources of dust, smoke, and pollutant are observable over East and South Asia (Reid et al., 2009; Eck et al., 2005). Long-range aerosol transports are shown. Asian dust plumes cross the Pacific Ocean and reach the West Coast of US; North African dust plumes cross the Atlantic Ocean and reach the Caribbean. A high AOD band is also noticeable over high latitude southern oceans. However, this feature is probably produced by cloud artifacts (e.g., Zhang et al., 2005; Shi et al., 2011; Kahn et al., 2010; Smirnov et al., 2011).

Figure 2b shows the corresponding operational MODIS DT AOD distributions. Because only pairs of MODIS and MISR data that possess valid AOD values were used in creating Fig. 2, the differences between Fig. 2a and b are mostly related to the uncertainties in the retrieval processes, and sampling biases between the two products are minimized. High AOD features over the Western US, the Andes Mountains, and the Namibian Desert from Fig. 2b are not found from the spatially and temporally collocated MISR AOD plot in Fig. 2a. Also, MODIS DT AOD values are higher than the collocated MISR AOD values over regions such as East and Central Asia, India, Indonesia, South Africa, and South America. Note that the differences seem significant, yet could mostly be explained with the known limitations of each product. For example, for the MODIS DT aerosol product, overestimation of AOD values that are greater than

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0.5 and are over the sparsely vegetated land (e.g.: the Andes Mountains, the Namibian Desert, and the Western US), could be due to the uncertainties in surface characteristics, which were deviating from the surface reflectance model used in the operational MODIS DT product. In another case, higher MODIS AOD values over South America, South Africa, and Central Asia could be related to the underestimation of the MISR aerosol product for high AOD (Kahn et al., 2009, 2010; personal communication with O. Kalashnikova). This effect can be observed in the Alta Foresta data (Fig. 1) in which the MISR retrieval underestimates the biomass burning aerosol.

Figure 2c and d are structured the same as Fig. 2a and b, but they show the comparison of MODIS DB and MISR aerosol products. Figure 2c shows the three-year (2005–2007) averaged spatial plot of MISR AOD (collocated with the MODIS DB product). Heavy aerosol loadings are found for dust over North Africa and the Arabian Peninsula, for smoke over South Africa, and for pollutant mixed dust over Northern India and East Asia. Figure 2d shows the corresponding MODIS DB AOD distributions. For South America, Northern India (e.g., the Kanpur site), and East Asia, higher AOD values are shown for the MODIS DB product. Conversely, Deep Blue has much lower AODs in central Africa and parts of the Arabian Peninsula. Over desert regions such as North Africa and the Middle East, the AOD values from the two products are consistent to a reasonable degree.

To better illustrate the differences, Fig. 3a and b shows the spatial plot of the AOD ratio of the MODIS DT (MODIS DB) AOD divided by MISR AOD. Red colors represent regions in which MODIS retrieves higher AOD than MISR , and blue colors show the opposite. For Fig. 3a, ratios larger than 1.3 are found over Western and Northeastern Canada, the Western US, the Andes Mountains, most of the Amazon, and Central and East Asia, indicating that the MODIS DB AOD values are much higher than the MISR AOD values over these regions. Ratios smaller than 0.75 are found over the Central US, the east coasts of South America and South Africa, and North-Central Asia. Also, even over regions like South Africa and South America, where we expect both sensors to have better performance due to relatively low surface reflectivity, ratio values

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of 1.1–1.5 are found. Some of this behavior also appears in the sensor-AERONET comparisons for the Alta Floresta site in Fig. 1. Figure 3b shows that over the Western US, Southern South America, North Africa, Central Asia, Northern India, and Eastern Australia, the ratios between MODIS DB and MISR AOD are greater than 1.3. Regions where MISR retrievals are much greater than those from MODIS DB are South Africa, the middle of the Arabian Peninsula, Mid-India, and part of Central Asia. However, the ratio plots from Fig. 3a and b can be misleading, because high ratio values over regions with small AOD values can skew the picture. Therefore, the AOD differences between MODIS DT (MODIS DB the tendency for MODIS DT AOD) and MISR AOD at the green channel are also shown in Fig. 3c and d. The main patterns of Fig. 3c and d are very similar to that of Fig. 3a and b. However, regions with low AOD values and very high ratio values, such as the Western US, have AOD differences on the order of 0.1–0.3. Conversely, over Central Africa, where the ratio plot does not show a large inconsistency, Fig. 3c and d highlight the regions with AOD differences larger than 0.1.

