Aerosol Observations from Satellites: Brief Theory & Existing Products

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Objectives

1. Gain a basic understanding of aerosol optical depth

2. Gain knowledge of and ability to access available aerosol products from NASA sensors
Aerosol Optical Depth

- AOD: Aerosol Optical Depth
- AOT: Aerosol Optical Thickness

- These **optical measurements** of light extinction are used to represent aerosol amounts in the entire column of the atmosphere
Optical Depth

The optical depth expresses the quantity of light removed from a beam by scattering or/and absorption during its path through a medium.

Optical depth $\tau$ as:

$$I = I_0 e^{-m\tau}$$

$$m = \sec \theta_0$$

$$\tau = \tau_{Rayl} + \tau_{aer} + \tau_{gas}$$
AERONET measurements of aerosol depth are considered *ground truth* and are used to validate satellite aerosol retrievals.
Satellites for Air Quality Data

- MODIS (Terra and Aqua)
  - AOD: columnar aerosol loading – can be used to estimate PM$_{2.5}$ or PM$_{10}$
- MISR (Terra)
  - Columnar aerosol loading in different particle size bins
  - In some cases aerosol heights
- OMI (Aura)
  - Absorbing aerosols, total aerosols
  - Trace gases
- VIIRS (NPP)
  - Aerosol optical depth
  - Aerosol type
Instrument Capabilities for Air Quality

Sensor Measurement: Spatial Resolution

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spatial Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS</td>
<td>250 m – 1 km</td>
</tr>
<tr>
<td>MISR</td>
<td>275 m – 1.1 km</td>
</tr>
<tr>
<td>OMI</td>
<td>13 x 24 km</td>
</tr>
<tr>
<td>VIIRS</td>
<td>750 m</td>
</tr>
</tbody>
</table>
MODerate resolution Imaging Spectroradiometer

• 2000 - present
• Spatial Resolution
  – 250 m, 500 m, 1 km
• Platform
  – Terra & Aqua
• Temporal Resolution
  – Daily, 8-day, 16-day, monthly, quarterly, yearly
• Data Format
  – Hierarchal Data Format – Earth Observing System Format (HDF-EOS)

• Spectral Coverage
  – 36 bands (major bands include red, blue, IR, NIR, MIR)
    • Bands 1-2: 250 m
    • Bands 3-7: 500 m
    • Bands 8-36: 1,000 m
Aerosol Retrieval
Aerosol Detection

Terra MODIS, May 8, 2007

Land

Water

Clouds

Smoke
Complex Image: Smoke & Clouds

Terra MODIS, May 14, 2007
Radiance to Aerosol Products

Terra MODIS, May 2, 2007
Aerosol retrieval algorithm is a complex inversion scheme where assumptions are made in simulating satellite observations with advance radiative transfer calculations to retrieve atmospheric aerosol properties.

Sources: Remer et al., 2005, Levy et al., 2013
MODIS Products

MOD01 Level-1A Radiance Counts
MOD02 Level-1B Calibrated Geolocated Radiances – also Level 1B "subsampled" 5kmx5km pro
MOD03 Geolocation Data Set
MOD04 Aerosol Product
MOD05 Total Precipitable Water
MOD06 Cloud Products
MOD07 Atmospheric Profiles
MOD08 Gridded Atmospheric Product (Level 3)
MOD09 Atmospherically-corrected Surface Reflectance
MOD10 Snow Cover
MOD11 Land Surface Temperature & Emissivity
MOD12 Land Cover/Land Cover Change
MOD13 Vegetation Indices
MOD14 Thermal Anomalies, Fires & Biomass Burning
MOD15 Leaf Area Index & FPAR
MOD16 Surface Resistance & Evapotranspiration
MOD17 Vegetation Production, Net Primary Productivity
MOD18 *Normalized Water-leaving Radiance
MOD19 Pigment Concentration
MOD20 Chlorophyll Fluorescence
MOD21 *Chlorophyll_a Pigment Concentration
MOD22 Photosynthetically Active Radiation (PAR)
MOD23 Suspended-Solids, Conc, Ocean Water
MOD24 Organic Matter Concentration
MOD25 Coccolith Concentration
MOD26 *Ocean Water Attenuation Coefficient
MOD27 Ocean Primary Productivity
MOD28 *Sea Surface Temperature
MOD29 Sea Ice Cover

