Suomi NPP VIIRS Aerosol Data Product Assessment Report

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Executive Summary

Atmospheric aerosols are a significant component of the global climate system due to their direct and indirect radiative/microphysical impacts on the Earth's radiation budget, clouds and rainfall [*Ramanathan et al*., 2001; *Rosenfeld et al*., 2008]. It was well recognized by the scientific community that aerosols could potentially counteract the effects of increasing green house gases in changing Earth's climate system (IPCC, 2007). Therefore, it is imperative to obtain accurate global information on aerosol properties from satellite in order to better understand and model both short-term and long-term physical and chemical processes related to aerosols. Such measurements also provide critical timely information for operational applications such as air quality and extreme events/disaster monitoring needed by the policy makers and stake holders.

This report details the work performed by the NPP VIIRS Science Team in their evaluation of both the short- and long-term applications of the operational aerosol EDR and IP products, which consist of aerosol optical depth, particle size (i.e., Angstrom exponent), and suspended matter. The VIIRS Science Team was also charged with determining the suitability of employing the heritage MODIS aerosol retrieval algorithm to the VIIRS data.

The major findings of the aerosol Science Team include:

- The current state of VIIRS cloud mask (VCM) is not robust enough to sufficiently screen out cloudy pixels for aerosol retrievals. The aerosol EDRs are also subject to the issue of snow/ice contamination at high-latitude regions.
- Compared to measurements from the ground-based AERONET network, the VIIRS IDPS aerosol optical depth (AOD) performs reasonably well over ocean. However, over land, the VIIRS AOD is generally biased high, particularly over urban regions.
- There is a lack of data coverage over desert and semi-desert regions in VIIRS IDPS data due to the fact that the heritage algorithm does not perform retrievals over bright surfaces.
- Major improvements in the performance of VIIRS suspended matter product are needed. Over ocean, we find that the detection of dust SM type is significantly underestimated in well-known dust-laden regions. In particular, significant portions of heavy dust plumes are often misidentified as volcanic ash.
- Qualitatively (e.g. spatial patterns of AOD), the VIIRS IDPS looks similar to MODIS C6 Dark Target and Deep Blue products over dark surfaces.
- Quantitatively, VIIRS AOD is biased high compared to MODIS on Aqua (by 50% or more over land, and 10% over ocean). *This difference is much too large to be considered acceptable for inclusion into the continuous climate data record (CDR).*
- The time required to implement calibration corrections, bug fixes, and other changes in the operational (IDPS) system is unreasonably long and does not meet the demand of the community.

- The IDPS operation system has no capability to reprocess data, resulting in data discontinuities every time a new build is implemented.
- The Science Team, working with the PEATE, has successfully implemented, on a research basis, the most recent NASA retrieval algorithms that are consistent with the MODIS C6 algorithms. These new NASA science products are currently being evaluated.

We emphasize that, similar to the ocean color measurements, accurate estimates of long-term aerosol trends cannot be achieved without high fidelity long-term aerosol climate data records, which rely on high quality and consistent sensor calibration and retrieval algorithms applied across different satellite platforms. Constructing such long-term continuous CDRs requires data continuity from the EOS-era MODIS to VIIRS. In order to achieve this goal, we make the following recommendations:

- Common retrieval algorithms should be used for both MODIS and VIIRS.
- Periodic recalibrations of VIIRS bands using rigorous solar and lunar measurements need to be made consistently throughout the whole time series.
- The capability of reprocessing of the data set is essential to ensure that the incremental improvements made in the retrieval aerosol algorithm are incorporated in the data and applied consistently across the entire time series.
- Level 3 (gridded) products for VIIRS aerosol products are needed to meet the needs of modeling community and to make the processes of intercomparison and consistency check with MODIS more efficient.
- The PEATEs play an important role in supporting the VIIRS aerosol Science Team by providing diagnostic tools as well as the facilities needed for testing and processing/reprocessing of NASA's science products. Their efforts should be continued and expanded, if possible.
- Although not originally planned by NASA, we strongly urge the continuation of a MODIS-like algorithm on VIIRS, or development of a VIIRS-like algorithm on MODIS. In this report, we will demonstrate that, without use of a consistent retrieval algorithm for MODIS abd VIIRS, the capability of deriving accurate long-term trends of aerosols on regional and global basis for climate sciences will be severely hindered.

1. Introduction

Aerosols play an important role in Earth's radiative energy budget, likely comparable in magnitude to the effects of increasing green house gases in our atmosphere (IPCC, 2007). However, accurate estimates of global, long-term aerosol trends cannot be achieved without first deriving high fidelity long-term aerosol climate data records (CDRs). Production of high-quality CDRs rely on high-quality techniques to retrieve aerosol information from high-quality measurements which, in turn, rely on detailed characterization of the instruments being used. This effort includes calibration, as well as a complete assessment of the sensor's strengths and weaknesses.

The EOS era ushered in a golden age of capable sensors, strong retrieval algorithms, and dedicated instrument and scientific characterization teams; one of the important results that came out of this era was the aerosol CDR. This CDR, derived from SeaWiFS and MODIS data, has provided coverage over both land and ocean for over 10 years. While measurements from the earlier AVHRR sensors extend over more than 3 decades, their limited spectral and spatial information content was not sufficient to retrieve complex and highly variable aerosol properties with high accuracy over both ocean and land. As the EOS era is transitioning to the JPSS era, the aerosol and climate communities cannot afford to lose the ability to continue this valuable aerosol data record.

With the launch of the VIIRS instrument onboard Suomi NPP in late 2011, the hope is to continue the EOS aerosol record unblemished. VIIRS was designed to have similar capabilities as MODIS, with similar visible/NIR/IR spectral channels, similar spatial and temporal resolution, and similar heritage when it comes to retrieval algorithms. Although several potential issues with radiometric performance (e.g., optical cross-talk, out of band contribution, polarization, and gain transition anomaly) were identified [Hsu et al., MODIS/NPP joint Science Team Meeting, January 2010], no major impacts are expected. Thus, VIIRS should be suitable for providing continuity with the current aerosol time series.

However, although similar in capabilities, VIIRS and MODIS are two different instruments, and in general serve different user communities. Our job is to determine whether any differences in sensor characteristics, calibration, retrieval algorithms or data processing/ reprocessing strategy will hamper the data continuity for constructing long-term aerosol CDRs and, if such differences exist, how to mitigate or account for them. Table 1 identifies some of the key differences between MODIS and VIIRS that may impact aerosol data continuity. For example, there are spectral shifts (from 0.47 μm to 0.49 μm; from 0.65 μm to 0.67 μm; from 2.11 μm to 2.26 μm) in three of the key visible channels used for retrieving aerosol properties over land. Over most land types, the surface reflectance varies across even these small spectral shifts, which means that surface reflectance assumptions used for MODIS would not be valid for VIIRS. Naïve application of MODIS surface assumptions would lead to possible significant errors in retrieving aerosol, which might be seen as discontinuities or "jumps" in the aerosol data record. Therefore, ensuring successful continuation of a high-quality aerosol CDR requires the involvements of algorithm expertise. Impacts resulting from other differences listed in Table 1 are discussed throughout this report.

Table 1. Characteristics of MODIS and VIIRS instrument and aerosol products

	Aqua-MODIS	**Suomi NPP-VIIRS**
Orbit altitude	705 km	824 km
Equator crossing time	13:30 LT	13:30 LT
Granule size	5 minutes	86 seconds
Swath	2330 km	3040 km
Sensor zenith angle range	±64°	±70°
Valid solar zenith angle (for high quality)	< 82°	≤ 65°
Sensor bands used for aerosol retrieval	0.412, 0.466, 0.554, 0.646, 0.856, 1.24, 1.63, 2.11 µm	0.412, 0.445, 0.488, 0.555, 0.672, 0.746, 0.865, 1.24, 1.61, 2.25 µm
Pixel size, nadir	0.25, 0.5, and 1 km	0.375 and 0.75 km
Bow-tie effects	Yes	No
Product resolution, nadir	10 km	6 km (AOT and Angstrom exponent) 0.75 km (Suspended matter)
Product resolution, edge	40 km	10 km (AOT and Angstrom exponent) 1.2 km (Suspended matter)
Products, land (vegetated regions)	AOT (Dark Target Approach)	AOT, Angstrom exponent, Suspended matter
Product, land (deserts, urban regions)	AOT, Angstrom exponent, Dust single scattering albedo (Deep Blue Approach)	None
Products, ocean	AOT (7 wavelengths), Size (fine mode fraction)	AOT (11 wavelengths), Angstrom exponent, Suspended matter
Global gridded product	Level 3 daily, 8-day, monthly mean	None

In this report, we evaluate whether the VIIRS sensor and operational algorithms are capable of filling the need for data continuity in addressing the short-term and long-term variability of aerosols.

- Is the quality of the VIIRS EDR adequate to provide the continuation of imagery and products used for monitoring short-term day-to-day geophysical parameters of the atmosphere and surface?
- Will the VIIRS aerosol product (produced by the IDPS) satisfy the needs of the communities experienced with and expecting a MODIS-quality data record?

The assessment of whether this EDR can provide continuity of information on short-term aerosol variability will be performed in this report by utilizing ground-based data (e.g. the AERONET sunphotometer network) to evaluate the accuracy and precision of the VIIRS-IDPS products. We will also employ existing MODIS (e.g., Deep Blue and Dark-Target products) and CALIOP data streams to evaluate the context and conformity of the VIIRS-EDR within the current MODIS data record.

The VIIRS EDR will also be assessed to determine if it can continue the CDR developed using MODIS to address the question of long-term aerosol variability. Generally, based on model simulations, any potential trend in AOD over the past decades would be less than 10% of the absolute AOD (which is typically on the order of 0.15), meaning that we need to characterize our data well enough to see a change in AOD of less than 0.015. Yet even with twin MODIS instruments (aboard Terra and Aqua) the AOD magnitudes differ by 0.015 and they do not agree on the trend. Although both MODIS sensors have the same pixel resolution, spatial information, and use the same aerosol retrieval algorithm, it seems likely that at least one (probably Terra) has experienced calibration drift (less than 2%) in a few key channels. However, with special effort, recalibration has been possible, and the MODIS sensors should now be in closer agreement. If different algorithms had been applied to Terra and Aqua separately, there would have been no way to identify calibration as a source of the discrepancy. Even if a single algorithm is used, there are still many obstacles to creating a merged MODIS/VIIRS aerosol CDR, particularly in light of the sensor differences listed in Table 1.

In this report, the team led by Hsu et al. will attempt to look into the data continuity issues on both short-term and long-term time scale (described in section 2), while team led by Levy et al. will focus primarily on addressing the consistency of long-term data records from MODIS to VIIRS (described in section 3). Although the two research teams (Hsu et al. and Levy et al.) have taken entirely different approaches to evaluating aerosol continuity from MODIS to VIIRS, there is overlap in the data used and the final message. There are many obstacles to creating a merged aerosol climate data record from different satellite platforms, however, given enough effort, such a data record is highly achievable. The recommendations from this study for a path forward will be discussed collectively in section 4.

2. VIIRS IDPS aerosol properties evaluations using AERONET, MODIS, and CALIOP, and the feasibility of extending MODIS Deep Blue products into VIIRS: Hsu, Sayer, Lee, Bettenhausen, Gautam

Retrieving aerosol properties from satellite measurements with sufficient accuracy for use in climate studies is a highly challenging task. There are more unknowns regarding the microphysical and optical properties of aerosols than the information content that can be measured by current satellite sensors. For the single view satellite sensors such as MODIS and VIIRS, the most important factors/components that could substantially impact the performance of aerosol retrievals involve:

1) surface reflectance determination, including both their spectral and angular dependences;

2) aerosol model selection;
3) cloud screening; and
4) identification of snow/ice-covered surfaces, particularly over the melting seasons.

In order to address whether the VIIRS IDPS aerosol products are suitable for use in continuing the climate data records (CDRs) created from the EOS-era MODIS sensors, we collected extensive data from both ground based measurements from AERONET and satellite products from MODIS and CALIOP to examine the performance of the VIIRS IDPS aerosol Environmental Data Record (EDR) and Intermediate Product (IP), with specific focus on how the factors mentioned above impact the quality of those products.

In this section, we will evaluate the VIIRS cloud mask (VCM), the aerosol optical depth EDR and IP, the Angstrom exponent EDR, and the suspended matter EDR. The VIIRS data included in this study, which were declared to be in beta status, were taken between May 1st and October 14th, 2012. Before this time, various factors relating to VIIRS radiometric calibration updates and the cloud masking algorithm caused the products to be in a state of flux. After this time, an update to the VIIRS operational processing rendered aerosol data unusable; a bug introduced the code caused the misapplication of the VIIRS cloud mask, leading to significant cloud contamination in the data. Although a fix was identified within several days of the introduction of the bug, the implementation was not completed until almost two months later, resulting in an extensive data gap in the VIIRS aerosol products.

Since the spatial and temporal resolutions of these ground based and satellite data are different from those of the VIIRS products, care has been taking to account for these differences in the procedures developed to collect the data used for evaluation purposes. Globally and regionally, comparisons between the VIIRS IDPS and other independent aerosol products were stratified against key factors such as surface, viewing geometry and aerosol conditions in order to determine areas of agreement and disagreement.

In order to better understand whether VIIRS IDPS aerosol products are suitable to provide data continuity from MODIS to VIIRS, this section answers the following questions:

1) Is the VIIRS cloud mask (VCM) robust enough to identify the presence of clouds for use in aerosol retrievals?
2) Can the VIIRS suspended matter product provide useful information for the user community to distinguish different aerosol types?
3) How good is the performance of the VIIRS aerosol EDR and IP products, on both global and regional scales, against the ground based AERONET measurements?
4) Can these VIIRS/AERONET comparisons help us identify the root causes of deficiencies in any of the retrieval components of the VIIRS algorithm, such as surface reflectance estimation or aerosol model?
5) How frequently does VIIRS provide retrievals, and how does that compare to MODIS?
6) Are there any systematic biases between these two satellite products that could hamper the accuracy in detecting long-term trends of aerosols and the suitability of VIIRS operational data to continue the MODIS data record?

7) Given the sensor design differences between VIIRS and MODIS, can we extend the Deep Blue aerosol products from MODIS to VIIRS for constructing long-term consistent climate data records of aerosols?

2.1 Evaluations of VIIRS IDPS aerosol EDR and IP against ground based AERONET

The ground based AERONET aerosol optical depth (AOD) and Angstrom exponent (AE) data are based upon the direct sun measurements and have been considered by the aerosol community as the benchmark for validating satellite products. In order to understand the performance and characteristics of each key component used in the VIIRS IDPS algorithm, the global VIIRS aerosol EDR AOD and AE and the IP AOD data generated within our study time period were collocated and compared with AERONET observations. Since the AERONET quality-assured level 2 data are not yet available for this time period, the global cloud-screened level 1.5 data were used here. The intercomparison of AOD between VIIRS IDPS and AERONET data was performed at 0.55 μm, since this is a common reference wavelength adopted by most of the aerosol satellite products. The VIIRS AE is defined between 0.488 and 0.672 μm over land and 0.865 and 1.61 μm over ocean, whereas the AERONET AE was calculated based upon the spectral AOD at 0.440 and 0.865 μm.

In addition, since AERONET measurements are taken at a single point and the VIIRS EDR data has a footprint of 6 km x 6 km at nadir, sampling differences between the two must be taken into account. Therefore, the EDR data was co-located by spatially averaging all of the VIIRS data within 25 km of the AERONET site and temporally averaging all of the AERONET data within 30 minutes of the satellite overpass. For comparisons of the IP data, which are taken at a high spatial resolution (~0.75 km), we calculated three different spatial averages of VIIRS data within 1, 3, and 6 km from the AERONET locations, and we interpolated the AERONET data into the nearest VIIRS observation time within 30 minute window.

(a) Comparison of VIIRS AOD EDR with AERONET

The scatter density plots and comparison statistics depicted in Figure 1 show that, using the AERONET measurements as the benchmark, the VIIRS IDPS AOD EDR data exhibit comparable performance over ocean but relatively poor performance over land when compared to the recent evaluation results of MODIS Collection 5 AOD data (Remer et al., 2008; Levy et al., 2010). Although the result over land improves with increasing quality flag, the VIIRS AOD data show large scatter with a positive bias in general, and the corresponding mean bias (MB) ranges from 0.06 to 0.11 depending on the quality flags used. Based on these comparison results, we can conclude that even high quality data (QF = 3) do not fall within the accuracies needed for use in various applications. However, data over ocean show reasonable accuracy, with a much smaller bias compared to those over land. The use of medium quality data as well as the high quality may be acceptable for some applications, but the use of low quality data significantly decreases the level of correspondence between the two datasets, implying a corresponding reduction in the quality of these data.

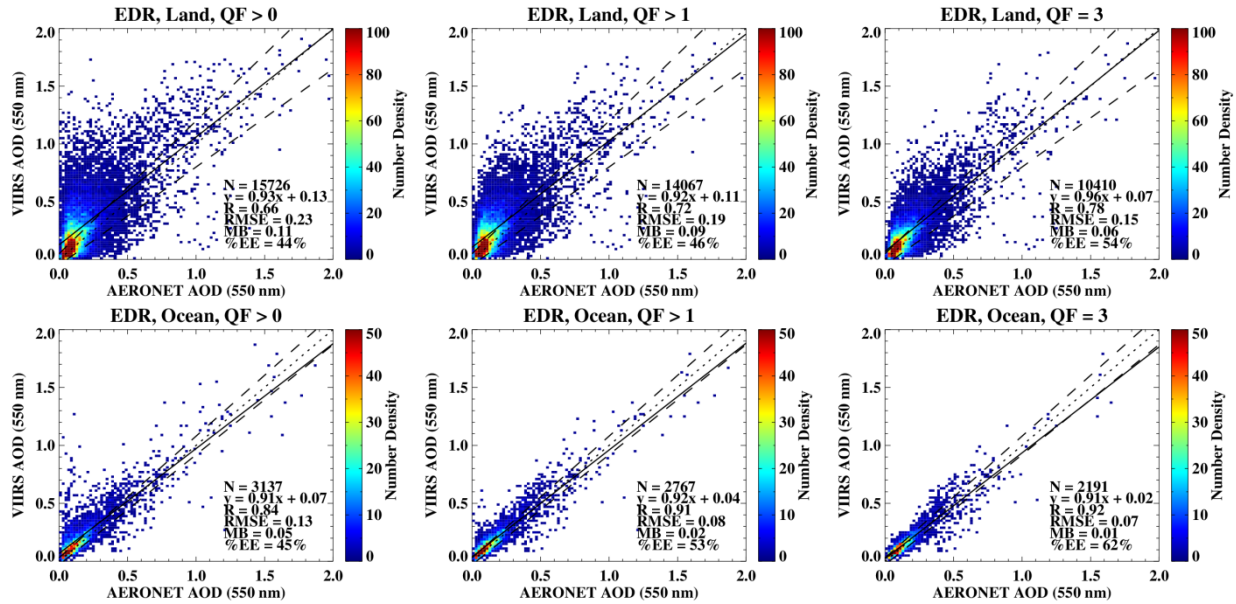

Figure 1: Scatter density plots of AOD at 0.55 μm between AERONET and VIIRS EDR. The top row shows data over land, and the bottom row data over ocean. Each column is for different quality flags (QFs). QF of 1, 2, and 3 represent low, medium, and high quality, respectively. The statistics superimposed on the figures are the number of data points (N), Pearson coefficient (R), root mean squared error (RMSE), mean bias (MB), and percentage of data within the expected error (%EE). The expected error was defined by 0.05 + 15% for land and 0.03 + 5% for ocean.

The AOD errors were further analyzed with respect to the physical properties of aerosol and observation geometries. Figure 2 shows the AOD difference between VIIRS and AERONET with respect to AE, scattering angle, and air mass factor. The data were sorted into 20 equal-number-of-data bins in these analyses, and only high quality flags (QF = 3) were used. Over land, the bias is positive in general; the MB tends to increase with AE, scattering angle, and to decrease with air mass factor. The 1-σ interval is highly correlated with AOD, showing more scatter for high AOD. The combination of MB increasing with scattering angle and decreasing with air mass factor clearly indicates that the error is closely related to the viewing geometry and most likely results from the uncertainty in estimating the effects of surface BRDF by the retrieval algorithm. The association of positive MB with high AE also suggests that the IDPS algorithm overestimated the AOD over most of the fine mode dominant regions.

Over ocean, the MB generally falls into the expected error range, but a distinct positive bias exists for low AE (< 0.5), and a negative bias is seen in the back scattering direction for a low air mass factor with large 1-σ interval. This suggests that the VIIRS AOD data over ocean show relatively low accuracy for those conditions.

In order to investigate regional characteristics of the retrieval accuracy, we calculated the percentage of VIIRS AOD data within the expected errors (%EE), which are defined as 0.05+15% over land and 0.03+5% over ocean (as in the current MODIS Dark Target and ocean

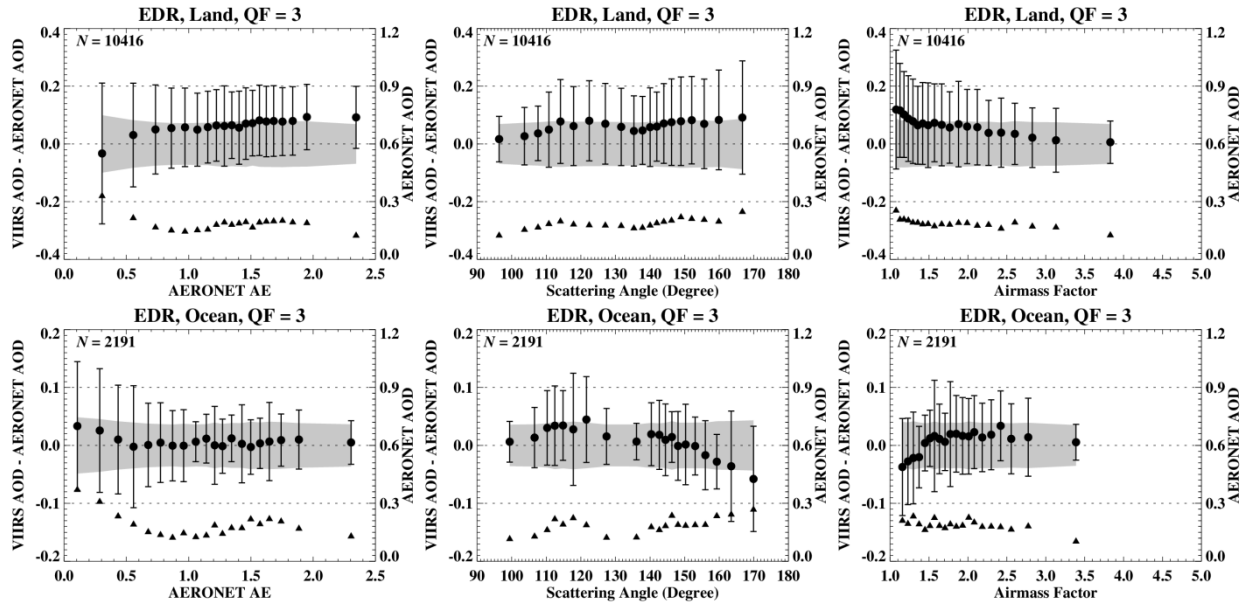

Figure 2: AOD difference between VIIRS and AERONET with respect to AE (left), scattering angle (middle) and air mass factor ($m_{Sun} \times m_{satellite}$, where m = sec[θ]) (right). The top row shows data over land, and the bottom row data over ocean. The data were sorted into 20 equal-number-of-data bins, and shown with mean (solid circle) and 1-σ interval (vertical bar). The grey shaded areas represent the expected errors based upon AERONET AOD values (defined in Fig. 1). Only high quality data were used for the comparisons. The triangle symbols represent AERONET AOD values.

datasets) against the AERONET data. The global distributions of the resulting %EE and mean bias of the best quality (QF=3) VIIRS data are depicted for each AERONET site in Figure 3. In this analysis, only the AERONET locations with the number of data points higher than 32 (about 20% of the number of days used) were included. Since the aerosol retrieval algorithm over ocean is different from that over land, the results are shown separately for land (left panel) and ocean (right panel). Overall, the performance of VIIRS over-ocean AOD is better than that of the over-land retrievals, which is consistent with the findings from Fig. 1. The number of locations with good performance (i.e., %EE ≥ 68%) was 35 out of 126 (28%) over land and 12 out of 25 (48%) over ocean. In addition, the mean biases in VIIRS AOD are much smaller over ocean compared to those over land. At first glance, the locations in Fig. 3 with good performance may appear to be random. However, as described in the next sections, they are actually closely linked to the surface reflectance determination and aerosol model selection procedures used in the VIIRS IDPS algorithm.

Aerosol Model Selection

To investigate the potential dependence of VIIRS product performance as a function of aerosol type, we separated the VIIRS data into two different categories, dominant coarse mode (AE < 0.8) and dominant fine mode (AE > 1.2), based upon the collocated AERONET products. Their corresponding %EE and mean bias are shown in Figures 4 and 5, respectively. Once again, only best quality (QF=3) VIIRS data are included in the analysis.

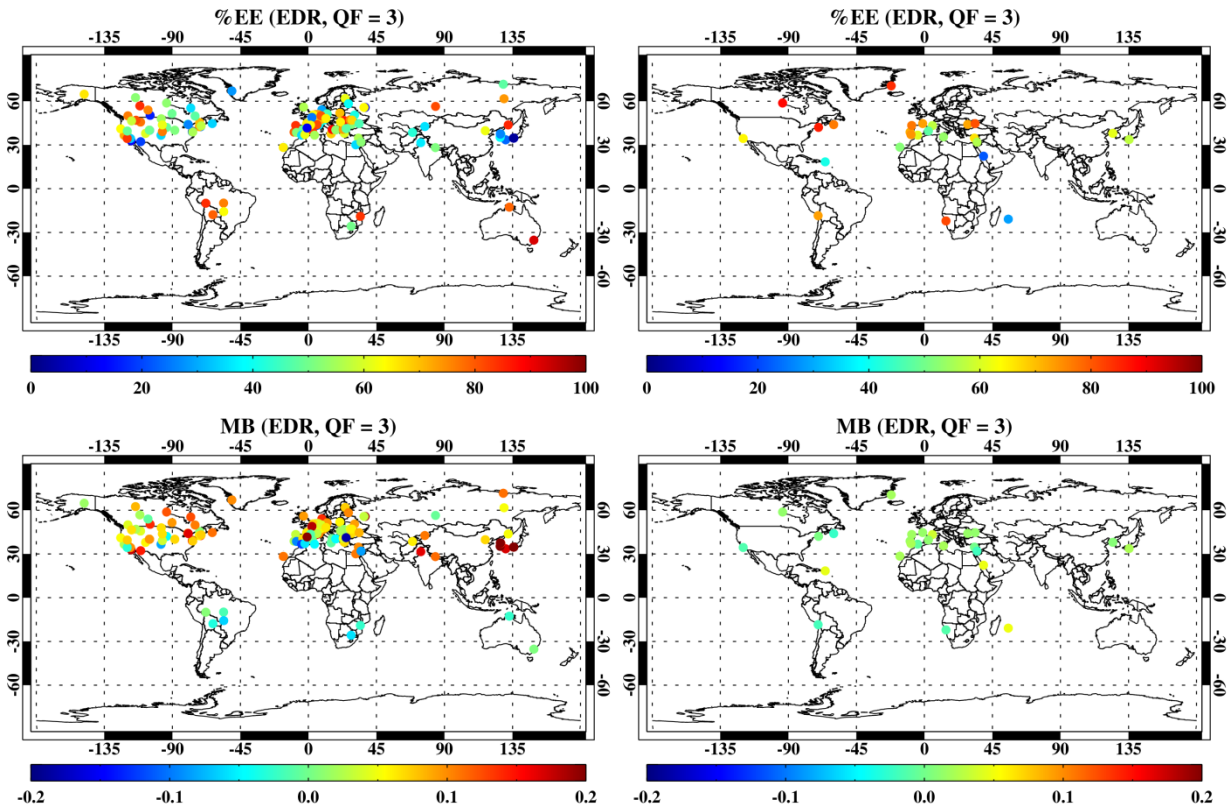

Figure 3: The percentage of AOD data within the expected error (upper) and mean bias (lower) at each AERONET location for over-land data (left) and over-ocean data (right). The AERONET locations with the number of data points compared higher than 32 are shown.

Compared to the fine mode aerosol category, Fig. 4 indicates that the VIIRS performance for coarse mode aerosols (AE < 0.8) seems to be more problematic for both land and ocean. The %EE values are generally lower than 68% for all surfaces. Also, the VIIRS AOD at the majority of the sites has a negative bias over land (except around the coast of Atlantic and northern India) and a positive bias over ocean (except near the coast around the Arabian Peninsula). This is consistent with Fig. 2. For fine mode aerosols (AE > 1.2) shown in Fig. 5, the VIIRS aerosol EDR performs well over ocean, except around East Asia. Over land, VIIRS performance seems better over the regions with biomass burning activities such as S. America and Canada. However, there are large positive biases in US, Europe, and East Asia, particularly over urban sites; this could be attributed to an erroneous assumption, discussed in the next section, that is used in the VIIRS IDPS algorithm for surface reflectance calculations.

