Evaluation of MODIS and VIIRS Aerosol Optical Depth Retrievals: An update

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Motivation

• In the NPP/NPOESS era the MODIS aerosol retrievals will be replaced by those from the Visible Infrared Imaging Radiometer Suite (VIIRS).

• Current MODIS and VIIRS aerosol algorithms are sufficiently different to potentially produce different AOD.

• The differences might effect the continuity of MODIS aerosol record, and they might effect the radiation budget derived from satellite measurements. Both are important climate parameters.

• Evaluation of VIIRS aerosol algorithm under a wide variety of real conditions over a long period are needed.
Two STMs ago …

- Have set up a system for routine retrieval and comparison of MODIS and VIIRS AOD.
- From the two days studied:
  - Water: bias = 0.007 (5% MODIS) (=2/10 of expected MODIS error (0.035) for typical (0.1) AOD) (but RMS = 40%!)
  - Land: bias = 0.009 (6% MODIS) (=1/10 of expected MODIS error (0.08) for typical (0.2) AOD)
- Aerosol model and FMW retrievals also differ.
  - Factors affecting the calculation of residual can affect the AOD by selecting very different models.
- AOD retrieval is most sensitive to the choice of reference channel and surface reflectance calculation/retrieval. ===> NGST has changed reference channel in over-ocean retrieval!
Strategy

- Use one year (2007) global MODIS Terra retrievals
- Use clear-sky TOA reflectance from C5 MOD04
  - Cloud-screened, gas-absorption-corrected, spatially-filtered/averaged MODIS reflectance
  - Use above reflectances directly in VIIRS algorithm (bypassing gas absorption correction) to avoid sampling difference.
  - Only algorithm differences affect the AOD!
- Compare VIIRS and MODIS retrievals
- NEW: Compare VIIRS and MODIS retrievals with AERONET measurements (Level 1.5, spatial (50km) and temporal (1hr) match-up)
The MODIS-VIIRS Test Bed

**MODIS Algorithm**

- Data screening
- Gas absorption correction
- Pixel selection
- Averaging
- Retrieval

**VIIRS Algorithm**

- Averaging
- Gas absorption correction
- Retrieval

**MODIS L1B and L2 data**
- MOD02-HKM: reflectances in first 7 bands
- MOD02-1KM: 1.38-μm reflectance and 11-μm brightness temperature
- MOD35: cloud mask
- MOD03: geolocation/geometry
- MOD07: O3 and water vapor amount

**Ancillary model data (NCEP)**
- [wind speed & direction]

**LUT (for MODIS bands)**
### Over water

<table>
<thead>
<tr>
<th></th>
<th>MODIS C5</th>
<th>VIIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface pressure</strong></td>
<td>Constant – sea level.</td>
<td>Rayleigh optical functions are corrected to actual surface pressure.</td>
</tr>
<tr>
<td><strong>Aerosol models</strong></td>
<td>4 fine modes 5 coarse modes</td>
<td>Same as MODIS collection 4</td>
</tr>
<tr>
<td><strong>Channels used</strong></td>
<td>0.55, 0.66, 0.86, 1.24, 1.64 and 2.13µm</td>
<td>0.672, 0.746, 0.865, 1.240, 1.610, 2.250µm</td>
</tr>
<tr>
<td><strong>Reference channel</strong></td>
<td>0.86µm</td>
<td><strong>1.24µm originally; was changed to 0.86µm</strong></td>
</tr>
</tbody>
</table>
Features of MODIS and VIIRS AOD … (cont)

