

Credit: TROPOMI, ESA, Copernicus, KNMI

# Aerosol Observations from Satellites: Brief Theory & Existing Products

Pawan Gupta, and Melanie Follette-Cook

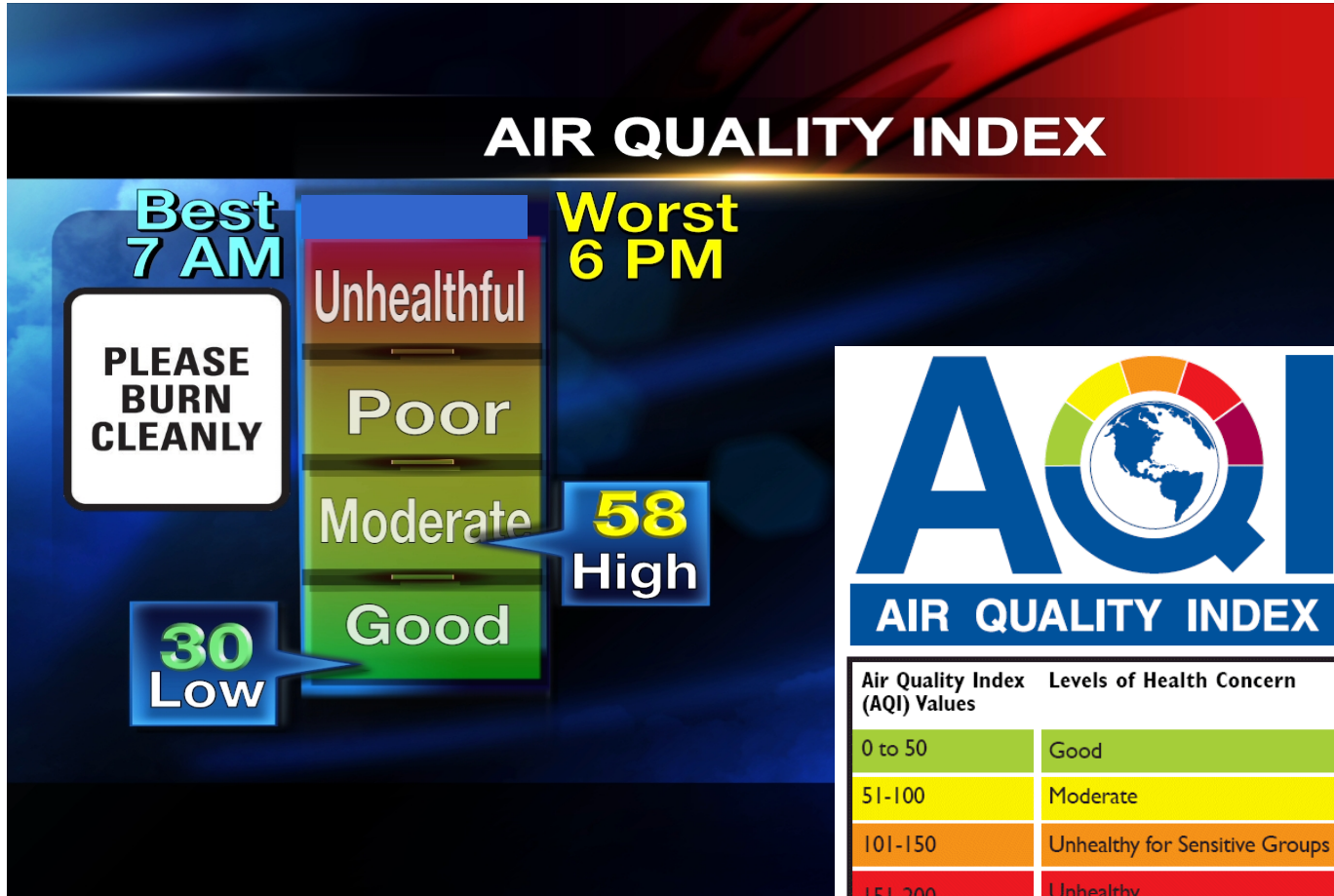
Application of Satellite Observations for Air Quality and Health Exposure, October 9-11, 2019



# 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



## Spatial Gaps

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

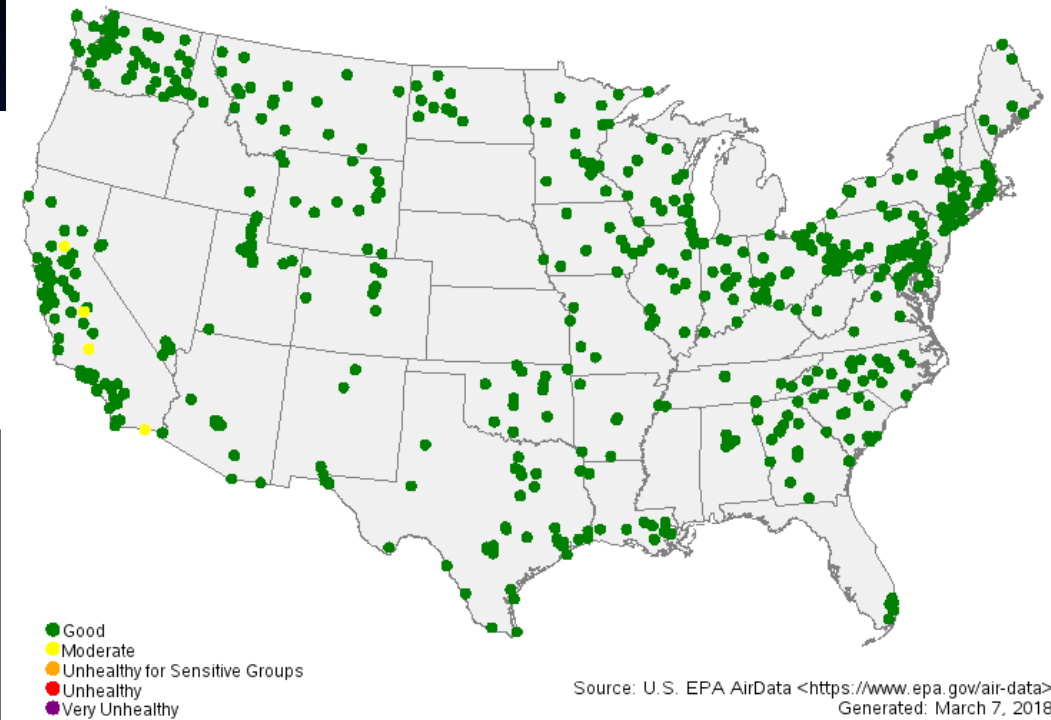
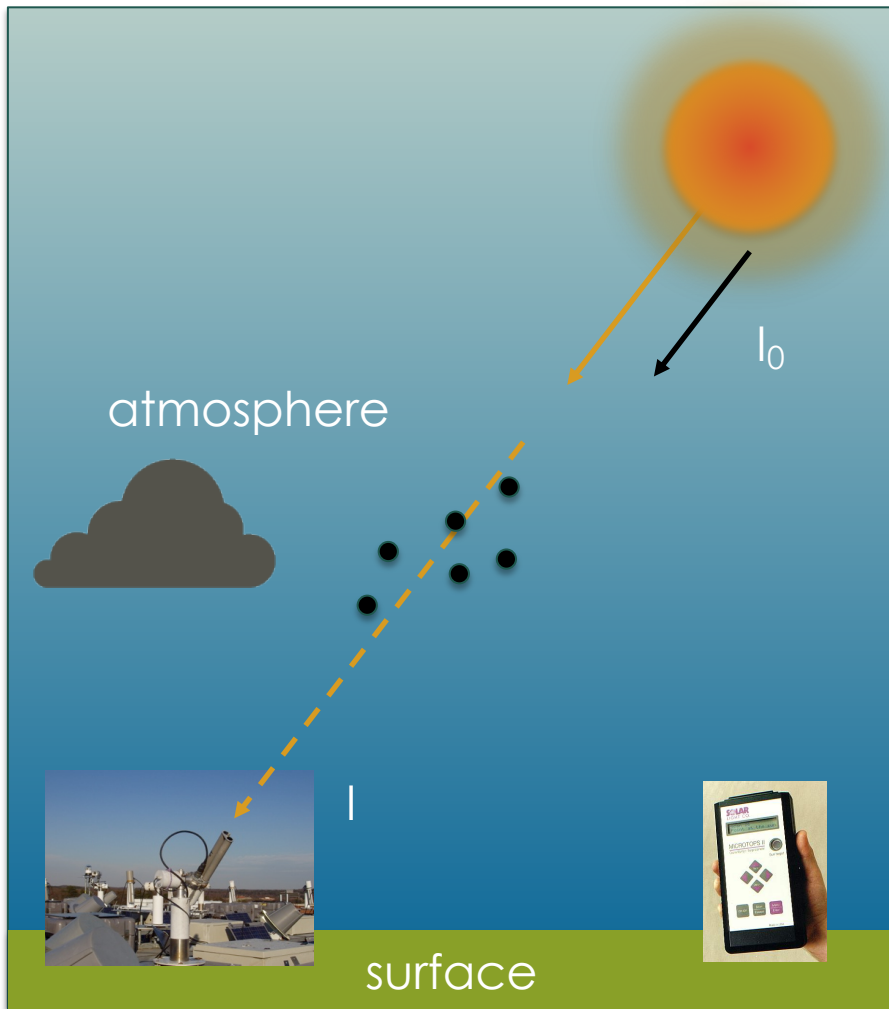


Image Credit: AirNow map, USEPA. <http://www.airnow.gov>

# 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:

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

$$m = \sec \theta_0$$

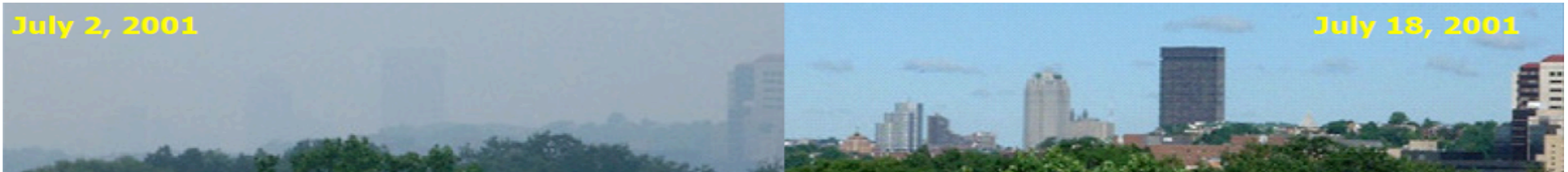
$$\tau = \tau_{Rayl} + \tau_{aer} + \tau_{gas}$$

