

Towards (Aerosol) Retrieval Consistency and Continuity across 2 MODIS + 3 VIIRS

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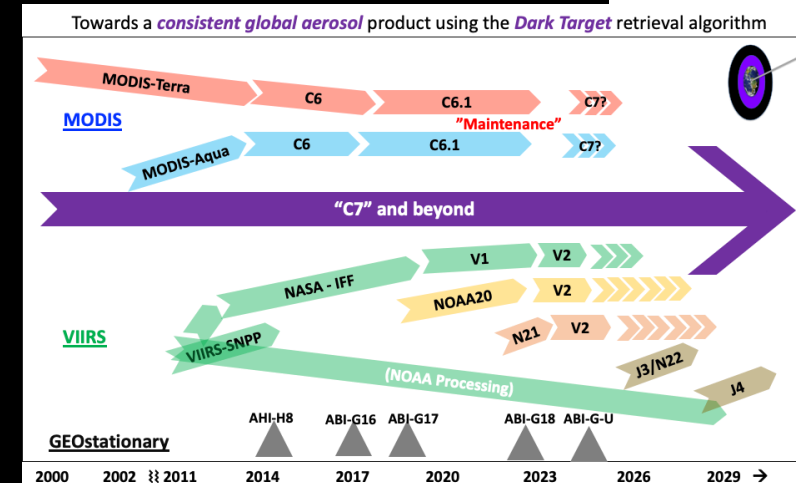
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Yingxi Shi (UMBC/GSFC)



Acknowledgements:

- MODAPS team at GSFC (MODIS processing)
- A-SIPS team at U. Wisconsin (VIIRS processing)



<https://darktarget.gsfc.nasa.gov>

(An update on GSICS presentation in March 2026)

Why do we care about aerosols?

- They affect visibility
- They affect human health and morbidity
- They enable clouds and precipitation
- They have roles in Earth's chemistry (carbon, sulfate, etc)
- They have roles in biology (e.g. transport nutrients)
- They directly and indirectly impact the radiative budget
- They are both natural and manmade
- They are inhomogeneous in space and time
- Their distributions are changing
- The science of aerosols is truly “interdisciplinary”
- **We need datasets that characterize climatology, trends and variability**

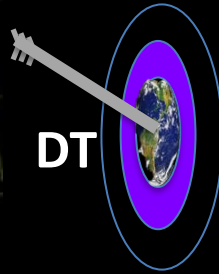
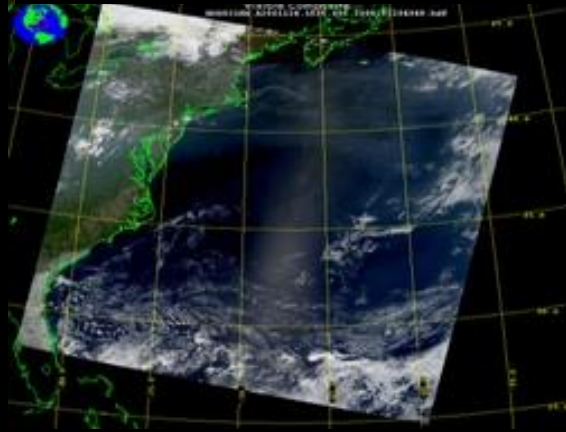
Why do we care about aerosols? (Bonus)

- They affect visibility
- They affect human health and morbidity
- They enable clouds and precipitation
- They have roles in Earth's chemistry (carbon, sulfate, etc)
- They have roles in biology (e.g. transport nutrients)
- They directly and indirectly impact the radiative budget
- They are both natural and manmade
- They are inhomogeneous in space and time
- Their distributions are changing
- The science of aerosols is truly “interdisciplinary”
- **We need datasets that characterize climatology, trends and variability**
- Their “retrieval” helps fine-tune VIS/NIR imager calibration!!!
- **Hopefully, their retrieval (in a consistent manner) helps the CERES process**

Dark Target (DT) Aerosol retrieval Algorithm

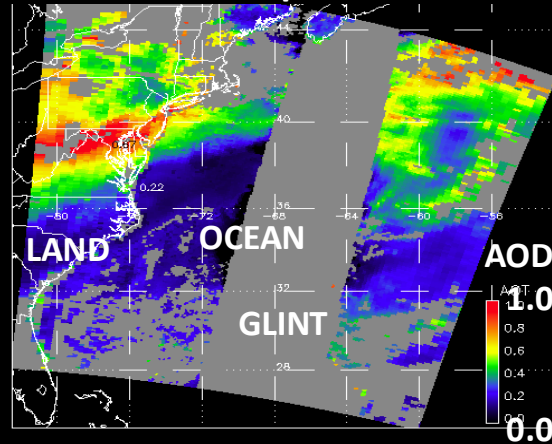
What a sensor observes

May 4, 2001; 13:25 UTC
Level 1 “reflectance”



Attributed to aerosol (AOD)

May 4, 2001; 13:25 UTC
Level 2 “product”

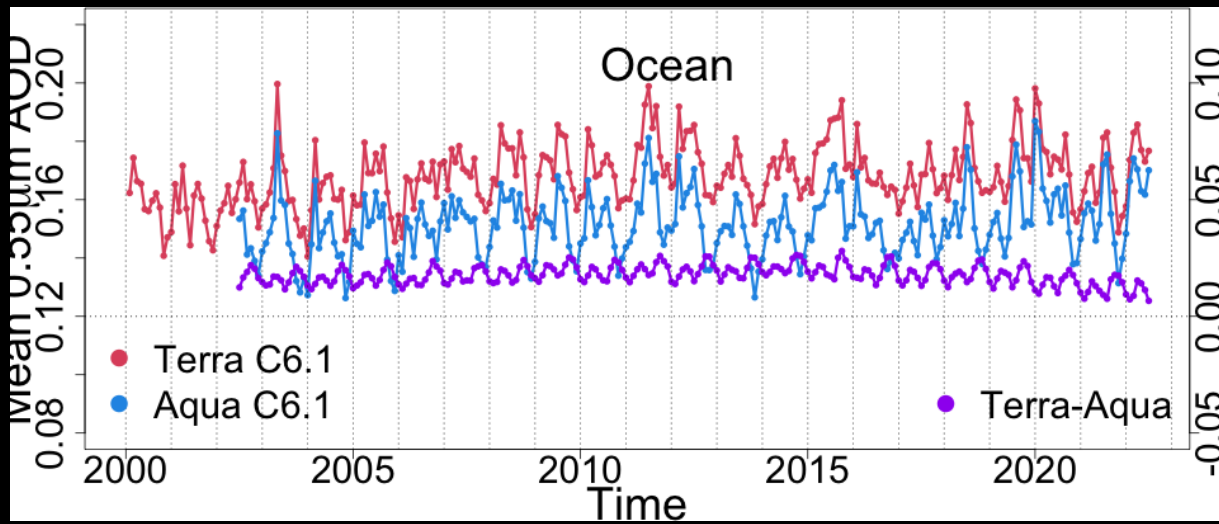
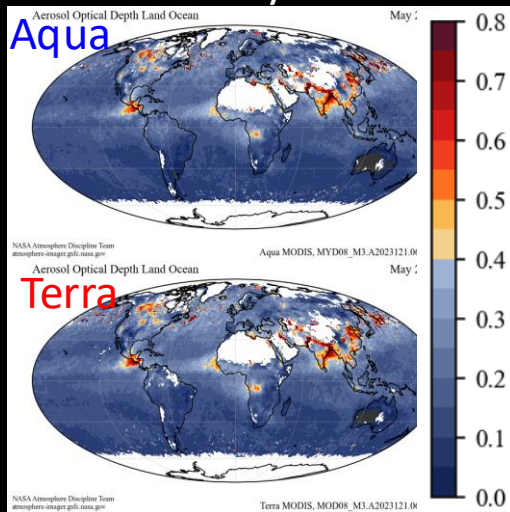


