

# 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



# Air Quality Monitoring and Reporting

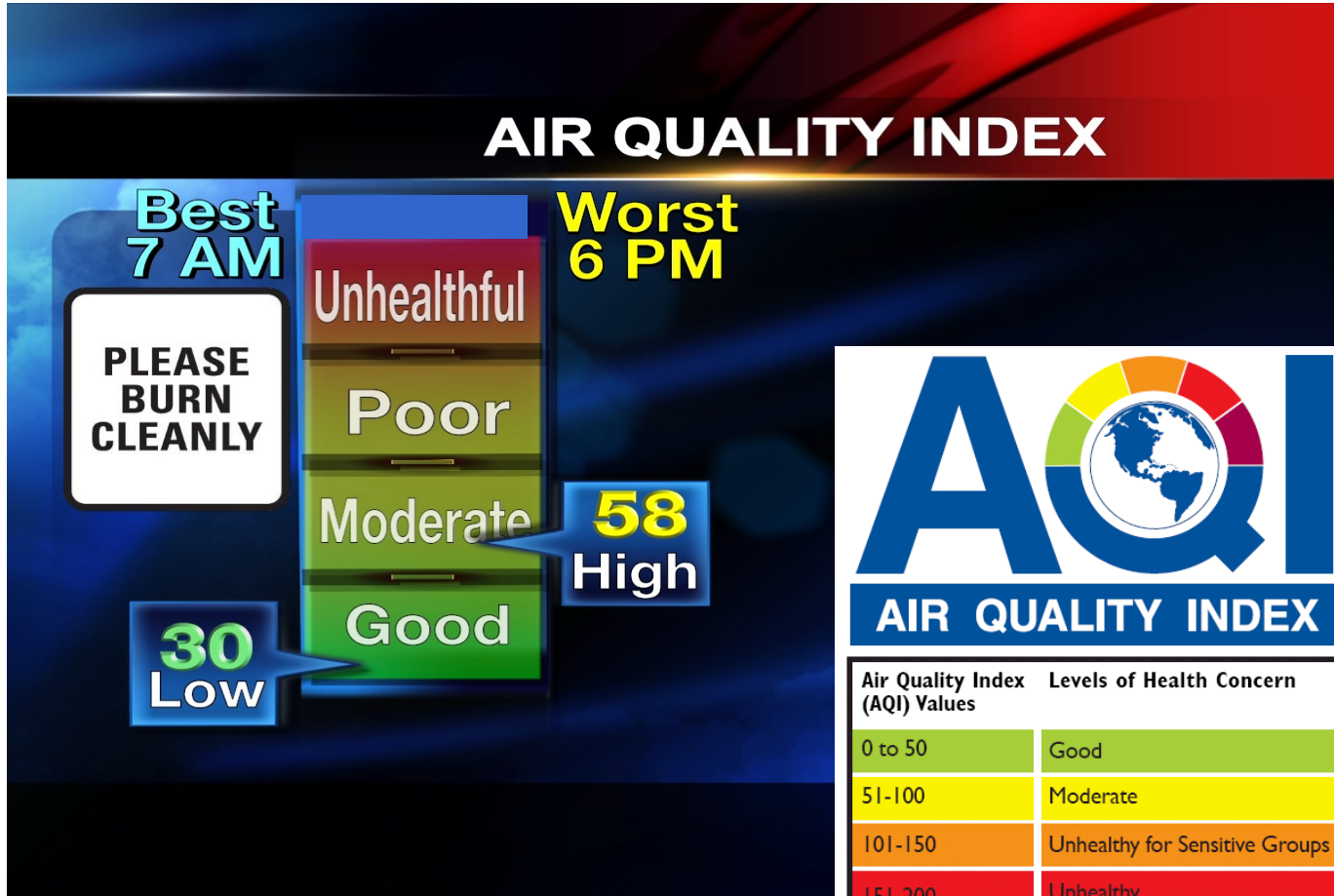
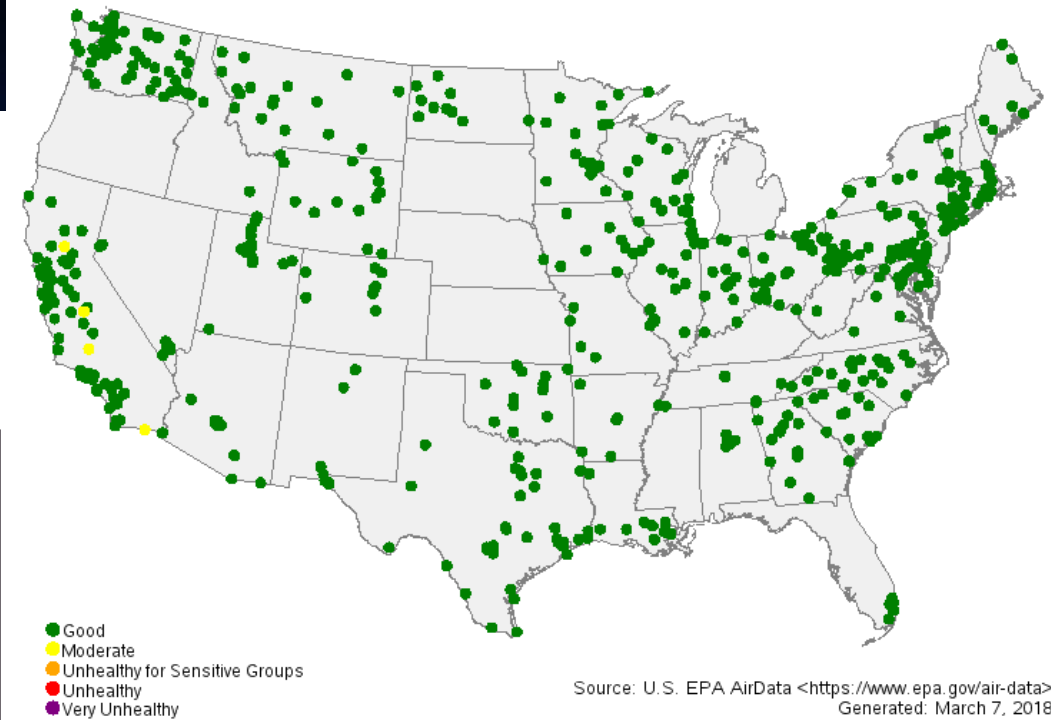


Image Credit: AirNow map, USEPA. <http://www.airnow.gov>

## Spatial Gaps

PM2.5 AQI Values by site on 10/08/2017





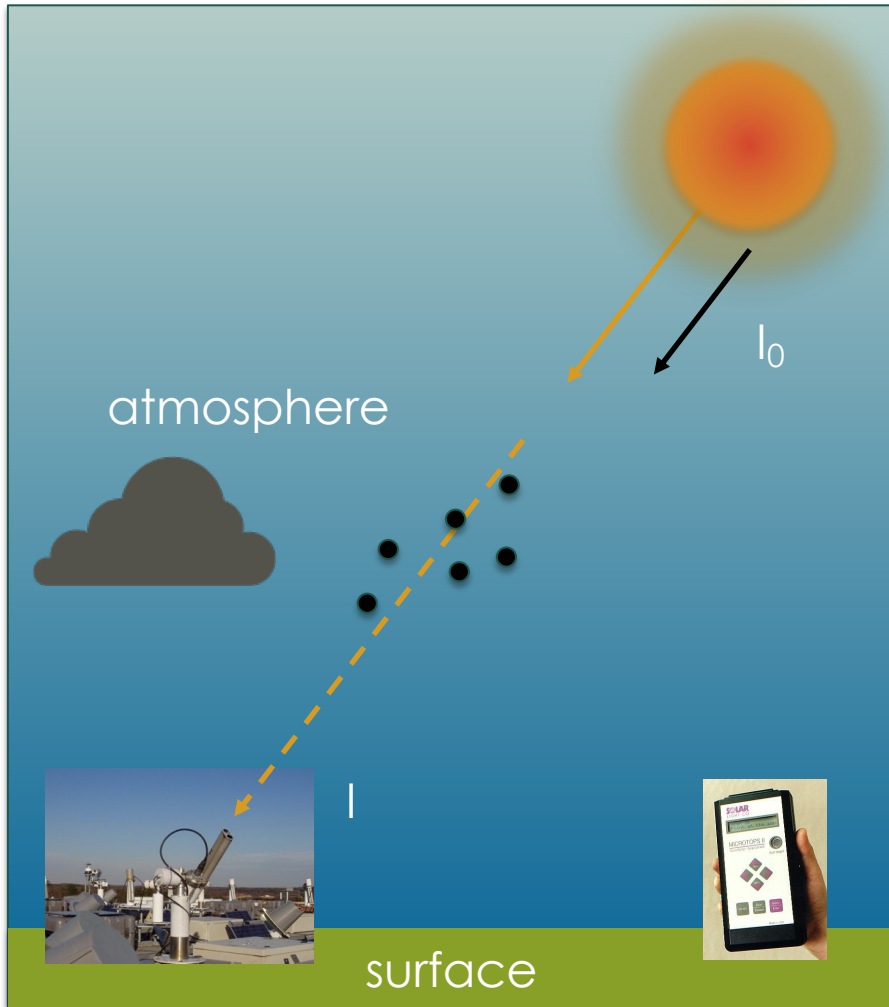
# Aerosol Optical Depth

- 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** and/or **absorption** during its path through a medium.

Optical Depth  $\tau$  as:

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

$$m = \sec \theta_0$$

$$\tau = \tau_{Rayl} + \tau_{aer} + \tau_{gas}$$



# Inferring AOD and PM<sub>2.5</sub> from Visuals

## Pittsburgh

$$PM_{2.5} = 45 \mu\text{gm}^{-3}$$

$$PM_{2.5} = 4 \mu\text{gm}^{-3}$$



Pictures are taken from the same location, at the same time of day, on two different days

$$AOD = \sim 0.8$$

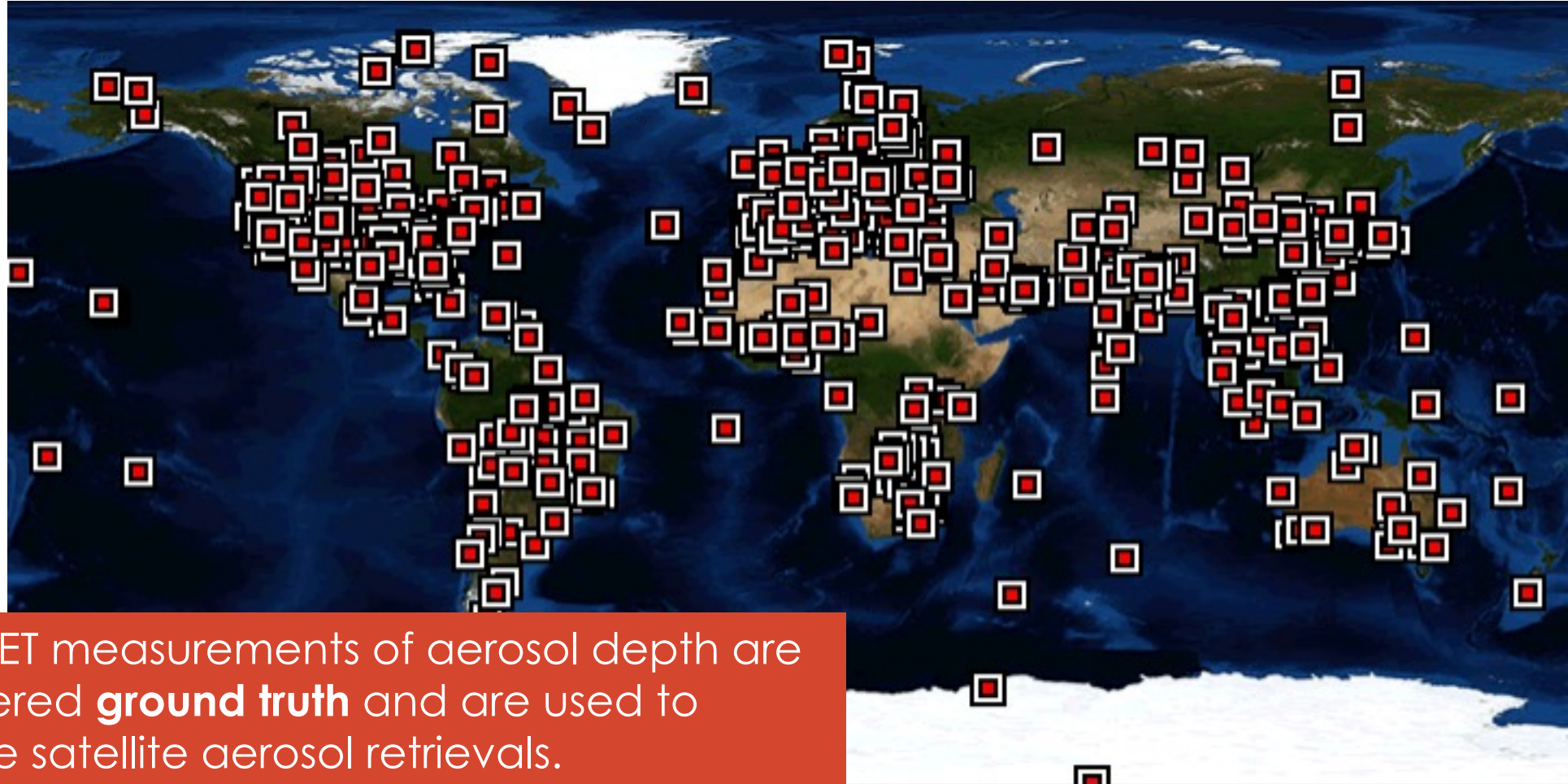
$$AOD = \sim 0.1$$

Image Credit: Learning with CLEAR: Introduction to Aerosols - What Are Aerosols? <http://caice.ucsd.edu/index.php/education/clear/learning-with-clear/introduction-to-aerosols/>



# AERONET

<http://aeronet.gsfc.nasa.gov/>



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, JPSS)
  - Aerosol optical depth
  - Aerosol type

CALIPSO, POLDER, etc. and more recent are TROPOMI, GOES-R, GOES-S

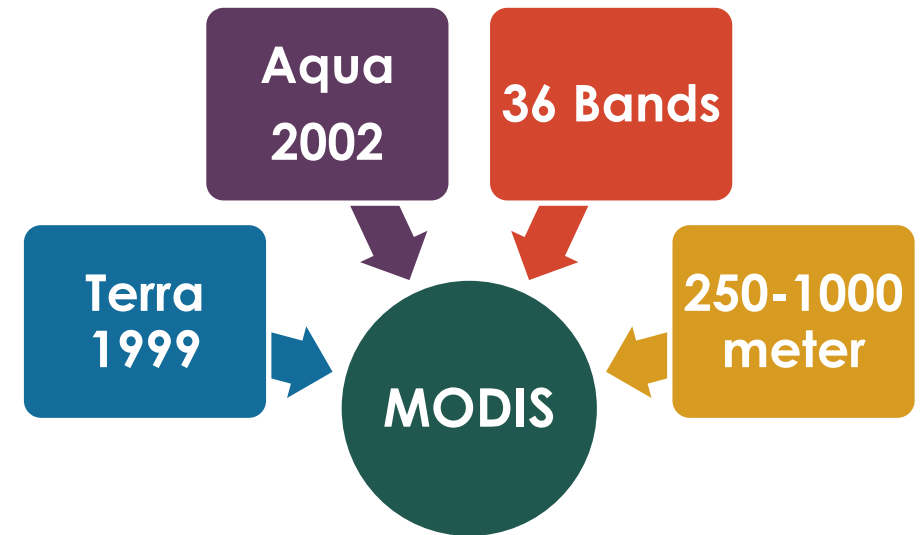


# MODIS vs. VIIRS – Historical Perspective

- S-NPP serves as the bridge between NASA EOS and JPSS satellites.
- JPSS previously called NPOESS
- JPSS is developed by NASA for NOAA

**MODIS** - Moderate Resolution Imaging Spectroradiometer  
**VIIRS** – Visible Infrared Imaging Radiometer Suite  
**NPOESS** - National Polar-orbiting Operational Environmental Satellite System  
**S-NPP** - Suomi National Polar-orbiting Partnership  
**JPSS** - Joint Polar Satellite System (NOAA 20)  
**EOS** - Earth Observing System