Surface Effects

In order to investigate the effect of surface properties on the retrieval accuracy, we examined, on a monthly basis, the correlations between the VIIRS performance (i.e., %EE) at the AERONET locations with the spatial variability of VIIRS AOD as well as the spatial variability of surrounding surface reflectances as determined by the standard deviation of normalized difference vegetation index (NDVI). The NDVI data were calculated using MODIS spectral surface reflectance data in the 'MCD43C4' 0.05^{o} resolution product. As shown in Figure 6, the

results indicate that the retrieval accuracy tends to be low for high spatial variability of the VIIRS AOD regardless of the surface variability, although high AOD variability generally corresponds to high surface variability. However, high surface variability does not assure low AOD accuracy as inferred from the AERONET locations with high %EE in quadrant 4. Also, no clear correlation was found between the retrieval accuracy and the brightness of underlying surfaces (not shown here).

To further investigate the different characteristics between the AERONET locations in quadrants 2 and 4, we searched high resolution surface features at each location using 'Google map', and found that most of the locations are in quadrant 2 of Fig. 6 are associated with large urban areas and/or bright surfaces within 25 km, whereas the locations in quadrant 4 are vegetated areas with high surface spatial variability. Therefore, the underlying surface material properties rather than their variability seem to be the dominant driver in the performance of the aerosol retrieval. The monthly mean AOD for June 2012, depicted in Figure 7, also show abruptly enhanced values over major urban areas in US, which are likely related to the surface effects described above. As a result, we can conclude that the VIIRS AOD over urban areas and/or bright surfaces shows poor quality despite the high quality flags, and thus improvements in the retrieval algorithm are needed over these regions.

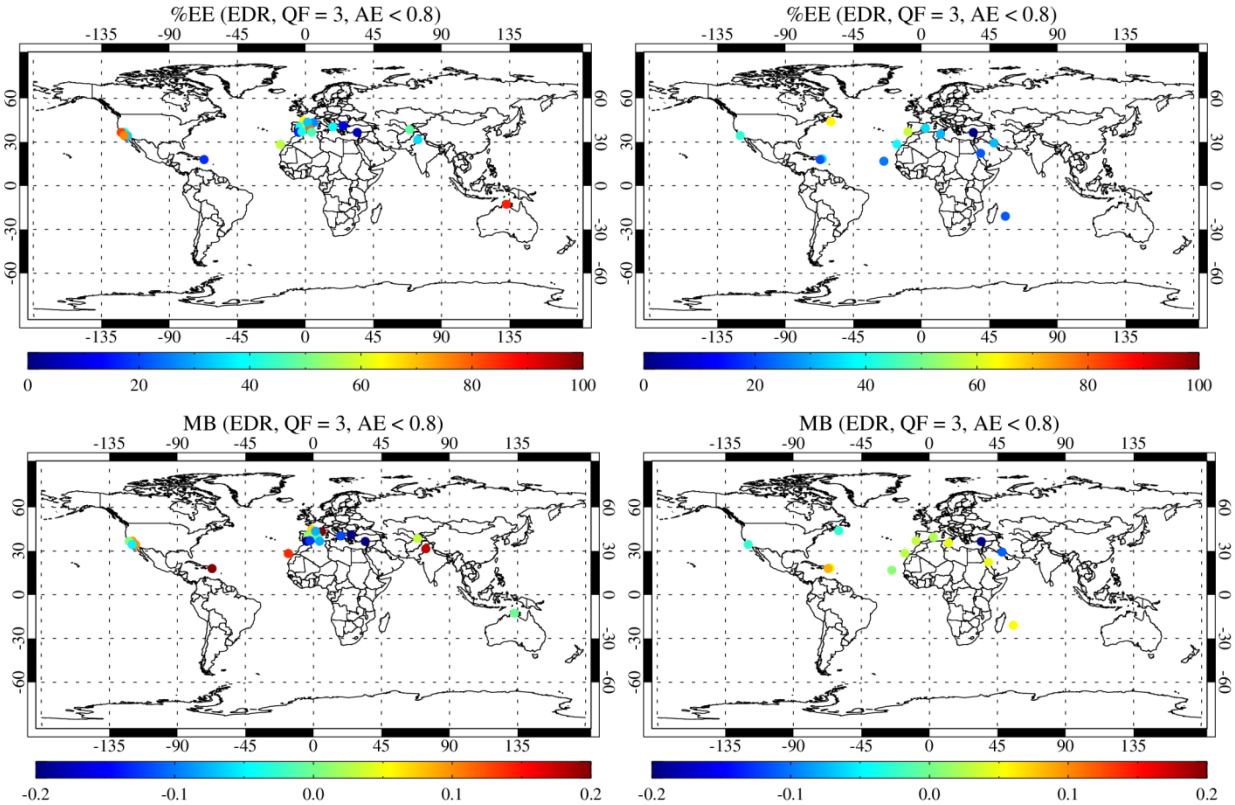

Figure 4: The percentage of AOD data within the expected error (upper) and mean bias (lower) over land (left) and ocean (right) for AE < 0.8. The AERONET locations with the number of data compared higher than 16 are shown.

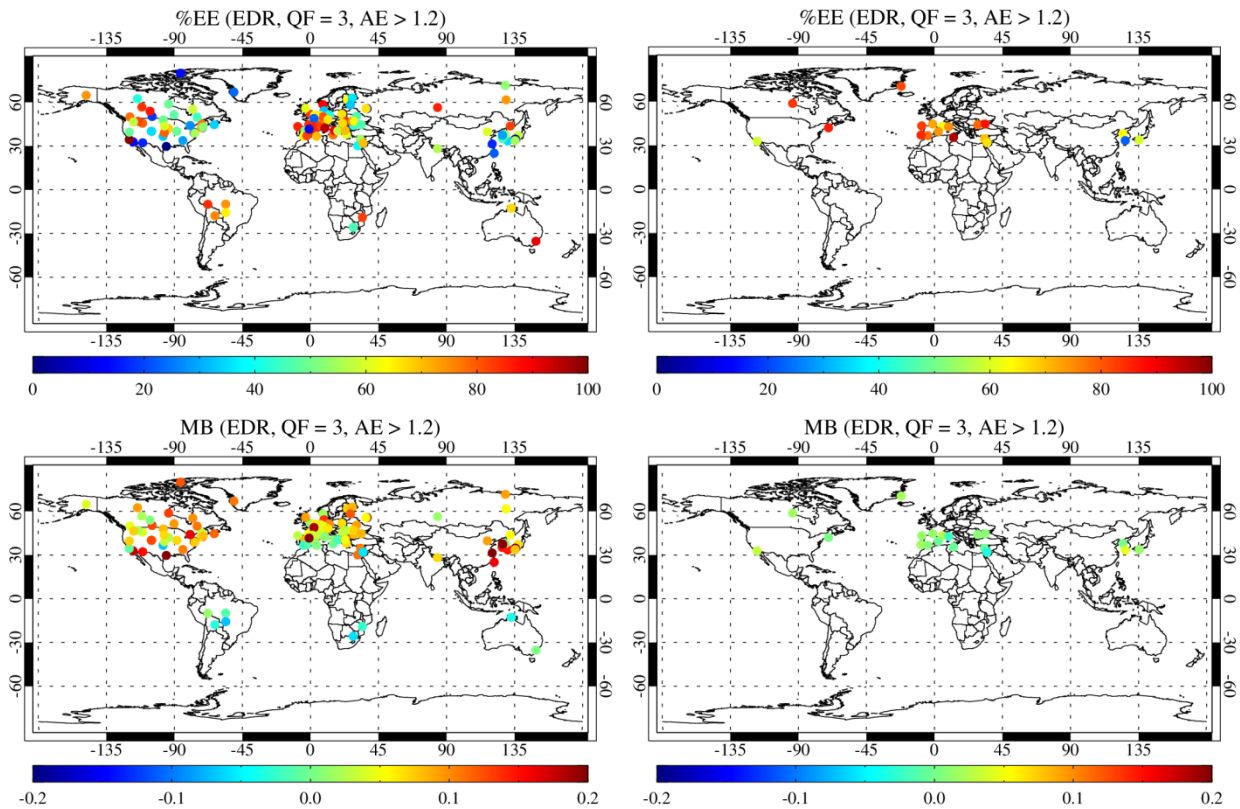

Figure 5: The percentage of AOD data within the expected error (upper) and mean bias (lower) over land (left) and ocean (right) for AE > 1.2. The AERONET locations with the number of data compared higher than 16 are shown.

(b) Comparison of VIIRS AOD IP with AERONET

There are increasing demands, particularly from the air quality community, for high resolution AOD products in order to help resolve the aerosol loading distribution in areas that often exhibit sharp aerosol gradients, such as urban regions. To evaluate the high resolution capability of VIIRS AOD retrievals, the Intermediate Product (IP) data were compared with the AERONET observations. As described previously, since the VIIRS IP products are at 0.75 km resolution, the AERONET AOD data were interpolated to the closest VIIRS observation time within a 30 minute window, instead of being averaged within this window as was done for the EDR evaluations. It should be also noted that the high quality data of the IP products are assigned a QF = 0 as opposed to those for the EDR. The comparisons were conducted for three different distances (1, 3, 6 km) of data aggregation centered at the AERONET sites to show the dependence of data quality on the spatial resolution.

These comparisons are shown in Figure 8 for land (top panel) and ocean (bottom panel), separately. The number of collocated data points shown in Fig. 8 for the IP products are considerably lower than those for the EDR comparisons in Fig. 1, which uses AOD averaged over 25 km and thus has more data with a high quality flag. Over land, the VIIRS IP comparison results against AERONET exhibit worse correlations than those for the EDR (i.e., 0.78), showing a significant overestimation in AOD likely caused by errors in the surface reflectance and cloud contamination. As the resolution of VIIRS AOD increases from 6 km to 1 km, the percentage of

data in agreement within the expected error drops from 46% to 36% and the correlation coefficient decreases from 0.68 to 0.50. The significant high bias in VIIRS AOD when AERONET indicates low AOD conditions is most likely associated with the bright surfaces around urban regions. Figure 9 displays such an example around the metropolitan area of Baltimore-Washington DC on May 11, 2012. As demonstrated in the previous section, the VIIRS EDR AOD values are overestimated over cities due to inappropriate spectral surface reflectance ratios. It is apparent in Fig. 9 that this problem is exacerbated for the high resolution IP products.

The improvement of data quality from IP to EDR implies that the data aggregation method of the VIIRS data processing system is effective in mitigating bright surface and cloud contamination issues. It should be noted that since the VIIRS AOD comparisons benefited from the cloud screening used in the AERONET observations, the IP data quality over land could be even worse. Over ocean, although there was significant reduction in the number of data points due to differences in the collocation process, the result for 6 km case is comparable with the EDR, with a small bias and a high correlation coefficient. Therefore, we recommend that the current VIIRS IP products not be used over land, although they are reasonable over ocean after being properly post-processed for cloud contamination.

(c) Comparison of VIIRS Angstrom Exponent EDR with AERONET

Since aerosols of different sizes can have very different impacts on Earth's radiation budget and most of the aerosols generated from anthropogenic sources are considered to be fine mode (<1 μm), the ability to distinguish coarse mode from fine mode particles using satellite data is highly desired. To investigate if VIIRS IDPS products can provide appropriate particle size information, we evaluated its AE EDR against AERONET using the same method we used

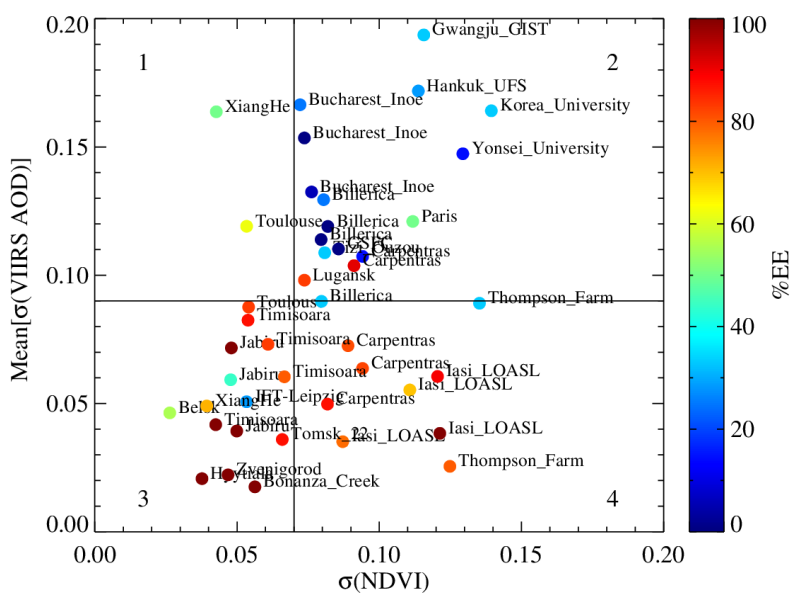

Figure 6: The percentage of AOD data within the expected error at various AERONET locations superimposed on the domain of the standard deviation of normalized difference vegetation index (NDVI) and the mean of standard deviations of VIIRS AOD. The spatial standard deviations of NDVI and AOD were calculated within 25 km from the AERONET locations. Each point is calculated on a monthly basis.

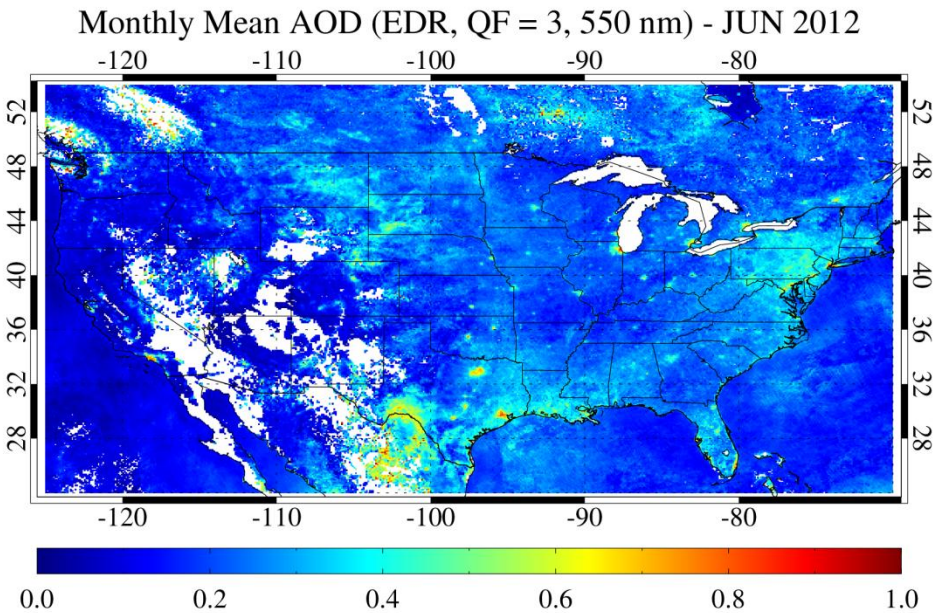

Figure 7: The monthly mean EDR AOD from VIIRS IDPS for June, 2012 over U.S.

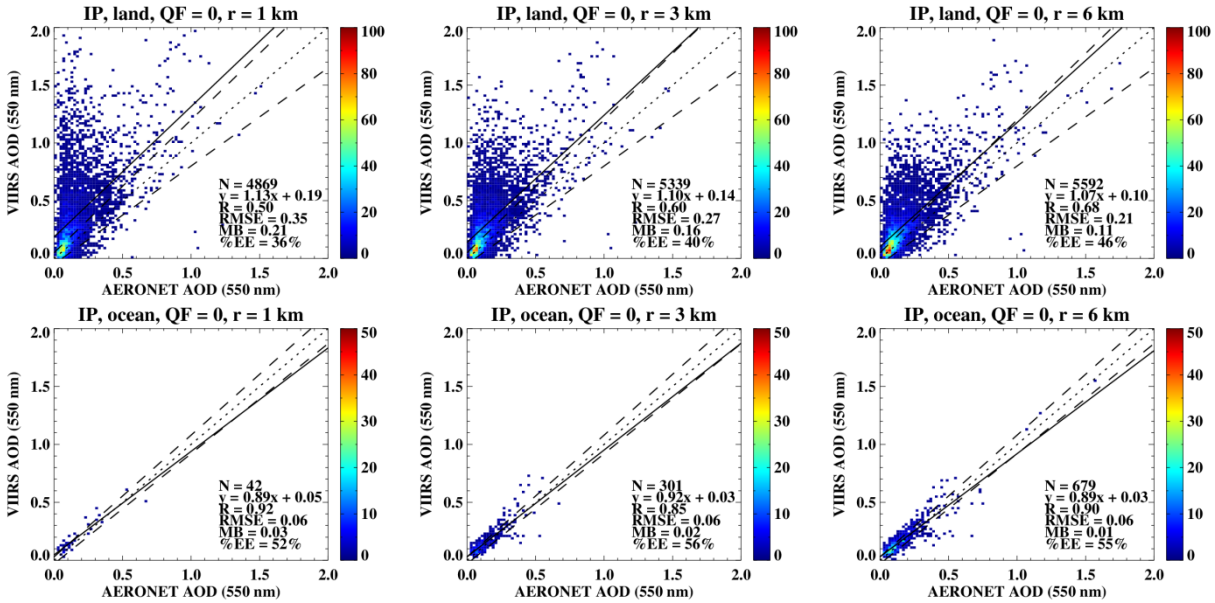

Figure 8: Scatter density plots of AOD at 0.55 μm between AERONET and VIIRS IP. The top row shows data over land, and the bottom row data over ocean. Each column is for different aggregation distance from AERONET locations. The high quality data (QF = 0) are only used in these comparisons. The statistics superimposed on the figures are the same as Figure 1.

for the AOD comparisons. The scatter density plots are depicted in Figure 10. We note that the VIIRS AE data were defined between 0.488 and 0.672 μm over land and 0.865 and 1.61 μm over ocean, whereas the AERONET AE data were calculated based upon spectral AOD at 0.440 and 0.865 μm. We should also keep in mind that the high quality VIIRS AE data (QF = 3) only include data with AOD $\geq$ 0.15.

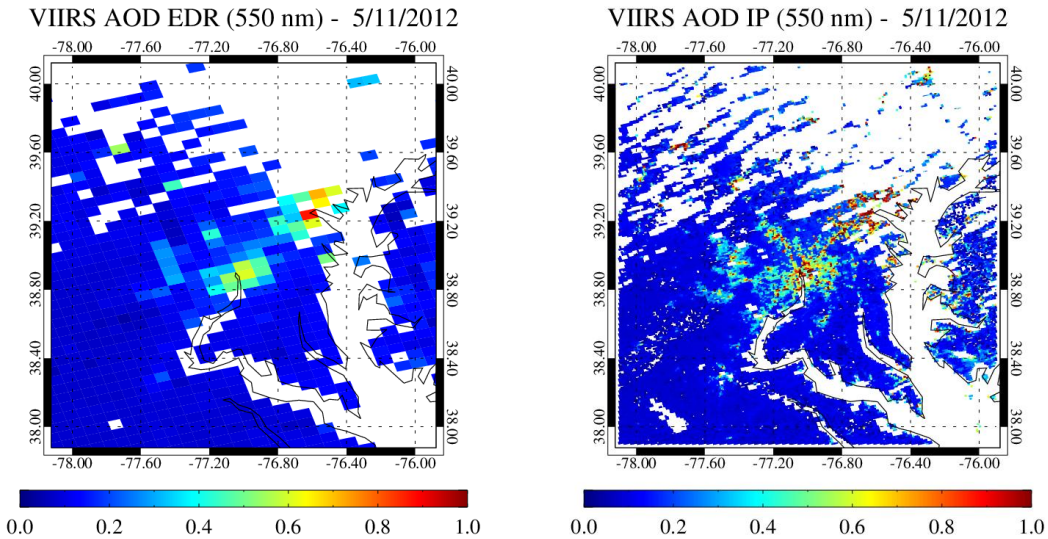

Figure 9: VIIRS AOD EDR (left) vs. IP (right) over Baltimore-Washington DC area on May 11th, 2012.

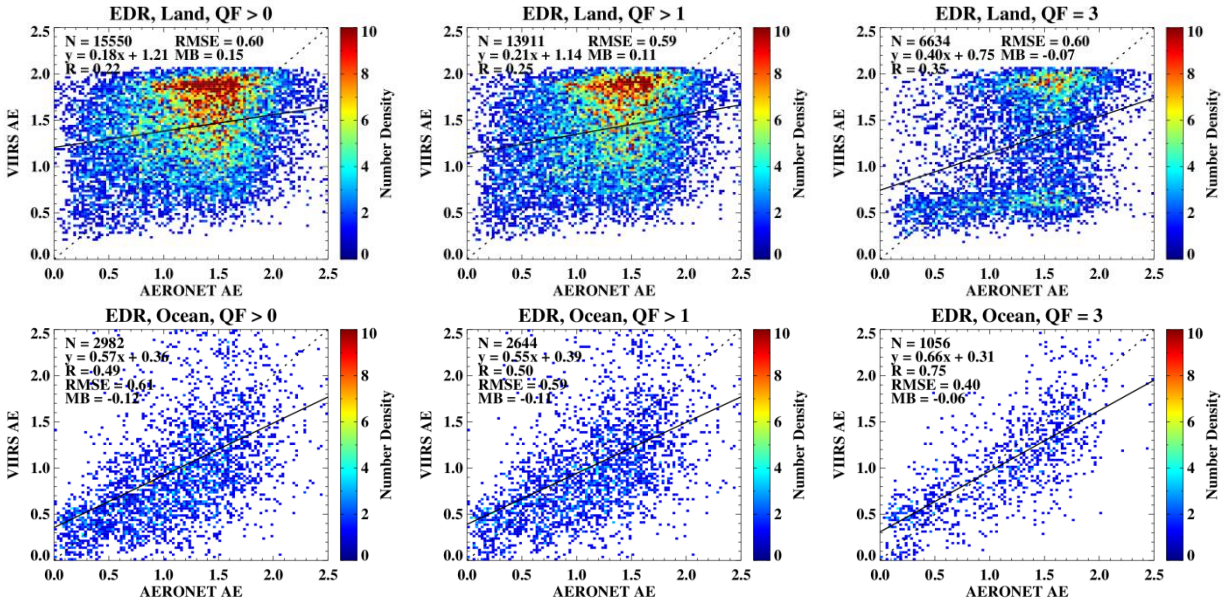

Figure 10: Scatter density plots of AE between AERONET and VIIRS EDR. The top row shows data over land, and the bottom row data over ocean. Each column is for different quality flags (QFs). QF of 1, 2, and 3 represent low, medium, and high quality, respectively. The legends are the same as Figure 1 except without %EE.

Fig. 10 shows that the AE data over land are of poor quality regardless of quality flags and seem to be unusable, as small and large particles could not be separated even for the high quality-only case. However, the MODIS C5 DT products of AE have similar problem. The inappropriate treatment of spectral surface reflectances in the IDPS algorithm mentioned above may be attributed to size retrieval issues over land since the AE is defined by AOD at two different wavelengths.

The over-ocean data show better correlation with the AERONET data, in particular for the high quality case. However, the particle sizes retrieved by VIIRS IDPS algorithm tend to be underestimated (i.e., high bias in AE) over the coarse mode dominant regions and overestimated (i.e., low bias in AE) over the regions influenced by fine mode particles over ocean.

2.2 Investigations of data continuity for long-term aerosol CDR by comparing VIIRS IDPS AOD with heritage MODIS products

The MODIS sensors aboard the Aqua and Terra platforms provide a well-used and well-characterised aerosol dataset (with 'Dark Target' algorithms detailed most recently by Remer et al., 2008 and Levy et al., 2007, 2010, and 'Deep Blue' by Hsu et al. 2004, 2006). As well as individual retrievals reported along orbital tracks ('Level 2' data), daily and monthly gridded composites ('Level 3' data) are widely used to provide global views of the evolving spatiotemporal distribution of aerosol. Some applications of these Level 3 products include comparisons with chemistry transport models or other satellite-derived aerosol fields; observing seasonality/trends in aerosol loading; and studies of aerosol direct and indirect radiative effects. Level 3 products are very popular with the user community because of their ease-of-use, and efficient and convenient summary of retrievals from all orbits in a day provided in a single file.

Therefore, before the question of "Are the VIIRS aerosol EDR products suitable to provide data continuity after MODIS in the EOS data suite for long-term climate study?" can be appropriately addressed, one must ask how the global spatiotemporal distribution of AOD retrieved by VIIRS compares with that from MODIS. Unfortunately, there is no operational Level 3 aerosol product from VIIRS. This is an immediate issue; it means users will have to generate such a dataset themselves, increasing data processing and storage overhead as well as the potential for error. Conversely, level 3 data are readily available not only for MODIS data but from almost all other NASA and third-party aerosol datasets as well.

In lieu of the availability of Level 3 operational VIIRS products, we generated our own Level 3-like product using the VIIRS EDR (Level-2 equivalent); we envision that those users mostly interested in global data will be using this, rather than the Intermediate Product (IP), to do such compositing. Further, only the AOD at 0.55 μm is considered, as this is the most frequently-used Level-3 aerosol product, and other quantities (such as the Ångström exponent, AE) derived from satellite measurements are less reliable, particularly over land (Wagner and Silva, 2008, Levy et al., 2010). Additionally, over ocean, VIIRS AE product is calculated over a different spectral range (0.86-1.6 μm) than the ones used, and that are considered, by other satellite and ground-based instruments (typically 0.44-0.87 μm or 0.55-0.87 μm); this inconsistency means that the quantity is simply not directly comparable with existing datasets and does not provide the same information (e.g. Eck et al., 1999, O'Neill et al., 2001).

Throughout our analysis, only MODIS data from the Aqua platform were used in order to reduce the effects of the diurnal cycle on the comparison (Aqua and NPP both have a daytime local solar time of approximately 1:30 pm at the center of the swath). Two MODIS products were used:

- The current Collection 5 'Dark Target' (DT) data products (Remer et al., 2008). Only those MODIS retrievals meeting the recommended criteria of quality assurance (QA) flag

values of 3 over land, and 1, 2, or 3 over ocean, are considered (Remer et al., 2008, Levy et al., 2010). This recommendation is also followed when the operational MODIS Level 3 products are created.

- The `Deep Blue' (DB) dataset (Hsu et al., 2004, 2006) from the forthcoming Collection 6 MODIS product suite. In Collection 5, Deep Blue provided coverage over only bright land surfaces such as deserts, but in Collection 6 data coverage was extended to all snow-free land surfaces. The Collection 6 DB products have been validated (manuscript in preparation) and results discussed below where relevant to the context of evaluating VIIRS data.

Use of two MODIS products illustrates the level of consistency which can be expected from two different mature algorithms applied to the same input data. For VIIRS, there are presently no official recommendations concerning QA flags, and so only retrievals with the highest QA flag (3) are used.

(a) Global comparison of AOD percentiles of VIIRS EDR with MODIS

First, statistics of the probability distribution functions (PDFs) for MODIS and VIIRS aerosol data were examined. To do this, retrievals were aggregated on a daily basis in 2.5° regular latitude/longitude bins. This size was chosen to provide a large number of potential retrievals on a daily basis, such that representative PDFs could be generated, but not cover so large a region that there would be great heterogeneity across each grid, which could lead to sampling-related differences in the data if VIIRS and MODIS did not sample the same parts of each grid cell (e.g. Sayer et al., 2010a).

For each grid cell, the 10th percentile, 50th percentile (median), 90th percentile, mean, and standard deviation of AOD at 0.55 μm were extracted. As the uncertainties associated with AOD retrieval over land and ocean are different, these statistics were calculated separately for over-land and over-ocean retrievals. Many grid cells contain both retrievals over land and water.

Then, the mean of each of these quantities was calculated for each grid cell over the study period (May – September 2012). This provides the typical values of the 10th, 50th, and 90th percentiles of AOD, the typical mean AOD, and the typical daily standard deviation of AOD in each grid cell. It is important to state that these are not the 10th percentiles of the daily mean values, but the means of the 10th percentiles (performing the analysis in this way provides a truer representation of the PDF of AOD). To mitigate the effects of spatial differences in sampling on the data (e.g. Sayer et al., 2010a), and to ensure each day's PDF of AOD can be considered reasonably representative, only days and grid cells where MODIS and VIIRS both contained at least 20 retrievals passing QA criteria were used. This process provides the maps shown in Figures 11 (over land) and 12 (over ocean), and the scatter plots in Figures 13 (for DT) and 14 (for DB). In Figure 11, only DT MODIS data are shown for brevity, as DB results are similar for most areas.