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<tr>
<th>Over water</th>
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<tbody>
<tr>
<td>Residual calculation</td>
<td>$\sqrt{\sum_{\lambda=1}^{6} N_\lambda \left( \frac{\rho^m_\lambda - \rho^{\text{LUT}}<em>\lambda}{\rho^m</em>\lambda - \rho^{\text{env}}<em>\lambda + 0.01} \right)^2 / \sum</em>{\lambda=1}^{6} N_\lambda}$</td>
<td>$\sqrt{\sum_{\lambda=1}^{6} \left( \rho^m_\lambda - \rho^{\text{LUT}}_\lambda \right)^2}$</td>
</tr>
<tr>
<td>Searching for the FMW</td>
<td>Interval halving</td>
<td>Brute force. (discrete 101 fractions with interval of 0.01)</td>
</tr>
<tr>
<td>Surface reflectance contribution</td>
<td>Constant wind speed (6 m/s)</td>
<td>Explicit calculation of the direct and diffuse water reflection given ancillary wind speed and direct. TOA reflectance is calculated by combining atmospheric and surface contributions.</td>
</tr>
<tr>
<td></td>
<td>Built into LUT</td>
<td></td>
</tr>
<tr>
<td>RTM for LUT</td>
<td>Ahmad and Fraser (1981)</td>
<td>6sV1.1</td>
</tr>
</tbody>
</table>
### Over land

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<th>VIIRS</th>
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<tbody>
<tr>
<td><strong>Surface pressure</strong></td>
<td>Actual pressure is from surface elevation.</td>
<td>Elevation and synoptic variation of surface pressure are considered.</td>
</tr>
<tr>
<td></td>
<td>LUT is adjusted to simulate different molecular optical depth by adjusting the wavelength.</td>
<td>Molecular contribution is adjusted in calculation of TOA reflectance.</td>
</tr>
<tr>
<td><strong>Channels used</strong></td>
<td>0.47, 0.66 and 2.12 ( \mu m )</td>
<td>0.488 and 0.672 ( \mu m )</td>
</tr>
<tr>
<td><strong>Reference ch</strong></td>
<td>0.47 ( \mu m )</td>
<td>0.488 ( \mu m )</td>
</tr>
<tr>
<td><strong>Aerosol models</strong></td>
<td>3 nondust and one dust model (updated using AERONET). Mixture is determined separately for each retrieval.</td>
<td>Five typical land aerosol models from AERONET.</td>
</tr>
</tbody>
</table>
Features of MODIS and VIIRS AOD … (cont)

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<tr>
<td>Surface reflectance</td>
<td>Surface reflectance at SWIR is determined in conjunction with AOD and FMW retrieval. Updated linear relationship between VIS and SWIR for dark surface.</td>
<td>Separate linear relationships between VIS and SWIR for vegetation and soil dominated surface.</td>
</tr>
<tr>
<td>Retrieval</td>
<td>Simultaneous retrieval of surface reflectance, AOD and FMW.</td>
<td>1) surface reflectance in each band; 2) AOD and residual for candidate models. 3) AOD and model from smallest residual.</td>
</tr>
<tr>
<td>RTM for LUT</td>
<td>RT3 (Evans and Stephens)</td>
<td>6sV1.1</td>
</tr>
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</table>
RESULTS

- Comparison of VIIRS AOD with MODIS AOD
  - global, hemispheric and regional averages
- Comparison with AERONET
Global AOD (550 nm) is underestimated by VIIRS relative to MODIS year round.

More significant in September.
Hemispheric Averages

VIIRS AOD relative to MODIS AOD

Over Land:
- Overestimation in NH (spring)
- Underestimation in SH (Sep)

Over Ocean:
- Underestimation in both hemispheres
- More negative bias in SH
Regional Monthly Averages

March

VIIRS

MODIS

VIIRS-MODIS

September

VIIRS

MODIS

VIIRS-MODIS
Regional Monthly Averages (cont.)

Land:
- Overestimation over bright surface
- Underestimation of biomass burning aerosol over South America

Ocean:
- Underestimation over mid- and high-latitudes
- Overestimation at dust dominated regions
- Underestimation of smoke AOD around South Africa
• Over land, VIIRS-MODIS AOD and surface reflectance differences are correlated. \( R = -0.49 \)

• Over ocean, underestimation of AOD by VIIRS is correlated with high wind speed. \( R = -0.63 \)
- In addition to surface effects, difference in aerosol model also contributes to the difference of AOD between VIIRS and MODIS:
  - South America
  - West coast of South Africa
• VIIRS retrieval suggests more fine mode particles than MODIS, therefore, higher Ångström Exponent.
Sensitivity Tests: FMW over Ocean

