Updates to the Dark Target products: (and MODIS/VIIRS consistency)

ECMWF

ICAP 2026 Meeting

Robert C. Levy. (NASA Goddard Space Flight Center)

And contributions from many, many folks

Photos from project's TEAMS (2024)

GODDARD EARTH SCIENCES

NASA Earth

MODIS (envisioned in the 1980s)
MODerate resolution Imaging Spectroradiometer

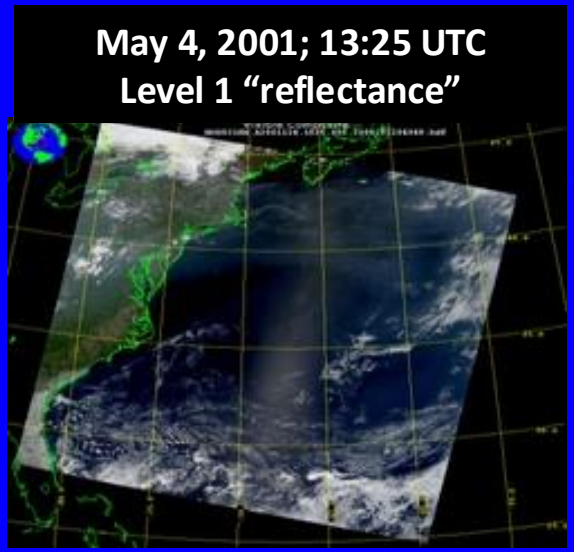
Many improvements compared to AVHRR

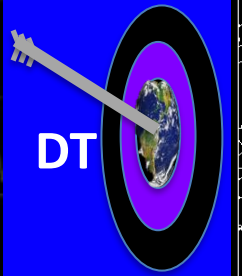
- Spectral / Spatial resolution
  - 36 bands (0.4 – 14 μm)
  - 250 m, 500 m, 1 km
- Swath width / Temporal Resolution
  - Swath = 2300 km
  - Near-daily with gaps in equator
  - Overlaps at poles
  - 16-day repeat cycle
- System of calibration and orbit tracking
  - Calibration on board and to surface targets
  - Continuous orbit maintenance

- Component of NASA's "mission to planet Earth" ; a fleet of satellites and sensors known as "Earth Observing System" (EOS)
- MODIS on Terra (since 2000) and Aqua (2002). End of missions later in 2026.
- Terra is AM orbit (10:30), Aqua is PM (13:30)
- **Since 2021, orbits have been "drifting". As of June 2026, each are nearly 2 hours closer to dawn/dusk**

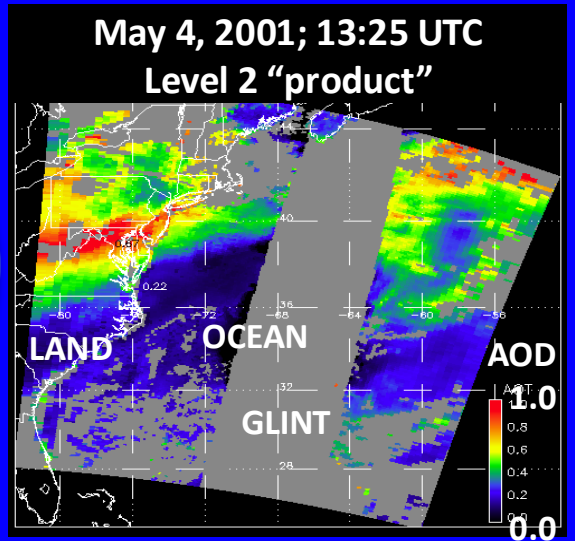
Dark Target Aerosol retrieval Algorithm

What a sensor observes





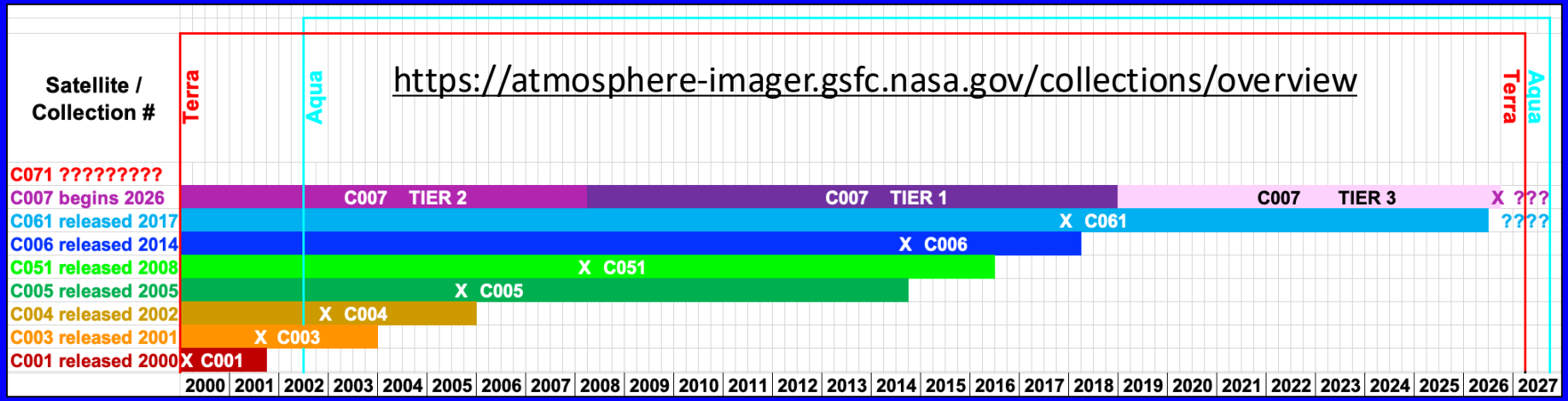
Attributed to aerosol (AOD)



- Established by Kaufman, Tanré, Remer, et al (1997)
- Modified by Remer, Levy, Gupta, Sawyer, Shi et al (2005, 2010, 2013, 2015, 2020, etc.)

- **Requires:** Observations of spectral reflectance in selected bands between "blue" and "SWIR" wavelengths (other bands help with cloud/surface masking and filtering)
- **Retrieves:** AOD at 0.55 μm, spectral AOD (AE), cloud-cleared reflectances, diagnostics, Quality Assurance and Confidence

MODIS Data "Collections"
Each time, we re-process back to beginning of mission



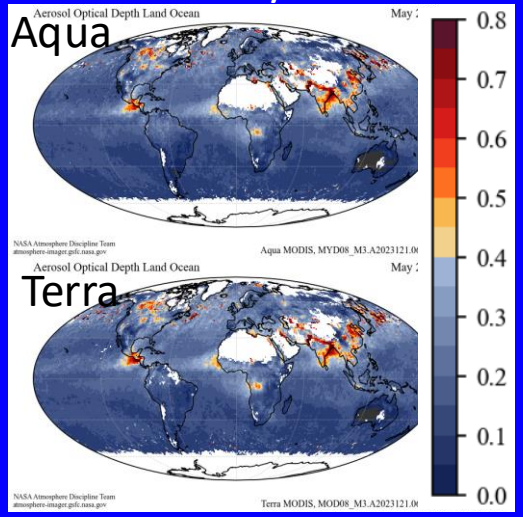
- C001: Initial algorithms at Terra launch
- C003: Provisional for both Terra and Aqua
- C004: First significant "validation" (2003)
- C005: Overhaul of algorithm (2005)
- C051: Some calibration and bug fix (2008)
- C006: Major upgrades to science (2013)
- C061: updates to the inputs/calibration. (2017)

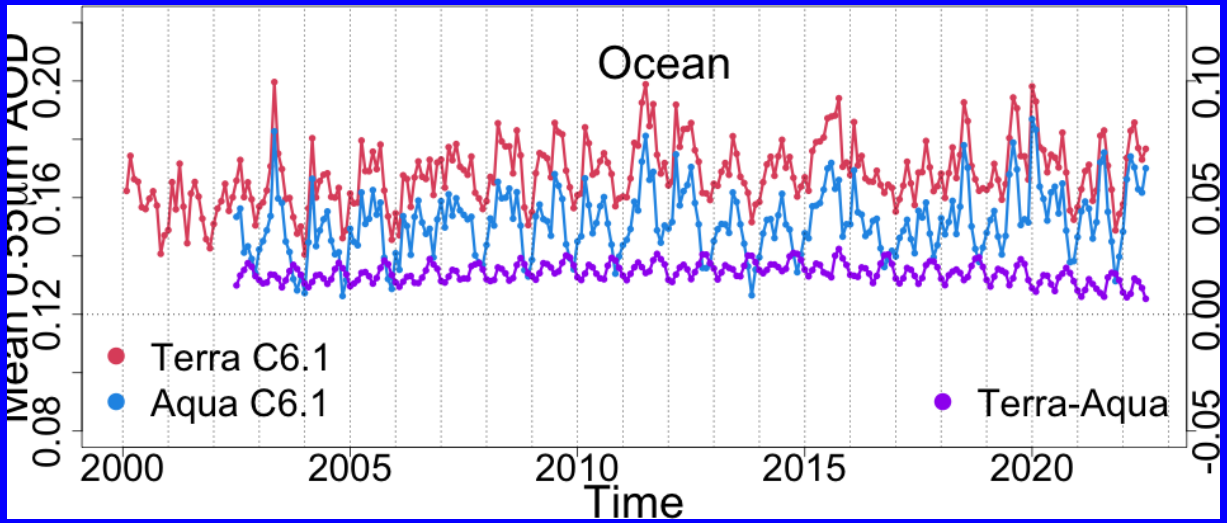
C007: L1B, Science, formats!: MID 2026???

- Upgrades to science/algorithm, Level 1B/calibration and new file formats.
- Maybe last "collection" before Terra and Aqua end in 2027.
- Hopefully, at least one more (a C071?) – pending funding support and NASA direction.

