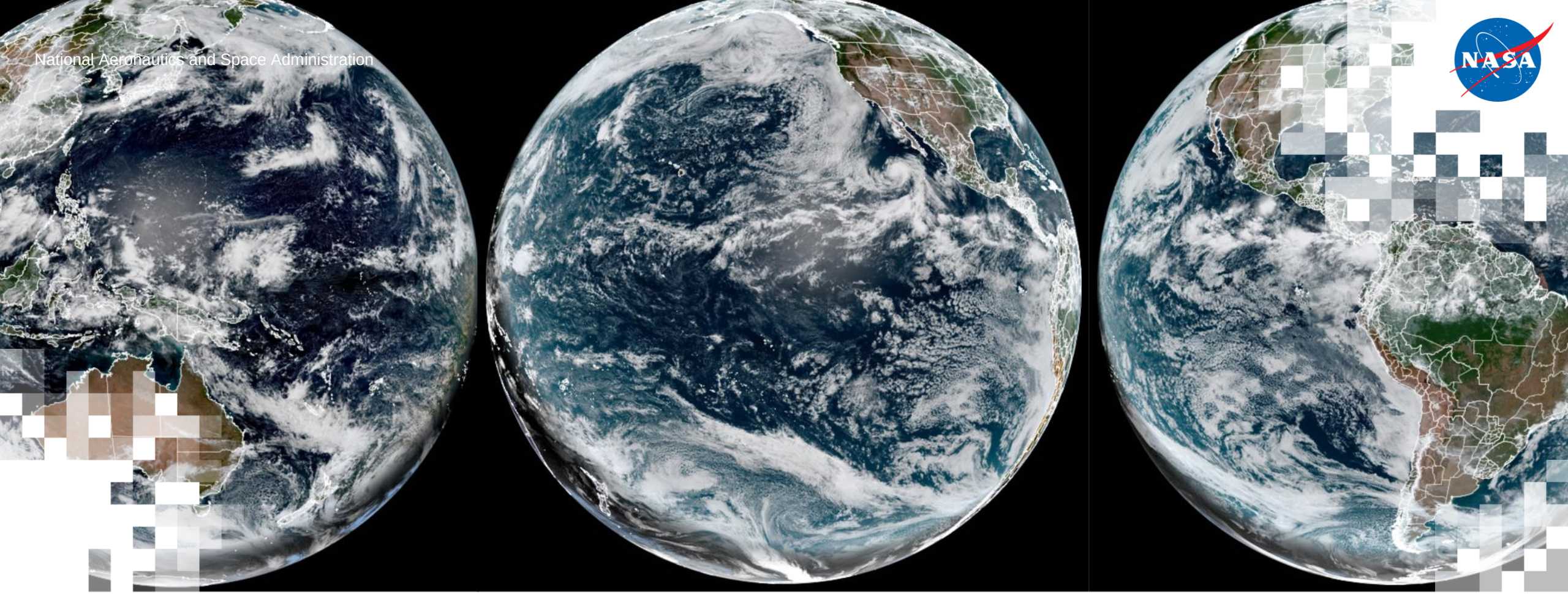

Part 2: Air Quality Products from the GOES-R Satellite

Amy K. Huff

Accessing and Analyzing Air Quality Data from Geostationary Satellites – Oct 18, 2022

Part 2: Air Quality Products from the GOES-R Satellites

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Aerosol Product Leads: **Shobha Kondragunta** and **Istvan Laszlo**

GOES-R ABI AOD product developers: **Mi Zhou, Hongqing Liu, Hai Zhang**

National Environmental Satellite, Data, and Information Service

Accessing and Analyzing Air Quality Data from Geostationary Satellites

October 18, 2022

Training Agenda: 18 Oct 2022 (all times EDT)

10:00 – 10:15 Overview of Aerosol Optical Depth (AOD) from the GOES-R Advanced Baseline Imager (ABI) (slide presentation)

10:15 – 10:25 Tour of NOAA's AerosolWatch Website (hands-on demonstration)

10:25 – 10:35 Working with GOES-R ABI Data Files (slide presentation)

10:35 – 10:40 Overview of Python (hands-on exercises)

10:40 – 11:30 Python Hands-On:

- 10:40 – 10:55 Download ABI Level 2 data files from AWS
- 10:55 – 11:10 Open and understand the contents of an ABI AOD file
- 11:10 – 11:25 Process and visualize ABI AOD data
- 11:25 – 11:30 Create an animation of ABI AOD image files

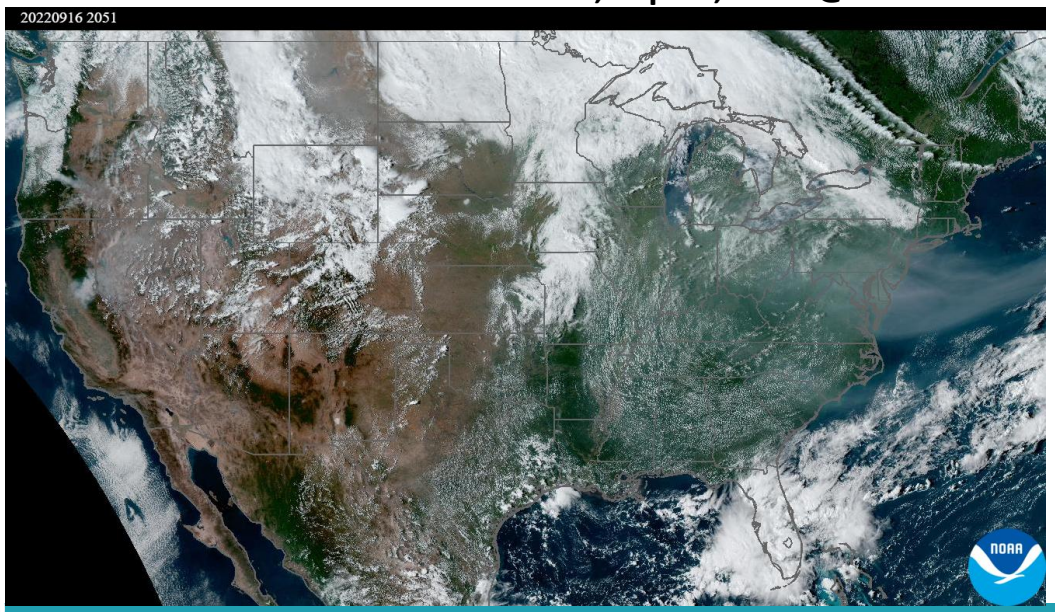
Overview of AOD from the GOES-R Advanced Baseline Imager (ABI)

Aerosol Optical Depth (AOD)

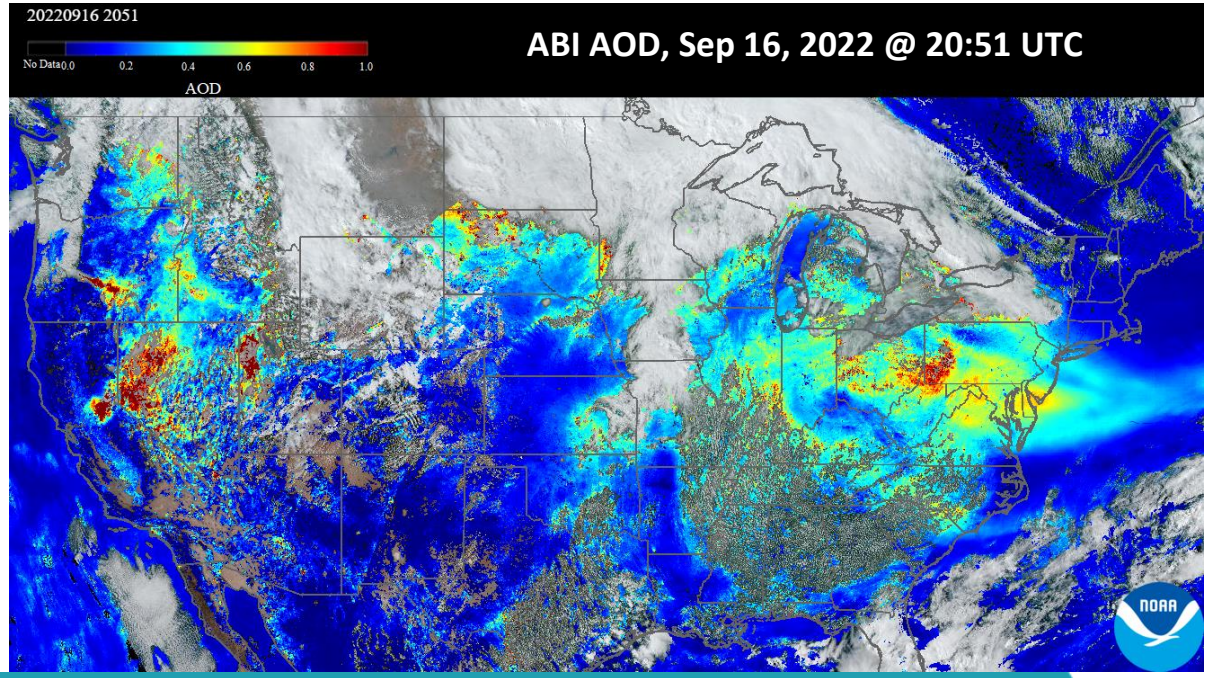
- AOD is a remote sensing measurement; from satellite, surface, or sub-orbital (aircraft)
- **Quantitative** measure of aerosols in a vertical column of the atmosphere
  - Measure of scattering & absorption of light by aerosols; ABI AOD reported for 550 nm light
  - AOD is unitless; values typically 0-1 in the US
    - Larger values for high concentrations of aerosols, like smoke & dust
    - Lower values for clean/clear atmosphere

Thick smoke from wildfires in the western US was transported across the CONUS in September 2022.

ABI GeoColor, Sep 16, 2022 @ 20:51 UTC

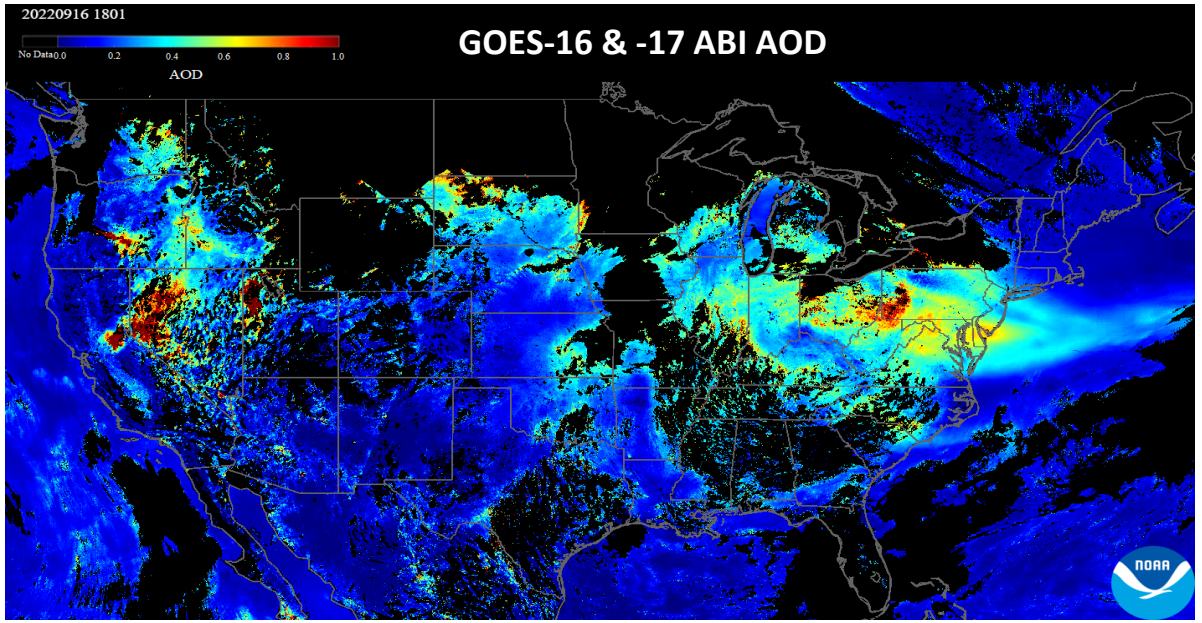


ABI AOD, Sep 16, 2022 @ 20:51 UTC



Why is AOD Useful for Air Quality?