MOD32 Processing Framework & Match-up Database
MOD33 Gridded Snow Cover
MOD34 Gridded Vegetation Indices
MOD35 Cloud Mask
MOD36 Total Absorption Coefficient
MOD37 Ocean Aerosol Optical Thickness
MOD39 Clear Water Epsilon
MOD43 Albedo 16-day L3
MOD44 Vegetation Cover Conversion

MYD – MODIS Aqua
MOD – MODIS Terra
A Few More Things About MODIS Data...

- MOD: Terra product
- MYD: Aqua product

- All MODIS products come in HDF format

- In HDF format each file contains both data and metadata

- **Scientific Data Set (SDS):** each parameter within a MODIS HDF file is referred to as an SDS
  - SDS must be referenced precisely according to name when analyzing the data within your own computer code
Things That Change with Each Instrument
(So you need to learn them!)

• Calibration Accuracy
• Quality Assurance – quality of the data
• Data Formats
• Product Resolutions
• Creating Level 3 products from Level 2
  – temporal and spatial averaging
• Current data release and data history
MODIS Aerosol Products

Three Separate Algorithms

- The dark target and deep blue products are separate and when both are available, the user must select which to use.
- In collection 6, there is a joint product that uses an automated procedure to select the appropriate product.
MODIS Aerosol Products
Two Algorithms

Dark Target

Deep Blue

Deep_Dark_Combined
MODIS 10 km vs. 3 km Products
High Resolution Aerosol Product
Quality Assurance is Extremely Important

QA indicates confidence in the quality of the retrieval

**Quality_Assurance_Ocean**
- Scale is 0 – 3
- Recommended Ocean QA above 1, 2, 3
- Factors:
  - number of pixels
  - error fitting
  - **how close to glint**

**Quality_Assurance_Land**
- Scale is 0 – 3
- Recommended Land QA of 3
- Factors:
  - number of pixels
  - error fitting
  - **surface reflectance**
Understanding a MODIS File Name

Level 2, 10 km, Aerosol Product

Product Name:
• Terra: MOD04
• Aqua: MYD04

MOD04_L2.A2001079.0255.006.2006289012028.hdf

Time

Date:
• Year
• Julian Day

File Processing Information

Collection

HDFLook, Panoply, IDL, Python, Fortran, MatLab, and more can be used to read the data
Understanding a MODIS File Name

Level 2, 3 km, Aerosol Product

Product Name:
- Terra: MOD04
- Aqua: MYD04

MOD04_3K.A2001079.0255.006.2006289012028.hdf

Date:
- Year
- Julian Day

Time

File Processing Information

Collection

HDFLook, Panoply, IDL, Python, Fortran, MatLab, and more can be used to read the data
MODIS Aerosol Parameters (SDS)

• Optical_Depth_Land_and_Ocean
  – Retrieved using Dark Target Algorithm
  – Only high quality data
    • Over land QA = 3
    • Over ocean QA = 1, 2, 3
  – 10 km and 3km
• Dark_Target_Deep_Blue_Optical_Depth_550_Combined
  – Deep Blue & Dark Target Algorithm Merged Product
  – 10km only
• Dark_Target_Deep_Blue_Optical_Depth_550_Combined_QA
  – Quality flag associated with DD product
Application of MODIS Aerosol Product

Source: van Donkelaar et al., 2006, 2009
Access to MODIS Aerosol Products

• NASA LAADSWeb
  – Searchable database, FTP access
  – https://ladsweb.modaps.eosdis.nasa.gov/