# 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/>

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

## Singapore



Image Credit: Roslan Rahman/AFP/Getty Images

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

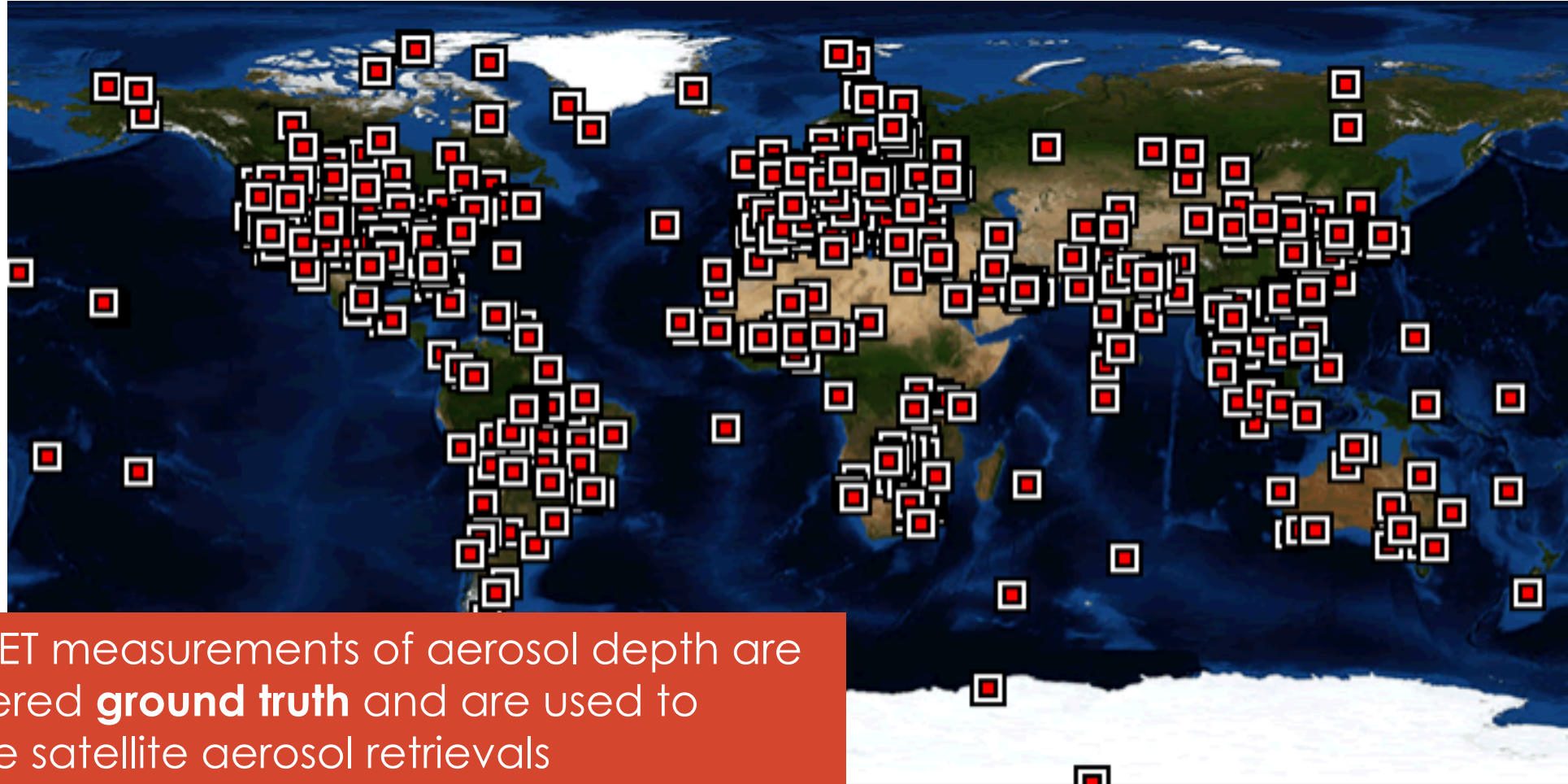


Image Credit: LLNL, Bobak Ha'Eri



# 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

# Instrument Capabilities for Air Quality

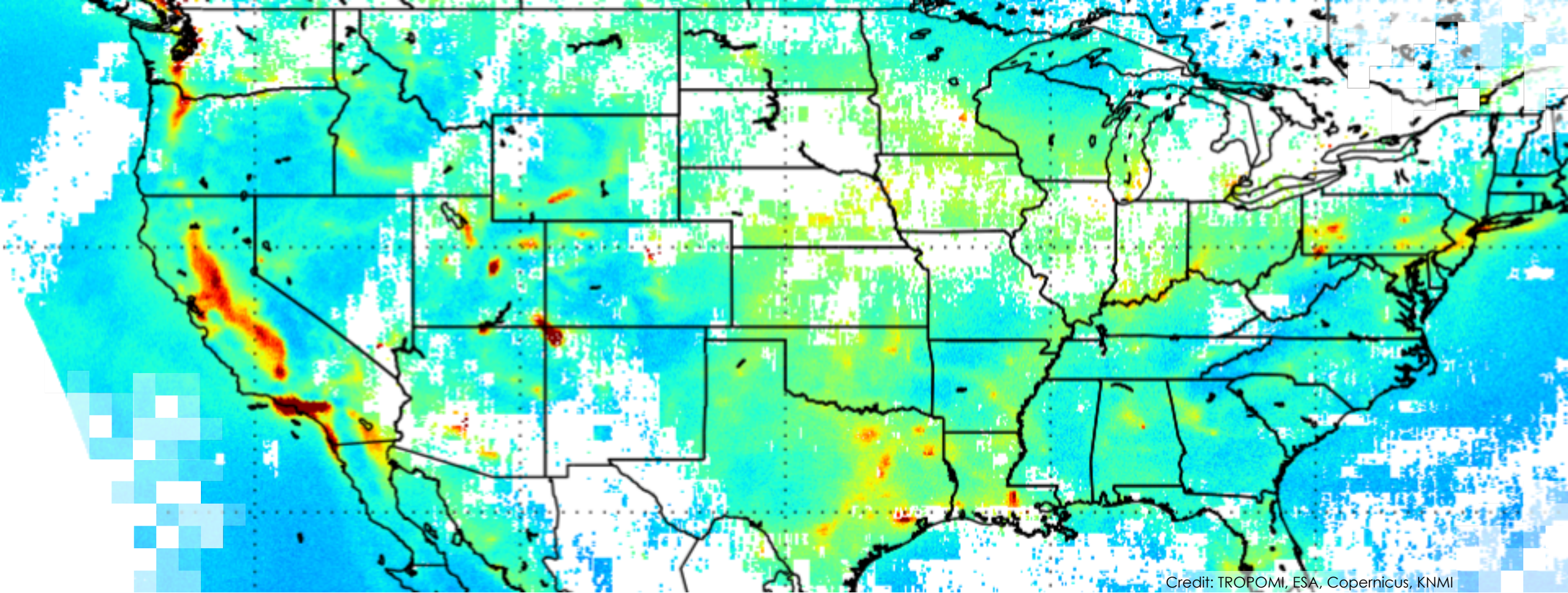
## Sensor Measurement: Spatial Resolution

MODIS:	250 m – 1 km
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MISR:	275 m – 1.1 km
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OMI:	13 x 24 km
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VIIRS:	750 m
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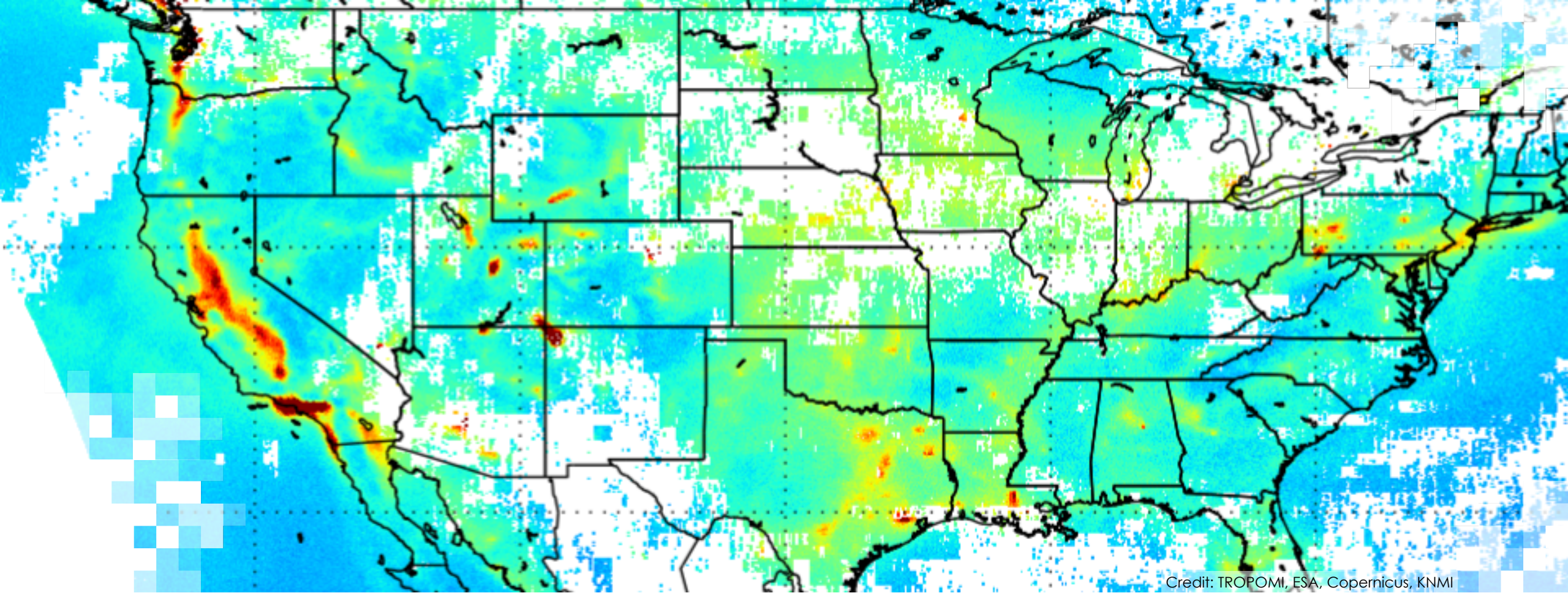
MODIS

# 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)

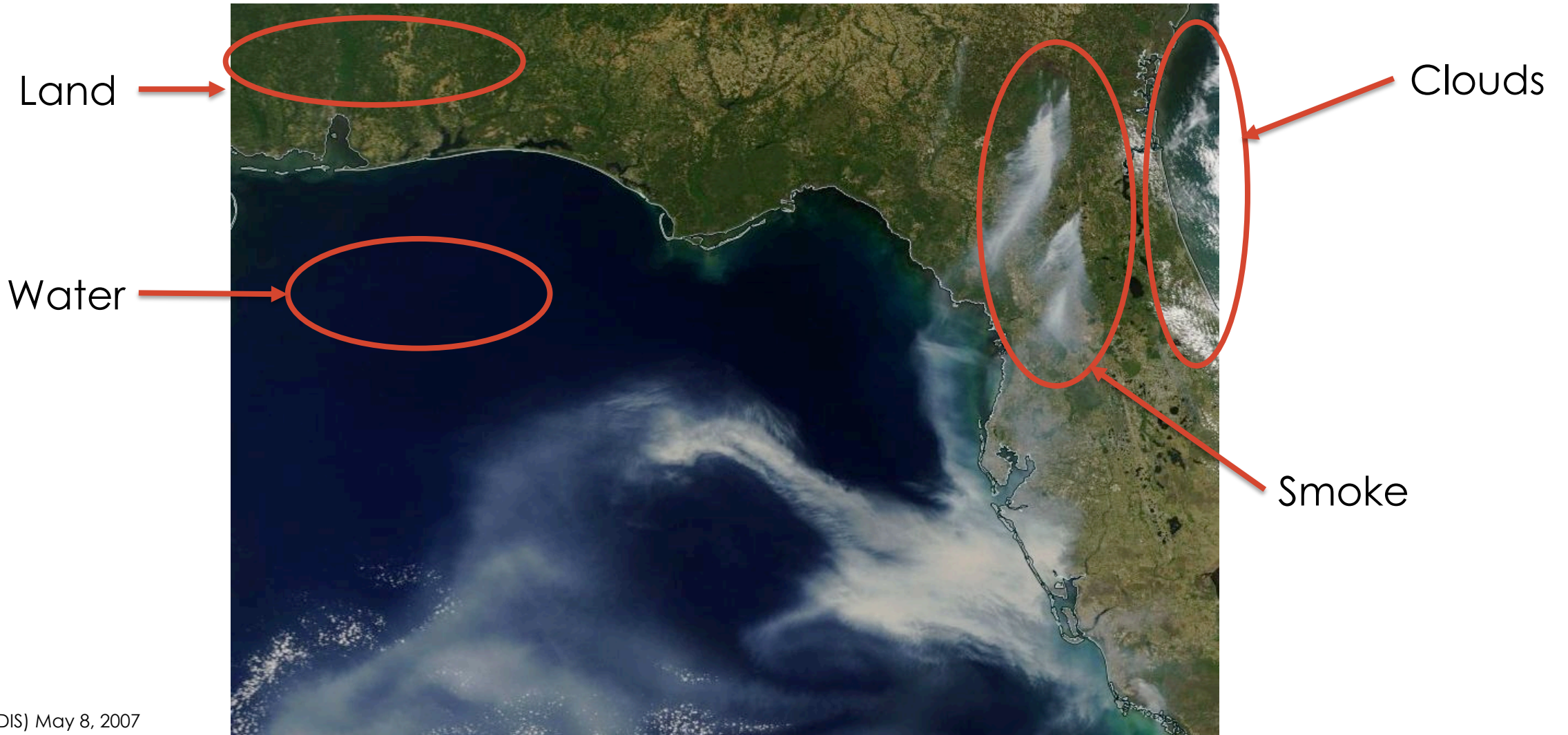


- Spectral Coverage
  - 36 bands (major bands include red, blue, IR, NIR, MIR)
    - Bands 1-2: 250 m
    - Bands 3-7: 500 m
    - Bands 8-36: 1,000 m