- Unlike true color (visible) imagery, which provides qualitative info only, **AOD is quantitative**.
  - AOD is proportional to the number or mass concentration of aerosols in the atmosphere.
  - **Surface $PM_{2.5}$ can be estimated from AOD.**
- New algorithm from our group **dynamically** updates the AOD-$PM_{2.5}$ relationships using a Geographically Weighted Regression (GWR) model
  - AOD-estimated $PM_{2.5}$ fills gaps in the surface regulatory monitor network
  - **New hourly $PM_{2.5}$ estimated from ABI AOD will be used by AirNow program**



ABI image from the AerosolWatch website

Zhang, H., & Kondragunta, S. (2021). Daily and hourly surface $PM_{2.5}$ estimation from satellite AOD. *Earth and Space Science*, 8, e2020EA001599. https://doi.org/10.1029/2020EA001599

Zhang et al. (2022). Nowcasting applications of geostationary satellite hourly surface $PM_{2.5}$. *Weather and Forecasting*, in press.

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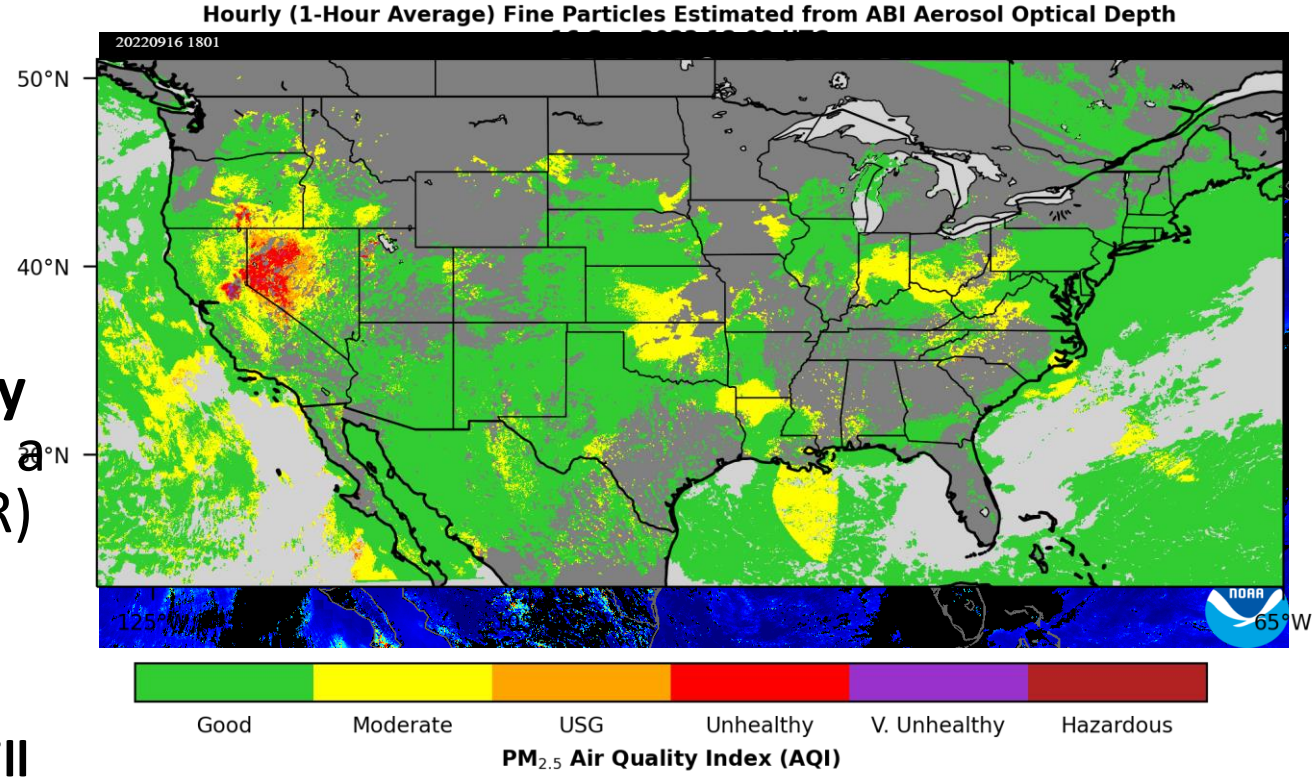


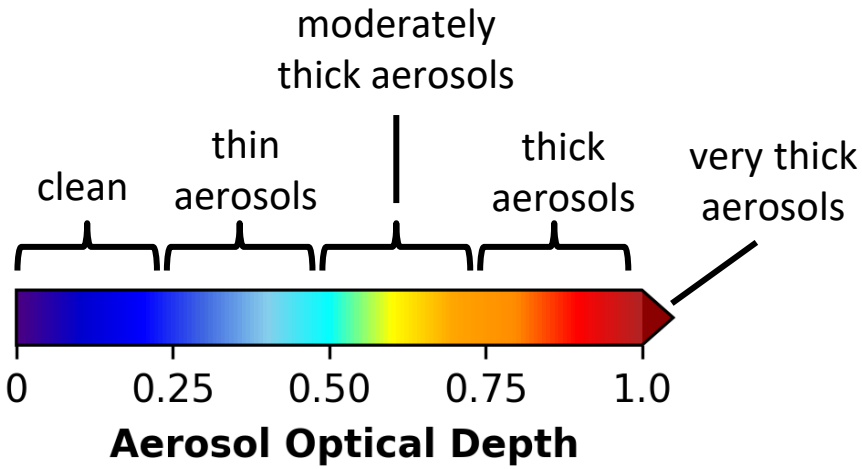
$PM_{2.5}$ Image Generated from netCDF4 Files using Python

Zhang, H., & Kondragunta, S. (2021). Daily and hourly surface $PM_{2.5}$ estimation from satellite AOD. *Earth and Space Science*, 8, e2020EA001599. https://doi.org/10.1029/2020EA001599

Zhang et al. (2022). Nowcasting applications of geostationary satellite hourly surface $PM_{2.5}$. *Weather and Forecasting*, in press.

ABI AOD Specifications and Availability

- AOD is available from ABI on GOES-16 (GOES-East) and GOES-17 (GOES-West).
  - GOES-18 will replace GOES-17 as GOES-West in January 2023.
- ABI AOD Data Range: [-0.05, 5]
  - AOD is unitless!
  - Values typically range from 0 to 1 in the US.
    - Can be as high as 5 in thick aerosol plumes, like smoke
  - Negative values indicate **uncertainty** in the AOD retrieval (think of them as very small positive AODs).



Sensor	Satellite	Spatial Resolution (km) at Nadir	Coverage**	Maturity Level†	Availability Starting
ABI	GOES-16	2.0	Full Disk CONUS	Provisional*	7/25/2018
	GOES-17			Provisional*	1/1/2019

AOD is **not available from the ABI Mesoscale sectors!

†Definitions of aerosol product maturity levels (e.g., validated, provisional, beta) are listed here.

*Provisional status means product quality may not be optimal; incremental product improvements are still occurring; product is ready for operational evaluation; and the research community is encouraged to participate in the quality assurance/validation of the product.

ABI AOD Algorithm

- AOD derived from **extinction (scattering & absorption)** of backscattered light by aerosols
  - Depends on wavelength; ABI AOD reported at **550 nm**
- An algorithm is a "formula" to calculate (retrieve) AOD.
  - AOD is a Level 2 (L2) product that uses ABI radiances (L1b data) as input (see table).
- A challenge in retrieving AOD is isolating the extinction of backscattered sunlight by **aerosols.**
  - Need to separate the aerosol signal from surface reflectance, scattering by clouds, and absorption by trace gases
- ABI AOD retrieved with a "multi-band" algorithm:
  - Similar to algorithms for VIIRS AOD, MODIS AOD
  - Separate algorithms for AOD retrieved over land and water
  - Key feature: 2.2 μm (ABI band 6) used to estimate surface reflectance over land
  - Internal tests use various bands to screen for "unfavorable" conditions, where it's difficult or impossible to retrieve AOD

ABI Bands used in AOD Algorithms

ABI Band	Wavelength (μm)	AOD Retrieval		Internal Test	
		Land	Water	Land	Water
1	0.47	x			x
2	0.64	x	x		
3	0.865		x	x	
4	1.378			x	x
5	1.61		x	x	
6	2.25	x	x		
14	11.2			x	x

AOD Algorithms Developed by Hongqing Liu (IMSG), Mi Zhou (IMSG), and Istvan Laszlo (NOAA)

Illustration of GOES-R ABI Multi-Channel AOD Retrieval

- AOD is retrieved by comparing calculated and observed reflectances at multiple wavelengths.
- Separate AOD algorithms for over land and water
  - Water: 4 fine- and 5 coarse-mode aerosol models
  - Land: generic, dust, smoke, urban aerosol models
- MODIS and early VIIRS heritage (*Tanre et al.*, 1997; *Remer et al., 2005; Levy et al., 2007, Vermote et al., 2007*)
- **A simplified version of the multi-channel AOD retrieval is shown in the figure.**
  - Example is for 2 aerosol models and 2 ABI spectral channels (bands)
    - Minimize residual; retrieved AOD = 1.0 using model 2