- Established by Kaufman, Tanré, Remer, et al (1997)
- Modified by Remer, Levy, Gupta, Sawyer, Shi et al (2005, 2010, 2013, 2015, 2020, etc.)

- **Requires:** Observations of spectral reflectance in 7 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

20+ years of MODIS: Terra vs Aqua time series

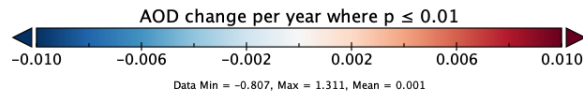
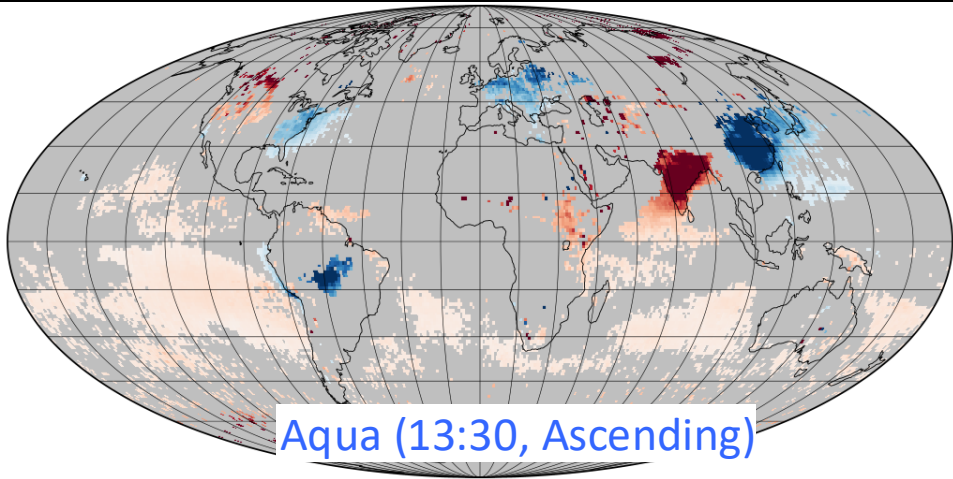
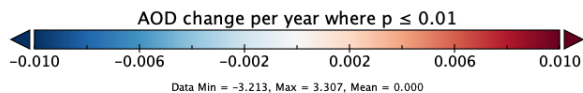
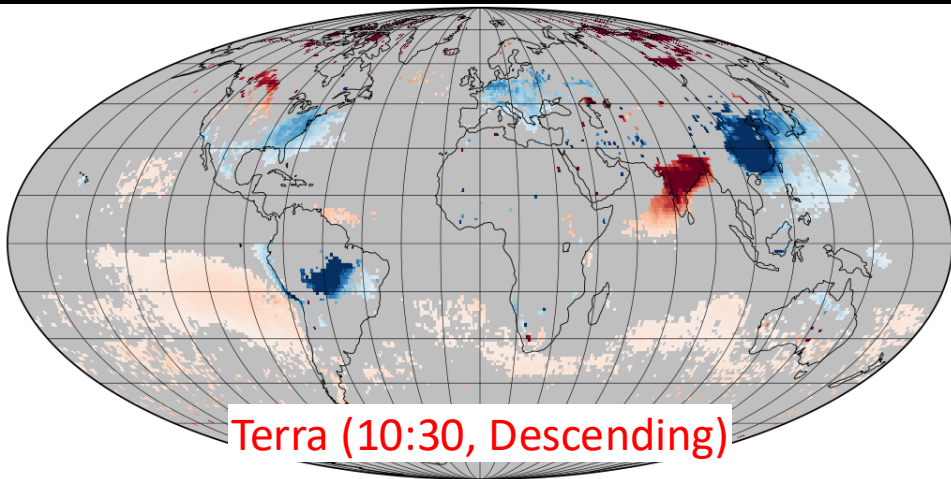
AOD: May 2023



- Collection 6.1 algorithm, **no visual difference between Terra and Aqua globes**
- Time series indicates Terra offset high compared to Aqua by about 0.015 (10-15%).
- 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 $p \leq 0.01$)

- **Terra and Aqua agree on regions that show significant increase or decrease in AOD over time!**
- **Note 1:** 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?

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** with VIIRS
EXPAND with GEO and other
platforms

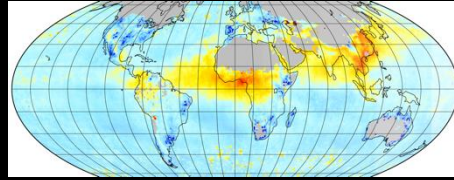
Focus on VIIRS today

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

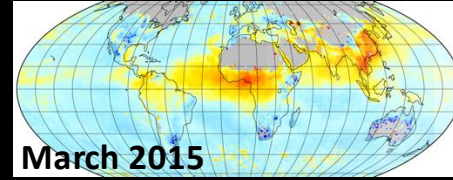


2000 ← MODIS → 2026

MODIS on Aqua (c. 2002)

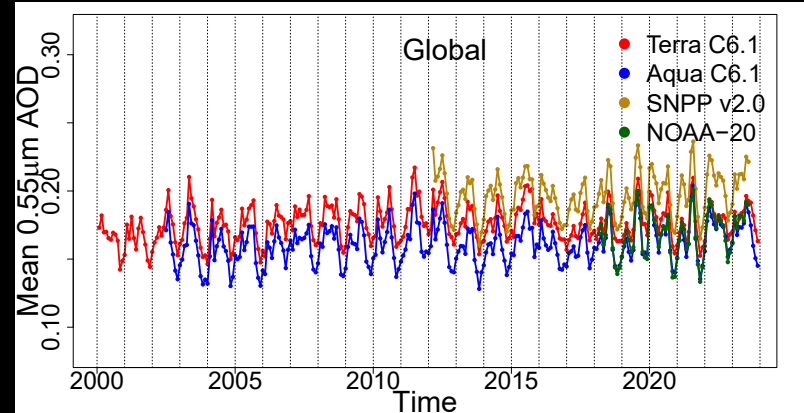


VIIRS on Suomi-NPP (c. 2011)