## Aerosol Retrieval

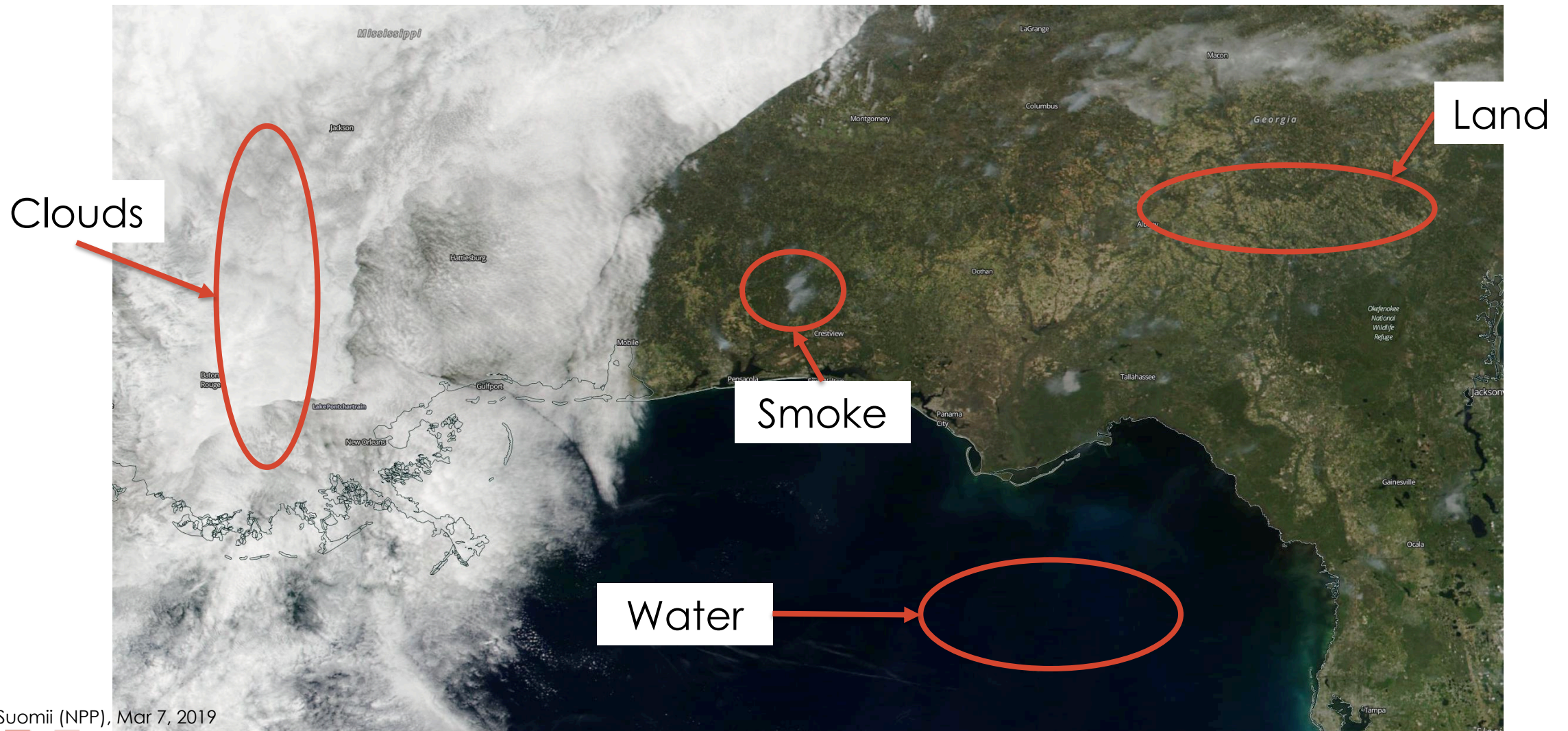
# Aerosol Detection



Terra (MODIS) May 8, 2007



# Aerosol Detection



Suomii (NPP), Mar 7, 2019

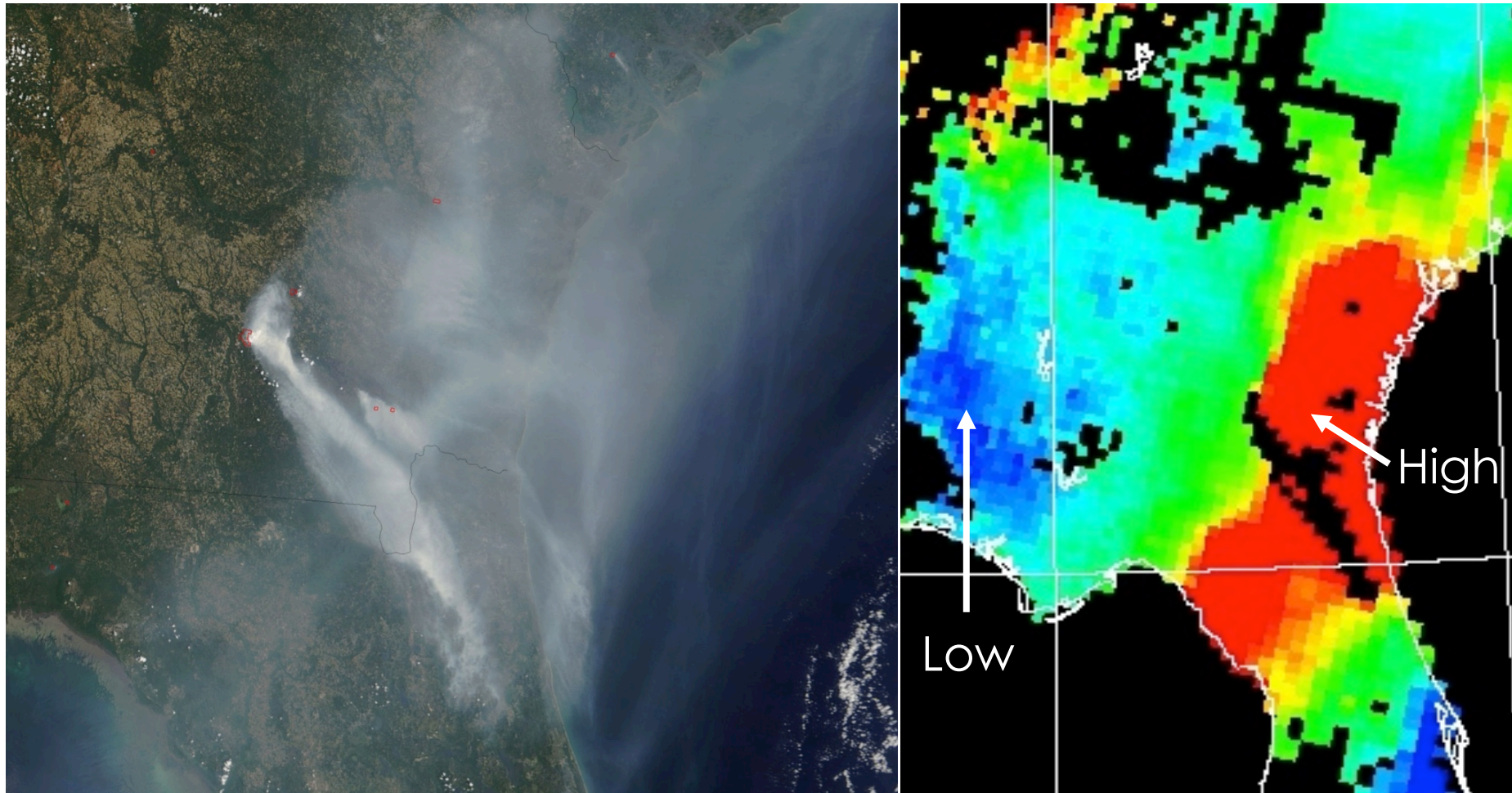


# Complex Image: Smoke & Clouds



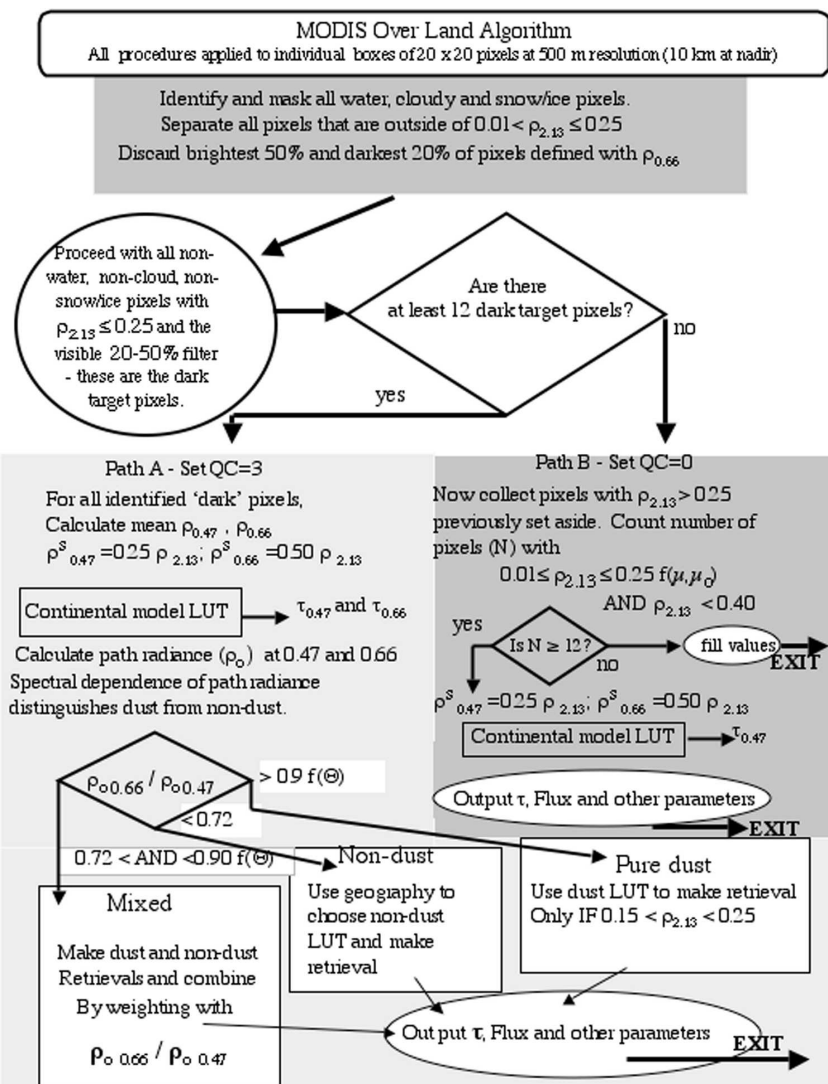
Suomi NPP (VIIRS) Mar 26, 2018

# 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

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

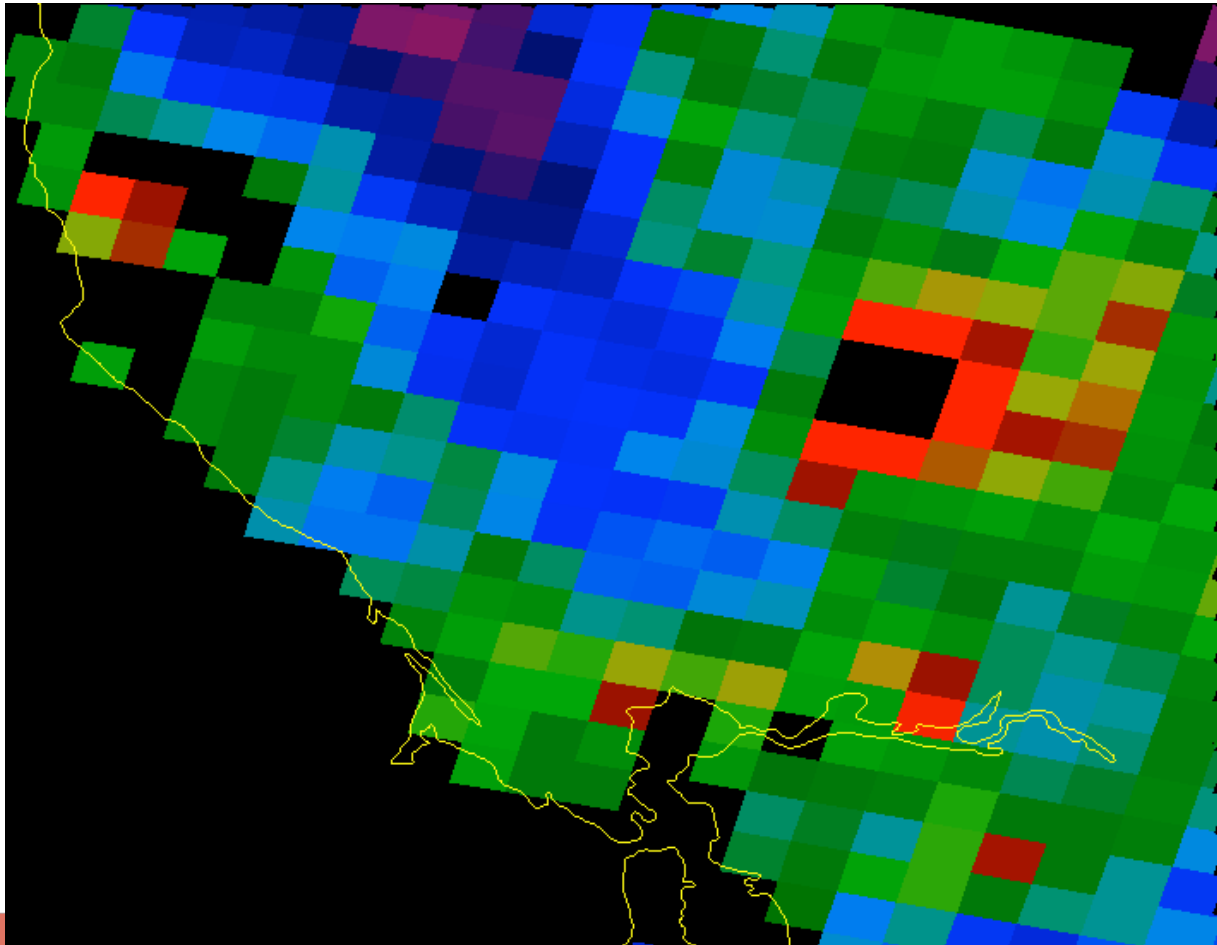
MOD44 Vegetation Cover Conversion

**MYD – MODIS Aqua**

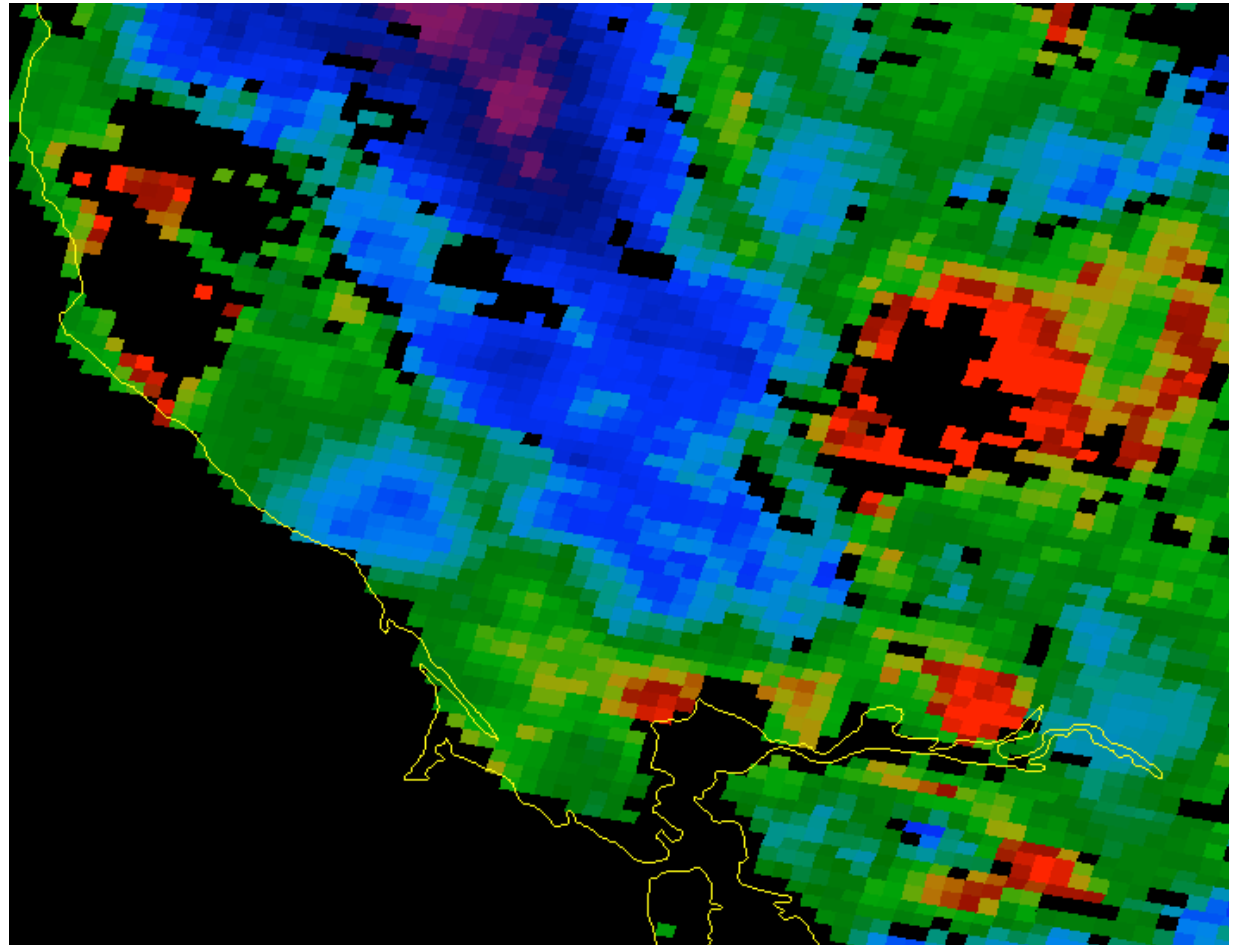
**MOD – MODIS Terra**

# MODIS 10 km vs. 3 km Products

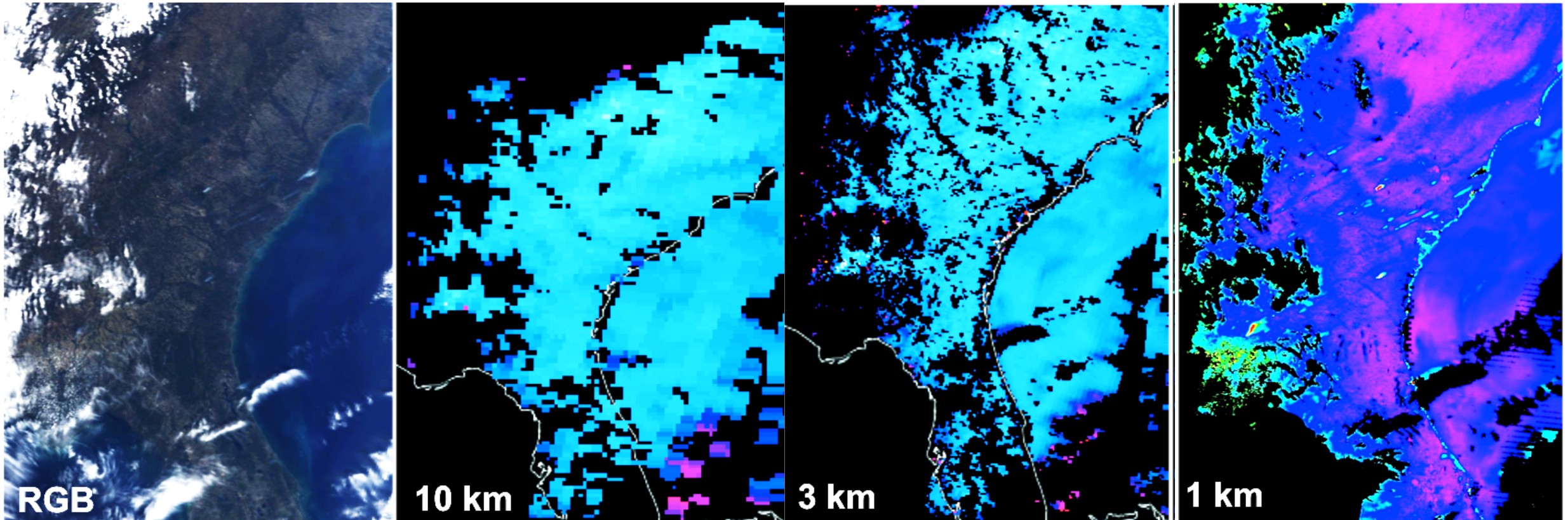
10 km



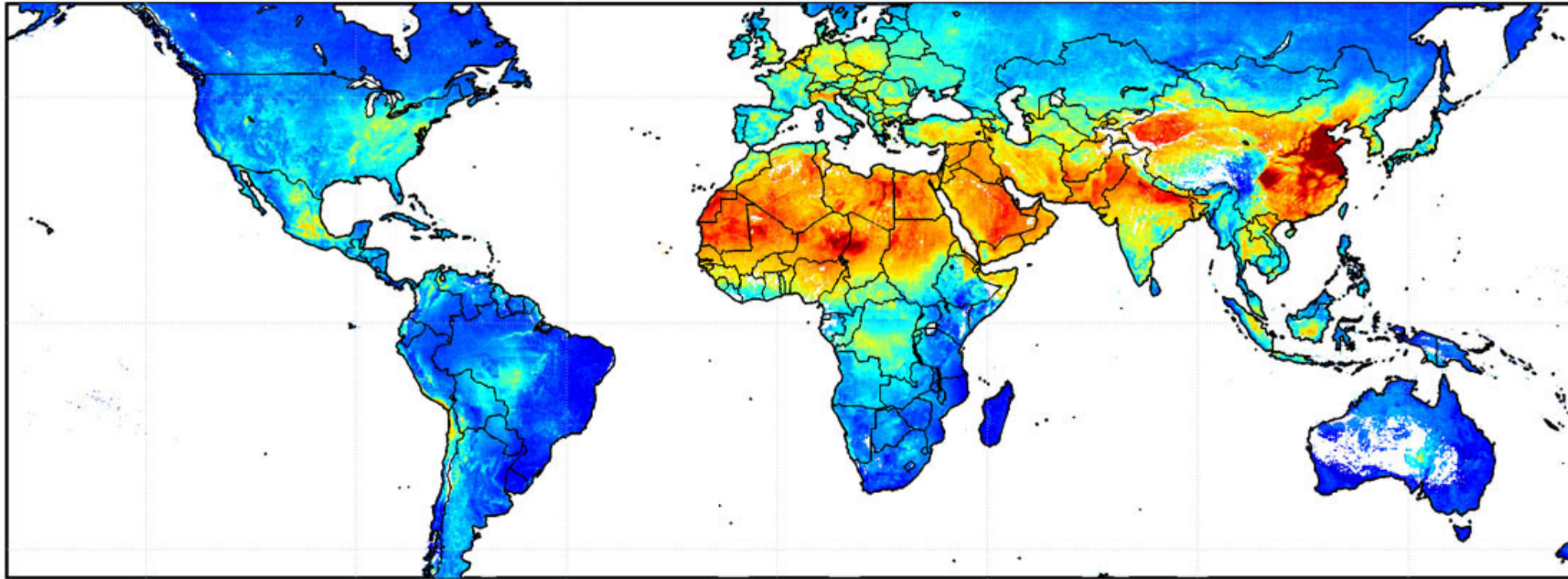
3 km



# High Resolution Aerosol Product



# Application of MODIS Aerosol Product



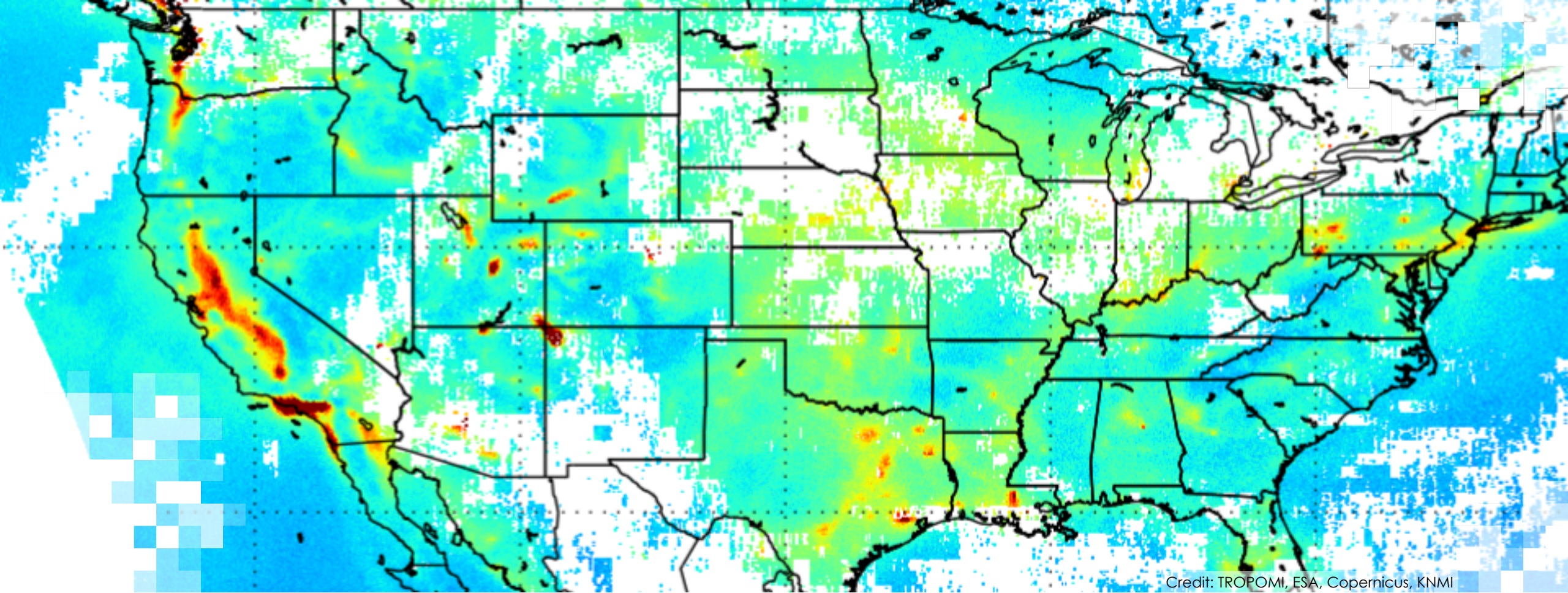