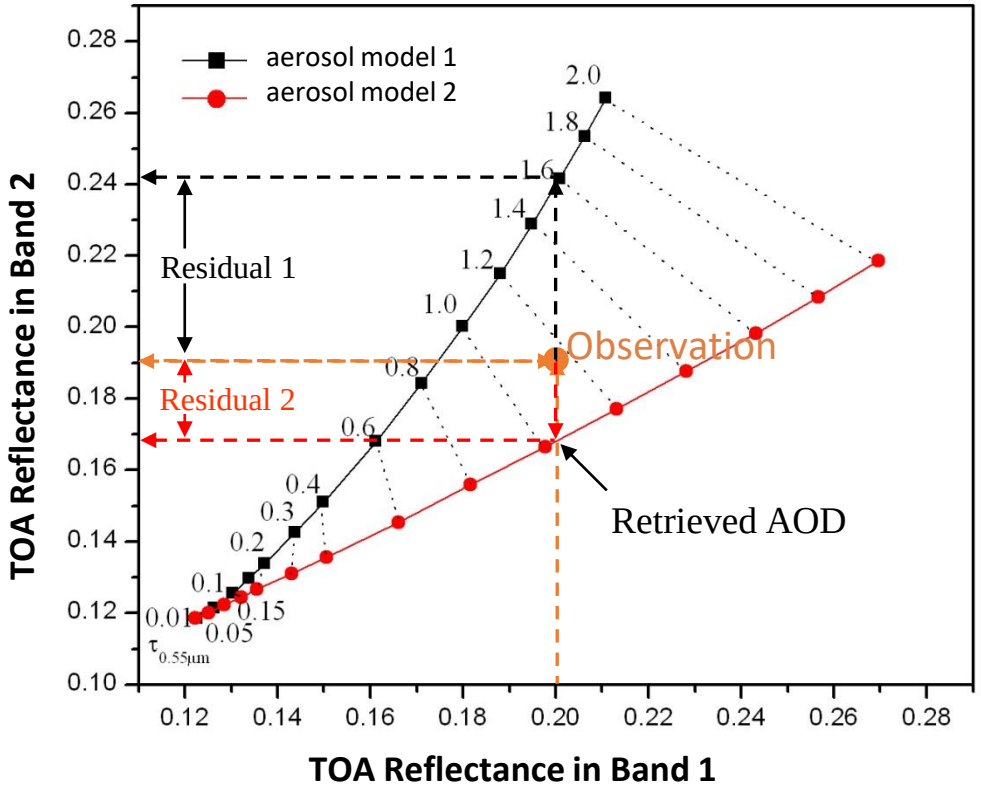
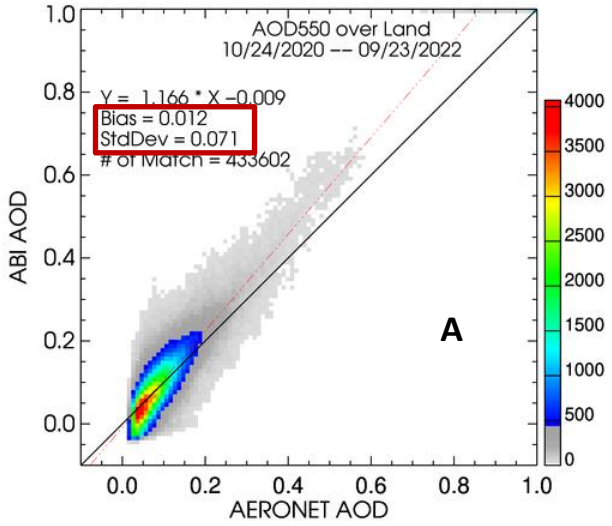
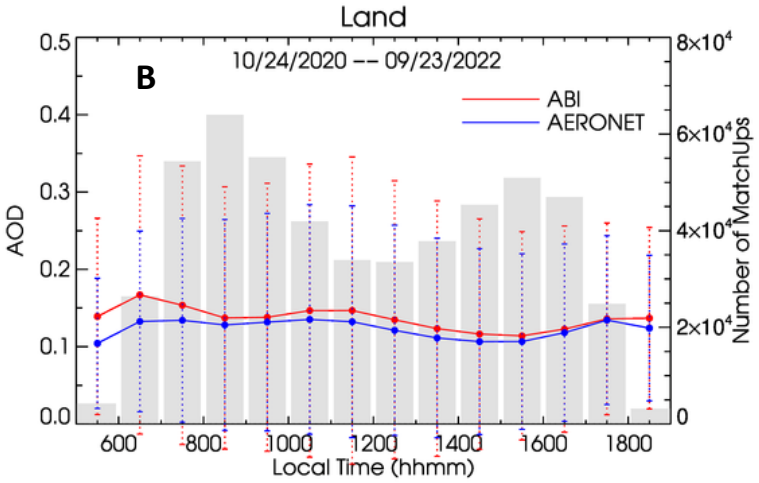


Figure Courtesy of Shobha Kondragunta (NOAA)

GOES-16 ABI AOD Validation

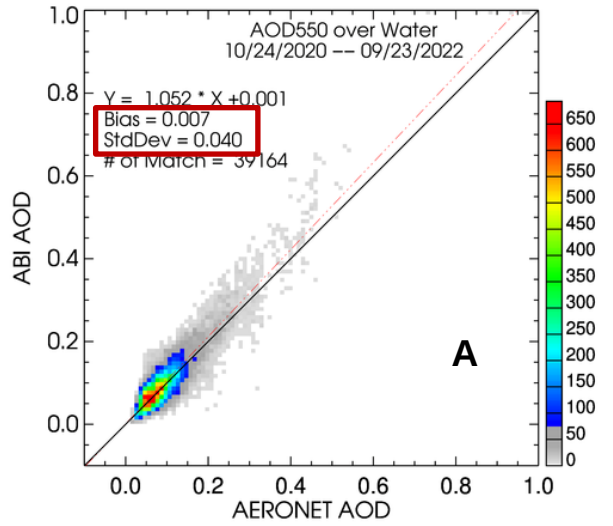
Over Land

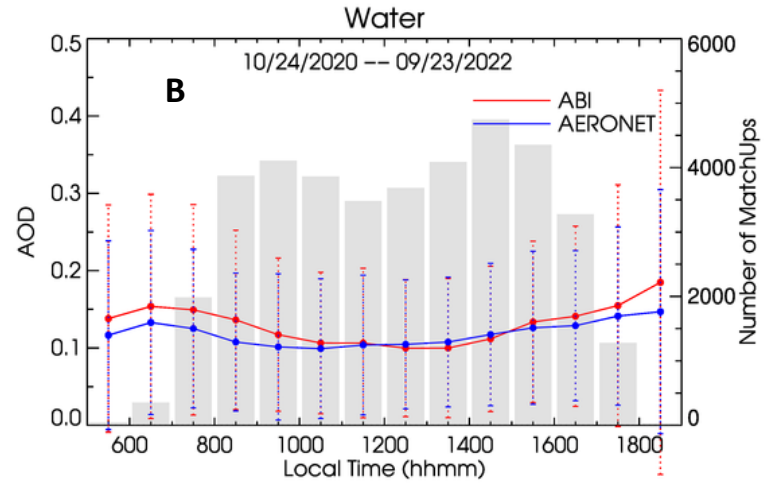




- High quality GOES-16 ABI AOD (most recent version)
- Validated with version 3 Level 1.5 near real-time AERONET AOD
- Validation Period: 24 Oct 2020 to 23 Sep 2022
- Results:
  - ABI AOD has a small mean positive bias (~0.01) over land and water (Fig. A)
  - ABI AOD standard deviation over land (0.071) is ~2x larger than standard deviation over water (0.040) (Fig. A)
  - ABI AOD captures diurnal variability observed by AERONET AOD (Fig. B)

Over Water





Figures Courtesy of Mi Zhou (IMSG)

ABI AOD Data Quality Flags

- ABI AOD data files include **data quality flags**.
  - Express confidence in AOD data
  - Figure: Example of ABI AOD quality flags
- **High Quality**: Most accurate, use for all quantitative applications (e.g., modeling)
- **Medium Quality**: Some uncertainty, use for qualitative applications (e.g., forecasting)
- **Low Quality**: High uncertainty, avoid for most applications
- ABI AOD **not retrieved** in areas with**:**
  - Clouds
  - Snow or Ice
  - Bright Land Surface
  - Sun Glint (measurement artifact; occurs when sunlight reflects off surface of ocean/lake at same angle that sensor is viewing surface)
  - Nighttime (need visible light)

H	High Quality
M	Medium Quality
	Low Quality
L1	Contradicting Cloud Masks
L2	Low Satellite Angle
L3	Low Sun Angle
L4	Out of Spec Range
L5	Coastal Area
L6	Shallow Inland Water
L7	High Residual
L8	High Inhomogeneity
	No Retrieval
N1	Invalid Input
N2	Cloud
N3	Snow
N4	Bright Land Surface
N5	Sun Glint

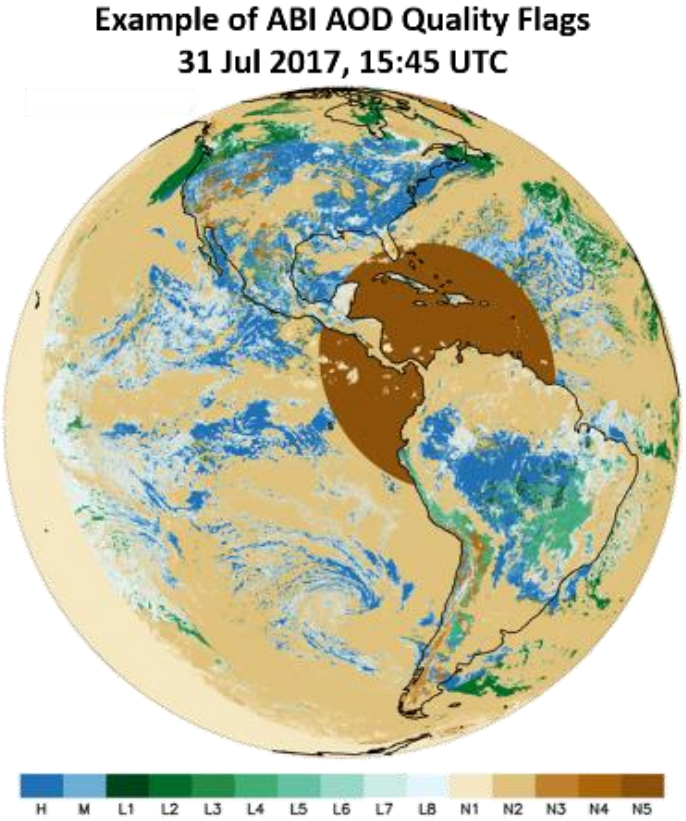
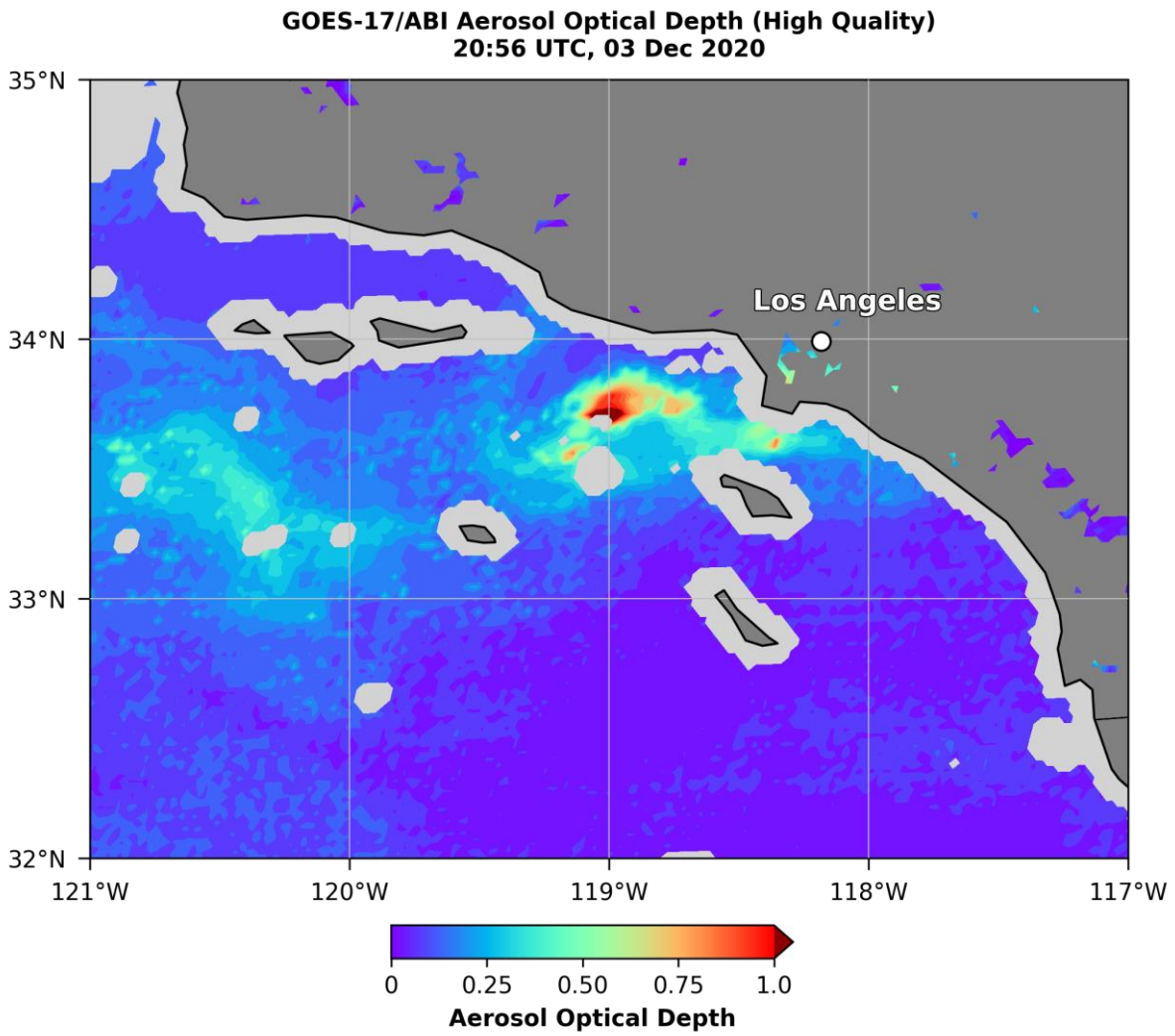