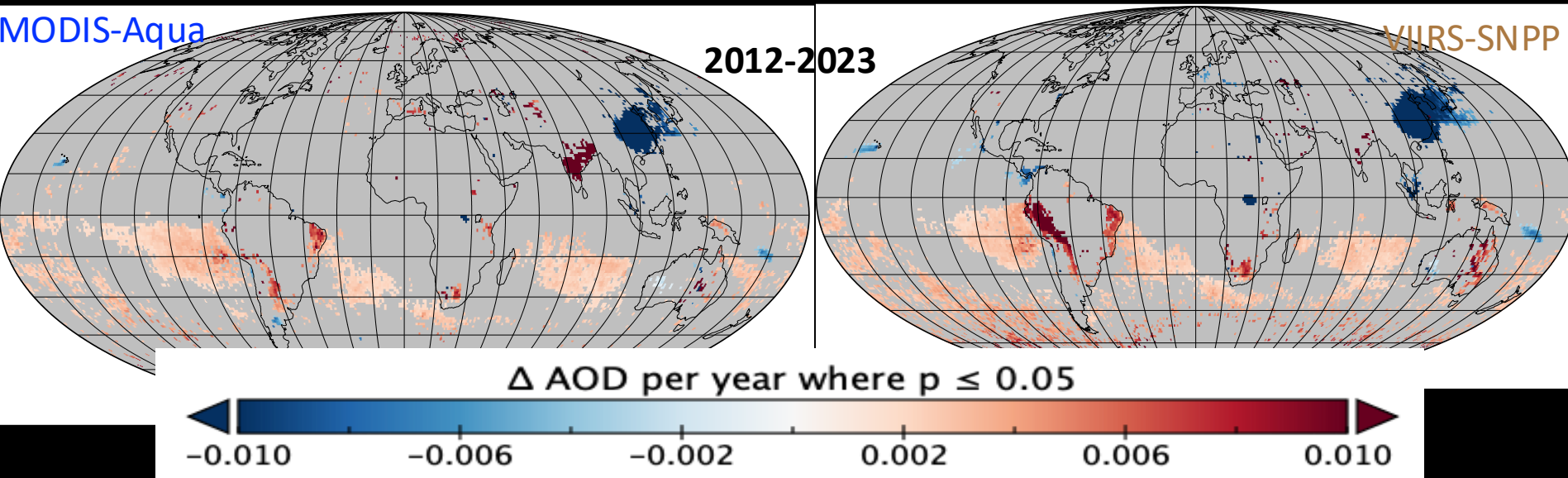
2011 ← VIIRS → 2030+

- 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)

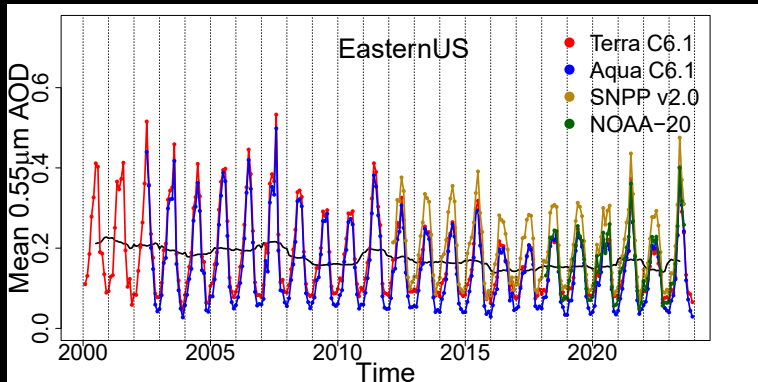
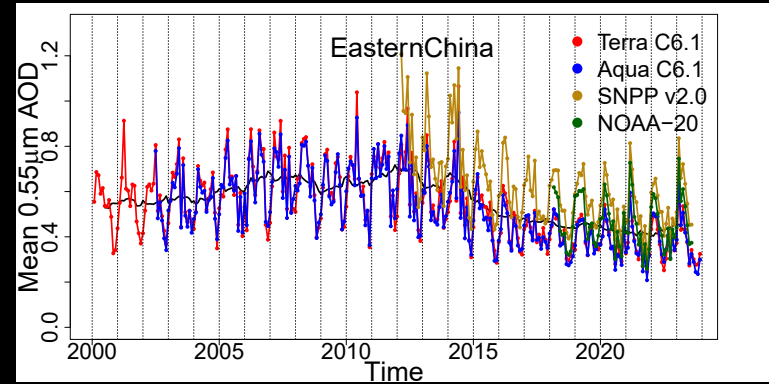
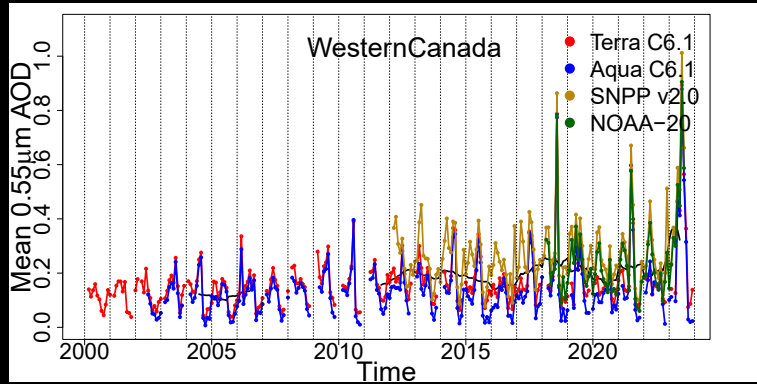
Consistency of Dark Target AOD 11-Year Trends (SNPP vs Aqua):



Slope of the linear regression where $p \leq 0.01$.

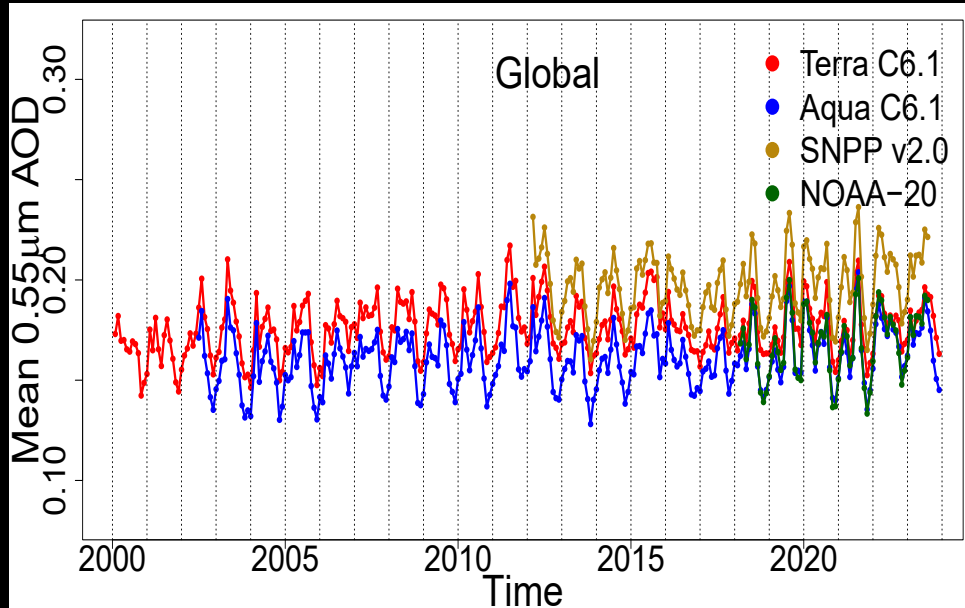
- Some places, the 10-year trends may be different than 20-year trends (of MODIS).
- Overall, SNPP sees the same world as Terra / Aqua (except for southern midlatitude ocean?)

