MODIS Atmospheres webinar series #3: Collection 6 ‘e-Deep Blue’ aerosol products

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Images from NASA Earth Observatory, http://earthobservatory.nasa.gov/Features/Aerosols/
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Overview

• Aerosol terminology
• MODIS terminology
• e-Deep Blue
  – Principles
  – Examples of level 2 data
  – New for Collection 6
  – Validation
• Summary
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Aerosol Optical Depth (AOD): total column optical extinction of aerosol at a given wavelength
- Most commonly, 550 nm ($\tau_{550}$)
- Related to how much aerosol is in the atmosphere
- Also termed aerosol optical thickness (AOT)
Aerosols can travel a long way

- Mineral dust from Taklimakan desert transported to North America
  - Hsu et al., IEEE TGARS (2006)
- We also see Asian pollution transported to North America, Saharan dust transported to the Amazon and Europe, African smoke transported to South America, Asian dust to Europe, high-latitude smoke circling the world in both hemispheres, etc...
Ångström exponent (AE, $\alpha$): spectral dependence of AOD

- Values < 1 suggest optical dominance of coarse particles (e.g. dust)
- Values > 1 suggest optical dominance of fine particles (e.g. smoke)
- Depends on wavelength range used to calculate it

From Eck et al., JGR, 1999
Aerosols and properties of interest: SSA

- Single Scatter albedo (SSA) : measure of light absorption by aerosols
  - SSA = 0: Pure absorbing aerosols (never encountered)
  - SSA = 1: Pure scattering aerosols
  - Typical range ~0.8 (some industrial/smoke) - 0.99 (‘clean’ continental, marine aerosols)
  - Also has wavelength dependence

From Dubovik et al., JAS, 2002
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MODIS data product terminology

MODIS: Moderate Resolution Imaging Spectroradiometer

• Data product ‘Level’ designations relevant to the MODIS Deep Blue aerosol products
  – Level 1b (L1b): calibrated/geolocated instrument data
  – Level 2 (L2): derived geophysical retrieval data (‘pixel’ level)
  – Level 3 (L3): gridded data (spatiotemporal aggregation of Level 2)

• MODIS data “Collection”
  – A (re)processing production run with consistent baseline algorithms
  – Collection 5 (C5) reprocessing (2006) was the first to include Deep Blue
  – Current version is Collection 6 (C6)
    • Aqua level 2 processing complete
    • Aqua level 3 imminent
    • Terra level 2/3 to follow after

• This webinar is about MODIS C6 (mostly Aqua Level 2) data
MODIS data product terminology

Terra MODIS:  MOD06_L2.AYYYYDDD.HHMM.CCC.YYYYYDDDHHMMSS.hdf
Aqua MODIS:  MYD06_L2.AYYYYDDD.HHMM.CCC.YYYYYDDDHHMMSS.hdf

Definition of highlighted text:

- **MOD06** = Earth Science Data Type name
- **L2** = Denotes a Level-2 product (or L3 for Level-3, etc.)
- **A** = indicates following date/time information is for the acquisition (observation)
- **YYYYDDD** = acquisition year and day-of-year
- **HHMM** = acquisition hour and minute start time
- **CCC** = collection (e.g., ‘006’ for Collection 6)
- **YYYYDDDHHMMSS** = production data and time
- **hdf** = denotes HDF file format

- Data products relevant to this presentation:
  - **MOD04, MYD04** (Level 2 aerosols)
  - **MODATML2, MYDATML2** (Level 2 joint atmospheres)
  - **MOD08, MYD08** (Level 3 joint atmospheres)
The MODIS sensor