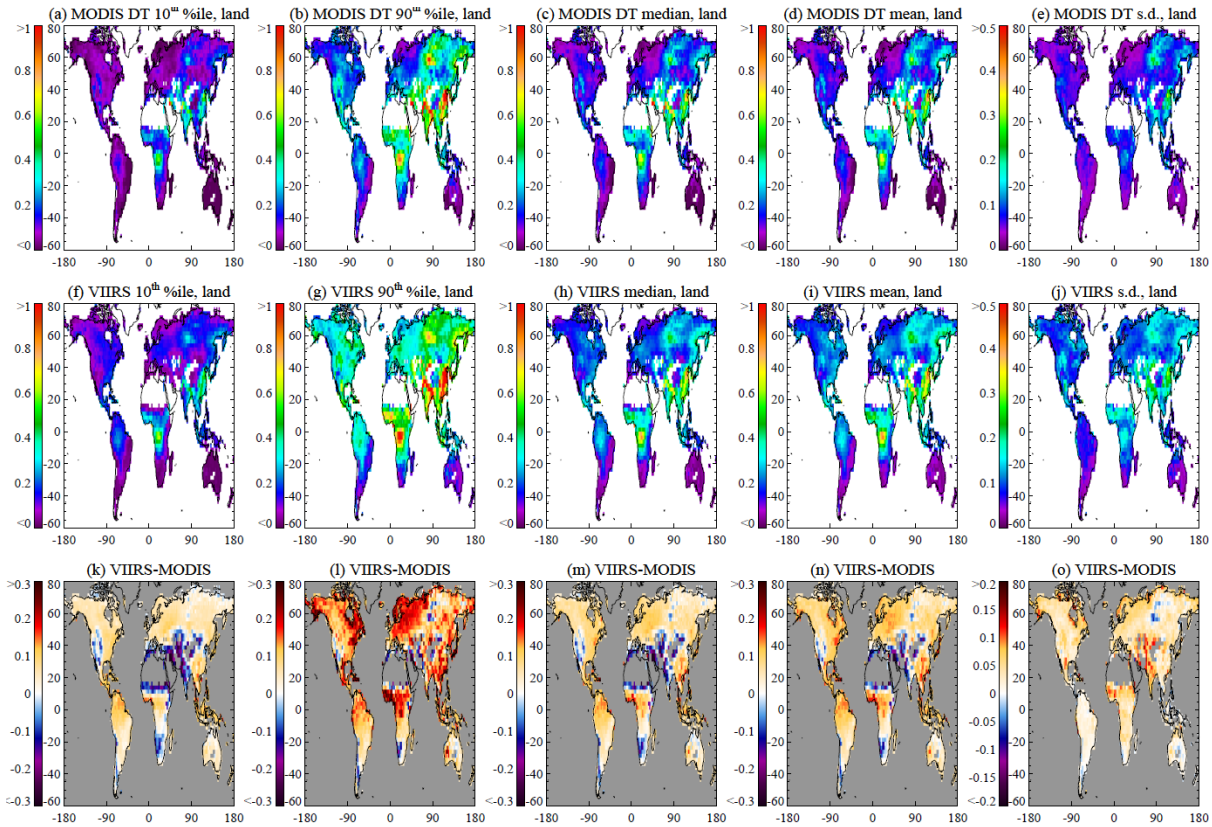

Figure 11: Statistics of AOD retrieved over land from MODIS Aqua (Dark Target) and NPP-VIIRS. All quantities are the mean of daily-averaged gridded statistics, as described in the text. The top row (a-e) shows MODIS data, the middle row (f-j) VIIRS data, and the bottom row (k-o) the difference (MODIS-VIIRS). From left to right, columns indicate the 10th percentile of AOD, the 90th percentile, the median, the mean, and the standard deviation (s.d.).

Comparison over land

Over land, Figure 11 shows that VIIRS, in general, retrieves higher AOD than MODIS. This relative high bias is most pronounced for the 90th percentile of daily retrieved AOD. One possible explanation for this would be increased levels of cloud contamination in the VIIRS data as compared with MODIS. The standard deviation of VIIRS AOD is generally larger than that for MODIS, which is consistent with an increased number of positive outliers in the VIIRS data. However, this positive bias is present even in the 10th percentile of the data, where VIIRS retrieves AOD higher by approximately 0.05 on average. This is observed in both high-AOD and low-AOD regions. This suggests that cloud contamination is not the sole cause for the difference, and it is likely that assumptions made about surface reflectance in the VIIRS retrieval are a leading cause of the high bias in these clean conditions. On average, the VIIRS relative high bias in the mean AOD over land is about 0.05-0.15, dependent on region. As the MODIS AOD for many of these regions (which has been validated as comparatively unbiased; Levy et al, 2010) is of order 0.2 or less, for both DT and DB algorithms, this is a highly significant difference.

There are some land areas, in contrast, where VIIRS AOD is systematically lower than MODIS. Most notably, these include the western USA, the Andes mountains, the Sahel, southern

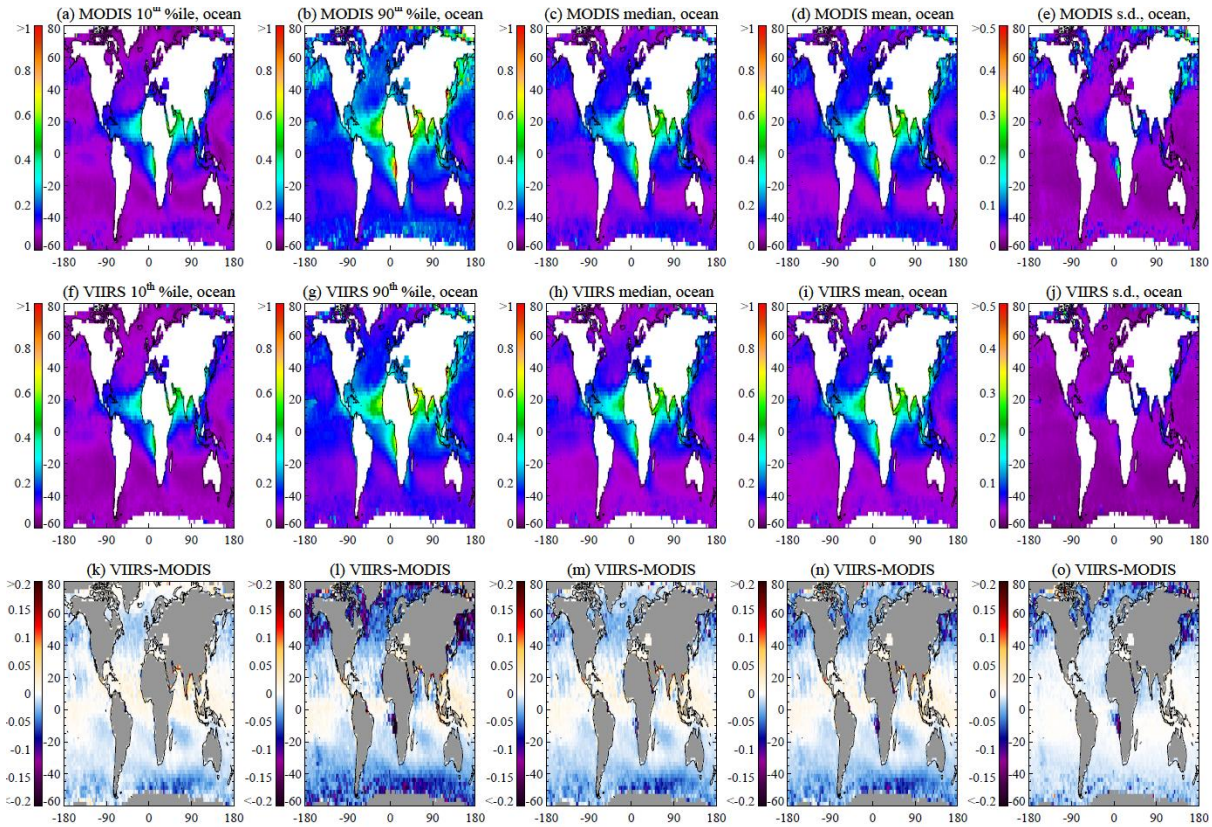

Figure 12: As Figure 11, except for data over ocean.

Africa, south-western Asia, India, and an area over Siberia (parts of Russia experienced widespread fires in July and August 2012). Again, these biases are observed for all percentiles of the AOD. Some of these areas are in elevated terrain, in which the Collection 5 MODIS DT algorithm is known to have a positive bias (Levy et al., 2010). Other regions with negative

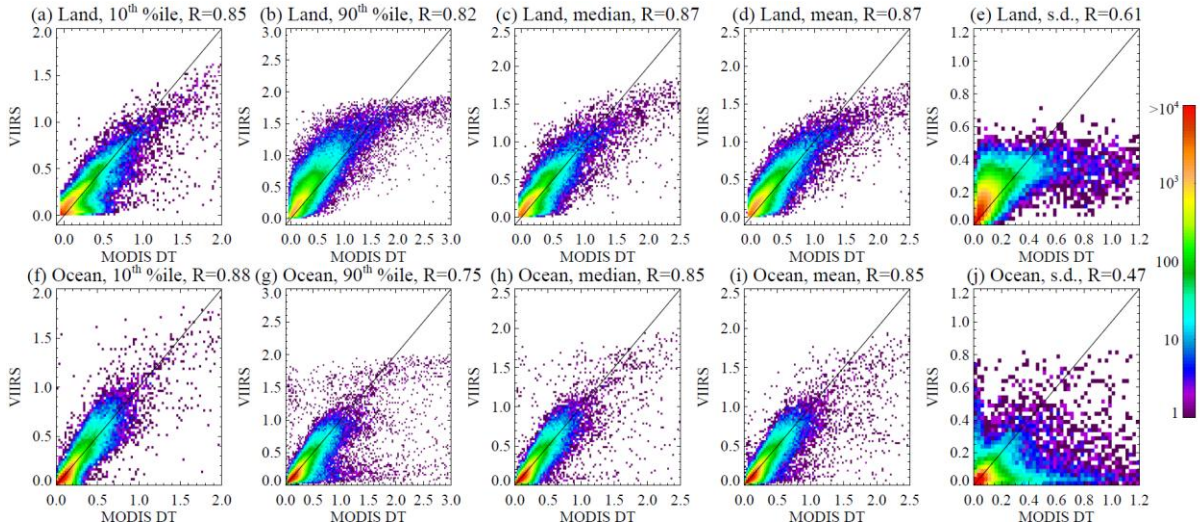

Figure 13: Scatter density plots from daily MODIS DT and VIIRS AOD PDF data used to create Figures 11 and 12. The top row (a-e) shows data over land, and the bottom row (f-j) data over ocean. The linear correlation coefficient is shown above each panel.

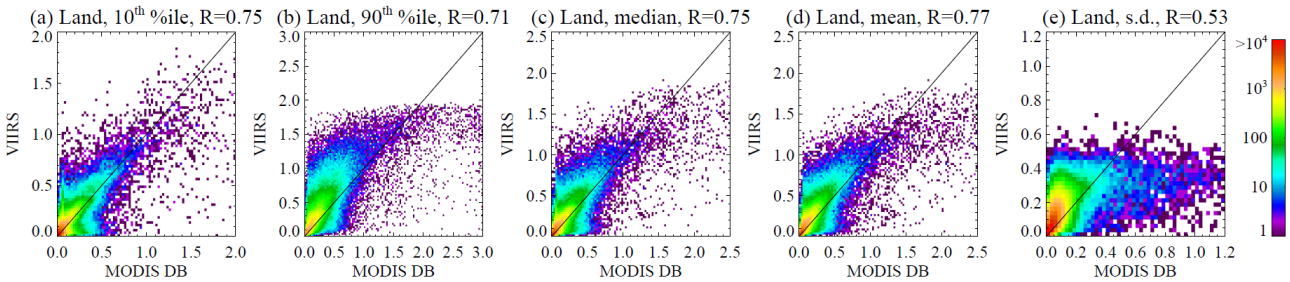

Figure 14: As Figure 13, except for MODIS DB data over land.

relative biases in VIIRS appear to be semiarid with mineral dust aerosol, and/or absorbing smoke aerosol. Levy et al. (2010) reported that over-land MODIS data have a small bias in these areas when all retrievals are considered together. When the AOD is approximately 0.4 or greater, MODIS data have a tendency to overestimate the AOD of certain smoke-dominant regions, a tendency to underestimate AOD in dust cases, and a tendency to overestimate AOD over brighter surfaces ('brighter' here being a relative term, as pixels which are too bright such as deserts are not processed by the Dark Target or VIIRS algorithms). The overall underestimate of VIIRS compared to MODIS for dust therefore suggests VIIRS may be even more low-biased.

For both MODIS and VIIRS, the mean standard deviation (i.e. spatial variability within a day) is typically of similar size to or smaller than the mean AOD, which suggests that this spatial scale provides a reasonable compromise between a small enough area to be sampling largely one aerosol regime, and a large enough area to generate sufficient statistics that the daily PDF of AOD from each sensor is described meaningfully.

Note that bright reflecting source regions (e.g. the Sahara Desert and Arabian Peninsula) lack coverage. This is because the VIIRS product does not retrieve AOD in these conditions. The MODIS DT algorithm also does not, although the DB algorithm does. Additionally, other heritage sensors such as the Multiangle Imaging Spectroradiometer (MISR), Polarization and Directionality of the Earth's Reflectances (POLDER) and Along-Track Scanning Radiometers (ATSRs) are able to retrieve AOD under such conditions (Martonchik et al., 1999, North et al., 2001, Dubovik et al., 2011, Sayer et al., 2012); the absence of such coverage in the VIIRS EDR is another shortcoming compared with other current datasets.

Figures 13 and 14 show that, despite the differences discussed above, the percentiles of the AOD PDF are well-correlated between the two sensors. In particular, the correlation in the grid-cell-averaged mean AOD is 0.87 for DT and 0.77 for DB. This suggests that the VIIRS EDR is able to resolve changes in AOD on these spatial and temporal scales, even if average values exhibit large relative biases. The difference between DB and DT statistics here probably reflects the fact that both the VIIRS and DT algorithms make global assumptions about the spectral dependence of surface reflectance, while DB uses a completely different approach (i.e., NDVI dependent surface reflectance database) for determining surface reflectance; it is likely that in some regions both DT and VIIRS will share errors which are correlated with each other due to these assumptions while DB will not.

These figures also reveal that the VIIRS AOD plateaus at 2, which is set as a hard limit in the VIIRS algorithm. The MODIS data suggest that, although infrequent, AOD above this limit is observed. Examination of individual cases reveals these to be largely dust or smoke plumes. The hard limit in VIIRS may therefore be truncating the upper range of AOD, and the effects of this truncation will be more or less severe in different regions. It is also noted that MODIS Dark Target allows retrievals of negative AOD (down to -0.05); although such quantities are not physical, they are within the approximate uncertainty of the data for near-zero true AOD, and so are retained for statistical purposes (Levy et al., 2010). DB and the VIIRS EDR do not allow negative AOD.

Comparison over ocean

The situation over ocean (Figure 12) is in some respects the reverse of that over land. VIIRS data have, over much of the open ocean, a negative bias against MODIS that is on the order of -0.01 to -0.04; in some clean tropical regions, VIIRS has a positive bias of approximately 0.01. However, the Collection 5 MODIS over-ocean algorithm is known to have a global average positive bias on the order of 0.01-0.02 in clean oceanic conditions due to the neglect of wind-speed-dependence on oceanic surface reflectance (e.g. Remer et al., 2008, Sayer et al., 2010a, Shi et al., 2011). Hence it is possible that VIIRS is closer to the truth than MODIS in these clean conditions. The upcoming Collection 6 MODIS over-ocean algorithm will improve on this; preliminary results suggest this bias has been much reduced (Sayer et al., 2012) and the global over-ocean AOD will decrease by approximately 0.02 (R. Levy, personal communication, 2012). Therefore, we suggest that this comparison should be repeated once the full final Collection 6 dataset is available. Note however that these biases are typically around the MODIS over-ocean uncertainty for clean conditions (approximately 0.03; Remer et al., 2008). The DB algorithm is not discussed here as it does not perform retrievals over ocean for MODIS.

Stronger negative biases in VIIRS (-0.05 to -0.2) are found in three main regions: dust outflow from the Sahara Desert and Arabian Peninsula; dust (and possibly pollution) outflow from north-eastern Asia into the Pacific; and smoke produced in western central Africa. Again, validation of individual cases is necessary to state with confidence how much of the difference is due to inadequacies in the VIIRS algorithm (although these differences often exceed the MODIS uncertainty of 0.03+5% over ocean, and studies suggest MODIS AOD over ocean in high-AOD conditions shows small bias; Remer et al., 2008).

Figure 13 shows, similarly to the case over land, a high degree of correlation between the data (0.85 in the mean AOD), indicating again that VIIRS is able to track changes in AOD over ocean. The hard limit of AOD=2 is encountered much less frequently over ocean than over land. Figures 12 and 13 also show that, as is the case over land, the standard deviation of AOD is lower than or similar to the mean and median, suggesting this spatial scale is appropriate for this type of analysis.

(b) Comparison using directly-matched retrievals

The VIIRS Atmosphere PEATE also produced 'matchfiles' containing VIIRS and MODIS Aqua DT retrievals collocated on an individual-retrieval scale from those orbits where the sensors collect data for a given location within five minutes of each other. As the sensors are not on the same orbital track, such collocations occur approximately once every other day, covering approximately one third (longitudinally) of the Earth at once. Therefore, these matchfiles provide a significantly reduced data volume compared to the previous comparison.

Using these matchfiles as an alternate data source allows a subtly different comparison. On the one hand, it further minimizes the effects of different spatial sampling on a daily timescale on noise in the comparison. On the other hand, it allows both datasets' cloud screening algorithms to reinforce each other (as the file will only contain a valid collocation if both sensors report a retrieval on such pixel scales), and thus using these may lead to an underestimate of the extent of any remaining cloud contamination in the data products. This is perhaps undesirable for this type of analysis, as a user interested in Level 3 data would not be using such collocations. In any case, performing the analysis of the previous sections using only the matchfiles for input results in qualitatively and quantitatively very similar results (plots omitted for brevity). This indicates that spatial sampling differences on a daily basis are not the major cause of the differences observed in the analysis.

(c) Sampling frequency

One further relevant question in terms of creating climatologies and time series of AOD is how often retrievals are obtained successfully. This is contingent on many factors, including (1) spatial coverage of the swath associated with sensor design, (2) cloud screening procedure, (3) quality assurance metrics, and (4) exclusion zones related to bright surfaces such as desert and/or snow/ice regions. The VIIRS sensor has an inherent advantage over MODIS in that it has a wider swath (roughly 3000 km vs. 2,300 km) and reduced bowtie effect (pixel expansion/ overlap near scan edges), meaning that all other conditions being equal VIIRS will have greater opportunities for performing an aerosol retrieval than MODIS.

Sampling rates are explored in Figure 15 using VIIRS and the DT data. To create this figure, the number of days with sufficient data (defined as 20 retrievals in a grid cell for MODIS, and 56 for VIIRS, these numbers corresponding to approximately equal minimum spatial coverage of 2,000 km^2 in a grid cell) is shown as a fraction of the total number of days in the considered period. Also shown is the difference between the two sensors. If the threshold on spatial coverage is adjusted, absolute patterns of coverage change, although spatial patterns of the difference remain similar.

These results show that, indeed, VIIRS does have a greater sampling frequency than MODIS over land. This would be expected from simple arguments about swath width, although it is interesting that the pattern of difference is nonuniform. In particular, over land, VIIRS sampling is greatest compared to that of MODIS in tropical areas affected by biomass burning and convective clouds, and in areas of snow cover. This implies MODIS is more conservative than VIIRS in determining when to perform an AOD retrieval (or rather, when to assign a high

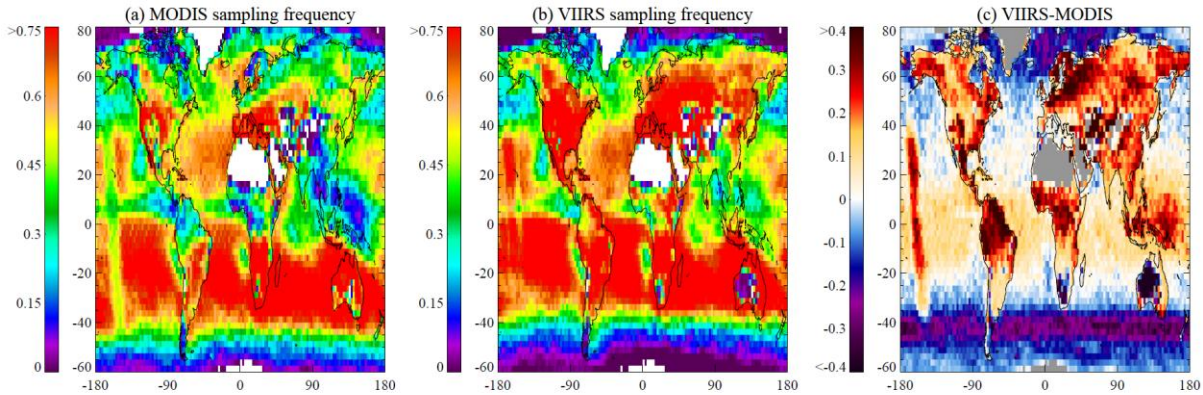

Figure 15: Sampling frequency (defined in the text) for (a) MODIS DT and (b) VIIRS. Panel (c) shows the difference between them. In panel (c), grid cells without retrievals by either algorithm are shown in grey.

quality flag to such a retrieval). These areas often coincide with areas where the VIIRS positive AOD bias against MODIS is largest, suggesting that some of the reason for this bias could be related to cloud or snow contamination in the VIIRS data. The comparison also reveals a few 'holes' in the VIIRS products over land, namely arid regions in southern Africa, and Australia, in which the DT algorithm provides coverage but VIIRS does not.

Over ocean, VIIRS has slightly greater sampling near the Equator and southern tropics, particularly from 90° E – 180° E, which is also a region of transported biomass burning aerosol. VIIRS sampling is slightly poorer than MODIS in the oceanic northern tropics and extratropics; the reasons for this are presently unclear. At high latitudes, sampling is much poorer in VIIRS; this is partially because the VIIRS 'cutoff' solar zenith angle for what is considered a valid daytime observation is stricter than in MODIS, as indicated in Table 1. This is an algorithmic limitation of VIIRS.

The streak of comparatively poorer sampling in MODIS and VIIRS, corresponding to a red stripe in Fig 15(c), is due to the aliasing of the satellites' orbital tracks and repeat cycle with the international dateline. This is a known feature of polar-orbiting satellite data when aggregated in calendar days.

(d) Annual cycles of retrieved AOD

The final question to address is how the annual cycle of VIIRS AOD compares with that observed by MODIS. At present this remains a challenging task, because the time series of beta-level VIIRS data (May 2012 onwards, minus much of October and November 2012) comprises less than a year, and some seasonal aerosol features simply have not been observed yet. The present analysis is hence necessarily incomplete, although results using the approximate half-year of available data can still provide a useful guide to expected performance. For this purpose, eight regions have been defined and are shown in Figure 16. These correspond to different geographic regions of interest with relatively well-known aerosol characteristics (e.g. Dubovik et al., 2002). The first three of these regions are oceanic, and only retrievals over ocean are used in

the analysis, and the remaining five conversely only use retrievals over land (even though the boxes in Figure 16 can straddle both).

The analysis in this section has been performed as follows. For MODIS Aqua, the operational Level 3 daily products (1° regular latitude/longitude) are used for both DT and DB. For VIIRS, similar products have been created by averaging QA=3 retrievals to 1° on a daily basis. Then, for each day, these daily mean Level 3 AOD data are averaged for each region, for those 1° grid cells where both MODIS and VIIRS contain valid retrievals. These daily regional time series are then averaged to create a monthly time series for each region. The resulting time series are shown in Figure 17. Also shown for reference is the climatology (mean +/- one standard deviation) from MODIS for the years 2003-2011, to provide an indication of interannual variability in each region, and illustrating how the presently single available year (2012) compares to the longer-term record.

Of the three oceanic regions in Fig. 16, the northern Atlantic exhibits dust transport from the Sahara (peaking in spring and summer), the Bay of Bengal is an outflow for pollution from the Indian subcontinent, and the South Pacific represents a remote ocean area with little transported aerosol. As depicted in Figure 17, during the peak aerosol months VIIRS retrieves lower AOD by up to 0.05 as compared to MODIS in the northern Atlantic and Bay of Bengal. In the South Pacific, VIIRS is also lower than MODIS; the absolute difference between the two sensors is 0.01-0.02, which could be due to aforementioned known MODIS overestimates in clean conditions. The seasonal variability is similar in both datasets.

Over land, the Sahel and Amazon regions are both known for biomass burning aerosols with a strong seasonality, peaking from December to February for the Sahel and late August to early October for Amazonia. Note that the peak in the Sahel has not yet been observed for VIIRS, as it predates the stable beta-level period. At other times the AOD is low, and retrieval in both regions is challenging due to high cloud coverage. VIIRS tracks both MODIS datasets well

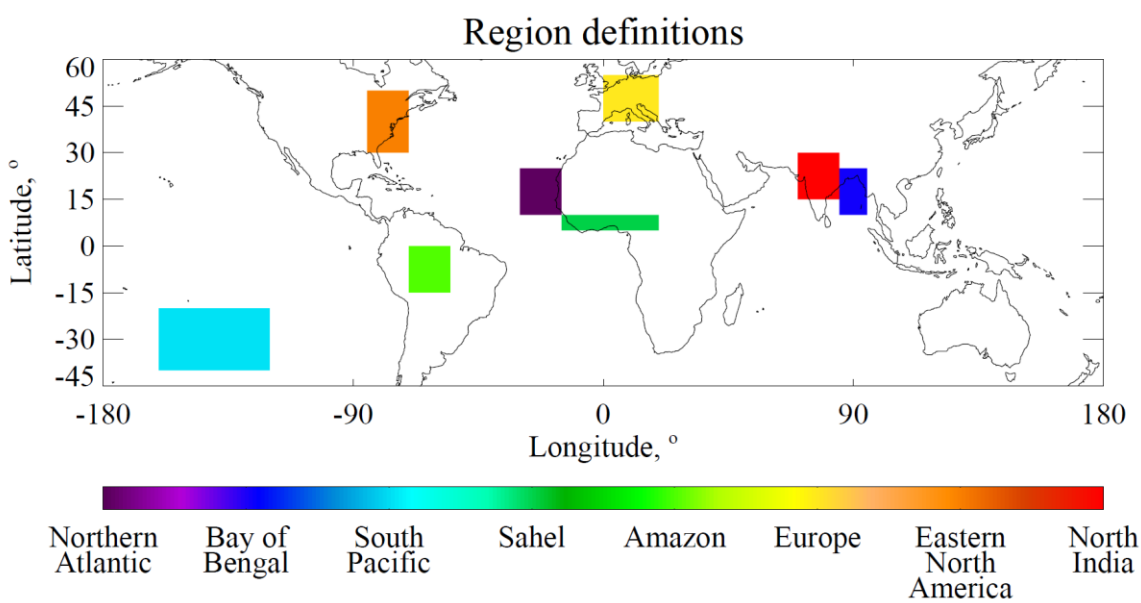

Figure 16: Geographic regions used for time-series analysis.