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.**

MODIS C6.1 vs VIIRS 2.0



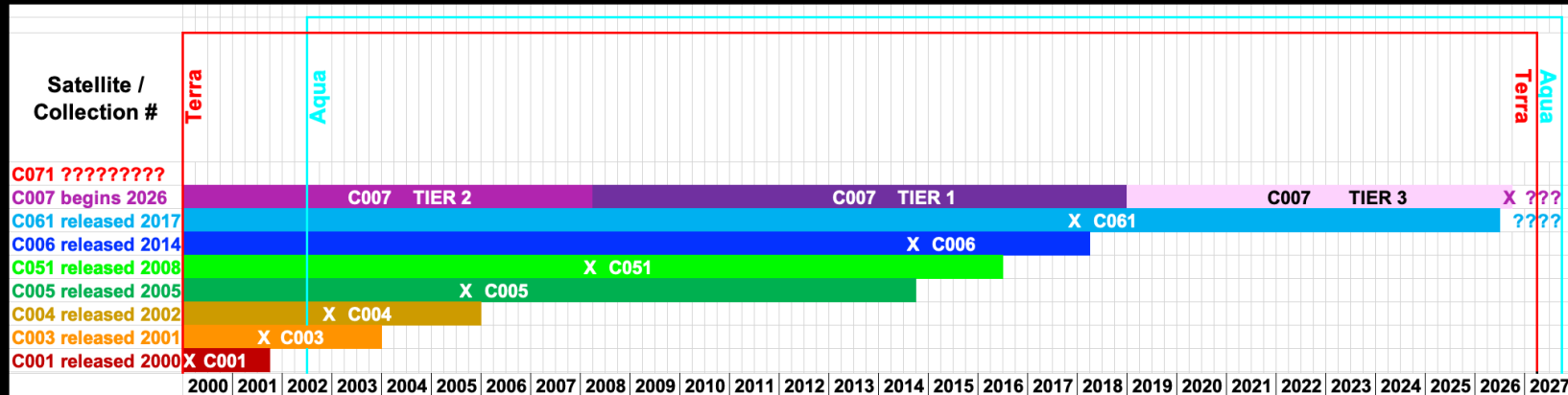
- Overall tendencies are consistent.
- All AODs within ± 0.02 -is to MODIS-Aqua but....
- SNPP > Terra > Aqua > N20
- And total range of ± 0.05
- 0.22 vs 0.17 “not insignificant” for understanding climate
- **Can we do better?**

MODIS “Collections” (L1B → L2 → L3)

Entire “Atmosphere” Team



<https://atmosphere-imager.gsfc.nasa.gov/collections/overview>



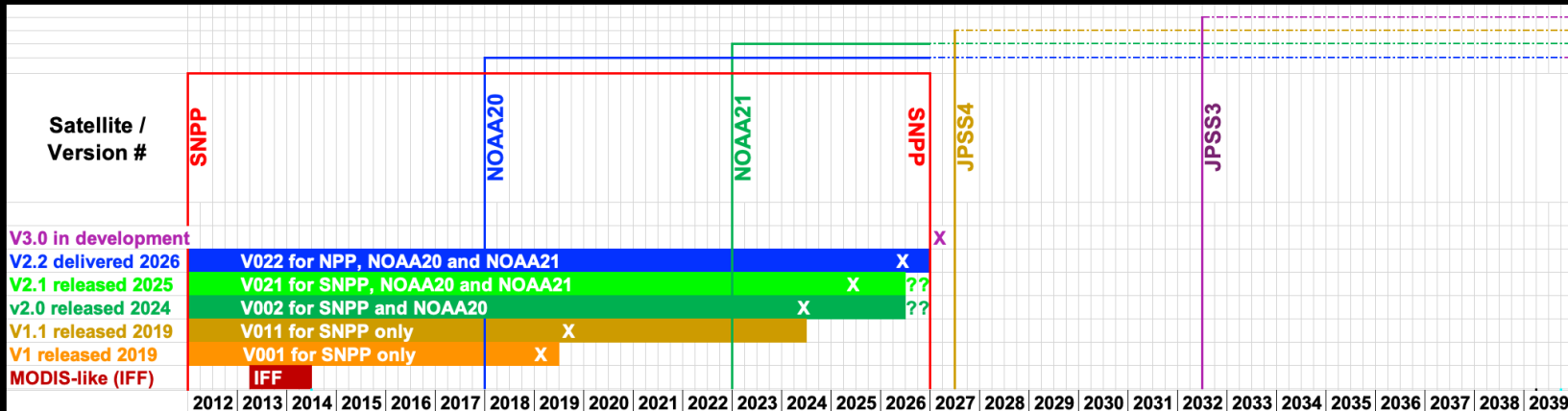
- C001: Initial algorithms at Terra launch
- C003: Provisional for both Terra and Aqua
- C004: First significant “validation” (2003)
- C005: First real “science” (2005)
- C051: Some calibration and bug fix (2008)
- C006: Major upgrades to science (2013)
- C061: updates to the L1B. (2017)

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

- Tier #1 = 2008 to 2018 (pending release from LAADS-DAAC)
- Tier #2 = beginning of mission through 2007 (after Tier #1)
- Tier #3 = 2019 to end-of-mission (after Tiers #1 and #2).
- Tiers dependent on funding support and schedule.
- Maybe a C071 for bug fixes if necessary before end of Terra and Aqua missions. (depends on funding/support)

VIIRS "Versions" (L2 → L3 only)

Individual teams update when ready



- 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)