- 36 spectral bands from visible to thermal IR
- Spatial resolutions (level 1b) 250 m to 1 km at nadir
  - ‘Bowtie effect’ leads to pixel enlargement and distortion near swath edges
  - Note standard MODIS aerosol products are at nominal 10 km resolution
- Swath width 2,300 km, giving near-global daily coverage
- Flying on polar-orbiting platforms
  - Near-constant local solar time of observation ~10:30 am (Terra, descending), ~1:30 pm (Aqua, ascending)
  - 14-15 orbits per day, 16-day orbital repeat cycle
  - Data organised into 5-minute ‘granules’

Images available online at [http://modis-atmos.gsfc.nasa.gov](http://modis-atmos.gsfc.nasa.gov)
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Deep Blue: original motivation

- ‘Dark Target’ AOD algorithm does not retrieve over bright surfaces
  - Violates algorithmic assumptions
- These are important aerosol sources, especially mineral dust
- Deep Blue filled in some gaps
  - (Now, it does more than that)
Deep Blue: key concepts

• Often, darker surface and stronger aerosol signal in the violet/blue (~400-490 nm) than at longer wavelengths
  – Prescribe surface reflectance
  – Retrieve AOD independently at several wavelengths

• **Advantages:**
  – Avoids regional artefacts arising from e.g. global prescription of surface reflectance ratios
  – Avoids requirement for auxiliary data (so can run in near real-time)
  – Can be applied to many sensors

• **Disadvantages:**
  – Drastic departures from expected surface cover type can lead to localised artefacts
  – Can’t directly calculate aerosol effective radius, volume etc

Fig. 2. SeaWiFS images over northeast Africa on February 10, 2001. The dynamical ranges of the grayscale used in (b)-(d) are individually adjusted to optimize the appearance of atmospheric features against the background surfaces.

Figure from Hsu et al., IEEE TGARS (2004)
Sensors Deep Blue has been applied to

<table>
<thead>
<tr>
<th>Year</th>
<th>SeaWiFS</th>
<th>MODIS (Terra)</th>
<th>MODIS (Aqua)</th>
<th>VIIRS (Suomi-NPP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>✔️</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>✔️</td>
<td></td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>✔️</td>
<td></td>
<td>✔️</td>
<td></td>
</tr>
<tr>
<td>Present</td>
<td>✔️</td>
<td></td>
<td>✔️</td>
<td></td>
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Images courtesy of SeaWiFS/MODIS projects and Raytheon
## MODIS vs. SeaWiFS Deep Blue

<table>
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<th>Dataset</th>
<th>MODIS (Collection 6, C6)</th>
<th>SeaWiFS (Version 4, V4)</th>
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<tr>
<td>Time series</td>
<td>MODIS Terra (2000 onwards)</td>
<td>SeaStar satellite (1997-2010, a few gaps)</td>
</tr>
<tr>
<td>Coverage</td>
<td>Daytime cloud-free snow-free land only</td>
<td>Daytime cloud-free snow-free land Daytime cloud-free ice-free non-turbid water</td>
</tr>
<tr>
<td>Data products</td>
<td>Main product is AOD at 550 nm Also provides AOD at 412/470/670 nm, Ångström exponent, and SSA (for heavy dust)</td>
<td>Main product is AOD at 550 nm Land: also provides AOD at 412/490/670 nm, Ångström exponent, and SSA (for heavy dust) Water: also provides AOD at 510/670/865 nm, Ångström exponent, fine mode fractional volume</td>
</tr>
<tr>
<td>Level 2</td>
<td>Nominal 10 x 10 km resolution ~2,330 km swath</td>
<td>Nominal 13.5 x 13.5 km resolution ~1,500 km swath</td>
</tr>
<tr>
<td>Level 3</td>
<td>1°; daily, 8-day, and monthly resolution</td>
<td>0.5° and 1°; daily and monthly resolution</td>
</tr>
<tr>
<td>Data access</td>
<td>Distributed by MODIS LAADS Level 3 visualisation through Giovanni</td>
<td>Distributed by GES DISC Level 3 visualisation through Giovanni</td>
</tr>
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</table>