Figure Courtesy of Mi Zhou (IMSG) and Istvan Laszlo (NOAA)

Examples of High, Medium, and Low Quality ABI AOD



ABI AOD Images Generated from netCDF4 Files using Python

- Example: GOES-17 ABI AOD, highlighting smoke from Airport and Bond fires near Los Angeles, CA on Dec 3, 2020
- **High Quality AOD** is most accurate but is missing part of the smoke plume, also big gaps along coastlines (very stringent screening)
- **High + Medium Quality AOD ("top 2 qualities")** fills in most of smoke plume and some of the gaps along coastlines
- **High + Medium + Low Quality AOD ("all qualities")** fully resolves the smoke plume, but at the expense of erroneous high AOD values along coastlines and over inland shallow lakes
- Bottom Line: **Make sure you process AOD using the appropriate data quality flags!**
  - Avoid low quality AOD for most situations.
  - **Use high + medium ("top 2") qualities AOD for routine operational applications!**

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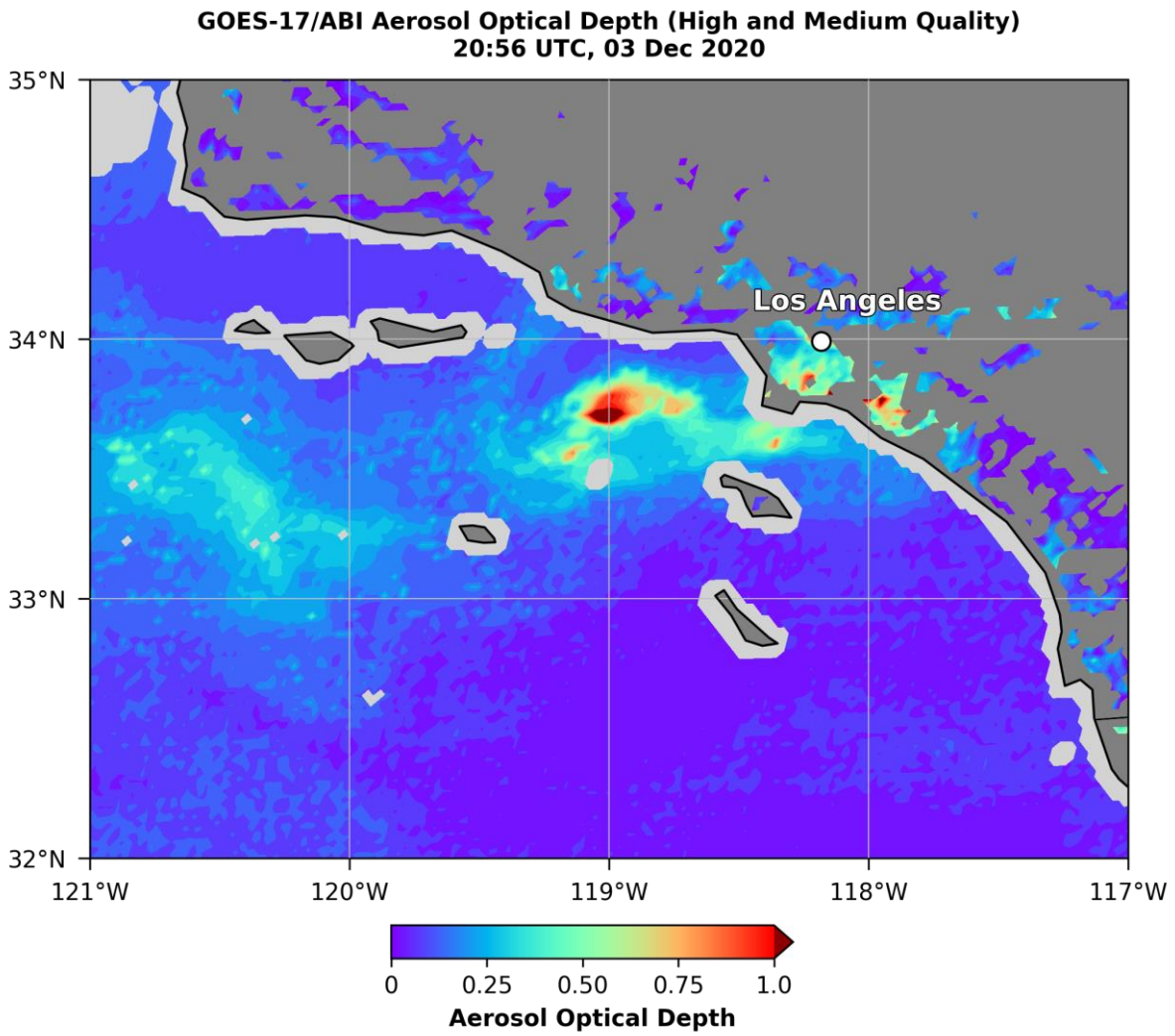

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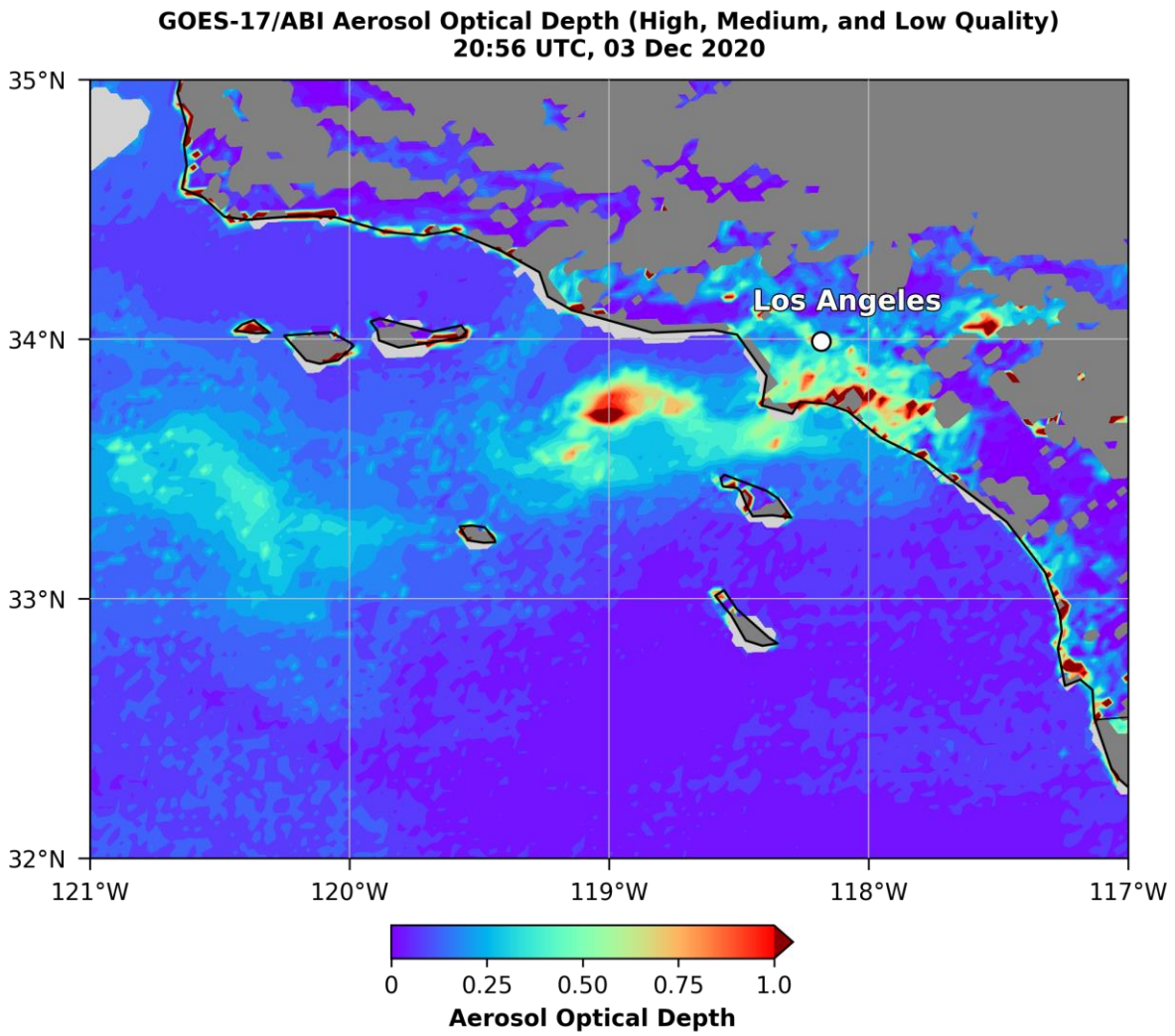