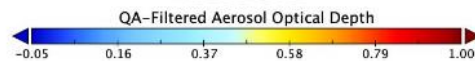
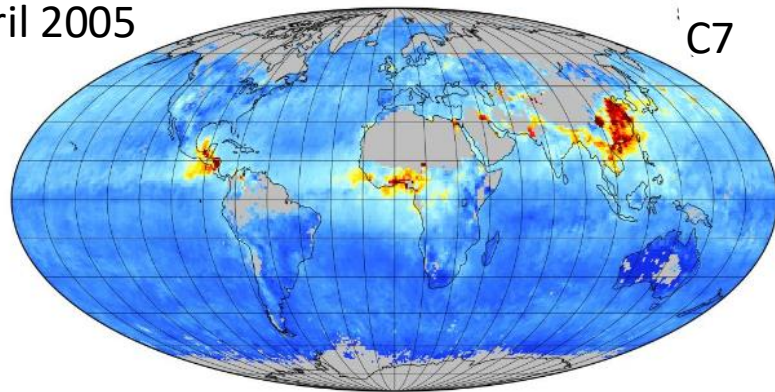
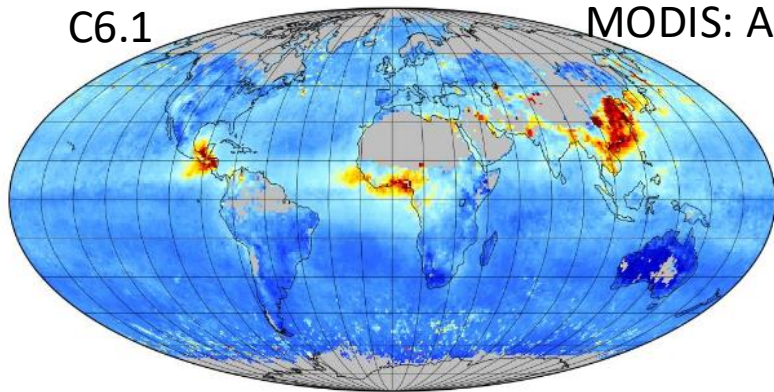
- SDS names exactly match MODIS C7
- Does not need a call-back to retrieve heavy surface-level aerosol over Asia
- Uses updated Wisconsin Continuity Cloud Mask
- Fixes QA-Filtering bug
- Introduces X-calibration between V2.0 and V2.1.
- Deep Blue (DB) retrievals remain in separate file (AERDB) and no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

Overall "Algorithm Updates"

C6.1

MODIS: April 2005

C7

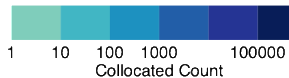


0.55 μm AOD, Land

N: 67945
Bias: 0.009
 R^2 : 0.99
 $Y=0.972X+0.015$

nearly unchanged distribution

AOD (Aqua C6.1)



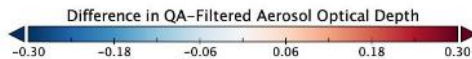
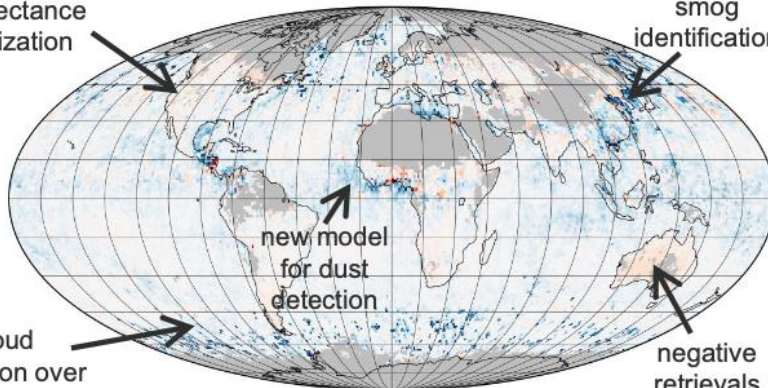
surface reflectance parameterization

smog identification

new model for dust detection

less cloud contamination over Southern Ocean

negative retrievals now positive

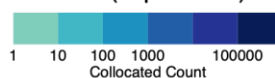


0.55 μm AOD, Ocean

N: 405957
Bias: 0.001
 R^2 : 0.966
 $Y=0.932X+0.01$

High outliers reduced

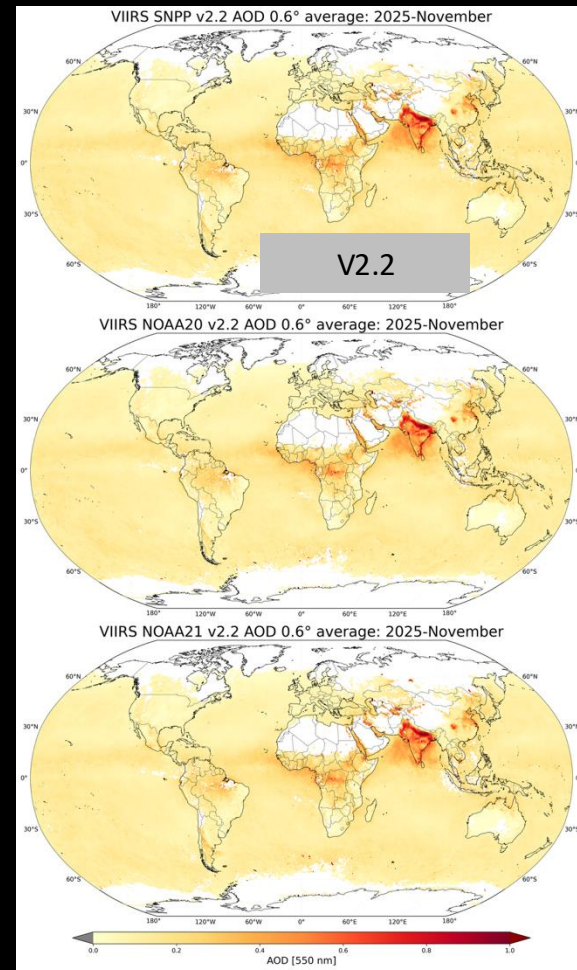
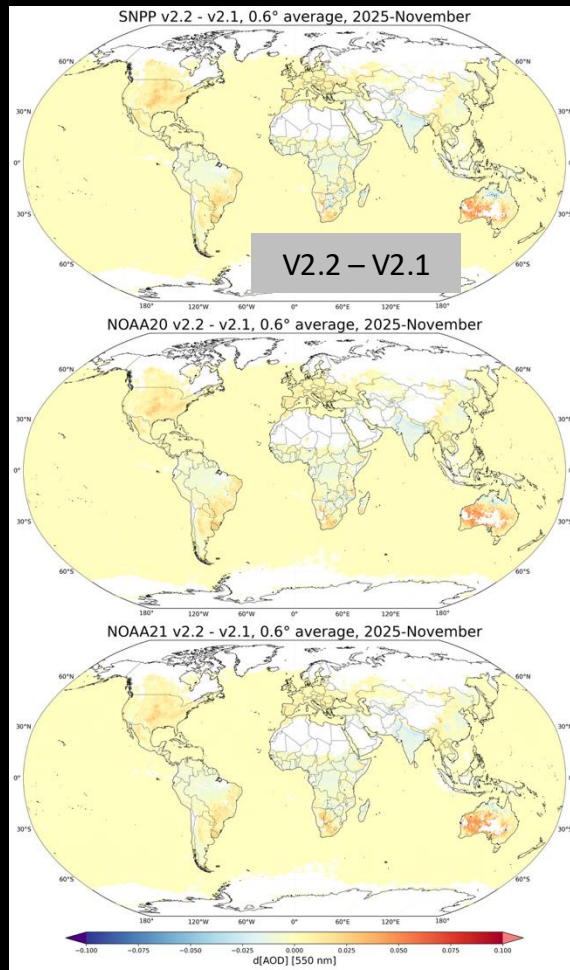
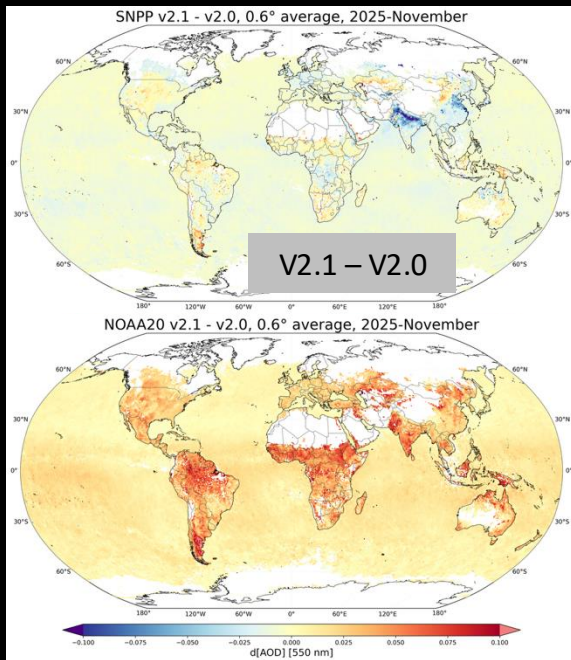
AOD (Aqua C6.1)