20+ years of MODIS: Terra vs Aqua time series (with C6.1)

AOD: May 2023

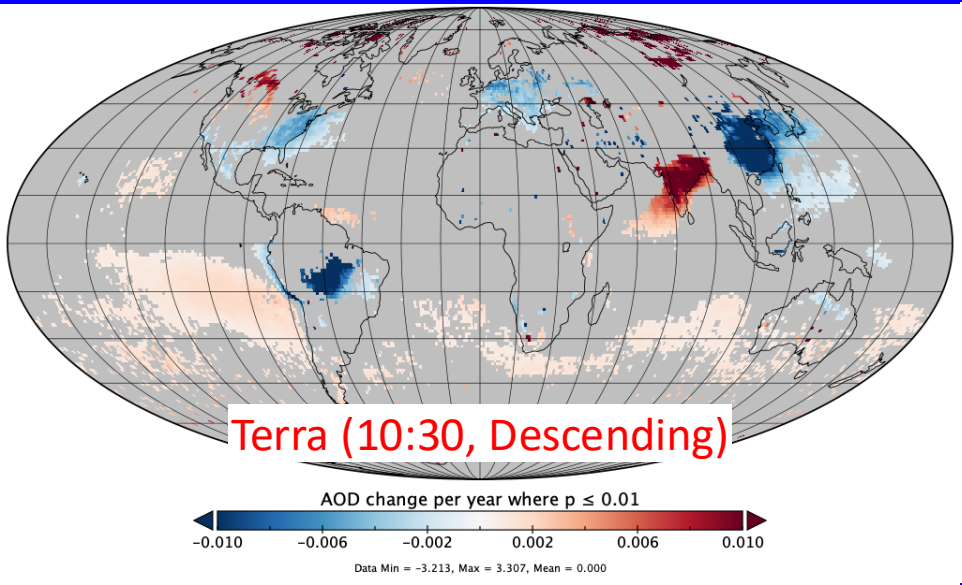


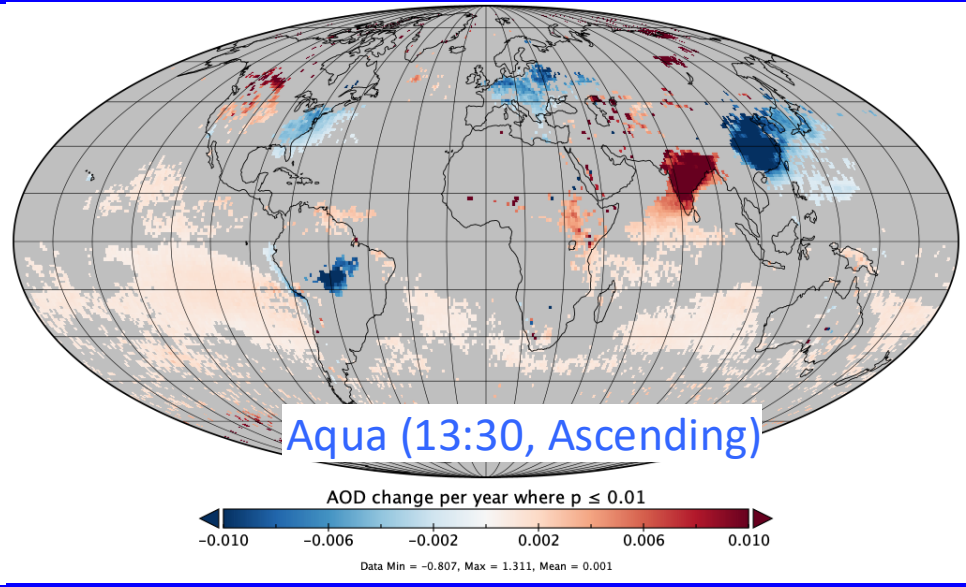


- With same Collection 6.1 algorithm, **no visual difference between Terra and Aqua**
- Terra offset high compared to Aqua by about 0.015.
- Yet, both within expected uncertainties
- Small calibration adjustments of 2% or less might help, but requires doing all wavelength bands and maybe also time-dependence

1° trends: Terra and Aqua agree!

AOD over 20 years. July 2002 – July 2022 (drifts not large yet)





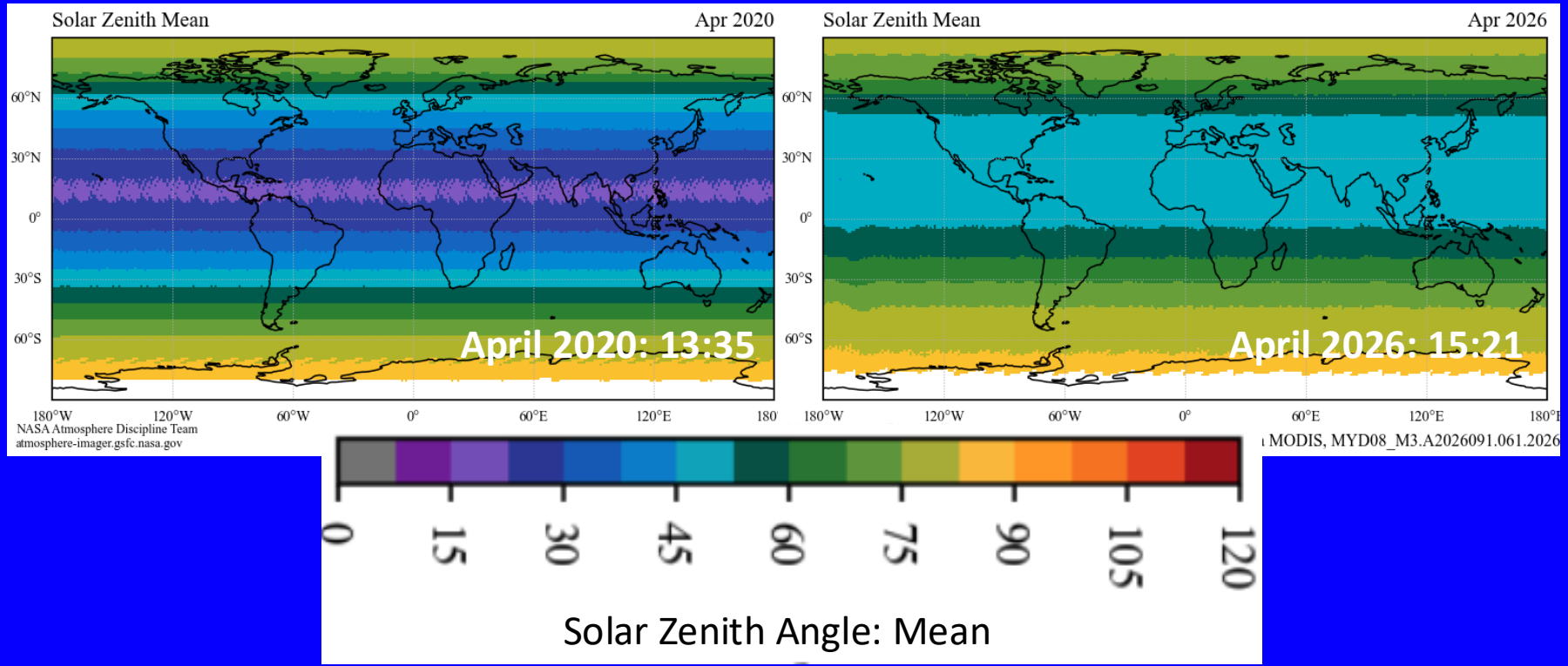
Slope of the linear regression for each 1°×1° grid cell (plotted where p ≤ 0.01)

- **Terra and Aqua agree on regions that show significant increase or decrease in AOD over time!**
- **Note1:** simple linear regression has limitations, and temporal autocorrelation may make these results "overconfident" where month-to-month progression gives the illusion of a trend
- **Note 2:** However, seasonal trends (e.g. Winter, Spring, Summer and Fall) each show consistency too.
- **Note 3:** After 2022, Terra and Aqua are drifting in orbits, so becoming unstable for longer trends.
- **Note 4:** All over-land and near-coastline trends fit expectation. **Why the southern hemisphere ocean trends?**

MODIS

- Currently, data are Collection 61 (C61)
- Towards "Collection 7" (C007)
  - Level 2: Modernize to NetCDF Climate and Forecast file format and metadata conventions
  - Updated L1B calibration, cloud masking, and science
  - Level 3: Looks much as does now (e.g. 1° x 1° grids at daily, 8 day and monthly).
  - Continued validation and documentation
  - Joint with Deep Blue: Deep Blue now does also over oceans
- "legacy" as MODIS missions (both Terra and Aqua) end sometime in 2026)
  - How does orbital drifting (since 2022) impact long term record (e.g., sampling of clouds, high latitudes, sun angles, etc.)

Geometry “sampling” drifting for MODIS on Aqua (Valid DT retrieval when SZA < 78°)



https://atmosphere-imager.gsfc.nasa.gov/product/standard/monthly

Global Climate Observing System (GCOS) requirements for **Aerosol Optical Depth (AOD)** climate data record (CDR):

Target metric	Target
Horizontal Resolution	5-10 km, globally
Accuracy	MAX(0.03 or 10%)
Stability / bias	<0.01 / decade
Time Length	**30+ years**
Temporal Resolution	**4 h**

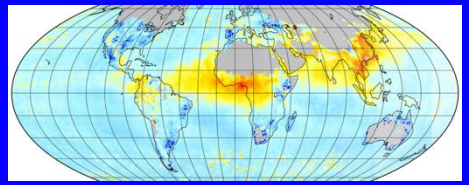
} MODIS data record

} **extend** and **expand** MODIS data record

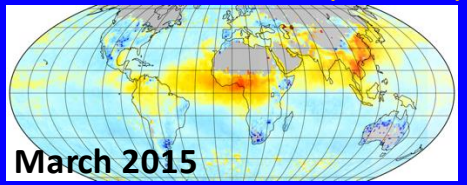
Extend record with VIIRS (Visible-Near Infrared Radiometer Suite)

2000 ← MODIS → 2026

MODIS on Aqua (c. 2002)

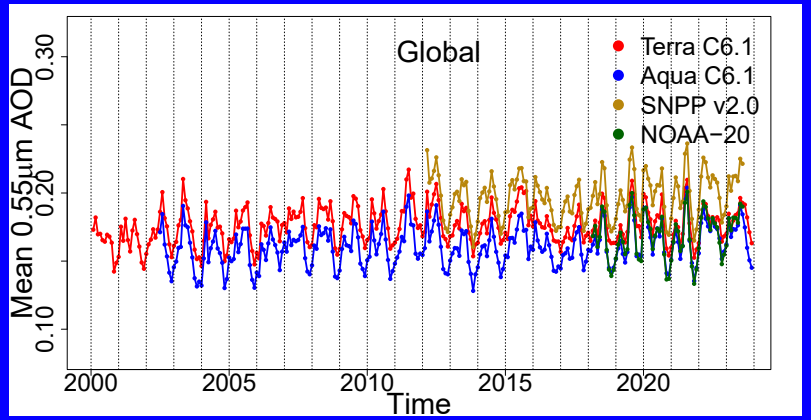


VIIRS on Suomi-NPP (c. 2011)