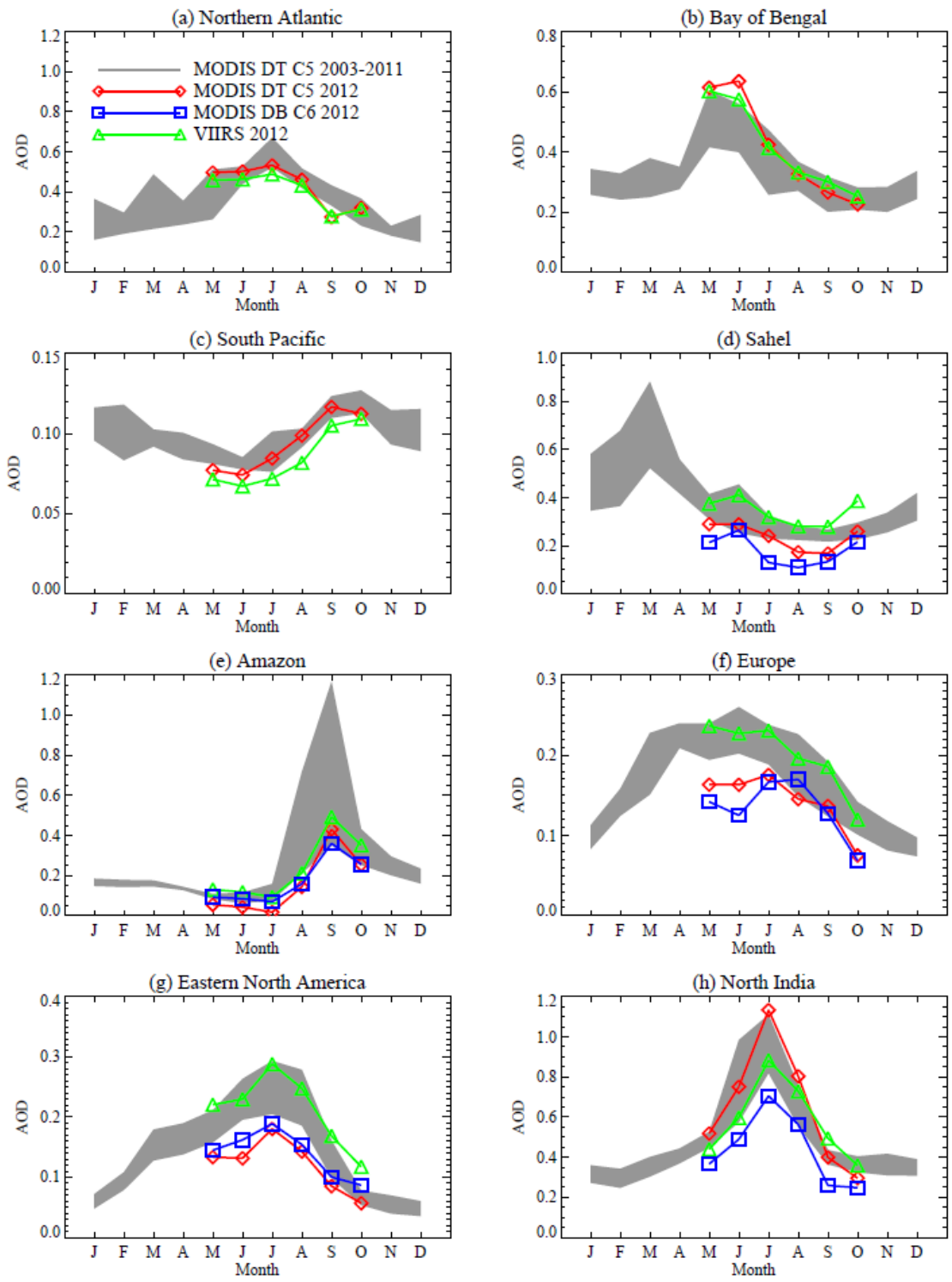

Figure 17: Annual cycle of AOD from MODIS and VIIRS for the eight regions shown in Figure 16. The shaded grey envelope indicates the mean +/- one standard deviation from MODIS DT for the years 2003-2012. The red, blue, and green lines show the collocated presently-available MODIS (DT/DB) and VIIRS (beta) records for the year 2012.

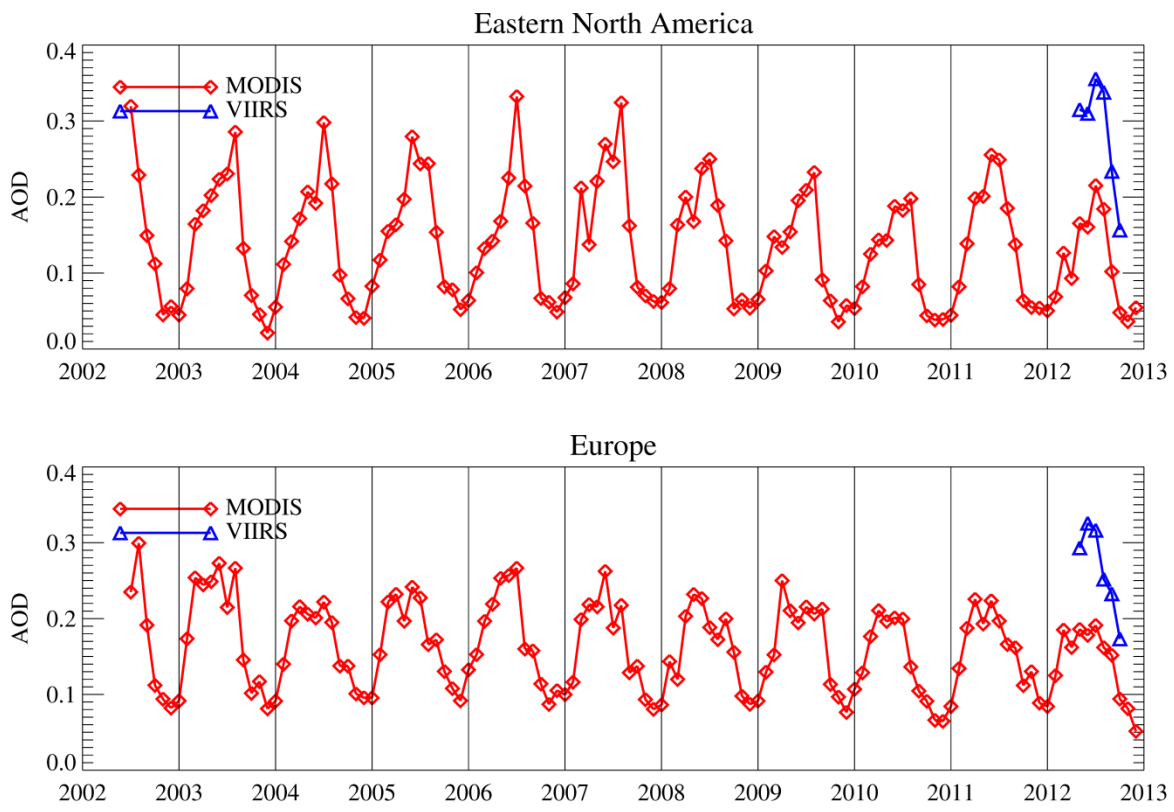

Figure 18: The comparisons of AOD time series from MODIS Aqua C5 and VIIRS IDPS products. Note that significant bias in AOD between MODIS and VIIRS over land creates discontinuity when switching from MODIS to VIIRS.

in these regions (with MODIS DT and DB AOD being lower than climatology in this latter region). VIIRS is persistently higher than both MODIS datasets by approximately 0.05-0.1 in both regions. MODIS DT is known to be biased slightly high in the Amazon during the burning season, meaning the VIIRS data may have a larger positive bias than suggested by the comparison here, although in clean conditions in both of these regions MODIS is biased low compared to ground-truth, indicating the VIIRS overestimate may be less severe than suggested by this comparison (Levy et al., 2010). Validation results suggest MODIS DB is relatively unbiased here.

Europe and eastern North America both represent cleaner atmospheric conditions, with a comparatively elevated AOD in boreal spring and summer. This year appears lower-AOD than the climatological average, and both MODIS datasets track well. The climatological envelope has a width of about 0.05 in AOD, and VIIRS AOD lies above this envelope by about 0.02, while MODIS DT/DB for 2012 lies below it by a similar amount. The seasonal variability is in good agreement (even though the absolute offset between the datasets is large), although the high relative offset of VIIRS (about 50%) is significant. These areas are heavily populated, and the quality of VIIRS data for applications related to air quality will be compromised here.

The final region (North India) is characterised by comparatively elevated AOD and seasonal variation of aerosol type from mixed dust and pollution to more hydrated pollution. The

boreal summer peak is observed in all datasets. VIIRS is lower than MODIS DT by 0.1-0.2 during the period leading up to this peak (from May to July), with August onwards being in closer agreement; the change in seasonal bias between the two may be related to aerosol type changes. Limited validation sites in this region suggest MODIS DT is biased high during high-AOD periods such as this boreal summer peak (Levy et al., 2010). MODIS DB is lower by a similar amount, and is thought to have a slight low-bias in high-AOD conditions here.

In order to investigate the effects of such biases between VIIRS IDPS and MODIS products on the data continuity for constructing long-term aerosol CDR, the time series of monthly averaged MODIS Aqua C5 AOD are plotted as function of the years in conjunction with the VIIRS. As illustrated in Figure 18, there would be a substantial "jump" in the AOD time series, if we just simply switch from MODIS to VIIRS. Obviously, such problem will severely hinder the capability of determining long-term aerosol trends accurately on global and regional scale.

2.3 Evaluations of IDPS Suspended Matter against CALIOP

While the development and evolution of AOD products have steadily improved our understanding of global and regional aerosol burden, relatively lesser attention has been given to aerosol type classification which provides important information about the relative components of the net aerosol loading, and helps in further quantifying climate forcing. In this section, we will examine the capability of VIIRS in retrieving *Suspended Matter* (or aerosol type) by employing RGB images for case-by-case studies and also by systematically comparing them with products from the CALIOP instrument on global scale.

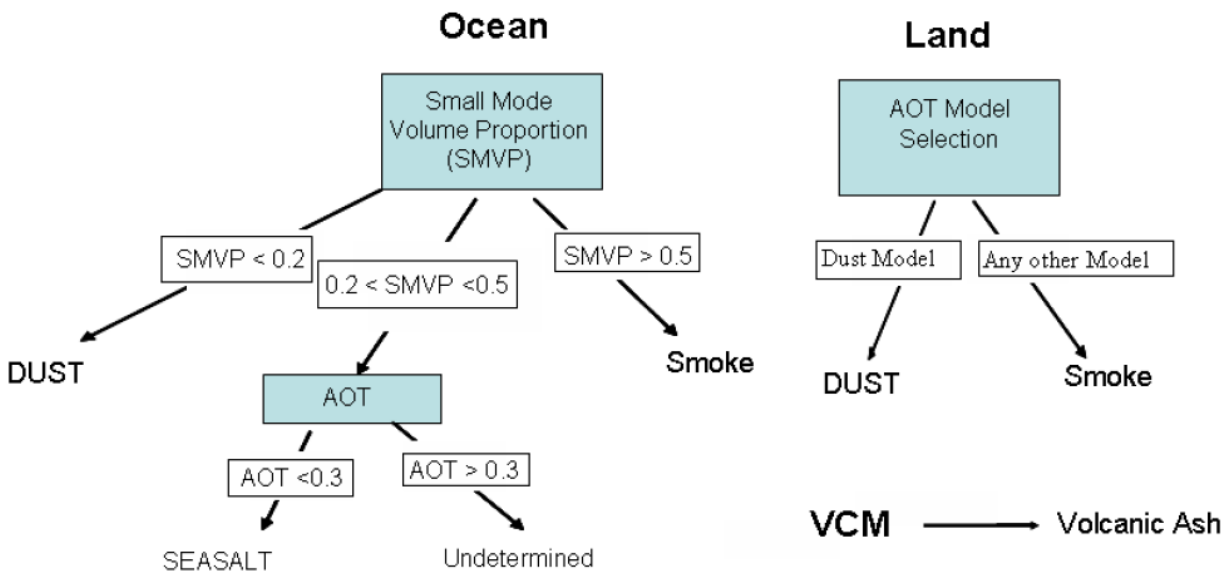

Figure 19: Suspended Matter Type flow diagram for retrieval over land and ocean. Figure source – VIIRS Suspended matter Algorithm Theoretical Basis Document (ref Y2390), Document Date – 03/17/2010.

(a) Data and Methodology

Currently, VIIRS routinely retrieves and reports the following 4 Suspended Matter types in the VSUMO EDR files: (i) dust, (ii) smoke, (iii) ash, (iv) sea salt. An additional SM is reported as "unknown", which represents aerosol type not determined. The VIIRS-SM product is produced at a fairly high spatial resolution of 0.75 km which, together with the equivalent-resolution VIIRS geolocation information, allows analysis via pixel-level SM data or such data uniformly gridded to a coarser resolution. The SM type flags are defined as 0 (Ash), 1 (Dust), 2 (Smoke), 3 (Sea Salt), 4 (Unknown). The retrieval scheme for SM type detection is different for

land and ocean; where pre-defined aerosol models in aerosol retrieval over land are used as land-SM, ocean retrievals follow a combination of thresholds applied on "Small Mode Volume Proportion (SMVP)" (equivalent to fine-mode fraction) and AOD, as depicted in the VIIRS-SM flow diagram (Figure 19).

As a potential benchmark and for the sake of comparison, CALIOP feature mask data [*Winker et al*., 2009] were also analyzed to compare the aerosol type distribution with VIIRS-SM. The CALIOP feature mask is reported for various aerosol types such as "dust", "polluted dust", "smoke", sea salt", etc, and they are retrieved in the vertical domain.

(b) Evaluation results of VIIR-SM Product

(I) Case studies

In order to better understand the VIIRS-SM product we present, in this section, some noted case studies specific to dust, smoke and volcanic ash events occurring across source as well as transported regions. The goal of this visual analysis is to better understand the capabilities of the product. A large pool of imagery was visually compared against the VIIRS-SM classification, out of which we present some interesting representative case studies in this report.

Fig. 20 and Fig. 21 show several case studies of (i) dust over northern India, Sahara and Arabian Peninsula; (ii) smoke plumes across North America, Europe and off the coast of Southern Africa; and (iii) volcanic ash plume in eastern Russia (Shiveluch Volcano). True-color imagery of the specific events (left column) are shown alongside the VIIRS-SM classification flags (right column) to aid visual comparison. We first examine the dust cases. For northern India, the month of June was selected for this study since, during this time period, westerly-wind driven dust activity is high and dominates the regional aerosol loading. According to Fig. 20a and b, the VIIRS-SM appears to successfully classify the aerosol loading over land as "Dust", while it fails to detect the heavy dust plume over the Arabian Sea. For these two days over the Arabian Sea, VIIRS-SM incorrectly classifies dust as "Ash" (2012-06-05) and as "Unknown" (2012-06-10). Near the Arabian Peninsula (Fig. 20c), it appears that "Dust" is correctly reported over patches of vegetated land surface (dark target regions), while over the dust-laden Persian Gulf, dust detection is not uniformly reported and large areas are classified as "Unknown".

This issue of misidentification of dust is also discernible over the Atlantic off the coast of Sahara, where Fig. 20d and e show that thick plumes of dust loading were observed. Extensive areas of dust-laden Atlantic Ocean are, instead, identified by VIIRS-SM classification as "Ash".

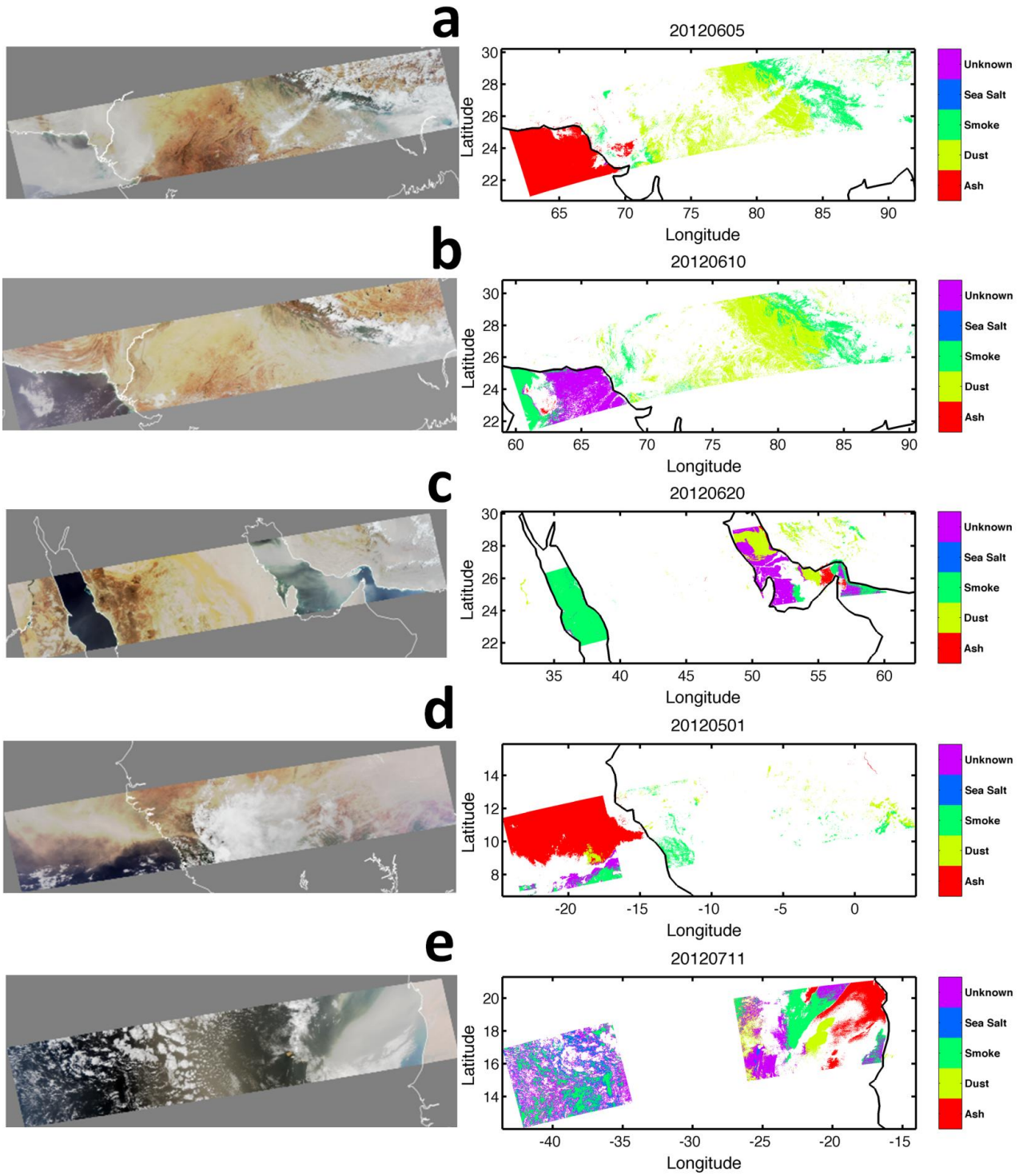

Figure 20: True-color VIIRS imagery (left column) is shown alongside VIIRS-SM retrievals (right column) for case studies of (a) dust over northern India and Arabian Sea on 2012-06-05; (b) dust over northern India and Arabian Sea on 2012-06-10; (c) dust over Persian Gulf on 2012-06-20; (d) dust over Atlantic off Sahara on 2012-05-01; (e) dust over Atlantic off Sahara on 2012-07-11.

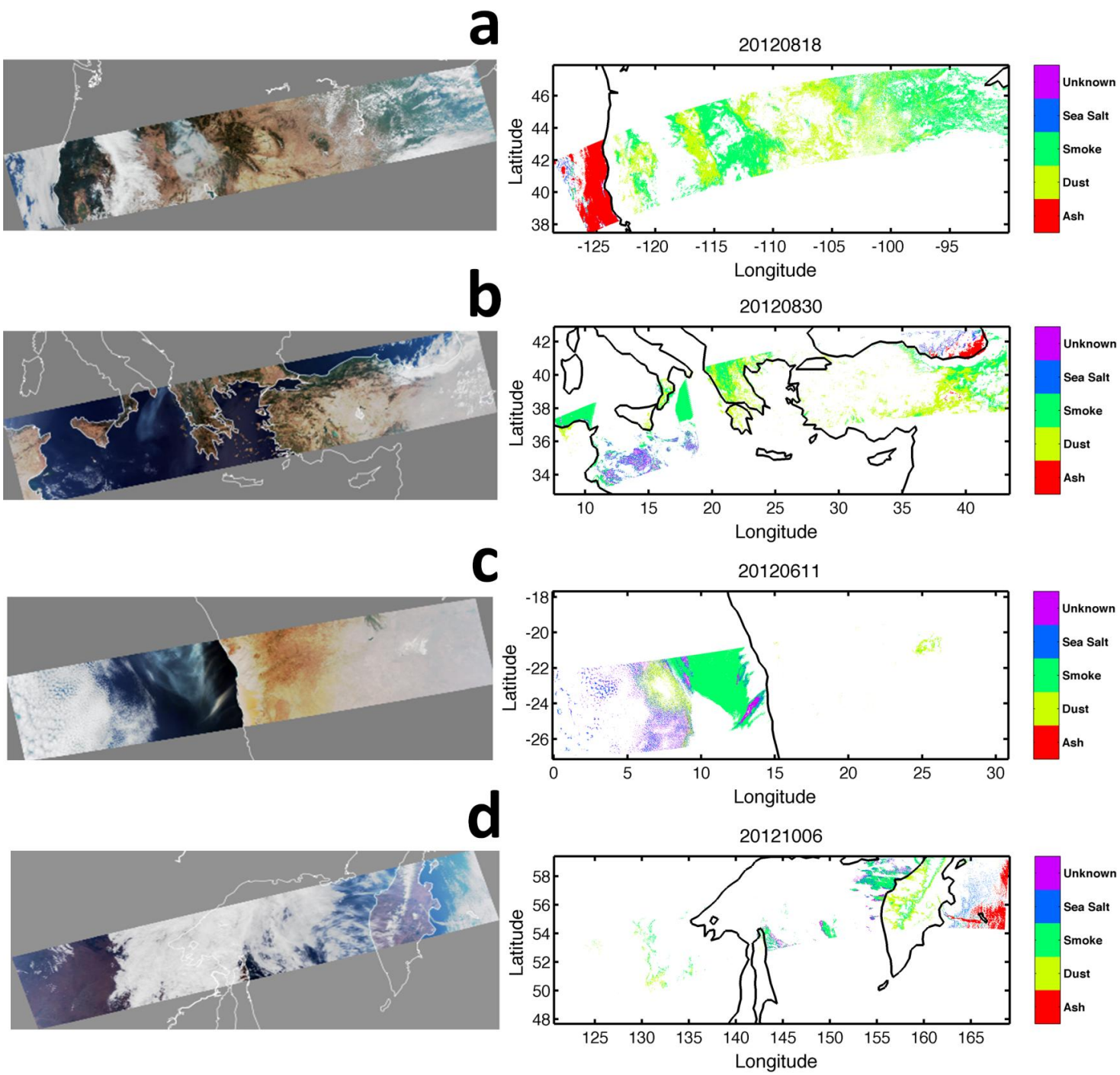

Figure 21: True-color VIIRS imagery (left column) is shown alongside VIIRS-SM retrievals (right column) for case studies of (a) smoke over mid-western USA on 2012-08-18; (b) smoke plume over the Mediterranean Sea on 2012-08-30; (c) Smoke and dust off the coast of Namibia on 2012-06-11; (d) Shiveluch volcanic ash plume on 2012-10-06.

Such noted observations lead us to posit that the VIIRS-SM flag has apparent difficulties in correctly distinguishing dust over ocean, while it appears to work better over land.

We also examine cases specific to smoke events shown in Fig. 21 over the mid-western US (a), over the Mediterranean (b), and over the Atlantic off the coast of southern Africa (c). For all three cases, the VIIR-SM classification indicates "Smoke", both over land as well as over ocean. It should be noted here that the three smoke cases shown here are inherently different – smoke over mid-western US is a land-specific case (Fig. 21a), smoke is transported over the Mediterranean Sea (Fig. 21b), and smoke is transported and mixed with dust over the Atlantic (Fig. 21c). It is also worth pointing out that in Fig. 21c, a fine but thick dust plume is also seen

over the southern Atlantic (originating from arid lands in western Namibia), which is not retrieved as "Dust" and is classified as "Unknown". Overall, case studies suggest a better detection of smoke based on the VIIRS-SM algorithm.

We report another interesting case of a volcanic ash plume from the Shiveluch Volcano in eastern Russia (this is probably the only obvious ash plume captured during VIIRS observations). The ash plume is detected over the ocean as a fine-scale plume extending into the cloudy region. Such a retrieval from VIIRS is noteworthy given the high resolution of the SM product. However, the mis-classification of cloudy regions as ash-filled, as discussed above, is problematic, leading to uncertainty as to whether this plume actually is ash, only clouds, or clouds mixed with ash. As per the VIIR-SM detection algorithm, the "Ash" classification flag heavily relies on the VIIRS Cloud Mask (VCM). Based upon the current state of the VCM algorithm, our study indicates that there numerous dusty or cloudy VIIRS scenes have been misclassified as "Ash" and further improvements in this regard are much needed before this product can become useful for the community.

(II) Global and Regional Distribution

Dust

We extend our analysis of specific case studies of dust and smoke towards a better understanding at a global/regional scale of the VIIRS-SM product. Global VIIRS-SM data, along with geolocation data, were analyzed for two months – June 2012 and August 2012. While both months, are associated with higher dust loading in the atmosphere from major source regions such as those from the Sahara and Arabian Peninsula, August also includes the onset of the biomass burning season in the southern hemisphere, in particular over the Amazon and southern Africa. In order to better understand the capability of the VIIRS-SM product, the percentage frequency of individual SM (dust, smoke, sea salt, ash, unknown) was calculated. The VIIRS-SM data obtained at a 0.75 km spatial resolution were first gridded to 0.5°x0.5° resolution and occurrences of individual SM types were recorded within each grid point, for this calculation.

Fig. 22 (left column) shows the percentage frequency of all SM types for June 2012. Some of the prevalent source regions across the globe are associated with higher percentage frequency. These regions include central/southern Asia, eastern Asia (Taklamakan and Gobi deserts), and the Sahel and the western USA. Specifically over southern Asia, where dust dominates during the pre-monsoon season (May-June), the VIIRS-SM indicates dust as a major aerosol type with its occurrence frequency >50% over the arid/semi-arid regions of northern

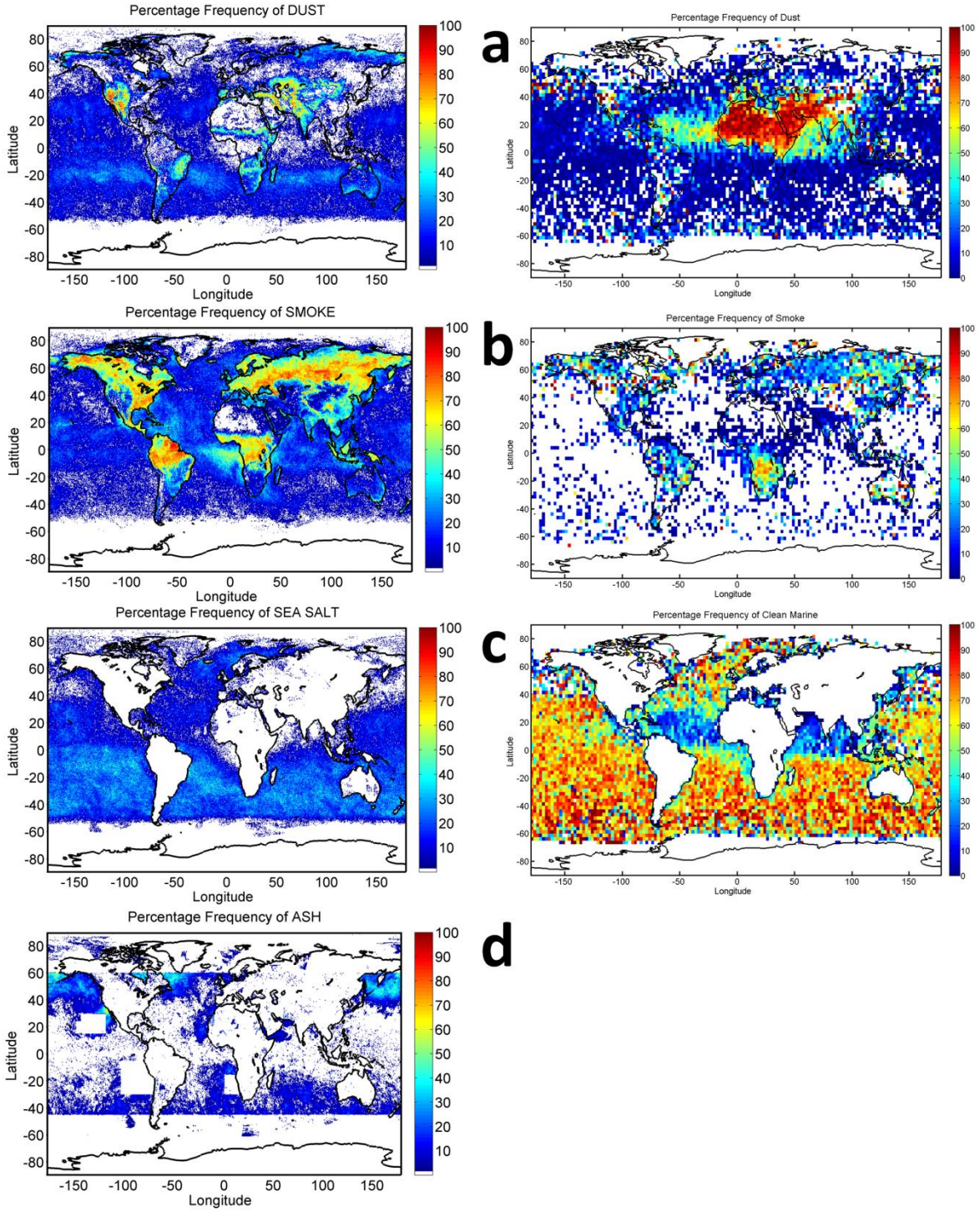

Figure 22: Percentage frequency of VIIRS-SM type (left column) and CALIOP feature mask (right column) for (a) dust; (b) smoke; (c) sea salt; (d) ash (only available for VIIRS) for June 2012. White-shaded regions represent no data.