Note that Fig. 3 reflects, in part, the fact that the version 22 MISR-retrieved AOD values tend to have a low bias in the high AOD regime (Kahn et al., 2010), combined with the tendency for MODIS DT AOD values to be overestimated over bright surfaces. The uncertainties in Fig. 3 due to ratios from small values of AODs are discussed in Sect. 4.0. Further, uncertainties in the microphysical models used in these retrievals are amplified when aerosol loadings reach multiple scattering regimes. Thus, as shown in Fig. 4, we performed regressions between MISR and MODIS DT (MODIS DB) AOD values using collocated MODIS and MISR data that have MISR AOD values between 0–0.5 (MODIS = MISR × slope + interception). Figure 4a, c and e show spatial distributions of correlation, slope, and intercept values, respectively, for the regression analysis using the collocated operational MODIS DT and MISR AOD data. Like Fig. 2, seasonal regressions are included in the Supplement. Similar to the studies of Kahn et al. (2009), correlation values greater than 0.8 are found over global oceans and most land regions. Regions with correlation values less than 0.7 are found over the Western US, the Andes Mountains, the Namibian Desert, part of the Middle East, Central Asia, and Northern Australia. Most of the regions showing poor correlations are highlighted in intercept plot of Fig. 4e as well. Regions with high intercept values are most likely attributed to surface characteristics, because all of these regions are semi-arid and have relatively high surface reflectance. Also, although the correlations between MISR and operational MODIS DT AOD data are above 0.8 over the Amazon region, slope values of 1.2 and above are found (Fig. 4c). Similar slope and correlations patterns can also be found over the middle of South Africa and Southeast Asia, suggesting potential aerosol microphysical biases over these regions. Field campaigns can help improve satellite retrievals over regions where better aerosol property information is needed. Also, for both satellite products, high correlations of 0.8 or greater were found compared with ground-based sun photometer observations on a global basis (Shi et al., 2009; M.S. thesis, Hyer et al., 2011; Shi et al., 2009, AGU), showing that:

1. There are still regions that have no or few sites that would assist in refining assumed aerosol properties for satellite retrievals.

2. Additional AERONET sites are desired for some of the regions with large MODIS/MISR ratio values, especially for regions where it is suspected that aerosol optical property assumptions have large uncertainties in satellite retrievals.

3. For regions where satellite products need better aerosol property information to constrain assumptions, field measurements can play an important role.

Figure 4b, d and f show similar spatial distributions of correlation, slope and intercept values for the regression analysis using the collocated MODIS DB and MISR AOD data. Compared with the analyses from the collocated operational MODIS and MISR data, lower correlation, larger intercept values and lower slope values were found. However, most regions shown in Fig. 4b, d and f are either desert regions or areas with complex surface features, and therefore, lower correlations between two aerosol products are understandable due to lower sensitivity to aerosol properties over bright surfaces. Still, detailed analyses of the uncertainties for the two aerosol products over these regions, similar to the studies conducted for the MODIS DT aerosol products (e.g., Shi et al., 2011; Hyer et al., 2011), are necessary.

In summation, the areas with large disagreements between satellite retrievals can be divided into three categories:

1. Complicated surface conditions: transition areas from bare land to areas with dense or sparse vegetation cover;

2. Complicated aerosol type: inaccurate representations of aerosol microphysics in the retrieval processes over the dark vegetation areas or dark surfaces;

3. Desert regions with very bright surfaces.

Most problematic areas belong in the first category. These regions include: the Somalia region (0–20° N, 35–50° E), the North Coast of Africa (20–35° N), the Sahel zone (~12° N across Africa), the West Coast of Africa (15–25° S), the East Coast of Africa and Madagascar (~10–20° S), the East Coast of Brazil, the Andes Mountains, the East Coast of Australia, Kazakhstan, and Mongolia. The Yellow Sea region near coastal China also has a surface-type problem, as it is a region with turbid waters. Regions that fall into the second category (complicated aerosol types) include: 5° N-5° S and 10–30° E of Africa, 20–35° N and 100–115° E of China and Korea, the south and north end of Japan, Malaysia, Indonesia, and the Philippines. Better agreements for aerosol retrievals among sensors are expected for the regions with low surface reflectivity at the visible spectrum. However, the AOD differences between the two products are still relatively large. This indicates that the complicated aerosol type is one of the uncertainty sources. For example, some places are known to have dark particles or mixtures of smoke or pollution and dust. Regions that fall into the third category include: Northwestern India (70° E and 35° N), Iran and Afghanistan regions (45–60° E and 25–35° N), Tibet, the East Coast of the Arabian Peninsula (45–60° E, 10–30° N), and high latitude areas. Also, differences in MISR and MODIS retrievals do not always point to a lack