- Hsu et al., *IEEE TGARS* 2004, 2006; *JGR* 2013; Sayer et al., *JGR* 2012a,b; *AMT* 2013
Example Level 2 data

MODIS Aqua: 13:40 UTC, 21 Jan 2010    Deep Blue AOD at 550 nm, passing QA

- Science Data Set (SDS) names relevant for most users:
  - Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate
    - This has our quality filters applied, i.e. any retrieval not set to the fill value (-9.999) should be usable
    - For the bulk of applications, quality assurance (QA) filters should be used
  - Latitude
  - Longitude

- Example granule shown here: MYD021KM.A2010021.1340.006.2012064111514.hdf
Example Level 2 data

Table 5. List of SDS Names for MODIS Collection 6 Deep Blue Aerosol Products

<table>
<thead>
<tr>
<th>Name</th>
<th>Dimensions*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep_Blue_Angstrom_Exponent_Land</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Angstrom Exponent Over Land.</td>
</tr>
<tr>
<td>Deep_Blue_Aerosol_Optical_Depth_550_Land</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Aerosol Optical Depth at 550 nm Over Land.</td>
</tr>
<tr>
<td>Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Aerosol Optical Depth at 550 nm Over Land Filtered by Quality (QA=2.3 only).</td>
</tr>
<tr>
<td>Deep_Blue_Aerosol_Optical_Depth_550_Land_STD</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Standard Deviation of Individual Pixel-Level Aerosol Optical Depth at 550 nm per Cell.</td>
</tr>
<tr>
<td>Deep_Blue_Algorithm_Flag_Land</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Flag Indicating the Path Taken Through the Algorithm.</td>
</tr>
<tr>
<td>Deep_Blue_Aerosol_Optical_Depth_550_Land_QA_Flag</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Quality Assurance Flag for Aerosol Optical Depth at 550 nm.</td>
</tr>
<tr>
<td>Deep_Blue_Aerosol_Optical_Depth_550_Land_Estimated_Uncertainty</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Estimated Uncertainty in Aerosol Optical Depth at 550 nm.</td>
</tr>
<tr>
<td>Deep_Blue_Cloud_Fraction_Land</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Fraction of Pixels per Cell Where Retrieval was not Attempted.</td>
</tr>
<tr>
<td>Deep_Blue_Number_Pixels_Used_550_Land</td>
<td>[Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Number of Aerosol Property Retrievals Performed per Cell.</td>
</tr>
<tr>
<td>Deep_Blue_Spectral_Aerosol_Optical_Depth_Land</td>
<td>[Num_DepBlue_Wavelengths, Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Retrieved Aerosol Optical Depth Over Land at 412, 470, and 650 nm.</td>
</tr>
<tr>
<td>Deep_Blue_Spectral_Single_Scattering_Albedo_Land</td>
<td>[Num_DepBlue_Wavelengths, Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Single-Scattering Albedo Over Land at 412, 470, and 650 nm.</td>
</tr>
<tr>
<td>Deep_Blue_Spectral_Surface_Radiance_Land</td>
<td>[Num_DepBlue_Wavelengths, Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Surface Reflectance Used in Aerosol Retrieval Over Land for 412, 470, and 650 nm.</td>
</tr>
<tr>
<td>Deep_Blue_Spectral_TOA_Radiance_Land</td>
<td>[Num_DepBlue_Wavelengths, Cell_Along_Swath, Cell_Across_Swath]</td>
<td>Top-of-Atmosphere Radiance at 412, 470, and 650 nm.</td>
</tr>
</tbody>
</table>

*Cell_Along_Swath = number of cells in the along-track direction. Cell_Across_Swath = number of cells across the swath. Num_DepBlue_Wavelengths = number of bands reported by the Deep Blue products, currently has a value of 3 (412, 470, and 650 nm).