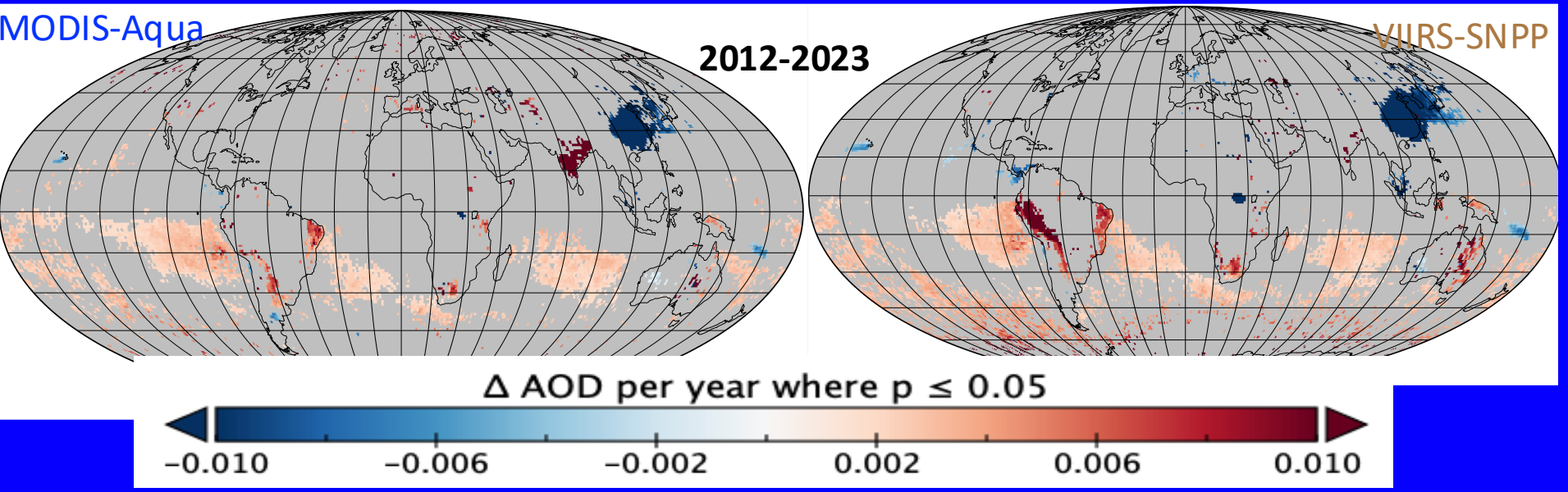
2011 ← VIIRS → 2030+

- With MODIS ending before 30 years, we need continuity provided by similar instrument = VIIRS. Ported DT algorithm from MODIS to VIIRS
- Multiple VIIRS in orbit. VIIRS V2.0 products agree with MODIS C6.1 to ±0.02 in AOD units.
- Additional VIIRS sensors to launch NOAA's JPSS4/3 into at least the late 2030s, thus satisfying the multi-decadal needs of GCOS.



Sawyer et al., 2025 (VIIRS V2.0)

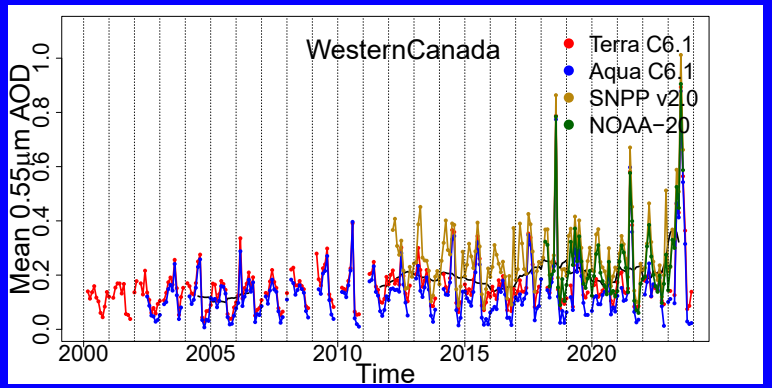
Consistency of Dark Target AOD 11-Year Trends (SNPP vs Aqua):

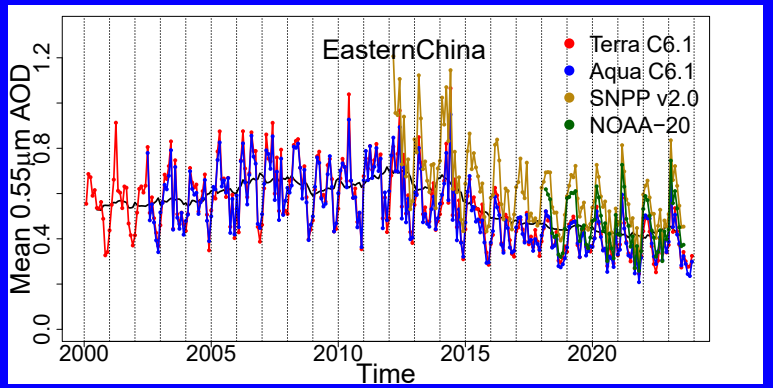


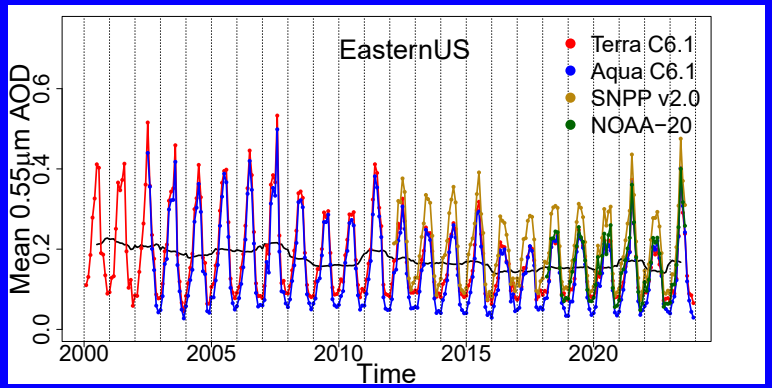
Slope of the linear regression where p ≤ 0.01, but only 10 years from 2012-2022.

- For 10-year record, half as much data = fewer grid cells meet a given significance threshold, but generally sharper slopes where they do
- Some places, the 10-year trends may be different than 20-year trends.
- Overall, SNPP sees the same world as Terra / Aqua (except for southern midlatitude ocean?)

Regional trends (picking some 10° x 10° boxes)

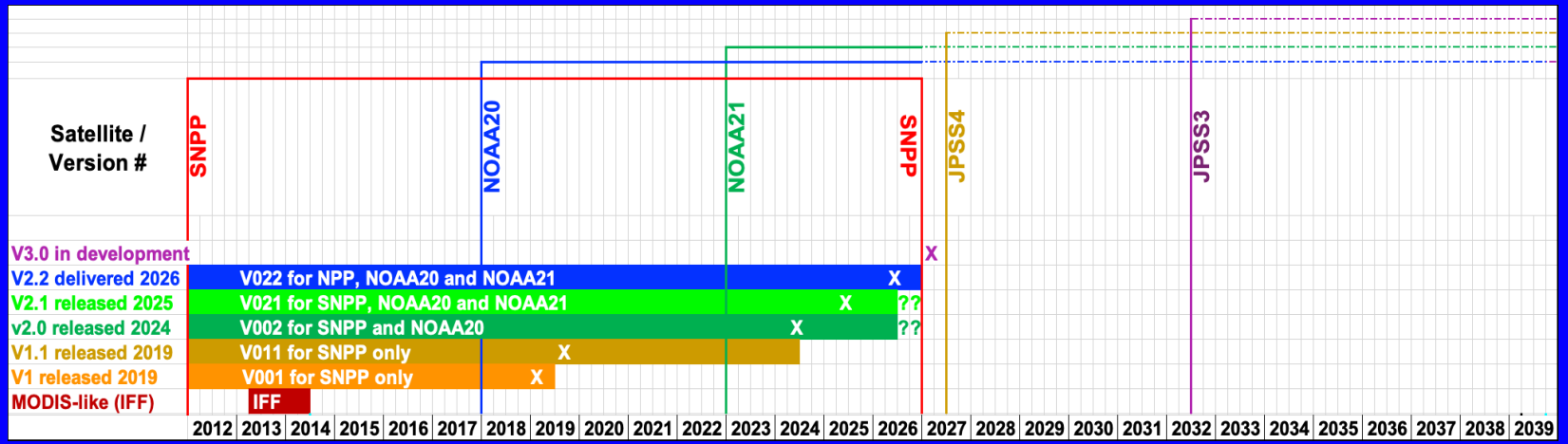






- Wildfires in western Canada drive variability. Autumn/winter flat.
- Reductions seen in Eastern U.S. due to policy regarding emissions. But no trend during SNPP lifetime. Spike in 2021 due to fires
- Coherent interannual change in eastern China, strong decrease during SNPP period.

VIIRS "Versions"



- MODIS-like (IFF): Intermediate File Format
- V1: Initial delivery
- V1.1: Fixing a bowtie-correction issue
- V2.0: Adds NOAA20, many updates
- V2.1: Adds NOAA21, cross-calibration, etc.
- **V2.2: Adds coastal retrieval, mitigates impact of new cloud mask (mid 2026)**

V3.0: Above cloud aerosol retrieval: TBD

- Assuming end of SNPP record
- TBD whether funding to work on JPSS4 and JPSS3
- TBD whether can use to reprocess SNPP
- TBD continued operation of NOAA20 and NOAA21

MODIS C6.1 → C7 : VIIRS V2.0 → V2.1 → V2.2

Algorithm improvements common to both streams

- High-resolution 3x3 red-band cloud masking over ocean (250 m for MODIS, 375 I-band for VIIRS)
- Log-fit to lookup table when AOD < 0.2 (disallows negative AOD)
- Detect (and retrieve) dust using non-spherical model over ocean
- Update formulas for Surface Reflectance Parameterization (SRP) over land that estimates Blue, Red & SWIR2.½ bands via NDVI, Urban Percentage & Angles. Now same formulas for both MODIS and VIIRS.
- Uses same “ancillary” GEOS-IT meteorological re-analyses.
- Same ”Yori” (University of Wisconsin) aggregation for Level 3 product
- Bug fixes as needed