• MODIS-Atmos Site
  – Complete RGB archive with Level 3 product imagery
  – http://modis-atmos.gsfc.nasa.gov/

• Giovanni for Level 3 data sets
  – Web tool for imagery visualization and analysis
  – https://giovanni.gsfc.nasa.gov/giovanni/

• Dark Target Algorithm Site
  – http://darktarget.gsfc.nasa.gov/

• Deep Blue Algorithm Site
  – http://deepblue.gsfc.nasa.gov/
Ozone Monitoring Instrument (OMI)

**Instrument Characteristics**
- Nadir solar backscatter spectrometer
- Spectral Range: 270-500 m
  - Resolution ~1 nm
- Swath Width: 2,600 km
  - Global daily coverage with 13x24 km spatial resolution

**Retrieval Products**
- Column Amounts
  - Ozone (O3)
  - Nitrogen Dioxide (NO2)
  - Sulfur Dioxide (SO2)
  - Others
- Aerosols

- One of four sensors on the EOS-Aura platform
  - OMI, MLS, TES, HIRDLS
- An international project
  - Holland, USA, Finland
- Launched July 15, 2004
Applications of the Aerosol Index

- Validation tool for transport models
- Separation of carbonaceous from sulfate aerosols
- Tracking of aerosol plumes above clouds and over ice and snow

Multi-angle Imaging Spectro- Radiometer (MISR)

- 9 View angles
- 7 minutes to view each scene from all 9 angles
- 275 m spatial resolution
- Swath Width ~ 400 km
- 4 Spectral Bands
  - 446 nm
  - 558 nm
  - 672 nm
  - 866 nm
Angular observations (which are not available in MODIS) makes MISR capable of providing additional information on particle size, shape and aerosol height under specific cases.
MISR Global Daily Coverage
Applications of MISR Data

Smoke signals from the July 2004 Alaska and Yukon Fires
VIIRS
**Visible Infrared Imaging Radiometer (VIIRS)**

A multi-wavelength imager like MODIS with similar wavelength bands

<table>
<thead>
<tr>
<th></th>
<th>MODIS</th>
<th>VIIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit Altitude</strong></td>
<td>690 km</td>
<td>824 km</td>
</tr>
<tr>
<td><strong>Equator Crossing Time</strong></td>
<td>13:30 LT</td>
<td>13:30 LT</td>
</tr>
<tr>
<td><strong>Granule Size</strong></td>
<td>5 min</td>
<td>86 sec</td>
</tr>
<tr>
<td><strong>Swath</strong></td>
<td>2,330 km</td>
<td>3,000 km</td>
</tr>
<tr>
<td><strong>Pixel Nadir</strong></td>
<td>0.5 km</td>
<td>0.75 km</td>
</tr>
<tr>
<td><strong>Pixel Edge</strong></td>
<td>2 km</td>
<td>1.5 km</td>
</tr>
</tbody>
</table>
VIIRS & MODIS

VIIRS
Nov 24, 2011

MODIS (Aqua)
Nov 24, 2011
SNPP VIIRS Advantages

Side Courtesy: Shobha Kondragunta
New Aerosol Optical Thickness Algorithm

- **New** Enterprise Processing System (EPS) expected to become operational July 2017: replaces current Interface Data Processing Segment (IDPS) algorithm
  - Retrieval over bright land, extended reporting range [-0.05-5.0], extensive internal test
- Separate algorithms for land and water

VIIRS AOD Retrieval Example

Aug 29, 2015

Slide Courtesy: Shobha Kondragunta
VIIRS Smoke Mask

- Smoke mask: qualitative indicator of smoke
- Derived using spectral and spatial threshold tests based on VIIRS measurements in visible and IR
- Useful for identifying local and transported smoke plumes
- Colored shades of pink
  - Light pink: thin smoke
  - Bright pink/magenta: thick smoke