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of understanding regarding the basic aerosol properties in the region. Rather, they sometimes indicate satellite algorithm issues for one or both instruments. For example: regions, such as 5–10° S and 60–70° W of South America, where numerous field campaigns have been conducted (e.g., Reid et al, 1998, 2005, SCAR-B and SMOCC campaigns) and many AERONET data are available, may also reveal the difficulty of fully understanding aerosol properties and their spatial/temporal variations from limited ground and in situ observations.

4 Discussion: Relationship to spatial distribution of AERONET sites

Most of the problem areas listed in Sect. 3 are very remote and under-developed. Hence, this increases the difficulty in establishing long-term AERONET sites, which would be useful for validating the satellite aerosol retrievals over those regions. Conversely, regions with the best agreement also often have the highest density of AERONET sites, even though the surrounding areas might have large inconsistencies. This is partially because the aerosol climatology used by the MODIS DT over-land algorithm is based on AERONET data (Levy et al., 2010). Also, this may, in part, be related to the concentration of sites in more developed "darker" regions where vegetation cover is greater. The distribution of sites results in a sampling bias. The use of global statistics to measure product efficacy biases verification statistics in favor of satellite retrievals. Long-term AERONET observations greatly improve the satellite retrievals regionally by providing developers with valuable verification data that is coupled with some aerosol optical property information from sun-sky retrievals.

However, several issues were raised with the previous analysis. First, some significant differences occur in regions with existing AERONET sites, and the differences between MISR and MODIS are due largely to the assumed aerosol properties in the satellite algorithms and/or limitations in the algorithm, such as high AOD for MISR (this is seen in Fig. 1 in Amazon region with dark surfaces) or high surface reflectance for MODIS. Second, the ratio of AOD retrievals between two sensors/algorithms in regions

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of low AOD is not necessarily a good measure of whether errors are significant. Third, even if there are AERONET sites in high surface reflectance areas, the main issue in satellite retrievals is often the poor surface reflectance characterization, and more AERONET sites will not necessarily improve that situation.

In response to these questions, a gradient map of AOD differences (ΔAOD, MODIS DT/MODIS DB minus MISR AOD at the green wavelength) between satellite aerosol products was computed, as shown in Fig. 5. Over-plotted in Fig. 5 are the frequency indexes of available AERONET data. To create the gradient map of ΔAOD, only regions with both satellite AOD values larger than 0.1 were used. The gradient is computed based on Equation 1,

$$\text{AOD Error Gradient} = \sqrt{\left(\frac{\partial \Delta \text{AOD}}{\partial x}\right)^2 + \left(\frac{\partial \Delta \text{AOD}}{\partial y}\right)^2} \quad (1)$$

where δx and δy (δx and δy are evaluated at half degrees Lat/Lon) represent spatial distances in west-east and south-north directions, respectively. The magnitude of the ΔAOD gradient shows the spatial variation of uncertainties in satellite aerosol products. Regions with small ΔAOD gradient values are shown in dark blue, indicating that a few AERONET sites would be sufficient to validate retrievals for the whole region. Regions with large ΔAOD gradient values are shown in lighter colors (such as white). These regions have large spatial variance in ΔAOD, and denser distributions of AERONET sites are needed for future validation efforts, for example: North India, and western South America.

For the AERONET density index, seventeen years of the AERONET level 2.0 data were used (1993–2009). A frequency index of 1 is defined as one AERONET site within a $1^{\circ} \times 1^{\circ}$ latitude and longitude region, having at least one measurement during one month of the time series. If there are two AERONET sites, and each has at least one observation during any one month, the index number is set to 2. We increment the index value for a given region even if only a fraction of a month has sun photometer data. For one AERONET site that provides continuous observations for a year, the

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index for the lat/lon grid that the AERONET site locations is set to 12. Regions with indexes of 0–12, 12–60, and above 60 (for the Seventeen year period) are defined as poorly observed (red), normal (yellow), and well observed (green) regions respectively. Figure 5 includes four by four (4 × 4) degree observation-density averages, which were developed from one by one (1 × 1) degree averages by picking the largest index value of any 1 × 1 degree box inside the 4 × 4 degree grid in order to highlight the signal. Since only regions with AOD values larger than 0.1 from both satellite products were used in creating Fig. 5, it is necessary to compare Fig. 5 with the AOD ratio/difference plot (Fig. 3) that includes all scenarios. Two regions that are not included in Fig. 5, but are highlighted in Fig. 3, are the Andes Mountains and the West Coast of the US. Again, both regions have complex surface characteristics that could introduce a problem to space-borne satellite aerosol retrievals.