## NASA EOS Missions



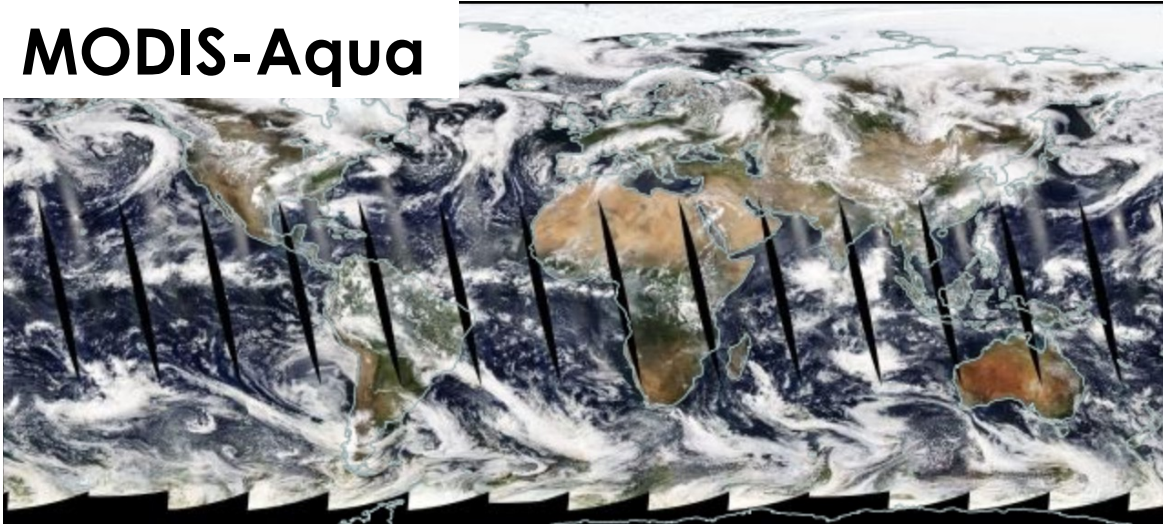
## NASA-NOAA Joint Mission



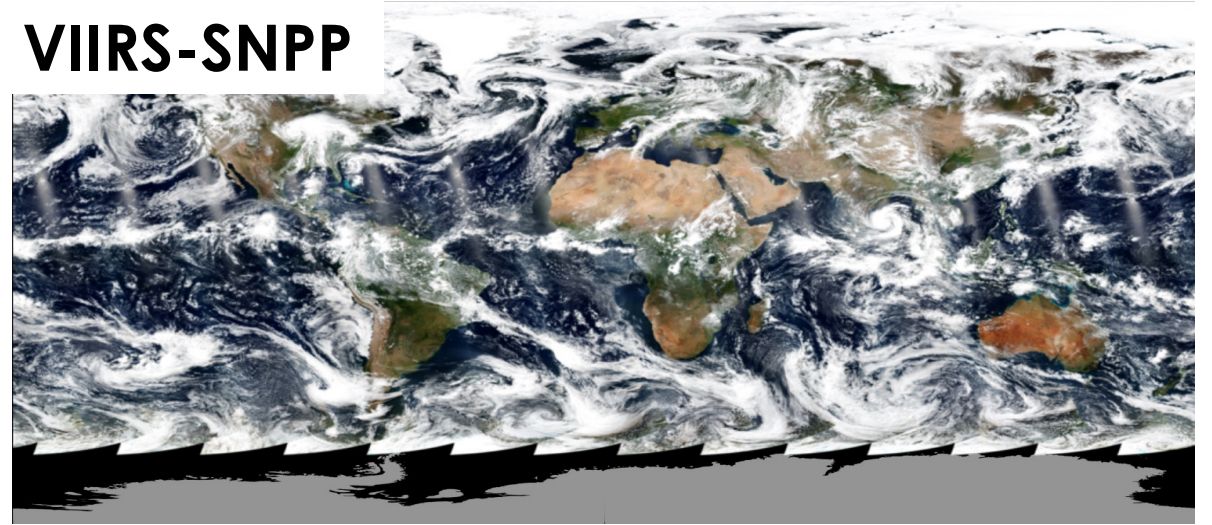


# MODIS vs. VIIRS - Coverage

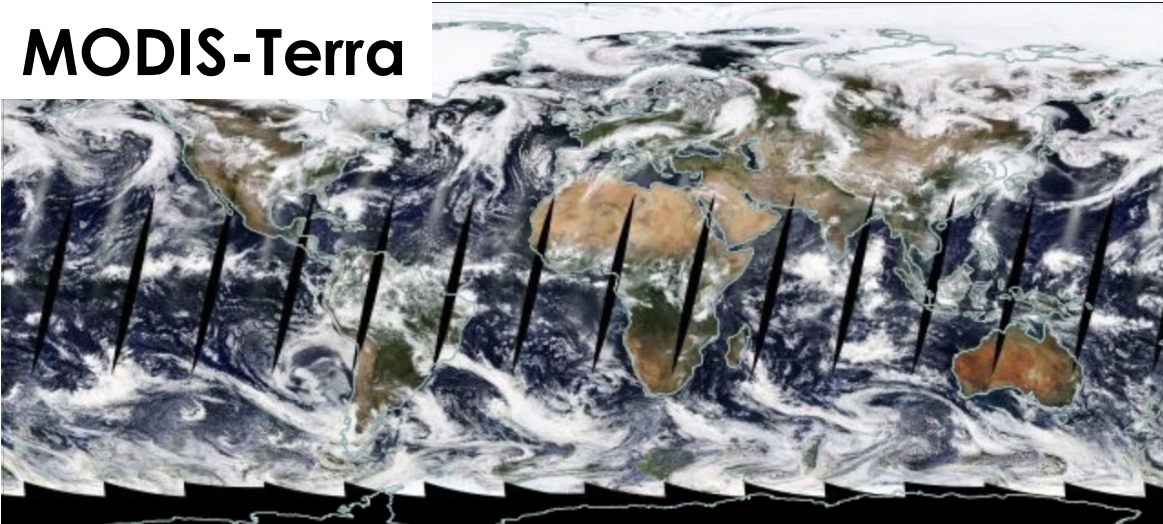
**MODIS-Aqua**



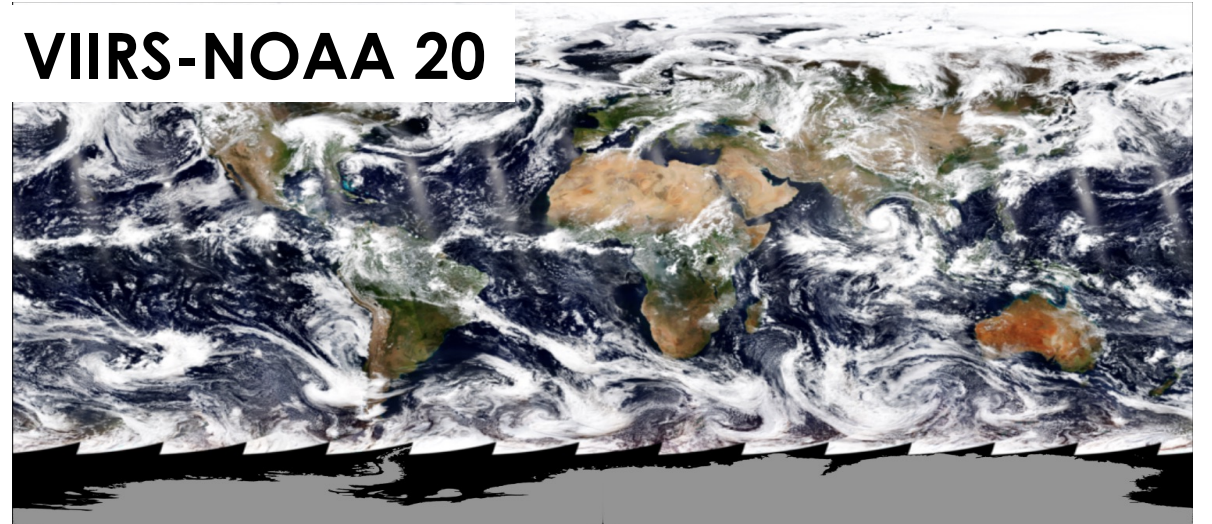
**VIIRS-SNPP**



**MODIS-Terra**



**VIIRS-NOAA 20**





# Visible Infrared Imaging Radiometer (VIIRS)

A multi-wavelength imager like MODIS with similar wavelength bands

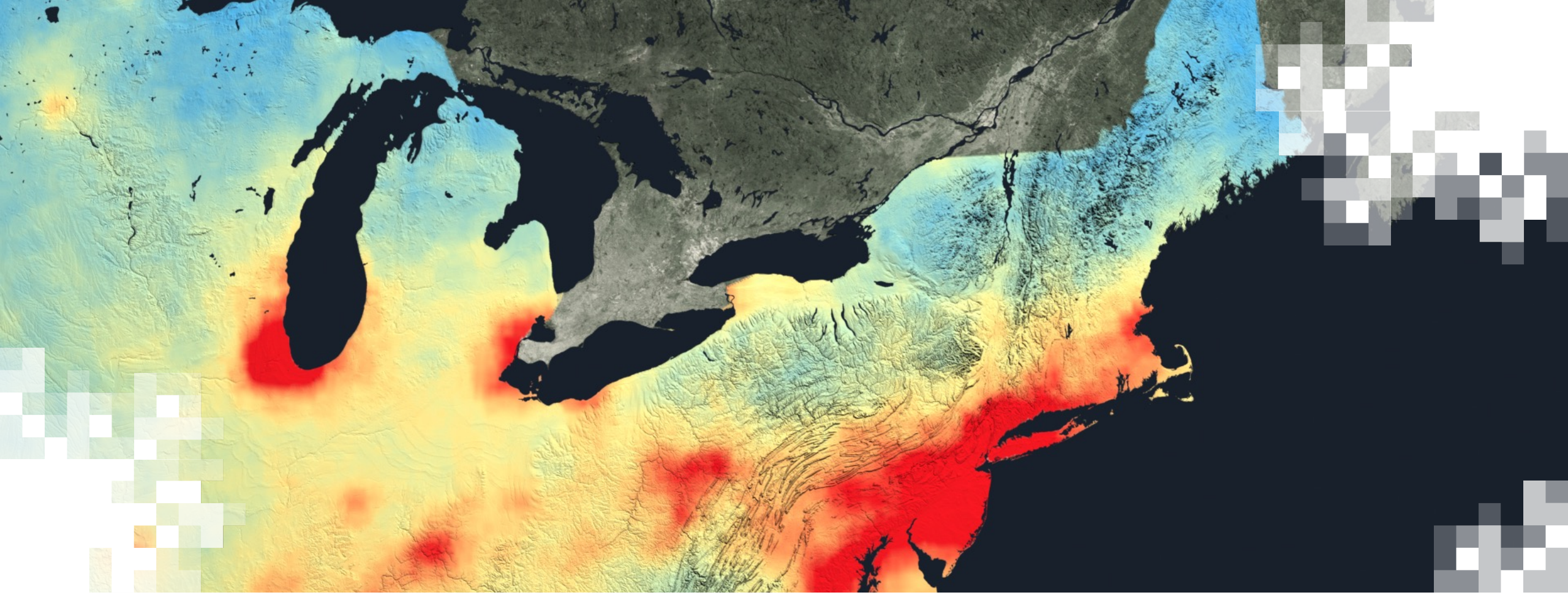
	MODIS	VIIRS-SNPP	VIIRS-N20
Orbit Altitude	690 km	824 km	824
Equator Crossing Time	13:30 LT	13:30 LT	12:40 LT
Swath	2,330 km	3,060 km	3,060 km
Pixel Nadir	0.5 km	0.75 km	0.75 km
Pixel Edge	2 km	1.5 km	1.5 km
Spectral Coverage	0.405 to 14.385 $\mu\text{m}$	0.412 to 12.1 $\mu\text{m}$	0.412 to 12.1 $\mu\text{m}$
Spectral Bands	36	22	22



# Data Products Relevant to Air Quality

	MODIS (T & A)	VIIRS-SNPP	VIIRS-N20/N21
Aerosol Optical Depth	✓	✓	✓
Smoke Detection	✗	✓	✓
Dust Detection	✗	✓	✓
Fire Detection	✓	✓	✓
True Color Image	✓	✓	✓





MODIS



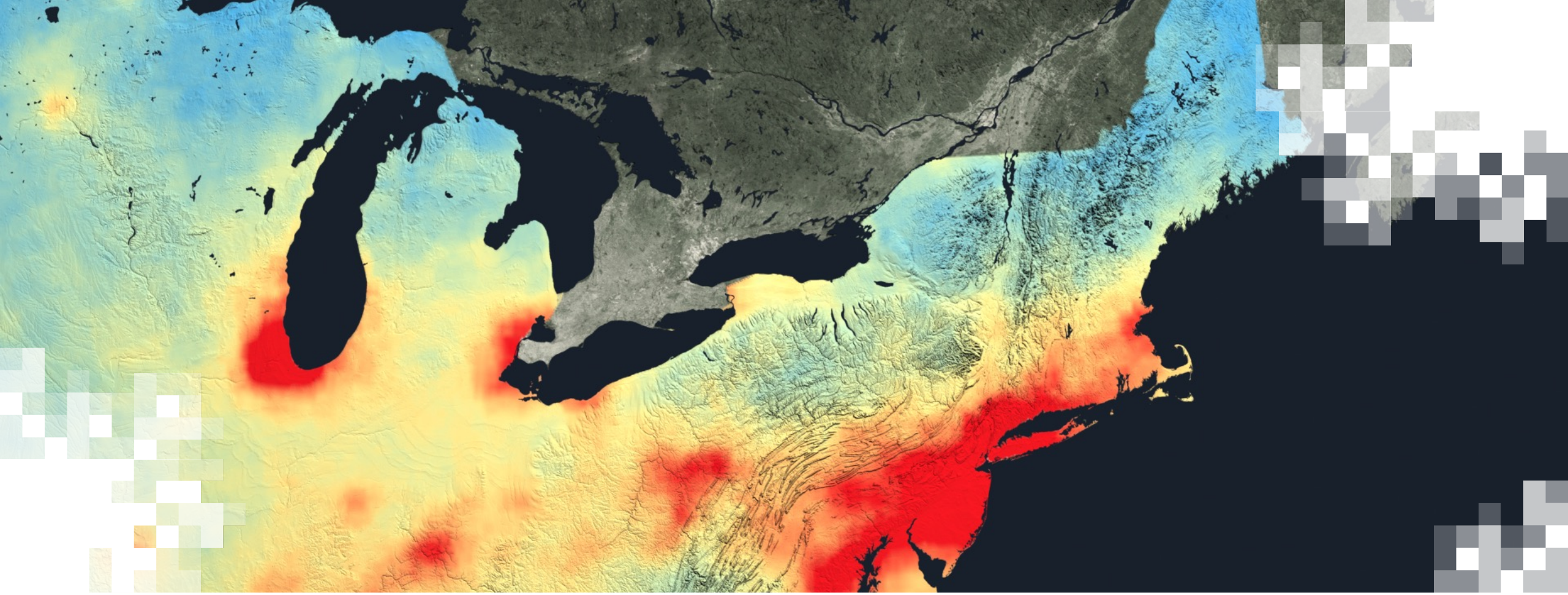
# MODerate resolution Imaging Spectroradiometer

- 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:
  - Hierarchical 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