Aug 24, 2015

Slide Courtesy: Shobha Kondragunta
Overview of Aerosol Detection Algorithm

**Input Reflectances**

- Dust: 412, 440, 2250 nm
- Smoke: 412, 440, 2250 nm
- Spatial Variability Test: 412 nm
- Turbid Water Test: 488 nm, 1.24 \(\mu\)m, 1.61 \(\mu\)m, 2.25 \(\mu\)m
- Bright Pixel Test: 1.24 \(\mu\)m, 2.25 \(\mu\)m
- NDVI Test: 640 nm, 865 nm
- Snow Test: 865 nm, 1.24 \(\mu\)m

**Slide Courtesy:** Shobha Kondragunta

**AAI = \(-100 \cdot \log_{10}(R_{412}/R_{440}) - \log_{10}(R'_{412}/R'_{440})\)**

**DSDI = \(-10 \cdot \log_{10}(R_{412}/R_{2250})\)**
eIDEA Domain Recently Expanded

eIDEA domain now includes CONUS, Alaska, Canada, Mexico, western Atlantic, and eastern Pacific

Slide Courtesy: Shobha Kondragunta
Other Sensors
CALIPSO: Vertical Profiles

Source: Meloë Kacenelenbogen
## Satellite Aerosol Products

<table>
<thead>
<tr>
<th>Strengths</th>
<th>MODIS</th>
<th>MISR</th>
<th>OMI</th>
<th>VIIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Coverage</td>
<td>• Calibration</td>
<td>• Indication of absorbing or scattering particles</td>
<td>• Coverage</td>
<td>• Bright surfaces*</td>
</tr>
<tr>
<td>• Resolution</td>
<td>• Accuracy</td>
<td></td>
<td>• Resolution</td>
<td>• Ocean glint</td>
</tr>
<tr>
<td>• Calibration</td>
<td>• Particle Shape</td>
<td></td>
<td>• Cloud contamination</td>
<td></td>
</tr>
<tr>
<td>• Accuracy</td>
<td>• Aerosol height for thick layer or plume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Particle Shape</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Aerosol height</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

## Weaknesses

<table>
<thead>
<tr>
<th>MODIS</th>
<th>MISR</th>
<th>OMI</th>
<th>VIIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Bright surfaces</td>
<td>• Coverage</td>
<td>• Resolution</td>
<td>• Bright surfaces*</td>
</tr>
<tr>
<td>• Ocean glint</td>
<td></td>
<td>• Cloud contamination</td>
<td>• Ocean glint</td>
</tr>
<tr>
<td>• Non-spherical particles</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Main Products

<table>
<thead>
<tr>
<th>MODIS</th>
<th>MISR</th>
<th>OMI</th>
<th>VIIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• AOD</td>
<td>• AOD</td>
<td>• AOD</td>
<td>• AOD</td>
</tr>
<tr>
<td>• Ocean-5 wavelengths</td>
<td>• 4 wavelengths</td>
<td>• AAOD</td>
<td>• Aerosol Type</td>
</tr>
<tr>
<td>• Land-3 wavelengths</td>
<td>• Spherical/Non-Spherical Ratio</td>
<td>• Aerosol Index</td>
<td></td>
</tr>
<tr>
<td>• Fine Fraction (Ocean only)</td>
<td>• Particle Size (3 bins)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Product Resolution

<table>
<thead>
<tr>
<th>MODIS</th>
<th>MISR</th>
<th>OMI</th>
<th>VIIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 10 km</td>
<td>• 17.6 km</td>
<td>• 13 x 24 km</td>
<td>• 0.75 km</td>
</tr>
<tr>
<td>• 3 km</td>
<td></td>
<td></td>
<td>• 6 km</td>
</tr>
</tbody>
</table>