MODIS C6.1 → C7 : VIIRS V2.0 → V2.1 → V2.2

Algorithm updates that are separate

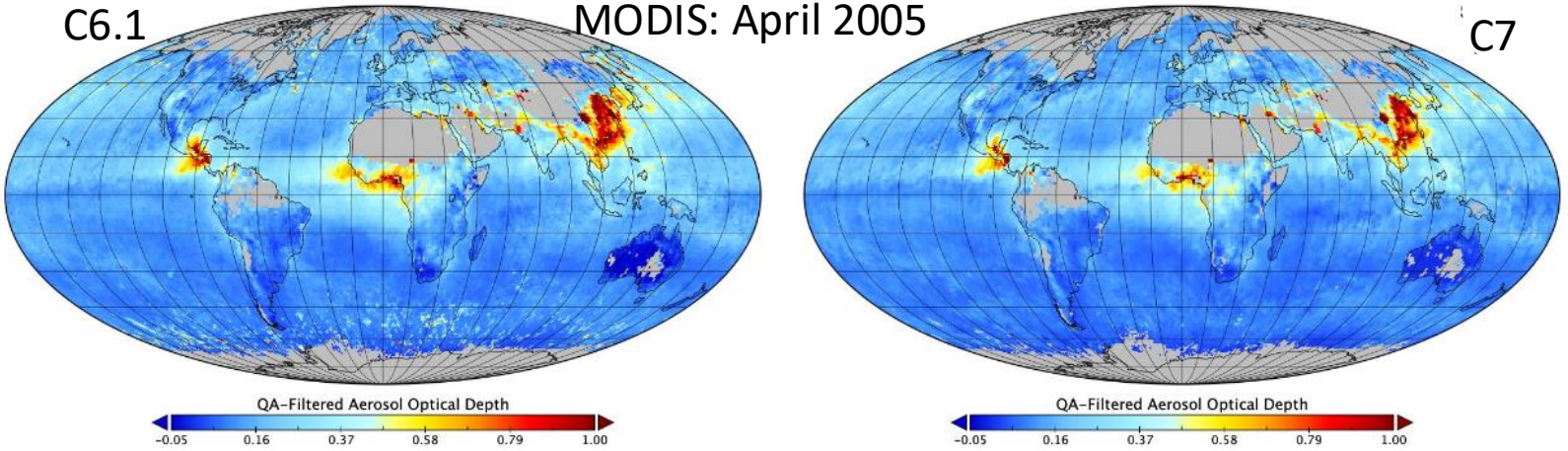
MODIS C6.1 → C7 (MxD04_L2)

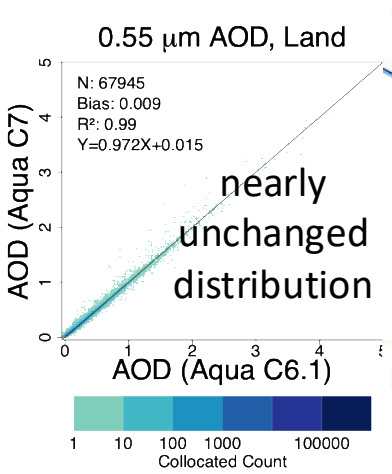
- Products are in NetCDF4 (to match VIIRS)
- DT-only SDS names, groups, and metadata are simplified (to match VIIRS)
- Reads in "entire" granule for cloud and other masking (to match VIIRS)
- New "call back" to retrieve heavy surface-level aerosol over eastern Asia
- C7 L1B files include "solar eclipse flag"
- Uses C7 Wisconsin Cloud mask (3 tests for clouds + other tests for Dust Detection
- Deep Blue (DB) retrievals and DB/DT "merge" remain in same MxD04_L2 file

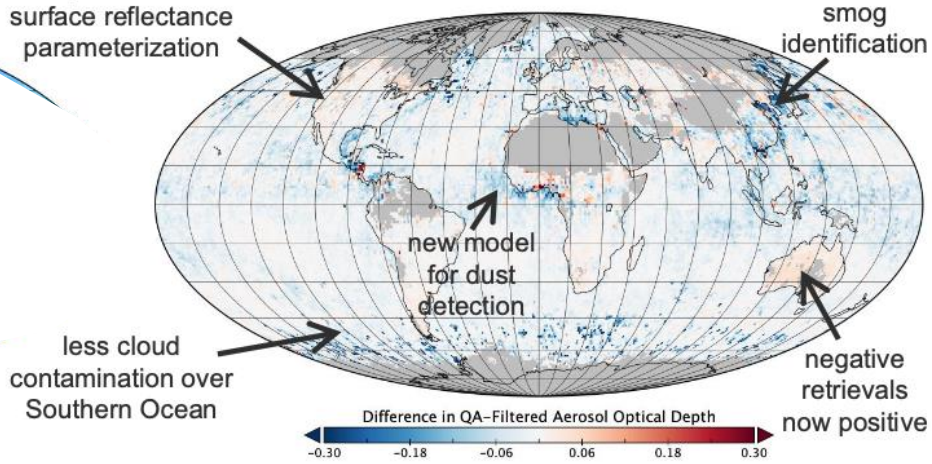
VIIRS V2.0 → V2.1 → V2.2 (AERDT_L2)

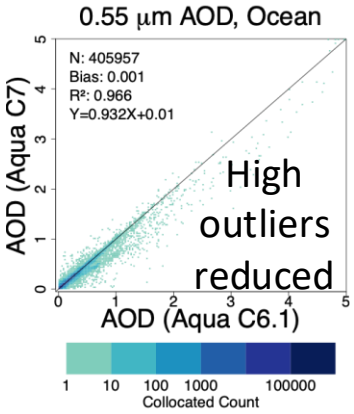
- SDS names exactly match MODIS C7
- Does not need a call-back to retrieve heavy surface-level aerosol over Asia
- Uses updated Wisconsin Continuity Cloud Mask
- Fixes QA-Filtering bug
- Introduces X-calibration between V2.0 and V2.1.
- Deep Blue (DB) retrievals remain in separate file (AERDB) and no DT/DB merge provided by the aerosol teams.

Overall “Algorithm Updates”









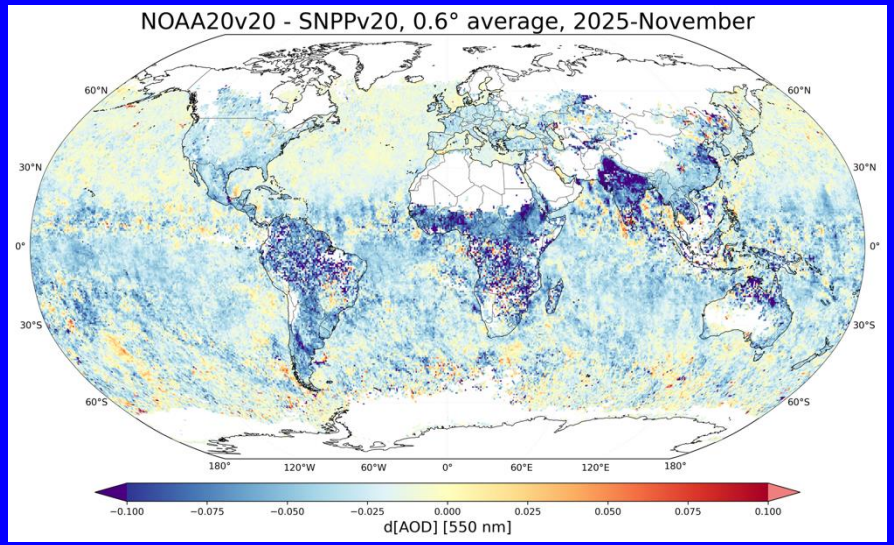
X-calibration Coefficients in DT algorithm (MODIS-Aqua → VIIRS). Not applied to MODIS

Band Pair [nm]				X-calibration Coefficient [1] Lyapustin et al. (2023), [2] Meyer et al. (2020), [3] Wang et al. (AGU 2024)				
				[1]	[2]	[1]	[2]	[3]
VIIRS		MODIS		AQUA/SNPP	AQUA/SNPP	AQUA/N20	AQUA/N20	AQUA/N21
M3	478 - 488	B3	459 – 479	**0.98**	-	**1.03**	-	1.06
M4	545 - 565	B4	545 – 565	**0.98**	-	**1.04**	-	1.08
M5	662 - 682	B1	620 – 670	**0.98**	0.95	**1.02**	1.00	1.02
M7	846 - 885	B2	841 – 876	**0.97**	0.97	**1.01**	1.01	1.02
M8	1230 - 1250	B5	1230 – 1250	-	**0.99**	-	**1.02**	1.04
M10	1580 - 1640	B6	1628 – 1652	-	**0.98**	-	**1.02**	1.07
M11	2225 - 2275	B7	2105 – 2155	-	**0.97**	-	**0.99**	1.00

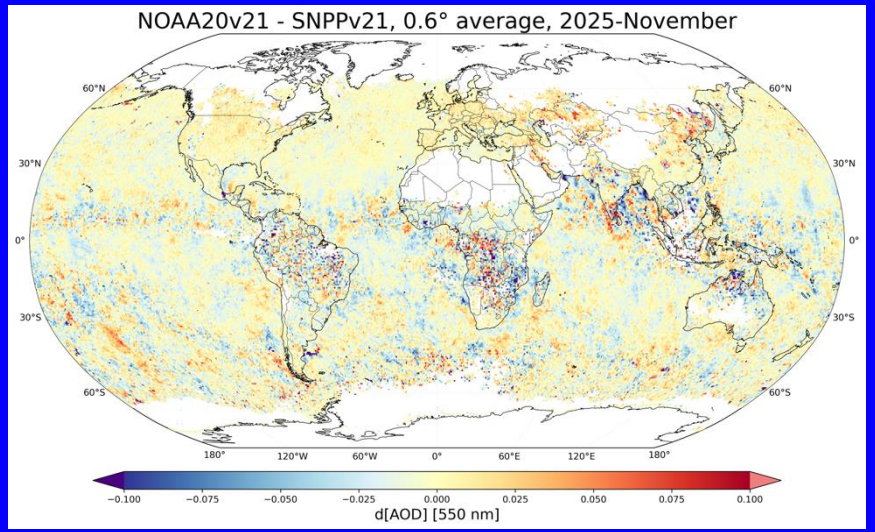
Courtesy Mijin Kim

X-Cal applied reduces overall bias
NOAA20 vs SNPP

V2.0 N20-SNPP (Before X-calibration)



V2.1 N20-SNPP (After X-calibration)



Overall offsets much closer to zero!
Differences are primarily due to cloud positions?