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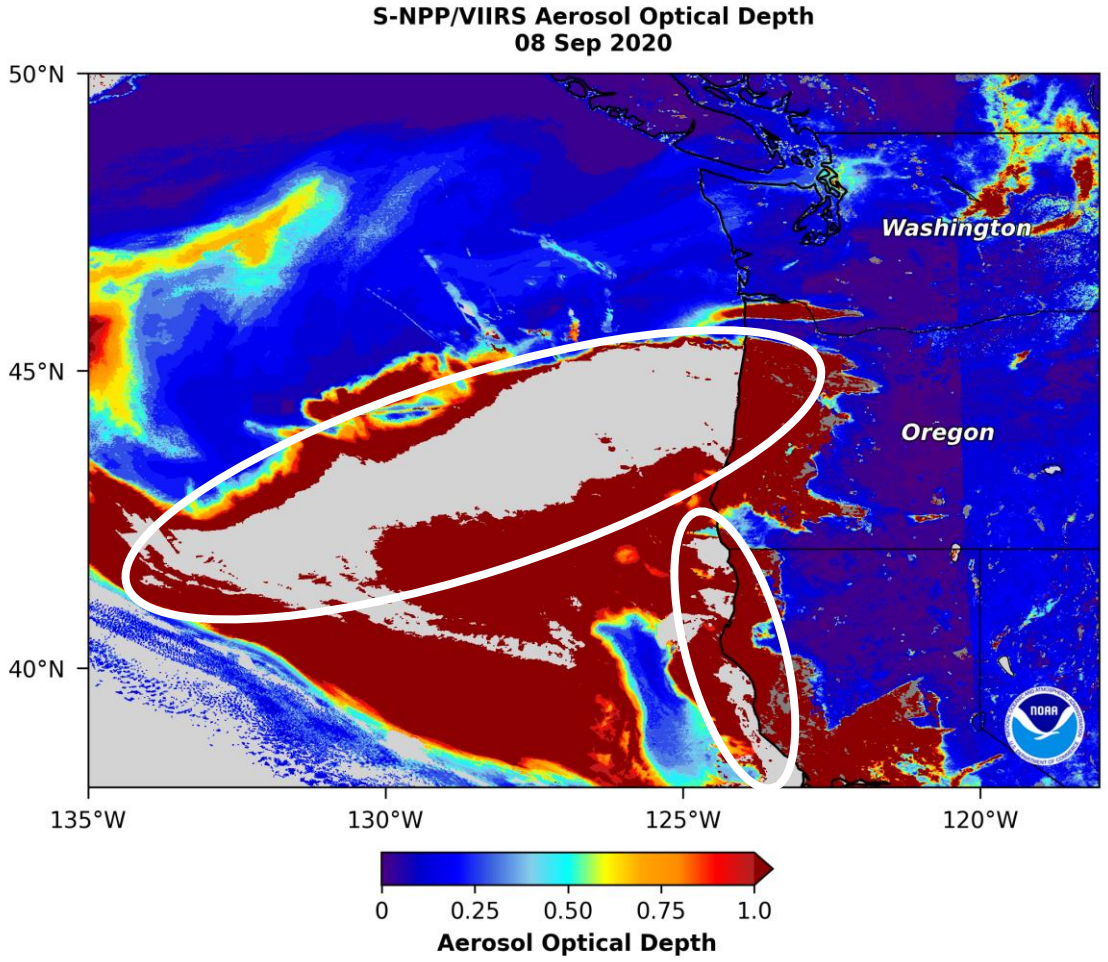
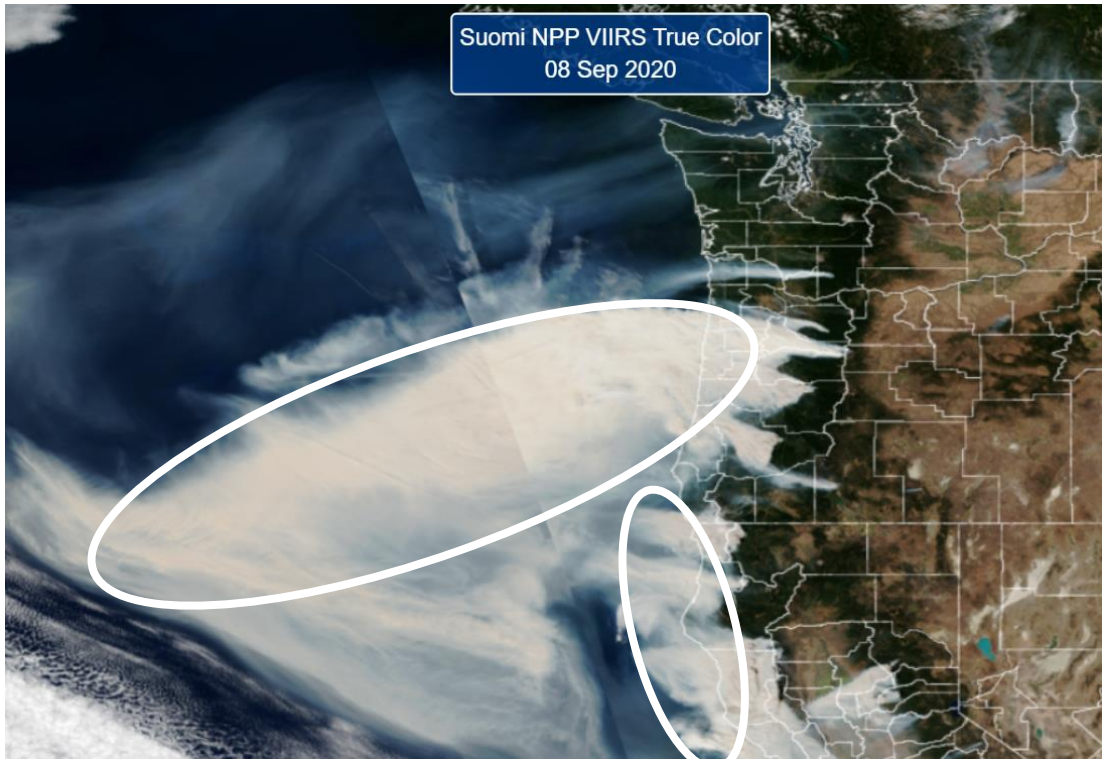
Missing AOD in Very Thick Aerosol Plumes

AOD algorithms can misclassify thick aerosol as a cloud, causing missed retrieval (occurs over land and water).

Example (VIIRS AOD): Very Thick Smoke from Oregon/California Wildfires, Sep 8, 2020 (ABI AOD displays similar behavior)





VIIRS AOD Image Generated from netCDF4 File using Python;
VIIRS True Color (RGB) Image from the JSTAR Mapper Website

Strengths and Limitations of GOES-R ABI AOD

- **Strengths**:
  - Quantitative measure of aerosols
    - Can be used to estimate surface concentrations of $PM_{2.5}$
  - Easy to interpret and identify areas of high aerosol concentration from smoke, blowing dust, haze
  - Supplements visible imagery
    - L1b radiances (e.g., ABI band 1 & 2)
    - True color or GeoColor imagery

- **Limitations**:
  - Column measurement
    - Geographic 2D location of aerosols only
    - No information about vertical distribution of aerosols in atmosphere
    - Smoke/dust/haze may not be reaching surface
  - No ABI AOD in areas with clouds, snow, ice, sun glint, bright surfaces
  - Available during daytime only

Working with ABI AOD Data Files

NOAA Satellite Data Files are in netCDF (.nc) Format

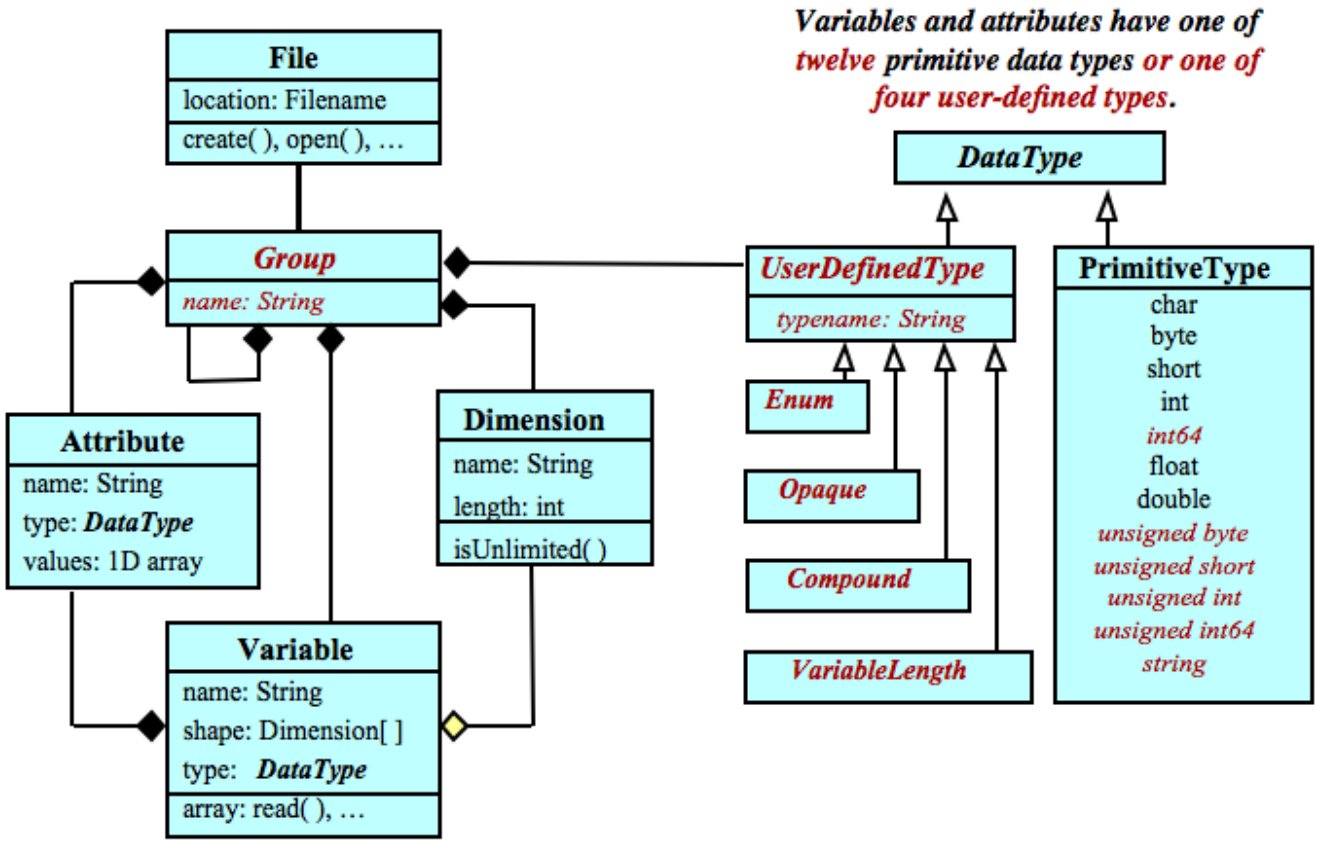


Image Courtesy of Unidata

- netCDF is a set of software libraries and data formats for creation, access, and sharing of array-oriented scientific data.
- netCDF files have a common organizational structure:
  - **Top-level group** (“root group”)
  - Contents organized by optional **sub-groups**
  - Data organized as **variables**
  - Groups and variables have
    - **Attributes** (descriptive information)
    - **Dimensions**
  - Attributes and variables have **data types**
  - Common data types you may encounter in satellite files:
    - String (str)
    - Integer (int)
    - Unsigned integer (uint)
    - Floating point number (float)
- In ABI data files, the data we want to work with (e.g., AOD) are **variables**.

ABI Data File Classification

- Data Processing Level
  - **Level 1b (L1b):** Band 1-16 radiances
  - **Level 2 (L2):** Products derived from radiances ← AOD data are L2
- Product Name (see slides 18-19)
- Scan Sector (data domain)
  - **Full Disk (F):** Full hemispheric disk (GOES-East centered 75.2 °W, GOES-West centered 137.0 ° W)
  - **CONUS (C):** Subset of full disk covering CONUS (GOES-East) or PACUS (GOES-West) (3000 x 5000 km)
  - **Mesoscale (M):** Two zoom-in regions adjusted based on current hazards (1000 x 1000 km)
- Scan Mode (observation frequency)
  - **M6:** Flex mode; default since 4/2/19 (**F** every 10 min, **C** every 5 min, 2-**M** every 1 min)
  - **M3:** Previous flex mode (**F** every 15 min, **C** every 5 min, 2-**M** every 1 min)
  - **M3G:** GOES-17 cooling mode (**F** every 15 min, 2-**M** every 2 min, no **C**)
  - **M4:** Continuous full disk (**F** every 5 min; no **C** or **M**)
- Satellite:
  - **GOES-16:** Current GOES-East
  - **GOES-17:** Current GOES-West; GOES-18 will replace GOES-17 in Jan 2023