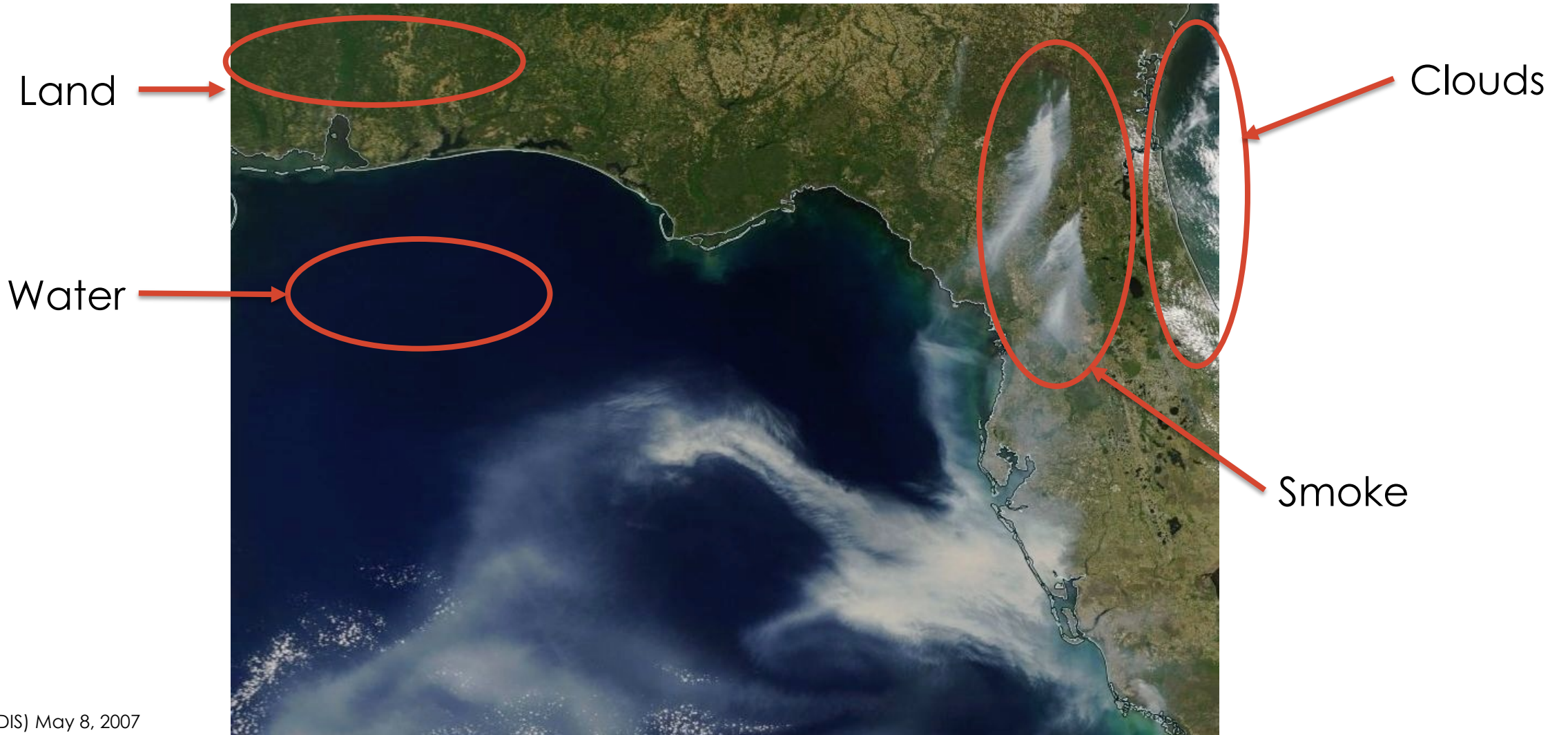




## Aerosol Retrieval



# Aerosol Detection

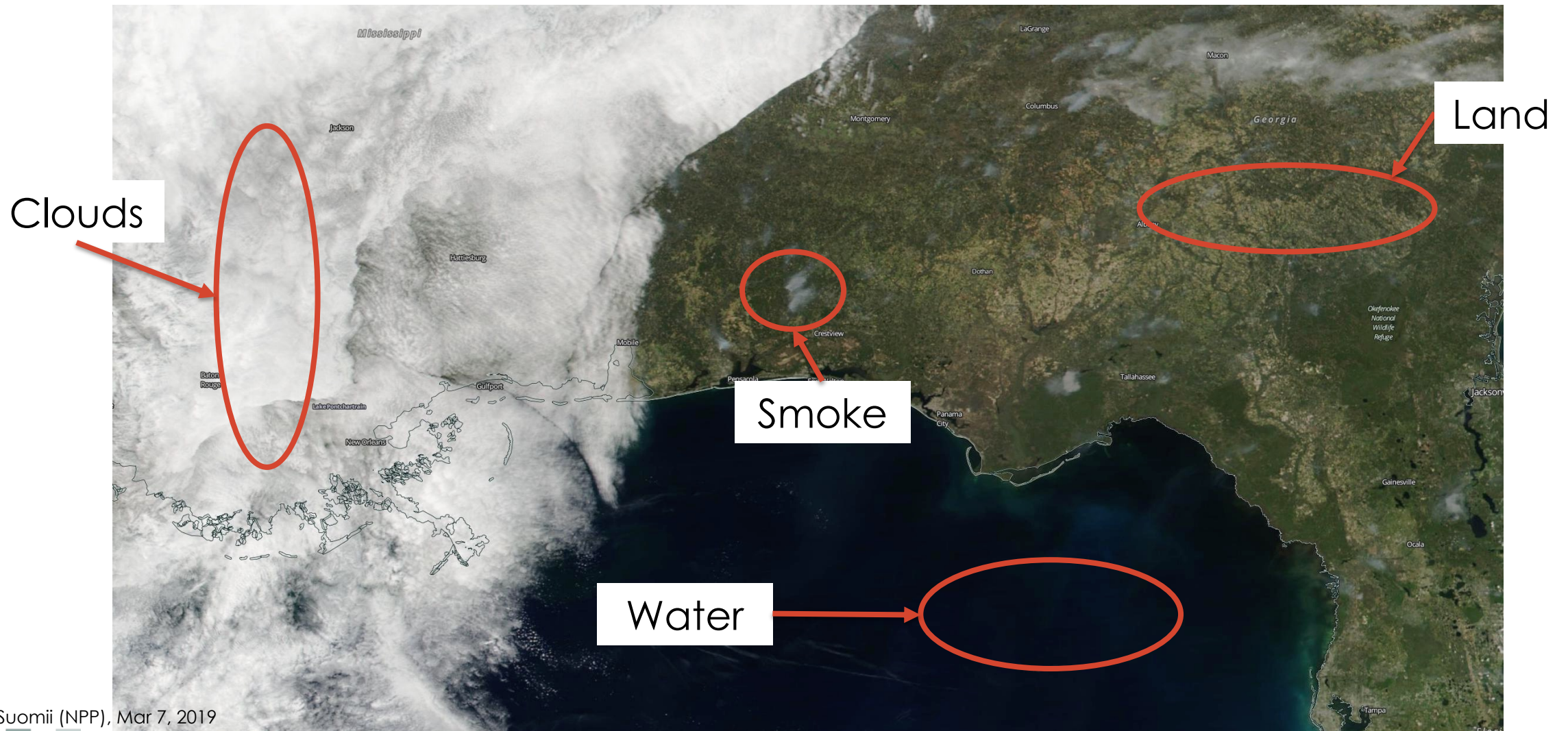


Terra (MODIS) May 8, 2007





# Aerosol Detection



Suomii (NPP), Mar 7, 2019



# Complex Image: Smoke & Clouds

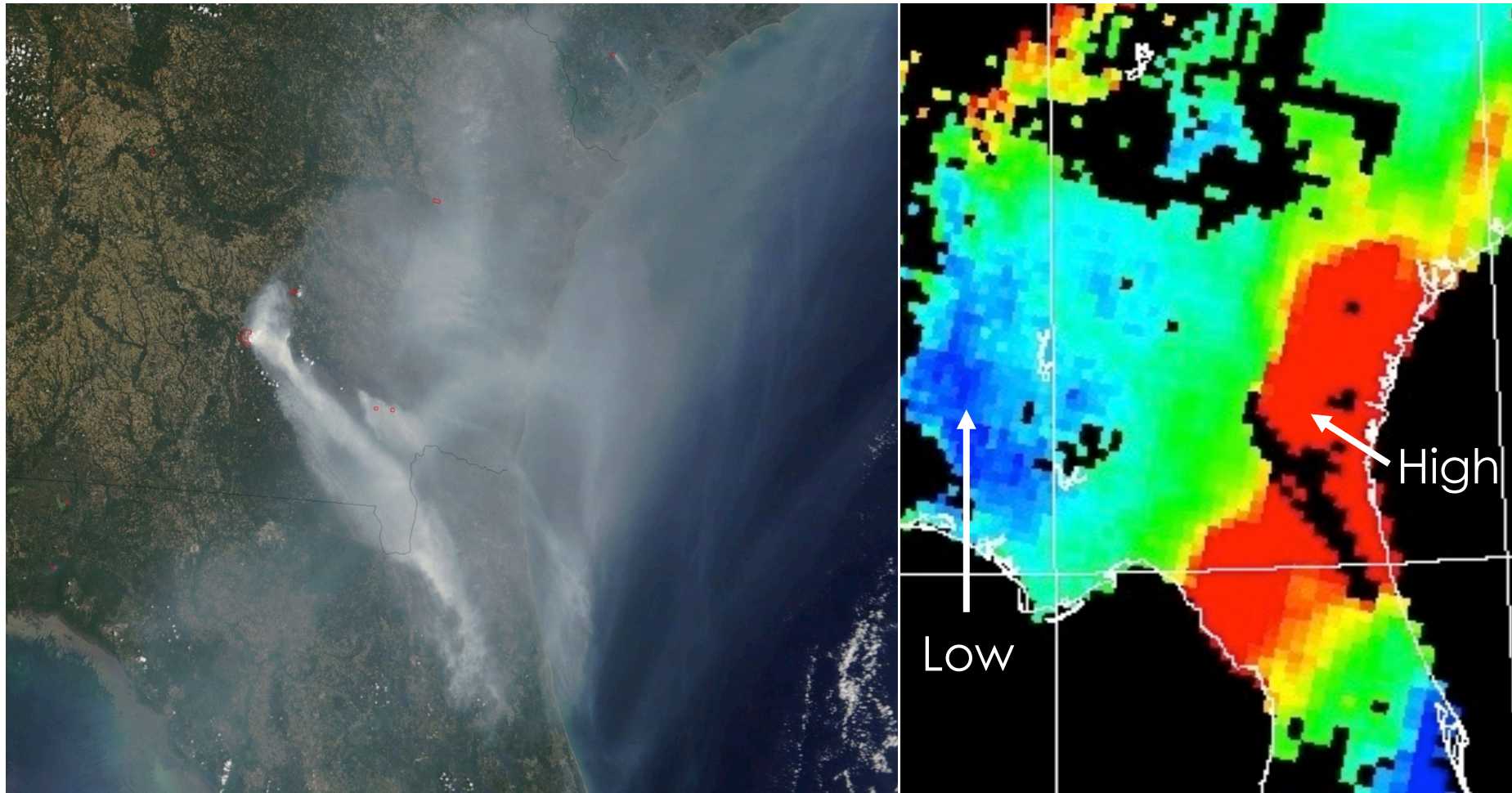


Suomi NPP (VIIRS) Mar 26, 2018





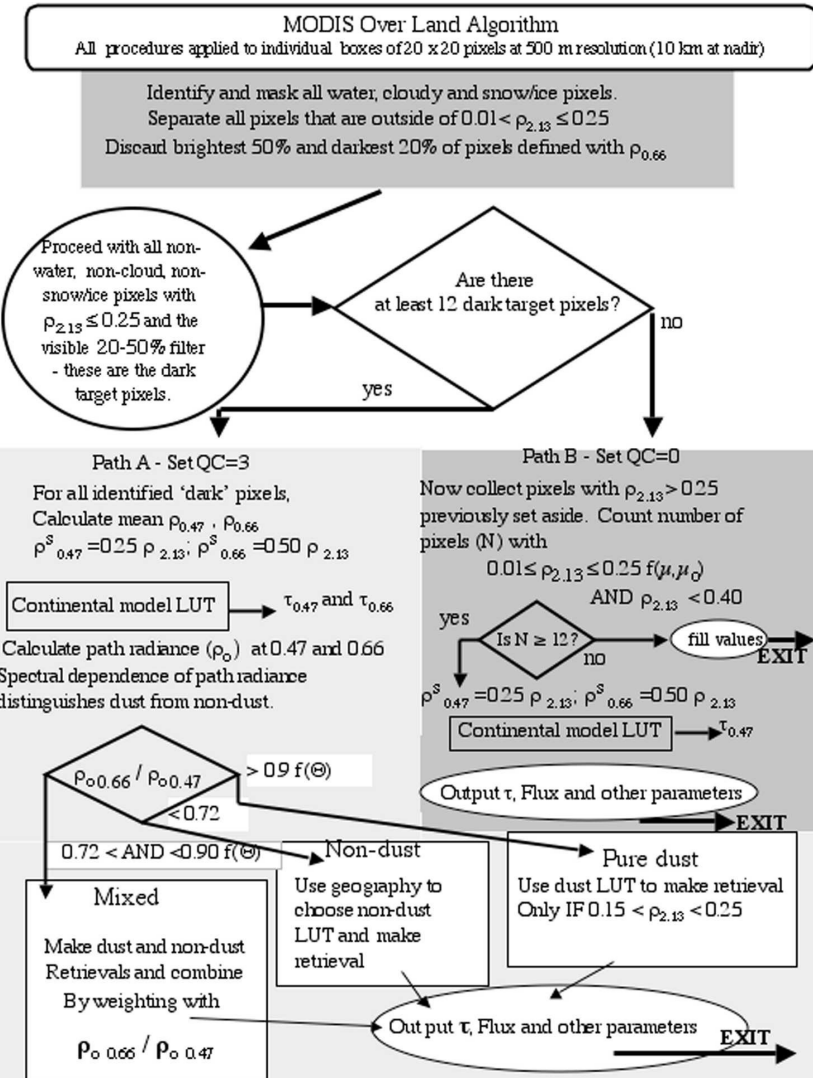
# Radiance to Aerosol Products



Terra MODIS, May 2, 2007



# Aerosol Retrieval Algorithm



Aerosol retrieval algorithm is a complex inversion scheme where assumptions are made in simulating satellite observations with advanced radiative transfer calculations to retrieve atmospheric aerosol properties.





# 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

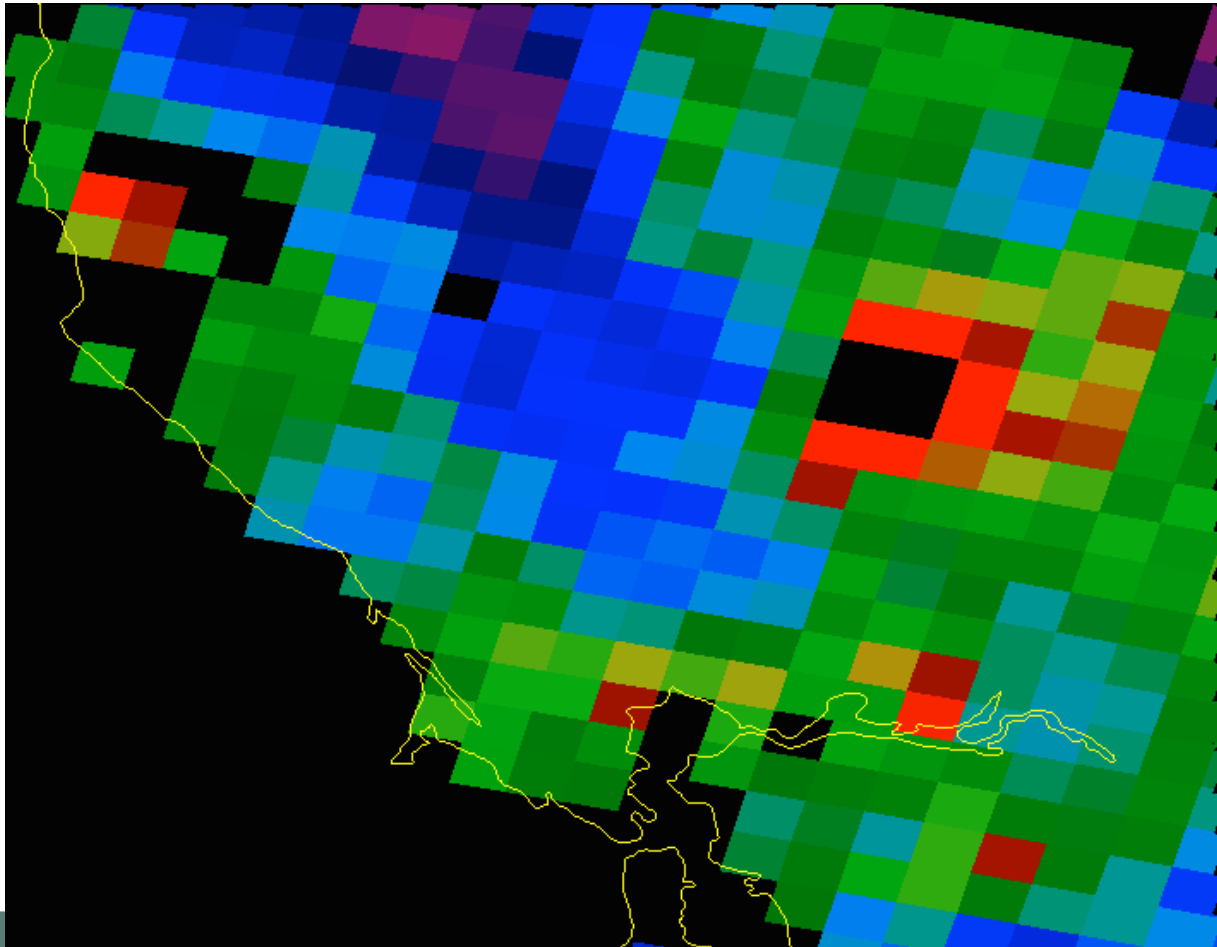
MOD44 Vegetation Cover Conversion

**MYD – MODIS Aqua**  
**MOD – MODIS Terra**

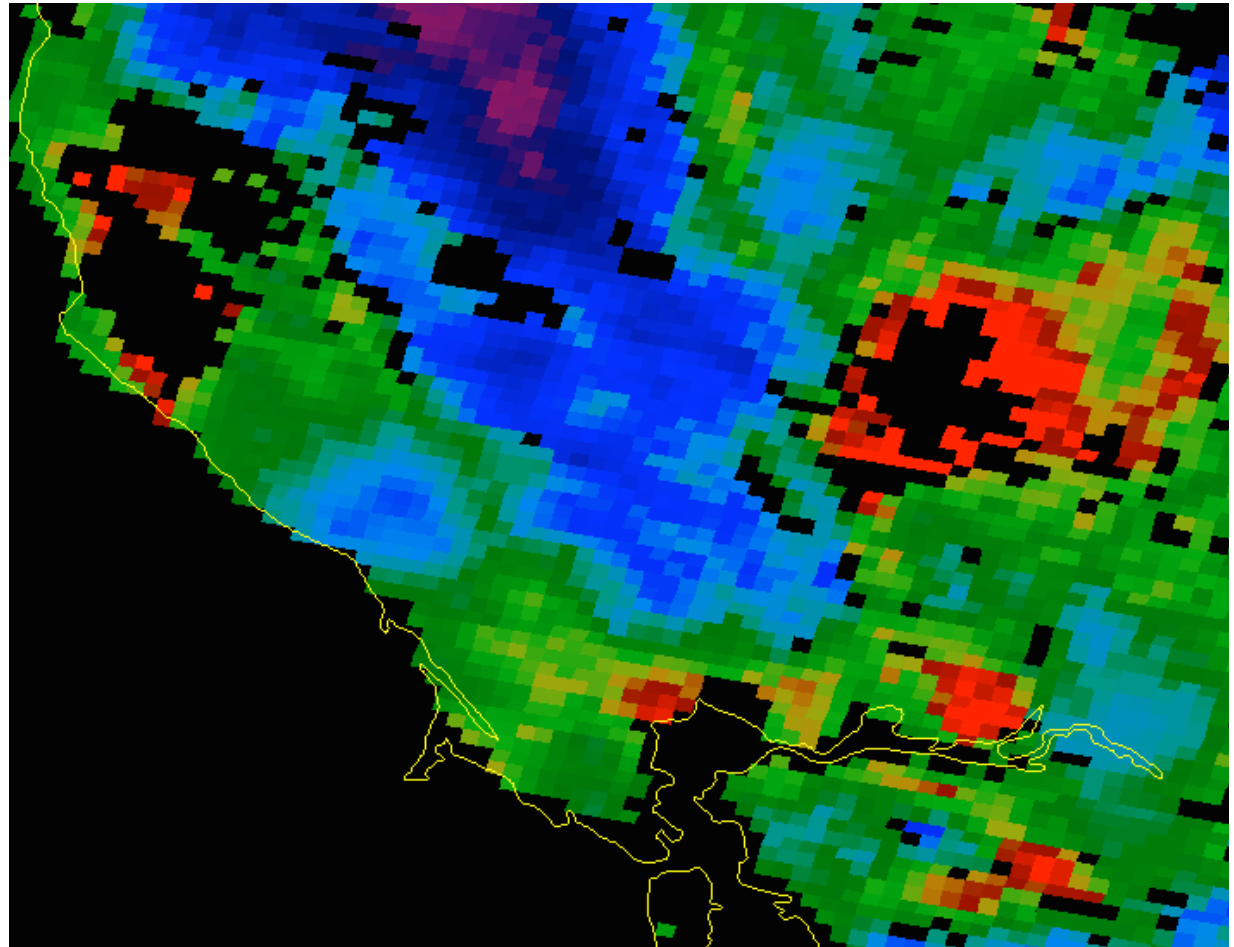


# MODIS 10 km vs. 3 km Products

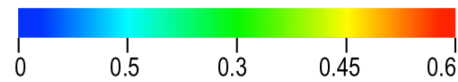
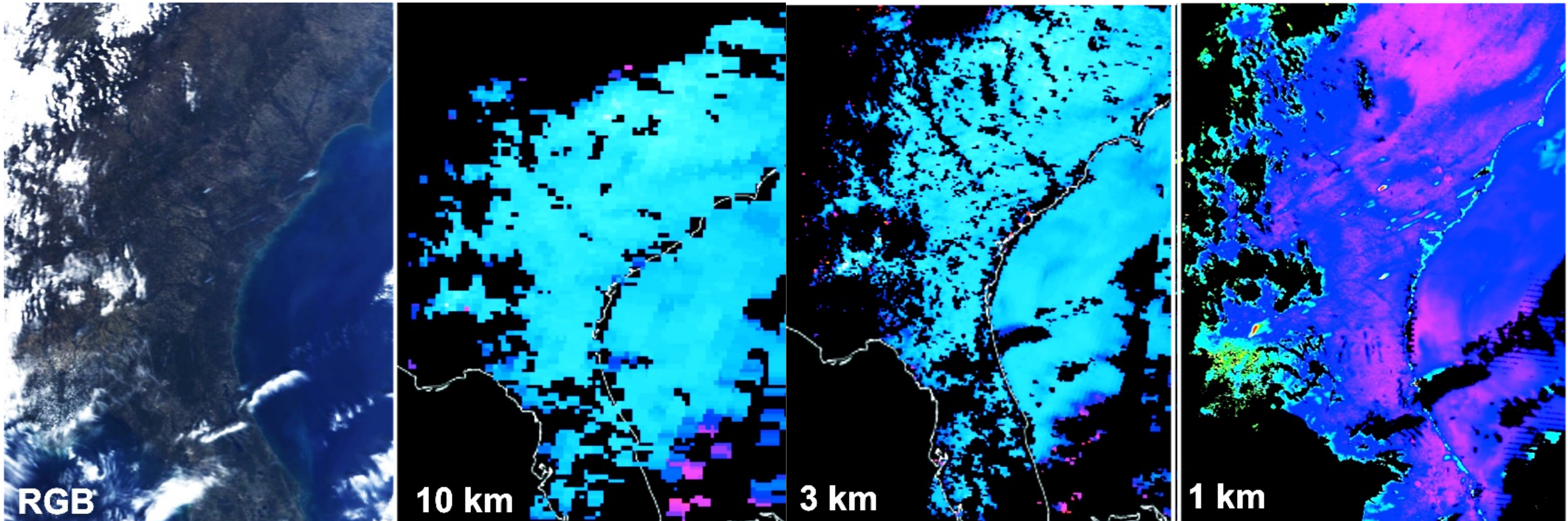
10 km



3 km

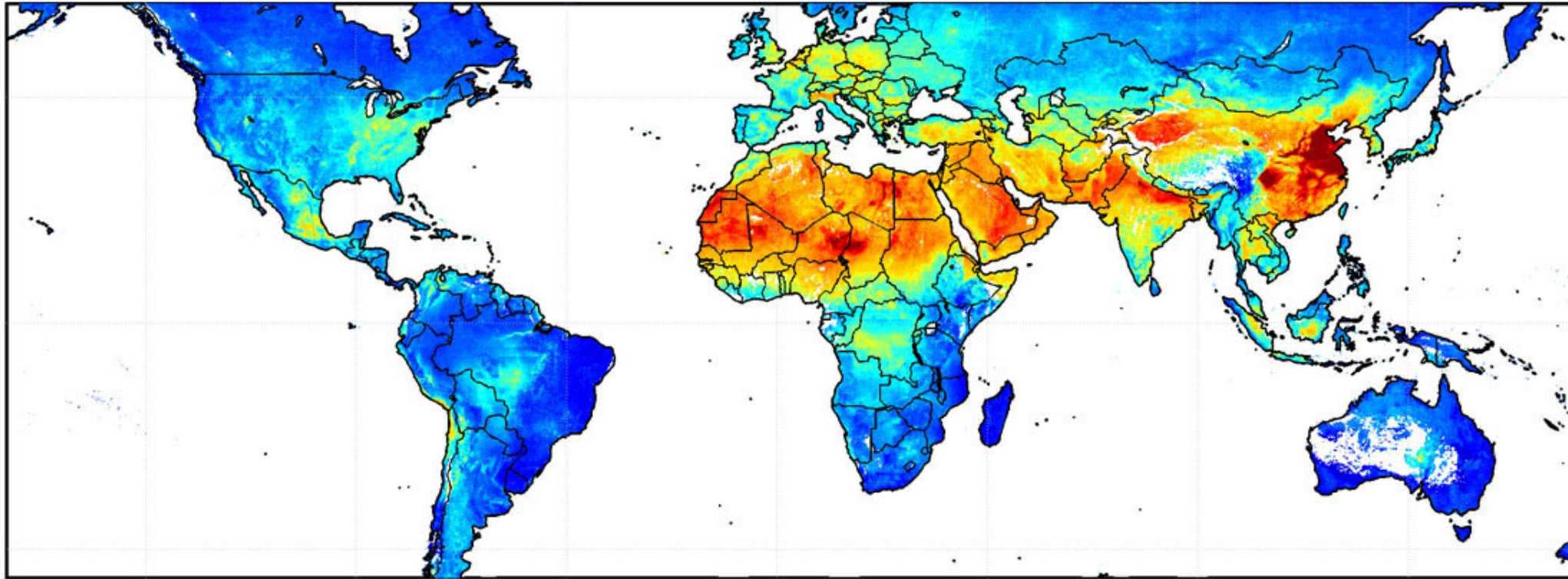


# High Resolution Aerosol Product





# Application of MODIS Aerosol Product



Satellite-Derived PM<sub>2.5</sub> [ $\mu\text{g}/\text{m}^3$ ]

Source: van Donkelaar et al., 2006, 2009

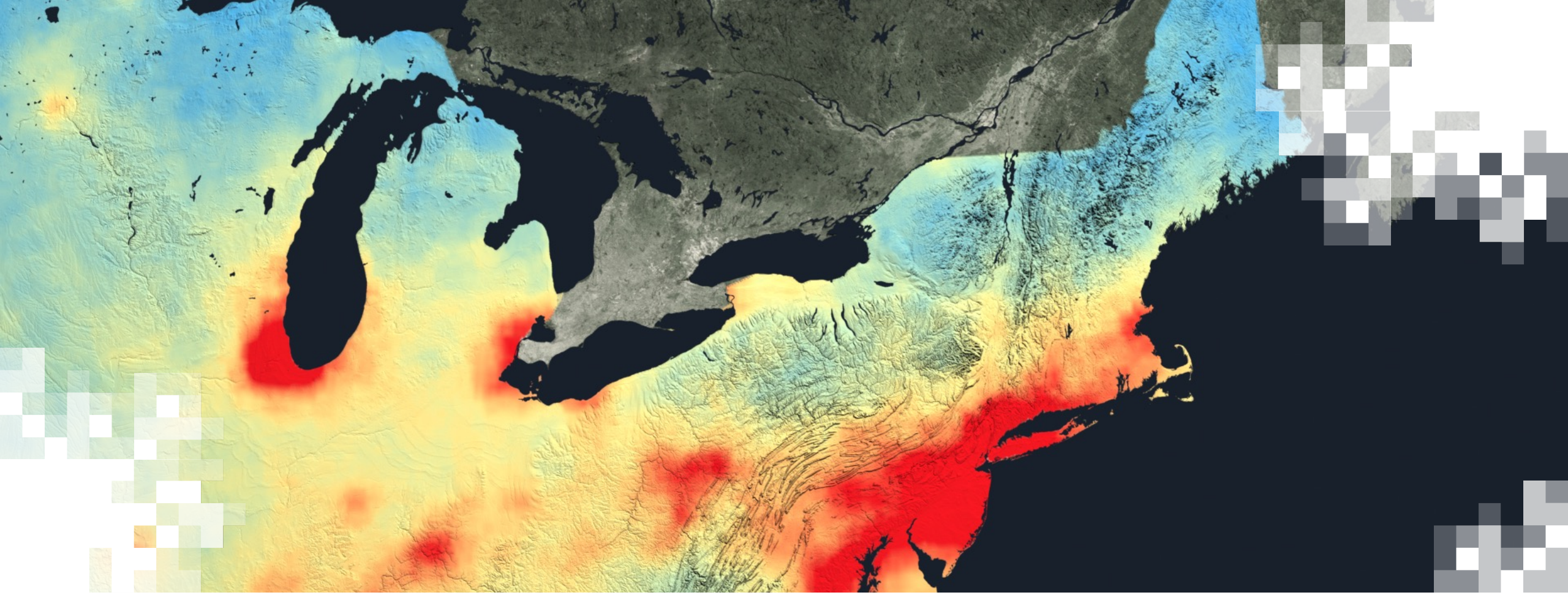


# Access to MODIS Aerosol Products

- 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 Datasets
  - 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/>