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

VIIRS DT AOD Changes : V2.2 vs V2.1 vs V2.0



Key Changes in V2.1: X-cal, SRP over land

- Decreased SNPP over land

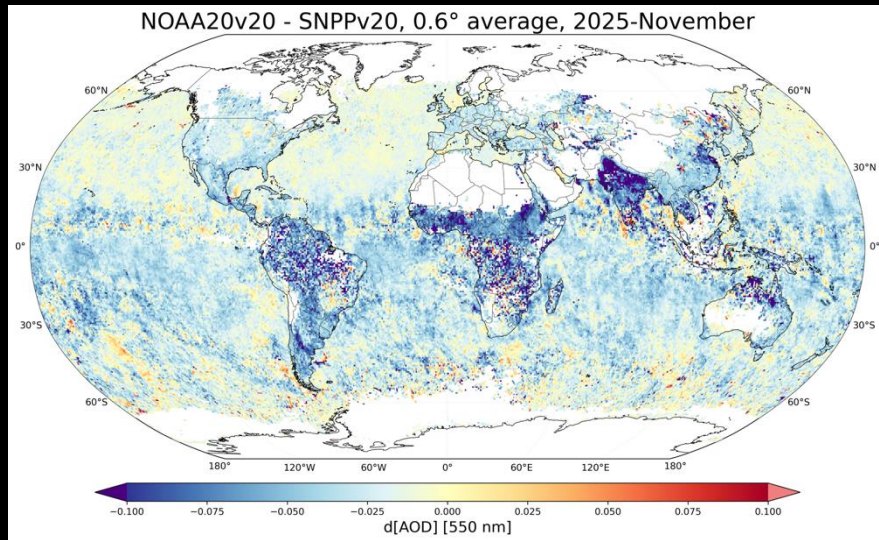
- Increased NOAA-20 everywhere

V2.2: Log-fit, Coastal retrieval

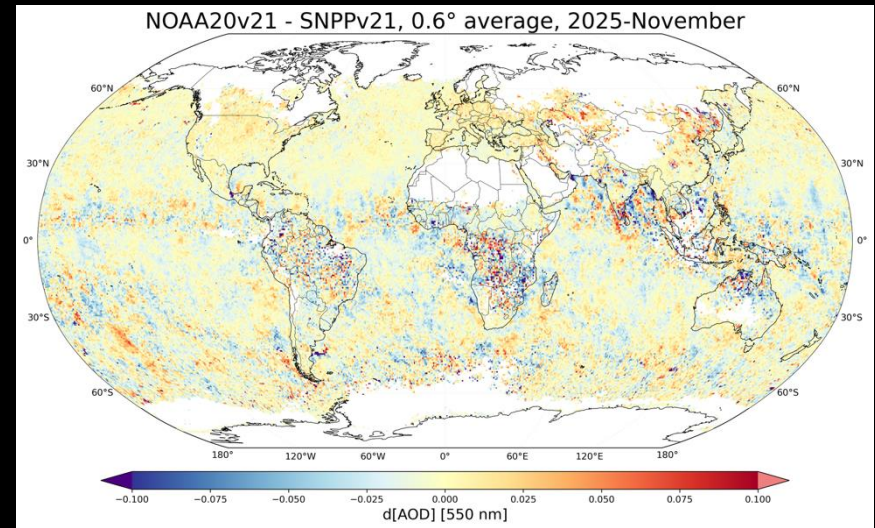
- Increased near-zero AOD over land

X-Cal applied reduces overall bias NOAA20 vs SNPP

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



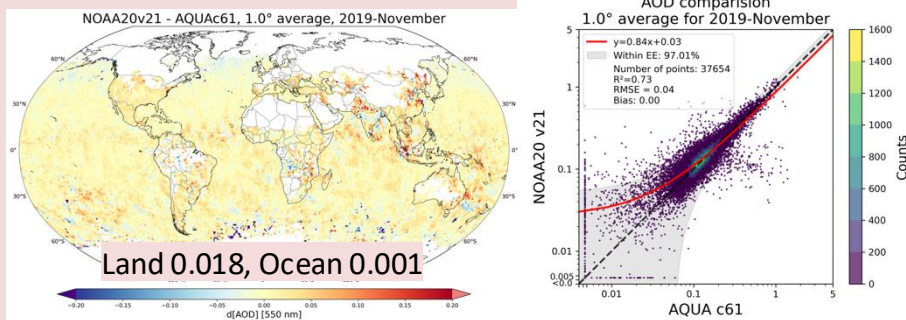
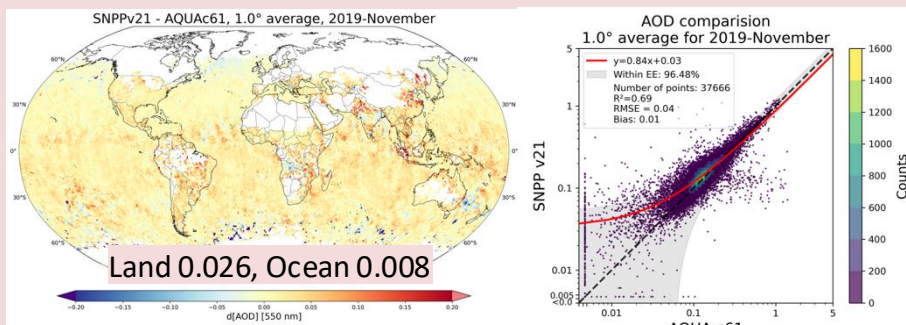
V2.1 N20-SNPP (After X-calibration)