GOES-East CONUS Sector

GOES-West PACUS Sector

Figures Courtesy of NOAA OSPO

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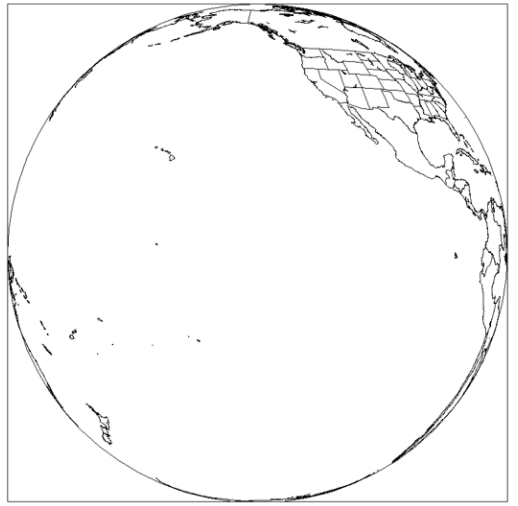
  - **M3G:** GOES-17 cooling mode (**F** every 15 min, 2-**M** every 2 min, no **C**)
  - **M4:** Continuous full disk (**F** every 5 min; no **C** or **M**)
- Satellite:
  - **GOES-16:** Current GOES-East
  - **GOES-17:** Current GOES-West; GOES-18 will replace GOES-17 in Jan 2023

GOES-East Full Disk Sector

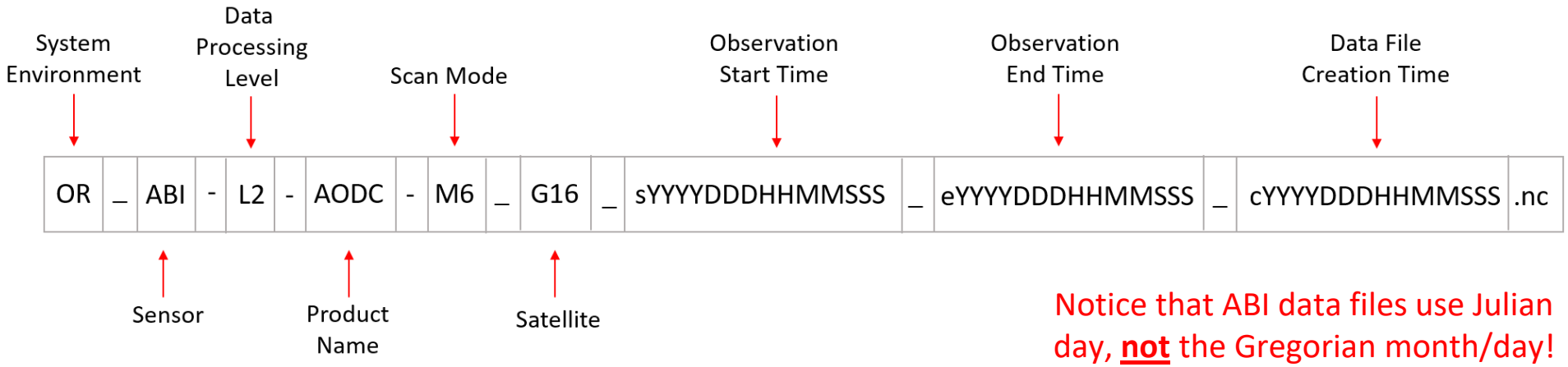


GOES-West Full Disk Sector

Figures Courtesy of NOAA OSPO

Decoding ABI L2 Data File Names

OR_ABI-L2-AODC-M6_G16_s20202601501123_e20202601503496_c20202601506349.nc



Notice that ABI data files use Julian day, **not** the Gregorian month/day!

- System Environment: **O**perational system using **R**eal-time data
- Sensor: **A**dvanced **B**aseline **I**mager
- Data Processing Level: **L**evel **2**
- Product Name: Abbreviation for product ("**AOD**") + scan sector ("**C**" = CONUS, "**F**" = Full Disk)
- Scan Mode: **M**ode **6** (current "flex mode"); also **M3**, **M3G**, **M4**
- Satellite: **G**OES-**16**; also **G17** and **G18**

- Observation **s**tart/**e**nd, file **c**reation time:
  - YYYY (4-digit year. e.g., **2020**)
  - DDD (3-digit Julian day, e.g., **260**)
  - HHMM (4-digit hour/minutes in UTC, e.g., **1501**)
  - SSS (3-digit seconds to tenth of second)
- **.nc** Extension: Indicates Network Common Data Format (netCDF) version 4 file

ABI L2 Product Names (Derived Products)

- Aerosol Detection:
  - ADPF
  - ADPC
  - ADPM
- **Aerosol Optical Depth:**
  - **AODF**
  - **AODC**
- Clear Sky Masks:
  - ACMF
  - ACMC
  - ACMM
- Cloud and Moisture Imagery:
  - CMIPF
  - CMIPC
  - CMIPM
- Cloud and Moisture Imagery Multiband:
  - MCMIPF
  - MCMIPC
  - MCMIPM
- Cloud Optical Depth:
  - CODF
  - CODC
- Cloud Particle Size Distribution:
  - CPSF
  - CPSC
  - CPSM
- Cloud Top Height:
  - ACHAF
  - ACHAC
  - ACHAM
- Cloud Top Phase:
  - ACTPF
  - ACTPC
  - ACTPM
- Cloud Top Pressure:
  - CTPF
  - CTPC

Scan Sector Abbreviations

- F = Full Disk
- C = CONUS
- M = Mesoscale

Link to detailed information on ABI L1b and L2 products, including "read me" docs

ABI L2 Product Names, Continued

- Cloud Top Temperature:
  - ACHTF
  - ACHTM
- Derived Motion Winds:
  - DMWF
  - DMWC
  - DMWM
- Derived Stability Indices:
  - DSIF
  - DSIC
  - DSIM
- Downward Shortwave Radiation:
  - DSRF
  - DSRC
  - DSRM
- Fire/Hot Spot Characterization:
  - FDCF
  - FDCC
  - FDCM
- Land Surface Temperature (Skin):
  - LSTF
  - LSTC
  - LSTM
- Legacy Vertical Moisture Profile:
  - LVMPF
  - LVMPC
  - LVMPM
- Legacy Vertical Temperature Profile:
  - LVTPF
  - LVTPC
  - LVTPM
- Rainfall Rate/QPE:
  - RRQPEF
- Reflected Shortwave Radiation:
  - RSRF
  - RSRC
- Sea Surface Temperature:
  - SSTF
- Total Precipitable Water:
  - TPWF
  - TPWC
  - TPWM
- Volcanic Ash (Detection and Height):
  - VAAF

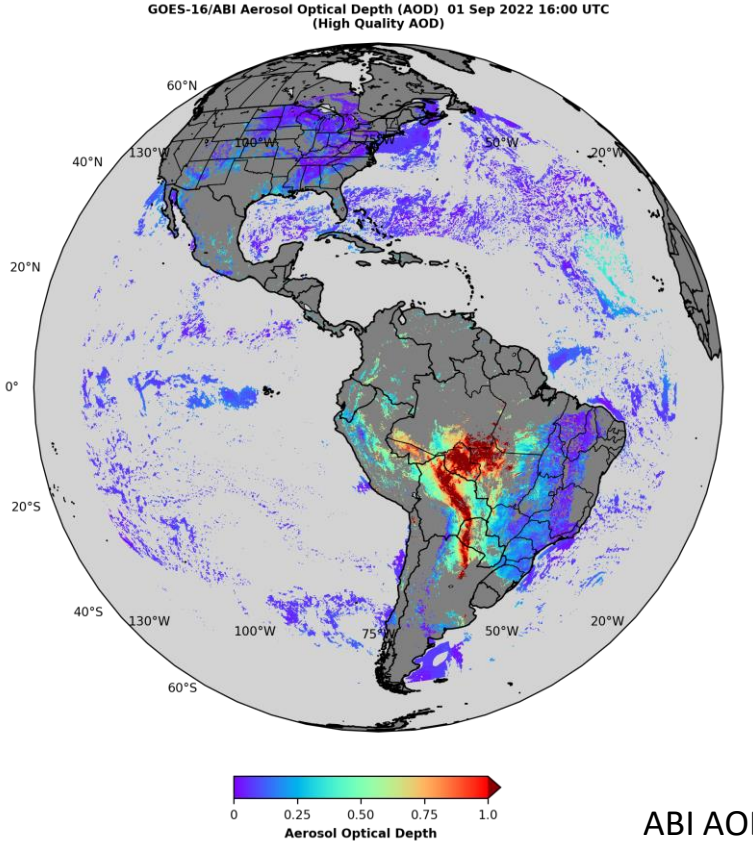
Scan Sector Abbreviations

- F = Full Disk
- C = CONUS
- M = Mesoscale

ABI AOD Level 2 Products (Examples for GOES-East)

Full Disk Sector (~30-40 MB data file)

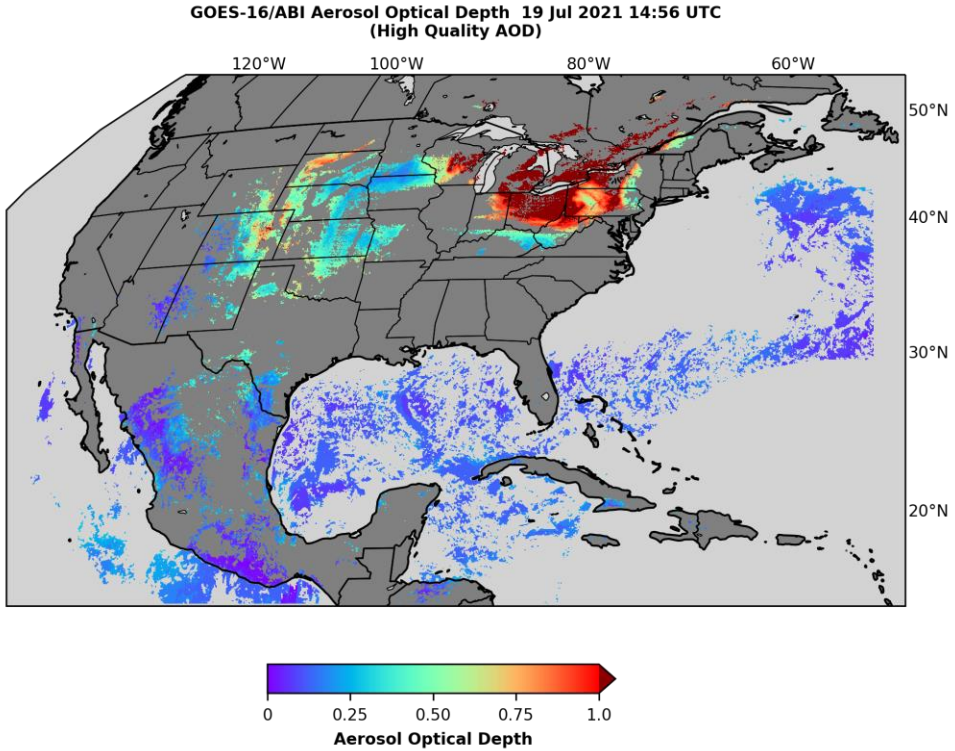
- 2 km resolution at nadir
- Observation frequency depends on ABI scan mode; typically every 10 min (mode M6)
- High, medium, and low quality AOD included



AOD is not generated for the ABI mesoscale sectors!