Satellite-Derived PM<sub>2.5</sub> [ $\mu\text{g}/\text{m}^3$ ]

Source: van Donkelaar et al., 2006, 2009

# Access to MODIS Aerosol Products

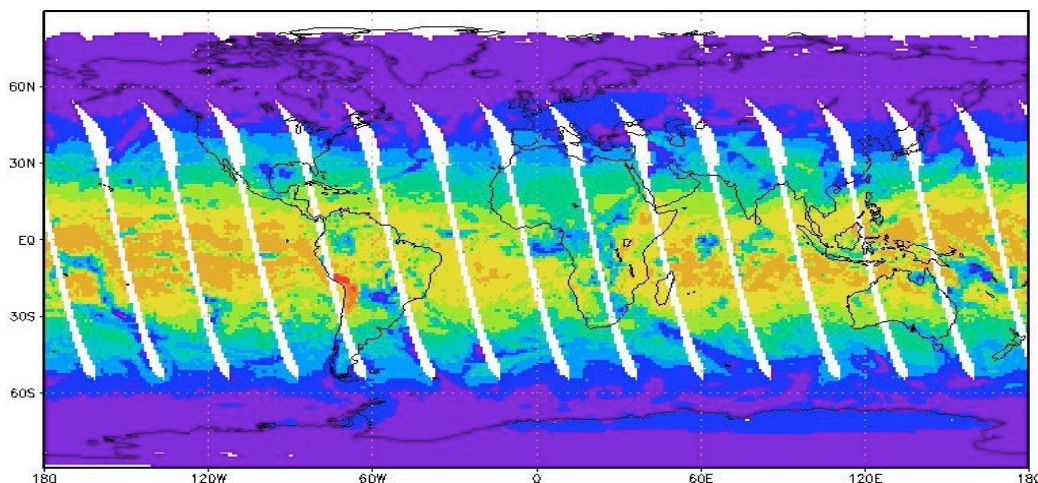
- NASA LAADSWeb
  - Searchable database, FTP access
  - <https://ladsweb.modaps.eosdis.nasa.gov/>
- MODIS-Atmos Site
  - Complete RGB archive with Level 3 product imagery
  - <http://modis-atmos.gsfc.nasa.gov/>
- Giovanni for Level 3 data sets
  - Web tool for imagery visualization and analysis
  - <https://giovanni.gsfc.nasa.gov/giovanni/>
- Dark Target Algorithm Site
  - <http://darktarget.gsfc.nasa.gov/>
- Deep Blue Algorithm Site
  - <http://deepblue.gsfc.nasa.gov/>





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

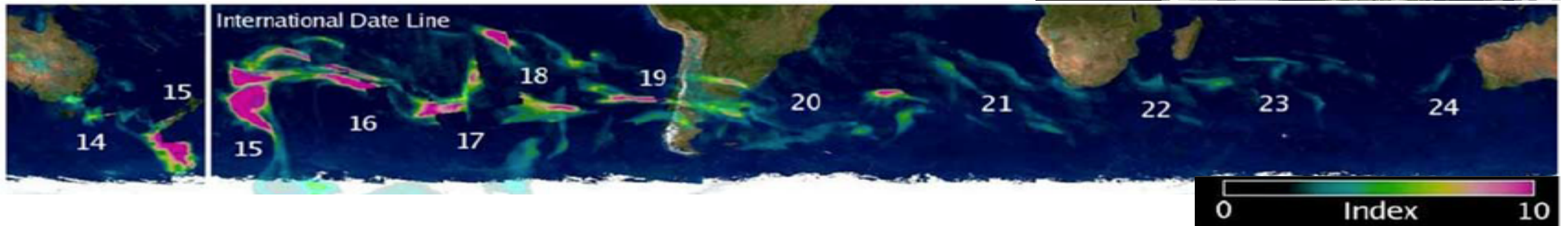
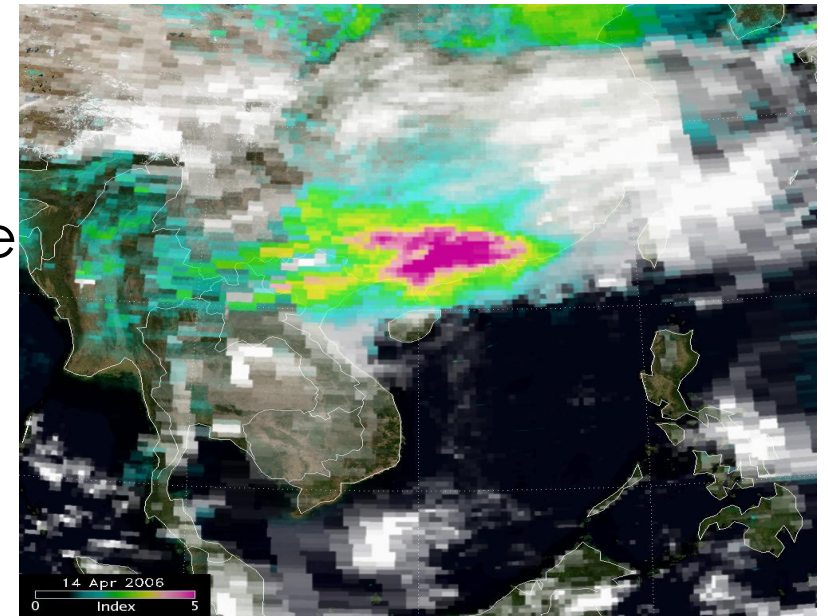
## Retrieval Products