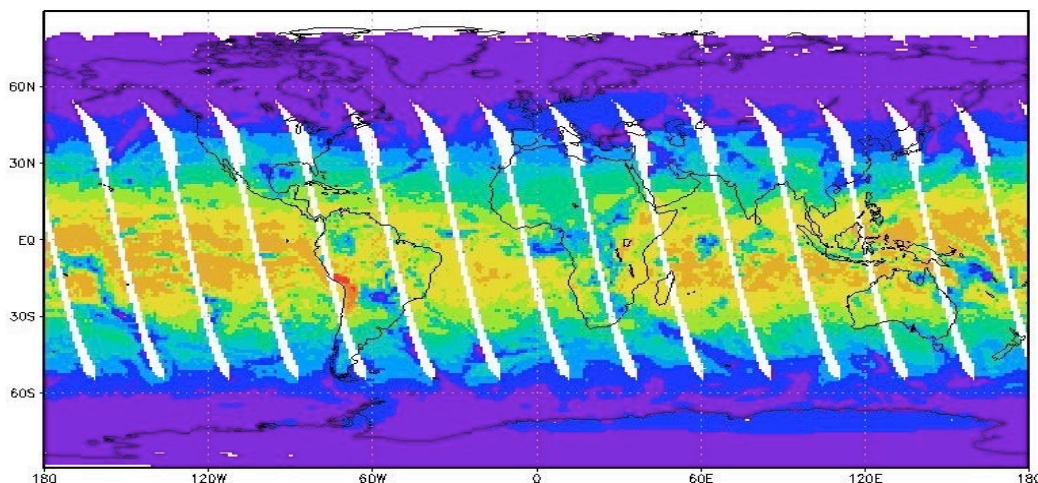




OMI



# Ozone Monitoring Instrument (OMI)



## Instrument Characteristics

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

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

## Retrieval Products

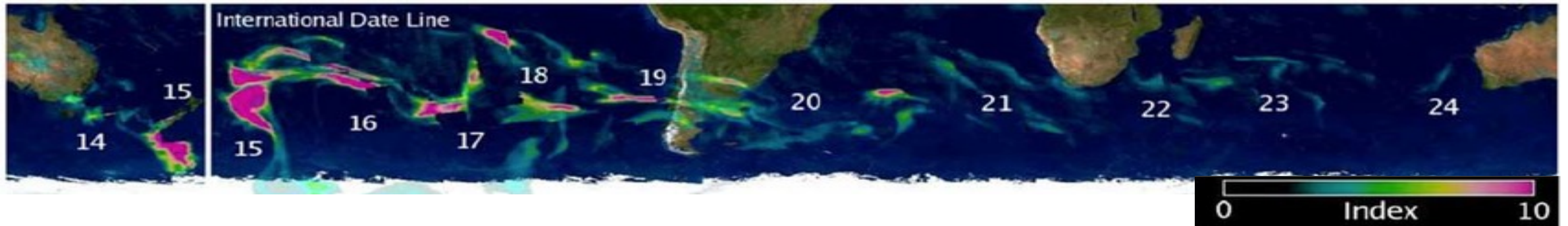
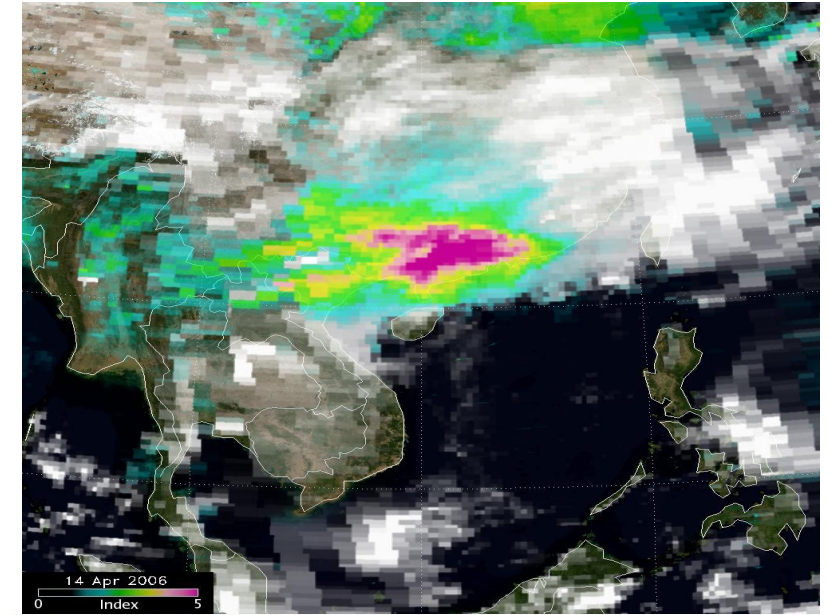
- Column Amounts
  - Ozone ( $O_3$ )
  - Nitrogen Dioxide ( $NO_2$ )
  - Sulfur Dioxide ( $SO_2$ )
  - Others
- Aerosols



# 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

Aerosols Over Clouds, April 14, 2006

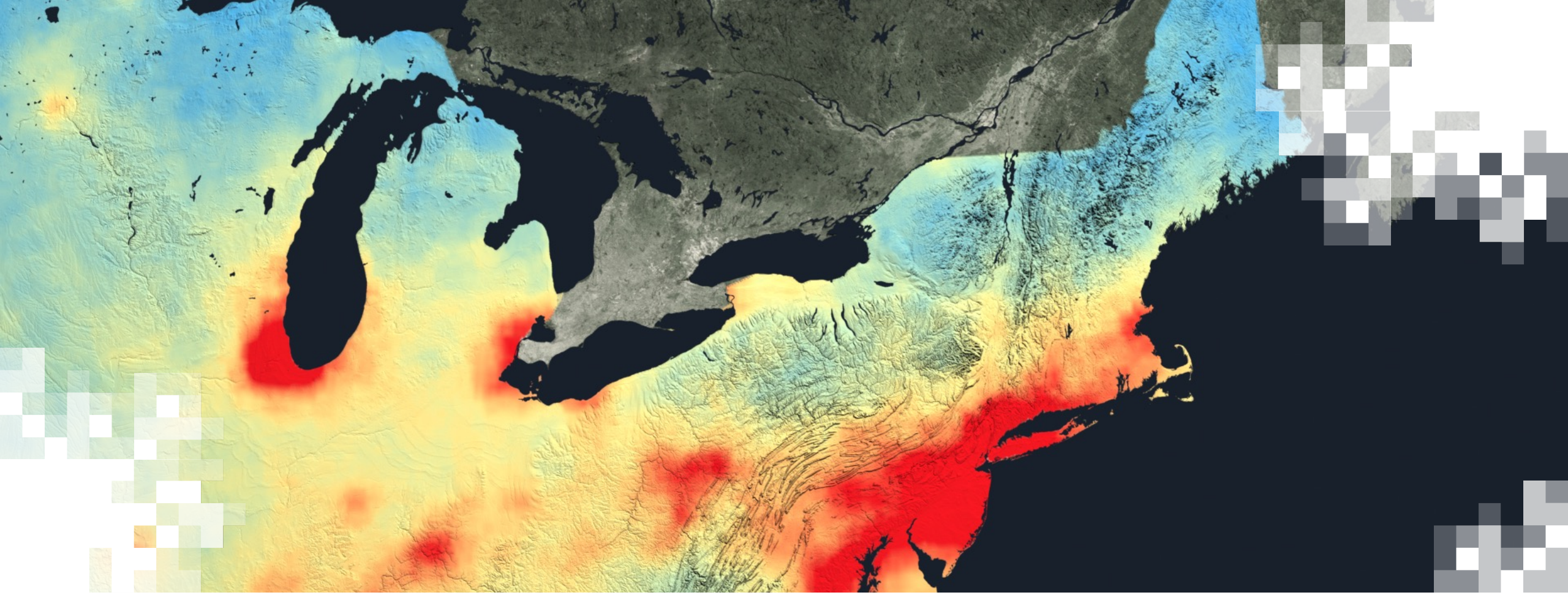


Above: Transport around the globe of a high-altitude smoke layer generated by the Dec 2006 Australian fires. Numbers indicate the day of the month.

Image Credit: Torres, Omar & Tanskanen, Aapo & Veihelmann, Ben & Ahn, Changwoo & Braak, Remco & Bhartia, Pawan & Veefkind, Pepijn & Levelt, P. (2007).





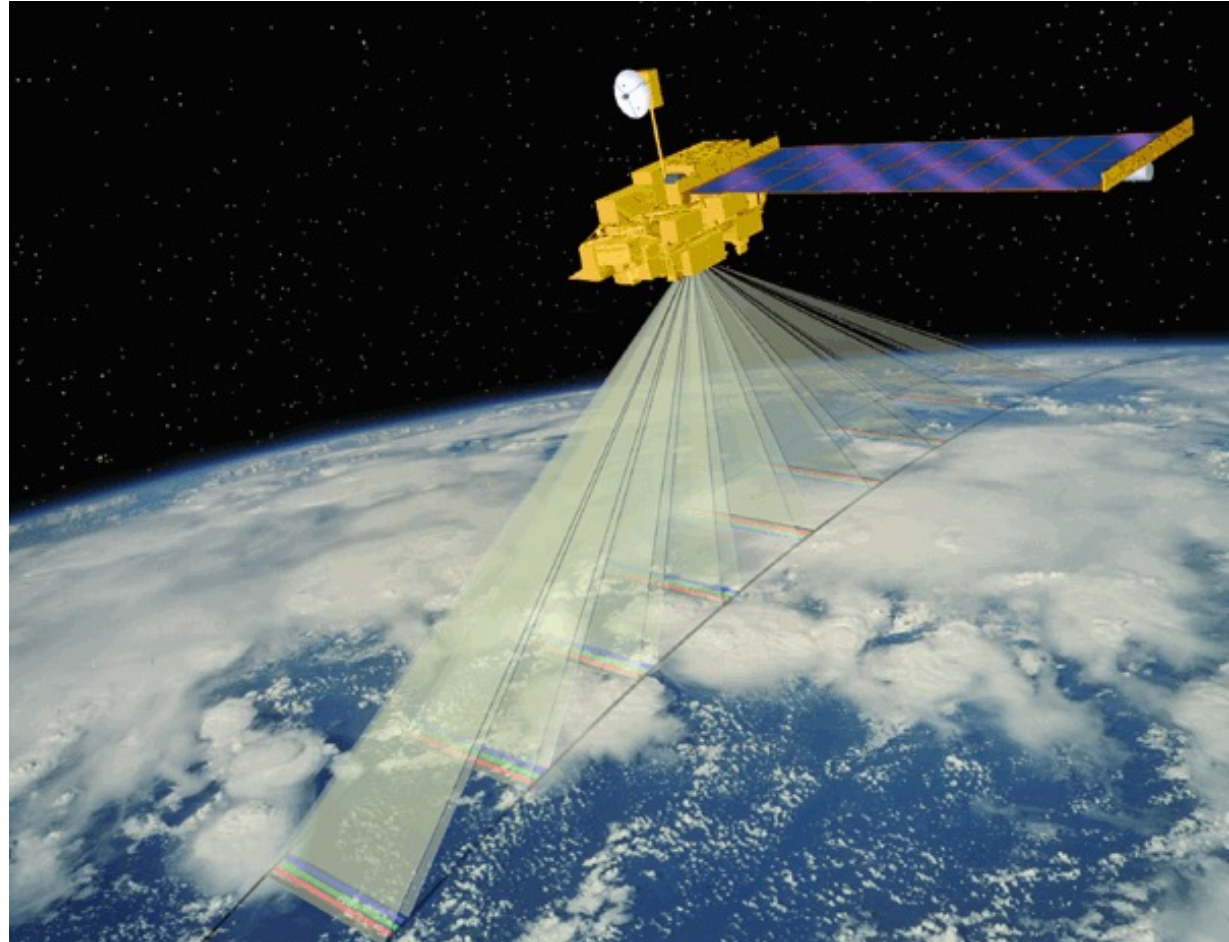


MISR

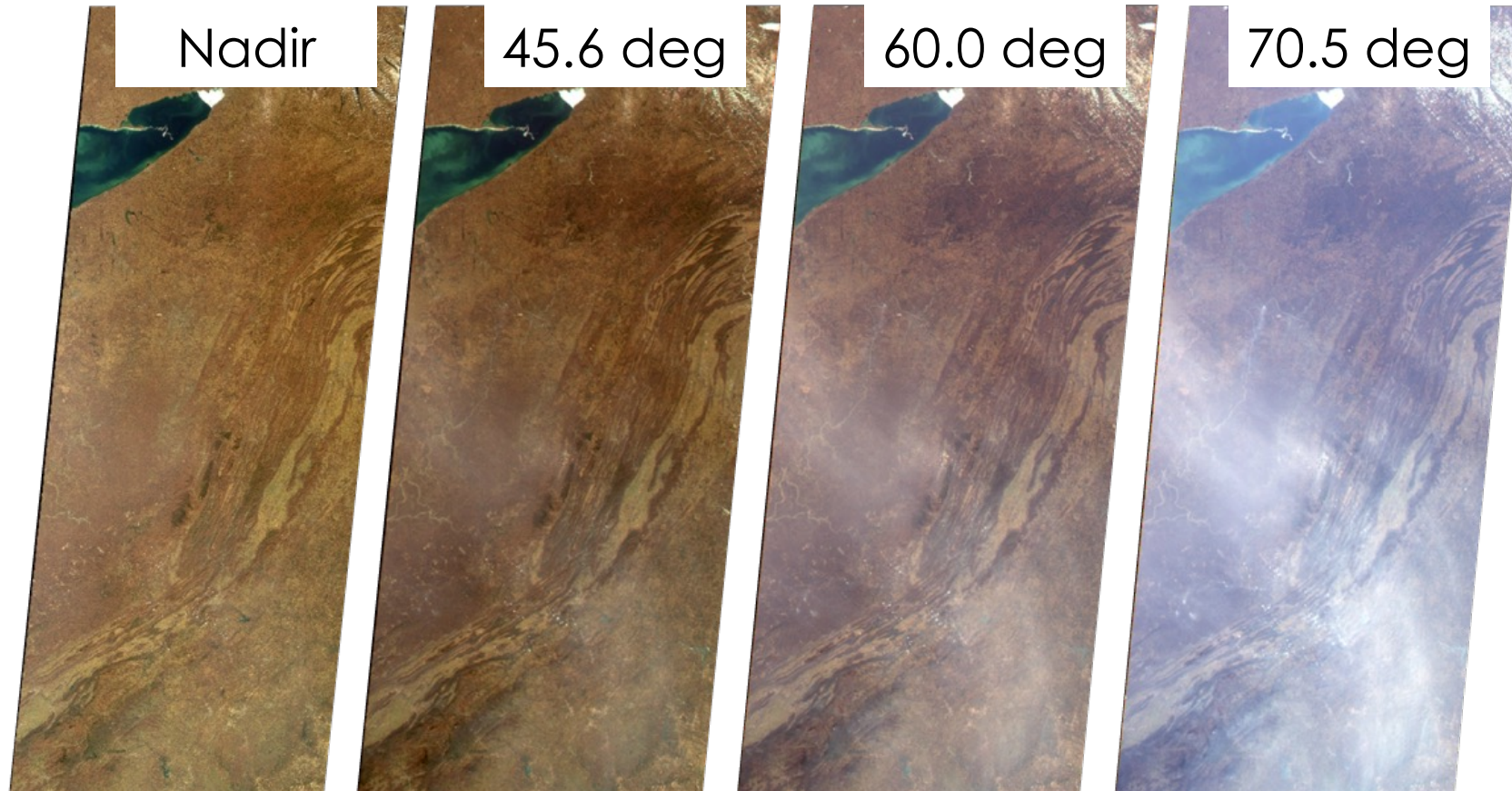


# Multi-angle Imaging Spectro-Radiometer (MISR)

- 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



# MISR Instrument



Angular observations (which are not available in MODIS) make MISR capable of providing additional information on particle size, shape, and aerosol height under specific cases.