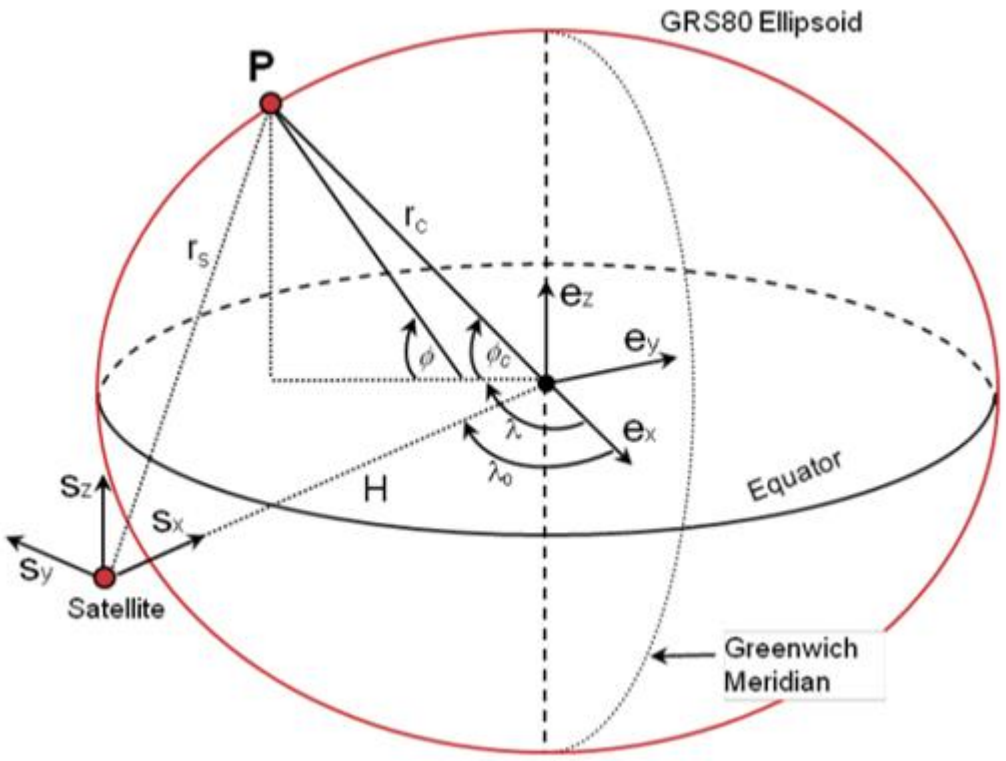
CONUS Sector (~8 MB data file)

- 2 km resolution at nadir
- Observation frequency depends on ABI scan mode; typically every 5 min (mode M6)
- High, medium, and low quality AOD included



ABI AOD Images Generated from netCDF4 Files using Python

GOES Imager Projection (ABI Fixed Grid)



Coordinate Frames for GOES Imager Projection (ABI Fixed Grid) Navigation
(Image Courtesy of GOES-R PUG)

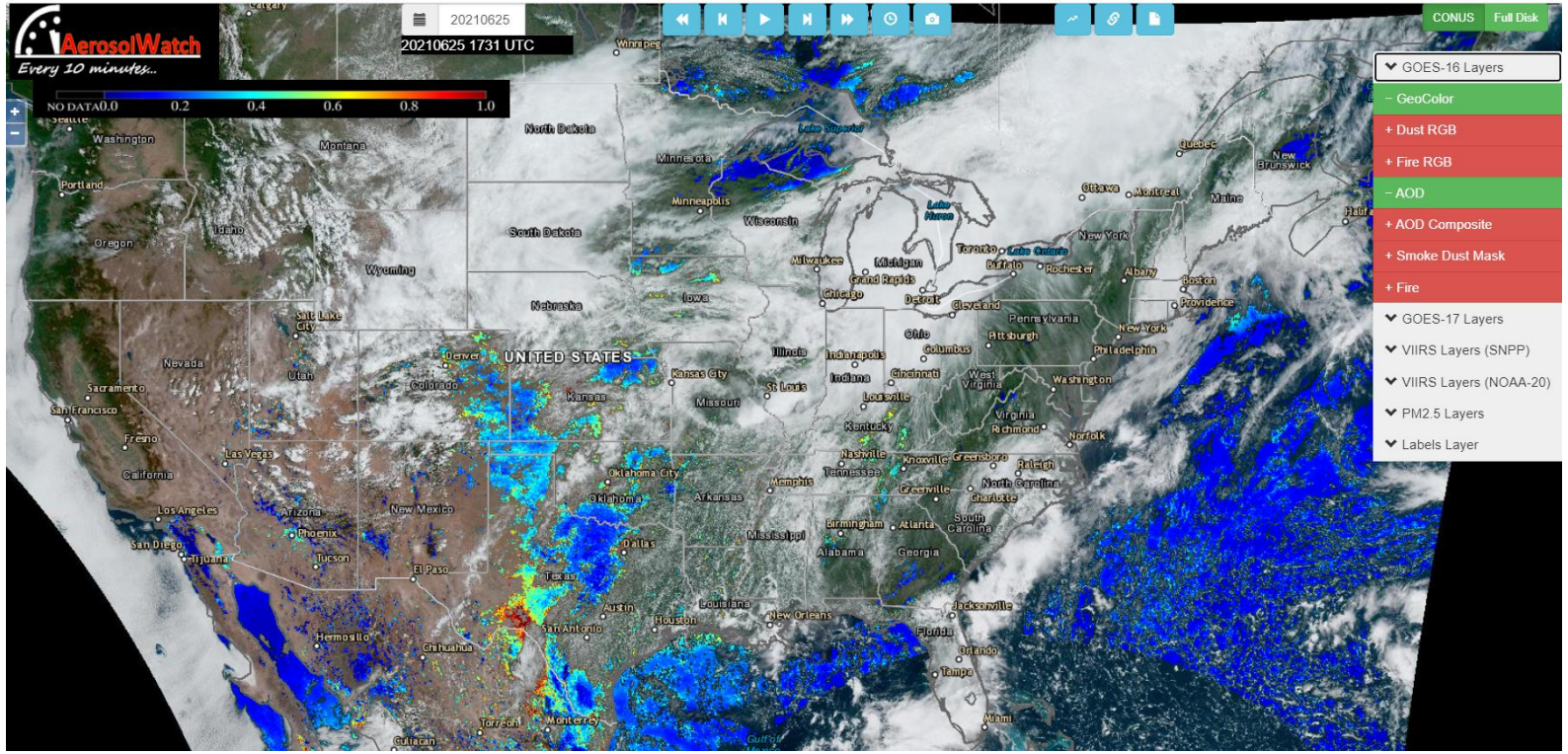
- To save file space, ABI L1b and most L2 data files do NOT include latitude and longitude as variables.
- Instead, the files contain information on the **ABI fixed grid**, which is a projection based on the geostationary viewing perspective of the GOES-16 or GOES-17 (or -18) satellite.
- The ABI fixed grid information can be used to **calculate latitude and longitude in units of degrees**.
  - ABI data files contain all necessary information:
    - "x" (fixed grid E/W scan angle in radians)
    - "y" (fixed grid N/S scan angle in radians)
    - Several constants (e.g., H, λ_0)
- Don't worry! We did the math for you! I'll provide a function to calculate latitude and longitude, so you can work with ABI AOD data!
- Details about the fixed grid and examples of the calculation of latitude and longitude are given in the GOES-R Product User Guides (PUG):
  - Volume 3, L1b products: Section 5.1.2
  - Volume 5, L2 products: Section 4.2

AerosolWatch Website: NRT & Archived ABI AOD Imagery

Aerosol Watch Website

Developed by S. Kondragunta (NOAA) & H. Zhang (IMSG)

Satellite	Coverage	Aerosol Products	Archive Starts
GOES-16	Full Disk, CONUS	AOD (top 2 qualities) ADP (smoke/dust mask)	Jan 2019
GOES-17	CONUS only		Mar 2019



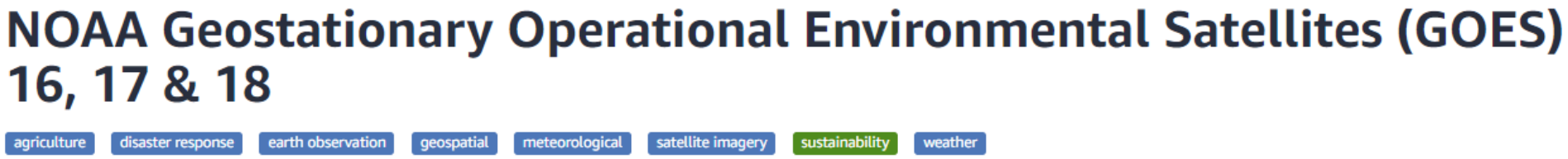
We'll do a hands-on demo of the website today!

AerosolWatch tutorial (slides) available here

Where to Find ABI AOD Data Files

- **ABI L1b (radiances) and L2 data files** (including AOD) are available via the NOAA GOES-R data archive on Amazon Web Services (AWS).
  - Separate links ("buckets") for GOES-16 and GOES-17 and GOES-18 data
  - Available files updated in near real-time
  - You can download files manually or programmatically
  - Free and easy! No registration is required!
  - You do NOT need to have an AWS account!!
- Part of NOAA's Open Data Dissemination (NODD) Program

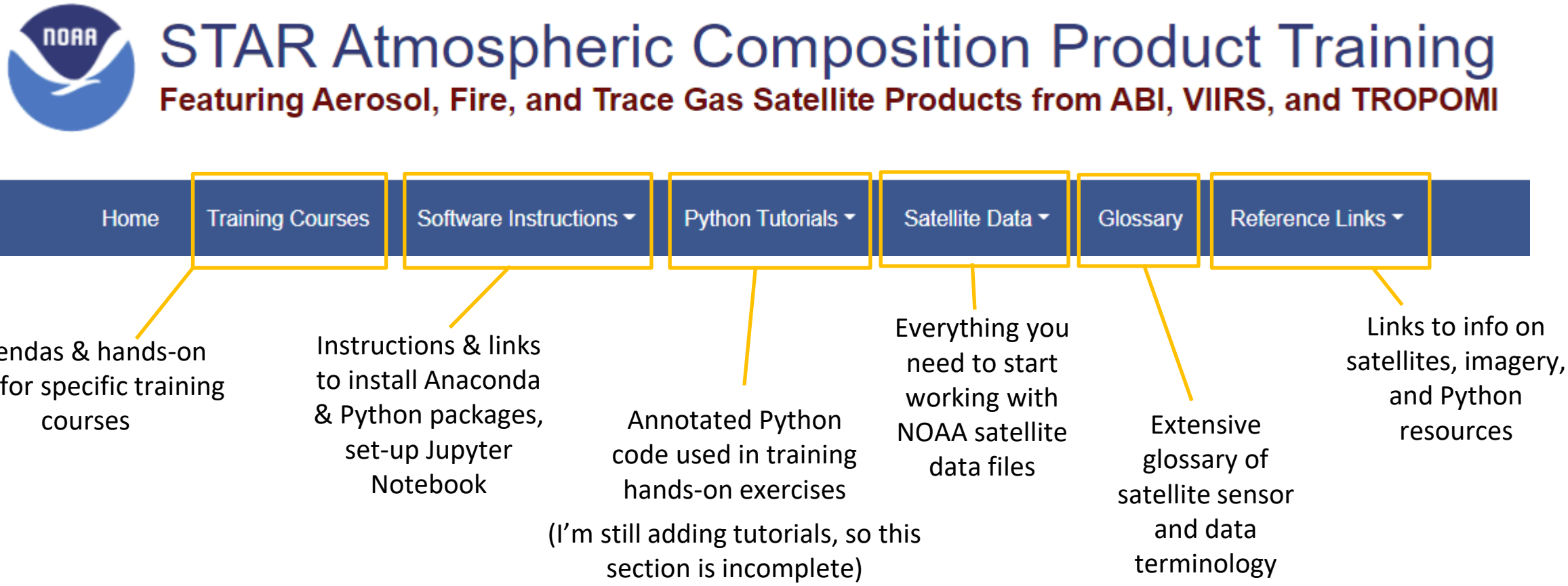
We'll download GOES-16 ABI AOD data files using Python in today's hands-on!



Looking for Information? Have a Question?