September

VIIRS with MODIS C5 Aerosol Models & Wind speed fixed at 6m/s
Sensitivity Tests: Effects on AOD

September

VIIRS with MODIS C5 Aerosol Models & Wind speed fixed at 6m/s
Summary of Sensitivity Tests Over Ocean

- Global average AOD and FMW for Sep 2007.
- Switching to MODIS C5 aerosol models and fixed wind speed in VIIRS reduces AOD and FMW differences.
- Changing aerosol models reduces FMW by -0.085 (12.65%), while increases AOD by 0.004 (3.28%).

![Graph showing sensitivity tests over ocean with key points for VIIRS and MODIS FMW and AOD550.](graph.png)
COMPARISON WITH AERONET
AERONET sites

Ocean (77)  Land (226)

Symbol size is proportional to number of comparisons.

- Uneven distribution of stations.
- Many ocean stations are in coastal areas.
• Orthogonal fit; standard errors are in parenthesis.
• Compared with AERONET, VIIRS has a slightly larger positive bias and RMSE than MODIS.
• Satellite estimates agree better with each other than with ground measurements.
Wind Speed Effect

- $\text{AOD}_{\text{VIIRS}} < \text{AOD}_{\text{MODIS}}$ for high (>10 m/s) wind speed.
- $\text{AOD}_{\text{MODIS}} > \text{AOD}_{\text{AERONET}}$ for high wind speed (Zhang & Reid, 2006)

- For high (>10 m/s) wind speed, VIIRS-AERONET bias $<<$ MODIS-AERONET bias, but RMSEs are about the same.
• Ångström Exponent (AE) calculated from AOD at 0.47 and 0.86 μm.

• Compared with AERONET, VIIRS AE bias is much higher than MODIS due to higher FMW retrieved by the VIIRS algorithm.
Comparison with AERONET over Land

- Compared with AERONET, VIIRS and MODIS biases are comparable.
- RMSD of VIIRS AOD is larger than that from MODIS.
Surface Effects

- Difference in surface reflectance estimation contributes to the difference of retrieved AOD.
- VIIRS applies two distinct relationships for ‘vegetation’ and ‘soil’ dominated surfaces
• Large difference of AOD even for the same surface reflectance.
• New surface scheme in VIIRS retrieval did not improve AOD retrieval.
Case study: Biomass Burning

- AOD_{VIIRS} < AOD_{MODIS} in South America in Sep.
- AOD is dominated by biomass burning in August and September.
- Compared with AERONET, VIIRS does underestimate smoke AOD.
Summary

Over Ocean
- Compared to MODIS:
  - VIIRS has a negative AOD bias (-0.016 ~ 11%), largely due to high wind speed over mid- and high- latitude regions.
  - VIIRS overestimates dust AOD.
  - VIIRS underestimates smoke AOD coming from South Africa.
  - VIIRS retrieves higher FMW (larger AE).
- Compared with AERONET:
  - VIIRS has larger positive AOD and AE bias and RMSE than those from MODIS.

Over land
- Difference in estimated surface reflectance contributes to difference of retrieved VIIRS and MODIS AODs.
- Compared to MODIS:
  - VIIRS retrieves higher AOD over relatively bright surfaces and underestimates smoke AOD over South America.
  - VIIRS AOD is more variable (Std is 1.5 times that of MODIS).
- Compared with AERONET:
  - VIIRS AOD has larger RMSE than MODIS.
• **NGST finding:** Compared to AERONET over ocean, the VIIRS 550-nm AOD retrievals have a smaller bias and a smaller standard deviation than the corresponding MODIS retrievals (Jackson and Vermote, March 2008 TIM):
  
  - Bias (MODIS) = -0.010, STD(MODIS) = 0.057
  - Bias (VIIRS) = -0.002, STD(VIIRS) = 0.046
  - Statistics from 78 points.

- VIIRS(NESDIS) ≈ VIIRS(NGST), but likely not identical (e.g., LUTs used with MODIS data are likely to be different)

- More investigation is needed!