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

# Applications of the Aerosol Index

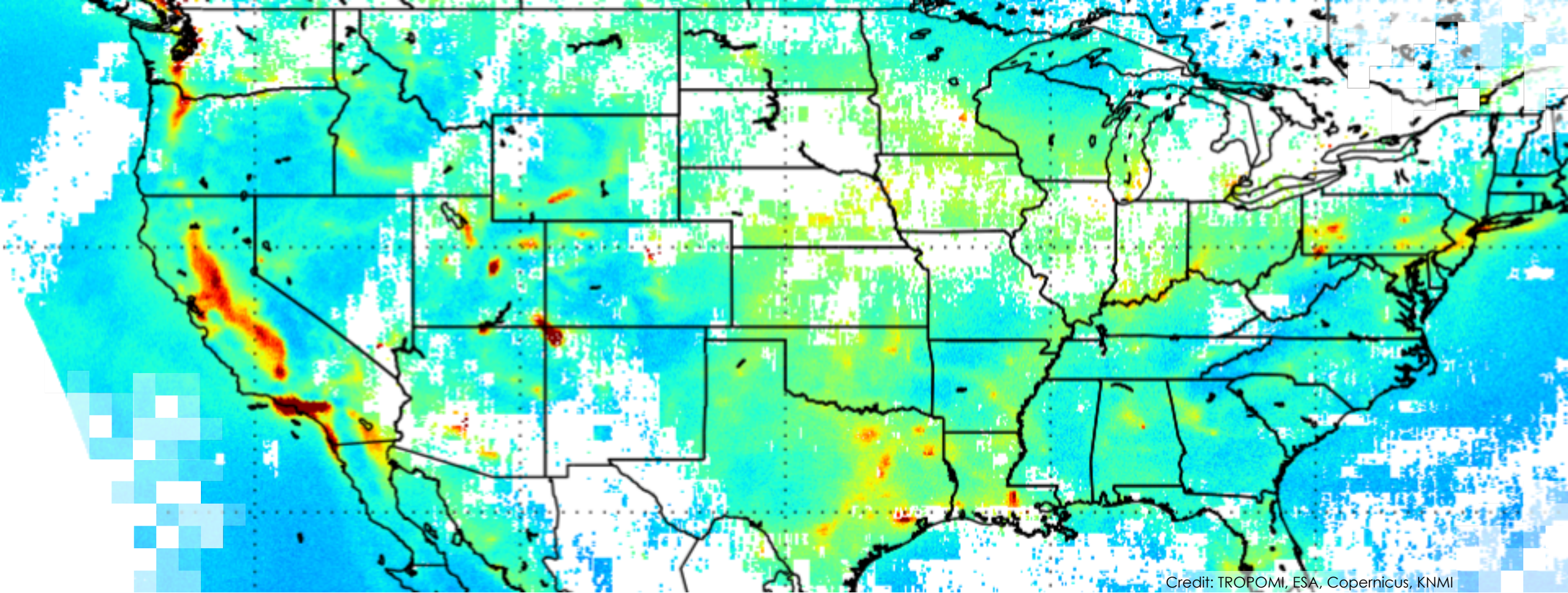
- Validation tool for transport models
- Separation of carbonaceous from sulfate aerosols
- Tracking of aerosol plumes above clouds and over ice

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.

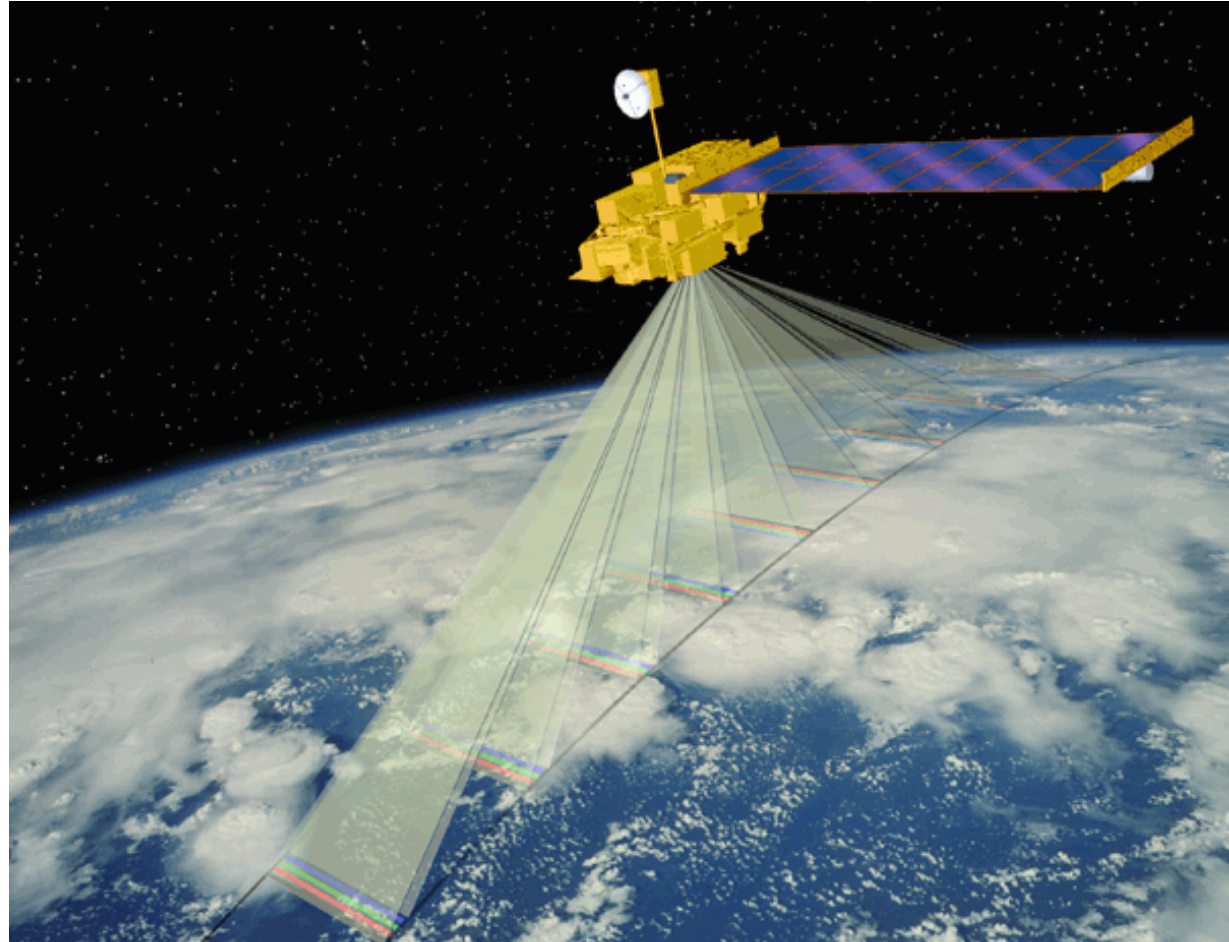
Image Credit: Torres, Omar & Tanskanen, Aapo & Veihelmann, Ben & Ahn, Changwoo & Braak, Remco & Bhartia, Pawan & Veefkind, Pepijn & Levelt, P. (2007).



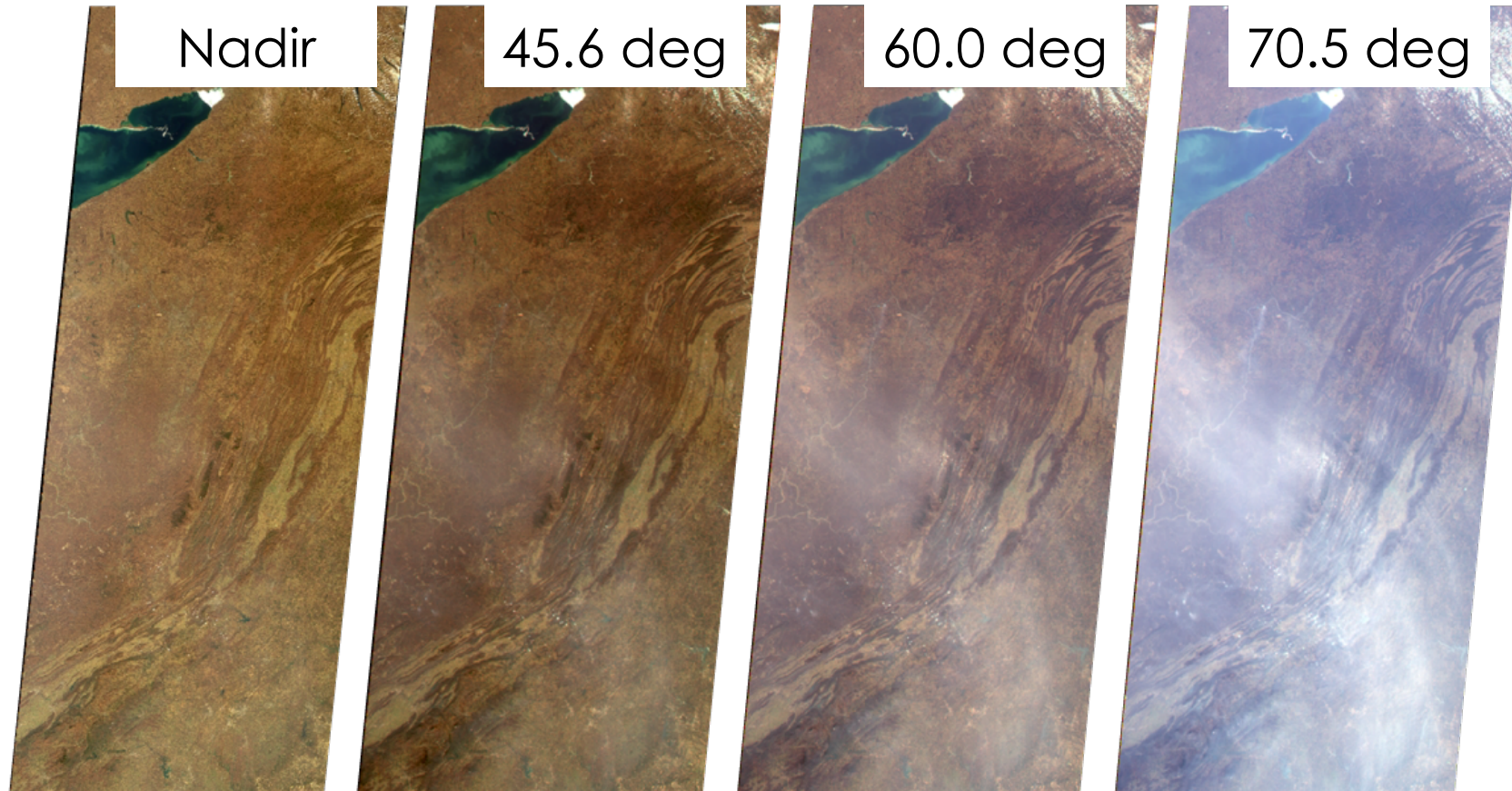
MISR

# 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

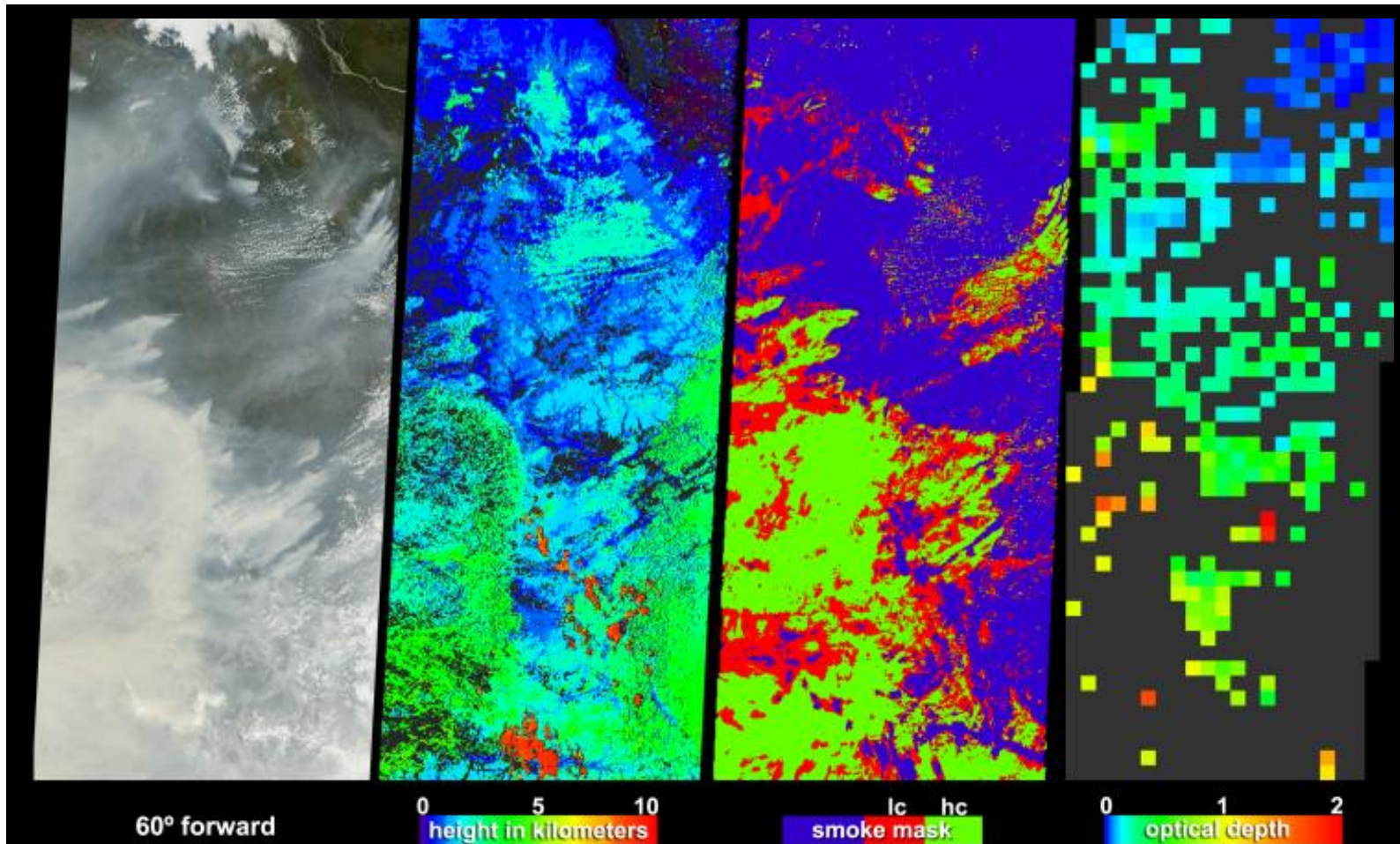
Appalachian Mountains, Terra MISR, April 18, 2000