Our new training website has all the answers!

https://www.star.nesdis.noaa.gov/atmospheric-composition-training/



Overview of Python Hands-On Exercises

Objective: Learn the proper workflow for visualizing NOAA GOES-R ABI Level 2 data files (e.g., AOD), from start to finish, using Python

1. Download 6 ABI full disk sector AOD .nc data files from AWS using Python
   - Case Study: Seasonal burning in Amazon Basin, September 7, 2022, 14:00-14:50 UTC
2. Open one of the ABI AOD data files, read the metadata, and understand the relevant data variables (e.g., AOD, DQF, x, y) using Python
3. Process and visualize the ABI AOD data files (make professional quality maps of AOD data) using Python
   - Make maps of individual AOD files or a multi-file AOD composite
   - Visualize AOD data on the native geostationary map projection or a Plate Carrée "flat" projection
4. Make an animated .gif file of the 6 individual ABI AOD maps using Python

All of the provided Python code files can be used on your own for your own needs! They are not limited to the hands-on case study!

Things to Remember About the Provided Python Code Files

1. Provided files are in Jupyter Notebook format (.ipynb); if regular Python format (.py) is desired, contact me.
   - The Python code is the same in both formats!
     - The only function that is **not transferrable** from .ipynb to .py is the Jupyter Widgets menus
   - Jupyter Notebook is great for beginners and for anyone troubleshooting or writing new code!
2. There is not enough time to review all the code line by line, but I will go over the major steps.
   - I have extensively commented the code for your reference.
   - Tutorials are available on our new training website (many tutorials still being added).
3. **There is a big difference between writing code for yourself and writing code for others to use!**
   - The provided code files are more complicated than what you would write for yourself.
   - I have included a lot of extra functions to facilitate ease-of-use, including error checks and user-friendly graphic user interface (GUI) menus to enter parameter variables.
   - You may wish to write your own Python code using the "core" functions I provided in the hands-on files (just please be sure to **acknowledge my work**!).

Settings to Download ABI L2 Data Files for Case Study

Download 6 ABI AOD full disk sector data files using "abi_level2_download_aws.ipynb"

- Block 6, use interactive menus to set the following search parameters:
  - Satellite: **GOES-16**
  - Product: **Aerosol Optical Depth**
  - View sector: **Full Disk**
  - Year: **2022**
  - Month: **Sep**
  - Day: **7**
  - Start Time: **14:00**
  - End Time: **14:50**
  - Directory to Save Downloaded Files: **current working directory**

OR_ABI-L2-AODF-M6_G16_s20222501400205_e20222501409513_c20222501412051.nc
OR_ABI-L2-AODF-M6_G16_s20222501410205_e20222501419513_c20222501421563.nc
OR_ABI-L2-AODF-M6_G16_s20222501420205_e20222501429513_c20222501431506.nc
OR_ABI-L2-AODF-M6_G16_s20222501430205_e20222501439513_c20222501441576.nc
OR_ABI-L2-AODF-M6_G16_s20222501440205_e20222501449513_c20222501451469.nc
OR_ABI-L2-AODF-M6_G16_s20222501450205_e20222501459513_c20222501501465.nc

6 Files
Each File is ~30 MB

Settings to Visualize ABI AOD for Case Study Event

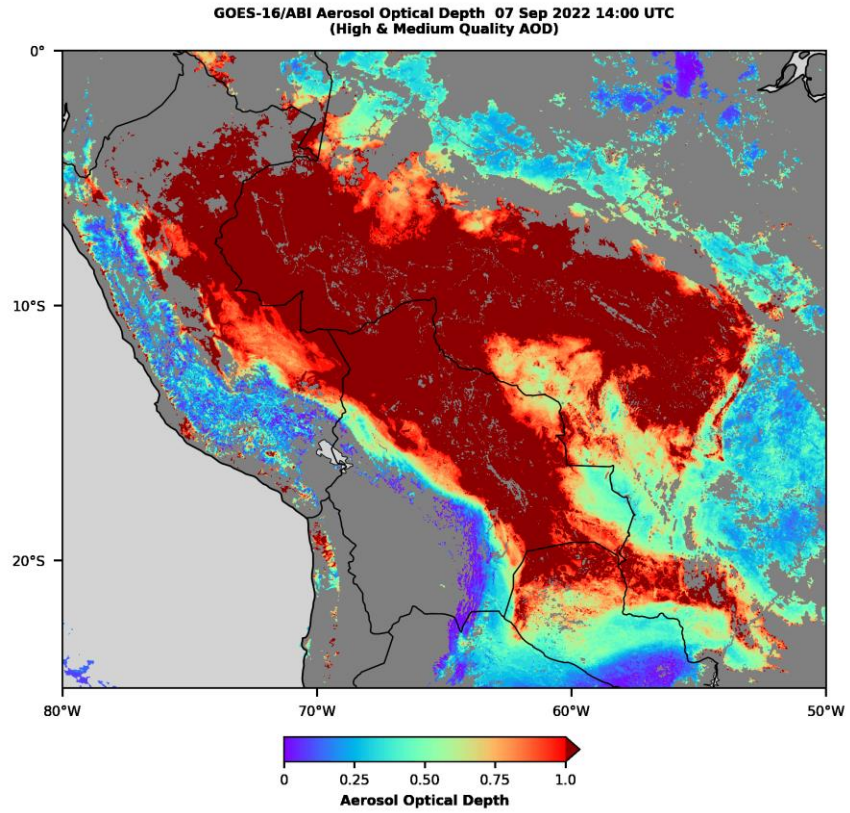
Visualize ABI AOD Data using "abi_aod_process_visualize.ipynb"

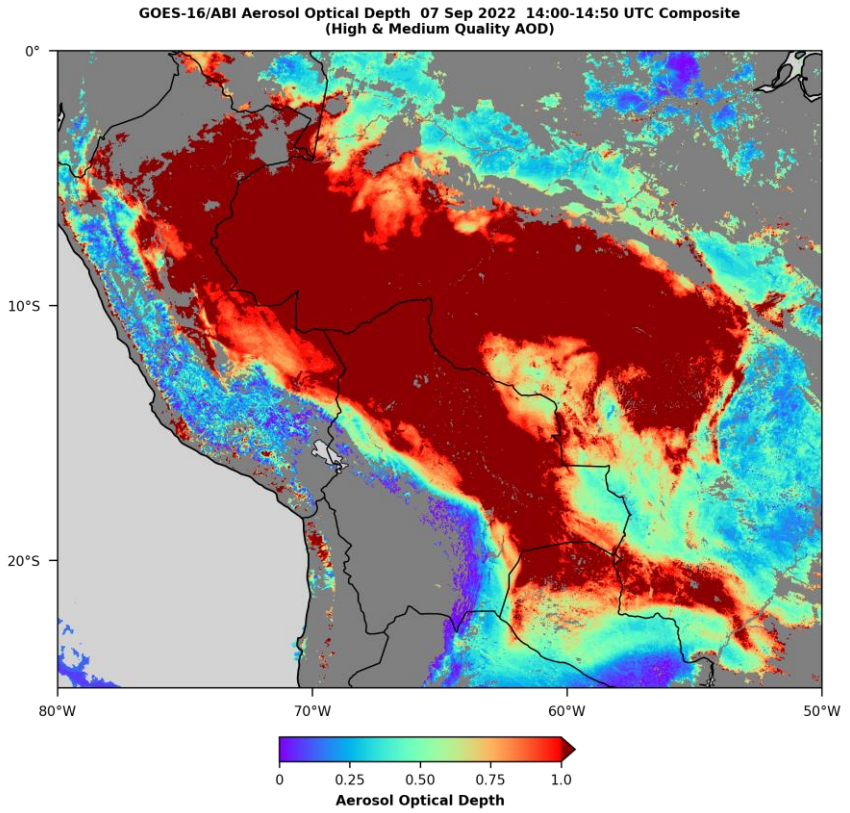
- Block 17, use interactive menus to enter the following settings:
  - Directory where ABI data files are located: **current working directory**
  - Directory where AOD map image files will be saved: **current working directory**
  - Settings for AOD data visualization:
    - AOD map type: (try both options)
    - AOD data quality: **High & Medium**
    - AOD map image file format: (whatever you want)
    - AOD map image file resolution (DPI): **150 or 300**
  - Settings for **manual** map domain: [-80, -50, -25, 0]
    - Northern-most latitude: **0**
    - Southern-most latitude: **-25**
    - Western-most longitude: **-80**
    - Eastern-most longitude: **-50**

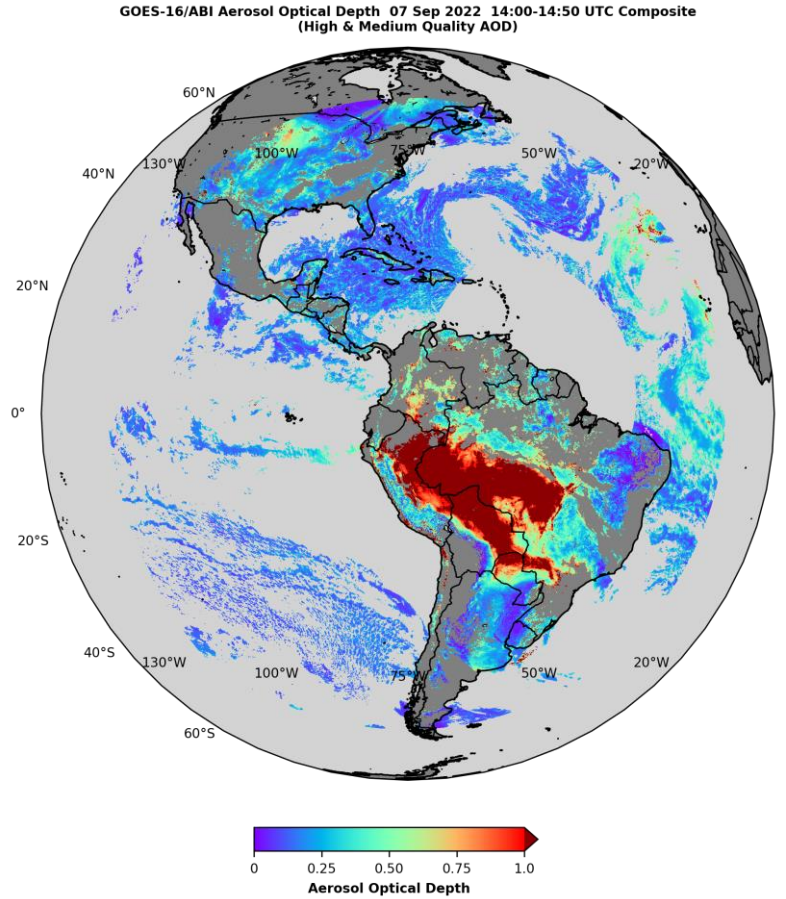
Top 2 qualities AOD, 300 dpi, **manual** map domain:
~11 min to make 6 total individual AOD maps
~3 min to make 6-file AOD composite map
Plotting full domain takes much longer!

  - Enter range of longitude ticks: [-80, -70, -60, -50]
    - Western-most longitude tick: **-80**
    - Eastern-most longitude tick: **-50**
    - Increment of °longitude between ticks: **10**
  - Enter range of latitude ticks: [-20, -10, 0]
    - Northern-most latitude tick: **0**
    - Southern-most latitude tick: **-20**
    - Increment of °latitude between ticks: **10**

Examples of ABI AOD Case Study Visualizations







Top 2 qualities AOD, 300 dpi, **manual** map domain:
~11 min to make 6 total individual AOD maps (Left)
~3 min to make 6-file AOD composite map (Right)

Top 2 qualities AOD, 300 dpi, **full** domain:
~20 min to make 6-file AOD composite map


APPLIED REMOTE SENSING TRAINING PROGRAM
TRAIN - EMPOWER - ADVANCE

Thank You!