Figure 5 shows that Europe and the West and East Coasts of US are well covered with sun photometer observations. However, it is still useful to identify regions for future AERONET sites for three scenarios: (1) type A region: regions where it is suspected that aerosol optical property assumptions are poor in satellite retrievals; (2) type B region: regions with moderate to high AOD and lack of AERONET sites; (3) type C region: any sites in the large regions of the earth that have no or few sites (type C region). Based on Fig. 5, the type A regions include Central Africa and Northwestern South America. The type B regions include the Middle East, the high latitude Asian part of Russia, Central Asia, Western India, and especially the Malaysia-Indonesia region. The type C regions include Australia and Greenland. All the previously discussed regions are highlighted with red boxes in Fig. 5.

Lastly, based on the discussions from this section, we identified regions that require better surface boundary conditions: (1) Central Asia; (2) Malaysia-Indonesia; (3) Central Africa, near Zaire; (4) the Central Sahara; (5) the Eastern Arabian Peninsula; (6) Greenland and Australia, where no long-term monitoring effort is present for a large area. The Malaysia-Indonesia region is also highlighted in this study, yet we expect new sites to be established for the 7-SEAS and SEAC4RS field campaign; some

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of these sites will likely remain as long-term sites. The AERONET has data from the UAE that helps address the Eastern Arabian Peninsula. Also, large discrepancies are found over the high-latitude southern ocean that invite further experiments in order to understand the cause of the high AOD band over this area. This question has been at least partially addressed by the ship based sun photometer measurements from the Maritime Aerosol Network (MAN network) (Smirnov et al., 2011). The measured AOD in this region is very low.

For topographically complex regions that introduce high AOD biases such as the Western US, the Andes Mountains, and the Namibian Desert, it would be useful for long-term AERONET sites to be established for satellite validation. Notice that most of the issues with satellite retrievals over these sites relate to surface reflectance characterization and not assumed aerosol optical properties.

5 Discussion: community effort

The purpose of this paper is not simply to point to areas of diverging AOD products, but rather to inform the larger scientific community that there are likely regions where local measurements that can be made to maximize the benefit for retrieval development. Our regressions show that spatially correlated biases in AOD retrievals are robust. Regional measurements of aerosol or lower boundary condition properties, even over short field studies, are likely to have significant value when measurements are made in poorly observed regions.

To this end, as part of the Supplement of this paper, we provide our annual data, as well as seasonal breakouts, for community use. These are provided in GeoTIFF and KML format. Indeed, even when using the simple overlay tools in KML in Google Earth, hotspots of divergence can be seen related to land surface features (e.g., Fig. 6).

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6 Summary and conclusions

Using spatially and temporally collocated MODIS and MISR aerosol optical depth retrievals, we examined the spatial difference between the operational MODIS and MISR aerosol products. Differences are indicative of the spatially correlated bias, which are highly detrimental to higher order data analysis methods, such as data assimilation and inverse modeling. The spatial comparisons of the two collocated aerosol products reveal regions that need further improvements in future satellite studies. For the first time, our analysis identified the regions that would most benefit from long-term point measurements and field campaigns for future satellite aerosol studies. The key results from our study are:

1. Comparisons of spatially and temporally collocated MODIS and MISR aerosol optical depth data revealed that the ratio of MODIS to MISR AOD is much larger than 1 for the Western US, South America, East and Central Asia, and Indonesia. Regions where the ratio is significantly less than 1 were found over the East Coast of South Africa, the East Coast of South America, and the Arabian Peninsula, Western Australia. Note that the ratio in regions of low AOD is not necessarily a good measure of whether errors are significant, as indicated by the AOD difference plot from Fig. 3c and d.

2. A closer look of the comparisons between MODIS DT and MISR data shows that over the Western US, the Andes Mountains, and Russia, high AOD "features", which are only visible from the MODIS DT aerosol product, are possibly due to the surface-reflectivity-introduced bias. Also, over South America, China, and the Indonesia regions, MODIS DT tends to overestimate, and MISR tends to underestimate AOD values, due, in part, to differences in the aerosol optical properties used in the MODIS DT and MISR AOD retrievals. Some of these observations support the results of previous studies in which some of the causes are identified (Kahn et al., 2009, 2010; Levy et al., 2011).