# MISR Global Daily Coverage

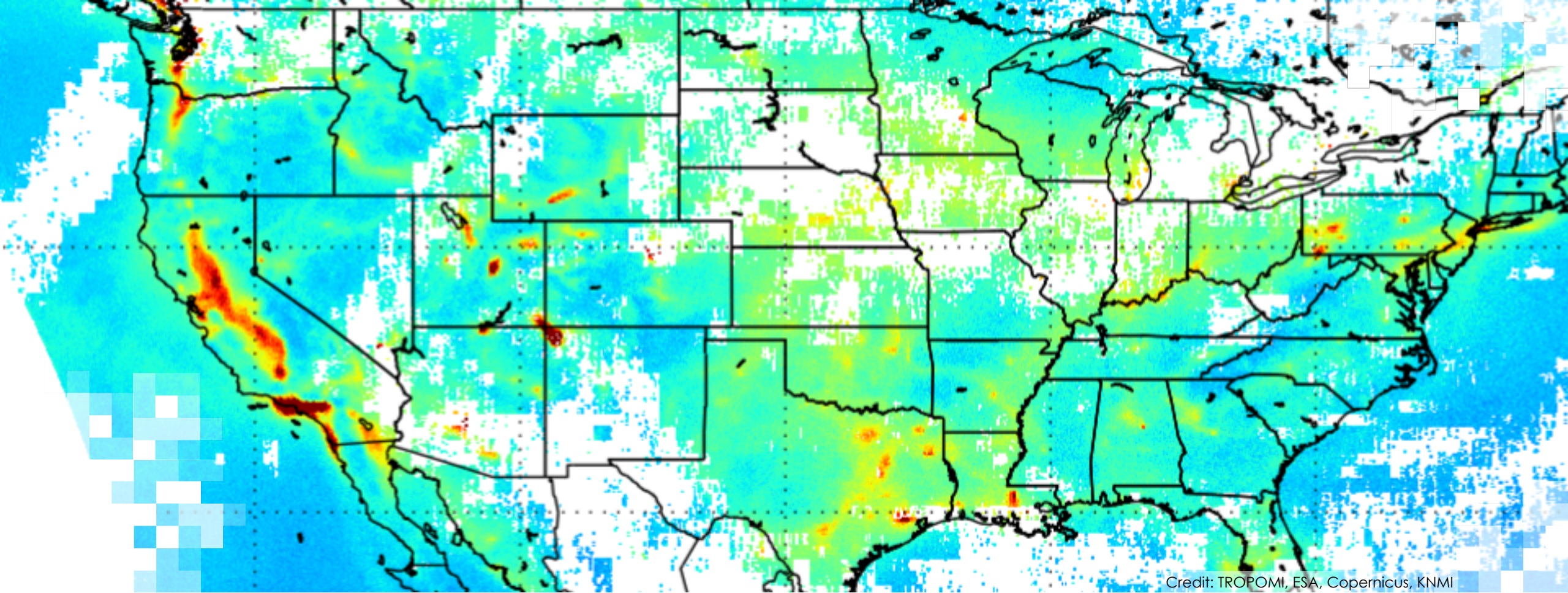


# Applications of MISR Data

Smoke signals from the July 2004 Alaska and Yukon Fires







VIIRS

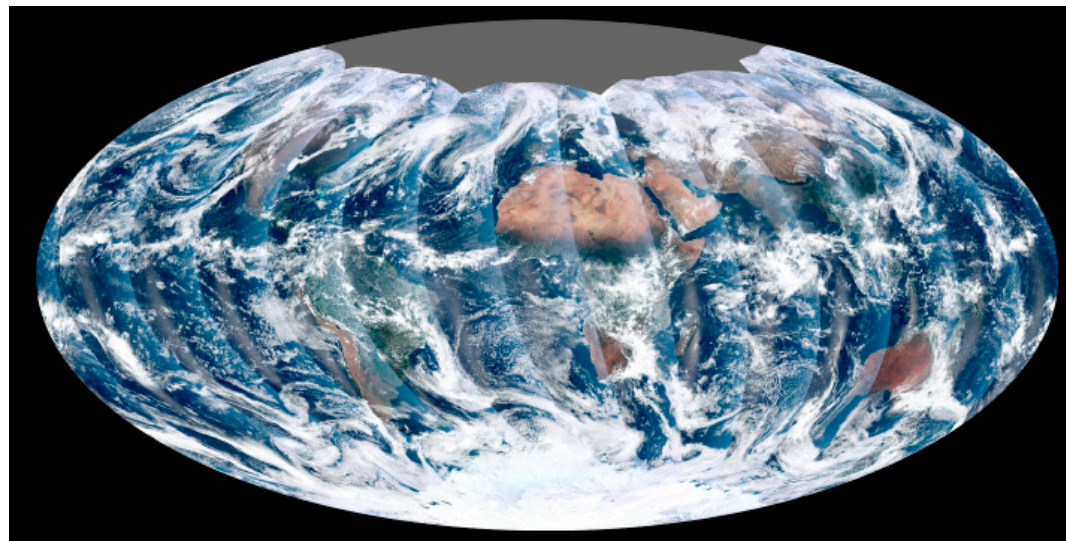
# Visible Infrared Imaging Radiometer (VIIRS)

A multi-wavelength imager like MODIS with similar wavelength bands

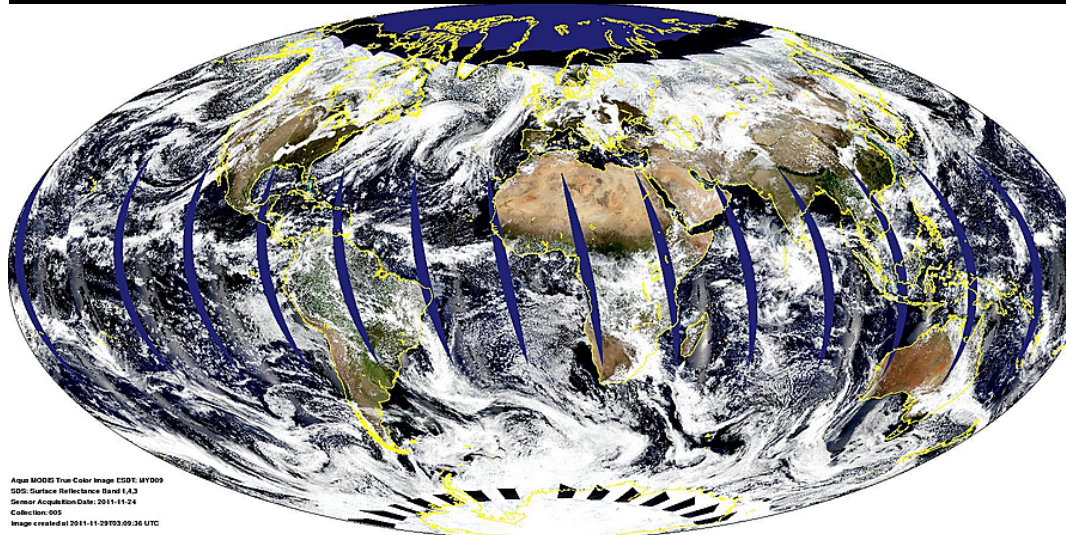
	MODIS	VIIRS
Orbit Altitude	690 km	824 km
Equator Crossing Time	13:30 LT	13:30 LT
Granule Size	5 min	86 sec
Swath	2,330 km	3,000 km
Pixel Nadir	0.5 km	0.75 km
Pixel Edge	2 km	1.5 km

# VIIRS & MODIS

**VIIRS**  
Nov 24, 2011

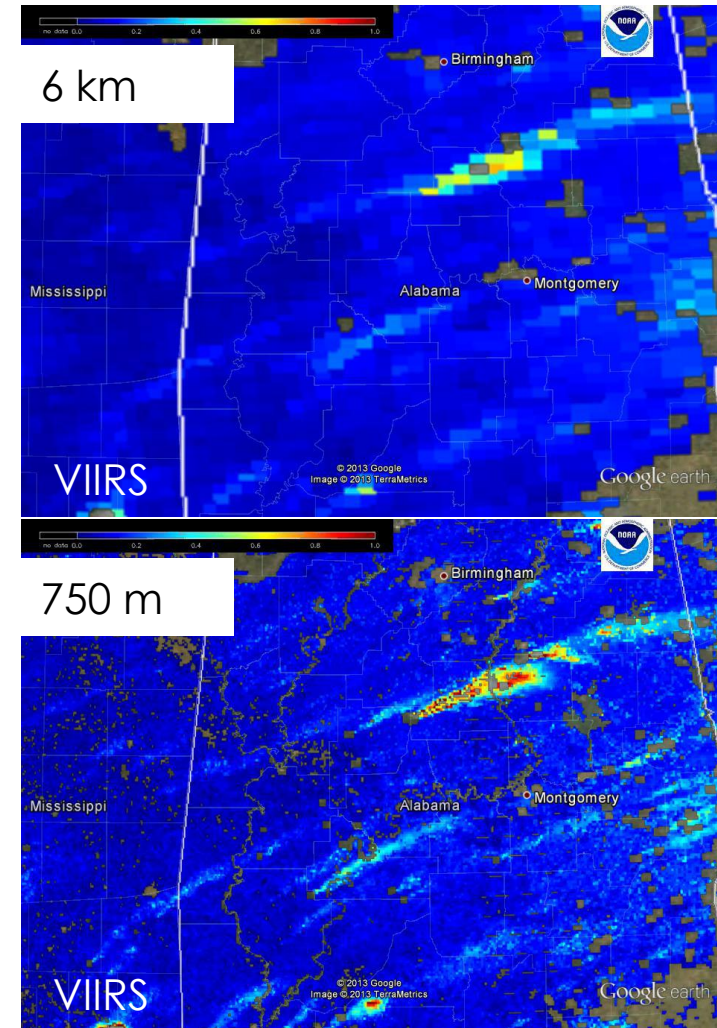
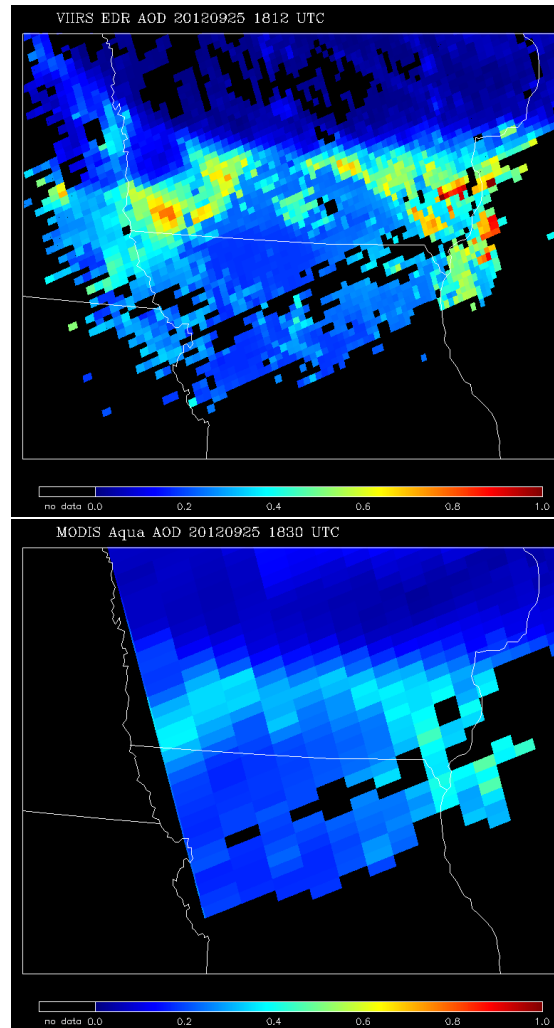
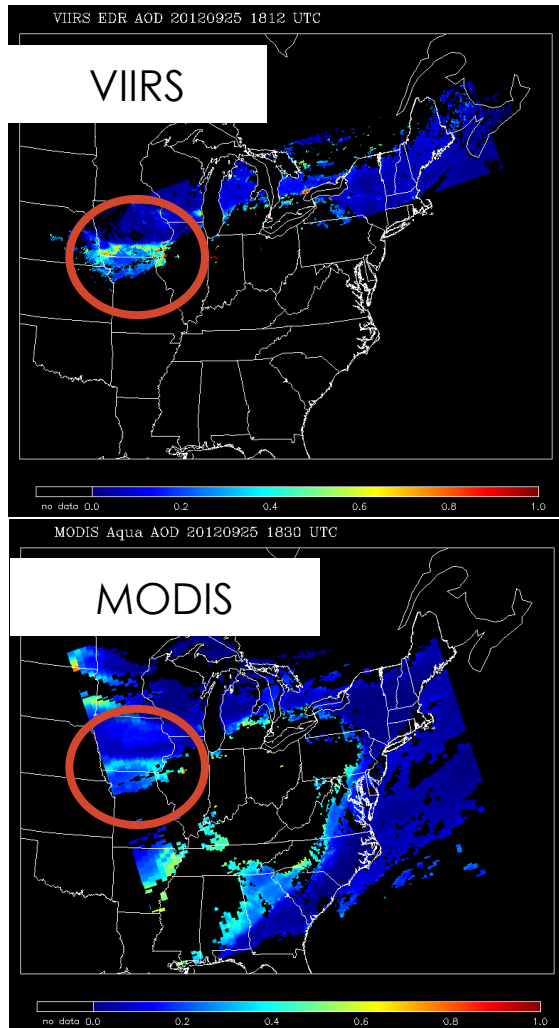


