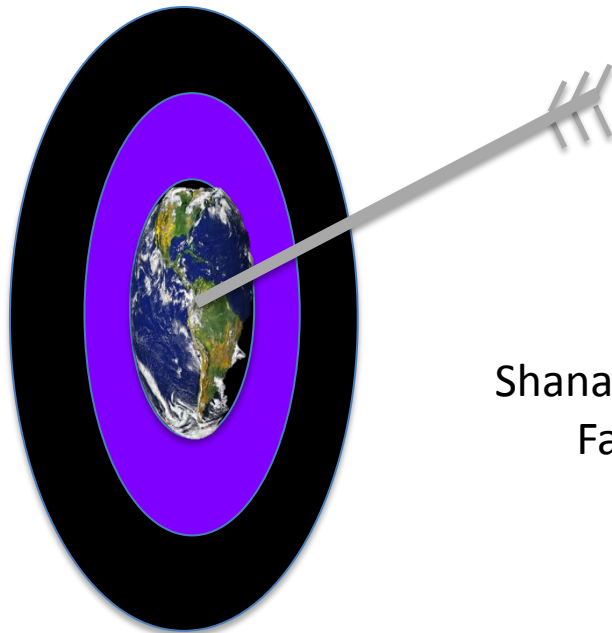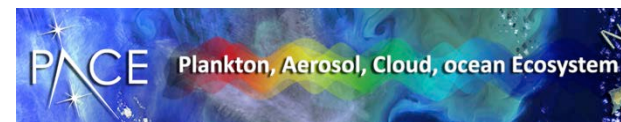# Creating a long (and wide) -term aerosol climate data record from passive satellite remote sensing

Robert C. Levy (NASA-GSFC)

Current "dark-target" group: * New in 2016.
Shana Mattoo, Virginia Sawyer* and Richard Kleidman (SSAI/GSFC)
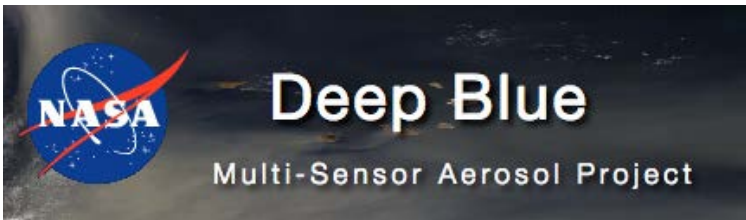Falguni Patadia and Yaping Zhou* (Morgan State U / GSFC)
Pawan Gupta and Yingxi Shi* (USRA/GSFC)
Lorraine Remer (UMBC/JCET)

AeroCom/AeroSat; Beijing, China; September 2016

Its not just dark-target algorithms based on MODIS

Slides and plots received/stolen from projects:

Slides, data and plots received/stolen from people:
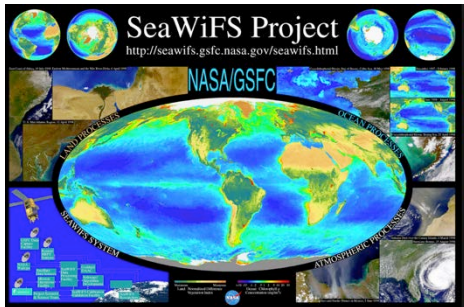Ralph Kahn, Omar Torres, Christina Hsu, Pete Colarco (NASA-GSFC)
Andy Sayer (USRA/GSFC)
Tom Zhou (NOAA-Maryland)
Andy Heidinger (NOAA-Wisconsin)
Mike Garay (NASA-JPL)
Tom Eck (JCET/GSFC)

And last years' AeroSat meeting

Some 10+ year passive satellite-based aerosol records in US

Variable(s)	Satellite	Time-Period	Who?
AOD (Dark-target) Ocean + land (dark)	MODIS → VIIRS	2000-?	GSFC
AOD (Deep-Blue) Land (all) + ocean	SeaWIFs/MODIS →VIIRS	1997-?	GSFC
AOD () Ocean + Land (dark)	VIIRS --> JPSS	2012-?	NOAA-STAR
AOD (AVHRR)	AVHRR	1980s -	Various (NOAA)
UV-AI	TOMS → OMI	1980s -	GSFC
SSA/AAOD	OMI	2005-	GSFC
AOD	MISR	2000-present	JPL/GSFC
Aerosol "type"	MISR	2000-present	GSFC
AOD/AE/etc	AERONET (ground!)	1990s-?	GSFC

GCOS Aerosol CDR* Requirements

Product A.10.1 Aerosol optical depth
Product A.10.2 Aerosol single scattering albedo

Product A.10.X Aerosol "type"

Product A.10.3 Aerosol layer height
Product A.10.4 Aerosol extinction profiles from the troposphere to at least 35km

Benefits

- Improved aerosol products, thereby leading to a reduction in uncertainty as to the quantitative role of aerosols in climate forcing identified by the IPCC;
- Improved products that are needed to validate and improve the capability of climate simulation models and reanalyses to represent aerosol effects.

Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Aerosol optical depth	5-10km	N/A	4h	Max (0.03; 10%)	0.01
Single-scattering albedo	5-10km	N/A	4h	0.03	0.01
Aerosol-layer height	5-10km	N/A	4h	1km	0.5km
Aerosol-extinction coefficient profile	200-500km	<1km near tropopause, ~2km in middle stratosphere	weekly	10%	20 %

European Space Agency

*CDR = Climate Data Record

Aerosol from space as a climate record

➤ Multiple aerosol parameters
➤ Aerosol optical depth (AOD or τ)
➤ "Essential Climate Variable" (ECV)
  ➤ As defined by GCOS
  ➤ Requires accuracy <±0.03
  ➤ Measured over multi-decades
  ➤ Stability of 0.01 / decade
➤ Yet, aerosol is mostly a "regional" problem.
  ➤ An ECV for each and every region?

➤ Also don't forget that our satellite data products are being used for near-real-time and air quality applications.
➤ E.g. do we need same stability for creating a PM2.5 exposure record?
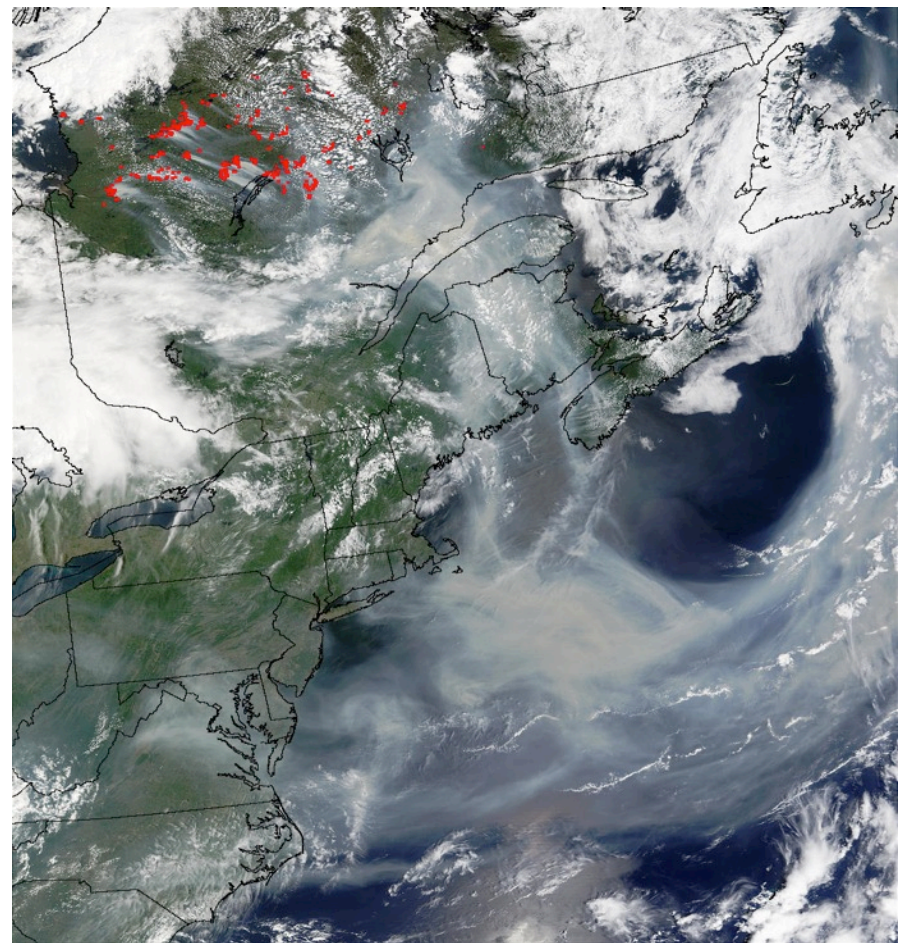
Smoke transported over Eastern Canada/USA (8 July 2002)

http://earthobservatory.nasa.gov/

Session 14
Long satellite records
Thomas's Seed Questions

Producing Satellite Climate Data Records (CDR)

1. How much do we need to do to produce climate quality?
2. How can we best characterize biases?
3. How can we produce consistent CDRs from different sources?
4. How many different satellite CDRs do we need /want?