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3. This study also identifies the locations where additional ground based and in situ measurements would have the greatest impact on improving satellite aerosol retrievals.

In the Supplement to this paper, GeoTIFF and KML files are provided. We hope these can be useful to the scientific community to develop priorities for enhanced sampling by sun photometers or regional in situ studies.

Supplementary material related to this article is available online at: http://www.atmos-meas-tech-discuss.net/4/4295/2011/ amtd-4-4295-2011-supplement.zip.

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Table 1. Regression coefficients for Fig. 1 with all AOD and satellite AOD smaller than 0.5 in parentheses.

Site	Satellite	Slope	Intercept	r^2
Alta Floresta	MISR	0.48(0.81)	0.09(0.00)	0.77(0.82)
	MODIS DT	1.33(1.01)	0.1(0.05)	0.92(0.82)
Shirahama	MISR	0.67(0.66)	0.03(0.03)	0.90(0.84)
	MODIS DT	1.01(0.85)	0.05(0.02)	0.83(0.79)
Kanpur	MISR	0.61(0.47)	0.11(0.13)	0.70(0.54)
	MODIS DT	1.06(0.54)	0.05(0.21)	0.79(0.43)
	MODIS DB	0.98(0.28)	0.04(0.19)	0.60(0.11)
Mongu	MISR	0.82(0.74)	0.03(0.04)	0.88(0.75)
	MODIS DT	0.76(0.67)	0.04(0.05)	0.83(0.71)
	MODIS DB	1.02(0.54)	0.17(0.04)	0.60(0.34)
Banizoumbou	MISR	0.51(0.33)	0.20(0.19)	0.61(0.34)
	MODIS DT	1.14(0.78)	0.13(0.01)	0.95(0.81)
	MODIS DB	0.63(0.49)	0.32(0.21)	0.81(0.50)
GSFC	MISR	0.72(0.80)	0.03(0.02)	0.87(0.90)
	MODIS DT	1.1(1.06)	0.01(0.01)	0.94(0.84)
Maricopa	MISR	0.8(0.77)	0.06(0.06)	0.35(0.39)
	MODIS DT	0.96(0.99)	0.25(0.24)	0.12(0.15)
	MODIS DB	0.82(0.82)	0.07(0.07)	0.94(0.94)
Sollar Village	MISR	0.9(0.68)	0.09(0.13)	0.74(0.66)
	MODIS DB	0.53(0.29)	0.19(0.21)	0.35(0.12)

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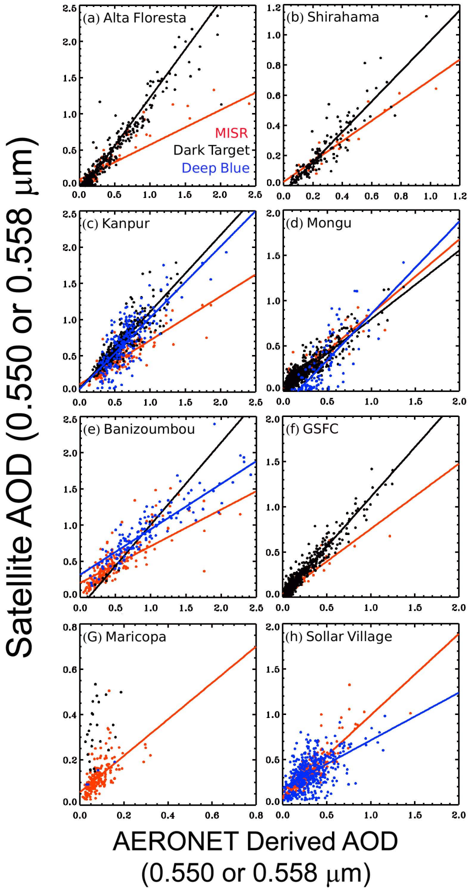

Fig. 1. One to one comparisons between MODIS Dark Target (MODIS Deep Blue)/MISR and AERONET AOD at seven sites for year 2000–2008. Plots for MODIS or MODIS Deep Blue locate at right panel with MISR at left panel. **(a)** Alta Floresta, **(b)** Shirahama, **(c)** Kanpur, **(d)** Mongu, **(e)** Banizoumbou, **(f)** GSFC, **(g)** Maricopa, **(h)** Solar Village.