**MODIS (Aqua)**  
Nov 24, 2011



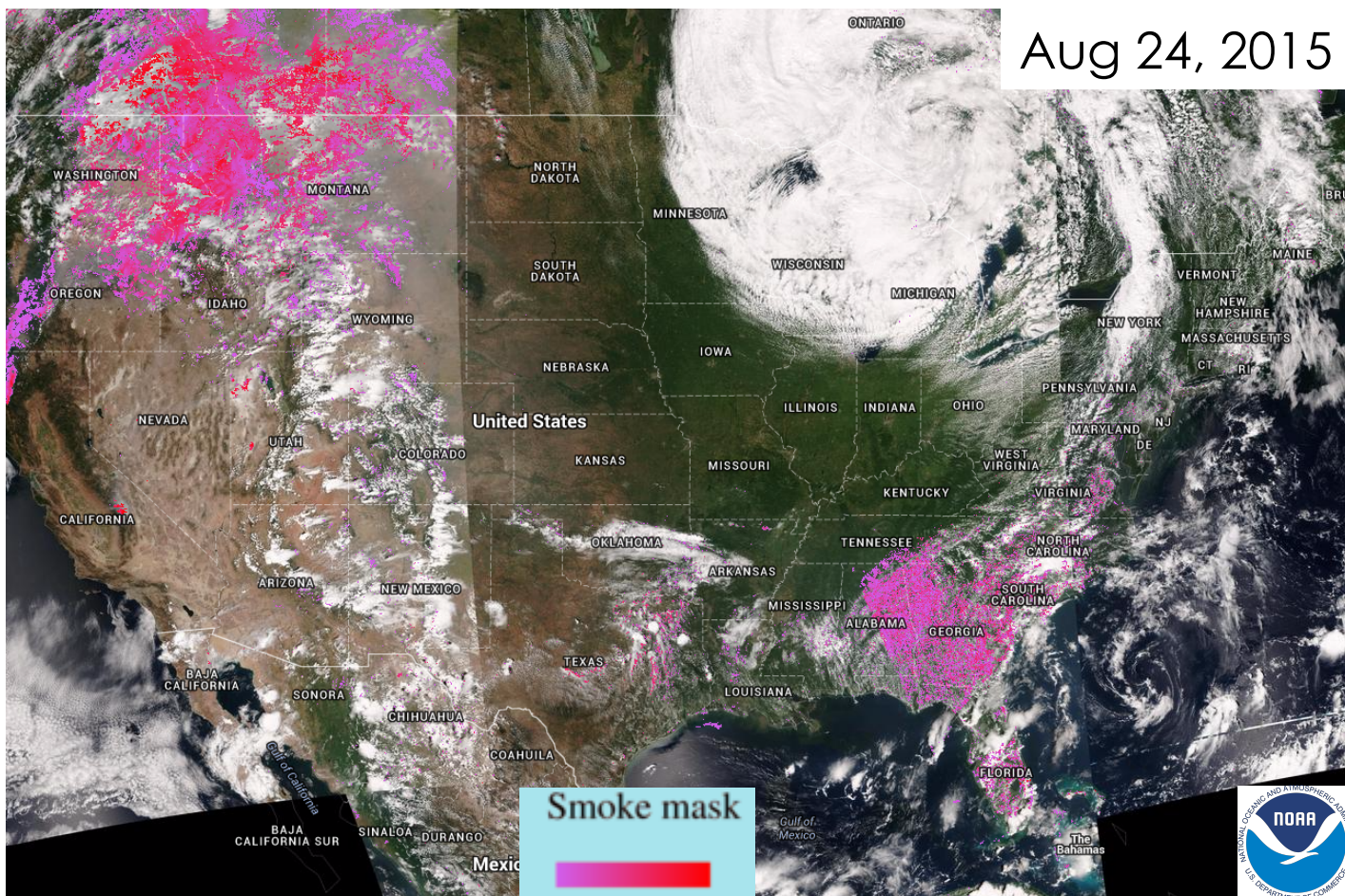
Aqua MODIS True Color Image EOP1 MY009  
S20: Surface Reflectance Band 1 A.2  
Sensor Acquisition Date: 2011-11-24  
Collection: 505  
Image created: 2011-11-29 09:36 UTC

# SNPP VIIRS Advantages



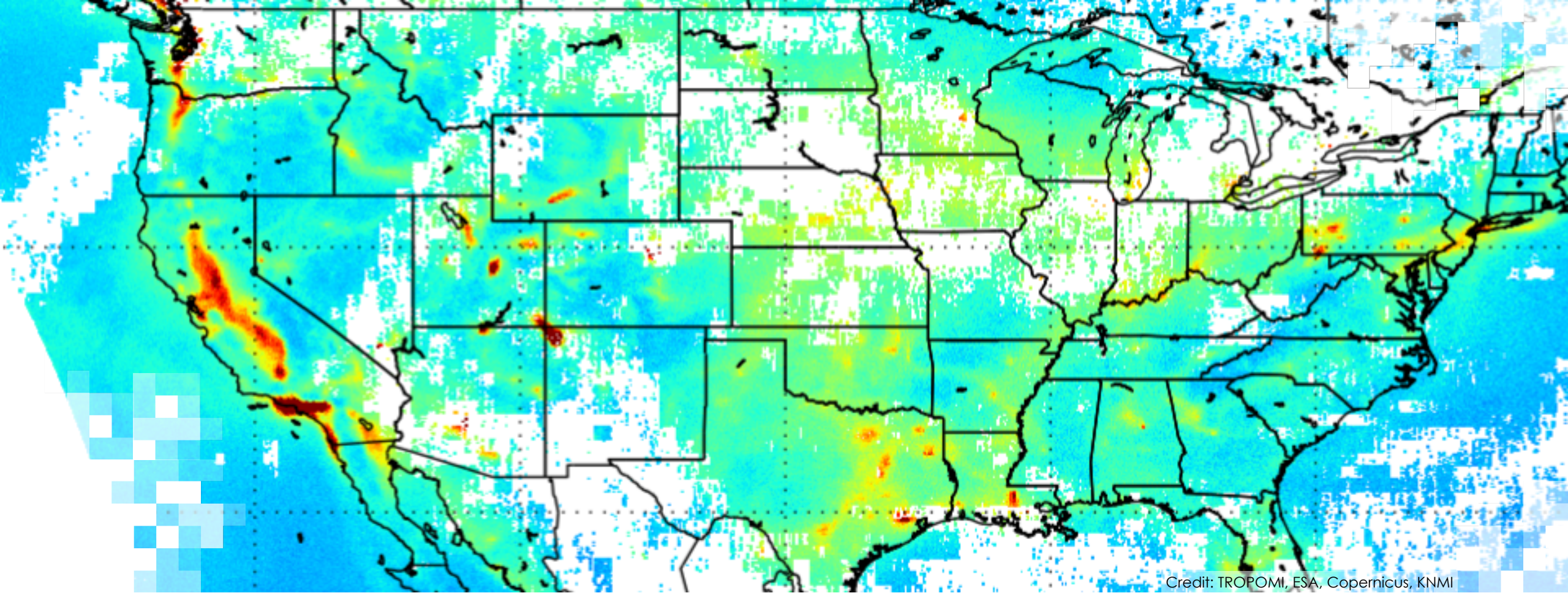
Side Courtesy: Shobha Kondragunta

# VIIRS Smoke Mask



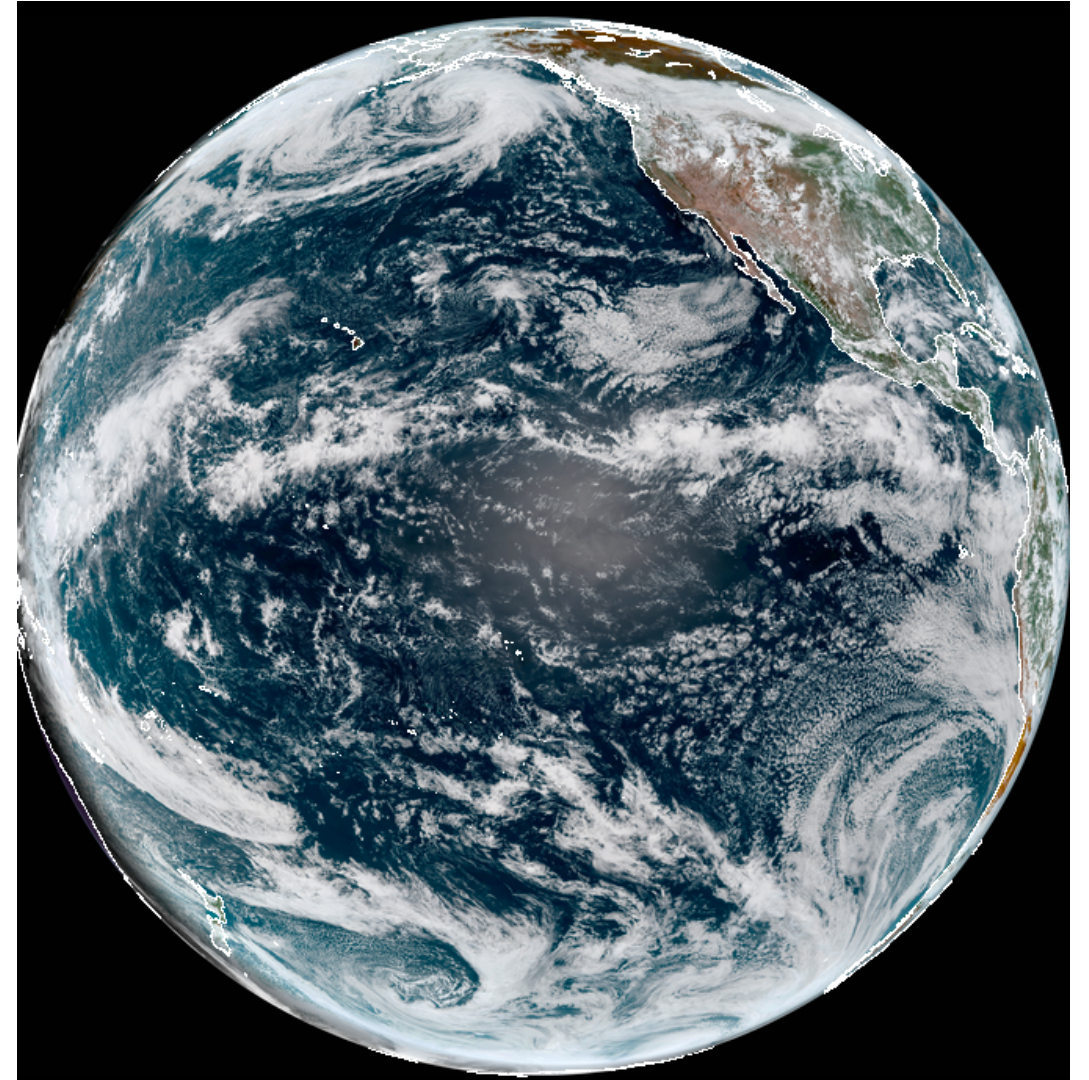
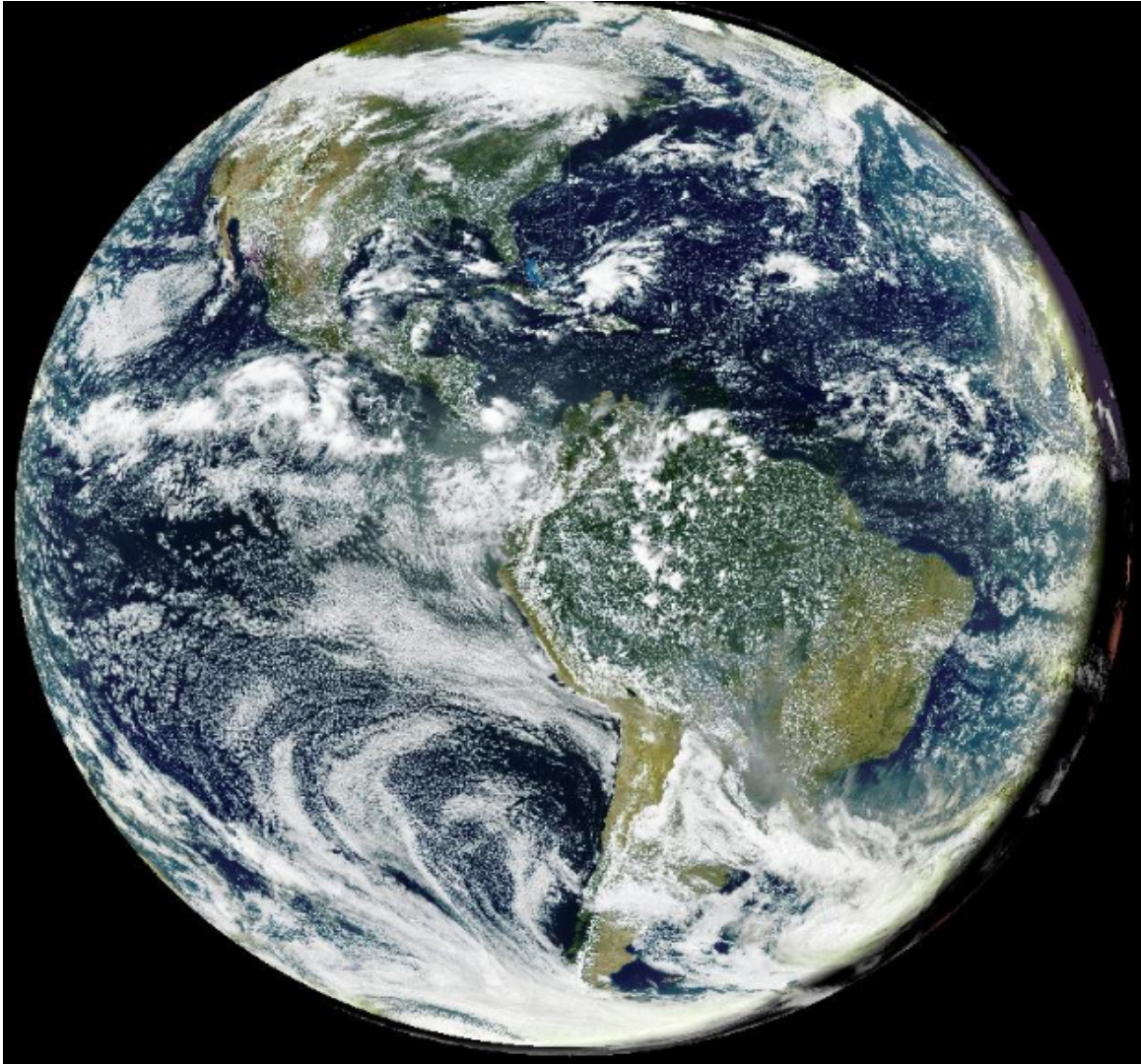
- Smoke mask: qualitative indicator of smoke
- Derived using spectral and spatial threshold tests based on VIIRS measurements in visible and IR
- **Useful for identifying local and transported smoke plumes**
- Colored shades of pink
- Light pink: thin smoke
- Bright pink/magenta: thick smoke