Appalachian Mountains, Terra MISR, April 18, 2000





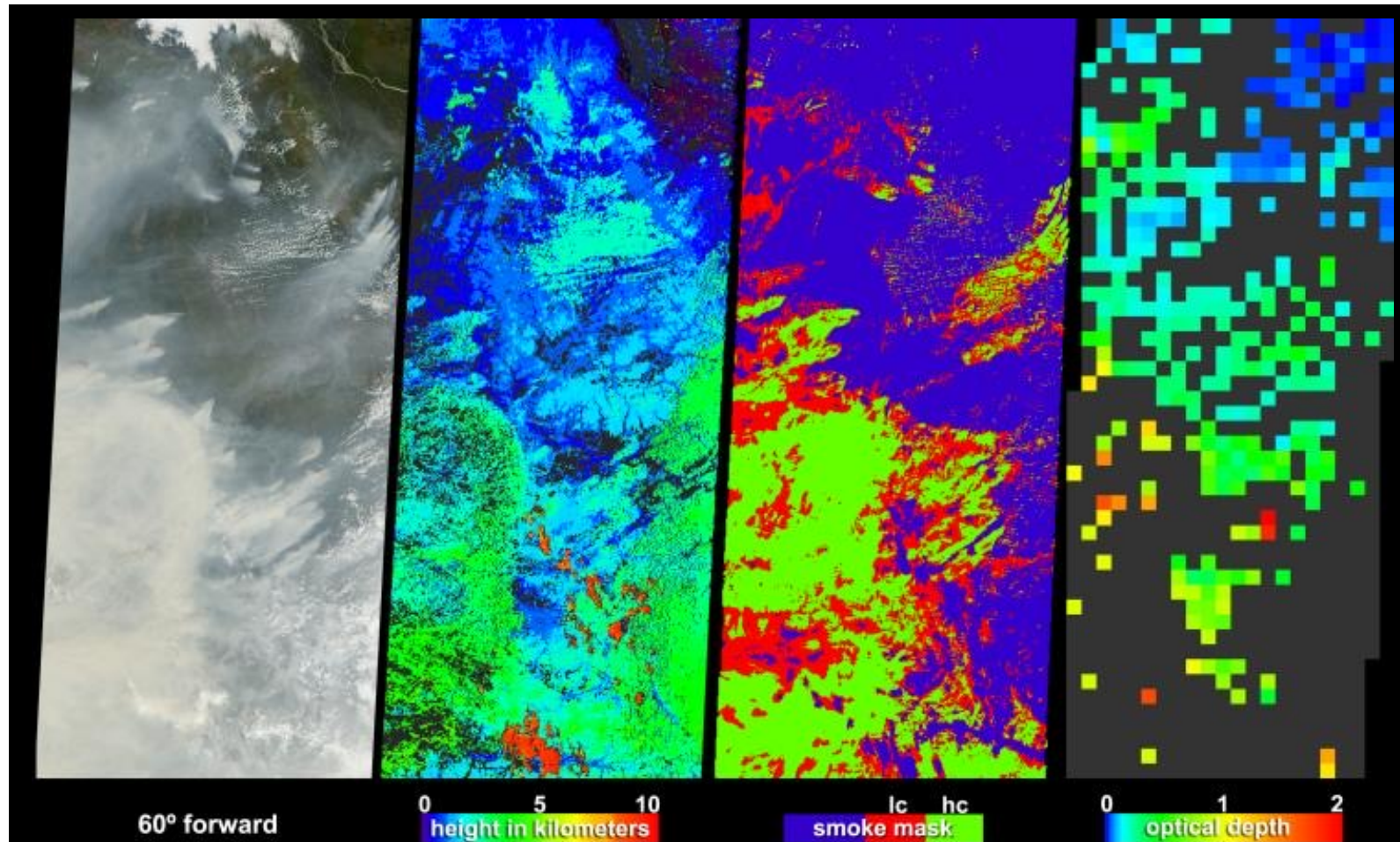
# MISR Global Daily Coverage



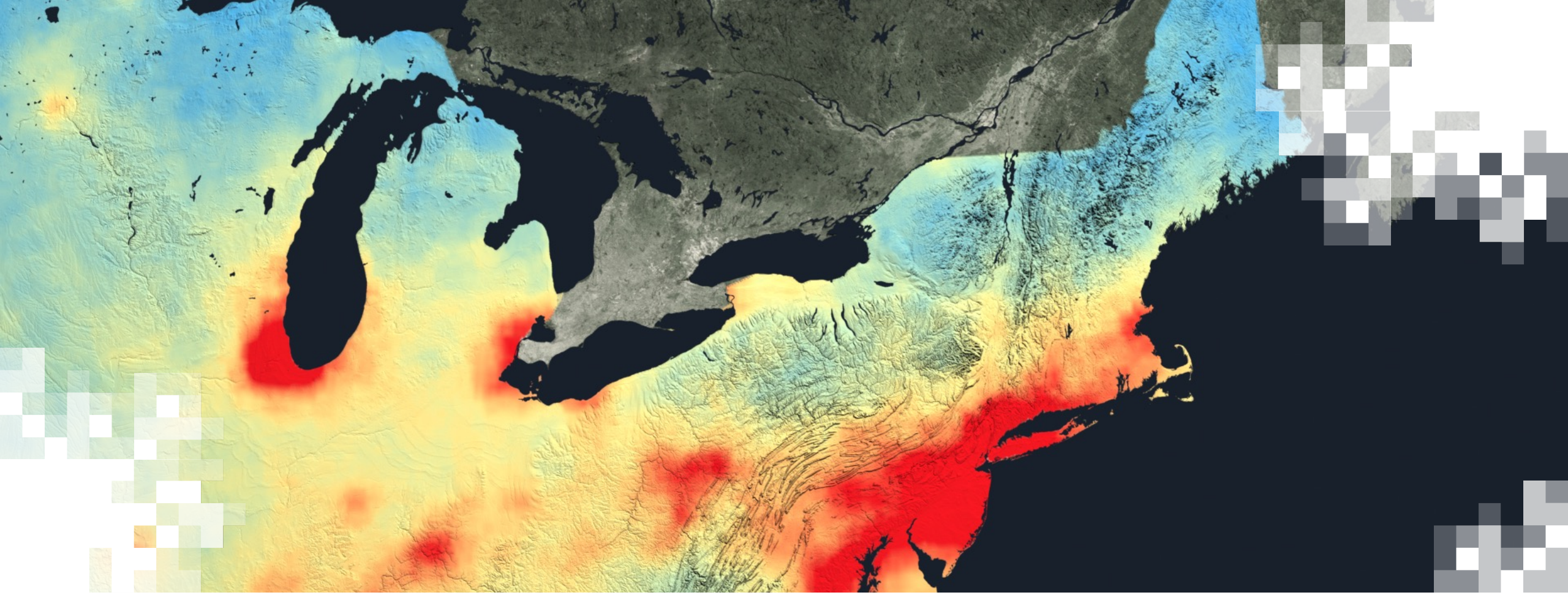


# Applications of MISR Data

Smoke Signals from the July 2004 Alaska and Yukon Fires







VIIRS

# Aerosol Data - NASA Products

	MODIS (T & A)	VIIRS-SNPP	VIIRS-NOAA20
Data	AOD	AOD	x
Spatial Resolution	1, 3, 10 km	6 km	x
Global Coverage	1-2 days	Daily	Daily
Algorithm	DT, DB, MAIAC	DB, DT	X
Data Availability	2000 (2003) - current	2012-Current	2017-Current
Data Format	HDF	NetCDF	x

DT = Dark Target

DB = Deep Blue

MAIAC = Multi-Angle Implementation of Atmospheric Correction

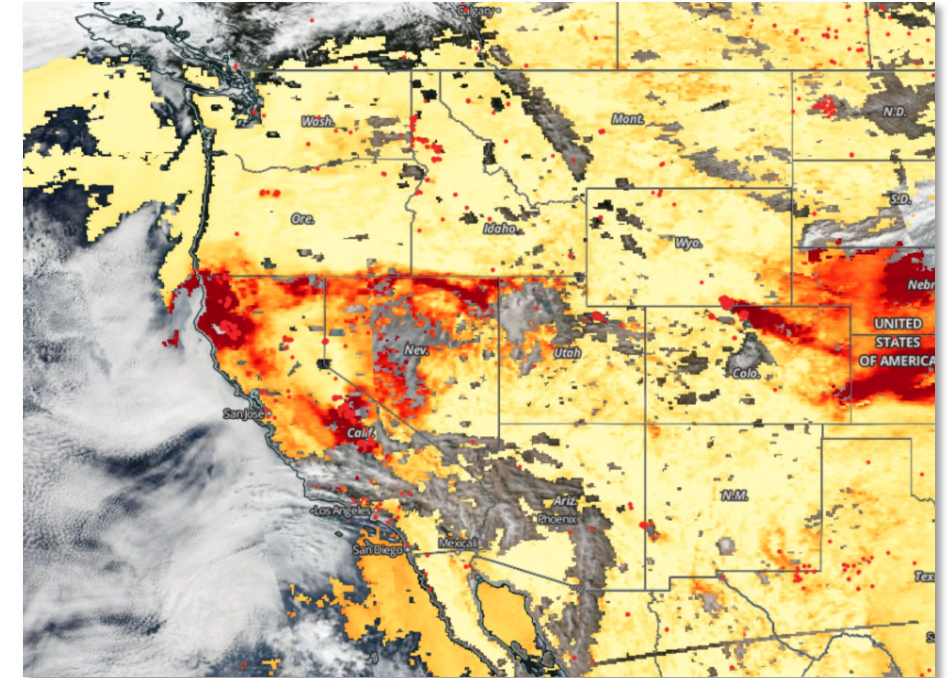




# SNPP VIIRS – NASA Products

- Deep Blue (DB)
  - Spatial Resolutions: 6 km (Level 2), 1 deg. (Level 3)
  - Products: AOD, Angstrom Exponent, Aerosol Type
  - Short Name: AERDB\_L2
  - <https://deepblue.gsfc.nasa.gov/>
- Dark Target (DT)
  - Spatial Resolutions: 6 km (Level 2), 1 deg. (Level 3)
  - Products: AOD
  - Short Name: AERDT\_L2\_VIIRS\_SNPP
  - [https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/AERDT\\_L2\\_VIIRS\\_SNPP/](https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/AERDT_L2_VIIRS_SNPP/)

October 05, 2020



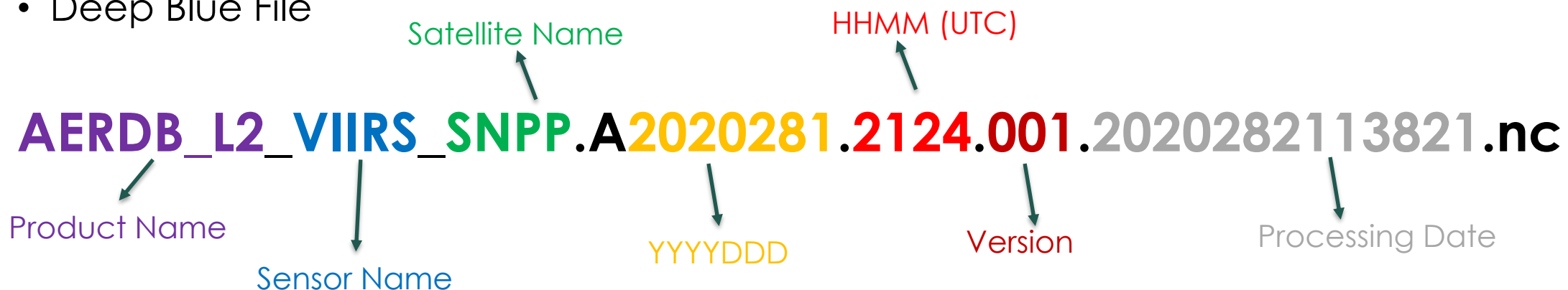
<https://go.nasa.gov/2GzTOye>



# File Names

- Deep Blue and Dark Target data sets comes in two different files

- Deep Blue File



AERDB\_D3\_VIIRS\_SNPP.A2020251.001.2020255000324.nc

AERDB\_M3\_VIIRS\_SNPP.A2020214.001.2020252000719.nc

- Dark Target File

– AERDT\_L2\_VIIRS\_SNPP.A2020251.2042.001.2020252071112.nc



# VIIRS DB/DT Aerosols

<https://deepblue.gsfc.nasa.gov/data#data-viirs>

- Level 2
  - 6-minute file
  - 6x6 km nadir resolution
- Level 3
  - Daily
  - Monthly
  - 1x1 degree
- NetCDF4

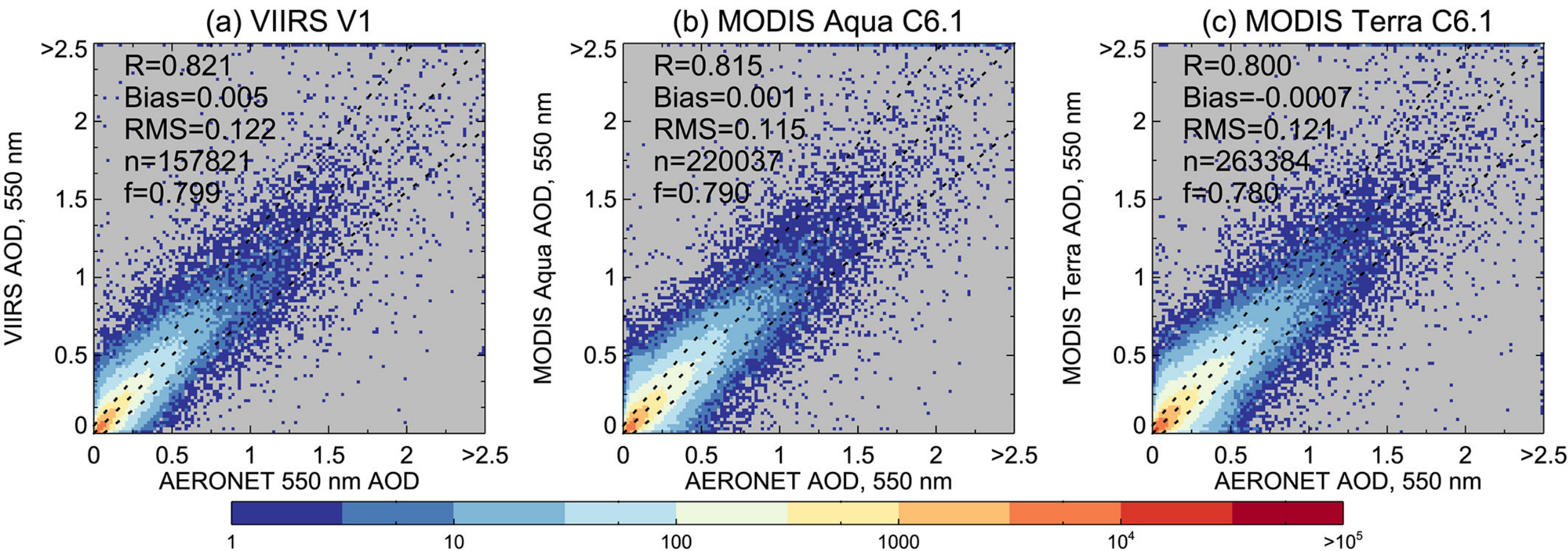
SDS name	Description
<b>L2 files (AERDB_L2)</b>	
Latitude	Central latitude of the retrieval pixel, degrees North.
Longitude	Central longitude of the retrieval pixel, degrees East.
Aerosol_Optical_Thickness_550_Land	The AOD at 550 nm over land.
Aerosol_Optical_Thickness_550_Land_Best_Estimate	As above, except only populated for those retrieval pixels passing quality assurance tests.  This is the SDS that is anticipated the majority of data users will use.
Aerosol_Optical_Thickness_550_Ocean	The AOD at 550 nm over ocean
Aerosol_Optical_Thickness_550_Ocean_Best_Estimate	As above, except only populated for those retrieval pixels passing quality assurance tests.  This is the SDS that is anticipated the majority of data users will use.
Aerosol_Optical_Thickness_550_Land_Ocean	The combined AOD at 550 nm, from the Deep Blue algorithm over land, and the SOAR algorithm over water.
Aerosol_Optical_Thickness_550_Land_Ocean_Best_Estimate	As above, except only populated for those retrieval pixels passing quality assurance tests.  This is the SDS that is anticipated the majority of data users will use.





# Validation

<https://doi.org/10.1029/2018JD029688>



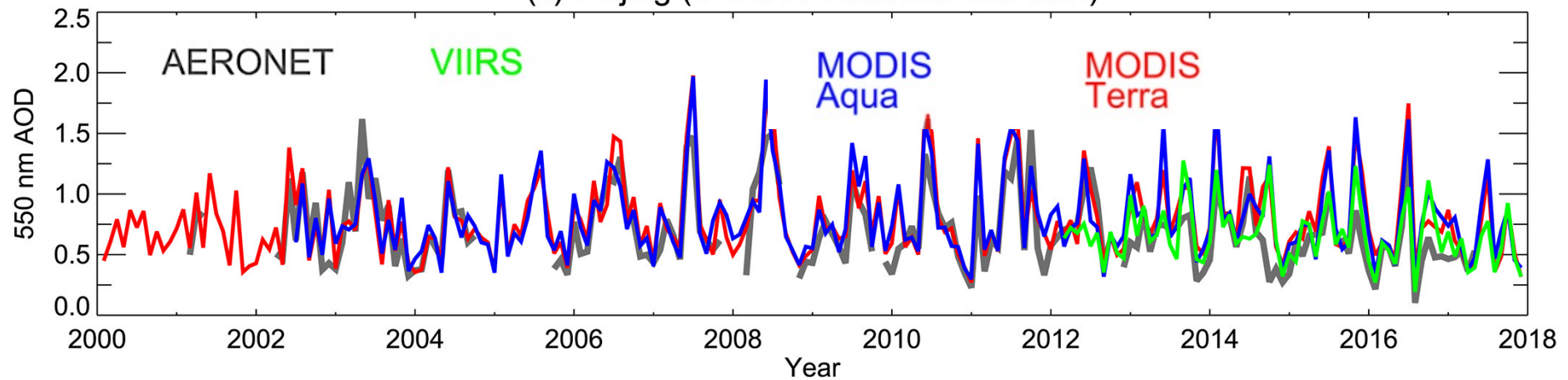
Hsu et al., 2019



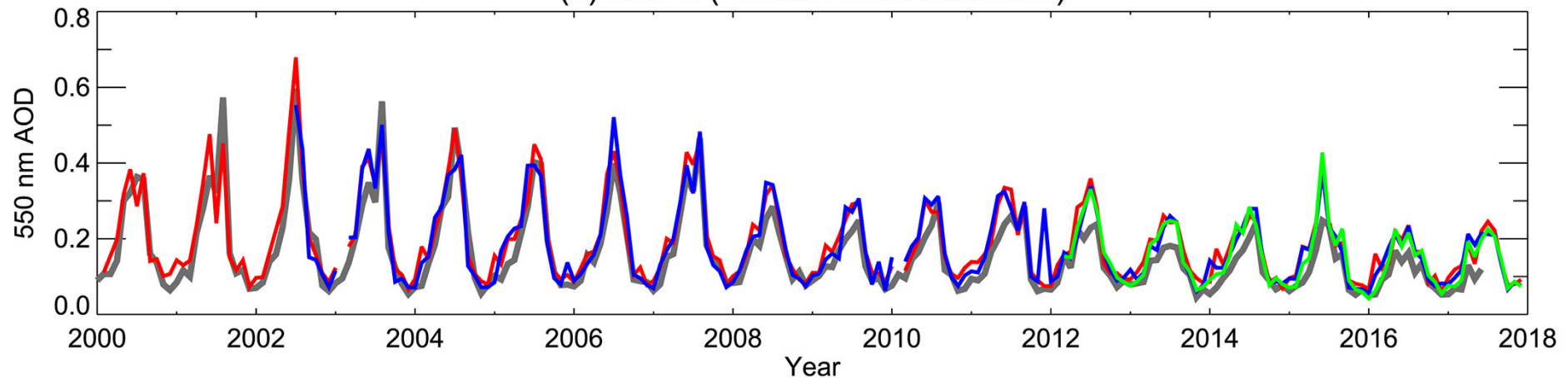
# Validation – Temporal Consistency

<https://doi.org/10.1029/2018JD029688>

(c) Beijing (Chinese industrial and dust)



(d) GSFC (Eastern USA suburban)

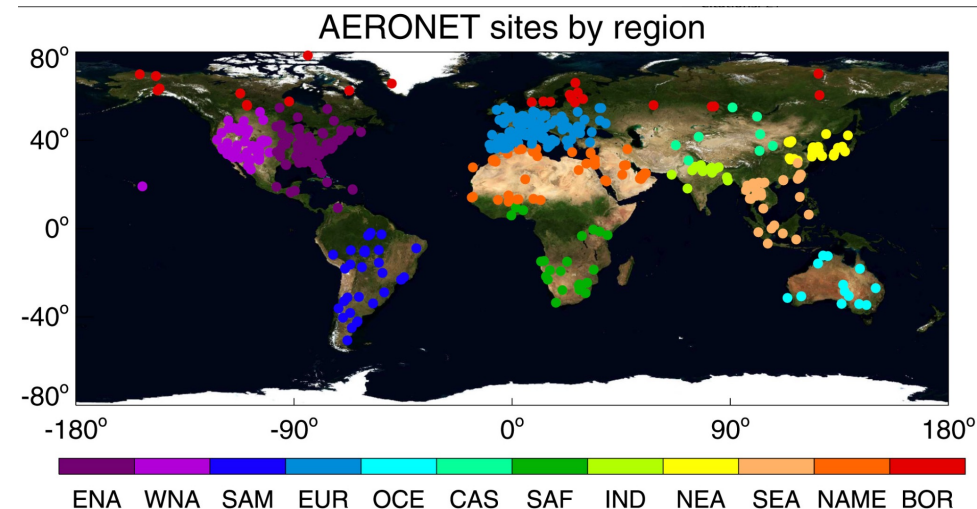
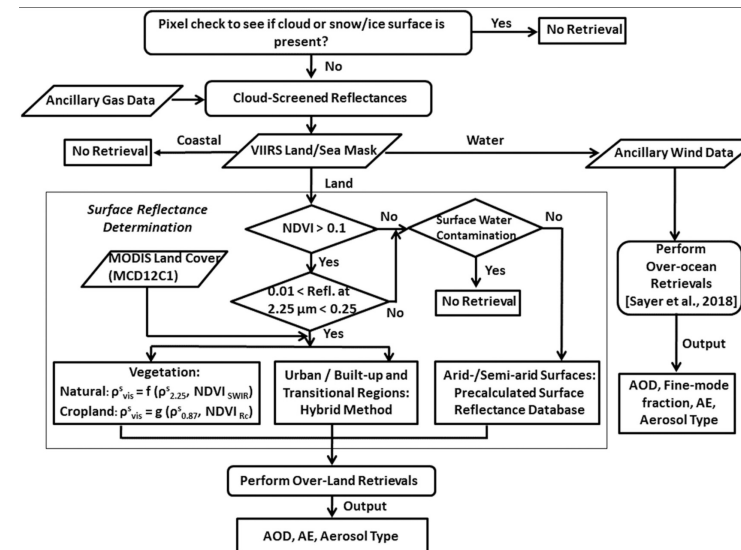