## Global L3 Aggregates

<table>
<thead>
<tr>
<th>MODIS</th>
<th>MISR</th>
<th>OMI</th>
<th>VIIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Daily</td>
<td>• Monthly</td>
<td>• Daily</td>
<td>• Daily</td>
</tr>
<tr>
<td>• 8 day</td>
<td>• 3 month</td>
<td>• Monthly</td>
<td>• Monthly</td>
</tr>
<tr>
<td>• 30 day</td>
<td>• Annual</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Available Satellites for Aerosol Monitoring

<table>
<thead>
<tr>
<th></th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS</td>
<td>• High spatial resolution (0.25-1km)</td>
<td>• No data under cloudy conditions</td>
</tr>
<tr>
<td></td>
<td>• Fine vs. coarse</td>
<td>• No vertical information</td>
</tr>
<tr>
<td></td>
<td>• Twice daily near-global coverage</td>
<td>• Larger uncertainties over bright targets</td>
</tr>
<tr>
<td>MISR</td>
<td>• Size/shape information</td>
<td>• Limited swath width (360km)</td>
</tr>
<tr>
<td></td>
<td>• Higher accuracy</td>
<td>• Limited vertical information</td>
</tr>
<tr>
<td></td>
<td>• Multi-angle view</td>
<td>• No daily observations for air quality</td>
</tr>
<tr>
<td>OMI</td>
<td>• Daily near-global coverage</td>
<td>• Lack of information on scattering aerosols</td>
</tr>
<tr>
<td></td>
<td>• Absorbing aerosols</td>
<td>• Coarse resolution to separate clouds</td>
</tr>
<tr>
<td></td>
<td>• Precursor measurements (sulfate, nox)</td>
<td>• Larger uncertainties</td>
</tr>
<tr>
<td></td>
<td>• Available over bright targets</td>
<td></td>
</tr>
<tr>
<td>POLDER</td>
<td>• Daily near-global coverage</td>
<td>• No data under cloudy conditions</td>
</tr>
<tr>
<td></td>
<td>• Sensitive to small mode aerosols</td>
<td>• No vertical information</td>
</tr>
<tr>
<td></td>
<td>• Available over bright targets</td>
<td>• Larger uncertainties over bright targets</td>
</tr>
<tr>
<td>CALIPSO</td>
<td>• Vertical information available</td>
<td>• Narrow swath (almost point measurement)</td>
</tr>
<tr>
<td></td>
<td>• Information on clouds</td>
<td>• Very limited global coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Larger uncertainties in retrieved data sets</td>
</tr>
</tbody>
</table>

**VIIRS, GOES-R, HIMAWARI, GOCI, and many more**
Satellite Limitations

• **Optical measurements**
  – only available in day time
  – very limited in night time

• Only available under
  – cloud free conditions
  – Snow/Ice free conditions

• **Accuracy** - vary (AOD) – Depends on satellite/algorithm
  – Very good over dark vegetated surfaces
  – Moderate over urban surfaces- Algorithm dependent
  – Moderate to low over bright surface
  – Complex topography (i.e. mountains) – can be problematic
  – More uncertain for complex mixture of aerosols

• **Chemical Composition** - Very limited capabilities, only at research level

• **Temporal Coverage**
  – Usually once a day
  – But can use multiple satellite to get 2-3 a day
  – Geostationary will provide more frequent observations

• **Spatial Resolution**
  – 10 km (good)
  – 3 km (moderate)
  – 1 km, 0.75 km etc.
References & Links

• ARSET air quality page
  – http://arset.gsfc.nasa.gov/airquality

• NASA air quality
  – http://airquality.gsfc.nasa.gov

• MODIS Atmos
  – http://modis-atmos.gsfc.nasa.gov/

• MISR data
  – https://eosweb.larc.nasa.gov/PRODOCS/misr/Quality_Summaries/L2_AS_Products.html

• OMI data
  – http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI

• IDEA:
  – http://www.star.nesdis.noaa.gov/smcd/spb/aq/

• Smog blog:
  – http://alg.umbc.edu/usaq/
Questions & Discussion