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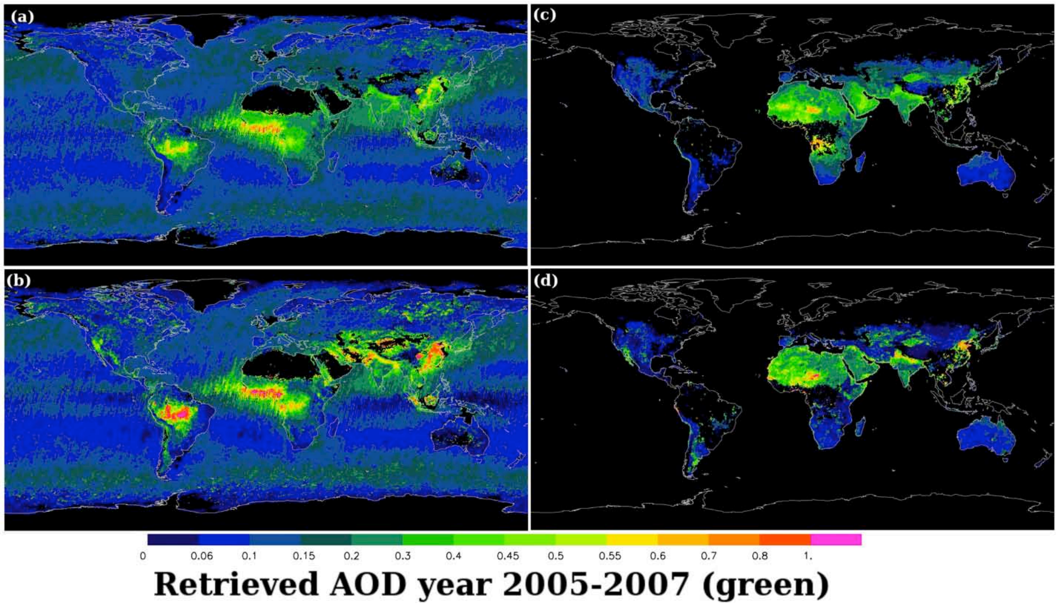

Fig. 2. Average of spatial distribution of MISR (0.558 µm) and operational MODIS Dark Target (DT) and MODIS Deep Blue (DB) (0.55 µm) for 2005–2007. The MISR and operational MODIS DT/MODIS DB AOD data were first collocated both in space and time, and only collocated MISR retrievals were used in generating this plot. Data were gridded every $0.5^{\circ} \times 0.5^{\circ}$ (Lat/Lon). **(a)** MISR AOD that corresponding to operational MODIS DT, **(b)** Operational MODIS DT AOD, **(c)** MISR AOD that corresponding to MODIS DB, and **(d)** MODIS DB AOD.

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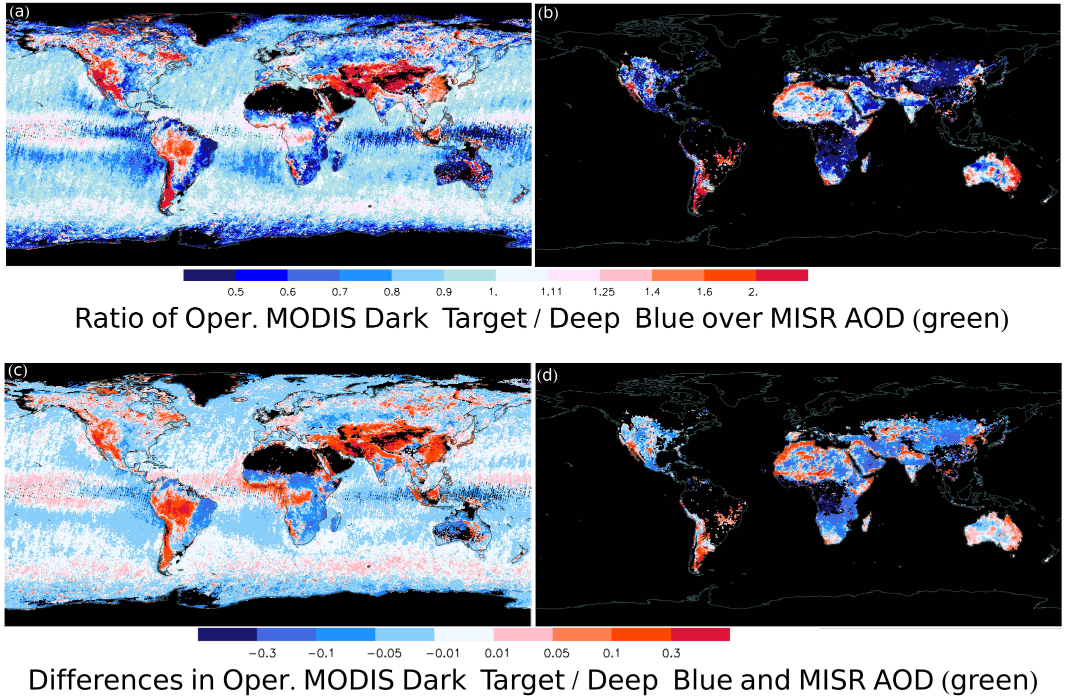