Table 2: Regional statistics of percentage frequency of Dust, Sea Salt, Smoke, Ash, and Unknown VIIRS suspended matter types for the period June, 2012.

	Ash	Dust	Smoke	Sea Salt	Unknown
Africa (Sahel)	0.14	59.04	40.82	0.00	0.00
Arabian Sea	8.49	5.35	42.76	1.39	42.00
Central America	2.02	11.64	53.06	15.14	18.15
Eastern China	0.09	22.16	77.67	0.00	0.09
Southern China	0.89	3.37	90.38	1.59	3.76
Europe	1.51	8.80	85.19	2.48	2.02
Northern India	0.02	52.90	47.08	0.00	0.00
Eastern USA	0.79	7.66	87.08	2.47	2.01
Western USA	0.05	73.10	26.85	0.00	0.00
North Atlantic (E)	14.10	15.80	26.28	15.49	28.33
South America	0.03	44.13	55.84	0.00	0.00
Southeast Asia	0.46	8.54	50.63	19.21	21.14

India, Pakistan and Afghanistan (Table 2 and Fig. 22). It should be noted here that the VIIRS-SM product is only available for dark-target regions, therefore the white-shaded regions represent no data over bright deserts and snow-covered areas and hence the aerosol retrievals over dust source regions such as the Sahara and Arabian Peninsula are entirely missing. Over oceans, however, the percentage frequency suggests a significantly suppressed dust activity, particularly over the Atlantic (off the coast of Sahara) and northern Arabian Sea, where dust transport is active during the summer season. For these two dusty regions, the percentage frequency for dust is <16% (Table 2), which is comparable or actually even lower than that for ash.

For comparison with VIIRS-SM, occurrences of the individual CALIOP feature mask detected in the entire column (from 0 to 30km altitude) were recorded with the criteria that each aerosol type was counted only once in the vertical domain. The resulting occurrences were gridded to 2.5°x2.5° resolution. A coarser resolution was chosen for the CALIOP analysis to account for the narrow width of CALIOP swath and thus avoid excess data gaps in the global maps. The goal of the CALIOP analysis is to provide a qualitative comparison with VIIRS-SM and to better understand spatial agreements/differences between the two datasets for various source/transport regions.

Fig. 22a (right panel) shows the spatial distribution of the percentage frequency of “dust”, as detected by CALIOP, which shows significantly higher dust activity over the Atlantic and

Arabian Sea (>50%). Similar results were found for August 2012 (Fig. 23) and are in contrast to the significantly lower dust detection as reported by VIIRS-SM (<10%). This is consistent with the mis-detection of dust observed over ocean in the studies shown in Fig. 20, suggesting the VIIRS-SM dust detection scheme needs to be investigated – particularly for retrievals over ocean. Here it is worth noting that, in addition to the issue of heavy dust plumes being mis-identified as "ash" by the VCM, the significantly lower dust detection over oceans is also attributed to the problem of aerosols being reported as "unknown" (not determined) by the VIIR-SM algorithm (~40% and ~30% for Arabian Sea and Atlantic, respectively) for moderate dust loading conditions. The "unknown" SM detection is set in the VIIRS-SM algorithm when SMVP is within 0.2 and 0.5 and when the given AOD>0.3 (Fig. 19). Whereas, dust is classified over oceans when SMVP<0.2. Since the starting point of the detection algorithm heavily relies on the SMVP, it needs to be investigated further and compared against MODIS and AERONET fine-mode fraction.

Smoke

For smoke, the percentage frequency from VIIRS-SM indicates relatively higher smoke detection frequency over continental regions. Smoke detection in VIIRS-SM is obtained from the aerosol model used over land, while for ocean retrievals an SMVP threshold of 0.5 is used. Essentially, smoke detection from VIIRS represents urban pollution as well as biomass burning. From Fig. 22b, 23b we discern that higher smoke frequency is detected over most of the continental urban regions including Europe, North America, China, India as well as over biomass burning regions in Amazon, southern Africa (Table 2). Smoke transport over oceanic regions is also present over the southern Atlantic off the coast of southern Africa. During August 2012 (Fig. 23b), a stronger smoke signal is observed over Amazon and southern Africa that is consistent with the seasonal variation of biomass burning (fires), as the onset of wildland fires and crop burning starts in August over the two noted regions. Although smoke detection appears to capture urban and biomass burning pollution, it would probably be more useful to be able to separate the fine mode particles produced by urban pollution from the smoke aerosols generated by biomass burning activities.

Sea salt

Similar distribution maps were generated for "Sea Salt" (Fig. 22c). For the case of Sea Salt, the southern hemisphere (SH) appears to be dominated by sea salt aerosols, as detected by VIIRS, in comparison to the northern hemisphere. The CALIOP data shows similar distribution of sea salt with higher occurrence over SH. The VIIRS-SM sea salt frequency in SH is around 30-40%, while it is within 70-80% from CALIOP. Although the two cannot be compared quantitatively due to a variety of reasons, including the fact that CALIOP provides information in the vertical domain and has sparse sample size compared to VIIRS. However, it is reasonable to expect the SH would have a strong component of sea salt in the annual aerosol loading cycle; a low-bias in VIIRS sea salt detection may therefore be possible due to the relatively higher frequency of "unknown" SM that contribute about 10-30% of the monthly aerosol load. Additionally, a rather peculiar "dust-band" is detected by VIIRS around 20°S with ~30% contribution to the monthly aerosol load. Dust detection over ocean follows the retrieval scheme when SMVP < 0.2 (Fig. 19), which most likely (and incorrectly) flags the 20°S region as dusty, whereas sea salt aerosols also have a strong coarse mode, may well fall within the SMVP<0.2 category, and (due to the present retrieval scheme) are probably not flagged correctly in the wide

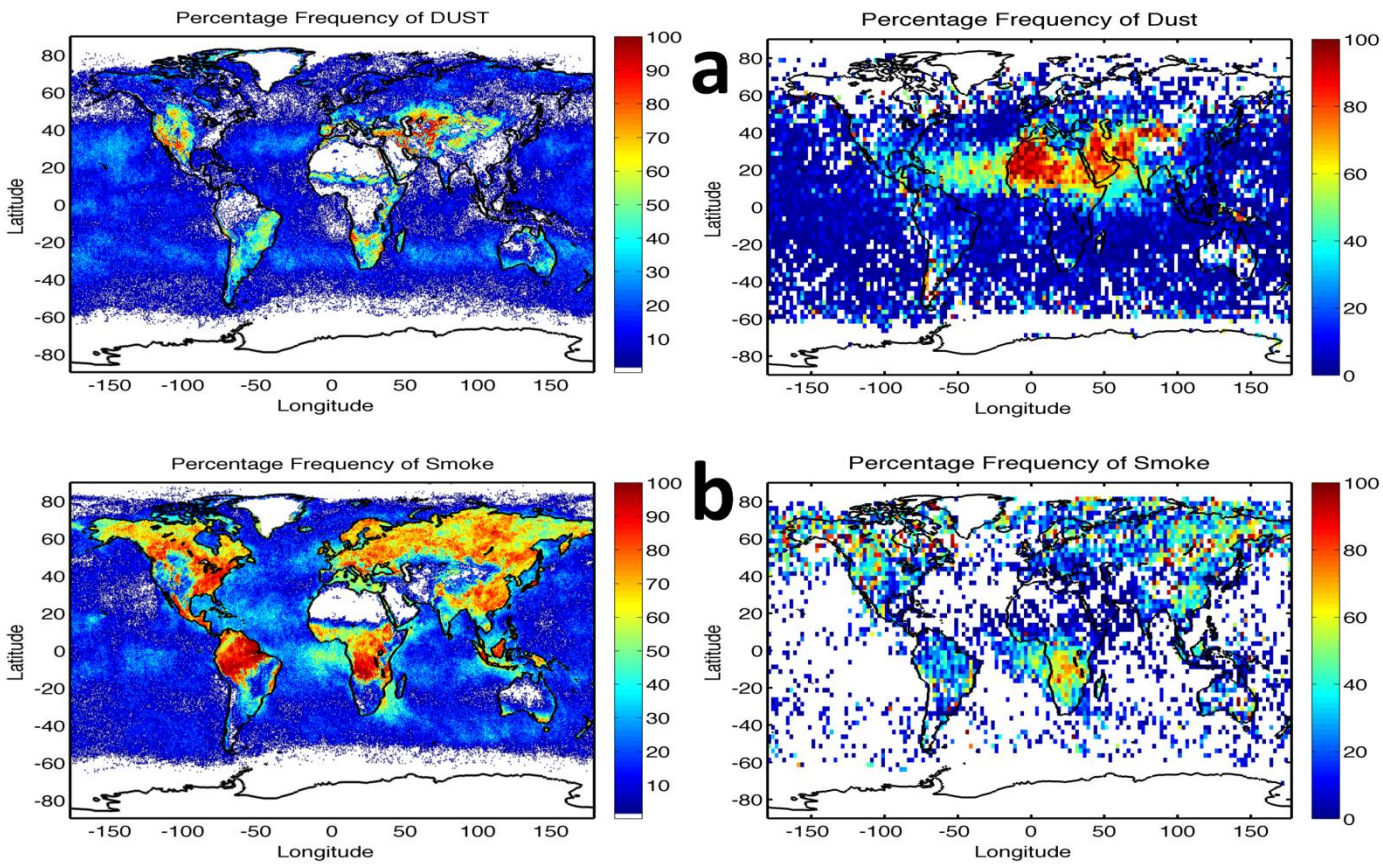

Figure 23: Percentage frequency of VIIRS-SM type (left column) and CALIOP feature mask (right column) for (a) dust; (b) smoke for August 2012. White-shaded regions represent no data.

20°S band. Again, the possibility of such artifacts may be closely related to the retrieval scheme involving simplified thresholds on SMVP and AOD.

Overall, the results of our studies, based upon a number of case studies as well as regional statistics based on two months of global data analysis of VIIRS-SM types, indicate that the classifications of dust and fine mode particles over land appear to be reasonable, while a significantly lower accuracy in such classification was found over ocean due to issues in both VCM and VIIRS-SM algorithms. In particular, the detection of ash cloud seems to be problematic and exhibits artificial boundary lines associated with latitude and longitude as shown in Fig. 22d. Therefore, although the VIIRS Suspended Matter (SM) type could potentially

provide a useful index regarding information about various aerosol types in the atmosphere such as dust, smoke, sea salt and volcanic ash, routinely on a global basis and retrieved at high spatial resolution of 0.75 km, much work needs to be done in the VIIRS IDPS SM algorithm, particularly over ocean, before this product could be usable for the public community.

2. 4 The application of the MODIS Deep Blue algorithm to VIIRS data

Many improvements made in surface reflectance determination and aerosol model selection schemes have been developed and incorporated into the MODIS Collection 6 aerosol retrieval algorithms over the past decade, and these new capabilities are not captured in the current operational VIIRS IDPS aerosol retrieval algorithms. In addition, there are large data gaps over desert and semi-desert regions in the VIIRS products because the Deep Blue algorithm is not implemented in the VIIRS processing streams. In order to construct consistent well-calibrated long-term aerosol CDRs, a consistent retrieval algorithm that performs well on a global basis is needed to process satellite products across different platforms (i.e., from MODIS to VIIRS). Otherwise, the resulting discontinuity in aerosol time series shown in Fig. 18 will severely hinder the capability to determine long-term aerosol trends accurately.

To provide an illustrative baseline of relative performance, VIIRS IDPS and MODIS DB data for the study period are jointly validated against AERONET Level 1.5 (cloud-screened) data, which have an absolute uncertainty of around 0.01 at midvisible wavelengths (Holben et al., 1998). For this purpose, retrievals from MODIS DB and VIIRS with sufficiently high QA were averaged within 25 km of each AERONET site, and AERONET data within 30 minutes of each satellite overpass. To be considered for a comparison, we required that at least two AERONET measurements were made during this time (typical sampling frequency is once per 10-15 minutes), and that both satellite datasets performed a successful retrieval during this 30-minute window. Thus, this is a direct three-way comparison of the products (i.e. each DB-AERONET matchup has a corresponding VIIRS-AERONET matchup and vice-versa), yielding 4,553 matchups for the study period.

The comparison results are depicted in Figure 24. Panels 24(a) and 24(b) show, for those sites with 5 or more matchups during the study period, the fraction of matchups where the satellite AOD is within 0.05+20% of the AERONET AOD (which was the approximate uncertainty of the previous version of the DB algorithm). It is apparent that in almost every region (except central Asia), a higher fraction of DB comparisons meet the criteria than those

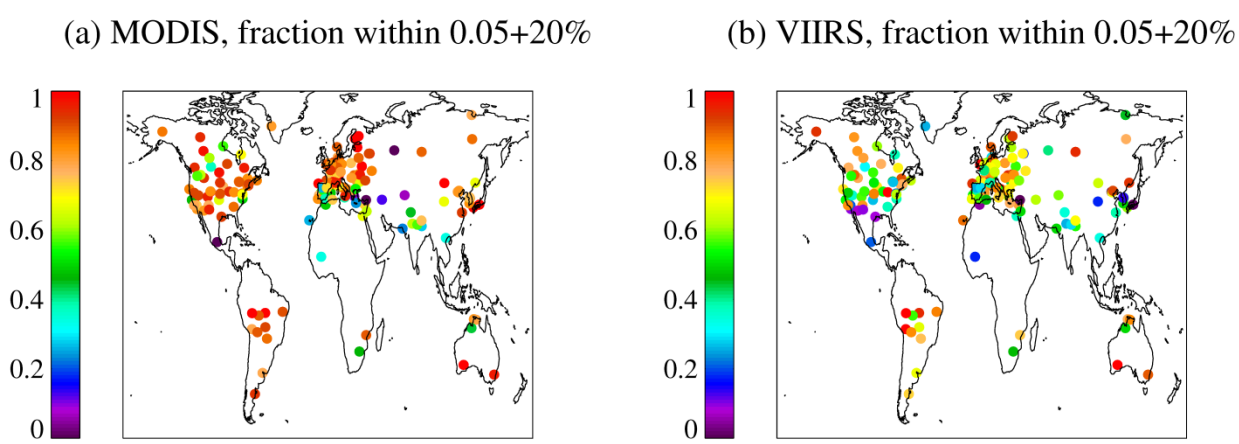

Figure 24: Statistics of joint comparison of MODIS DB and VIIRS IDPS data against AERONET. Panels (a) and (b) show global distribution of the fraction of matchups for MODIS DB and VIIRS IDPS AOD products, respectively at each site in agreement to within 0.05+20% of the AERONET value.

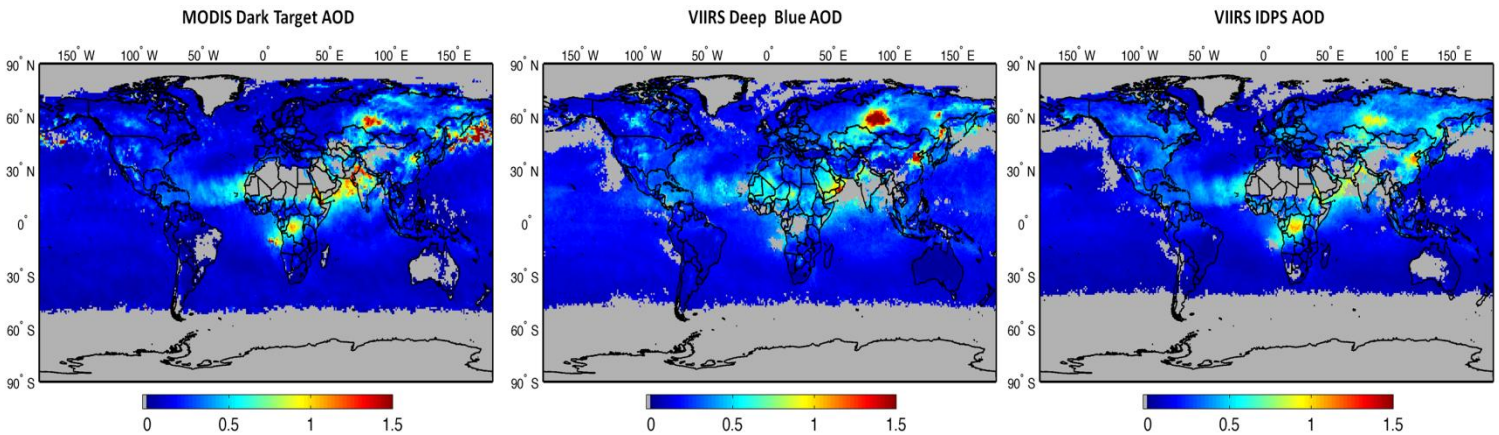

Figure 25: The monthly mean of VIIRS Deep Blue AOD (center panel) for July 2012 reveals smoke generated from biomass burning over N. America and Russia as well as dust plumes over Sahara and Arabian Peninsula, in comparison to MODIS DT (left panel) and VIIRS IDPS (right panel) products.

from VIIRS. In particular, high biases that are observed in the VIIRS IDPS AOD over urban regions in North America, Europe, and Asia are not present in the DB comparisons with AERONET AOD, indicating the ability of DB to more accurately monitor urban air pollution.

With the support of the Atmosphere PEATE at Madison, Wisconsin, we have completed implementing the Deep Blue algorithm over land and ocean for use in processing VIIRS data, including use of the cloud mask, for aerosol retrieval. The Deep Blue algorithm was designed to have the flexibility of being used as a stand-alone algorithm and can be easily ported to any satellite sensor without significant modifications, given the required bands for aerosol retrievals are available. Currently, the VIIRS DB algorithm uses reflectance measurements from the original 86 second VIIRS SDR granule files as input without any additional reformatting. The resulting DB aerosol products generated by Atmosphere PEATE consist of spectral AOD, Angstrom exponent, and single scattering albedo, which are consistent with the MODIS

products. Since there are changes in the key spectral channels between MODIS and VIIRS (from 0.47 μm into 0.49 μm, from 0.65 μm into 0.67 μm, and from 2.1 μm into 2.2 μm, see Table 1), different sets of DB lookup tables have been generated for VIIRS bands to account for the effects of gas absorption and the response function from visible to SWIR wavelengths. Extensive efforts have also been made to modify the MODIS DB surface determination schemes over land to fit the VIIRS spectrum for aerosol retrievals.

The over-land VIIRS Deep Blue data have been complemented by inclusion of an over-ocean AOD retrieval algorithm, based upon the state-of-the art SeaWiFS Ocean Aerosol Retrieval (SOAR) algorithm (Sayer et al, 2012d), which was recently applied to generate a high-quality time series of AOD from SeaWiFS data as part of the NASA MEaSuRES program [Hsu et al., 21012; Sayer et al, 2012c]. The SOAR algorithm is a physically-based and self-consistent inversion, and has been updated to take account of advantages offered by the VIIRS sensor (such as improved spectral and spatial resolution as compared to SeaWiFS).

One example of the resulting VIIRS DB products for July 2012 is shown in Figure 25 (center). For comparison purposes, the monthly AOD mean of MODIS DT and VIIRS IDPS for the same time period are also depicted in Fig. 25 (left) and (right), respectively. Both the VIIRS DB and IDPS AOD EDR are gridded into 1^0 x 1^0 deg resolution using the same methodology. Also, in order to avoid biases due to insufficient data in the frequently cloudy regions, a minimum of 5 days with retrieved AOD are required for calculating the monthly mean. The MODIS DT monthly mean products do not have such requirements on sampling size and thus result in the differences in data coverage of the monthly mean between MODIS DT and the two VIIRS (DB and IDPS) data sets over India, the Arabian Sea, and the high-latitude north Pacific.

It is apparent that the large gaps in AOD over desert and semi-desert regions in northern Africa, the Arabian Peninsula, Asia, and Australia seen in both the MODIS DT and VIIRS IDPS products due to the surface brightness are filled in by the VIIRS DB algorithm. Over vegetated areas, the VIIRS DB values are generally comparable to MODIS DT, while the VIIRS IDPS AOD values are biased high against both MODIS DT and VIIRS DB in North America, Europe, East Asia, except over the most intense biomass burning regions in central Russia. On the other hand, Fig. 25 shows the broad similarity in over-ocean AOD features observed by these three algorithms.

2. 5 Conclusions

Based upon the results from this study, we recommend that many of the key algorithm components described at the beginning of section 2 need to be improved in the VIIRS IDPS algorithm before the resulting aerosol products can be used quantitatively as CDRs to continue the heritage MODIS products. Indeed, even before examining the retrieved AOD, the VIIRS products “as-is” are lacking compared to other existing records because there are no operational Level 3 (daily/monthly composite) aerosol products. These are widely-used by the scientific community, and placing the burden of creation on users decreases the likelihood of user uptake, increases user overheads, and increases the possibility of errors. For NASA’s (and the world’s) climate science objectives, Level 3 products are imperative.

Through extensive comparisons with AERONET, MODIS, and CALIOP data, our evaluation results of the VIIRS IDPS aerosol products indicate that the current state of the IDPS aerosol retrieval and cloud mask algorithms is out-of-date, particularly over land. In addition, there are large data gaps over desert and semi-desert regions in the VIIRS products because the Deep Blue algorithm is not implemented in the VIIRS IDPS processing streams. Many improvements have been developed and incorporated into the current MODIS collection 6 surface reflectance determination and aerosol retrieval algorithms over the past decade, and this new knowledge is not captured in the current operational VIIRS aerosol EDR algorithms.

Our results also show that the VIIRS AOD EDR data over land was significantly affected by surface properties, showing large uncertainty over urban and/or bright surfaces. The errors are further exacerbated in IP products due to the enhanced surface brightness, variability and cloud contaminations in high spatial resolution. This is likely due to the issue in the surface reflectance determination scheme of VIIRS IDPS algorithm related to the use of inappropriate constant spectral surface reflectance ratios regardless the viewing geometry and NDVI values. Also, the changes in the key spectral channels (from 0.47 μm into 0.49 μm) will definitely require

significant effort and expertise from algorithm specialists to modify the MODIS surface determination schemes over land to fit the VIIRS spectrum for aerosol retrievals. Specifically, our findings from this study for assessing the performance of VIIRS IDPS aerosol products are summarized as follows:

Aerosol Optical Depth and Angstrom Exponent products

- A lack of a Deep Blue-equivalent algorithm means that coverage over bright surfaces, such as the Sahara Desert and Arabian Peninsula, which are immensely important natural aerosol sources, has been lost. This is a step backwards from previously-existing capabilities. The development and application of such an algorithm is within the VIIRS sensor's capabilities, and should be done.
- Using the AERONET measurements as a benchmark, the VIIRS over-land algorithm has limited capability to retrieve AOD data quantitatively at this moment.
  - Over land, compared to MODIS DB and DT AOD, VIIRS has a significant relative high bias of order 0.05-0.15 (regionally-dependent) in the mean; the mean AOD itself in many of these regions is 0.2 or less, so this bias will lead to a large step change in time series constructed using VIIRS to extend older records. This bias is observed for most aerosol types, with the possible exception of absorbing fine-dominated aerosols and dust, and persists across low-AOD and high-AOD regimes. This bias is most likely due to algorithmic inadequacies rather than sensor-related issues.
  - In some of these land regions, the high bias is likely because VIIRS is less conservative than MODIS in terms of filtering for residual cloud and snow, causing greater potential for contamination in retrievals.
- The over-ocean AOD data show comparable capability with the MODIS products, exhibiting much smaller biases and high correlation compared to the land products.
  - Over ocean, the VIIRS AOD tracks MODIS well, although is low-biased over smoke and dust continental outflow regions. There is a small negative offset around -0.01 to -0.04 over open ocean compared to MODIS, although for clean (unpolluted) marine regions approximately half of this can be attributed to limitations with the current (Collection 5) MODIS algorithm over ocean.
- An inconsistent definition of Ångström exponent (α) retrieved over ocean compared to previous datasets means that this data product is physically not providing the same information as the user community have been used to for previous decades; this severs continuity of data, and increases potential for confusion.
  - The VIIRS over-land AE data are not recommended to be used for scientific analyses at this moment since they are not able to separate small and large particles, whereas over-ocean data seem to be usable in a qualitative way.

Suspended Matter product

- For dust-dominated and smoke-laden regions over land, the VIIRS-SM type classification appears to capture the spatial distribution as well as frequency of occurrence based on comparison with visible imagery and regional statistics obtained from both VIIR-SM and CALIOP feature mask. However, over ocean, we find that the detection of dust SM type is significantly underestimated.

- It is found, particularly for these heavy dust-laden regions, that the majority of aerosol loading is not determined by the detection algorithm and is flagged as "Unknown". Additionally, case studies and percentage occurrence show a non-negligible frequency (~8-15%) of "Ash" detection, which is comparable to that of "Dust" in these well-known dusty regions and which further impacts the true dust-detection capability.
- Dust detection over ocean heavily relies on SMVP (equivalent to fine-mode fraction) and the VIIRS-SM algorithm uses a simple threshold of <0.2 for detection of dust. Since detection of dust is strongly tied to the SMVP parameter, the SMVP needs to be further investigated to assess its accuracy. Additionally, a simplified threshold on the SMVP (current version) may not be entirely accurate as marine sea salt aerosols are also, in general, characterized by a strong coarse mode.
- The current version of VIIRS-SM over land is only applied to vegetated surfaces; extending detection capabilities over bright arid/semi-arid surfaces [*Hsu et al*., 2004], could provide a more complete picture of the regional aerosol type distribution, in particular over dust source regions.
- Detection of smoke currently represents both urban pollution aerosols as well as biomass burning aerosols. A further sub-classification of Smoke into "urban pollution" and "biomass burning smoke" could be particularly useful in broadly discriminating smoke from anthropogenic origin vs. biomass sources.
- While it is particularly useful in monitoring and mapping volcanic ash plume, especially at a considerably high resolution (e.g. Fig. 21d), the ash detection algorithm also shows artifacts where case studies indicate dust being flagged as ash. Such artifacts are problematic.

Therefore, extensive improvements are recommended for better accuracy in the AOD, AE, and SM products generated by the VIIRS IDPS algorithm. Deriving more accurate surface properties as input into the retrieval algorithm and more sophisticated cloud screening procedures require the most urgency.

Finally, a lack of reprocessing of operational products means that there will always be potential for discontinuities in the data when algorithm updates are made. This has, for example, already precluded use of the initial months of VIIRS data (prior to May 2012), and is well-illustrated by the unusability of VIIRS data from October 15th until November 26th due to the bug introduced in application of the VIIRS cloud mask. This renders the application to studies such as trend analysis or seasonal variability very difficult. However, since there are systematic biases between VIIRS and MODIS over many regions of the Earth, even if there were periodic whole-mission reprocessings performed for VIIRS, consistent long-term climate-quality aerosol datasets from MODIS to VIIRS still cannot be achieved without applying the same consistent retrieval algorithms to both MODIS and VIIRS.

3. Aerosol climate data records from combination of MODIS and VIIRS aerosol products
Named Team: PI: Robert Levy, Co-I: Istvan Laszlo, Software: Shana Mattoo, Leigh Munchak, Hongqing Liu

For more than ten years NASA's spaceborne EOS sensors have been observing the Earth system, providing hundreds of products that have seen wide use within the community. One such product is the "dark-target" aerosol optical depth (AOD) at 0.55 μm over both land and ocean, derived from Moderate resolution Imaging spectrometer (MODIS) observations. MODIS aerosol data are used extensively by both the operational (e.g. Zhang et al., 2006; Hyer et al., 2011) and research communities (e.g. Kato et al., 2011). The product has become integrated into forecasts of air quality (Al Saadi et al., 2005), visibility and monitoring of major dust and smoke events. It is also applied towards answering major questions concerning Earth's climate, including discussions of aerosol trends, and changes to radiative forcing. As of Dec 2012, there were 1,737 total publications found for the search AEROSOL* AND MODIS using the Science Citations index, with Remer et al., (2005) being a top twenty-five most highly cited AEROSOL* paper of all time, out of 85,879 papers. The MODIS dark-target aerosol product has been fully integrated into the community.

As we transition out of the EOS era and into successor programs such as JPSS, the community is looking to continue the long-term satellite data record provided by MODIS. Aerosol products have been developed for the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi-NPP satellite. With the launch of VIIRS in 2011, the community now has products to examine. Based on more than twenty papers being presented at the recent Fall-2012 meeting of the American Geophysical Union, the VIIRS aerosol product is of high interest.

What is data continuity? There are two varieties. The first is continuity of the "environmental data record" (EDR). By this we refer to continuation of imagery and products used for monitoring geophysical parameters of the atmosphere and surface. We have become accustomed to an uninterrupted data stream of information from satellite that is currently used by operational forecasters, decision and policy makers, researchers, the media and the public. Although continuation of the EDR is very important question, we try to assess the continuity of the "climate data record" (CDR). Attaining CDR status is more difficult, because it requires not only the availability of data and imagery, but also a long-term, seamless time series showing neither discontinuities nor jumps. Generally, based on model simulations, any potential "trend" in AOD would be less than 10%, meaning that we need to characterize our data well enough to see a change in AOD of less than 0.02 over a 20-year period. If we want to use our satellites to detect this aerosol trend, we must be able to separate out background noise, uncertainty in the retrieval, calibration drifts and transitions between sensors.