Courtesy Mijin Kim

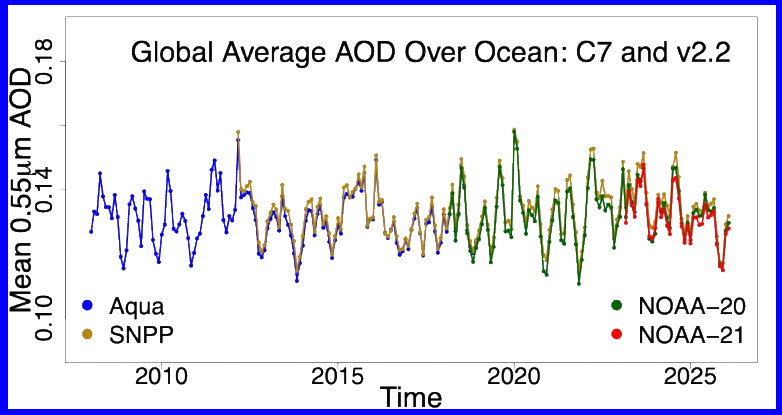
Initial comparison of MODIS C7 and VIIRS V2.2

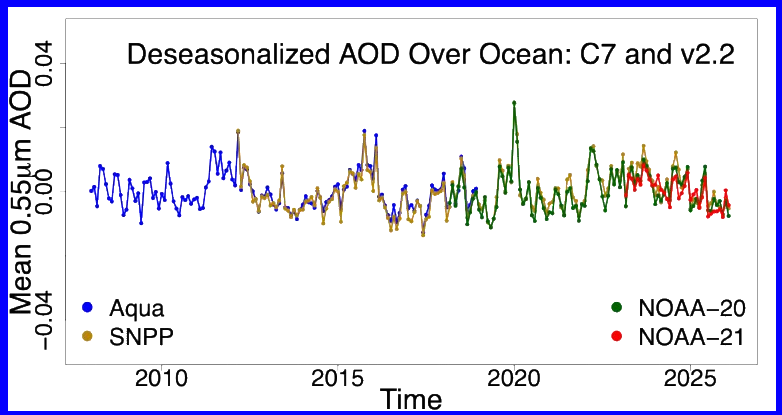
(Note only 2008-2018 data processed for MODIS)

Monthly Mean AOD

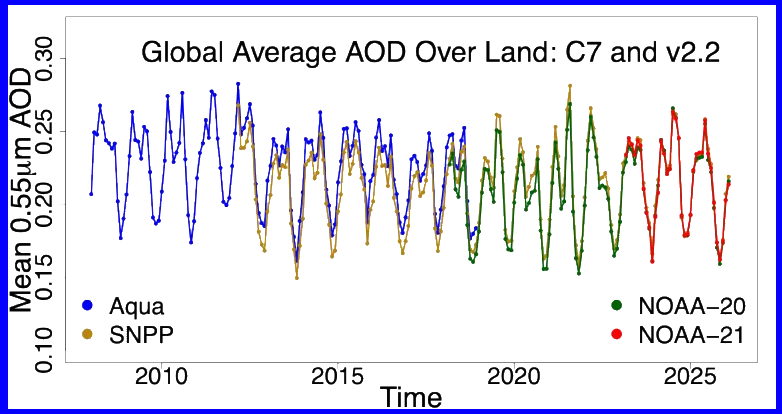
De – Seasonalized

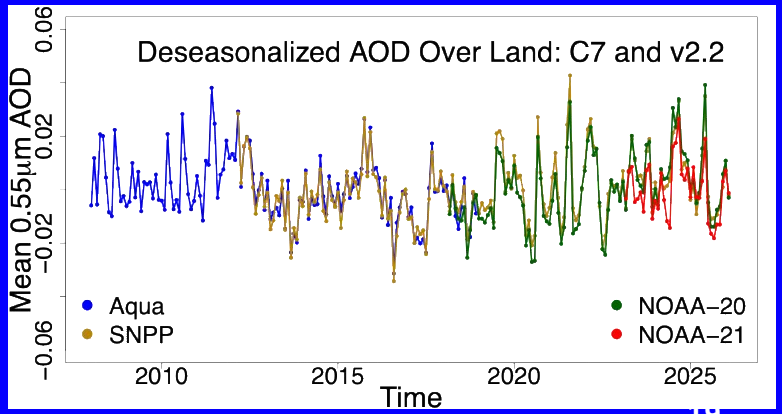
Ocean



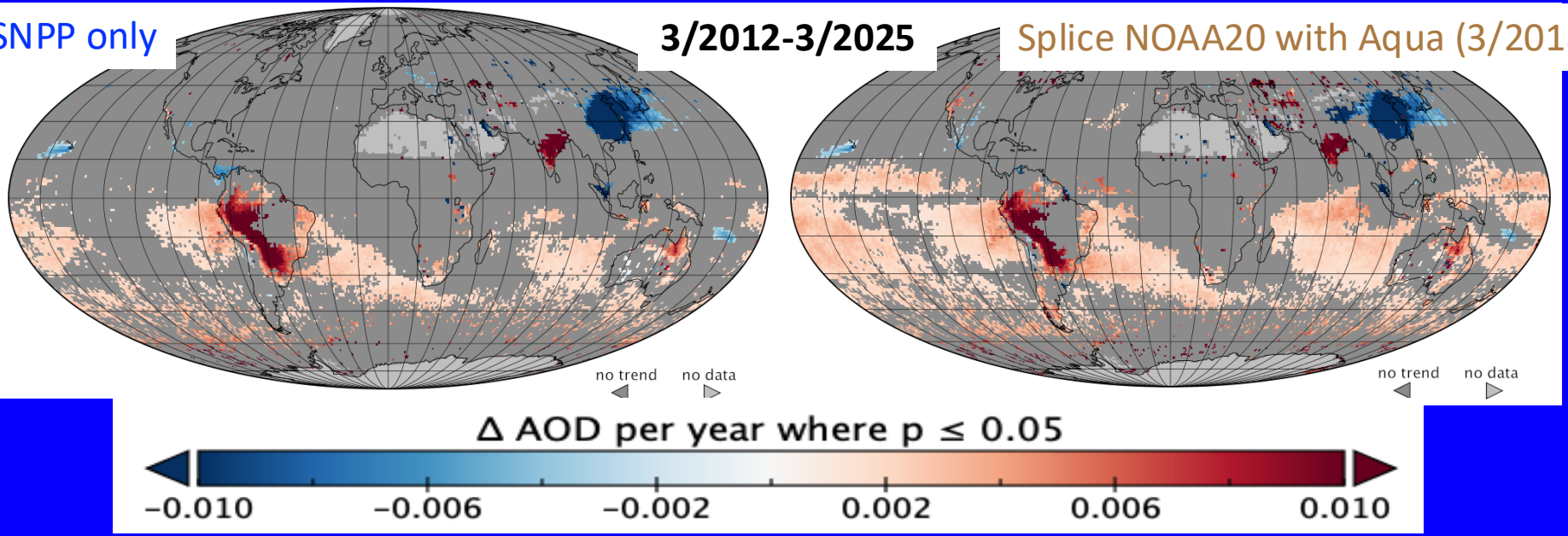


Land





Consistency of Dark Target AOD 17-Year Trends (2012 - 2025)

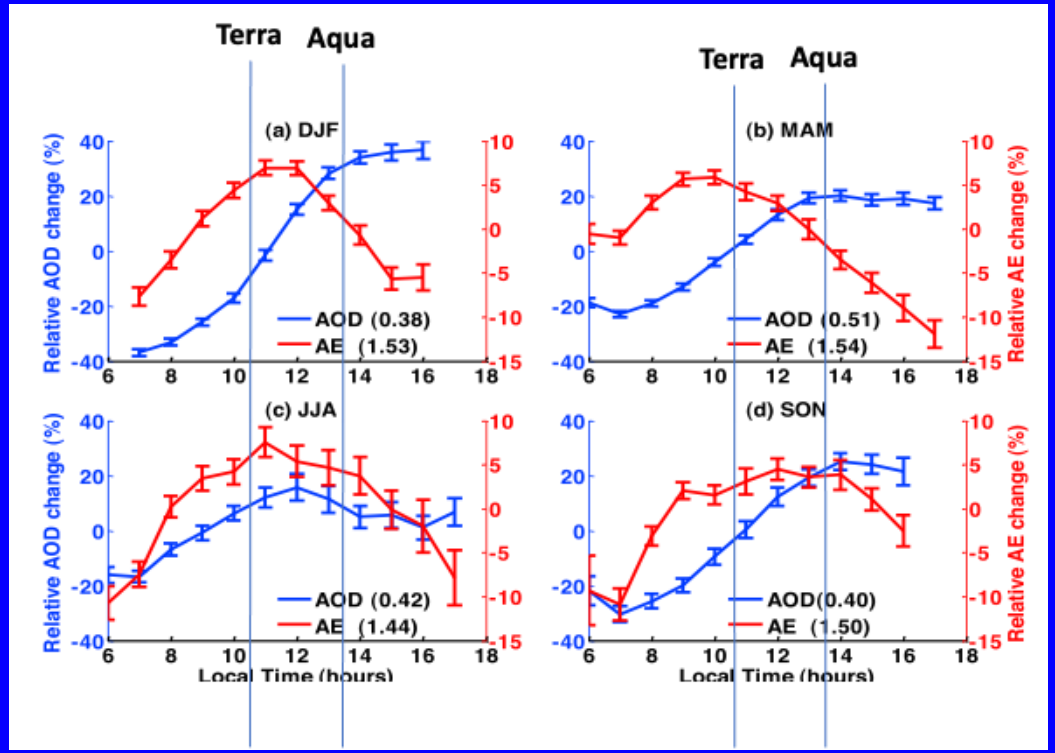


Slope of the linear regression where p ≤ 0.01.

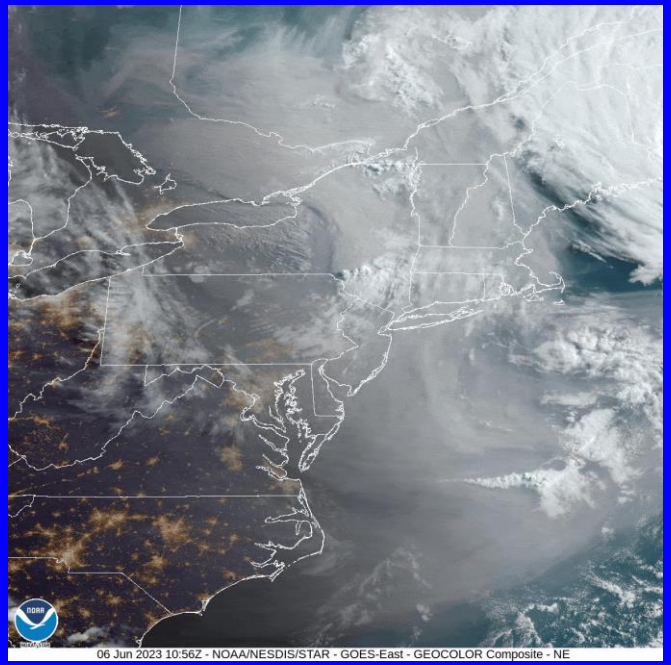
- They are truly seeing the same world!
- Still curious about the southern ocean?? Next steps look into higher complex products (e.g. fine mode fraction, trends in cloud fraction, etc. seasonal cycles, etc.) . Ideas here from CERES team?
- Awaiting further MODIS “Tier” processing to go back to 2002.