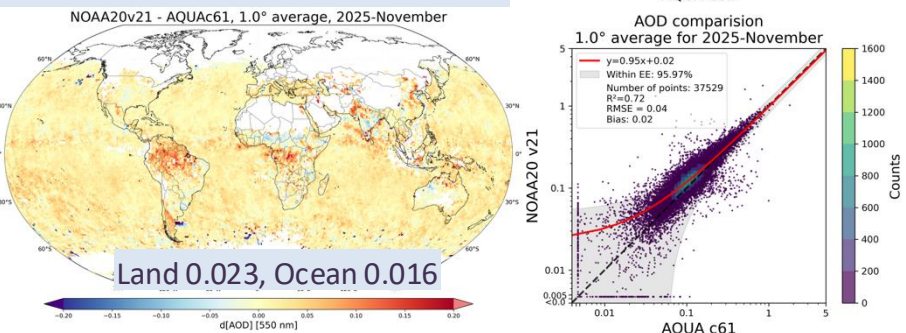
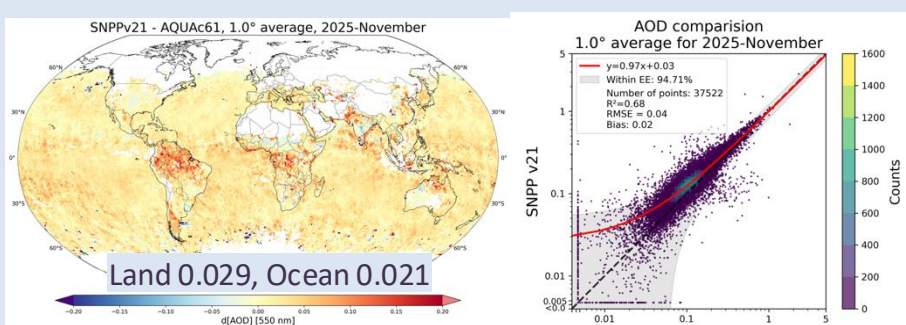
Overall offsets much closer to zero!
Differences are primarily due to cloud positions?

Changes in VIIRS vs. MODIS Aqua (C6.1) relationship before and after Aqua drift

V2.1 vs Aqua C6.1: November 2019 (before Aqua drift)



V2.1 vs Aqua C6.1: November 2025 (1.5 hours apart!)

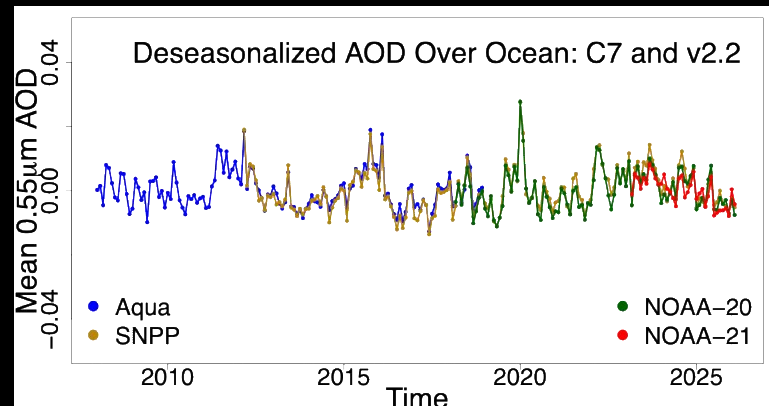
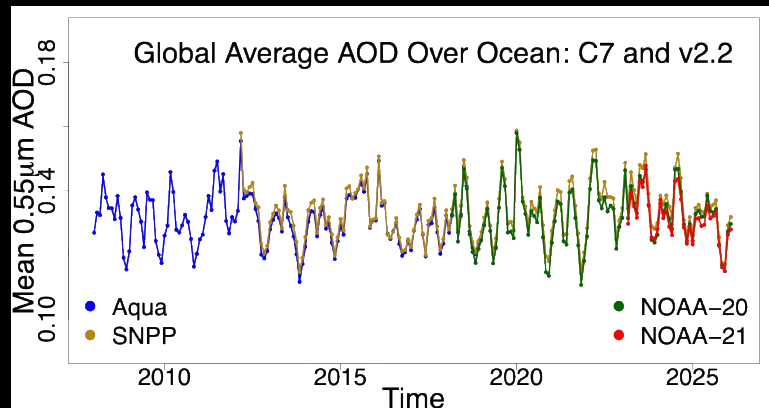


MODIS C7: "Tier 1" (2008-2018) and three VIIRS V2.2

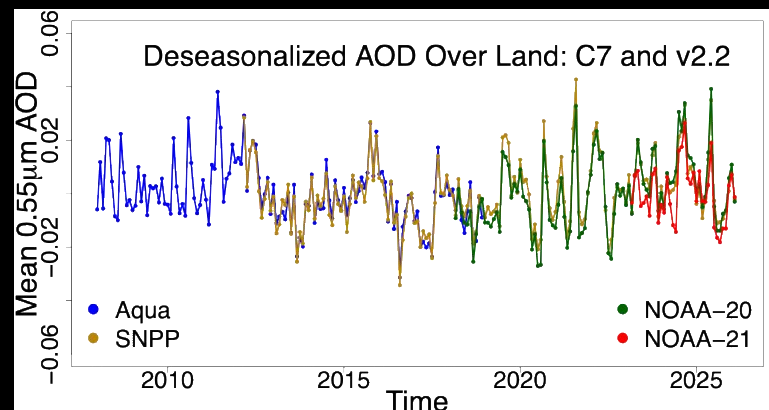
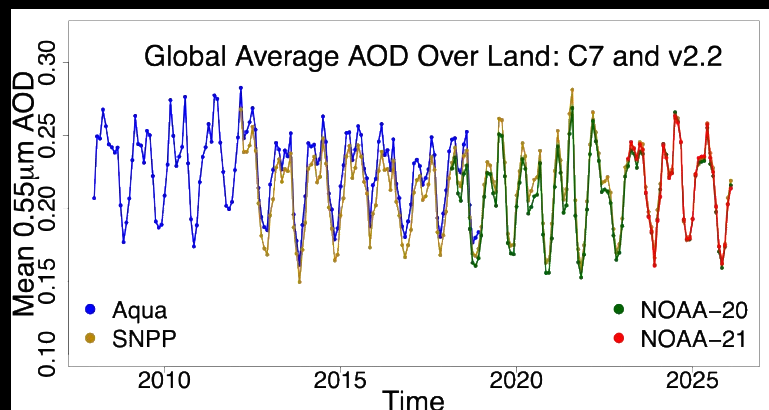
Monthly Mean AOD