However, it is very difficult to get two sensors to agree. For example, Liu et al., (2008) showed that the Multi-angle Imaging SpectroRadiometer (MISR) and MODIS do not agree even though they are on the same satellite platform. Offsets and biases between data records have been traced to different sampling strategies, spatial resolutions and sensitivities. All these instruments measure "aerosol", but they do not necessarily measure the same quantity. Even more illuminating, is that it is difficult to get twin MODIS instruments (aboard Terra and Aqua) to agree. Both MODIS sensors have the same pixel resolution, spatial information, and use the

same aerosol retrieval algorithm. Yet like identical human twins exposed to different environments, differences crept in. In 2006, Remer et al. showed that Terra-MODIS and Aqua-MODIS retrieved nearly identical aerosol statistics over the ocean. Two years later, Remer et al. (2008) found different results. In the reprocessing occurring between the two studies, Terra had acquired a 0.015 (12%) offset from Aqua. The Terra offset was traced later to calibration changes introduced by the MODIS Characterization Science Team (MCST) to the Level 1b radiances used as input to the aerosol retrieval. The aerosol team had made no changes to the algorithms on either Terra or Aqua, and yet a bias was introduced. Thus, we see that a CDR is susceptible to errors due to a variety of sources.

Based on pre-launch simulations and calculations, VIIRS should be able to continue the MODIS EDR. In particular, all of the channels used by the MODIS aerosol retrieval are available on VIIRS, although there are variations in spectral response function and central wavelength. Furthermore, the aerosol algorithms used by VIIRS are based on MODIS algorithm heritage. Therefore, it should be possible to stitch the VIIRS aerosol record onto the long term MODIS data record, producing a long term CDR. While both VIIRS and MODIS are currently in orbit, we have a unique opportunity to evaluate the potential continuity of a MODIS→ VIIRS aerosol CDR. For this, we need to characterize all uncertainties in both the MODIS and VIIRS product.

Based on recent efforts to recalibrate and homogenize the two MODIS instruments, it seems possible to create a consistent MODIS data record. We hope that the MODIS aerosol replacement products from NPP-VIIRS will continue seamlessly into the future. However, creating this aerosol CDR from the merged aerosol products requires in depth understanding of the issues affecting production of real time data and a consistent long-term record. There are many obstacles to creating a merged aerosol climate data record from MODIS and its continuation sensor NPP-VIIRS, including:

- sensor differences
- retrieval algorithm differences
- sampling differences
- calibration/characterization differences
- pixel selection differences, including cloud and other masking
- aggregation from along-orbit products (e.g. Level 2/EDR) to gridded, global products (e.g. Level 3).

With all of these obstacles, our job is to quantify the uncertainties involved in joining the two time series together. Currently, we know that the *VIIRS IDPS products* are sufficiently different from the products in the MODIS 12-year data record that a smoothly merged CDR is not possible. Yet theoretically, there is nothing inherent in the *VIIRS sensor itself* to prevent the creation of a long-term CDR if one applies a consistent algorithm to both sensors (whether it be MODIS-like or VIIRS-like). We believe that a reliable MODIS→VIIRS CDR is possible, but will take much more work. The community cannot afford to lose the MODIS data continuity.

3.1 Short history of MODIS and VIIRS aerosol algorithms

The MODIS operational processing derives aerosol loading and particle properties many different ways. Table 3 presents six aerosol algorithms used for MODIS. Three algorithms result in aerosol products that are packaged and presented to the public, as parameters within Terra (MOD04) or Aqua (MYD04) aerosol product files (collectively denoted as MxD04). Two of these algorithms derive aerosol information internally and use the aerosol information for deriving "atmospheric corrected" surface products. Another is an algorithm that derives both aerosol and land properties.

For our discussion, we focus on the first three products (in red) of Table 3. The first two algorithms make use of visible, near-IR and IR spectral (0.47 – 2.11 μm) information to detect "dark targets" (DT) on the surface of the Earth, and derive aerosol information over ocean (DT-O: Tanré et al., 1997; Remer et al., 2005) and over land (DT-L: Kaufman et al., 1997; Remer et al., 2005; Levy et al., 2007ab). The products of DT-O, DT-L are used in creation of MxD04. The algorithm for "atmospheric correction" over land (AC-L; Vermote et al., 1997a, 2002) is used to derive the land surface reflectance products of MxD09.

The AC-L algorithm used for MxD09 shares a common developer heritage with the DT-L used for MxD04 (note overlap of authors between Kaufman et al. (1997) and Vermote et al., (1997a)). However, since 1997, the AC-L and DT-L algorithms and products have diverged because of different needs. DT-L must derive climate-quality aerosol statistics (Remer et al., 2005; Levy et al., 2007ab), regardless of surface conditions, and AC-L must derive climate-quality land statistics regardless of atmosphere conditions (Vermote and Kotchenova, 2008). DT-L must retrieve accurately at all aerosol loadings, including very heavy aerosol events, while AC-L can choose to ignore these heavy events to ensure accurate surface retrievals. On the other hand, AC-L must retrieve land surface properties for all land surface types, meaning that AC-L should not just be limited to dark-targets.

Table 3 Six MODIS aerosol algorithms and their products. Those marked in red are discussed in this section 3.

Index	MODIS procedure	Geophysical parameters	MODIS L2 product name	References
DT-O	Dark-target aerosol over ocean	AOD, fine fraction	MxD04,	Tanré et al. (1997) Remer et al., (2005)
DT-L	Dark-target aerosol over land	AOD	MxD04,	Kaufman et al. (1997); Remer et al., (2005) Levy et al. (2007ab)
AC-L	Atmospheric correction over land	Surface reflectance	MxD09,	Vermote et al. (1997), Vermote and Kotchenova (2008)
DB-L	Deep blue aerosol over land	AOD, ω_o	MxD04,	Hsu et al., (2004, 2006)
AC-O	Atmospheric correction over ocean	Water leaving radiances	MxD18,	Gordon and Wang (1994)
MAIAC	MAIAC	AOD and surface reflectance		Lyapustin et al. (2011)

These MODIS algorithms have gone through many iterations since formulation in the 1990's and implementation on Terra and Aqua. In MODIS terminology, a stable combination of algorithm version and product version is known as a Collection, which we refer to by CX where X is a number. C2 began at launch, C3 began soon after, and C4 denoted the first attempt to combine forward processing and reprocessing of old data. By late 2005 the DT-L and DT-O aerosol retrieval algorithms became frozen. The C5 dataset (MxD04) was processed with identical DT aerosol retrieval algorithms, theoretically leading to a CDR-quality aerosol data record for the entire Terra and Aqua missions. However, as explained in the introduction, using a common algorithm for the entire data mission did not ensure a CDR-quality dataset from MODIS. Differences in calibration crept in. Starting in 2013, the entire MODIS mission will be processed again, this time using updated DT and AC aerosol retrieval algorithms. Corrections to calibration have been applied, and the products will be known as Collection 6 (C6). In MxD04, the MODIS aerosol team has introduced a merged product that includes both DT and DB retrievals. Although the MODIS aerosol team has a vested interest in this new combined MODIS product, the primary focus of this work remains the continuation of the DT record. Although not yet "operational" for MODIS, we rely on our understanding of the C6 algorithms and products to evaluate the MODIS → VIIRS transition.

Development for the VIIRS algorithms began in the early 2000s, concurrent with earlier versions of MODIS algorithms. At this point the personnel overlap between algorithm teams disappeared, allowing the algorithms to diverge. The VIIRS algorithm development contract was awarded to the Northrop-Grumman Space Technology (NGST, now Northrop Grumman Aerospace Systems, NGAS). While the MODIS Aerosol Science Team (MAST) continued to build upon the DT algorithm (and add in DB capability) for improving the MxD04 product over land (C4 → C5 → C6), the VIIRS (NGST) team adopted a variant of the AC-L algorithm that was used for creating MxD09. By this time, the AC-L algorithm for MODIS had taken on qualities of both the DT-L and DB-L algorithms, including visible, infrared, as well as "deep blue" wavelengths (0.41 and 0.44 μm). The extra blue wavelengths were used to help constrain aerosol type (Vermote and Kotchenova, 2008). For over-ocean, the VIIRS-NGST team generally continued with the DT-O logic, however they made their own adjustments and modifications. Again, if we want an aerosol CDR, our job is to explain how differences in algorithms, both over land and ocean, will lead divergences in aerosol products.

3.2 Key differences between MODIS and VIIRS sensors, aerosol algorithms and products

As listed in Table 1, there are many differences between MODIS and VIIRS sensors, algorithms and products.

(a) Orbit, swath width and view angle differences

VIIRS on NPP orbits at 824 km, compared to MODIS aboard Aqua orbiting from 705 km. This means that the VIIRS ground swath view is wider (~3040 km) compared to MODIS (~2330 km). As seen from the ground target, the sensor view zenith angle for VIIRS ranges through ±70° compared to ±64° for MODIS. Also, because of the higher orbit, it takes VIIRS a little longer to complete one revolution compared to MODIS. Thus, although VIIRS and MODIS-Aqua both have similar local equator crossing times, they do not necessarily overlap each other. MODIS

and VIIRS will observe a given midlatitude site location at varying time intervals; only a few minutes apart (with similar solar/viewing geometry) on some days, but multiple hours apart (with different geometry) on others. The combination of differences in orbit path, swath width and view angle differences make "apples to apples" comparison difficult, but not impossible.

(b) Sensor spatial resolution differences

MODIS has 36 wavelength bands, of which 20 are in the solar spectrum ($\lambda < 3.8\mu m$). Depending on band, MODIS pixels are either 0.25 x 0.25 km (2 bands), 0.5 x 0.5 km (5 bands) or 1 x 1 km (the remainder) at nadir. For the aerosol retrieval, the 0.25 km bands are aggregated to 0.5 km, meaning that the retrieval relies on 7 bands with 0.5 km resolution. Some of the other bands (at 1 km) are used for cloud masking. VIIRS has 22 bands of which 18 are in the solar spectrum. Except for specific high-resolution "imagery" bands (*I-bands*), all bands have moderate (0.75 x 0.75) km resolution at nadir (*M-bands*). The aerosol retrieval, as well as cloud masking, uses the M-bands. See Table 4. The finer resolution I-bands have such wide spectral ranges (extending into gas absorption regions), that they cannot be used for accurate aerosol retrieval.

In both sensors spatial resolution becomes coarser away from nadir towards the edges of the scan. For MODIS, pixel size grows four-fold so that a 0.5 x 0.5 km pixel at nadir becomes roughly 2 x 2 km at swath edge. VIIRS is designed to mitigate this degradation in resolution. Despite VIIRS's longer swath width, a VIIRS pixel at swath edge has only doubled in size to roughly 1.2 km.

Also, MODIS uncorrected images are noted for their "bowtie effect" in which there is overlap of subsequent scans towards swath edge. VIIRS's data sampling protocol eliminates this bowtie effect. There are no overlapping scans in the VIIRS imagery, but this creates apparent rows of fill values where the overlapping scans would have occurred. Mapping the image to a projection using its geo-location information eliminates the odd look of its raw imagery.

(c) Sensor spectral differences

Table 4 shows the instrument configuration for Suomi-NPP VIIRS and Terra/Aqua MODIS. Only the visible through Shortwave Infrared bands are shown. In addition to these bands, the operational MODIS algorithms employ several cloud mask tests based on Thermal Infrared channels. In the table, *NG-L* refers to the VIIRS IDPS (NGST) aerosol land retrieval and *NG-O* refers to the VIIRS aerosol ocean retrieval.

While there is a corresponding VIIRS (M-band) channel for every MODIS channel used in the Dark Target aerosol algorithm, the spectral center wavelength and spectral response function are not always the same. The greatest spectral shift is in the "blue" channels used in the MODIS DT-L and AC-L algorithms. MODIS Band 3 (B3) is centered at 0.466 μm, while B8, B9 and B10 are at 0.412, 0.442 and 0.487 μm, respectively. While there is a nearly direct overlap between VIIRS bands M1, M2 and M3 and MODIS bands B8, B9 and B10, there is no VIIRS band that corresponds to MODIS B3. This is important because B3 is the anchor point for both MODIS algorithms over land (DT and DB). There is also a relatively large difference between the MODIS aerosol bands (B1 and B7 at 0.646 and 2.113 μm) and the corresponding VIIRS bands

(M5 and M11 at 0.672 and 2.257 μm) used for aerosol retrieval over land. Table 4 lists MODIS and corresponding VIIRS channels used for aerosol retrieval, along with their center wavelengths and main purposes. The effect of these sensor differences on the retrieved aerosol products, both spectral and spatial, must be understood. This includes effects on the pure retrieval, but also the effects on the masking, primarily cloud masks but also sediments, snow and ice.

Table 4: MODIS and VIIRS spectral (VIS-NIR-SWIR) configuration and aerosol algorithm use of channels

MODIS band* (μm)	MODIS-C6 aerosol algorithm	VIIRS band** (μm)	VIIRS-IDPS aerosol algorithm
B8: 0.412 (1 km)	DB-L, AC-L	M1: 0.412 (750 m)	NG-L
B9: 0.442 (1 km)	AC-L	M2: 0.444 (750 m)	NG-L
B3: 0.466 (0.5 km)	DT-L, DB-L, AC-L		
B10: 0.487 (1 km)	AC-L	M3: 0.486 (750 m)	NG-L
B4: 0.554 (0.5 km)	DT-O	M4: 0.551 (750 m)	
B1: 0.646 (0.25 km)	DT-L, DT-O, AC-L	M5: 0.672 (750 m)	NG-L, NG-O
B15: 0.746 (1 km)		M6: 0.745 (750 m)	NG-O
B2: 0.857 (0.25 km)	DT-L, DT-O	M7: 0.862 (750 m)	NG-L, NG-O
B5: 1.242 (0.5 km)	DT-L, DT-O Snow/Ice/Sediment/ Cirrus mask	M8: 1.238 (750 m)	NG-O and Snow/Ice/Sediment/ Cirrus mask
B26: 1.382 (1 km)	Cirrus mask for DT	M9: 1.375 (750 m)	Cirrus mask
B6: 1.629 (0.5 km)	DT-O	M10: 1.601 (750 m)	NG-O
B7: 2.113 (0.5 km)	DT-L, DT-O, AC-L	M11: 2.257 (750 m)	NG-L, NG-O, bright surface mask

* MCST (1% response)
** NG_VIIRS_NPP_RSR_filtered_Oct2011 (1% response)

(d) Cloud masking issues

When the work of the MODIS-VIIRS continuity team was proposed for ROSES 2010, we envisioned that it would be relatively straightforward to learn how to read and interpret VIIRS data, as well as be able to access open literature about the details of the VIIRS retrieval algorithms. One of our original goals was to "investigate differences introduced by masking and sampling strategies". Masking and pixel choice is known as the fundamental part of any aerosol algorithm. Cloud "contamination" has been identified in the MODIS AOD product in a variety of studies for a variety of reasons (Kaufman et al., 2005; Zhang et al., 2005; Wen et al., 2007; Marshak et al., 2008; Koren et al., 2007), and that there may be a residual 0.015 (or more) AOD bias in the global mean due to cloud contamination.

Our proposed strategy was to create an input data set from the MODIS Level 1B spectral reflectance (i.e. the 0.25, 0.5 and 1km data) and be able to recreate steps analogous to the NGST retrieval algorithm. Specifically, we wanted to apply the VIIRS cloud masking methodology, the VIIRS pixel selection and then the actual VIIRS retrieval algorithm. The results would be analyzed in such a manner to identify biases, and then link the biases to root causes due to specific channels, ocean/land, surface parameterizations, particle properties, type of masking and logic branches in the decision trees. How does VIIRS handle the cloud masking and does it show

the same increase of AOD with cloud fraction as seen in MODIS? How does VIIRS respond to sun glint, to snow and ice, and to bright surfaces? Will the pixels sampled by VIIRS be the same as those sampled by MODIS? Do the differences introduce a bias on a regional or global scale?

Unfortunately, answering these questions required in depth knowledge of the VIIRS IDPS algorithms. The proprietary nature of the NGST meant that there was scarce availability of publicly accessible documentation. The algorithms themselves are embedded in a complicated Interface Data Processing Segment (IDPS) and are of a completely different structure and programming language than traditional MODIS algorithms.

(e) Aerosol product resolution and pixel selection differences

As listed in Table 3, MODIS's primary products (from DT-L and DT-O within MxD04) are total aerosol optical depth (*AOD* at 0.55 µm) over land and ocean, plus particle size parameter over ocean only. The MODIS over-ocean size parameter is given in four manifestations: the fraction of AOD (at 0.55 µm) contributed by small particles, known as *fine mode fraction* or *FMF*; Ångström exponents (*AE*) for two wavelength pairs (0.55/0.86 µm and 0.86 µm/2.11 µm); effective radius; and as spectral AOD in seven wavelengths. All other MODIS products are either derived from these primary products or are diagnostics of the retrieval. Note that prior to Collection 6, MODIS also included AE over land (0.47/0.65 µm) but was dropped from the product list due to having no quantitative value (e.g. Levy et al., 2013).

VIIRS currently produces the same basic information as MODIS: AOD at 0.55 µm over land and ocean, plus a particle size parameter over ocean. However, the VIIRS size parameter over ocean is given only as an AE for the wavelength pair 0.86/1.61 µm and as spectral AOD in 11 wavelengths. There is neither FMF nor effective radius. VIIRS produces an AE over land (0.49/0.67 µm), but preliminary validation suggests there is no quantitative skill. We do not further discuss land AE.

In addition to the basic retrieved products (AOD and size), VIIRS also produces a product called "suspended matter", which currently is an identification and classification of aerosol events when AOD > 1.0. Those events are classified as "dust", "smoke or pollution" or "volcanic ash". The product is currently under revision. The suspended matter product is provided at sensor resolution, 0.75 km at nadir and approximately 1.2 km at swath edge. There is no precedent from MODIS, so we do not discuss it here.

The fundamental product resolution of a MODIS aerosol product is 10 x 10 km at nadir, which is constructed from 200 x 200 sensor pixels of 0.5 km. The fundamental resolution of a VIIRS aerosol product is 6 km, constructed from 8 x 8 sensor pixels (0.75 km). It is unknown whether there is any systematic difference between the NGST operating on 8x8 boxes of 0.75 km resolution VIIRS input data versus MAST algorithm working on 20 x 20 boxes of 0.5 km resolution MODIS input, however, any difference is probably small.

The two algorithms make different assumptions on how to derive the final product. MODIS constructs the 200 x 200 box and discards inappropriate pixels through a chain of masking (e.g. clouds, sediments, ice/snow), and then statistically samples the "good" pixels to pull out the

"best" pixels. What remains are at most 120 pixels over land, or 200 over ocean. The MODIS algorithm averages all remaining "best" pixels and computes a single set of spectral reflectance observations to drive the aerosol retrieval. *One retrieval* (AOD, size) is made on the entire 200 x 200 box. On the other hand, after discarding inappropriate pixels through masking, the VIIRS algorithm makes a retrieval for *every* "good" pixel for the grid cell. Then, the algorithm aggregates the collection (of up to 64) retrievals to report one value (AOD, AE) for the grid cell. We note that the VIIRS method has the potential of reporting aerosol products for every sensor pixel at sensor pixel resolution (~1 km). This is not done now, but could be in the future.

A major difference between MODIS and VIIRS aerosol products is that MODIS produces an operational Level 3 product, a global gridded product. The only way to access VIIRS aerosol products is to download individual on-orbit ungridded granules with their geolocation files separate.

(f) Retrieval algorithm differences

As briefly discussed in Section 3.1, although built on MODIS dark-target heritage, the VIIRS retrieval algorithm was developed independently by the NGST. Here when we mean "retrieval" algorithm, we mean the recovery of the aerosol properties by comparing observed reflectance with simulated reflectance in the lookup tables (LUTs). This assumes that cloud masking, pixel selection, etc, has already been performed. Here, we compare the VIIRS algorithms (as far as we understand) with the corresponding DT algorithms used for MODIS Collection 6 (see Levy et al., 2013). Most information is based on private communication with members of the NGST team, as well as conference presentations (e.g. Jackson et al., 2012).

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Over ocean, the NG-O retrieval strategy is similar to that of the DT-O for MODIS. Following Tanré et al. (1996), we know that the satellite-measured spectral reflectance (in at least four channels between visible, NIR, and SWIR) contains almost three pieces of independent information about the aerosol loading and size properties. With some assumptions, the algorithm can derive three parameters: the AOD at one wavelength (e.g., 0.55 μm), the FMF (at the same wavelength) and the "effective radius", which is the ratio of the 3rd and 2nd moments of the aerosol size distribution. The effective radius is represented by choosing a single "fine" and single "coarse" aerosol mode for combining with the FMF parameter to give the total AOD. The inversion is based on a look-up table (LUT) of four fine modes and five coarse modes, where although the LUT is defined by a single wavelength of AOD, the parameters of each of the single mode models is unique. The trick is to determine which of the (4 x 5 =) twenty combinations of fine and coarse modes and their relative optical contributions best mimics the satellite-observed spectral reflectance. Equality is required at the 0.86 μm (or 0.87 μm for VIIRS). The solution is the combination of single fine and coarse modes, the FMF, and the total AOD, that together minimizes a residual "fitting error" (ε) as compared to the observed spectral reflectance. Once the solution is complete, other products (e.g. AE, spectral AOD, etc) are derived. Finally, the algorithm applies quality assurance confidence (QAC) based on diagnostic tests performed during retrieval.

However, although very similar in concept, there are a number of differences between the VIIRS and MODIS retrieval over ocean, as indicated in Table 5. For example, to reduce potential glint contamination, the DT-O uses a glint mask at 40°, whereas the NG-O employs a variable glint mask that is based on the conditions. Theoretically, when the wind speed is low, the water surface is smoother, and the glint/glitter patch is better constrained. Sensitivity testing performed during DT-O C6 algorithm development showed this was true, as long as the wind speed was well known. Although wind speed is included in C6, the 40° glint mask is retained. In addition to different global coverage due to glint masking, the two algorithms have different assumptions on to what is a valid solar zenith angle to be considered a "high quality" retrieval. The MODIS algorithms allow retrieval under lower light intensity than does VIIRS, and as a result, MODIS C6 product will show aerosol product coverage closer to the poles in the winter hemispheres.

While both algorithms must "couple" the ocean surface with the atmosphere (aerosol + molecular), their procedures differ to when the coupling occurs. For DT-O, there is a single LUT created by radiative transfer (TOA = atmosphere + ocean), whereas for NG-O, the LUTs are computed separately for atmosphere and ocean, which are then coupled during the aerosol retrieval procedures. Presumably, there is a computational or accuracy advantage to one method or the other. The point, however, is that the differences in procedures will lead to different results. Also noted in Table 5, is that different radiative transfer codes are used in LUT computations, and that VIIRS retrieval includes a dependence on wind direction, in addition to dependence on wind speed. During MODIS Collection 6 development (Levy et al., 2013), it was found that gas absorption and errors in gas absorption assumptions can lead to systematic biases (on order of 0.01 in AOD) in the retrieval. Biases of similar magnitude can result from assumptions in radiative transfer, and ocean/atmosphere coupling. It is not known whether the differences in RT, surface/atmosphere coupling, and other assumptions listed will be additive or cancel out.

Tanré et al., (1996) demonstrated that the DT-O retrieval algorithm works with six wavelengths bands. Even though the NG-O uses only five VIIRS bands, sensitivity tests show there should not be a major loss of information. With the 0.55 μm band, the DT-O retrieval has an advantage for retrieving fine-mode aerosol information, but there is added uncertainty due to ocean color and underwater sediments. The 0.75 μm (VIIRS) channel does not have ocean color contamination.

In addition to differences in wavelengths, the residual (or error) is computed differently. While the NG-O computes an "absolute" least squares error, the MODIS algorithm includes a denominator, so that the error is relative to Rayleigh only conditions. The 0.01 in MODIS is to prevent dividing by zero. Both DT-O and NG-O sort the fine/coarse model solutions by residual error magnitude. The NG-O sets the solution as the "best" retrieval (lowest error), and derives additional products (e.g. AE) based on this single solution. The DT-O, while also noting the "best" solution, uses all solutions that meet a given error criteria (e.g. $\varepsilon<0.03$), and derives the "average" solution. Again, it is not known how differences in residual calculation will impact the global aerosol product.

Table 5 Comparable MODIS and VIIRS –assumptions used in aerosol retrieval over ocean.

	MODIS	VIIRS
Valid Glint Angle	> 40°	>30° (but variable based on internal consistency)
Valid Solar Zenith Angle (for high QAC)	< 82°	≤ 65°
Bands used in inversion	6: 0.55, 0.65, 0.86, 1.24, 1.63, 2.11 μm	5: 0.67, 0.75, 0.87, 1.61, 2.26 μm
Ocean surface	Cox-Munk, Koepke, plus wind speed dependence	Cox-Munk, Koepke, plus wind speed and direction dependence
Ocean surface coupling	Ocean surface included in LUTs	Ocean surface computed and coupled during inversion.
Radiative transfer used for LUT	MODRAD (Ahmad et al., 1991)	6SV (Kotchenova et al., 2008)
Gas absorption assumptions (H_2O, O_3, CO_2 + …)	Formulas based on measured filter functions, and 6sV	Formulas based on hypothetical square filter functions and 6sV.
Residual formula	$\epsilon^c = \frac{1}{N}\sum_{\lambda=1}^{N}\left(\frac{\rho_\lambda^{OBS} - \rho_\lambda^{LUT}(\tau_A^c)}{(\rho_\lambda^{OBS} - \rho_\lambda^{RAY} + 0.01)}\right)^2$	$\epsilon^c = \frac{1}{N}\sum_{\lambda=1}^{N}\left(\rho_\lambda^{LUT}(\tau_A^c) - \rho_\lambda^{OBS}\right)^2$
Solution type	Products are based on average of "good" solutions.	Products are based on "best" solution.
Quality Assurance	According to MODIS QA plan	According to VIIRS QA plan.

LAND

As compared to relatively "similar" over-ocean algorithms, the NG-L (based on MODIS AC-L) and DT-L are significantly different. From the presentation given at Fall 2012 AGU (Jackson et al., 2012), the NG-L algorithm proceeds as:

- The surface reflectance in the red (0.67 μm) and blue (0.49 μm) bands is calculated for each value of AOT and each (of four choices of) aerosol model in LUT by solving the Lambertian TOA reflectance equation:
- The best AOT value for each model is the one which satisfies the *expected surface reflectance ratio* between the blue and red bands for vegetated surfaces.
- Then, for each aerosol model, solve for the surface reflectance at 0.41 μm, 0.44 μm and 2.26 μm using the AOT value for that model.
- Compute a residual based on the expected 0.41 μm, 0.44 μm and 2.26 to 0.67 μm surface reflectance ratios.
- Select the model with the lowest residual.
- The assumed VIIRS surface reflectance band ratios are unchanged from those assumed for MODIS (even though VIIRS bands are different than MODIS).
- Updated surface reflectance band ratios computed using VIIRS / AERONET match-up data are currently undergoing testing.

The DT-L algorithm, on the other hand, has a different philosophy.

- Fine-model aerosol type is assumed as a function of season and location, and is iteratively mixed with a global dust model

- The aerosol reflectance in the red (0.65 μm), blue (0.47 μm) and SWIR (2.11 μm) bands is calculated for each value of AOT and many values of fine-model/dust fraction:
- There is an *expected surface reflectance relationship* between red and blue channels for vegetated surfaces, as well as between red and SWIR.
- Aerosol reflectance is coupled with surface, with the expected surface reflectance used as a constraint. Matching is imposed in the red.
- For each combination of AOT and fine/dust weighting, solve for the coupled TOA reflectance in blue and SWIR.
- Compute a residual based on the simulated blue and SWIR (compared to observations).
- Select the combination of AOT and weighting with the lowest residual.

These are different retrieval philosophies, although the products (AOD at 0.55 μm) are the same. Based on never doing an extensive comparison of the DT-L and AC-L algorithms for MODIS, we do not have a strong feeling whether one algorithm is significantly better than the other. However, they are different and the results will be different. In addition, many of the differences in assumptions (as listed in Table 5, above), such as radiative transfer, formats of LUTs, gas corrections, etc, are also issues when it comes to comparing MODIS and VIIRS algorithms and products.

(g) File format differences

While not a retrieval/algorithm/product difference, per se, there are also significant differences in MODIS and VIIRS product file formats. For example, as already indicated in Table 1, the VIIRS "granule" size is 86 seconds, compared to 5 minutes for MODIS (factor of 3.5). A full days' (daylight) AOD retrieval for VIIRS requires close to 475 granules, compared to 135 for MODIS. At the same time, VIIRS IDPS products use "HDF5" format, rather than the "HDF4" format used for MODIS. Most tools built for reading and interpreting MODIS data will not work for VIIRS.