MODIS and VIIRS are in Low-Earth-Orbit (LEO)

But LEO cannot observe diurnal or rapid aerosol changes!



Smoke from GOES-East

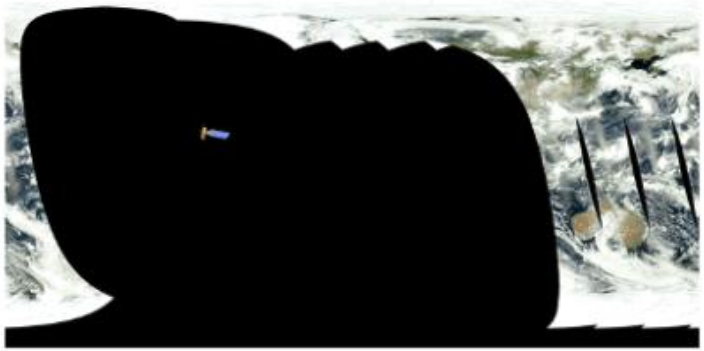


From: Zhang, Y., Yu, H., Eck, T. F., et al, (2012). Aerosol daytime variations over North and South America derived from multiyear AERONET measurements, *J. Geophysical Research*.

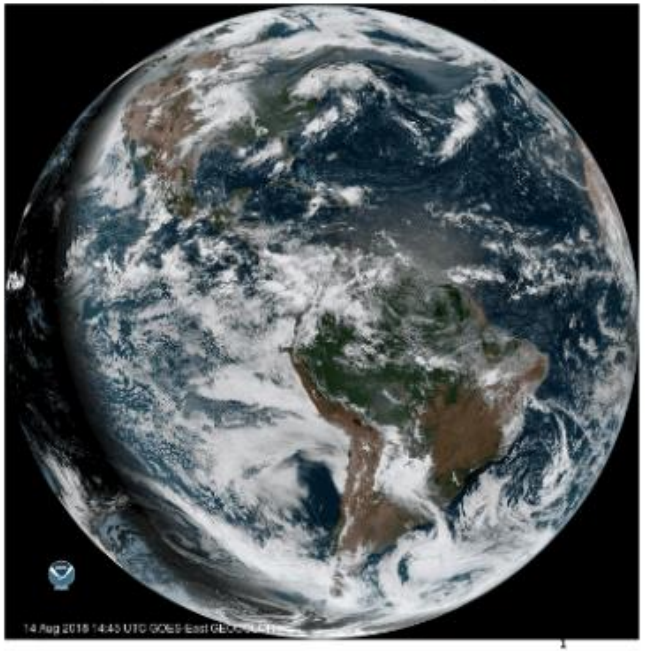
Expand! DT Algorithm can be applied to GEO sensors!

Low Earth Orbit (LEO) & Geostationary Satellites Orbiting the Earth

Imager in LEO Orbit (MODIS on Aqua)



Imager in GEO Orbit (ABI on GOES-East)

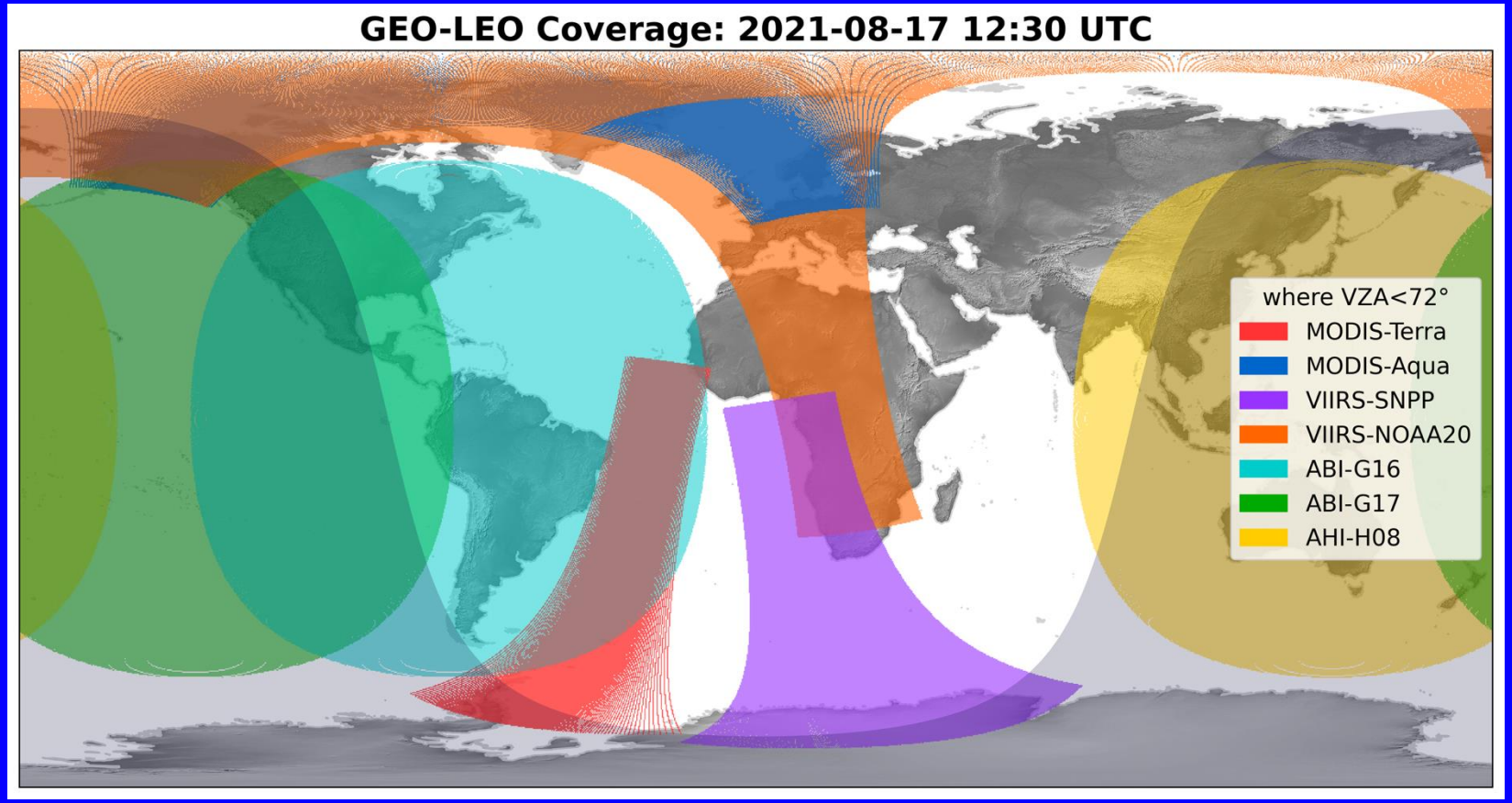


LEO takes a full day to orbit the globe
GEO observes one place all day

Animations from: https://arset.gsfc.nasa.gov

Animations from: https://arset.gsfc.nasa.gov

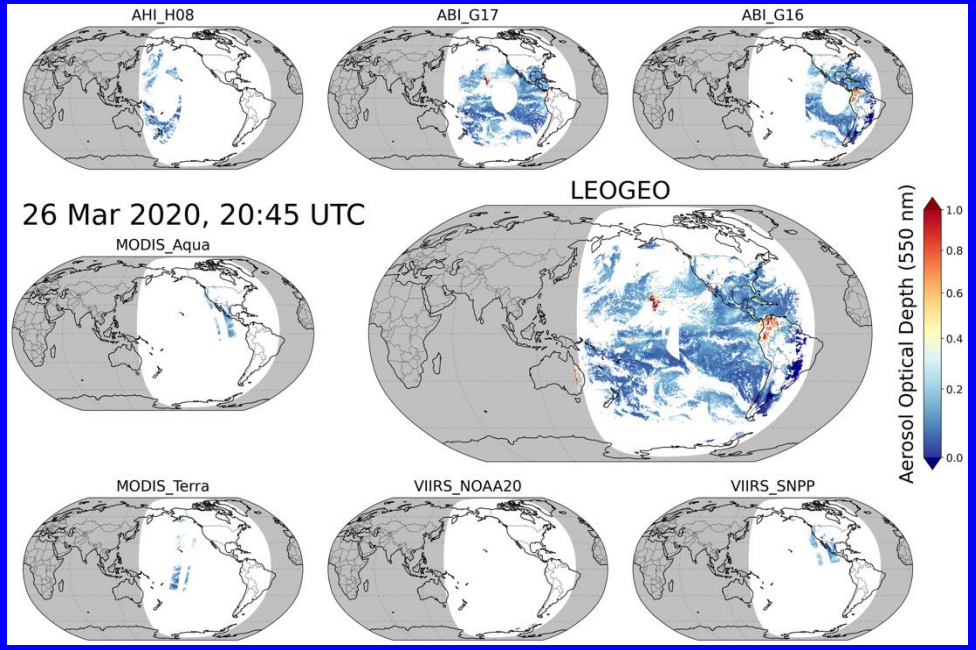
DT can be applied to many sensors at same time!