Hsu et al., 2019

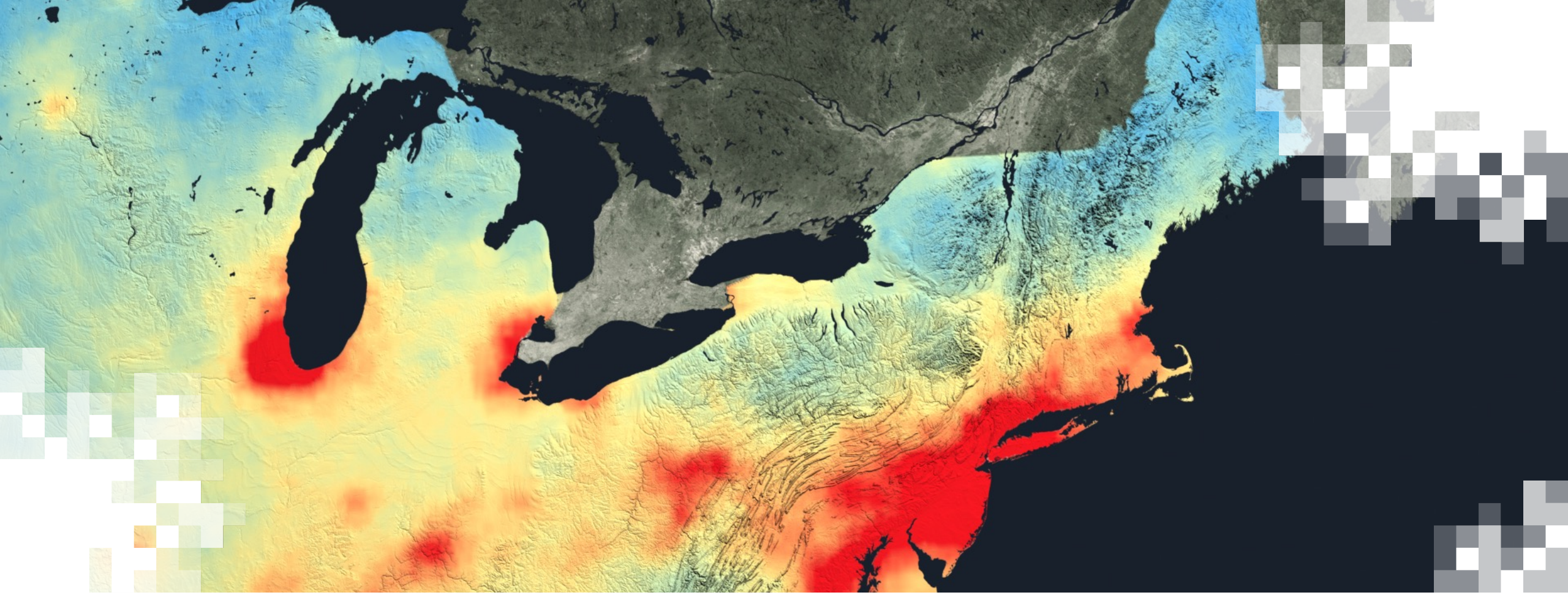


# VIIRS Deep Blue/Dark Target Aerosol Reference

- [Hsu, N. C., J. Lee, A. M. Sayer, et al.](#) 2019. "VIIRS Deep Blue Aerosol Products Over Land: Extending the EOS Long-Term Aerosol Data Records." *Journal of Geophysical Research: Atmospheres* **124** (7): 4026-4053  
[[10.1029/2018jd029688](https://doi.org/10.1029/2018jd029688)]
- [Sayer, A. M., N. C. Hsu, J. Lee, W. V. Kim](#), and S. T. Dutcher. 2019. "Validation, Stability, and Consistency of MODIS Collection 6.1 and VIIRS Version 1 Deep Blue Aerosol Data Over Land." *Journal of Geophysical Research: Atmospheres* **124** (8): 4658-4688  
[[10.1029/2018jd029598](https://doi.org/10.1029/2018jd029598)]
- Sawyer, V.; Levy, R.C.; Mattoo, S.; Cureton, G.; Shi, Y.; Remer, L.A. Continuing the MODIS Dark Target Aerosol Time Series with VIIRS. *Remote Sens.* **2020**, *12*, 308.  
<https://doi.org/10.3390/rs12020308>





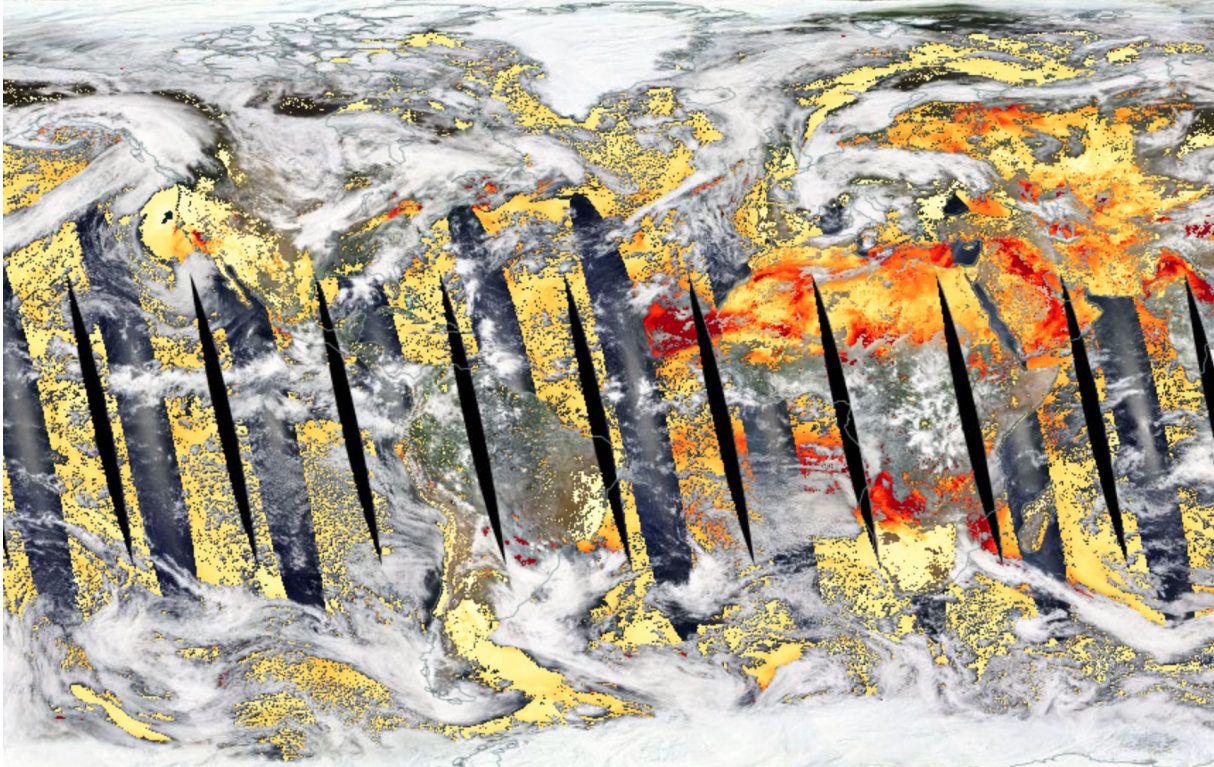


AOD Example

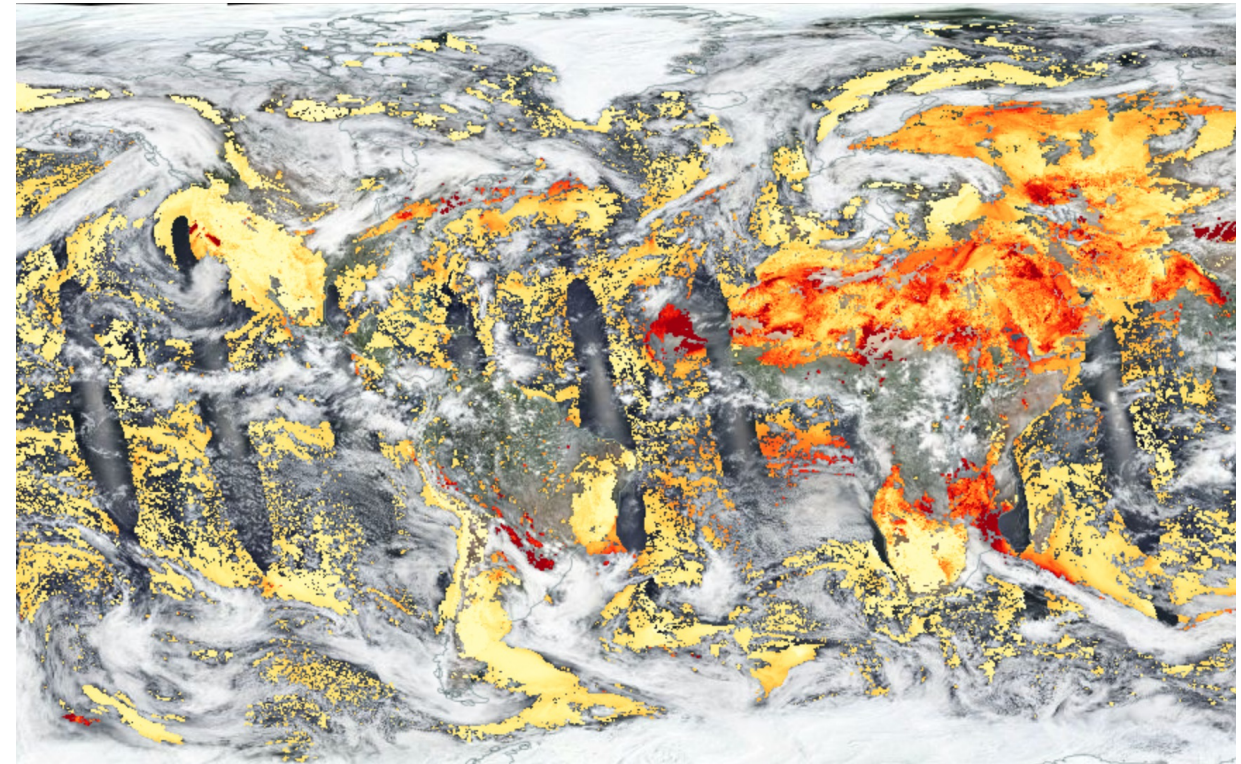


# MODIS vs. VIIRS – September 27, 2020

<https://go.nasa.gov/3nIrOyz>



**MODIS-Aqua (DB)**

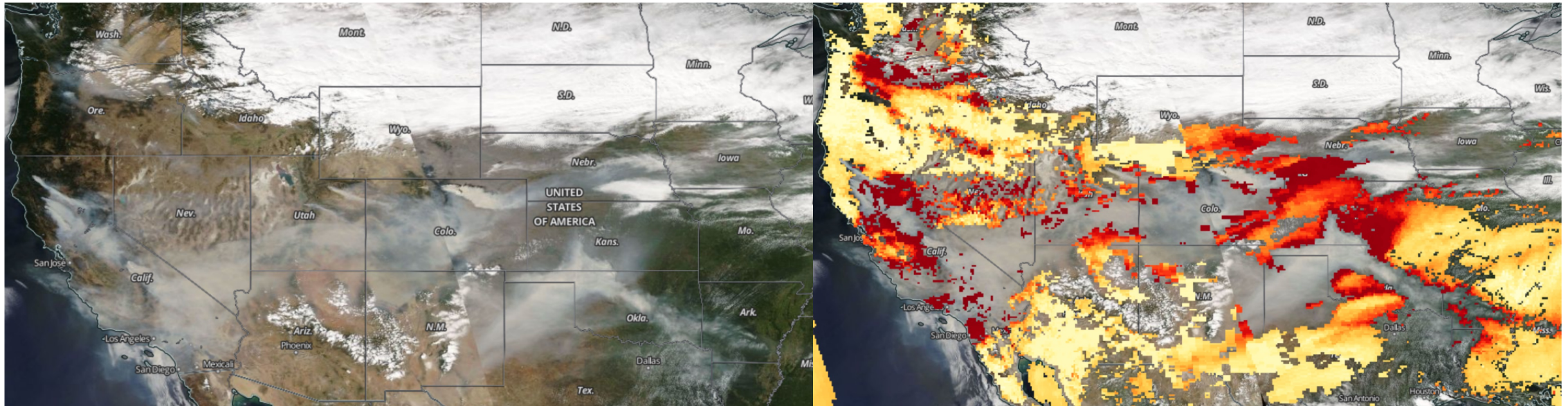


**VIIRS-SNPP (DB)**



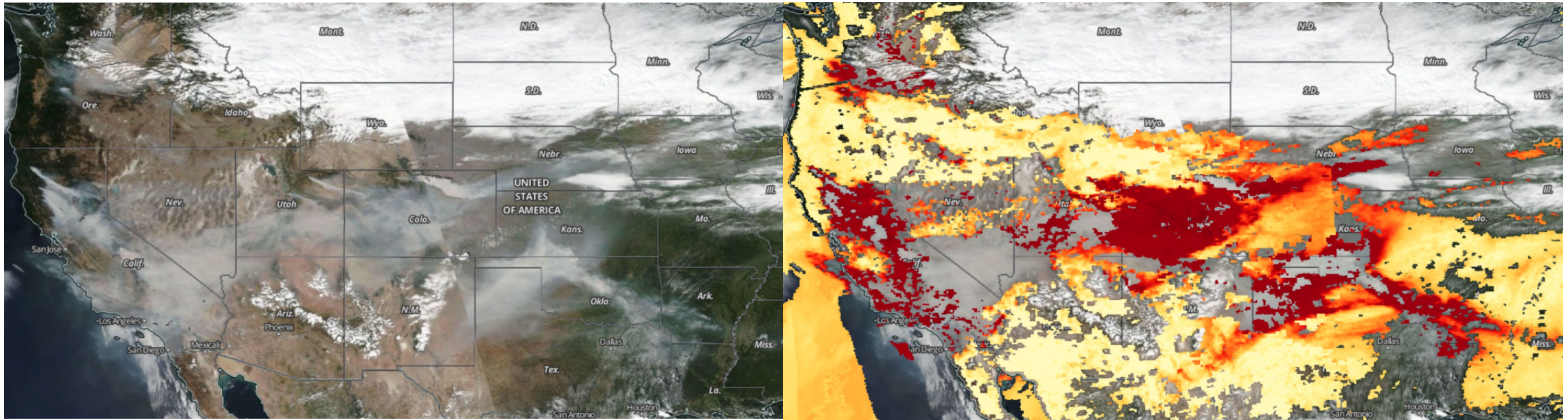


# Application – MODIS- Aqua (Sep 7<sup>th</sup>, 2020)

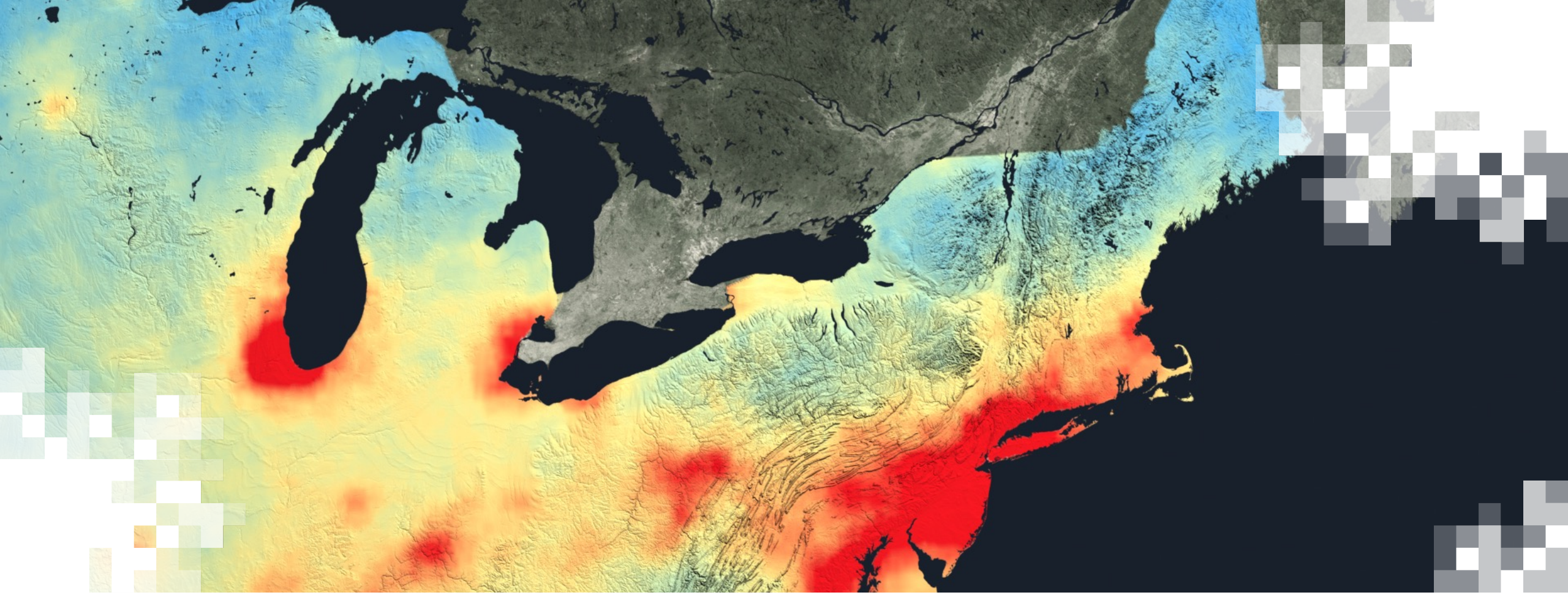




# Application – VIIRS-SNPP (Sep 7<sup>th</sup>, 2020)







NOAA Aerosol Data

# Aerosol Data - NOAA Products

	MODIS (T & A)	VIIRS-SNPP	VIIRS-N20
Data	X	AOD Smoke, Dust Mask	AOD Smoke, Dust Mask
Spatial Resolution	X	750m, 6 km	750m, 6 km
Global Coverage	X	Daily	Daily
Algorithm	X	NOAA	NOAA
Data Availability	X	2012-Current	2017-Current





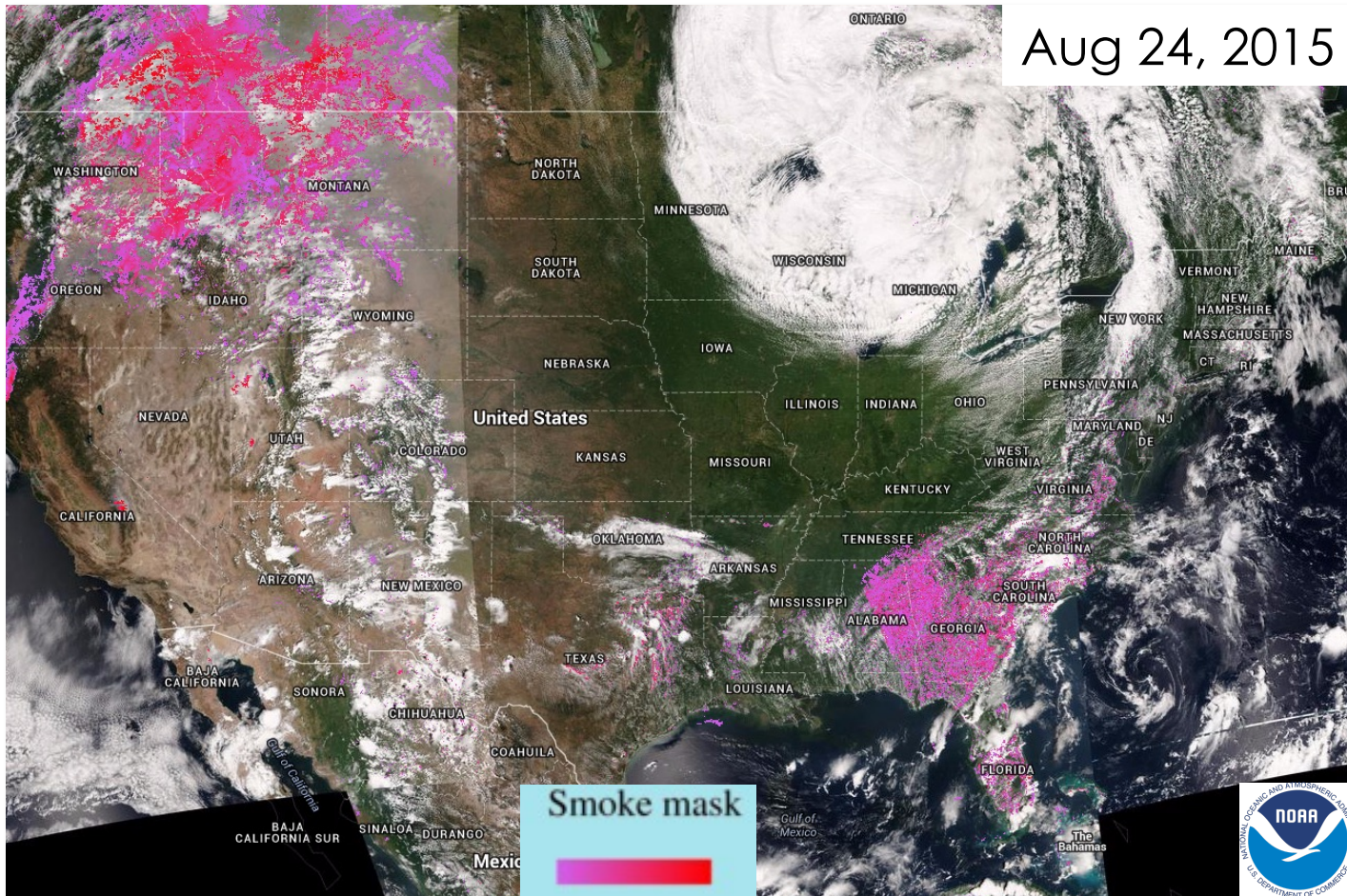
# Aerosol Data - NOAA Products

## Filenames

- NOAA has two aerosol products (datasets).
- Aerosol Optical Depth
  - JRR-AOD\_v2r3\_ **j01** \_s202009280811382\_e202009280813027\_c202009280832280.nc
  - JRR-AOD\_v2r3\_ **npp** \_s202009280709032\_e202009280710274\_c202009280749220.nc
- Aerosol Detection Product (ADP)
  - JRR-ADP\_v2r1\_npp\_s201911010742162\_e201911010743404\_c201911010834210.nc
  - 6 Type Flags: (1=Presence; 0=Absence) 1. Volcanic Ash Flag 2. Dust Flag 3. Smoke Flag 4. Nuc (none/unknown/clear) 5. Cloud Flag 6. Snow/Ice Flag
  - Dust/smoke aerosol index value
  - Quality Flags (low, medium, and high confidence for each type)