Fig. 3. **(a)** The ratio of operational MODIS DT over MISR AOD in green channel for year 2005–2007. **(b)** Similar as **(a)** but for MODIS DB. **(c)** The differences between operational MODIS DT and MISR AOD in green channel for year 2005–2007, and **(d)** Similar as **(c)** but for MODIS DB.

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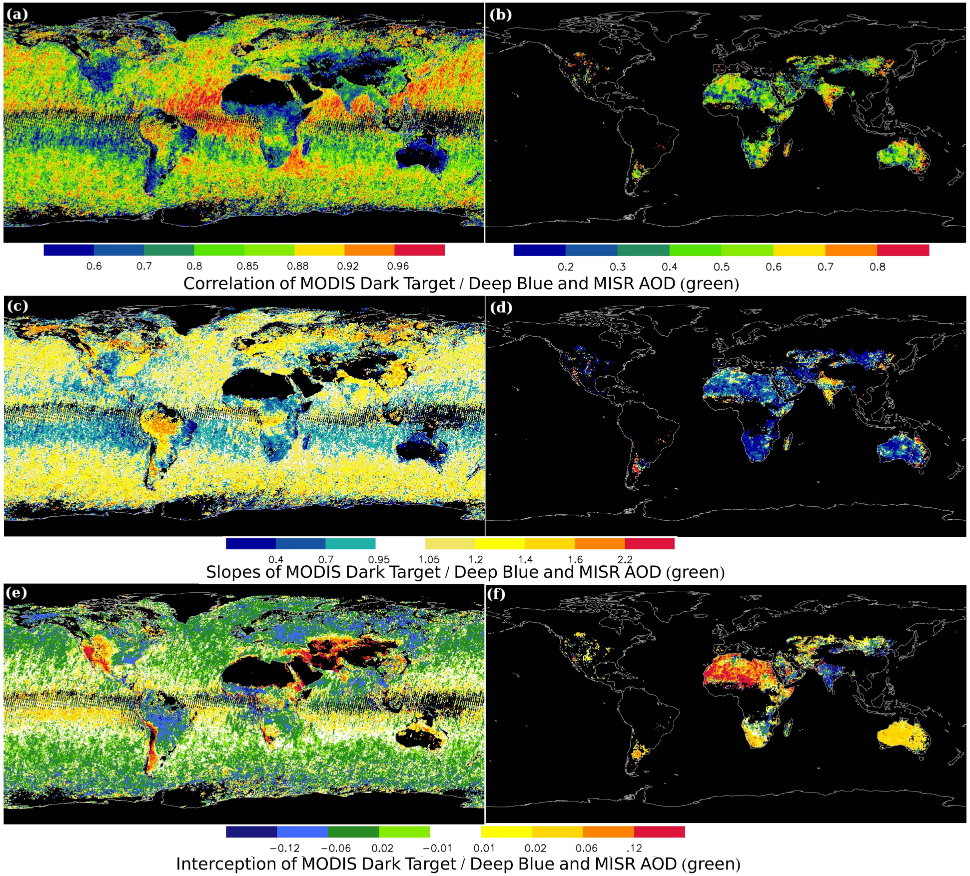

Fig. 4. The regression and correlations between MISR and operational MODIS DT (right panel)/MODIS DB (left panel) for year 2005–2007 (MODIS = MISR × slope + interception). Only collocated MODIS and MISR data that have MISR AOD values between 0–0.5 were used. **(a)** and **(b)** Correlation, **(c)** and **(d)** Slope, and **(e)** and **(f)** Interception.