XAERDT: A joint GEO-LEO aerosol product

A NASA "MeASUREs" (Making Earth Data Useful -2017) project

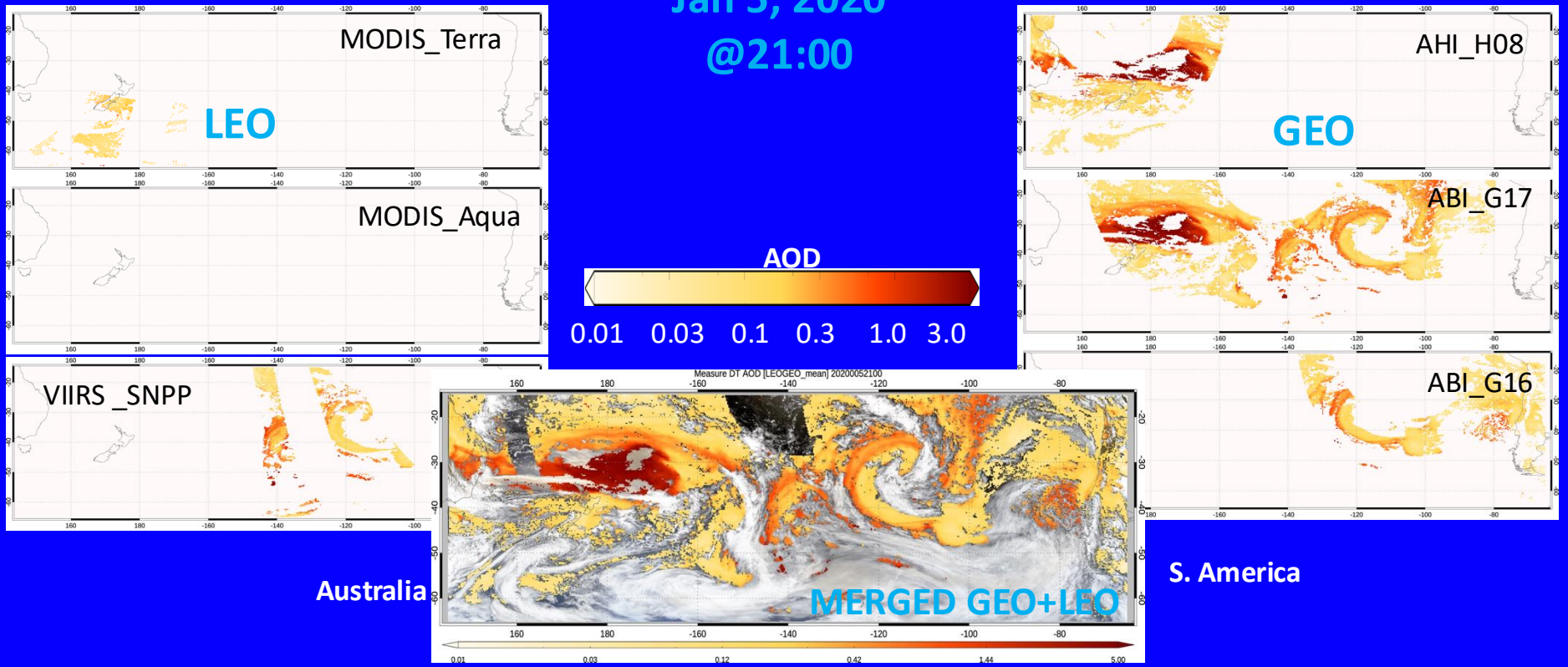
- **Uses DT-'package'**
- **Level 2: 7 Individual sensors**
  - **MODIS on Terra & Aqua**
  - **VIIRS on S-NPP & NOAA20**
  - **ABI on GOES-East & GOES-West**
  - **AHI on Himawari (10 km)**
  - **AODs, reflectance, QA**
- **Level 3:**
  - **30-minute intervals**
  - **Global 0.25° x 0.25° grid**
  - **Merge: Combines all sensors**



Level 2 and Level 3 data for 2019-2022 available!

https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/applications/geoleo/

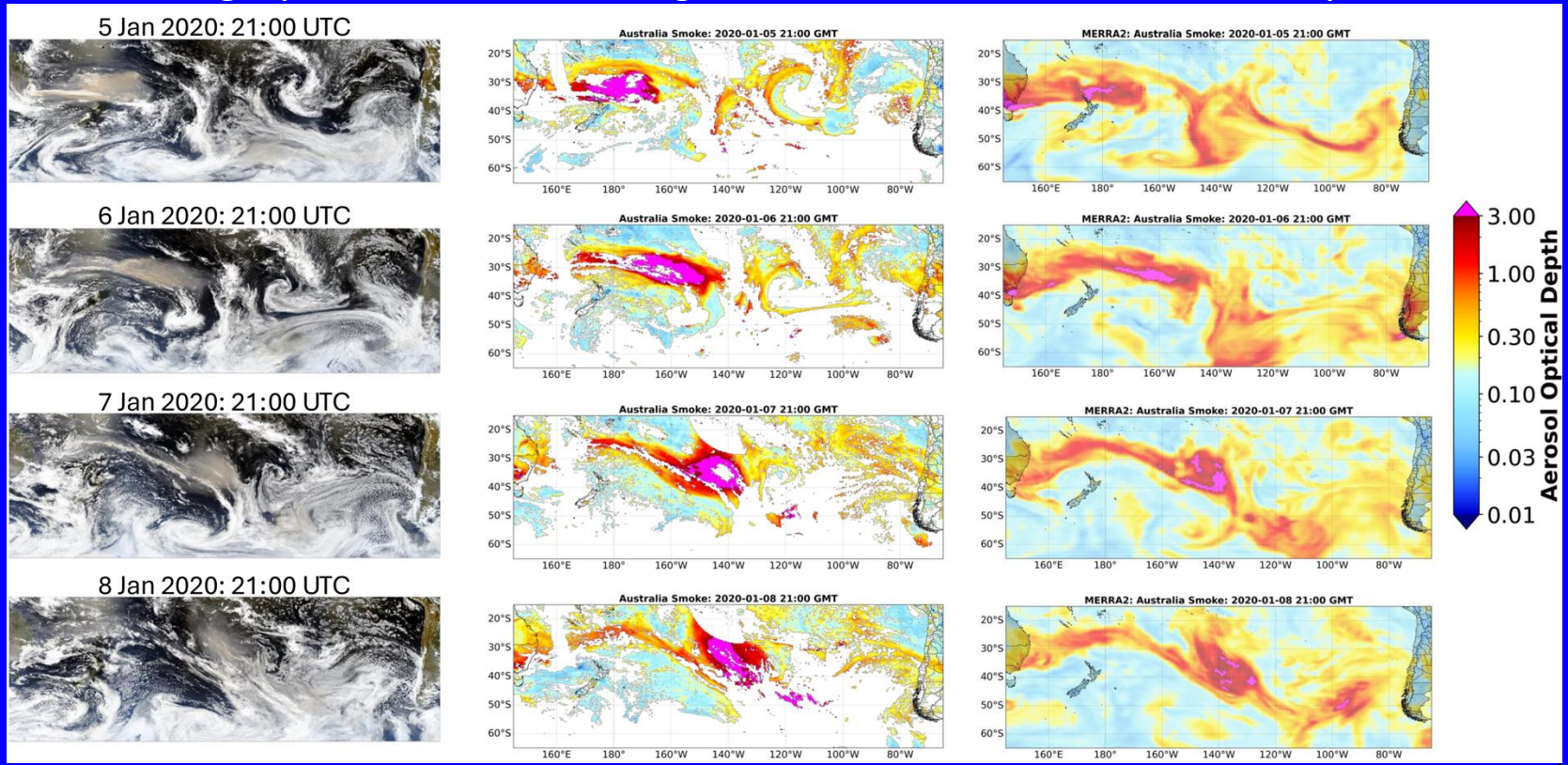
Australia bushfires: Smoke travels to South America!



Note: merged is overplotted on RGB blended from the three GEO. Note how sensors complement each other to fill in some holes. However, there still a bit of missing data over "glint".

Can be compared with models or analyses...

Snapshots at 21:00 UTC: Jan 5, 2020 – Jan 8, 2020



Level 2 (all sensors) and Level 3 merge products for 2019-2022

EARTHDATA Other DAACs Feedback

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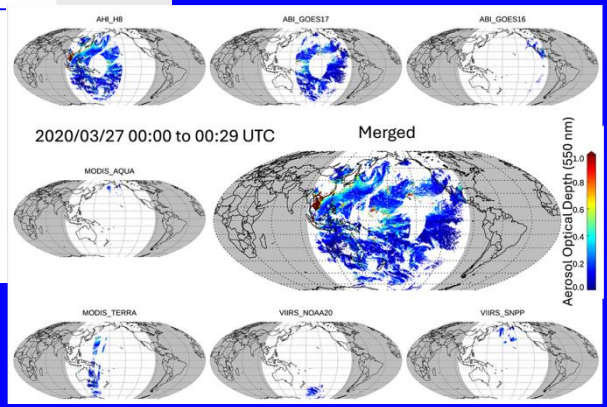
Home › Alerts & Issues › GEO-LEO Dark Target Aerosol data products suite available

GEO-LEO Dark Target Aerosol data products suite available

Platform	G16,G17,H8,SNPP,N20,Terra,Aqua
Instrument	ABI,AVI,VIIRS,MODIS
Source	MODAPS, LAADS
Issue	Alert
Last Updated	2024-04-03 15:10:00
Start	2024-04-03 15:00:00
End	2024-07-01 00:00:00
Description	NASA's Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center is pleased to announce the release of the GEO-LEO Dark Target Aerosol data products suite. The Geostationary Earth Orbit (GEO) - Low-Earth Orbit (LEO) Dark Target Aerosol is a suite of global aerosol products both from geostationary and low-earth orbit satellites for a three-year timespan between January 2019 and December 2022 that shows aerosol movement across the globe every ten minutes.

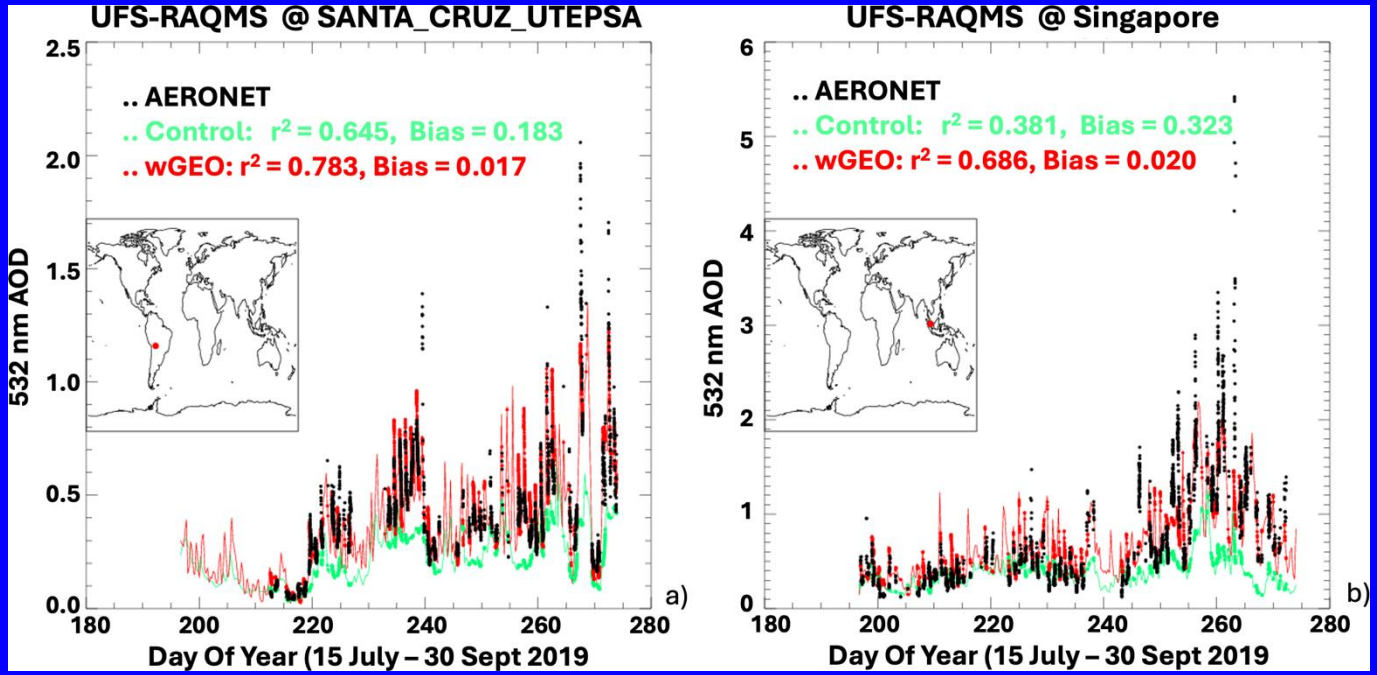
https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/applications/geoleo/