# VIIRS Smoke Mask - NOAA



- 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

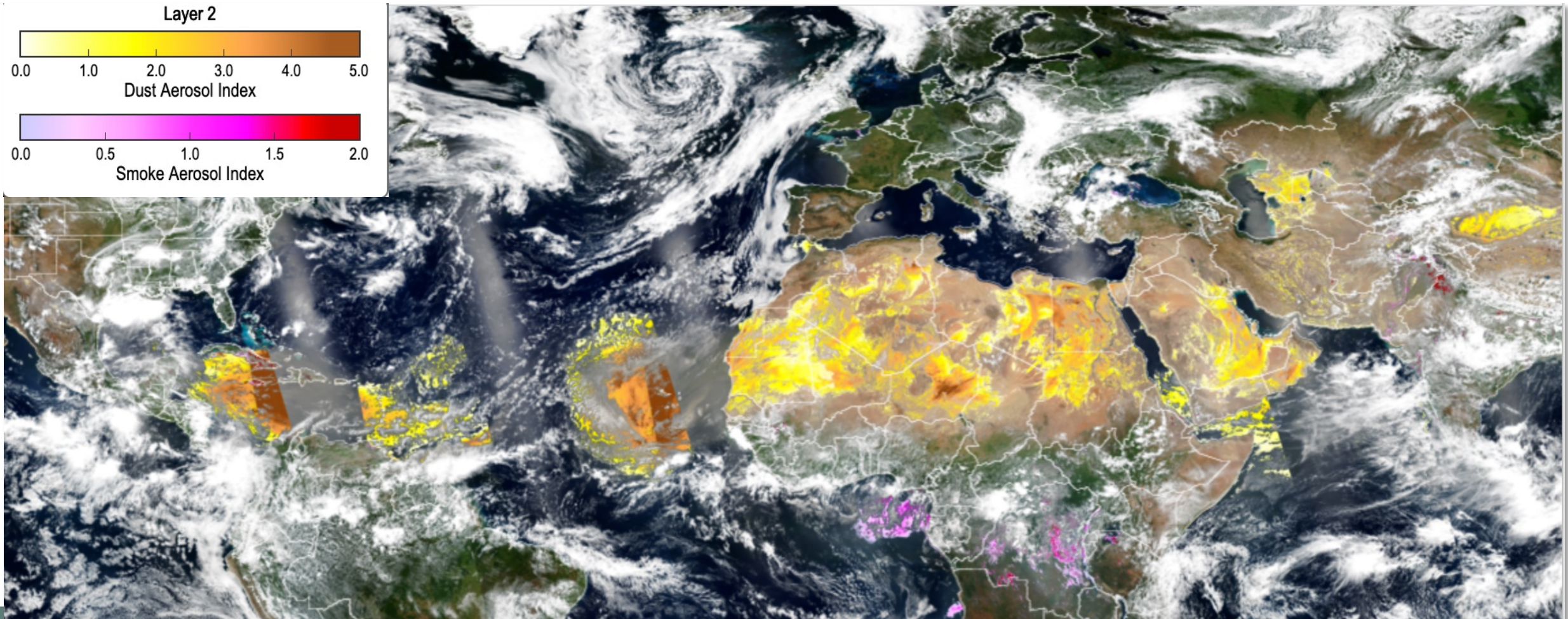
Side Courtesy of Shobha Kondragunta





# Dust Mask – Saharan Dust Transport of Summer 2020

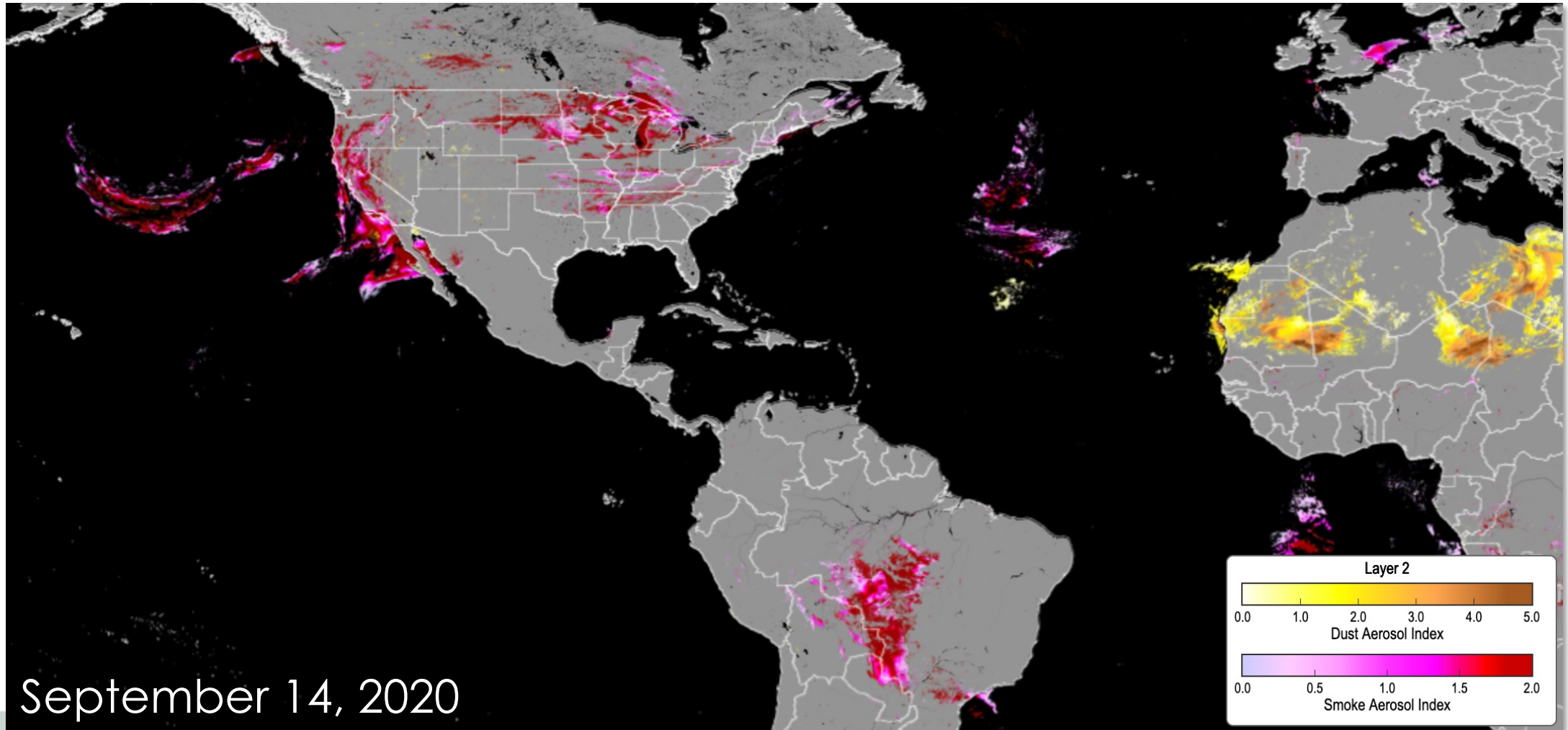
<https://www.star.nesdis.noaa.gov/jpss/mapper>





# Smoke from Western US Fires – Smoke Mask

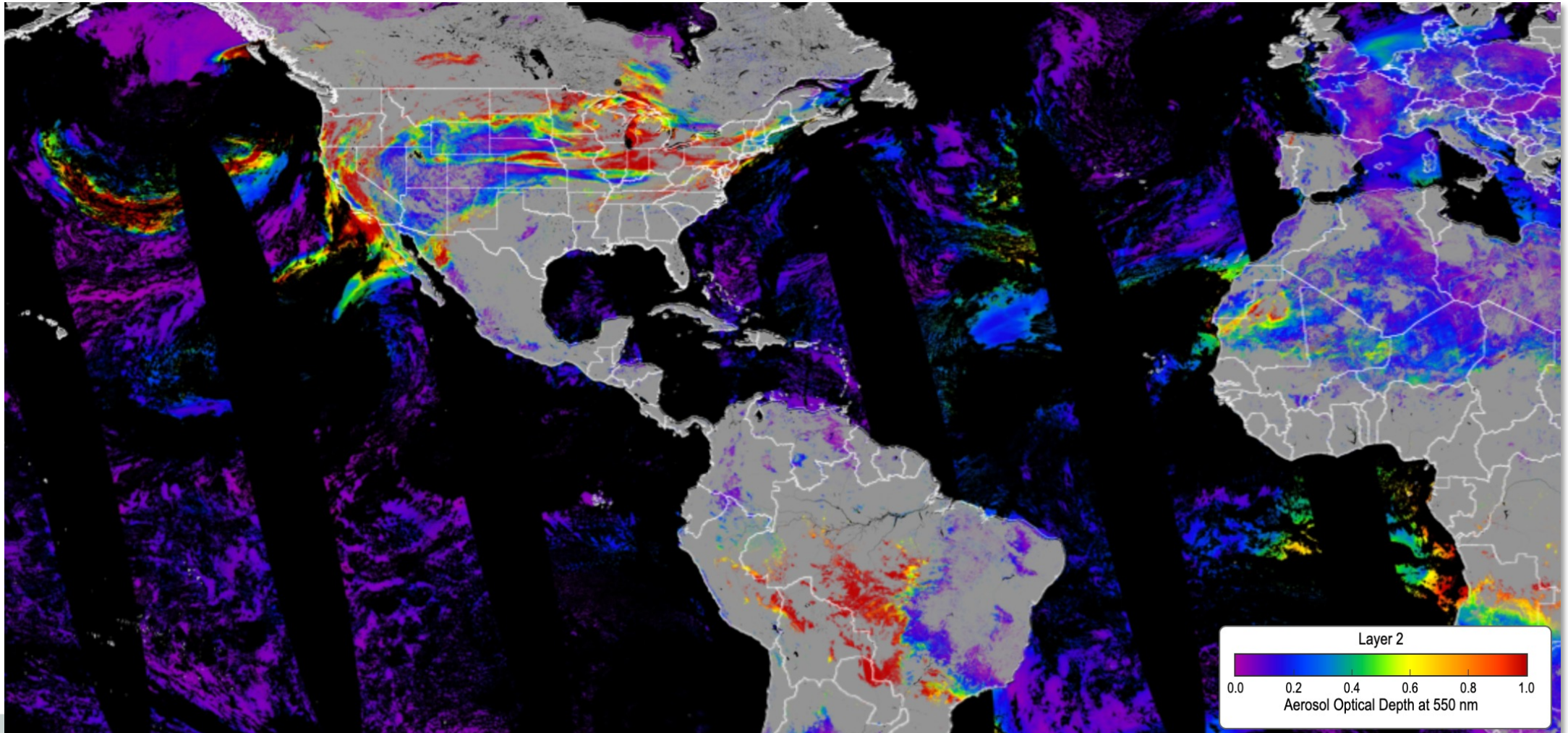
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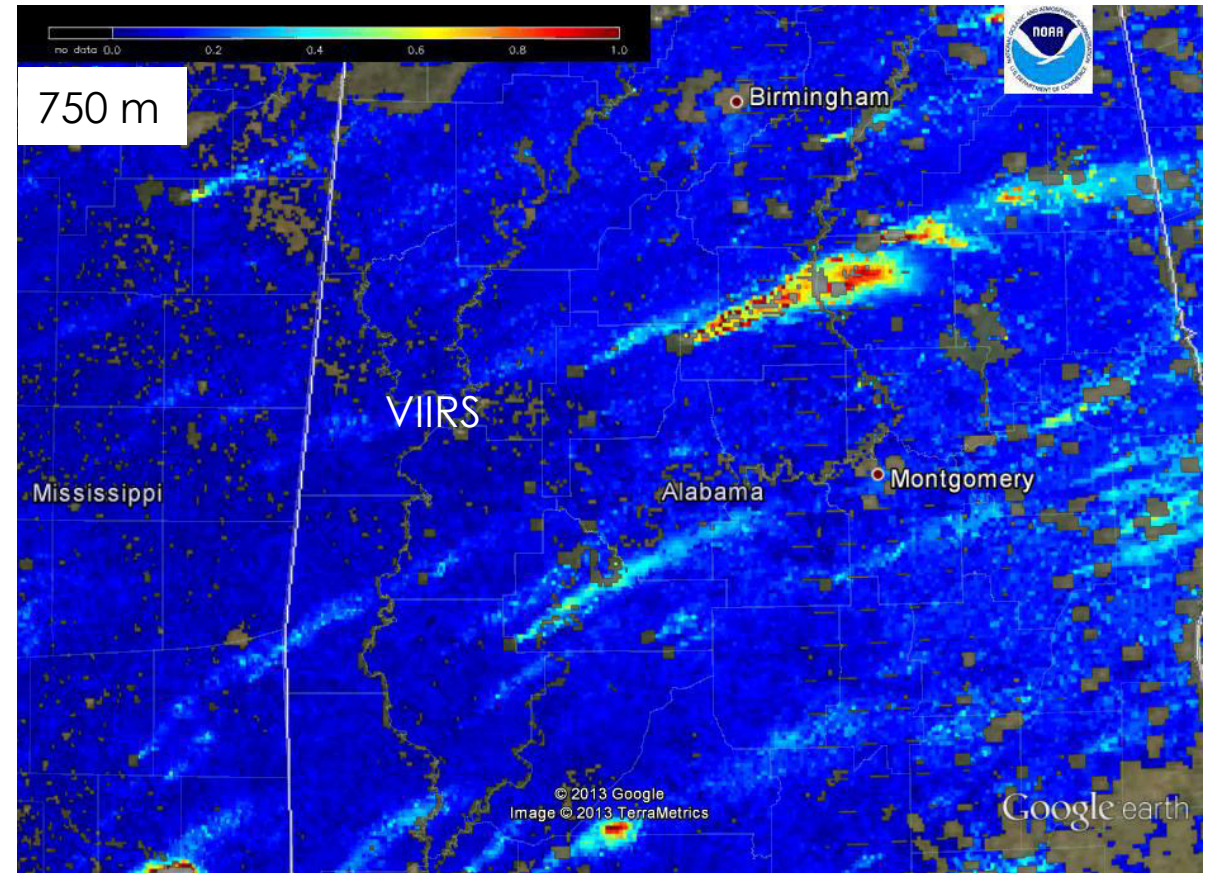
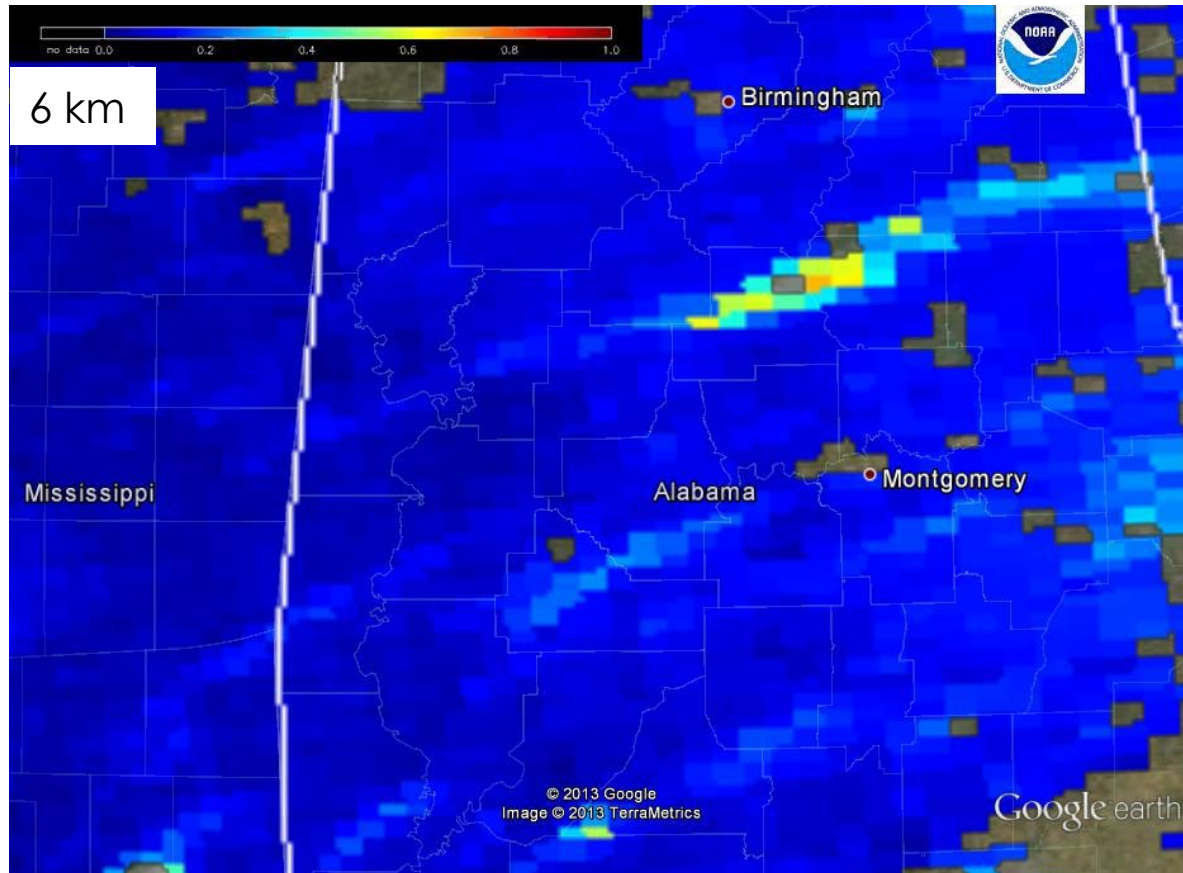
# Smoke from Western US Fires – Aerosol Optical Depth

<https://www.star.nesdis.noaa.gov/jpss/mapper>





# Low vs. High Resolution AOD Data

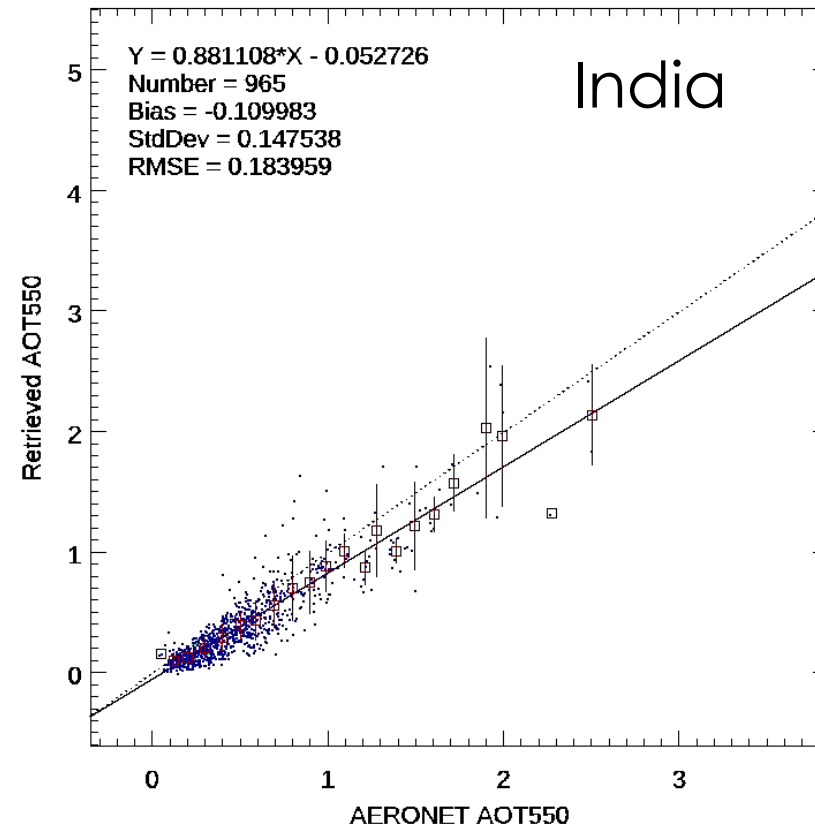
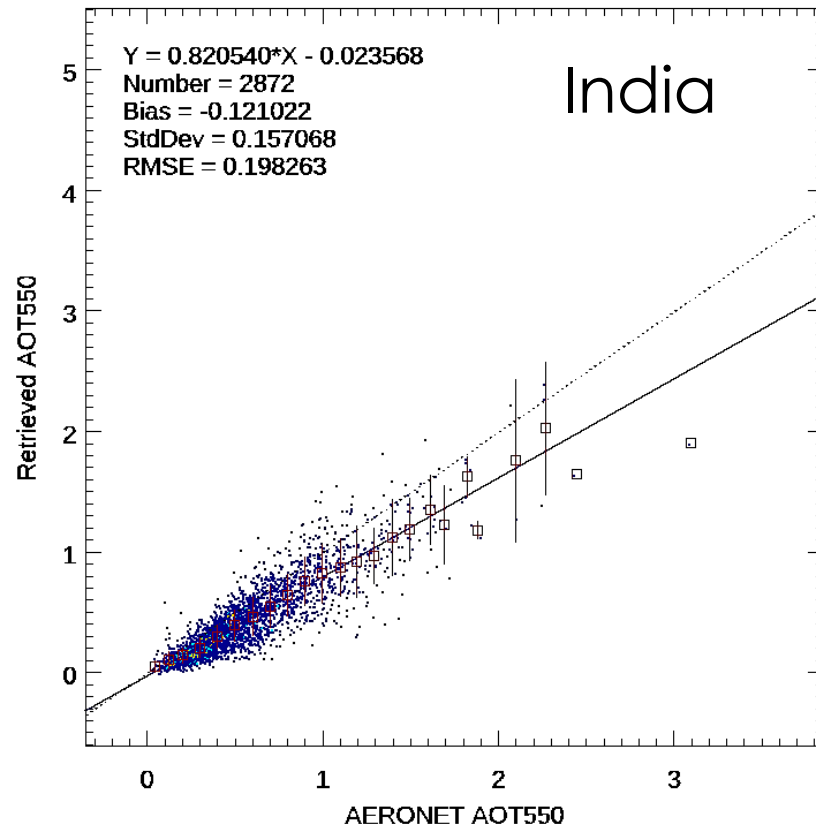