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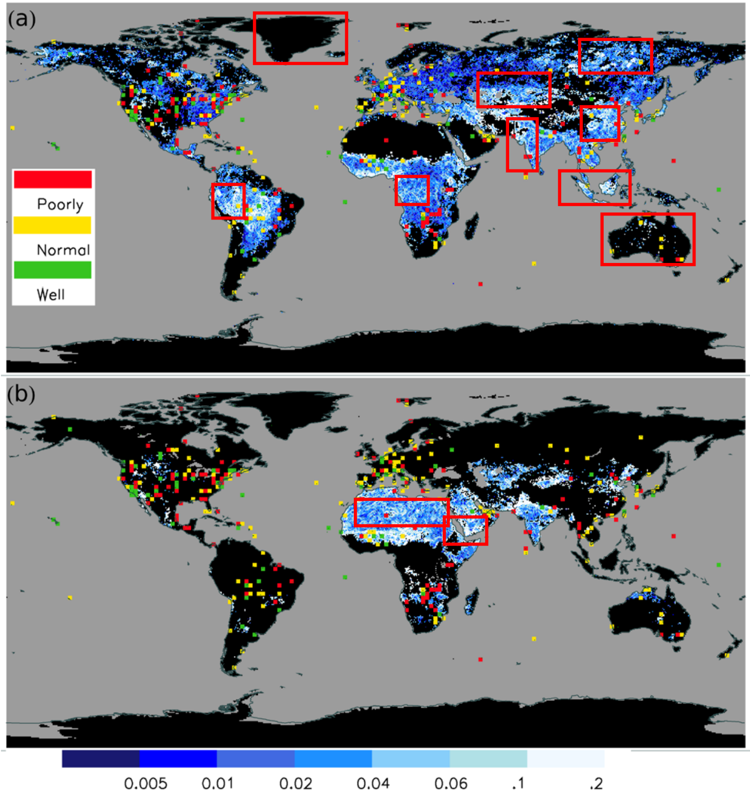

Fig. 5. The spatial distribution of the gradient of AOD differences (ΔAOD) between the MODIS and MISR aerosol products. The ΔAOD was computed by subtracting MODIS DT/MODIS DB (0.55 µm) AOD from MISR AOD (0.558 µm). Only land regions that have reported AOD larger than 0.1 from both products were used for computing the gradient. Over-plotted on top of the gradient map is the AERONET density map. For AERONET observation density, for every one by one degree grid, one AERONET site that has observation for a month during the 1993–2009 periods is counted as one. Regions that have index of 0–12, 12–60, and above 60 are considered poorly, normal, well observed area, and indicated as green, yellow and red, respectively. Oceans are plotted in grey. **(a)** for MODIS DT, **(b)** for MODIS DB.

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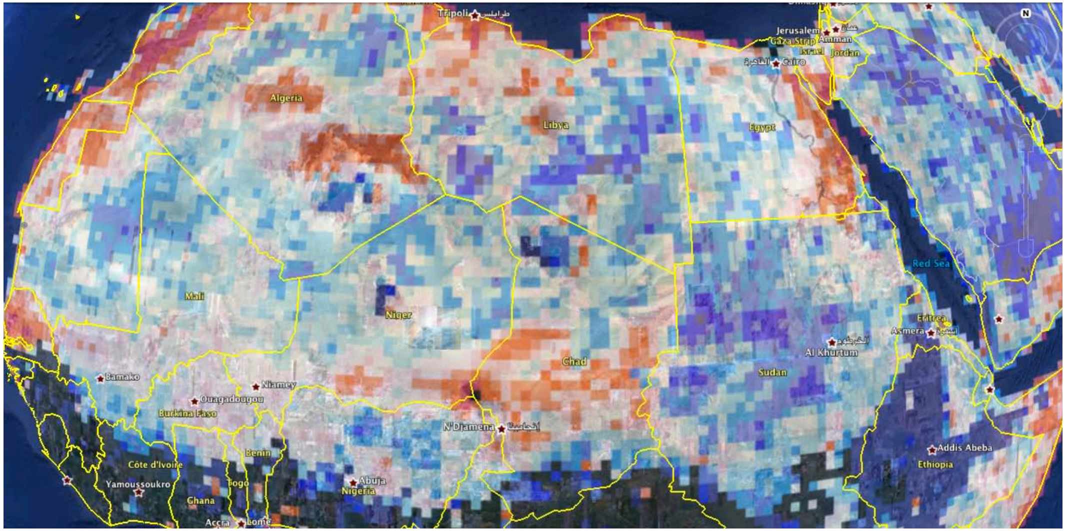

Fig. 6. Overlay of Fig. 3b on Google Earth over North Africa.

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