Side Courtesy: Shobha Kondragunta



# Geostationary Satellites

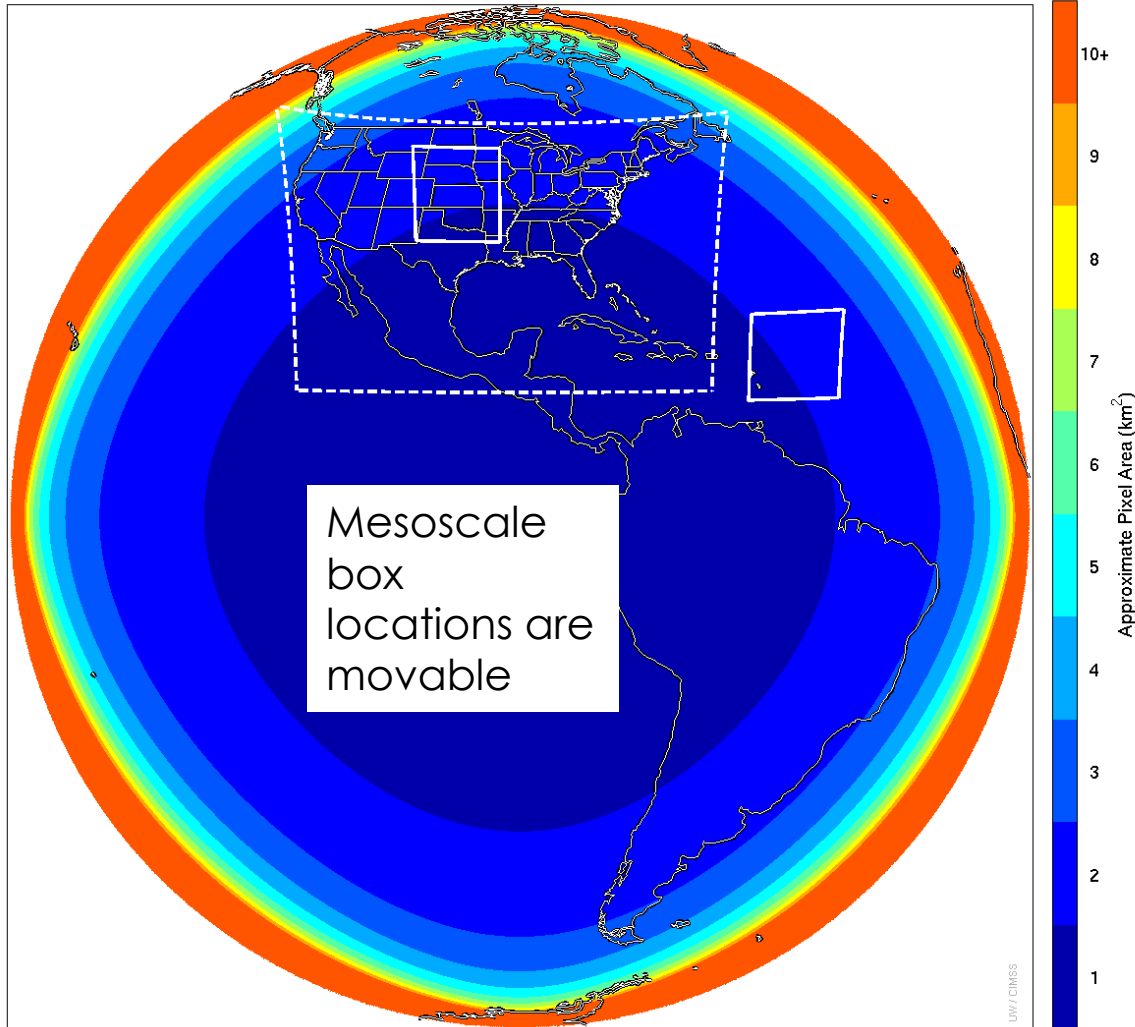
# GOES- East & GOES - West



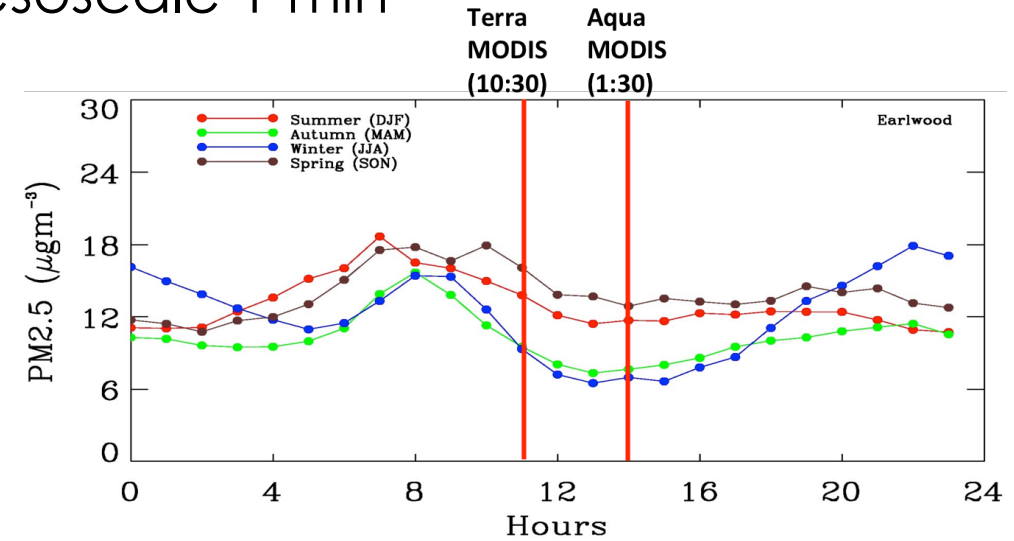
# GOES-R ABI



Approximate Pixel Area (Nominally 1km at Nadir) from -89.5 West



- Default Operational Mode:
  - Full Disk ± 10 min
  - CONUS 5 min
  - Mesoscale 1 min

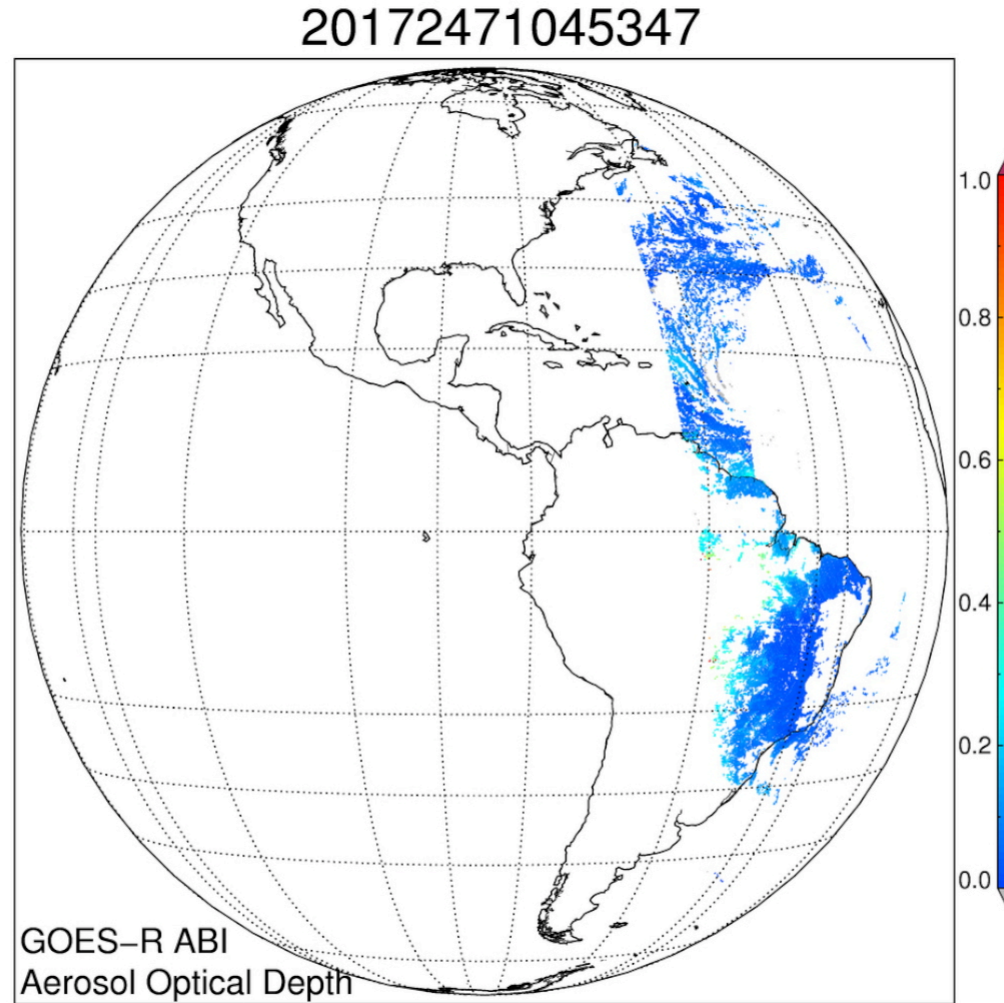


**Polar orbiting satellites only provides 1-2 observations per day, which limits the application for continuous air quality monitoring.**





# Aerosols from ABI

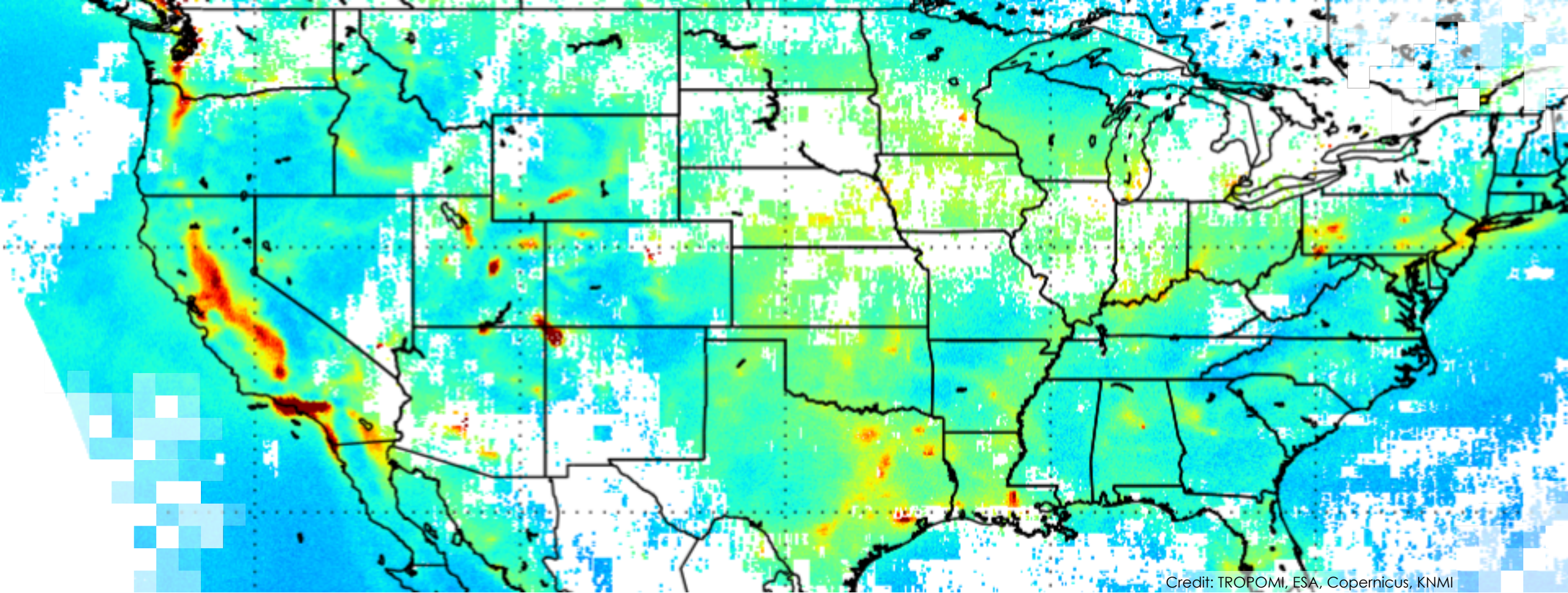


# Satellite Limitations

- **Optical measurements**
  - only available in day time
  - very limited in night time
- Only available under
  - cloud free conditions
  - Snow/Ice free conditions
- **Accuracy** - varies (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](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