The MODIS Level 2 files (MxD04) include significant diagnostic information about the aerosol retrieval process. This information includes the input data (spectral reflectance and geometry) used for each retrieval box, as well as multiple parameters about the quality of the retrieval such as fitting errors and quality assurance information. The metadata for each variable (scale factors, fill value information, valid range information, etc) is also included within the MxD04 file. On the other hand, most of this information is not included within the VIIRS file, but rather requires download of additional files.

Each MxD04 output files is based on a small set of input files. Specifically, based on the filename, it is easy to determine which set of seven input files were used to drive the MODIS retrieval algorithm. Specifically, these inputs include three files containing calibrated reflectance data, one file containing geo-location information, a cloud mask file, an atmospheric profile file, and two "ancillary" input files from NOAA. On the other hand, a single VIIRS retrieval requires separate input files for each wavelength band, each metadata of each wavelength band, plus dozens of other files. The VIIRS file structure, although optimized for hyper-parallel computer processing, makes it difficult for a user to follow and re-create the VIIRS retrieval. This

becomes very important when diagnosing problems, and specifically for our problem of evaluating MODIS → VIIRS product continuity.

None of these are insurmountable problems, but many users of the MODIS data, when attempting to transition to the new VIIRS data, will most likely face a steep learning curve.

(h) Potential consequences of differences

Each of these differences introduces challenges in creating a smoothly joined aerosol CDR from MODIS and VIIRS data records. Orbit and resolution differences introduce sampling differences that can create offsets in global mean aerosol statistics. Spectral differences make it impossible to apply the current MODIS algorithm blindly to the VIIRS-measured radiances. Then, decisions in how to mask inappropriate pixels, organize pixels for retrieval and apply retrieval algorithms introduce wide openings of opportunity for final results to differ significantly.

In the work here we focus on two questions:

1. Does the current operational VIIRS aerosol EDR product continue the MODIS record sufficiently well to create a seamless CDR? (sensor + algorithm)
2. If not, is there anything about the VIIRS sensor itself that would prevent the creation of a continuous MODIS+VIIRS CDR if a uniform aerosol algorithm were to be applied to the entire dual-sensor record?

3.3 Evaluation strategy

As summarized in section 3.2, there are many differences between MODIS and VIIRS sensor, algorithms, production and product formats. We can begin by comparing the MODIS L2 and VIIRS EDR products. However, this will not explain why there are particular differences, nor identify which of the differences have the biggest impacts.

On the other hand, if it was possible to make MODIS and VIIRS data "look more like each other", then it may be possible to more accurately and logically study the true MODIS → VIIRS differences. At the same time, if we can run the "same" retrieval algorithm on both datasets, then we can begin to ***quantitatively*** account for differences between the data. This is the strategy we have applied to evaluate the MODIS → VIIRS continuity.

(a) Pre-launch evaluation by NOAA/NESDIS/STAR

The first step of this approach was started pre-launch by Co-I Laszlo (see http://www.star.nesdis.noaa.gov/smcd/emb/aerosols/research_NPP_NPOESS_VIIRS.php). Here, the pre-launch VIIRS algorithm was modified to run with MODIS "proxy" data. The changes were necessary because the VIIRS aerosol algorithm contains routines that were specifically designed for the VIIRS spectral bands, specifically the estimation of surface reflectances in bands M1, M2, M3 and M5 from that in the near infrared band (M11), and the correction of top of atmosphere radiances for gaseous absorption. In order to directly use the MODIS radiances in

the algorithm the appropriate modules were replaced with ones that are based on the MODIS bands (B8, B9, B10, B1 and B7). The look-up-table appropriate for the MODIS spectral bands using the VIIRS aerosol models and Mie calculations was also calculated. Like the VIIRS-NGST algorithms, the STAR team used 6SV radiative transfer code (1997) to create the LUTs. Thus, there was now a VIIRS-like (VL) retrieval code that could be run on MODIS input data.

At the same time the MODIS Aerosol Science Team (MAST) produced a version of the MxD04 file that included spectral reflectance at these three "extra" channels, in addition to the seven channels (B1-B7) normally included. One year (2006) of these "modified" MODIS reflectances were input into the VIIRS algorithm and processed Note that these special MOD04 reflectance files contained cloud-screened, gas-absorption-corrected, spatially-filtered/averaged spectral reflectances. It is stressed that the STAR team used the spectral reflectance in the MODIS aerosol product, NOT the inherent Level 1 radiances input by the operational MODIS code. The reflectances that Laszlo used were the exact reflectances used by the MODIS aerosol code. *They had already been cleared of clouds, sediments and inappropriate land surface, selected for retrieval and averaged to represent the mean spectral reflectance in a 10 km retrieval grid box.* They had also already been corrected for gaseous absorption. Using such pre-prepared input reflectances eliminates all inconsistencies due to different sampling, and tests directly the consistency between the two different retrieval codes. Theoretically, the only difference was the slightly different spectral configurations of the two instruments (Table 4).

The time series of daily global, and land vs. ocean AOD retrievals from VL on MODIS were examined and compared to those in the C5 MOD04 product. Even with this extreme care for consistency, there was systematic difference between using the VL code and the operational MODIS aerosol results. It was found that global AOD was underestimated by VIIRS relative to MODIS year round, but especially in September. Overestimation in NH (spring) and underestimation in SH (September) was observed over land. Over ocean, VIIRS underestimated the AOD in both hemispheres.

The results described above were obtained from an earlier version of the VIIRS algorithm in which the over-land retrieval used a DT approach similar to the one used in MODIS C4. The current version (IDPS-like) was later applied to a set of MODIS 10-km aerosol reflectances for six months of data (days 1-32 and 182-213 of 2003, 2008 and 2010). These reflectances were specifically processed by the GSFC MODIS team so that they included reflectances in MODIS bands 8, 9 and 15 in addition to those already available in the MODIS aerosol product. In running the VIIRS aerosol algorithm the gas absorption calculations were turned off for MODIS bands 1-7, since these were already corrected for gas absorption by the MODIS aerosol team, but they were handled by the algorithm for bands 8, 9 and 15, since these reflectances included gas absorption. The results from this dataset indicated that, relative to MODIS, the VIIRS AOD were biased high by 0.018 and 0.024 over land for January and July, respectively. The overall VIIRS positive bias came from overestimation of MODIS AOD values less than 0.6. Over ocean VIIRS AOD was lower than MODIS AOD on average; VIIRS-MODIS biases were -0.023 and -0.026 for January and July, respectively. VIIRS also reported significantly lower AOD over dust plums and polluted regions. On the other hand, at high latitudes VIIRS AOD tended to be larger than MODIS AOD.

Why were there differences between VL on MODIS and MODIS itself? Of course most of the differences were due to the details of the retrieval algorithms, but was there anything more specific? Some of these specifics could have included:

- Over ocean:
    - Surface dependence on wind speed: VL Yes, MODIS C5 No.
    - Radiative transfer and LUTs: VL used 6SV, MODIS uses MODRAD. Plus LUTs are organized differently.
    - Gas correction assumptions: VL used 6SV, MODIS uses something historical
    - Quality assurance and retrieval confidence issues. What is a "good" retrieval?
    - Major differences in particle property assumptions.
    - Dynamic retrieval of aerosol model from a set of candidate models in VL as opposed to mix a geographically and seasonally dependent single model with dust in MODIS.
    - Etc
- Over land:
    - VIS/SWIR Surface reflectance relationships. VL on MODIS was not tuned for MODIS-specific bands
    - AC-L versus DT-L algorithm heritage (different wavelengths, different inversion process, etc)
    - Radiative transfer and LUTs: VL uses 6SV, MODIS uses RT3. Plus LUTs organized differently
    - Gas correction assumptions
    - Quality assurance and retrieval confidence issues. What is a "good" retrieval?
    - Major differences in particle property assumptions.
    - Etc

Yes, there are major differences, and prior to VIIRS launch, the STAR team did get into details of an early version of the NGST algorithm, which also applied DT approach over land. However, a similar detailed analysis of the final VIIRS algorithm was not done. Now after VIIRS launch, we have the ability to get into more detail and more understanding about both the now-operational VIIRS algorithm and have better understanding and control over the MODIS retrieval algorithm. We can do this statistically by sorting data into different categories. Low AOD conditions highlight issues introduced by surface assumptions. High AOD highlight issues introduced by particle property assumptions. Also comparing diagnostics can prove to be even more valuable than comparing primary products. Fitting error, quality flags, information on chosen model and size parameters all provide clues into why two algorithms applied to exactly the same inputs would result in systematically different AODs. While AOD has been emphasized, we will also examine carefully the respective retrievals of size parameters over ocean (fine fraction and/or Angstrom Exponent). Size parameter over land holds little quantitative physical value. It is being removed from the MODIS Collection 6 data set, and will not be examined in the work proposed here.

(b) The A-PEATE and the Intermediate File Format (IFF)

One of the biggest hurdles to evaluate the MODIS-VIIRS transition (with real VIIRS data) is the difference between file formats and diagnostic information. Few of the tools MAST has developed over the last dozen years work for reading VIIRS data. In addition, we found the sheer effort for VIIRS file bookkeeping to be nearly insurmountable.

However, in support of traditional MODIS users and other members of the VIIRS science team, NASA created the *Product Evaluation and Algorithm Testing Elements* (*PEATE*). In fact, there are three PEATEs, each focused on the needs of major research disciplines (Atmosphere, Land and Ocean). The Atmosphere-PEATE (A-PEATE), run by the University of Wisconsin, has been tasked with helping the VIIRS-Atmosphere Science team members attain their respective goals. A-PEATE has provided global imagery for both VIIRS and MODIS, along with tools to extract and visualize imagery and products over specific locations. The Land-PEATE (L-PEATE), run at NASA-GSFC, has also contributed data to our efforts.

For the MV-ACT, both PEATEs have worked to repackage the VIIRS data in a more familiar format. They have aggregated the tedious 86-second granules into MODIS-like five-minute granules, and have created tools to convert the VIIRS 'hdf5' format into traditional MODIS 'hdf4' format.

Most importantly, in direct collaboration with the MV-ACT and other instrument teams, the A-PEATE has created a product known as the Intermediate File Format (IFF). The IFF is intended to:

- Make it easier to test algorithms that use either MODIS or VIIRS data
- Create the same format for both MODIS and VIIRS
- Bypass issues with VIIRS including granule size (85.7 sec), ridiculous number of files, and HDF5 format
- Restore bowtie deletion zone pixels in VIIRS

The IFF is designed so that:

- One file format for both MODIS and VIIRS data
- HDF4 format with all data stored as 32-bit floats
- HDF4 internal compression to save space
- All bands with the same spatial resolution are stored in one file (e.g., all MODIS 1 km bands in one file, all VIIRS M-bands (0.75 km) in one file)
- Geolocation data are stored with image data in the same
- Land/sea masking information is the same (both based on MODIS)
- Granule size is 5 minutes for both MODIS and VIIRS. VIIRS data are aggregated the same way as MODIS. If the start time of a VIIRS scan falls within a 5-minute window, that entire scan is assigned to that 5-minute granule.
- Bowtie deleted VIIRS pixels are restored

Fig. 26 displays imagery based on a single channel (NIR) of both MODIS (B2, 0.86 μm) and VIIRS (M7, 0.87 μm), acquired on June 3, 2012, from orbits over North America. Although the orbits are nearly overlapping (five minute difference), note slightly different positions of clouds and glint. Also note the wider swath width for VIIRS.

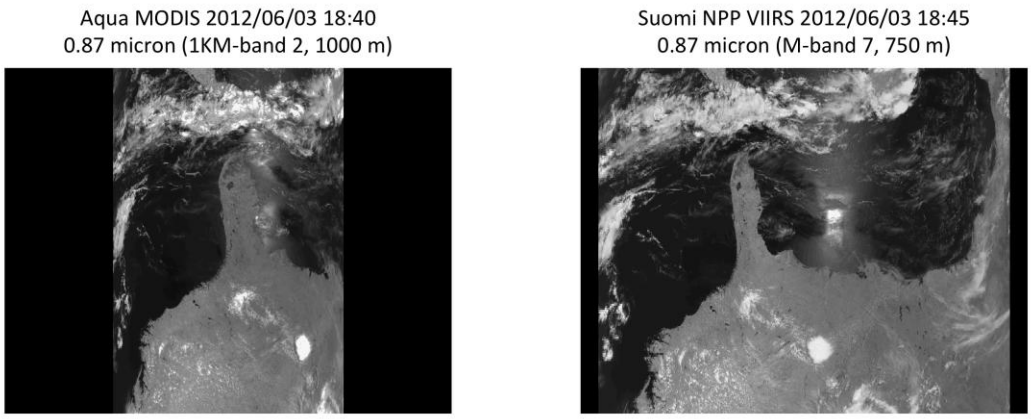

Figure 26: Un-projected imagery of NIR (0.86/0.87) bands as reported in MODIS and VIIRS IFF files. Note ascending orbits, so North is down.

It turns out that a minor difference between the two IFF is that MODIS L1B reflectance data are scaled by cosine of the solar zenith angle, whereas VIIRS SDR reflectance data are not. Fig. 27 presents histograms of L1B/SDR reflectance taken from standard MODIS/VIIRS files and IFF files, once cosines are properly taken into account. All histograms are taken from a small bounding box over Africa (20°S, 8°E) to (28°S, 12°E), observed on Jan 11, 2012. There are slight differences in time (MODIS overpass at 12:40, VIIRS at 12:35 UTC), and thus, slight differences in geometry (also see Fig. 30). Nonetheless, one can see from Fig. 27 that generally, the two satellites are measuring similar quantities, yet there are systematic differences between observed reflectances in each set of wavelength bands. While most bands have a systematic shift (from shorter MODIS wavelengths to longer VIIRS wavelengths), the largest differences are seen in blue (shifts from 0.466 μm for MODIS to 0.486 μm for VIIRS) and red (shifts from 0.644 μm for MODIS to 0.672 μm for VIIRS). As a sanity check, we note that the IFF files are perfectly corresponded with the appropriate L1B files.

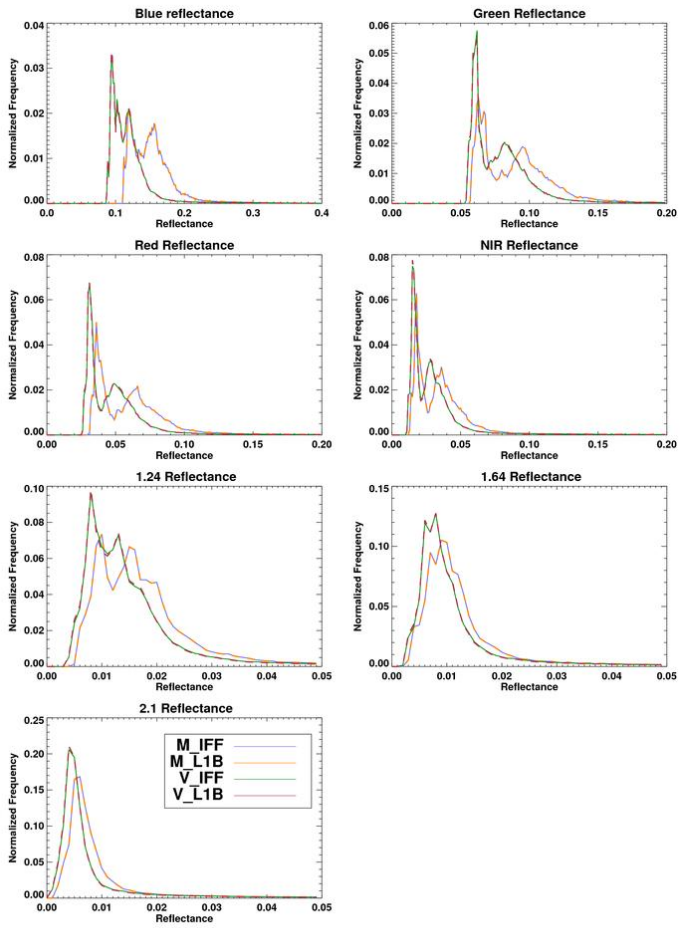

Figure 27: Histograms of MODIS and VIIRS reflectance taken from standard operational files (L1B/SDR) as well as IFF files, all extracted from a region near Africa on June 11, 2012. The bounding box is (20°S, 8°E) to (28°S, 12°E). Panels are associated with wavelength region, for MODIS/VIIRS (blue = B3/M3; green = B4/M4; red = B1/M5; NIR = B2/M7; 1.24 = B5/M8; 1.64 = B6/M10; 2.1 = B7/M11). Note that the VIIRS and MODIS observations were taken 5 minutes apart, and will not have identical geometry (see Fig. 30).

(c) MODIS-like retrieval run on IFF

In section 3.3(a), we discussed a preliminary attempt to run the VIIRS-like algorithm on MODIS data. However, while the algorithms were run on the same dataset, the algorithms themselves were inconsistent. The VIIRS-like algorithm was not tuned for MODIS wavelengths, nor was the same ancillary data used for both, so it was difficult to interpret the results. It was clear that the VIIRS-like algorithm derived lower AOD than MODIS over the ocean, and higher over land, but there was no way to determine why this was the case.

With the two IFF files (MODIS at 1KM and VIIRS at 0.75KM), now it was possible to run nearly the same *algorithm* on both datasets. In this case, based on our experience in MODIS algorithm development, we could modify the C6 algorithm so that it could be tuned to either dataset. Following is a list of the work that was performed to create MODIS-Like (ML) algorithm to be run on both IFF file inputs:

- Create analogous LUTs for VIIRS (over both land and ocean), using the same assumptions as for creating LUTs for MODIS (C6, Levy et al., 2013). This meant
    - Confirming center wavelengths from Table 4
    - Calculating Rayleigh (molecular) optical depths
    - Assuming refractive indices for aerosols are identical as those for analogous MODIS wavelengths
    - Lookup tables in same format, and can be read by the same read-code.
    - Over-land computed by RT3 (as DT-L) and over-ocean computed by MODRAD (as DT-O).
    - Computed for VIIRS channels M3, M4, M5, M7, M8, M10, M11
- Calculate (using 6SV) gas absorption coefficients:
    - Substituting actual VIIRS filter functions for VIIRS "placeholder" filter functions in 6S code
    - Perform same procedures for gas corrections as discussed in Levy et al., 2013 for MODIS C6.

Next, we created a software structure so that "if VIIRS" the retrieval would use VIIRS LUTs and gas assumptions, and "if MODIS" it would use MODIS LUTs and gas assumptions. The ancillary data (e.g. ozone and wind speed from NCEP) is the same for both sensors.

We ignored the issue of spatial resolution (MODIS 1 km versus VIIRS 0.75 km), and considered all retrievals to be performed by aggregating 10 x 10 "boxes" of the input resolution. This means that final results would be at 10 x 10 km (nadir) for MODIS and 7.5 x 7.5 km (nadir) for VIIRS, but would spread out towards edges of each. Since neither IFF file includes IR channel information ($\lambda \geq 3.7$ μm), and the standard MODIS IR tests could not be used for cloud masking (introducing possible cirrus contamination over ocean to both datasets), both ML-IFF algorithms relied only on 3x3 spatial variability (visible and 1.24 μm) and visible reflectance threshold tests. Although VIIRS wavelengths are slightly shifted spectrally from MODIS wavelengths, we assumed that for masking cloudy pixels, underwater sediments, ice/snow, and bright surfaces, the thresholds for spatial variability and absolute reflectance were the same as for MODIS C6. The non-cloud pixel filtering remained the same as MODIS C6 (25-75% over ocean; 20-50% over land). Of course, because all masking and filtering is set to work on 10 x 10 pixels (rather than 20 x 20 pixels for MODIS C6), retrieval availability may be impacted.

3.4 Results

(a) Imagery: Granule and gridded AOD

Figs. 28 and 29 present two examples of single granule retrievals from MODIS and VIIRS, including the operational products (MODIS C6 and VIIRS EDR) as well as the two MODIS-like retrievals applied to the A-PEATE's IFF inputs. Retrieved data having sufficient QAC are plotted, which means for MODIS C6 and MODIS-like, we require QAC=3 over land and QAC≥1 over ocean. For the VIIRS EDR, the requirement is QAC=3 over both land and ocean.

For both Figs 28 and 29, there is a strong degree of similarity between each panel. Both the patterns and magnitudes of the AOD are consistent. However, for each set of four panels, there is an outlier. For Fig 28 (over North Asia), the outlier is the VIIRS-EDR. There is a larger percentage of aerosol "coverage", and the general magnitude is larger. There are clouds in this image, which seems to indicate that the major difference is cloud mask, and not necessarily aerosol retrieval. For Fig. 29 (over Africa), the outlier is probably the MODIS-like on MODIS IFF. Here the issue is not clouds, but identification of "bright" scenes not suitable for retrieval. The retrieval is set up to degrade results (to lower QAC values) when the observed reflectance in SWIR channel (2.11 for MODIS, 2.26 μm for VIIRS) is greater than 0.25. Due to slight differences in the reflectance histograms at this channel (as suggested in Fig. 27), the decision to use or not to use a particular ground location will vary between retrievals. The slight differences in solar/sensor geometry (five minute differences) will also add to the discrepancies. Note however, the consistency between all retrievals as to the spatial pattern and magnitude of the plumes off into the ocean.

Fig. 30 presents a comparison of the preliminary MODIS C6 data and the VIIRS-EDR for an entire day, the date (June 11, 2012) chosen because there was significant overlap of MODIS and VIIRS orbits. Data are gridded to 1° x 1° boxes (similar to MODIS Level 3), where all data with sufficient QAC values (QAC=3 over land for all retrievals; QAC=3 over ocean for the V_EDR and QAC≥1 for M_C6). From Fig 30, we see a significant difference in aerosol coverage, even for a day with near overlap of orbits. For this day, there was closer orbit "overlap" for the Eastern hemisphere (bottom right panel). Clearly, the V_EDR has a wider swath and smaller glint mask. At the same time it has reduced coverage in the southern hemisphere oceans, due to solar zenith angle thresholds (see Table 5), and simply "different" coverage over much of Asia and the rest of the continents, most likely due to variety of reasons. The bottom left panel of Fig. 30 shows the differences (V_EDR – M_C6), for cases where both reported data. Over ocean, there is both high bias and low bias, but no strong indication that the overall bias is one way or another. Over land, however, the V_EDR is generally biased high.

Fig. 31 provides, in addition to the M_C6 and V_EDR, 1° x 1° gridding of the MODIS-Like retrievals based on MODIS and VIIRS IFF files. The MODIS-Like data requires the same QAC as the MODIS C6. In addition, Panel 5, grids only the ML on VIIRS when the solar zenith angle is less than 64° (ML_V_64). This constraint excludes the VIIRS wide view angles, thus providing a dataset that is theoretically more similar to the conditions experienced by MODIS. The last panel plots the differences (ML_V_64 - ML_M) data, showing that there remains a consistent high bias over land. Over ocean, there are both positive and negative differences, with the largest biases along the Saharan dust track. Presumably, these biases are less about aerosol retrieval, and more about differences in orbital coverage. Even with the 64° threshold, the VIIRS swath is slightly wider than MODIS (this putting more dust retrievals into each grid box).

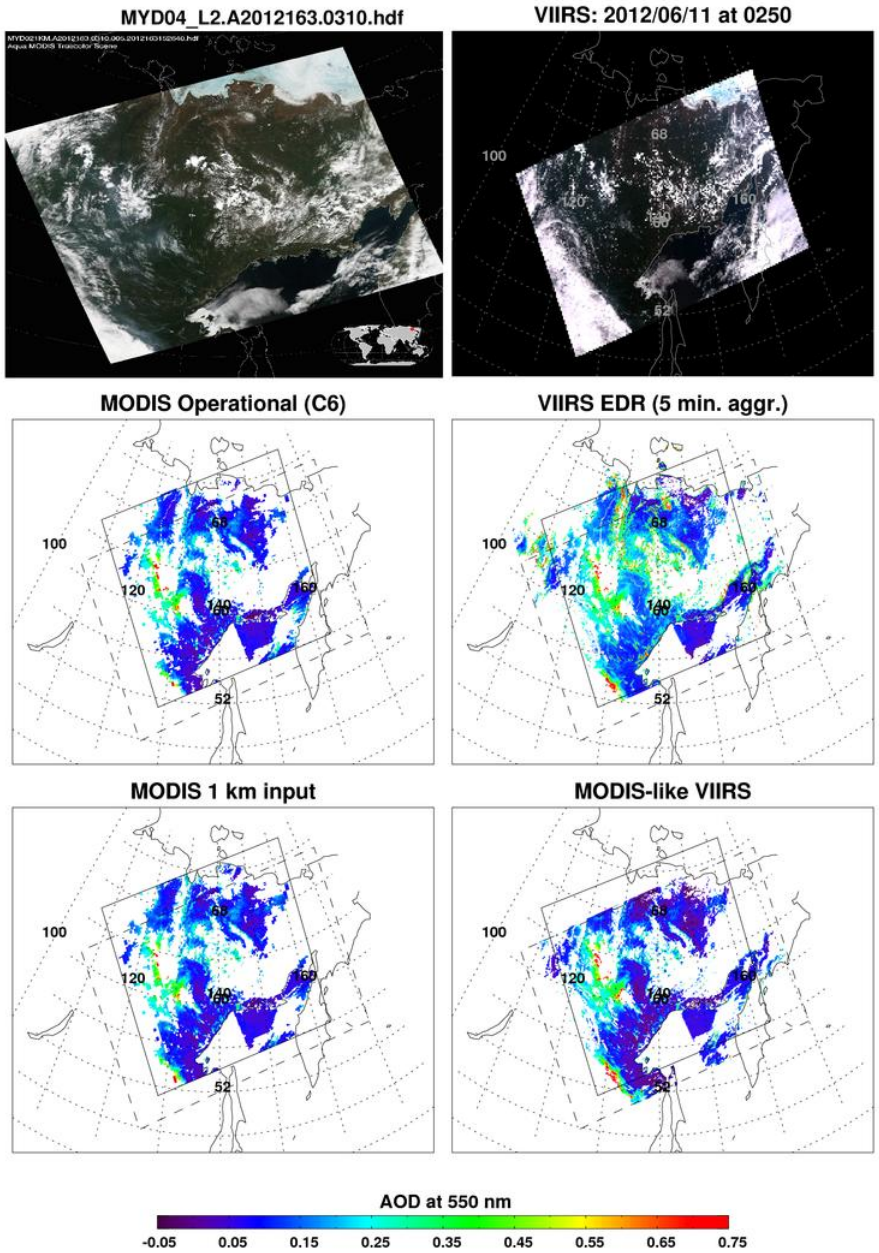

Figure 28: Multiple aerosol retrievals (AOD at 0.55 μm) for north Asian scene from June 11, 2012. RGB "true color" images are presented for MODIS and VIIRS in the top row. The second row displays high quality (recommended QAC levels) for MODIS C6 and the VIIRS EDR retrievals. The third row displays MODIS-Like retrievals based on MODIS-IFF and VIIRS-IFF. For each retrieved panel, MODIS granule box is solid, whereas VIIRS is dashed line. Note that the MODIS-VIIRS overlap is not complete, and that there is twenty minutes between satellite overpasses.