Link to LAADS_DAAC "Webinar"



Final paper in accepted for JGR-atmospheres
https://doi.org/10.1029/2025JD046107

Data Assimilation Example

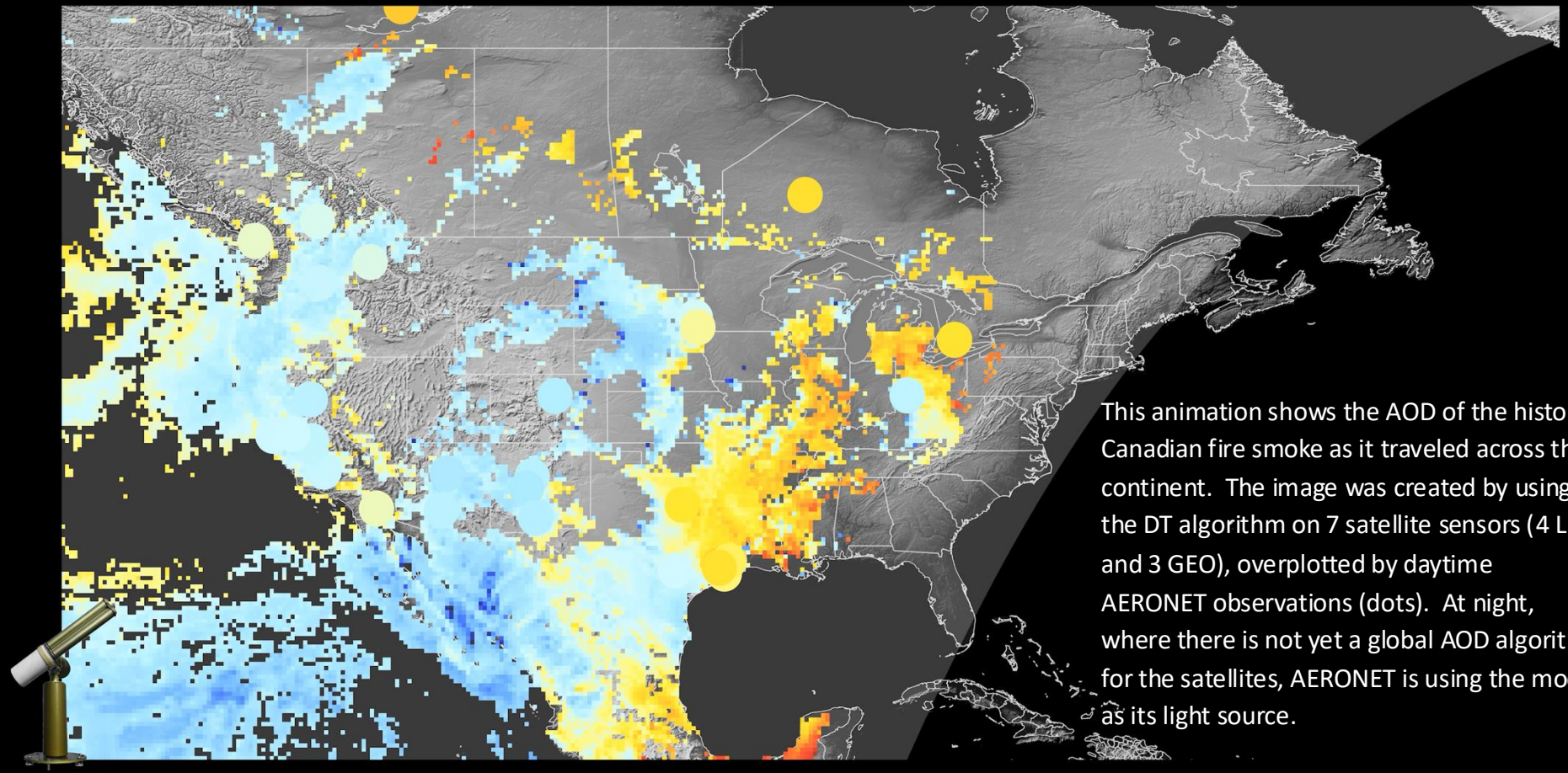


- Summer-Fall 2019
- CAMP2Ex time period
- UFS-RAQMS
- Assimilation with AOD
- Two sites near Tropics
- Most improvement for cases of high AOD near tropics

From Brad Pierce and group, University of Wisconsin

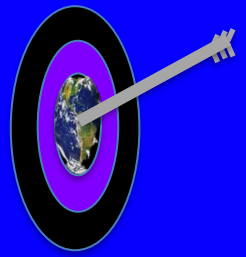
Smoke from Canadian Fires Enters NE United States (June 2023)

Aerosol Properties from 7 Satellite sensors + AERONET



This animation shows the AOD of the historic Canadian fire smoke as it traveled across the continent. The image was created by using the DT algorithm on 7 satellite sensors (4 LEO and 3 GEO), overplotted by daytime AERONET observations (dots). At night, where there is not yet a global AOD algorithm for the satellites, AERONET is using the moon as its light source.

Summary (1)



Currently, Dark Target retrieval algorithm works on

- **2 LEO sensors (MODIS, VIIRS)**
  - **On 5 current satellites (Terra, Aqua, Suomi-NPP, NOAA20, NOAA21)**
  - **Provides *global* coverage on near daily basis.**
  - **20+ year history of aerosol optical depth and other aerosol properties**
  - **products include a Near Real Time version**

- **2 GEO sensors (ABI, AHI),**
  - **on 3 current satellites (GOES-E/W and Himarawi-8)**
  - **Also works on GOES-18, 19 and Himawari-9.**
  - **Provides *regional* coverage at high temporal resolution**
  - **Does not include a Near Real Time product**

- **Also airborne sensors like MAS, MASTER, PICARD (not shown)**

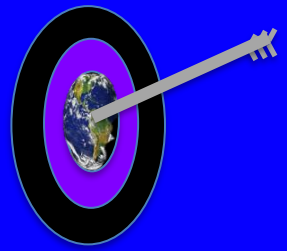
- **All L2 data includes "clear sky radiances" at product resolution**

https://darktarget.gsfc.nasa.gov

Summary

- The Dark Target (DT) aerosol retrieval algorithm is a validated, robust algorithm that be run on multiple sensors with appropriate wavelength sampling
- The current "continuity" includes MODIS C6.1 and VIIRS V2.1. The retrieved AODs are relatively consistent with each other, but overall AOD spread for given month is ±0.05.
- We have delivered codes for MODIS C7 and VIIRS V2.2 which should be released – soon???? Many improvements including upstream L1B, cloud mask, X-calibration, bug fixes, and QA filtering.
- overall MODIS vs VIIRS AOD spread is order ±0.02 in a given month. Hopefully, increased confidence in splicing datasets to achieve 30+ years.
- Further improvements to MODIS and VIIRS aerosol products and consistency are pending funding and support.
- DT applied to Geostationary sensors leads to a GEO+LEO dataset that provides direct observations of aerosol transport (magnitude/location) that makes good movies and can be used for DA applications. No pending funding and support for improvement

Conclusion



With a simple Dark Target retrieval algorithm, we are learning much about global aerosol

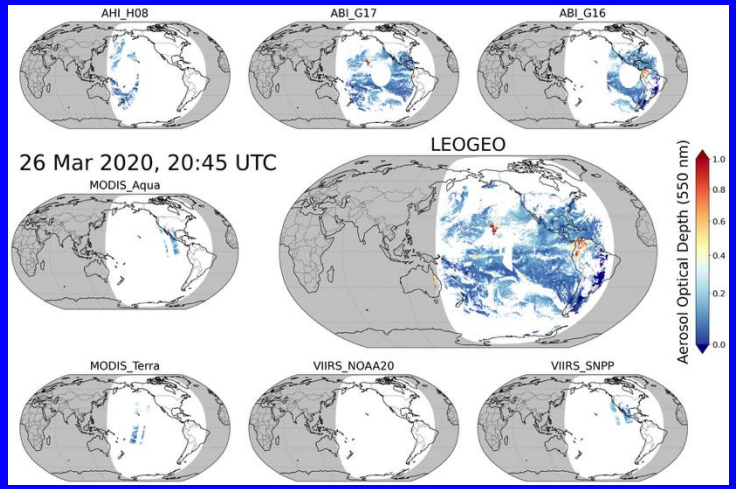
- Seasonal hot spots
- Trends
- Use for Air Quality and other applications
- Effects including air quality, climate, radiation, etc.
- Use as baseline algorithm to develop more sophisticated algorithms.

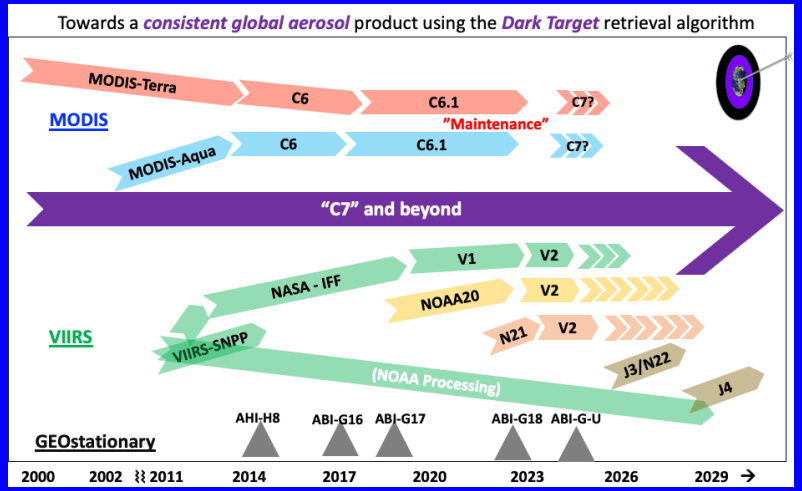
But challenges

- Homogenization of calibration
- Leveraging of funding under new agency priorities
- Use as Program of Record for future missions

Dark Target (DT) Aerosol Retrieval Project

One algorithm + many sensors = **All daylight globe**





https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/applications/geoleo/

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