Side Courtesy of Shobha Kondragunta





# Validation

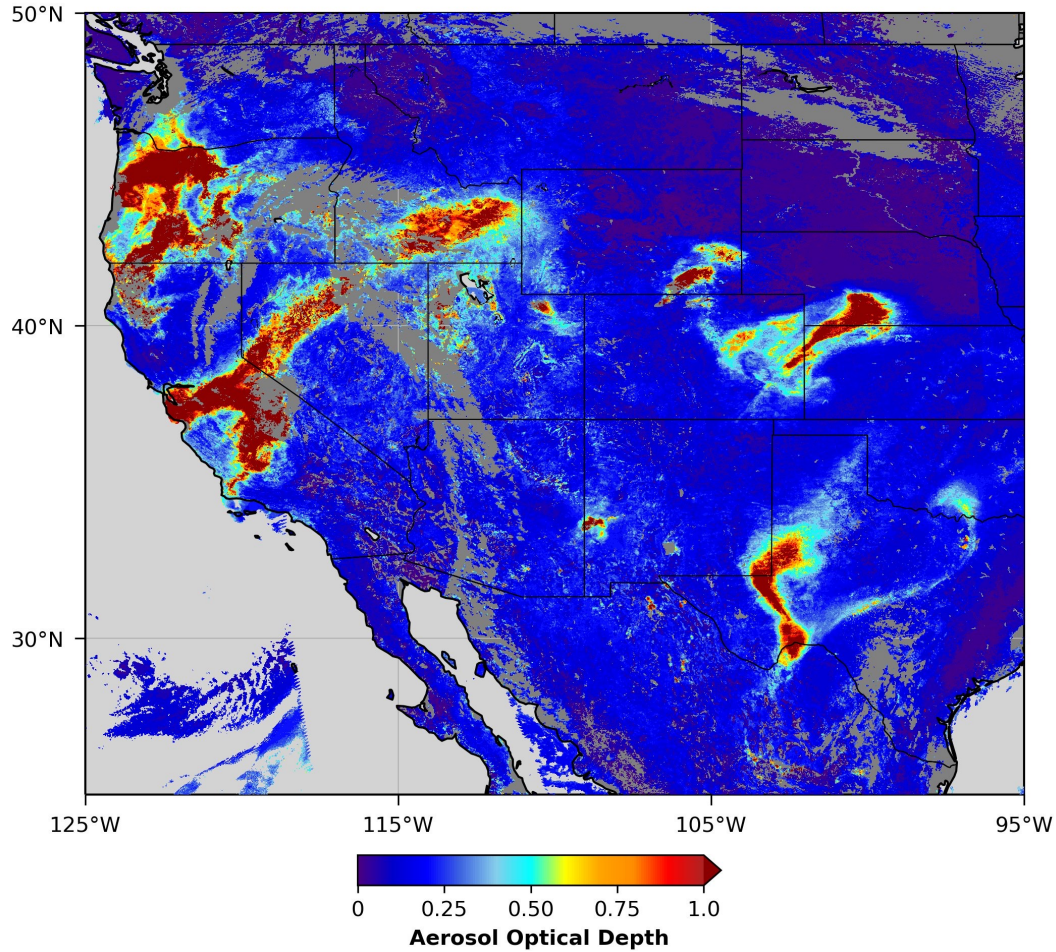


Slide by Hongqing Liu (NOAA)

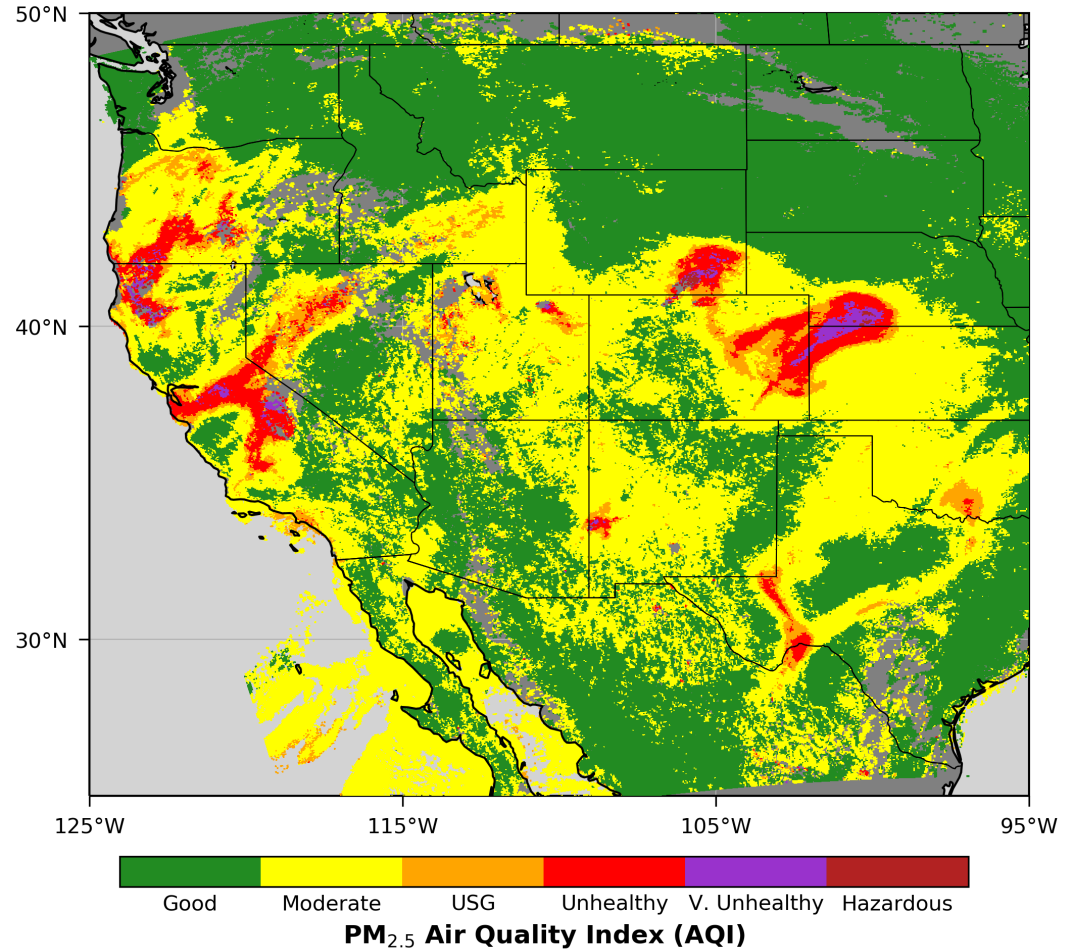


# Aerosol Optical Depth – Application

NOAA-20/VIIRS  
Aerosol Optical Depth  
07 Oct 2020



Daily (24-Hour Average) Fine Particles  
Estimated from VIIRS Aerosol Optical Depth  
07 Oct 2020



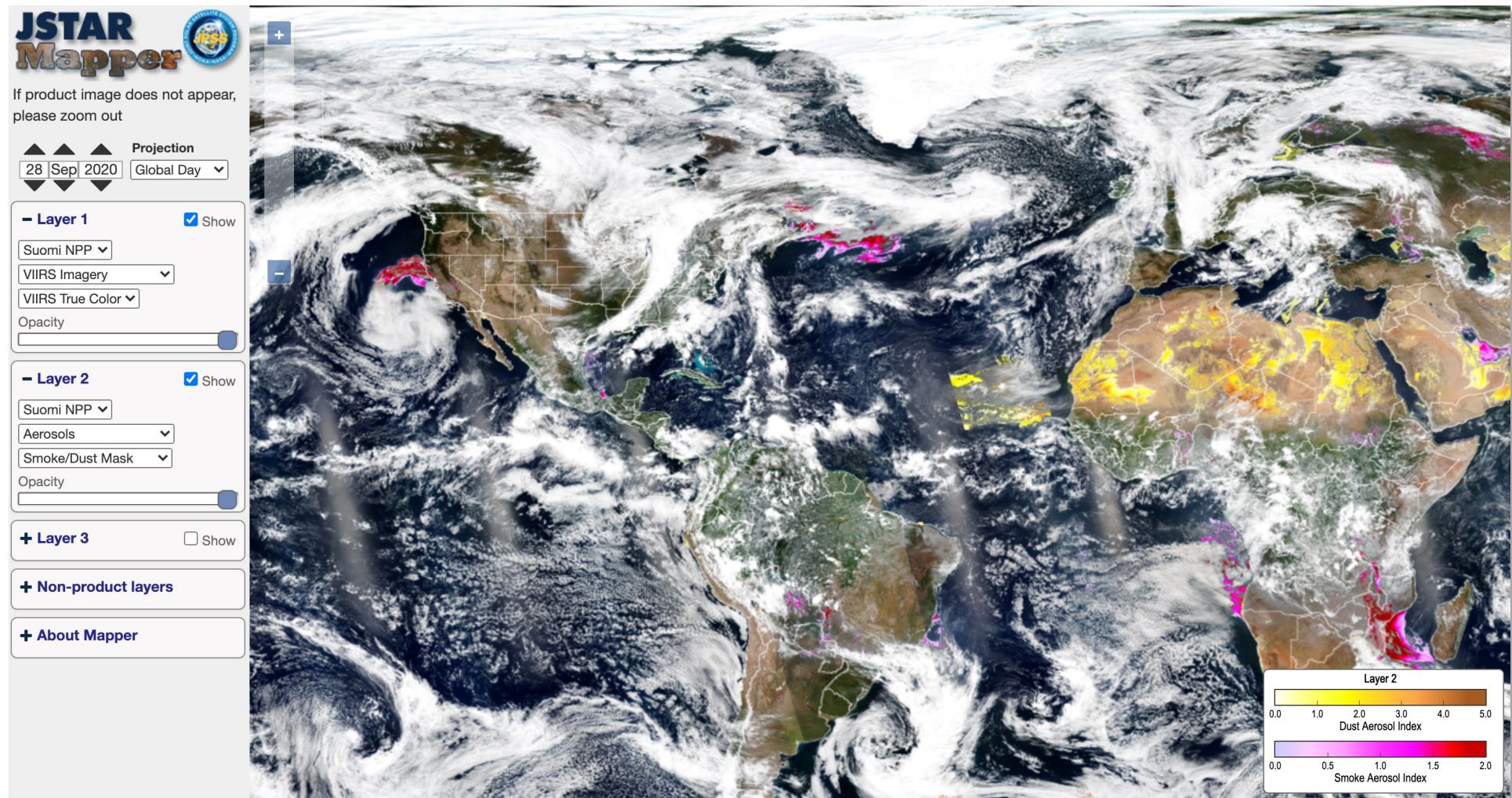
<https://twitter.com/AerosolWatch/status/1314208278222569472>





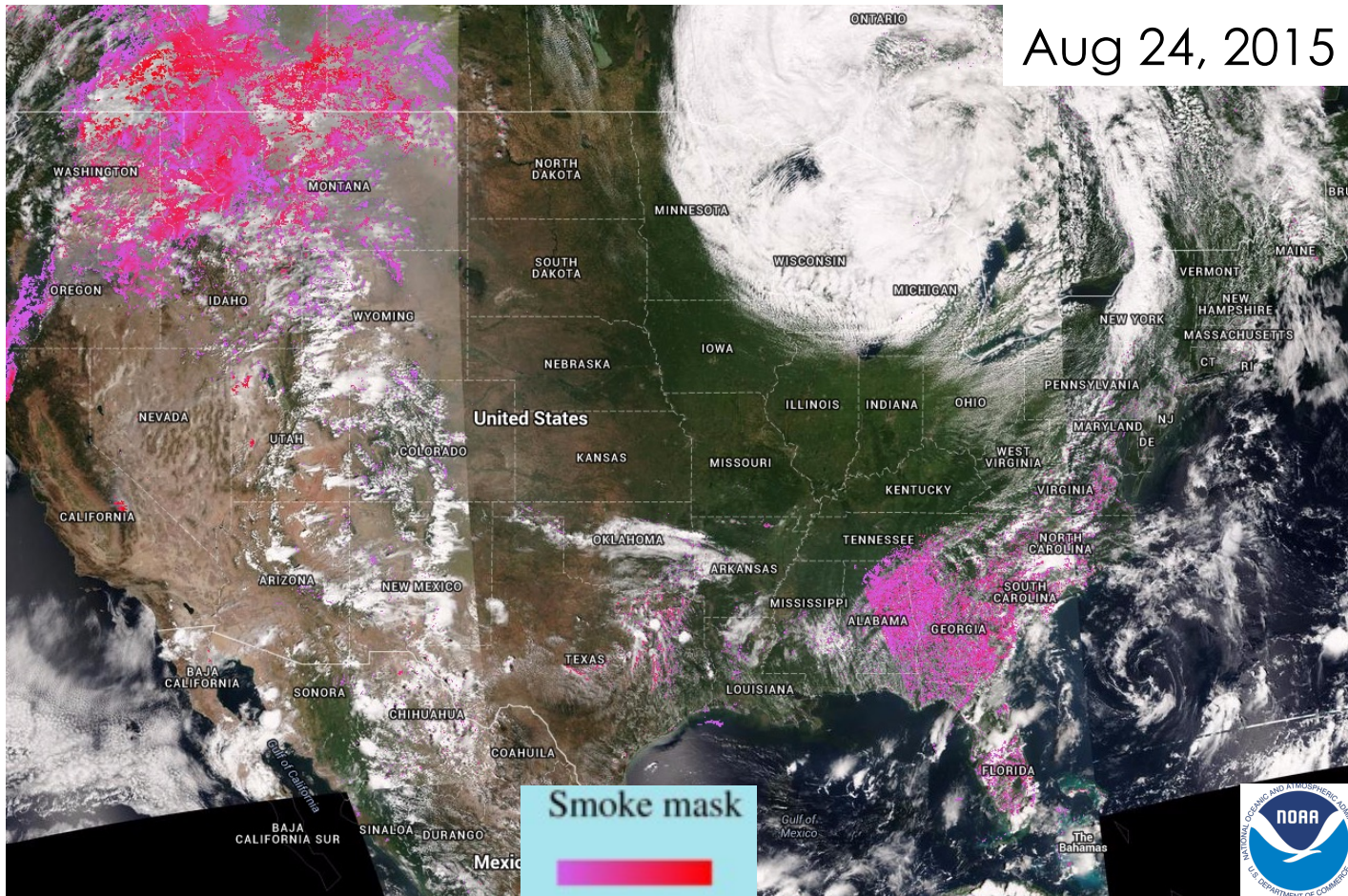
# NOAA Data Visualization

<https://www.star.nesdis.noaa.gov/jpss/mapper/>





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Side Courtesy: Shobha Kondragunta





# Satellite Limitations

- **Optical Measurements**
  - Only available in daytime
  - Very limited in nighttime
  - Only available under:
    - Cloud free conditions
    - Snow/ice free conditions
- **Accuracy** - Varies (AOD) – Depends on satellite/algorithm
  - Very good over dark, vegetated surfaces
  - Moderate over urban surfaces – algorithm dependent
  - Moderate to low over bright surfaces
  - 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 provides more frequent observations
- **Spatial Resolution**
  - 10 km (good)
  - 6 km
  - 3 km (moderate)
  - 1 km, 0.75 km etc.

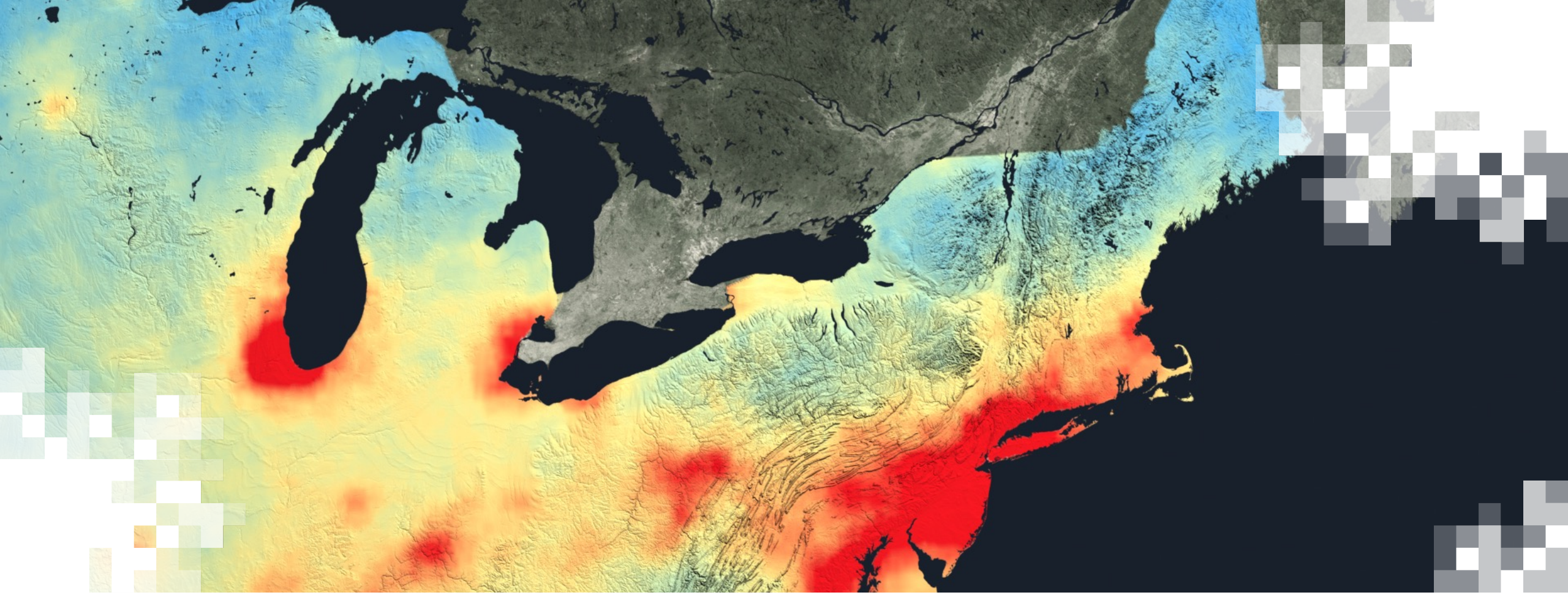


# References & Links

- ARSET Air Quality Page
  - <https://appliedsciences.nasa.gov/what-we-do/capacity-building/arset/arset-health-air-quality-trainings>
- NASA Air Quality Page
  - <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](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/aa/>
- Smog Blog:
  - <http://alg.umbc.edu/usaq/>







Questions & Discussion