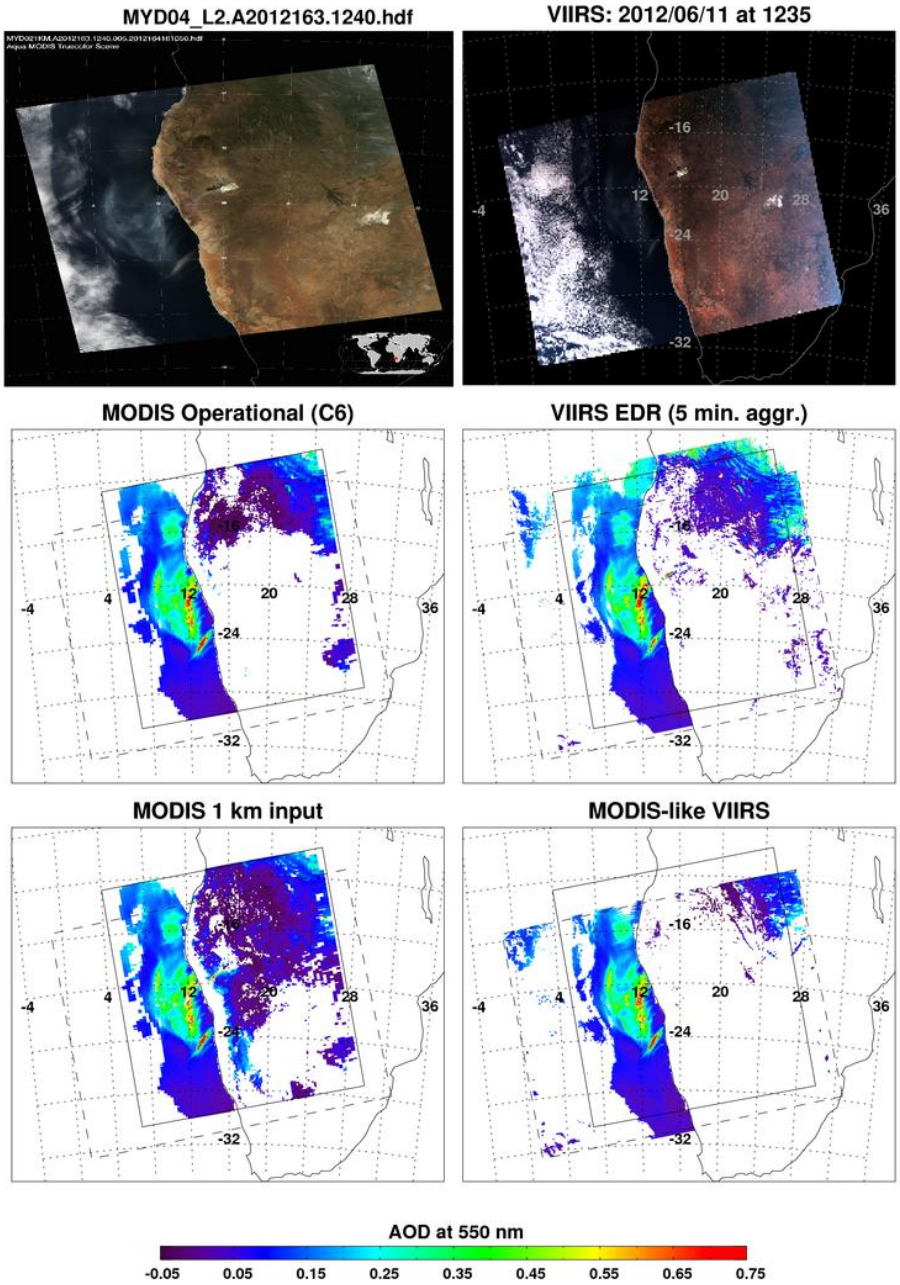

Figure 29: Same as Fig. 28 but for a region off coastal Africa. For this location, there is five minute difference in overpass time.

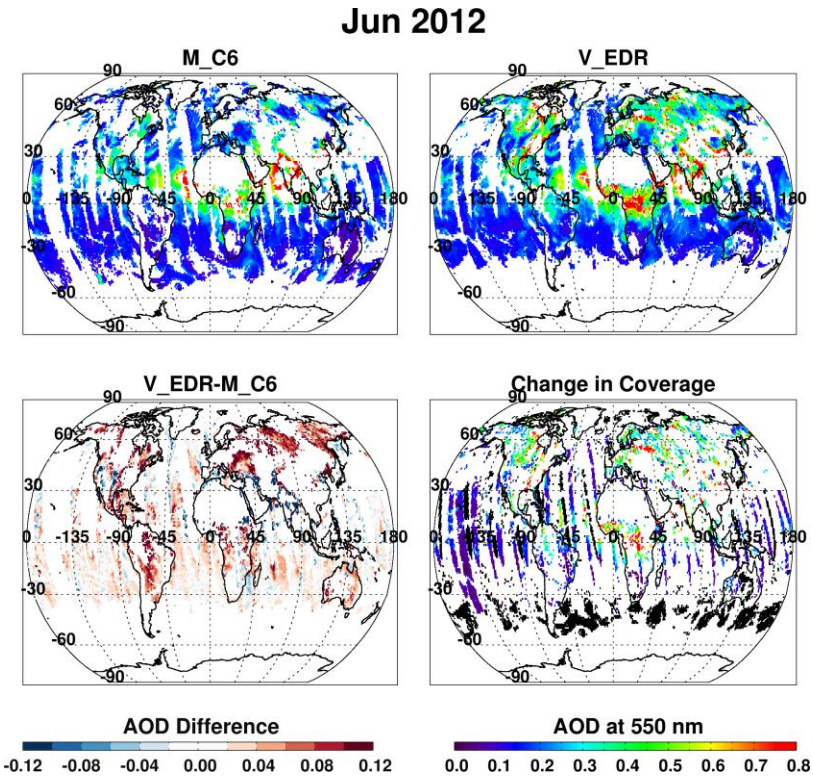

Figure 30: Global, gridded AOD (at 0.55 μm) for entire day, June 11, 2012, showing MODIS C6 (top left), VIIRS-EDR (top right), the differences between the two (bottom left) and the difference in Level 2 coverage (bottom right). The colorbar for the AOD is also used for the "change in coverage", where colors represent additional coverage of VIIRS-EDR (compared to MODIS), and the black shows reduced coverage.

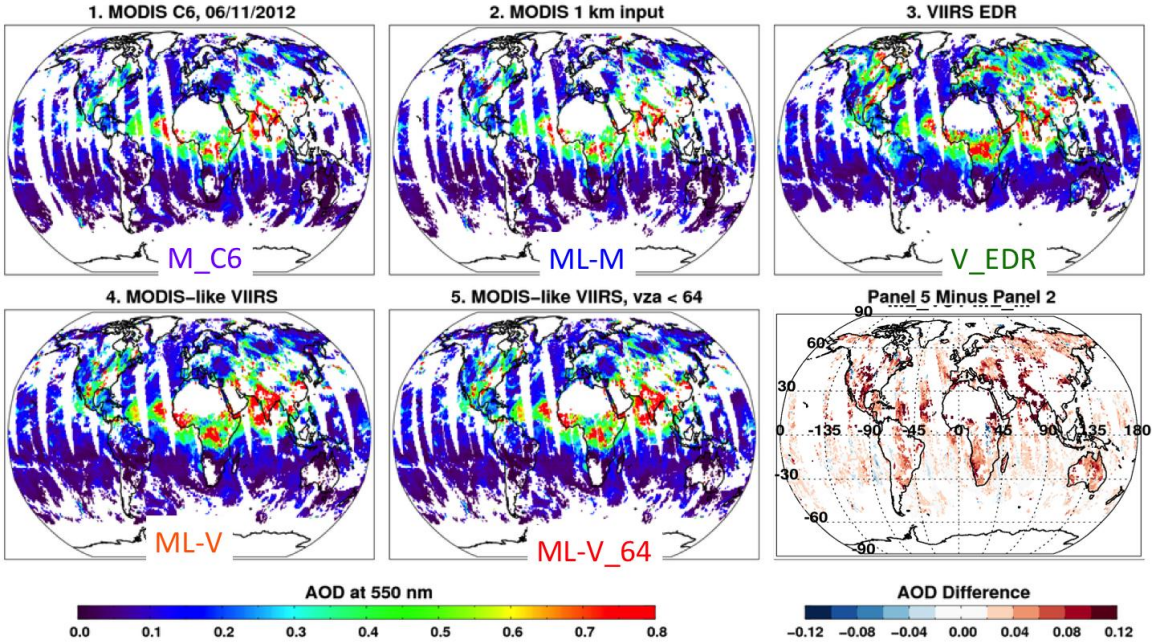

Figure 31: Global, gridded AOD (at 0.55 μm) for entire day, June 11, 2012. Each panel is a version of aerosol retrieval. The last panel is the difference between the MODIS-Like on VIIRS-IFF (constrained by VZA ≤ 64°) versus MODIS-Like on MODIS-IFF.

(b) Statistics: Global means and histograms

Granule imagery and global maps do not tell the whole story. When it comes to climate applications such as global aerosol loading and radiative forcing, we also require a number of other statistics. To assess climate continuity, how does the global average AOD compare between the different datasets? Tables 6 and 7 report AOD statistics (mean only) for the same day, June 11, 2012, over ocean and land, respectively. Clearly, by only assessing the global mean AOD, one would find that the V_EDR is approximately 0.015 higher than M_C6 over ocean, and 0.09 higher over land. As we go from M_C6 to ML on MODIS-IFF, we have changed sampling and cloud masking enough to have a small impact on global mean AOD (-0.005 for ocean, +0.006 for land). Going to the ML on VIIRS-IFF, we increase AOD towards the V_EDR levels on both ocean and land. Over land, the ML_V has split the difference.

However, these mean AOD values need some more interpretation. "Granule count" refers to the number of 5-minute granules in the dataset, and we note that there may be one or more missing granules in the dataset. In the case of ML_M versus M_C6, there are 19 granules that have been thrown out by the operational algorithm due to being in nearly complete darkness near the poles. This contributes to the ML_M attempting 0.2% more retrievals than operational M_C6. However, because of the difference in resolution (1km versus 0.5 km) between the ML_M and M_C6 inputs, plus the lack of the IR-based cloud masking in the ML_M, there are bigger percentage differences in the number of QAC-filtered pixels. Because of the difference in resolution between VIIRS-IFF (0.75 km) and MODIS-IFF (1 km), and the wider spatial coverage of VIIRS, MODIS-Like on VIIRS-IFF attempts triple the retrievals as on MODIS-IFF over ocean, with a comparable increase in the number of successful, filtered retrievals. Over land, this is less straightforward; the fraction of successful retrievals for ML_V is much higher than ML_M, which for the reason is not known. We know that this analysis is not yet complete.

Table 6: Granule statistics for AOD over ocean, for June 11, 2012.

Version	Granule Count	Total pixels attempted	QAC-filtered pixel count	QAC-filtered Mean AOD
M_C6	131	2313053	460357	0.1086
ML_M	150	2364192	327765	0.1031
ML_V	152	7677777	1244976	0.1245
ML_V64	152	6726560	1084340	0.1201
V_EDR	151	11045900	1341926	0.1212

Table 7: Granule statistics for AOD over land, for June 11, 2012.

Version	Granule Count	Total pixels attempted	QAC-filtered pixel count	QAC-filtered Mean AOD
M_C6	131	1160502	133837	0.1473
ML_M	150	1196077	159091	0.1533
ML_V	152	3781527	561976	0.1953
ML_V64	152	3274176	493534	0.1988
V_EDR	151	4530845	820357	0.2367

Another way of looking at these global AOD statistics is to look at histograms. Fig 32 displays relative frequency histograms (normalized to the total number of QAC-filtered pixels) for each

of the five datasets. Over ocean (top), there is not a strong difference between each of the datasets. The most significant difference is that the VIIRS EDR does not provide data in the smallest bin (between -0.05 to 0.00). It turns out that the MODIS DT-O (Collection 6) algorithm has a procedure for setting AOD to "exactly zero" in certain conditions, yet receive high confidence (QAC=3, see Levy et al., 2013). The NG-O algorithm does not, and will degrade AOD retrievals when the algorithm tries to retrieve zero (or negative). As for the ML on VIIRS (ML_V and ML_V64), the source of the larger global mean AOD is a small relative increase in the frequency of moderate AOD (0.10-0.20) at the expense of the near zero bins. This could be a result of small calibration differences between VIIRS and MODIS (analogous to offsets between MODIS-Terra and MODIS-Aqua; Remer et al., 2008). Nonetheless, the upshot of the over-ocean histogram is that based on one day, all retrievals over ocean are similar.

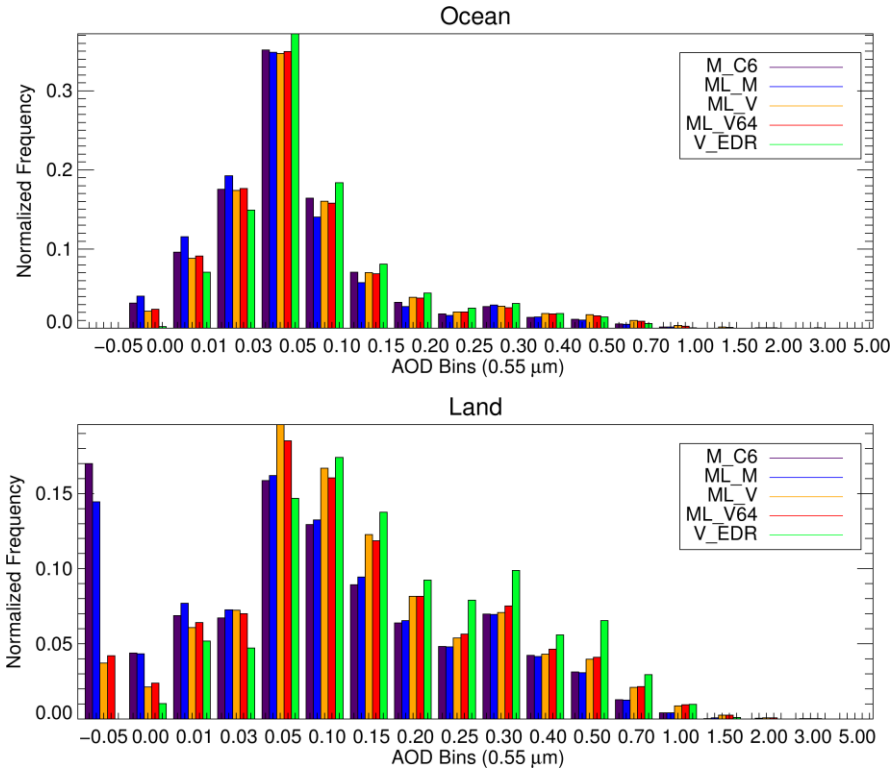

Figure 32: Normalized frequency histograms for retrieved AOD during June 11, 2012 for all algorithms.

On the other hand, the histograms for land retrievals show very large differences as we go from MODIS to ML_V to the V_EDR. The MODIS DT-L algorithm allows retrievals of zero and small negatives (to -0.05) where the VIIRS NG-O algorithm does not. The V_EDR are significantly skewed high compared to MODIS, with the ML_V (and ML_V64) less so. It is interesting to note that even though the ML algorithm allows negative AOD, that there are much fewer of these values retrieved on VIIRS-IFF as compared to MODIS-IFF. The reason may be related to decisions based on thresholds of SWIR (2.26 versus 2.11 µm) reflectance (discussion in section 3.4c), instrument calibration, or some other reason. Also, this is only for a single day, so specific plume sampling will also be an issue. On the other hand, while there are differences for the ML algorithm applied to the two IFF datasets, their histograms are more similar to each other than V_EDR compared to the M_C6. The updated surface-reflectance ratios in the VIIRS

algorithm are expected to shift the V_EDR to the left, hopefully making it more similar to that for ML_V.

(c) A major loose end: land surface reflectance assumptions

While we believe that aerosol reflectance properties, and even cloud masking algorithms should not change "much" with respect to small spectral shifts (MODIS versus VIIRS), we probably cannot assume the same is true for assumptions of land surface optical properties. Fig. 33 plots typical reflectance spectra for green vegetation (grasses), demonstrating that surface properties in VIIRS bands will be different from those in MODIS bands. For MODIS, Levy et al., (2007b) derived VIS vs 2.11 surface relationships of approximately 0.53 and 0.49, for 0.65 μm /2.11 μm and 0.47μm /0.65 μm, respectively (with additional dependencies upon scattering angle and NDVI). These values were considered "global", so they would be representative of many vegetated surfaces. These relationships were chosen in order to minimize systematic bias in retrieved AOD for MODIS DT-L.

Fig. 33 suggests that relative changes in surface reflectance, as a function of small shifts in wavelengths, will not be the same in all three MODIS/VIIRS channel pairs. The surface reflectance contribution (to total TOA) may not change much when shifting in the blue (from 0.466 to 0.486 μm) or in the SWIR (from 2.113 to 2.257 μm) channels, but there may be a significant changes to magnitudes of red band reflectance (from 0.645 to 0.672 μm). This means that there could be significant bias in ML on VIIRS if the MODIS-developed ratios (e.g. Levy et al., 2007b) were to be directly applied. In fact, the relationships derived for AC-L (on MODIS) were copied to the NG-L operational algorithm (on VIIRS), and is likely the major cause for systematic high bias in the operational NG-L products. Likewise, since we did not have any "new" information (e.g. atmospheric correction of VIIRS data like was performed for MODIS; Levy et al., 2007b), we applied the same coefficients for ML on VIIRS as were used for the NG-L algorithm. For the purposes of our generic MODIS-like aerosol retrieval algorithm, although we know that the MODIS-derived land surface relationships should not be used for VIIRS wavelengths, we do not yet know how to tune them. Therefore, our results were for non-tuned surface reflectance relationships. We discuss this issue in our recommendations of Section 3.5.

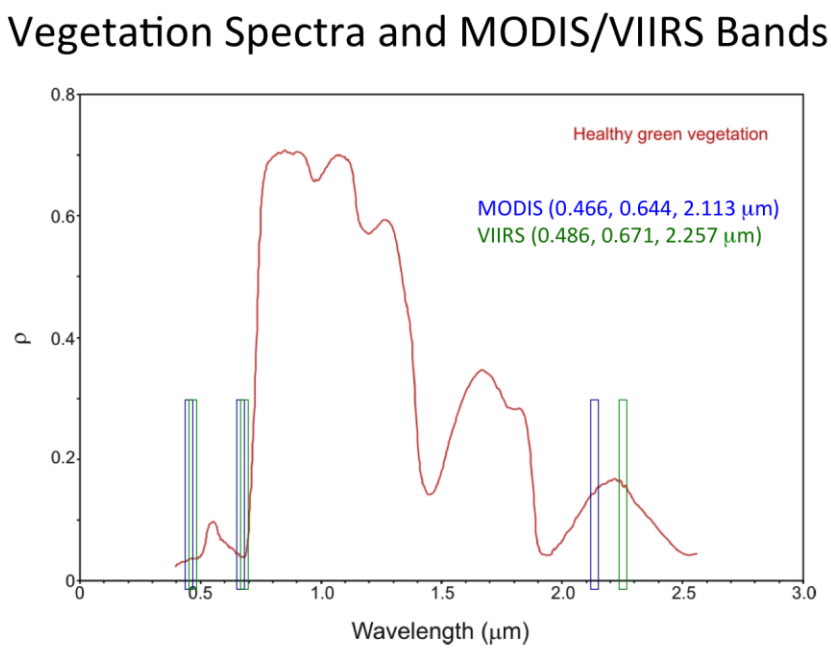

Figure 33: Typical spectra for green vegetation, showing relative position of MODIS-like aerosol retrieval on MODIS and VIIRS IFF inputs.

3.5 Summary/Next steps

For more than ten years NASA's MODIS sensors have been producing the "dark-target" aerosol products over land and ocean (DT-L and DT-O), within an HDF4 file format known as MxD04. The MODIS retrievals of aerosol optical depth (AOD) at 0.55 μm, have been embraced and are now indispensable for many applications, both operational and research oriented. As we move toward the JPSS era, we have a strong need to assess the continuity of the aerosol data record. Specifically, as research "climate" scientists, our team (the MV-ACT) is interested in the ability for VIIRS to continue the aerosol climate data record (CDR) as begun by MODIS. We are lucky to have both MODIS (on Terra and Aqua) flying concurrently with VIIRS. This means that as of January 2013, we have nearly a full year of overlapping data to evaluate and assess the continuity of the aerosol data records. In fact, a casual user can see that the operational VIIRS AOD looks qualitatively very much like the MODIS AOD product. Is this good enough?

As we discussed in section 3, although MODIS and VIIRS have similar capabilities, and the aerosol retrieval algorithms come from the same heritage, there are a huge number of differences between the VIIRS-derived and MODIS-derived aerosol products. The instruments have different orbits and thus different ground sampling. They have different strategies for dealing with bowtie effects and oversampling near swath edges. While all spectral bands used in the MODIS aerosol retrievals have analogues on VIIRS, their central wavelengths and filter-functions differ. This means that many assumptions made for MODIS (such as Rayleigh optical depths, gas absorption corrections, surface optical properties and cloud masking/clearing thresholds) should not be directly transferred over to VIIRS. Any and all of these differences can lead to systematic differences in regional and global AOD. Without detailed and published

sensitivity studies, a focused user would not have any idea "how" different these two datasets really are. In addition MODIS and VIIRS have different strategies for masking clouds and other inappropriate pixels (including ice/snow/sediments/glint/bright surfaces, etc), so it is impossible to make apples-to-apples comparisons.

Unfortunately, while the problem is quickly being solved, currently there is scarce documentation for the VIIRS products and algorithms. At this point, we know (Hsu's section) that the operational IDPS VIIRS products are different from MODIS operational (Collection 5). The work of the MV-ACT team is to determine how big the differences are, and whether the differences could be reduced or mitigated in some way. Since there are so many differences of instruments, approaches, algorithms and products, we would like to isolate as many as we can.

Therefore the strategy of the MV-ACT (discussed in section 3.3) is to determine if it is possible to continue the MODIS data record by applying the MODIS retrieval algorithm to VIIRS observations. We accomplished the following:

- Worked with the Atmosphere-PEATE (A-PEATE) to create Intermediate File Format (IFF) data for both MODIS (M-IFF) and VIIRS (V-IFF)
- Created aerosol LUTs and gas absorption corrections for VIIRS, using the exact same techniques as for MODIS, but tuned for VIIRS spectral bands
- Developed cloud masking that worked with 10 x 10 boxes of either M-IFF or V-IFF, ignoring differences in resolution (1 km versus 0.75 km), and issues of bowtie effect near edges
- Modified the pre-operational Collection 6 MODIS retrieval algorithm code to create a MODIS-Like (ML) algorithm to apply onto either IFF dataset.

After setting up all algorithms, we ran pre-operational C6 on standard MODIS L1B data (M_C6), ML on M-IFF data (ML_M), and ML on V-IFF data (ML_V). This was done for a single day (June 11, 2012), the date chosen because of a high degree of orbital overlap between MODIS and VIIRS. Results from all three datasets (M_C6, ML_V and ML_M) were then compared with each other, and to the standard VIIRS-EDR (V_EDR) products from IDPS. In addition, we created the ML_V_64 which was the ML_V constrained to sensor zenith angles less than 64° (more similar to maximum MODIS view angles).

When going through this exercise (for one day only), we found that (Section 3.4):

- Imagery shows that the spatial patterns and magnitudes of V_EDR look very much like the M_C6 data. The ML_M and ML_V also look similar.
- As designed, the statistics of the ML_M and the M_C6 are nearly indistinguishable, however, there are tiny differences in imagery, global means and histograms, due to input spatial resolution (1 km versus 0.5 km), lack of IR cloud masking in the ML algorithm, and strict flagging of "night" granules in the pre-operational M_C6 code. All differences are too small to be significant.
- Spatial coverage of the V_EDR is both less (stricter thresholds on solar zenith angle, impacting pole-ward regions) and more (wider swath and less glint angle restriction)

than M_C6 (or ML_M). The transition to ML_V improves upon the spatial coverage near the poles.

- For this one day, as compared to M_C6 (or ML_M), global mean AOD for V_EDR is higher by 0.015 over ocean and by 0.09 over land. We note that one reason for the difference is that neither the NG-O or NG-L algorithms allow retrievals of zero or negative AOD. This is clearly seen in the histograms.
- Over ocean, as we transition to ML_V, the high bias remains. The histograms show that the source of the high bias is a tiny shift towards higher bin values, although the shape is the same. We hypothesize that this slight bias (0.015) may in fact be a calibration difference (e.g. Terra compared to Aqua), although this needs to be proved.
- Over land, as we transition to ML_V, the extremely high bias is reduced by half. There are many fewer retrievals of negative AOD, which may be calibration, or is more likely related to blindly applying the surface reflectance relationships that are tuned to MODIS (section 3.4c).

At this point, the MV-ACT has demonstrated that it is possible to apply a MODIS-Like algorithm to VIIRS data, and produce results that are more consistent with historical MODIS (C6) data. However, there are still inconsistencies that need to be solved. While histograms show that MODIS and VIIRS, if using the same algorithm, seem to be observing the "same world" over ocean, there must be reasons for the remaining difference. Is it calibration? Over land, the differences are still too large to be acceptable. Of primary interest is the assumptions related to surface reflectance assumptions. Co-I Laszlo and other members of the NOAA Cal/Val team have calculated new values for surface reflectance assumptions appropriate for VIIRS spectral bands. Preliminary indications are that these new values are likely to improve comparability with operational MODIS data, however they have not been tested within the framework we have presented here. This is ongoing research.

We realize we have analyzed these MODIS-Like algorithms with only a single day (June 11, 2012) of overlapping data. At this time, we are running the ML on an entire month. Since this is not (currently) intended as operational dataset, there are still some issues to be worked out before we are satisfied that the results would be consistent. This is also ongoing research.

Our intention is to study not only products of total AOD (at 0.55 μm), but also aerosol size (e.g. AE and FMF) over ocean. It may be much more difficult to achieve CDR "continuity" for size (or spectral dependence of AOD) than it is to achieve continuity of AOD. Studies of aerosol retrieval "availability" (e.g. Remer et al., 2012) will be needed in light of the differing resolutions of MODIS and VIIRS. This is also ongoing research.

Finally, we understand that running a MODIS-Like algorithm on both datasets, while providing a better continuity of data products, may not be the optimal solution for creating the best aerosol CDR. There is not necessarily a reason why the MODIS DT algorithms should be "better" than the NG algorithms. It may be possible to create a satisfactory CDR using the VIIRS algorithm. There is a continuing effort by Co-I Laszlo and the STAR/NOAA group to update the VIIRS algorithm on MODIS data. As long as a single algorithm is applied to both datasets, and it is applied consistently, then we have the possibility of CDR continuity.

4. Recommendations for the way forward: The entire NPP VIIRS aerosol science team

Deriving the long-term aerosol trend for climate studies is a highly challenging task. The long-term aerosol variability is small and usually embedded in the much larger variability associated with the shorter (such as seasonal) time scale. Average AOD over the globe is on the order of 0.15, and the global trends over the last decade are at most 0.01/decade [Hsu et al., 2012]. Therefore, it is critical that long-term aerosol data records be constructed with adequate accuracy, precision and, most importantly, long-term stability (i.e., consistency) before satellite measurements can provide useful information to help constrain climate models and thus address the question as to how climate responds to changes in aerosols on global scale. At this point, based on our study presented in this document, we can make the following statements

- Compared to the AERONET measurements, the VIIRS IDPS aerosol EDR performs reasonably well over ocean. However, over land, the current VIIRS AOD is generally biased high, in particular over urban regions.
- Qualitatively (e.g. spatial patterns of AOD), the VIIRS IDPS looks similar to MODIS C6 DT and DB over dark surfaces.
- There is a lack of data coverage over desert and semi-desert regions in VIIRS IDPS data due to bright surfaces.
- Quantitatively, VIIRS is biased high compared to MODIS on Aqua (by 50% or more over land, and 10% over ocean). *This difference is much too large to be considered acceptable for inclusion into the continuous climate data record (CDR).*
- There are many reasons for the VIIRS biases, but *one is that it is uses a different retrieval algorithm.*
- Using common algorithms will help to quantify the differences between the two sensors.

Through extensive efforts made by the MODIS algorithm teams over the past years, the MODIS aerosol products from both DT and DB have become mature and well-characterized, and they have become widely accepted by the community. We believe that the VIIRS IDPS algorithm will continue to improve and, with time, may eventually reach the level of maturity to address the operational needs on the short-term variability of aerosols.

However, constructing long-term continuous CDRs requires data continuity across different satellite platforms. We found that there are a number of critical elements currently lacking in the VIIRS IDPS processing system that could impede the data continuity from MODIS to VIIRS, including:

- Periodic recalibrations of VIIRS bands using rigorous solar and lunar measurements consistently throughout the whole time series.
- Development of Level 3 (gridded) products for VIIRS aerosol products to meet the needs of modeling community and to make the processes of intercomparison and consistency check with MODIS more efficiently.
- Use of common retrieval algorithms for both MODIS and VIIRS.

- Reprocessing of the data set, which is essential to ensure that the incremental improvements made in the retrieval aerosol algorithm are incorporated in the data and applied consistently across the entire time series.

Processing VIIRS data with the same algorithms as those used for MODIS is only one step that must be taken before there is true aerosol continuity from MODIS to VIIRS. There are still many other issues that need to be addressed as well, including:

- How do the different "sampling" of VIIRS swath width and orbital coverage impact aerosol product statistics?
- How do differences in input resolution (0.5 km and 1 km for MODIS; 0.75 for VIIRS) impact aerosol product statistics?
- Even though we can (theoretically) account for spectral differences in calculating lookup tables and gas absorption corrections, how does wavelength "shifting" affect statistics?
- Can differences in instrument "calibration" be quantified?
- How do any of the above differences affect retrievals of aerosol seasonal cycles?

Fortunately, MODIS and VIIRS are both currently flying and performing well and, to this point, there is at least a year of overlapping observations. For the future, we recommend the following:

- The comparison datasets should be extended for as long as possible.
- The PEATEs have been providing valuable support in terms of developing diagnostic tools and processing science data; their effort should be continued and expanded if possible.
- Although not originally planned by NASA, we strongly urge continuation of a MODIS-like algorithm on VIIRS, or development of a VIIRS-like algorithm on MODIS. These products should be available through the normal avenues (e.g. available on the PEATEs), so that long-term MODIS users can transition to them successfully. As demonstrated by the results in this report, without the consistency in the retrieval algorithm from MODIS to VIIRS, the capability of deriving accurate long-term trends of aerosols on regional and global basis for climate sciences will be severely hampered, if not impossible.

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