De - Seasonalized

Ocean



Land



MODIS C7 vs VIIRS 2.2

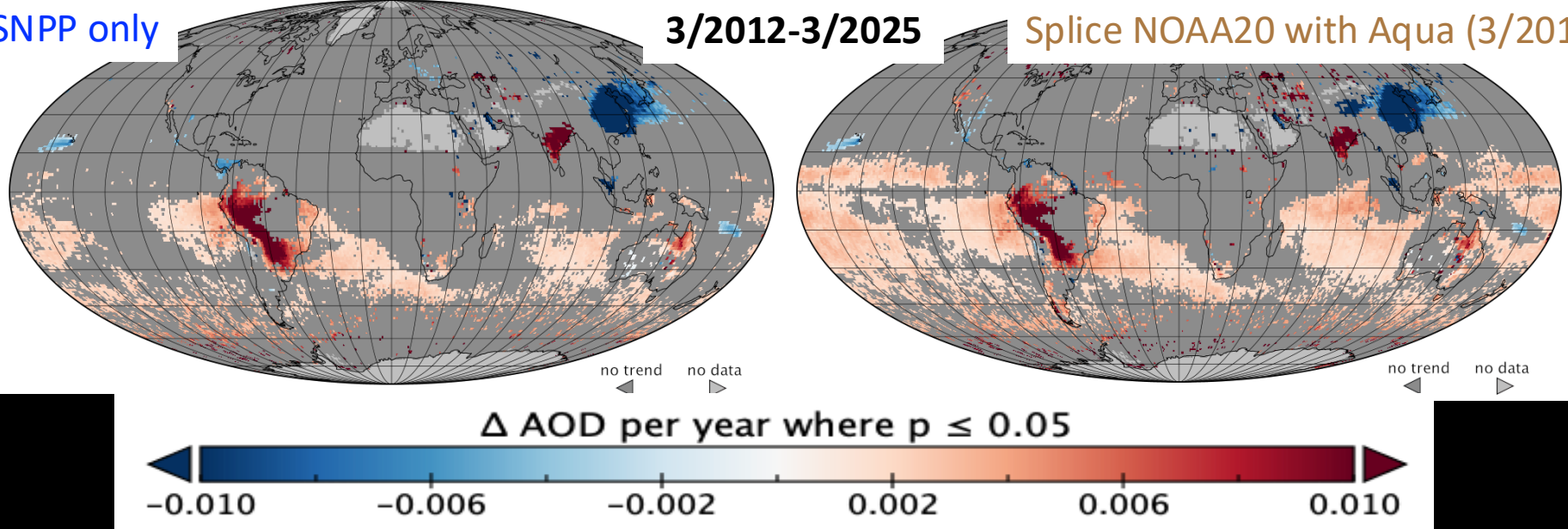
- Overall tendencies are even more consistent!
 - All AODs within ± 0.01 -ish!
 - **We are doing much better!!!**
 - Note, no X-Cal applied to MODIS-Terra
-
- **What about trends: Are we getting more similar?**

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

SNPP only

3/2012-3/2025

Splice NOAA20 with Aqua (3/2018)



Slope of the linear regression where $p \leq 0.01$.

- 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.

Summary

- The Dark Target (DT) aerosol retrieval algorithm is a validated, robust algorithm that began with MODIS but can be run on imagers including VIIRS (to create 30+ year record)
- We are currently running 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 are producing products but not released yet – hopefully by this summer? C7 and V2.2 have many improvements including upstream L1B, cloud mask, X-calibration, bug fixes, and QA filtering.
- Initial comparisons with “Tier 1” MODIS suggest overall AOD spread may be reduced to ± 0.02 in a given month. Offsets are reduced enough so that we have more confidence in splicing datasets to achieve 30+ years.
- Further improvements to MODIS and VIIRS aerosol products and consistency are pending funding and support.

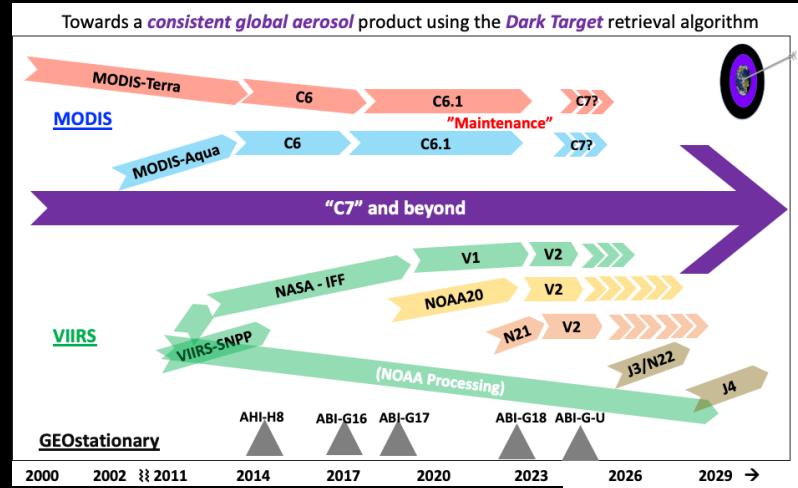
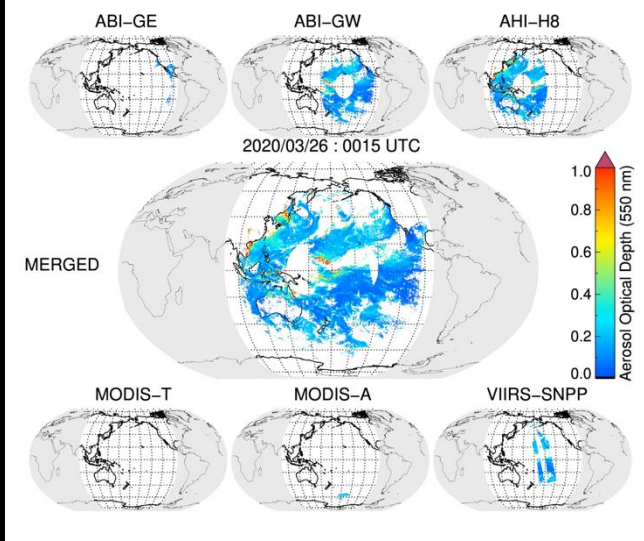
Some questions?

- I would like to know more about the overall “increasing AOD” over the southern oceans.
- Assuming that we now have sufficient confidence in overall AOD, can we work towards consistency in retrieving spectral AOD and fine mode fraction?
- We only are showing Dark Target products here. Can we get similar consistencies with Deep Blue? With other aerosol products, models, and ground-measurements?
- With C7 and V2.2 (or better), how much can aerosol explain observed variability and trends in CERES data?
- Thinking about yesterday’s discussion; could we achieve sufficient AOD consistency with an off-the-shelf, low-cost imager in space? Even if it had all the spectral and spatial capabilities of a MODIS or VIIRS?



Dark Target (DT) Aerosol Retrieval Project

One algorithm + many sensors = All daylight globe



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



<https://darktarget.gsfc.nasa.gov>