Table from Hsu et al., JGR (2013)

- Other stuff included in files but not listed above:
  - Diagnostic information (e.g. geometry, land/sea mask)
  - Dark Target and ocean aerosol data (cf. Rob Levy’s webinar last week)
  - Deep Blue/Dark Target ‘merged’ SDS (cf. next week’s webinar)
Example Level 2 data

MODIS Aqua: 13:40 UTC, 21 Jan 2010

Deep Blue AOD at 550 nm, all QA

AOD estimated uncertainty

Deep Blue AE

QA flag

Algorithm flag

0: database  1: spectral  2: mixed
e-Deep Blue: main developments in C6

- Described by Hsu *et al.*, *JGR* (2013); Sayer *et al.*, *JGR* (2013)
  - Enhanced Deep Blue (e-Deep Blue)
  - Summary: more retrievals, better retrievals

**Refinements to e-Deep Blue in MODIS Collection 6:**
- Extended coverage to vegetated surfaces, as well as bright land
- Improved surface reflectance models
- Improved aerosol optical models
- Improved cloud screening
- Simplified quality assurance (QA) flag reading
- Radiometric calibration improvements

e-Deep Blue: C6 flow chart

- Described by Hsu et al., JGR (2013)
MODIS C6: extended spatial coverage
MODIS C6: improved cloud screening

MODIS RGB image over northern Africa on March 7, 2006

TOA Reflectance at 1.38 μm

BTD, 11-12 μm, K

MODIS C6 Deep Blue AOD

MODIS C5 Deep Blue AOD

Precipitable water vapor, cm

Brightness temperature at 11 μm, K

- Traditional cirrus detection techniques can fail over moisture-deprived regions
Validation

- See Sayer et al., JGR (2013)
- AOD at 550 nm well-correlated with AERONET
  - AOD at other wavelengths shows similar behaviour
- AE (denoted $\alpha$ here) shows little skill in low-AOD cases, some skill for higher-AOD cases
  - Note AERONET AOD also has some uncertainty in low-AOD conditions
Retrieval-level uncertainty estimates

• See Sayer et al., JGR (2013) for Aqua (Terra is similar)
• AOD at 550 nm uncertainty estimates as a function of AOD, QA level, and geometric air mass factor (AMF)
  – For typical AMF, uncertainty of order 0.03+20%
  – Provided within level 2 products for each individual retrieval
  – Prognostic, not diagnostic
  – Determined by validation against AERONET, in line with theoretical values
  – Estimates designed to represent a Gaussian one standard deviation confidence interval
**Importance of Level 1 radiometric calibration**

- Effort by MODIS Characterization Support Team to improve absolute and temporal stability of MODIS level 1 calibration
  - Important for minimising error in AOD/AE retrieval, especially long-term trends (Sayer et al., JGR 2013)
  - Assess calibration via long-term stable surface targets, the moon, and intersensor calibration
  - Verify through validation at long-term AERONET sites
  - Aqua drift became more noticeable in more recent years (2008+)
  - MODIS Terra is older and has degraded more strongly, which is why C6 has taken longer for Terra

- Collection 6 data for both Terra and Aqua have a better Level 1 calibration, leading to more stable Level 2 data, with lower uncertainties
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Summary

• e-Deep Blue provides aerosol data at ~10 km spatial resolution over vegetated, urban, and arid land surfaces, in near real time, suitable for quantitative use in scientific applications
  – Primary data product AOD at 550 nm
  – Ångström exponent, SSA useful in some situations
  – Collection 6 has more and better retrievals than Collection 5
  – Aqua L2 available now, Aqua L3 imminently, Terra L2/L3 shortly after

• Please use the data, ask questions, tell us when you find something unusual/exciting
  – We are happy to help, and it’s nice to hear from users

Links:
MODIS Atmospheres website: modis-atmos.gsfc.nasa.gov
NASA LAADS (data distribution) website: ladsweb.nascom.nasa.gov
MODIS Collection 6 on the NASA LAADS ftp server: ladsweb.nascom.nasa.gov/allData/6/<product name>

Key references: