Dark-target aerosol algorithm: status of products from Terra, Aqua, and Suomi-NPP
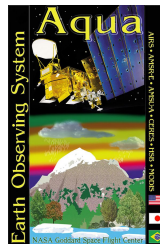
Robert C. Levy (NASA-GSFC), robert.c.levy@nasa.gov

Shana Mattoo[2,1], Virginia Sawyer[2,1], Yingxi Shi[3,1], Lorraine Remer[3], Geoff Cureton[4], Pawan Gupta[5,6], Falguni Patadia[5], Zhaohui Zhang[7,1], Yaping Zhou[8,1], Rich Kleidman[2,1], Erick Shephard[3,1]

[1]NASA/GSFC , [2]SSAI, [3]UMBC, [4]SSEC/U. Wisconsin, [5]USRA, [6]MSFC, [7]ADNET, [8]Morgan State U.
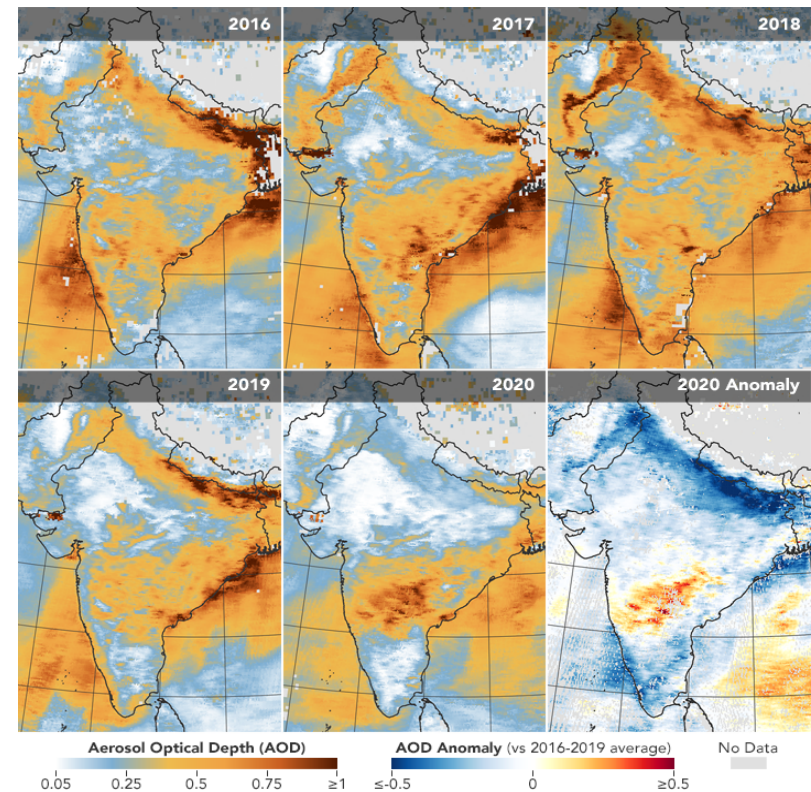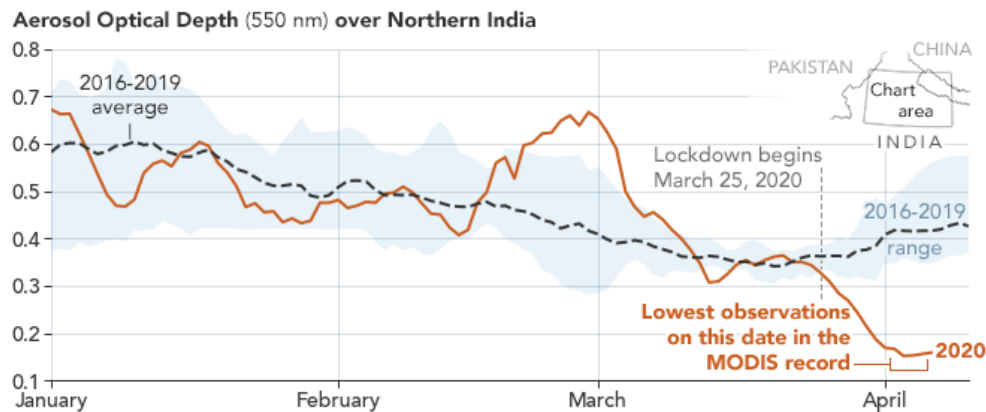
**https://darktarget.gsfc.nasa.gov/**

COVID-related aerosol decrease?

https://earthobservatory.nasa.gov/images/146596/airborne-particle-levels-plummet-in-northern-india

- MODIS aerosol data show unusually low AOD in early April over Northern India, coincident with COVID-19 related lockdowns.
- MODIS-Terra, MODIS-Aqua, and VIIRS-SNPP all see this drop-off.

- In no way "statistically significant", but very interesting.
- We have been looking for other such drop-offs, but natural variability dominates

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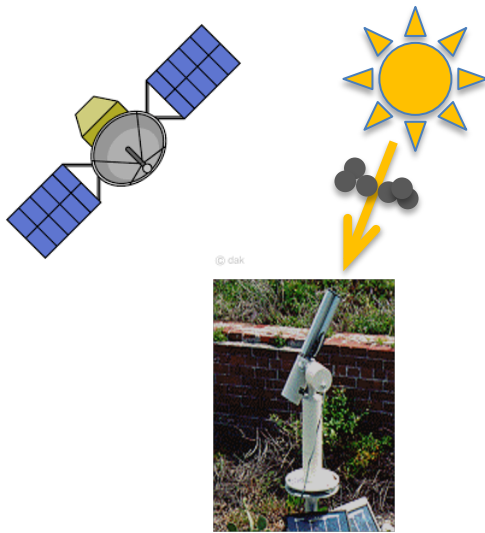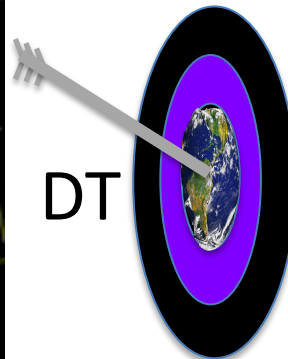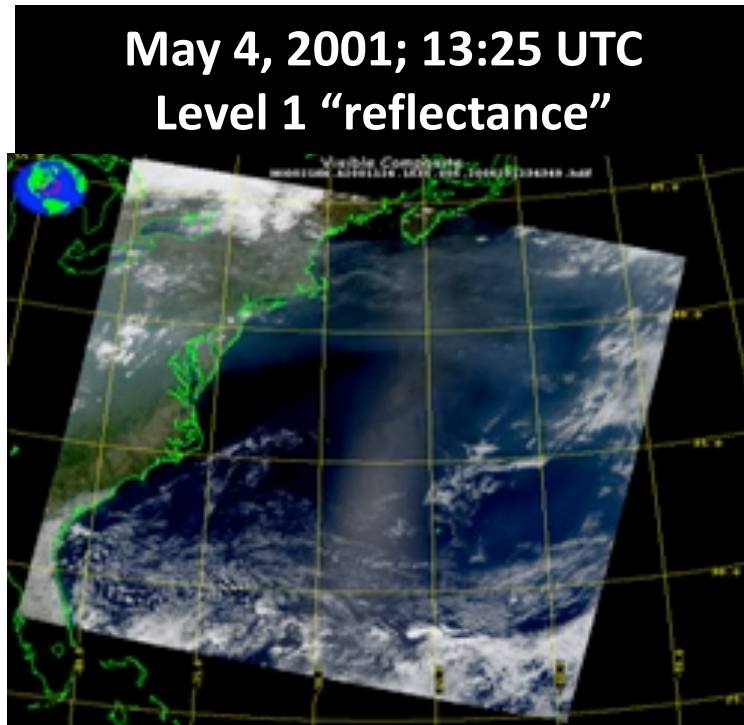

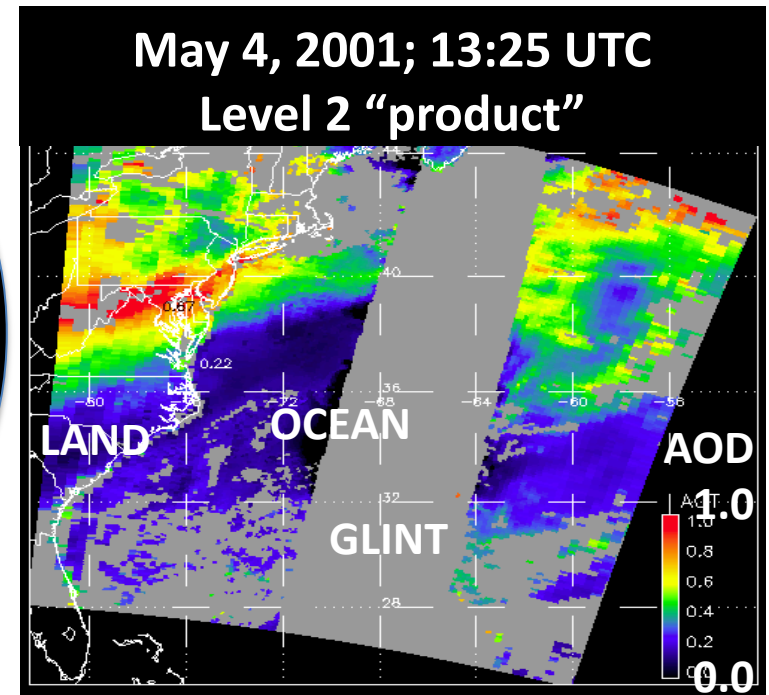| Target metric	Target
Horizontal Resolution	5-10 km, globally
Accuracy	MAX(0.03 or 10%)
Stability / bias	<0.01 / decade
Time Length	30+ years
Temporal Resolution	4 h

These are requirements for "climate" monitoring
Maybe different requirements for other applications
   (air quality, ocean fertilization, weather forecasting...)

Dark-Target (DT): A "Single View" aerosol algorithm developed for MODIS (Terra and Aqua)

What a sensor observes

Attributed to aerosol (AOD)

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

DT

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

LAND

OCEAN

GLINT

AOD
1.0

0.0
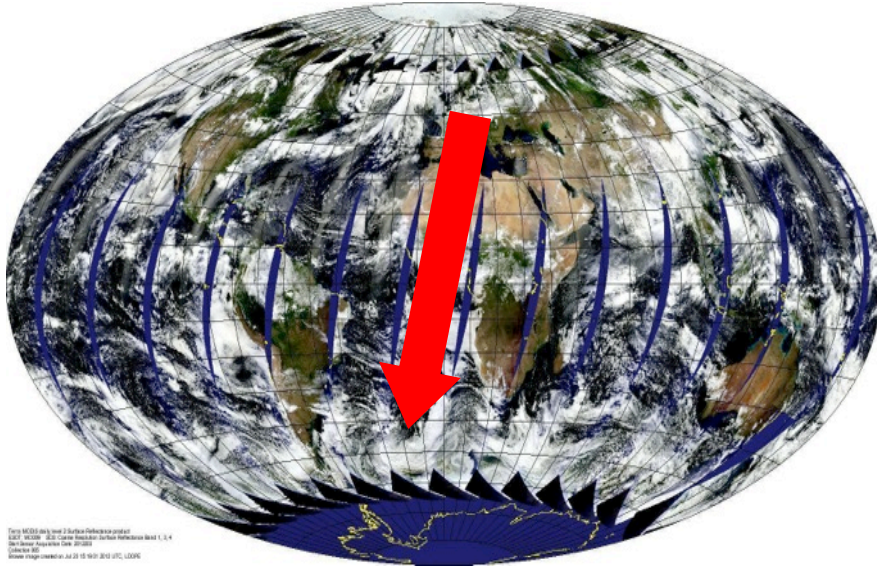
"Established 1997" by Kaufman, Tanré, Remer, Mattoo, etc)
"Modified 2005, 2010, 2013, 2015" by Remer, Levy, Mattoo, Gupta, etc
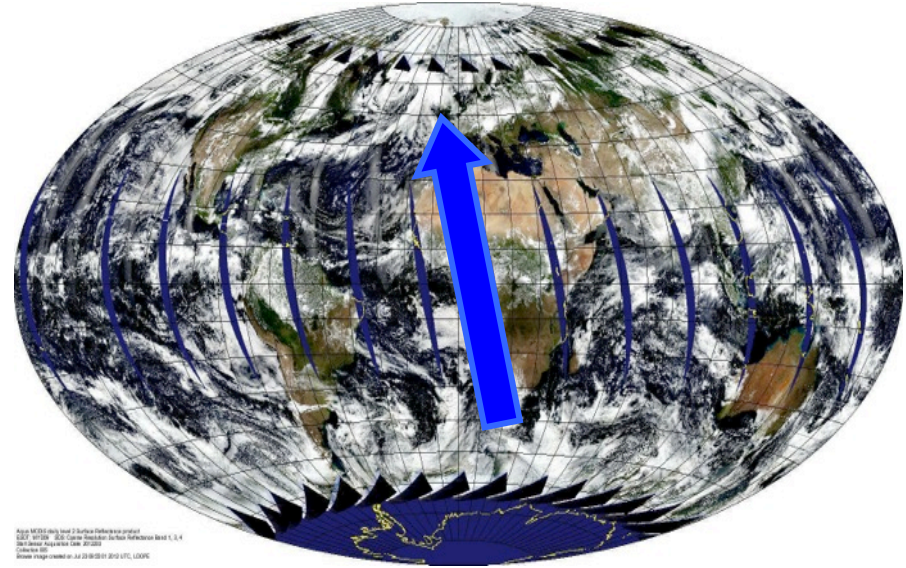
Separate logic over land and ocean
Retrieve: AOD at 0.55 μm, spectral AOD (AE), Cloud-cleared reflectances, diagnostics, quality assurance

MODIS-Terra vs MODIS-Aqua

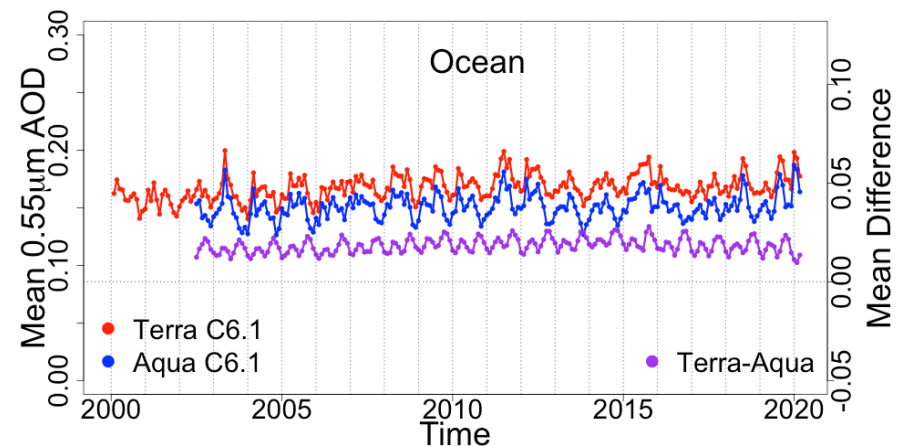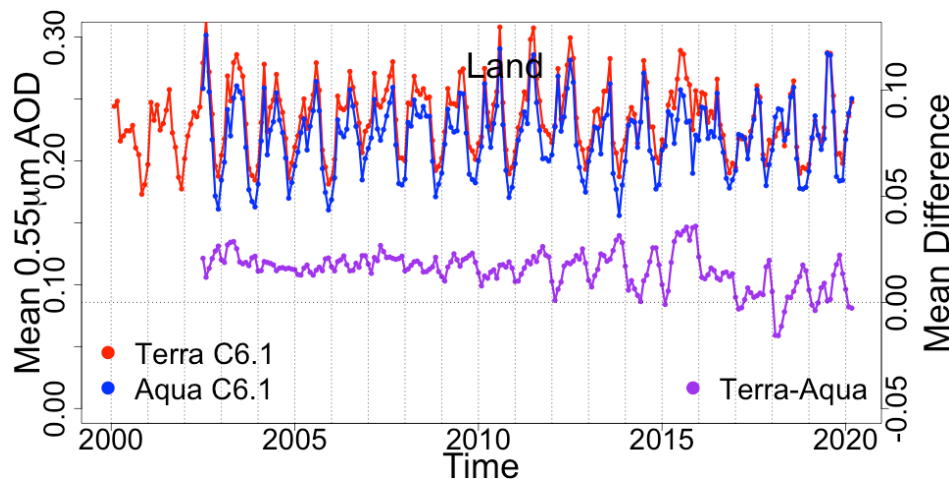Terra (10:30, Descending)

Aqua (13:30, Ascending)

Do the "twin" MODIS observe the world in the same way?

MODIS Terra versus Aqua:
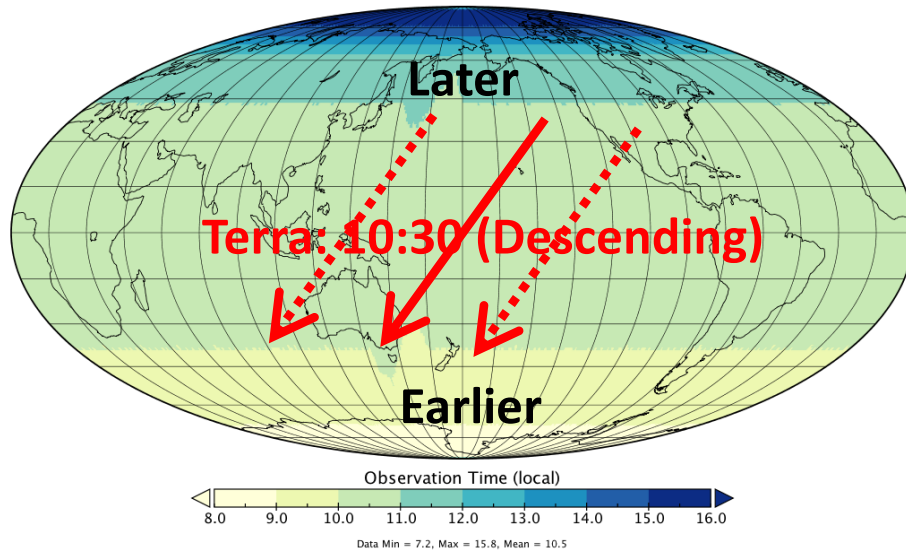# Collection 6.1 global time series (monthly)

- Reprocessed from 2000-2017 with smoothed-out (re-)calibration

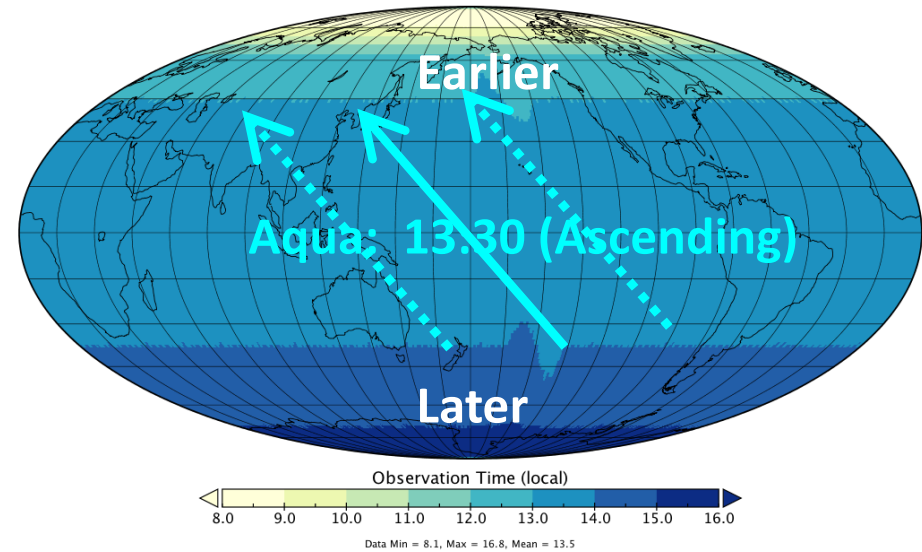- Processed forward from 2017-present with piecewise calibration

- Over land:
  - Offset averages 0.02 prior to 2011
  - Becomes more variable through 2017
  - Average closer to zero after 2017

- Over ocean:
  - very consistent seasonal cycle
  - Offset of 0.015 (15%)
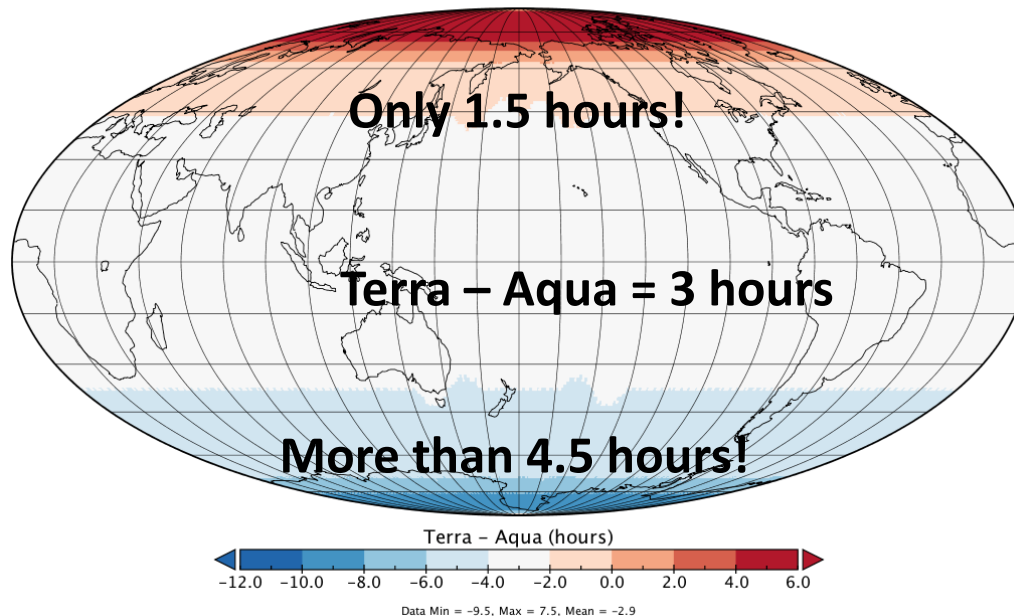
overpass differences are not exactly 3 hours

Terra Local Observation Time, 2008

Later

Terra: 10:30 (Descending)

Earlier

Observation Time (local)

8.0   9.0   10.0   11.0   12.0   13.0   14.0   15.0   16.0

Data Min = 7.2, Max = 15.8, Mean = 10.5

Aqua Local Observation Time, 2008

Earlier

Aqua: 13:30 (Ascending)

Later

Observation Time (local)

8.0   9.0   10.0   11.0   12.0   13.0   14.0   15.0   16.0

Data Min = 8.1, Max = 16.8, Mean = 13.5

Average Difference in Local Observation Time, 2008

Only 1.5 hours!

Terra – Aqua = 3 hours

More than 4.5 hours!

Terra – Aqua (hours)

−12.0   −10.0   −8.0   −6.0   −4.0   −2.0   0.0   2.0   4.0   6.0

Data Min = −9.5, Max = 7.5, Mean = −2.9

C6: "model" does not explain AOD offset

MERRA-2 (replay) sampled at 12:00 UTC on May 25, 2008
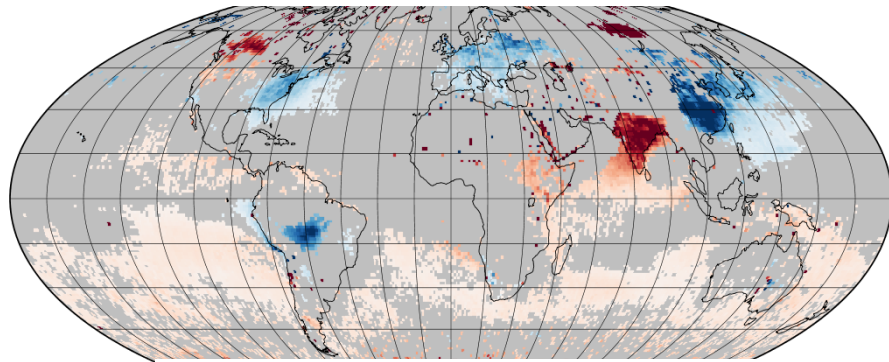
Overpasses within ±30 minutes
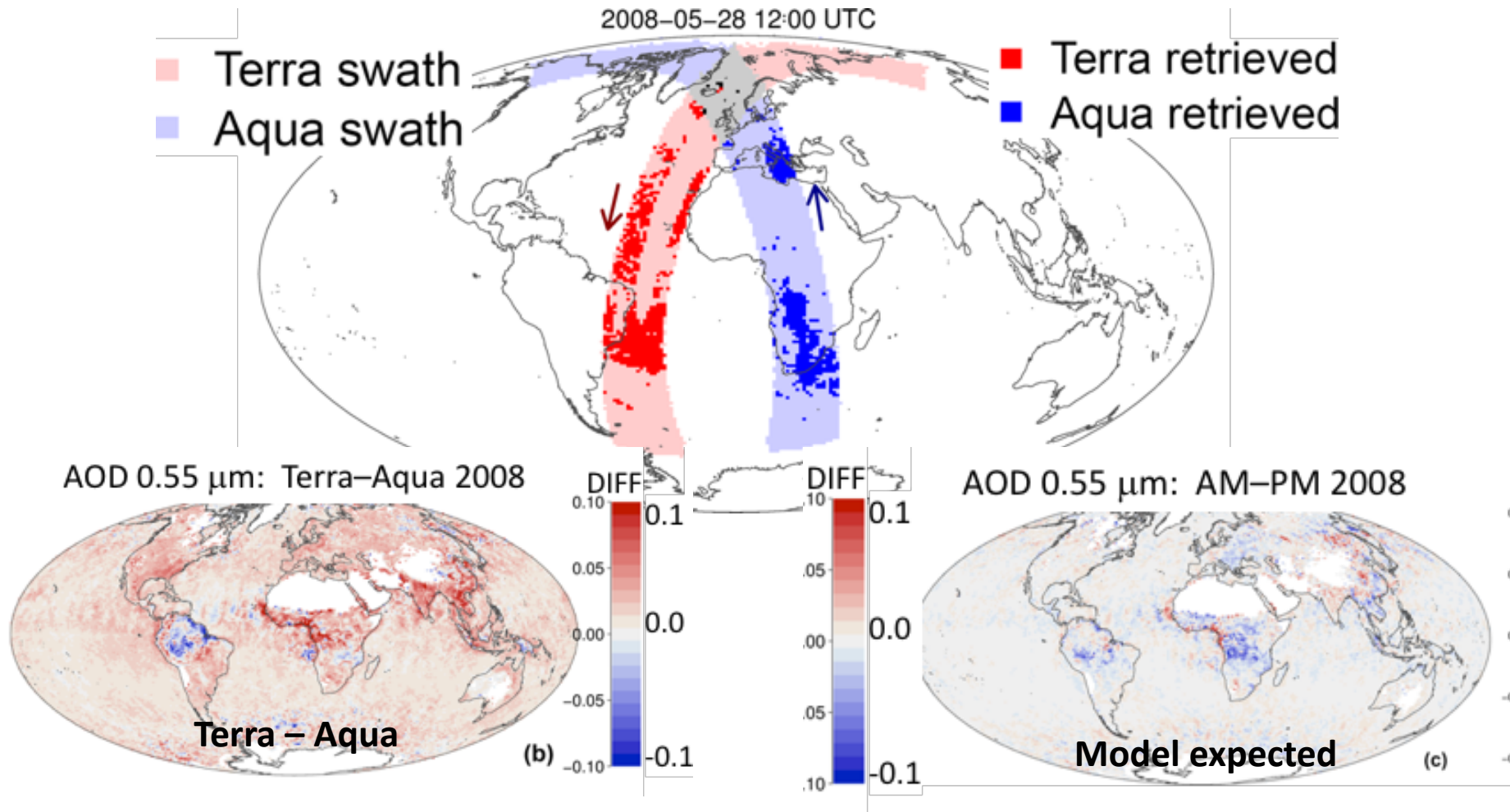
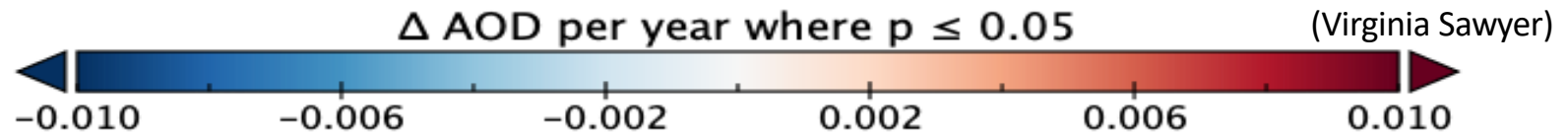
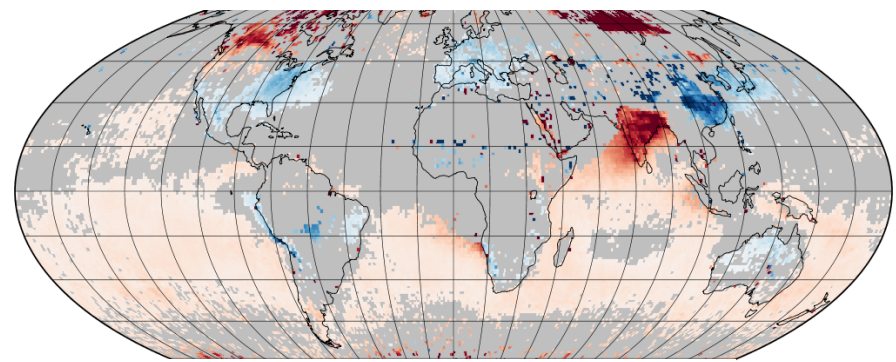Some similarities in "smoke" regions

But MODIS trends are consistent!

MODIS AOD from Aqua: 2002-2020

MODIS AOD from Terra: 2000-2020

Δ AOD per year where p ≤ 0.05

(Virginia Sawyer)
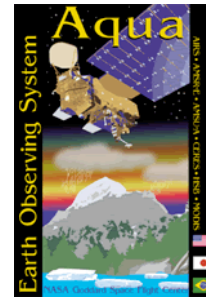
−0.010   −0.006   −0.002   0.002   0.006   0.010

Why the general increasing trend in the Southern Oceans?
Note slightly better agreement when Terra is restricted to 2002-2020

We also have "seasonal" trend plots if time.

Beyond **MODIS**

- Terra (20+) and Aqua (17+) have well-exceeded their planned lifetimes.
- With luck, they will last through 2022-23 before drifting out of orbit.
- For (30+), we need to continue the MODIS record (with no jumps!)
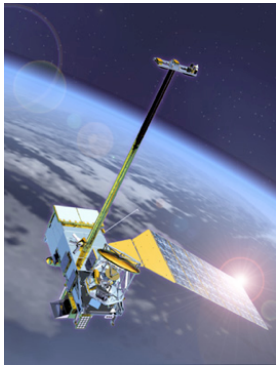
VIIRS!
Visible-Infrared Imager Radiometer Suite
aboard Suomi-NPP, NOAA-20 and beyond

Terra (10:30, Descending)   Aqua (13:30, Ascending)   VIIRS (13:30, Ascending)

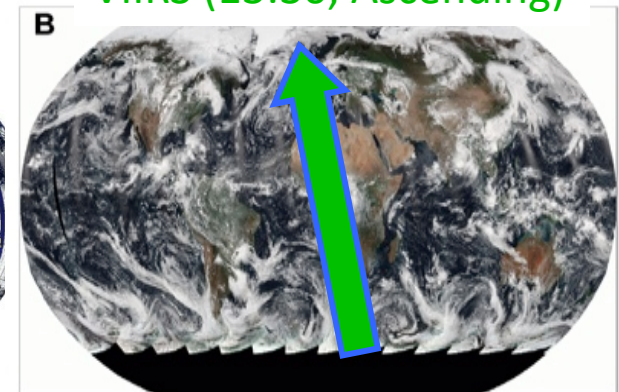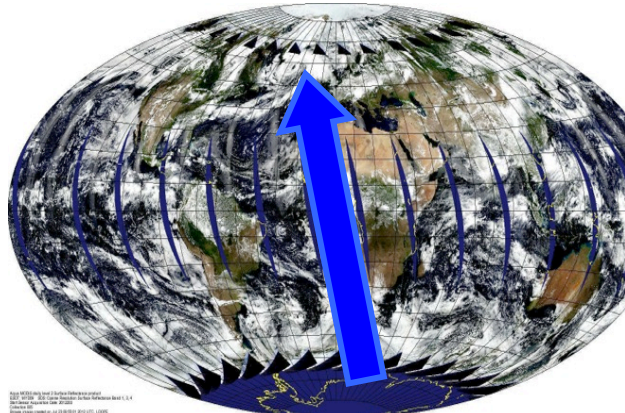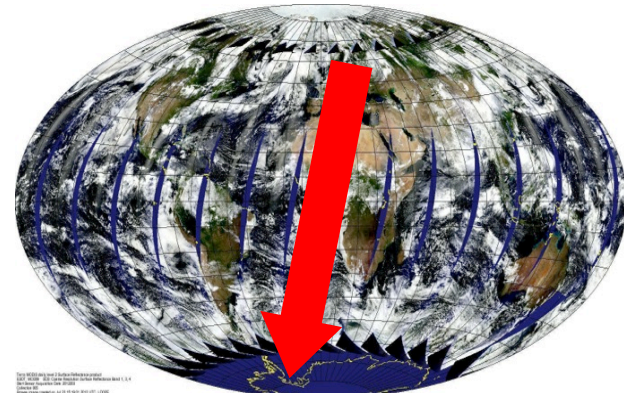# For "continuity" we port the algorithm

- Account for differences in wavelengths (gas corrections/Rayleigh, etc)
- VIIRS specific lookup tables

Wavelength bands & surface spectra

Example: 0.86 μm channel over "clear" sky
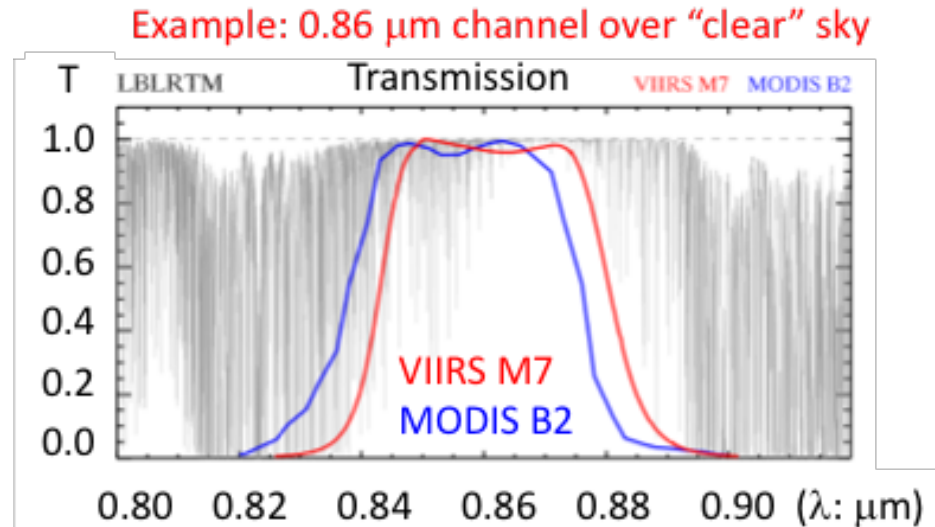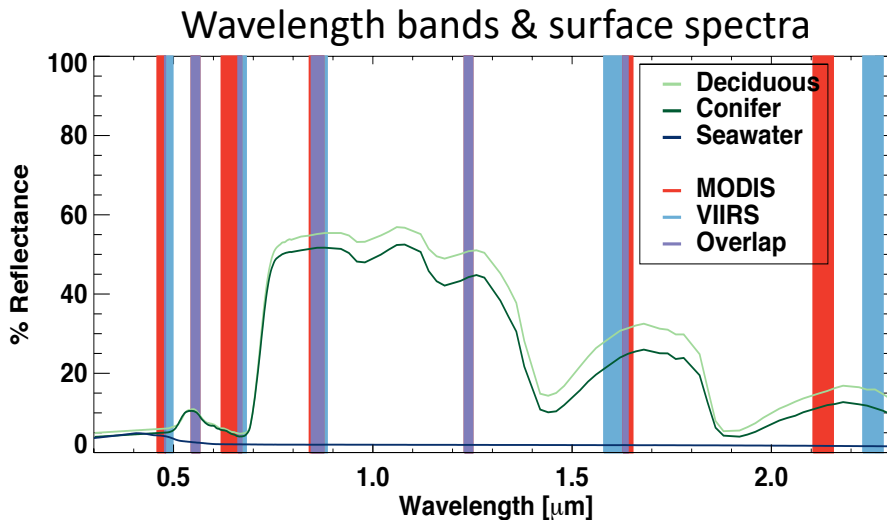
- And deal with cloud-mask and resolution differences
- To retrieve or not to retrieve?

10 km

6 km

Overcast: 0%
Partly Cloudy: 78%
Clear: 22%

Overcast: 8%
Partly Cloudy: 64%
Clear: 28%
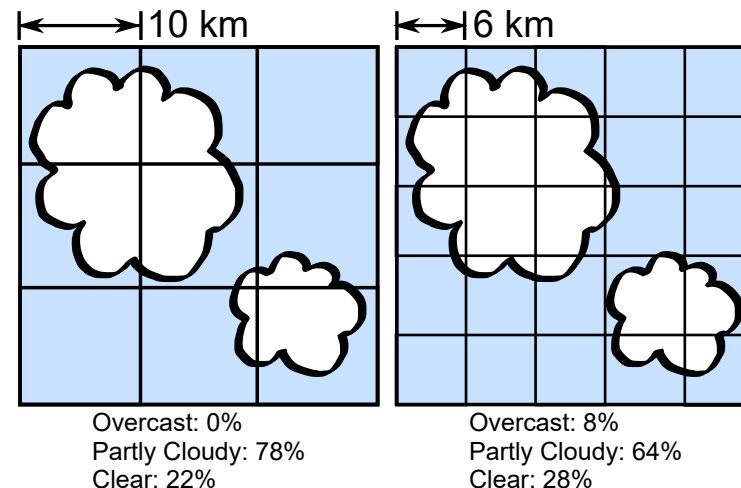
Looks pretty good (AOD)
Gridding = 1°x1°

MODIS-Aqua
QA–Filtered Aerosol Optical Depth, MODIS Aqua C6.1, March 2015

VIIRS-SNPP
QA–Filtered Aerosol Optical Depth, VIIRS SNPP v1.1, March 2015

March 2015

Monthly Average 0.55 μm AOD

0.01   0.10   1.00

Monthly Average 0.55 μm AOD

0.01   0.10   1.00
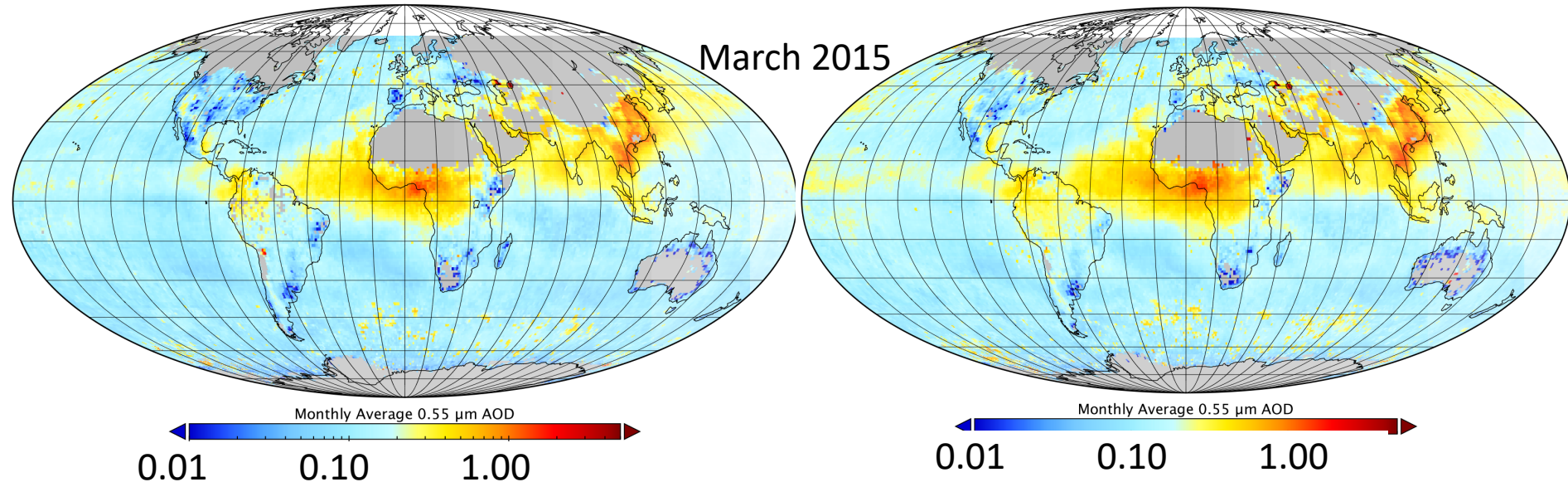
Of course, the devil is in the details…….

Ångström Exponent (AE)

MODIS-Aqua

MODIS Aqua Ångström Exponent, 2015

VIIRS-SNPP

VIIRS SNPP Ångström Exponent, 2015

March 2015

Annual Average Ångström Exponent Over Ocean

0.50 0.75 1.00 1.25 1.50 1.75

Annual Average Ångström Exponent Over Ocean

0.50 0.75 1.00 1.25 1.50 1.75

AE defined using 0.55 / 0.86 μm.

VIIRS – SNPP versus MODIS-Aqua

AOD: VIIRS - MODIS

Difference in Annual Average 0.55 μm AOD

-0.20   -0.10   0.00   0.10   0.20
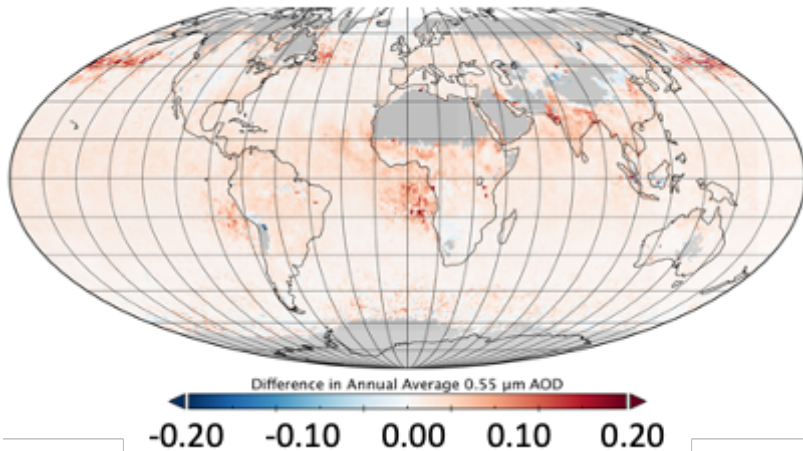
Why the overall 0.01 offset between the two sensors?

- 1°x1° grid daily

- 1-to-1 where MODIS and VIIRS both retrieve (dotted lines)

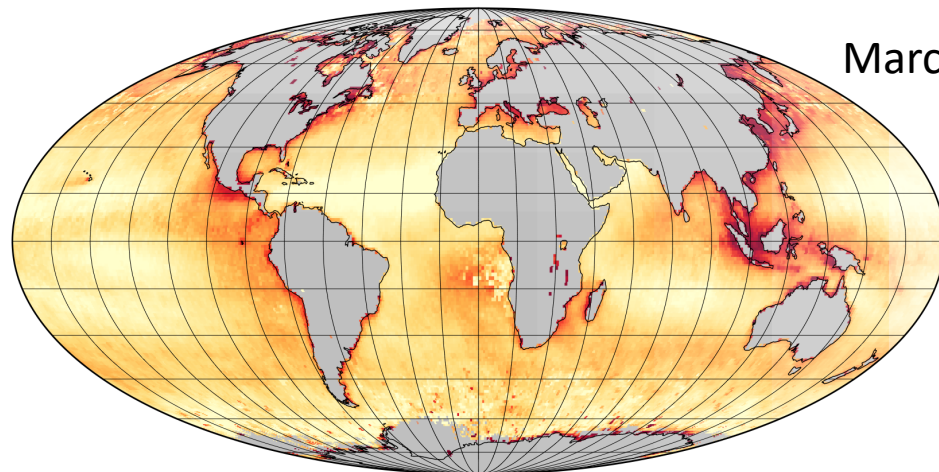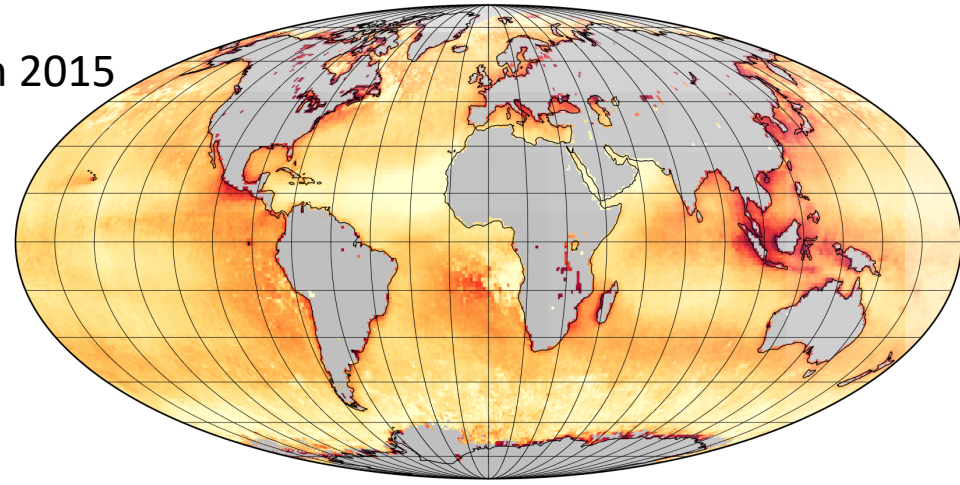- 'VIIRS not MODIS' vs 'MODIS not VIIRS' (solid lines)
    - More frequent
    - Skewed higher
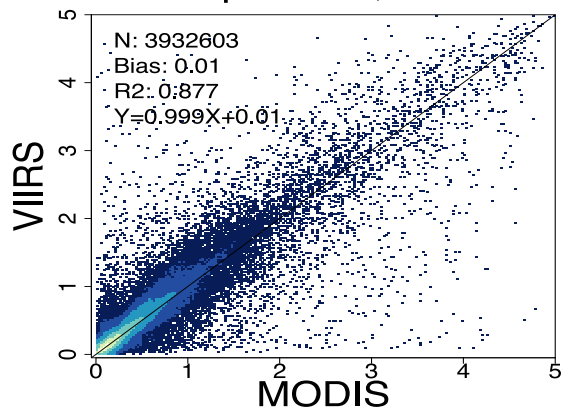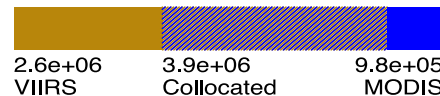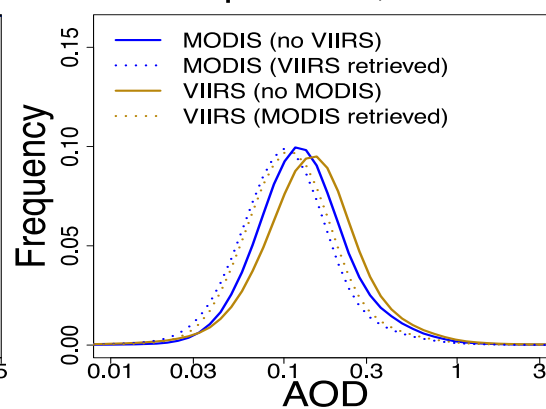
(Sawyer et al., Remote Sensing 2020)

0.55 μm AOD, Ocean

N: 3932603
Bias: 0.01
R2: 0.877
Y=0.999X+0.01

VIIRS / MODIS

1e+00   1e+02   1e+04   1e+06

0.55 μm AOD, Ocean

— MODIS (no VIIRS)
···· MODIS (VIIRS retrieved)
— VIIRS (no MODIS)
···· VIIRS (MODIS retrieved)

Frequency / AOD

2.6e+06   3.9e+06   9.8e+05
VIIRS   Collocated MODIS

MODIS-Terra vs MODIS-Aqua vs SNPP-VIIRS
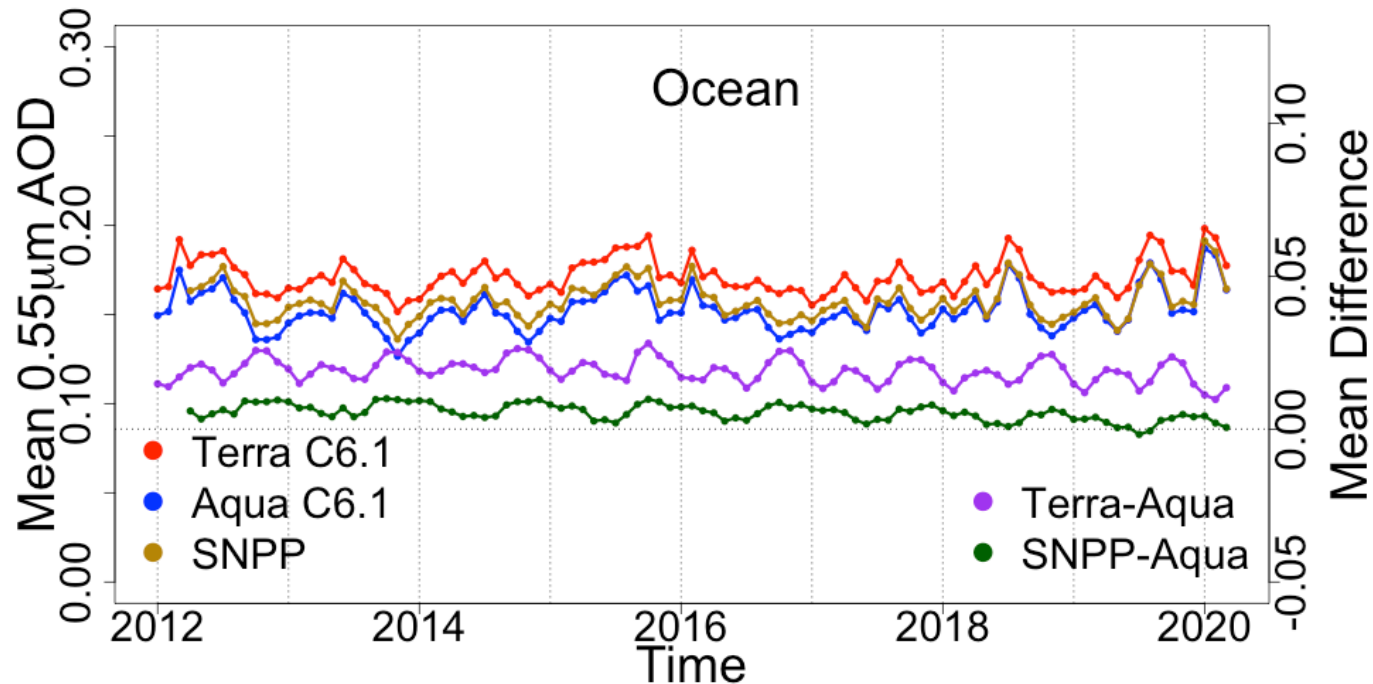
- **Didn't we just see that many ocean grids had biases of 0.01-0.03 or more?**
- **Yet global (area-weighted) differences come closer (0.01).**
- Why different seasonal cycles of offsets (Terra-Aqua versus VIIRS-Aqua)?

  - Calibration?
  - Sampling?
  - Cloud detection?
  - Cloud diurnal cycle?

MODIS-Terra vs MODIS-Aqua vs SNPP-VIIRS
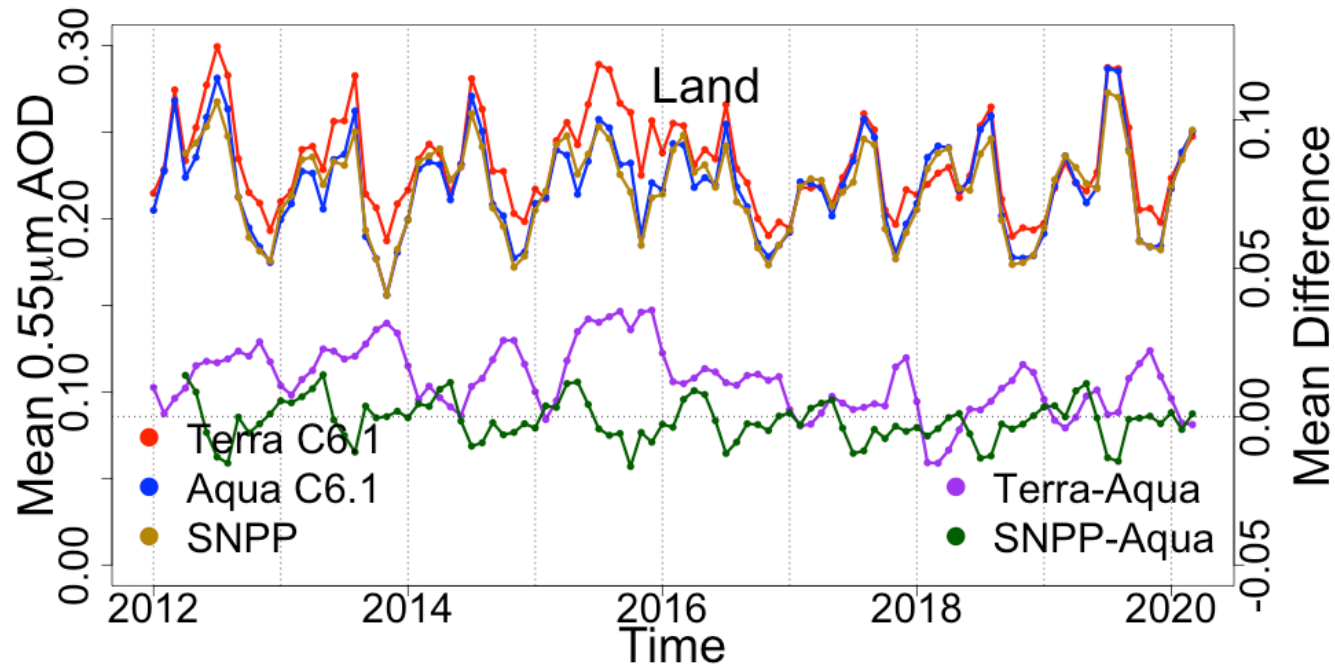
- **Didn't we just see that many land grids had biases of 0.01-0.03 or more?**
- **Yet global (area-weighted) differences come closer (0.00).**
- Why different seasonal cycles of offsets (Terra-Aqua versus VIIRS-Aqua)?

- VIIRS minus Aqua is consistent:
    - positive in Spring, negative in Summer Ffall ,

NASA MODIS vs VIIRS (DT)

Parameter	MxD04	AERDT_L2_VIIRS_SNPP
Mission length	Terra (2000-)　　10:30 LST Aqua (2002-)　　13:30 LST	SNPP (2012-)　13:30 LST JPSS1 (2017-)　13:30 LST
Pixel / Product size (km) nadir (Level 2)	0.5 km → 10 km	0.75 km → 6 km
Granule size (pixels)	5 minute (203x135)	6 minute (404x400)
File Format	HDF4	NetCDF4
Upstream cloud mask	MODIS Cloud mask (MxD35)	MODIS-VIIRS Continuity Cloud Mask (MVCM)
Production	LAADS (at GSFC)	SIPS (at U Wisconsin)
Level 3	LAADS (files=MxD08)	SIPS (files = TBD)
Public Archive	LAADS (at GSFC)	**Now at LAADS!**

Virginia Sawyer et al., Remote Sensing, [https://doi.org/10.3390/rs12020308]

Status of MODIS and VIIRS

- **MODIS Collection 6.1 (MxD04) available from 2017**
  - All data reprocessed (2000 – 2017) use 'reprocessed' calibration for L1B,
  - >2017 data use 'step-forward' calibration for L1B
  - Data available in HDF4 format, scripts to convert to NetCDF4.
 - Provides 'reflectance' information for data assimilation
  - Includes Dark-Target / Deep Blue (DT/DB) merge product
  - Includes 3 km resolution product (MxD04_3K)
  - Level 3 (daily/monthly) = MxD08
  - Near Real Time (WorldView)
  - **We are funded for "maintenance"**

- **VIIRS Version 1.0 Dark-Target ('AERDT_VIIRS_SNPP') now available.**
  - All data (2011-present) use 'step-forward' calibration (no de-trending applied)
  - DT available in NetCDF4.   All output parameters same as MODIS
  - Deep Blue already ('AERDB') available since early 2019.
  - Currently, no DT/DB merge, but we could develop.
  - Testing on NOAA-20.
  - Level 3 (testing using Yori)
  - Near Real Time in production (will soon be in Worldview)
  - **We were not funded for VIIRS, but are leveraging other funds**

VIIRS on JPSS-1/NOAA-20 (02 Dec 2018)

MODIS-Aqua

VIIRS-SNPP

VIIRS-N20

QA–Filtered 0.55μm AOD
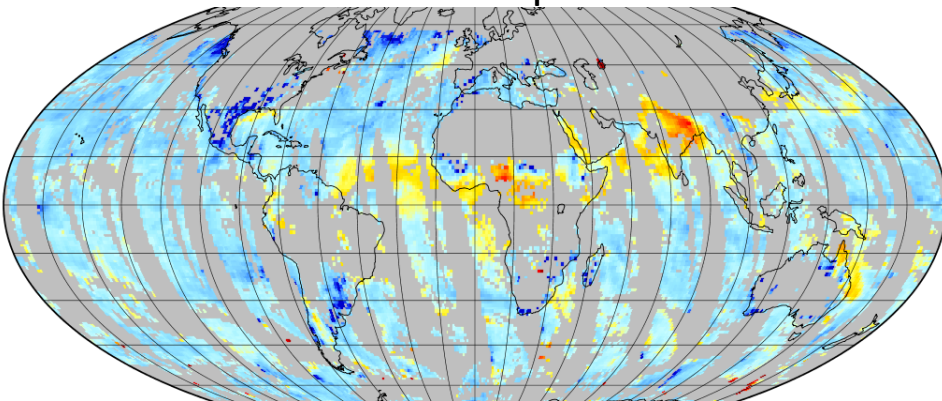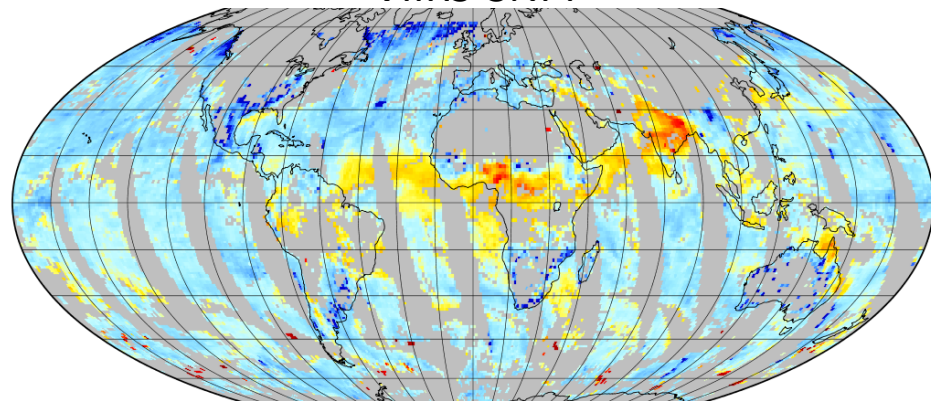
0.01   0.10   1.00
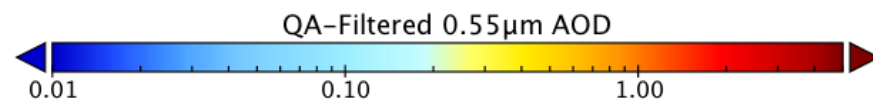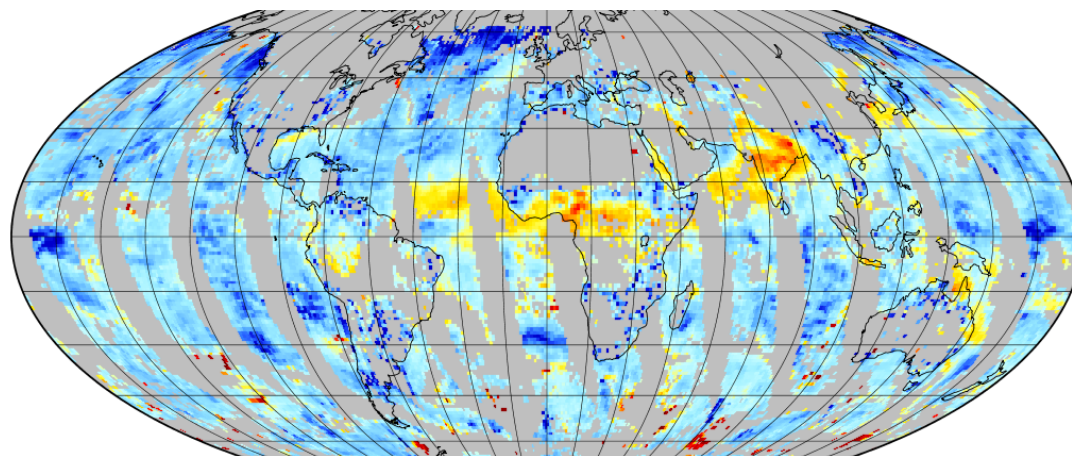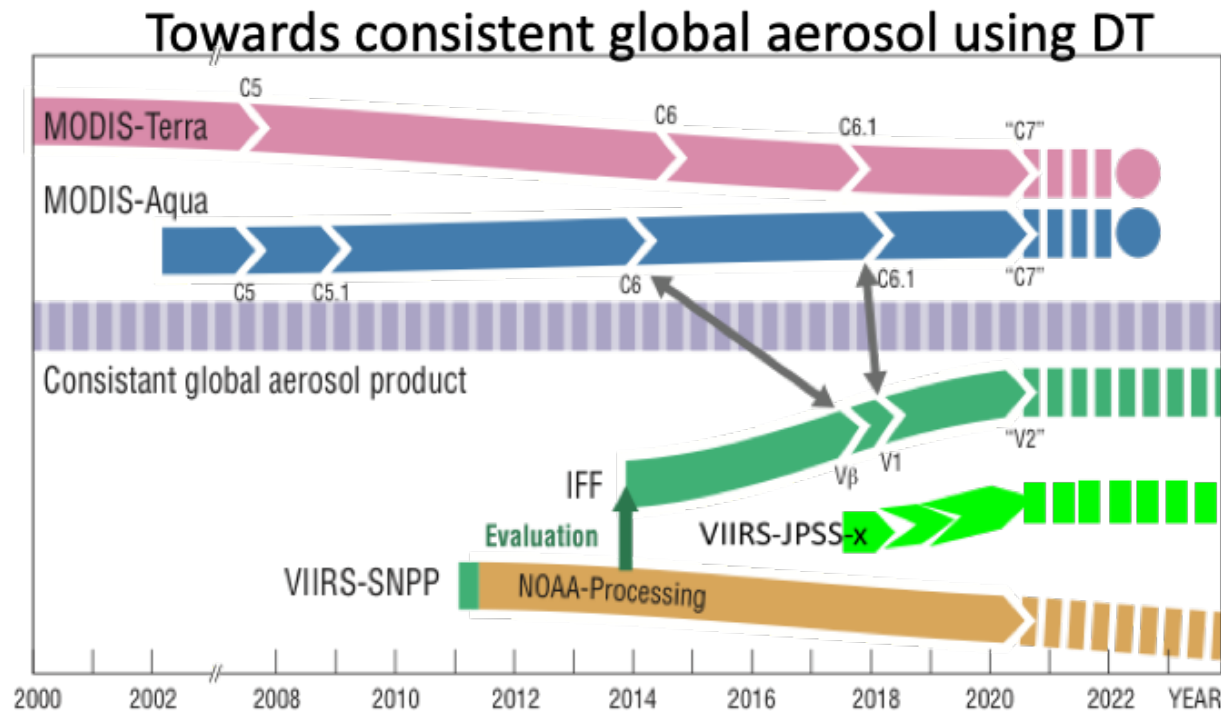
Towards Collection 7
(2 MODIS + 2 VIIRS → all LEO sensors)?

- Many "improvements" (if funded).

- "***The Package***" = Modular code that can run for any sensor and on multiple computer environments.

Towards consistent global aerosol using DT

LEO versus GCOS (for AOD)

Target metric	Target	Current with MODIS
Horizontal Resolution	5-10 km, globally	≤10 km over ice-free and cloud-free scenes
Accuracy	MAX(0.03 or 10%)	±(0.04+10%): Ocean ±(0.05+15%): Land
Stability / bias	<0.01 / decade	Nearly stable trends, but offsets still
Time Length	30+ years	Can do with MODIS + VIIRS
Temporal Resolution	4 h	2+ / day (Terra + Aqua/VIIRS)

Temporal variability??

% deviation in hourly AOD and AE relative to the daily means in Mexico City.

GOES-R, From Africa to New Zealand
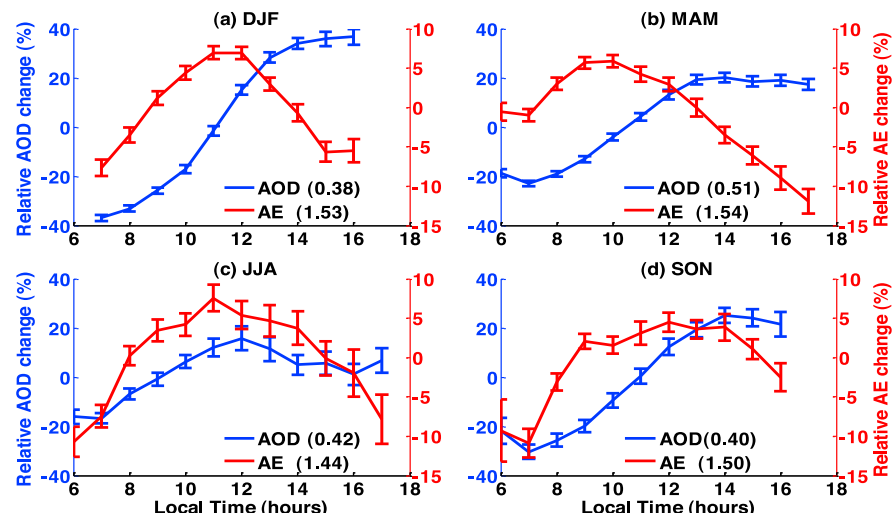
And west into Asia (Himawari)

ABI = Advanced Baseline Imager on GOES-16 (East) and GOES-17 (West)

AHI = Advanced Himawari Imager on Himawari-8 (Japan),

and

AMI = Advanced Meteorological Imager on KOMPSAT-2A (Korea)

(Pam Sullivan, NOAA/GOES-R program)

Every 10 minutes!

Expanding to GEO!

Spectral/Spatial: AHI / ABI ≈ MODIS / VIIRS

|	MODIS	VIIRS	AHI	ABI
Blue	0.47/0.5	0.49/0.75	0.47/1.0	0.47/1.0
Green	0.55/0.5	0.55/0.75	0.51/1.0	
Red	0.66/0.25	0.67/0.75	0.64/0.5	0.64/0.5
NIR	0.86/0.25	0.86/0.75	0.86/1.0	0.86/1.0
NIR	1.24/0.5	1.24/0.75		
Cirrus	1.38/0.5	1.38/0.75		1.38/2.0
SWIR	1.61/0.5	1.61/0.75	1.61/2.0	1.61/1.0
SWIR	2.11/0.5	2.25/0.75	2.25/2.0	2.25/2.0

Some details need to be worked out (e.g. lack of "cirrus" band on AHI);

Green band: MODIS/VIIRS @ 0.55 μm, AHI @ 0.51 μm, ABI @ none
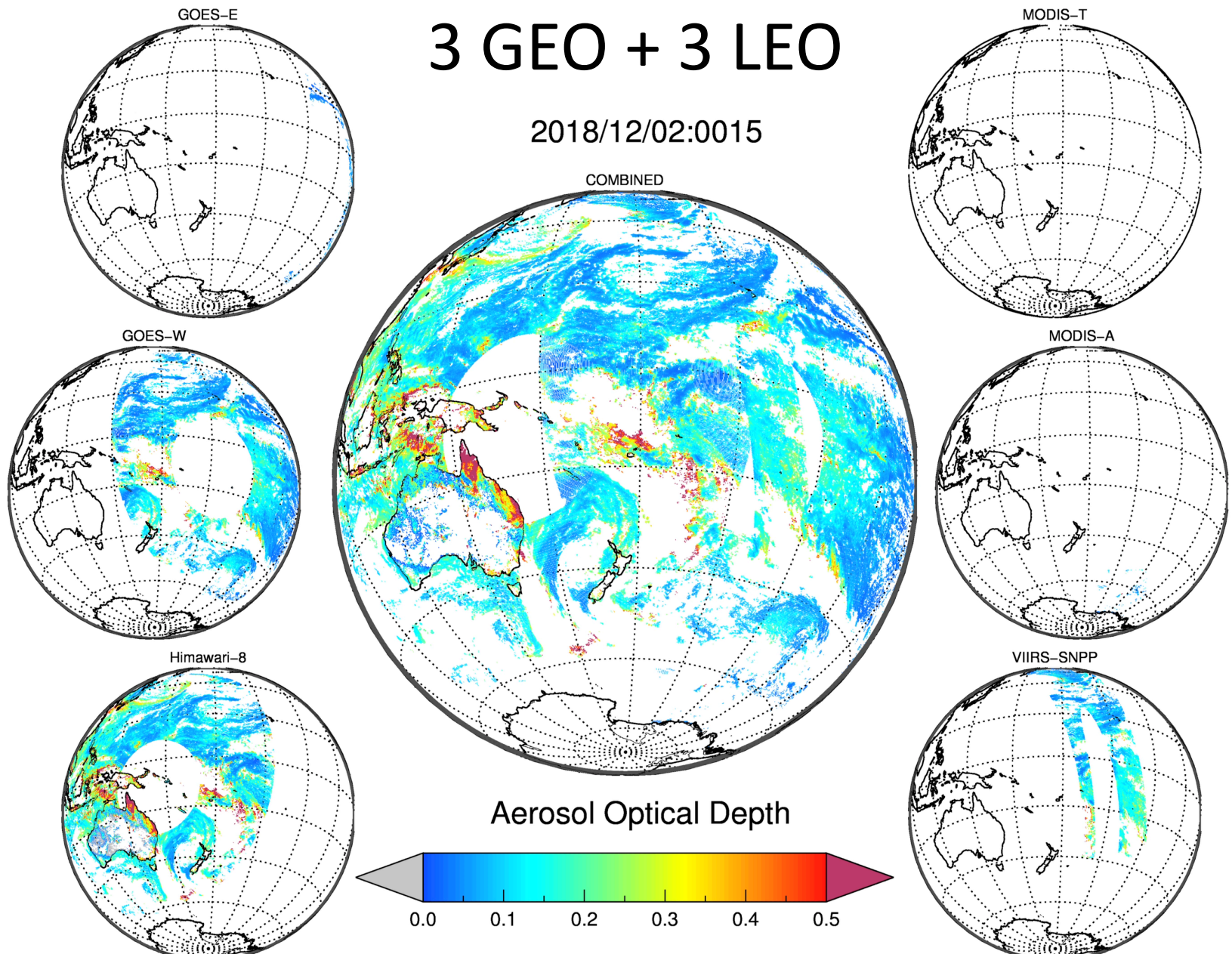
In the end, we will report AOD at 0.55 μm for everyone!

Same products as MODIS, including spectral AOD, cloud-cleared reflectance, etc
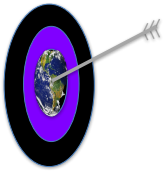
Introducing:
Dark Target on GEO (synergy with LEO)!

3 GEO + 3 LEO

2018/12/02:0015

GOES-E

MODIS-T

GOES-W

MODIS-A

COMBINED

Himawari-8

VIIRS-SNPP
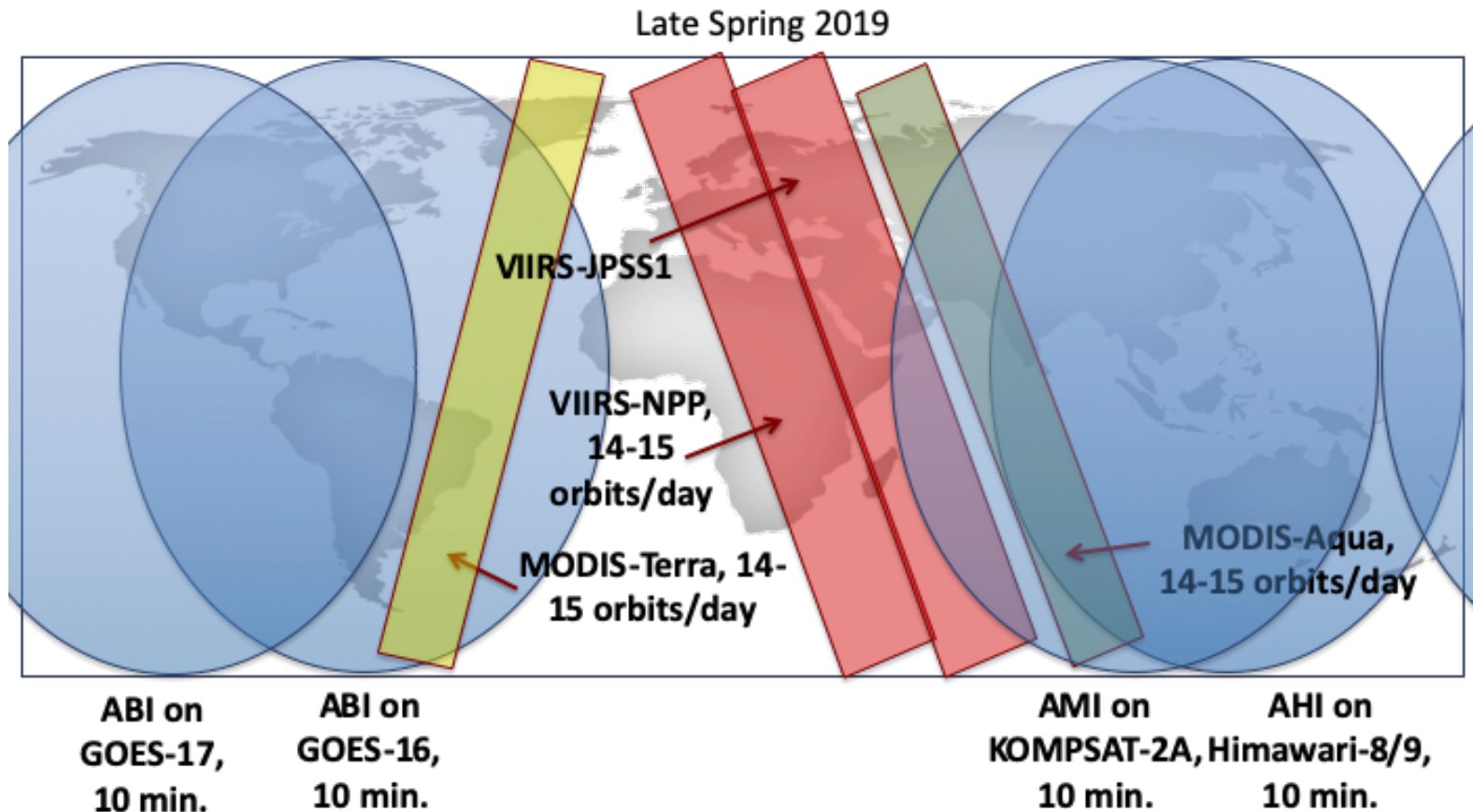
Aerosol Optical Depth

0.0   0.1   0.2   0.3   0.4   0.5

(Pawan Gupta)

Conclusion: Long and wide aerosol climatology

- **Aerosol Optical Depth (AOD) is an Essential Climate Variable**, and can be retrieved from passive sensors having sufficient observations of multi-spectral (VIS/NIR/SWIR) reflectance.

- The Dark Target algorithm, envisioned way before the launch of Terra 20 years ago, has been used to "start" the Climate Data Record (CDR) for AOD. There are 5 GCOS requirements for the CDR.

  - Collection 6.1 of MODIS (DT + DB) nearly meets requirements for spatial resolution and accuracy over non-ice/snow and cloud-free parts of the globe.

  - While there is still **10-15% global offset** between Terra and Aqua, similarity of nearly 20-year trends suggest meeting requirement for consistency/drift**.

  - Retrieval on **VIIRS** should extend time series beyond 30 years, meeting requirement for length.

  - Retrieval on **GEO sensors**, allows many regions to meet daytime temporal resolution.

- In addition to extending and expanding the aerosol data record, we can study fine scale aerosol using high-resolution (aircraft) and other remote sensing

Conclusion II: Long and wide aerosol climatology

- There are still **significant improvements that are possible** for DT algorithm and products

- Synergy with other algorithms, sensors and datasets

THANK YOU!

https://darktarget.gsfc.nasa.gov
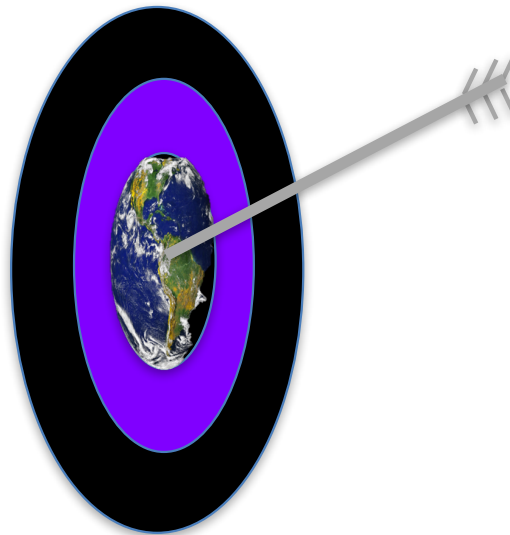
20-year trends – revisited
(but I want more years!)

Δ AOD per year where p ≤ 0.05