Validating Satellite Climate Data Records (CDRs)

1. How can we validate stability with changing ground networks?
2. What can we do to validate early periods (1980s)?

Session 14
Long satellite records
Thomas's Seed Questions

Producing Satellite Climate Data Records (CDR)

3. How can we produce consistent CDRs from different sources?

Long satellite records
Main Issues (and examples)

0.   Consistency of **single instrument**
        MISR-Terra (and drift)

1.   Consistency of **subsequent instruments**
        MODIS-Terra vs MODIS-Aqua

2.   Consistency of **similar but differing instruments**
        SNPP VIIRS vs MODIS-Aqua
        AVHRR

3.   Consistency of **different retrieval algorithms**
        No examples today!

4.   Consistency of **reference datasets**
        AERONET

Long satellite records
Main Issues

0. Consistency of **single instrument**
    MISR-Terra (calibration)

Ten Years of Seasonally Averaged Mid-visible Aerosol Optical Depth from **MISR**
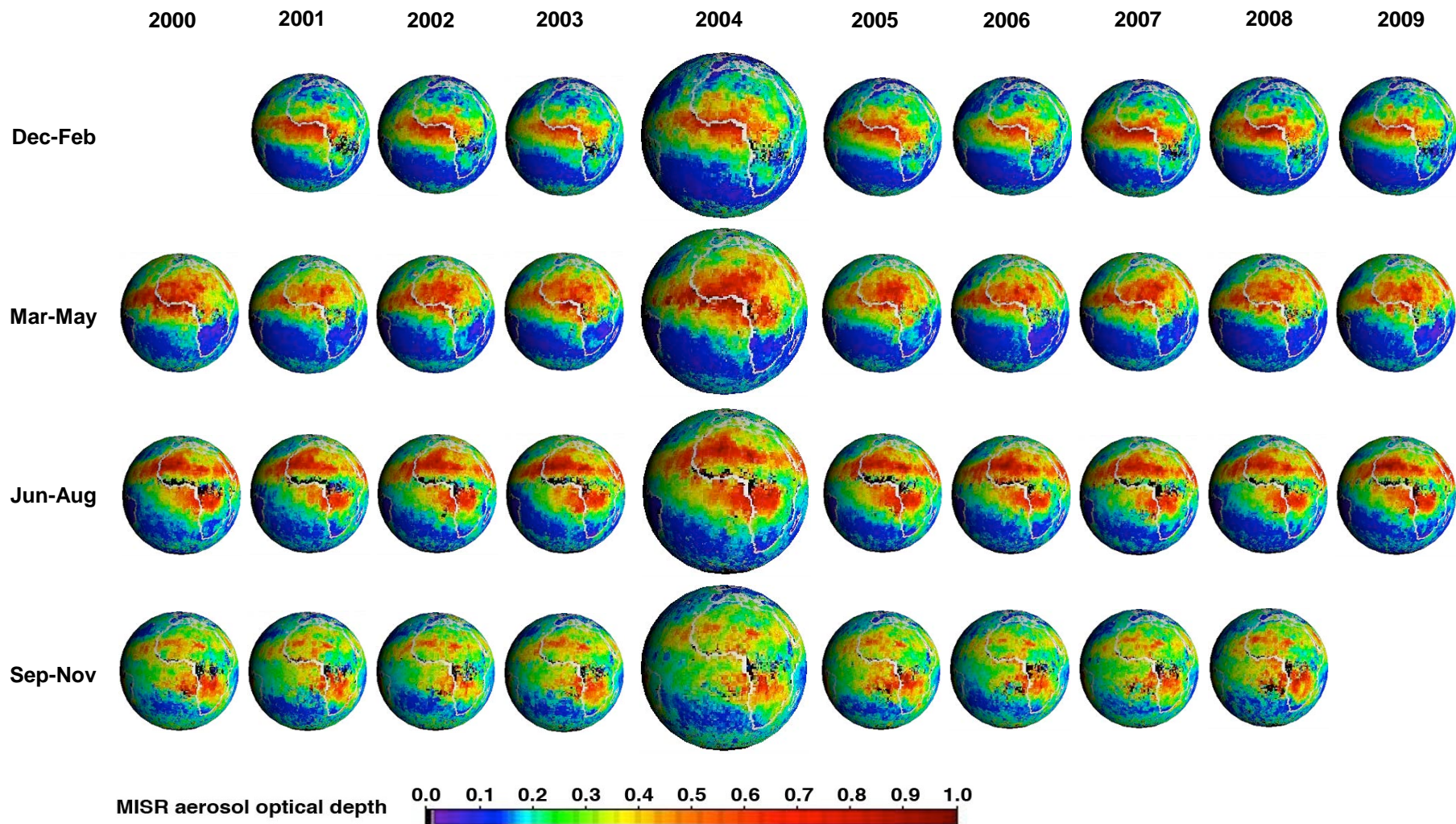
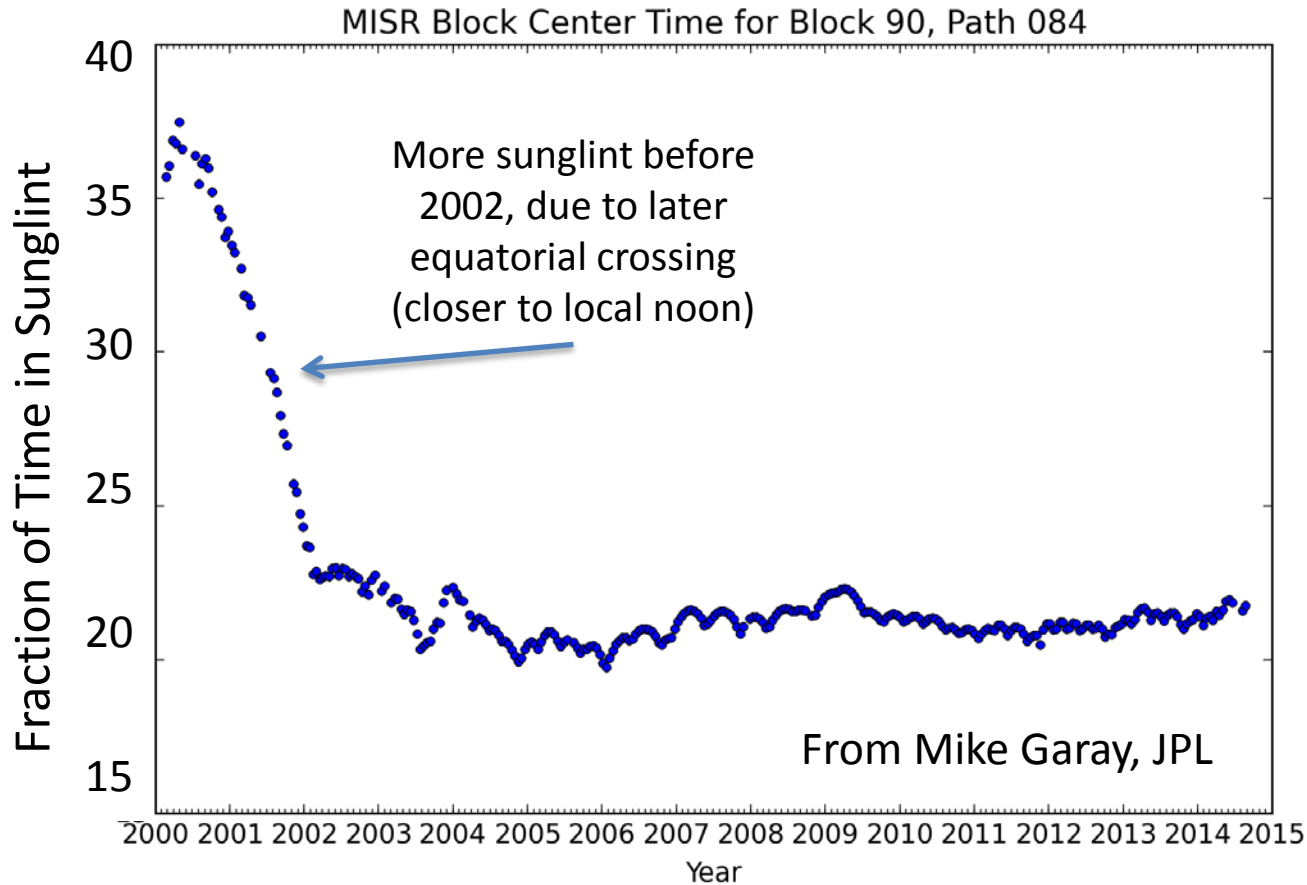*…Could this be a CDR? Can we detect AOD trends with confidence?*

MISR Team, JPL and GSFC

MISR Calibration Drift Per Decade
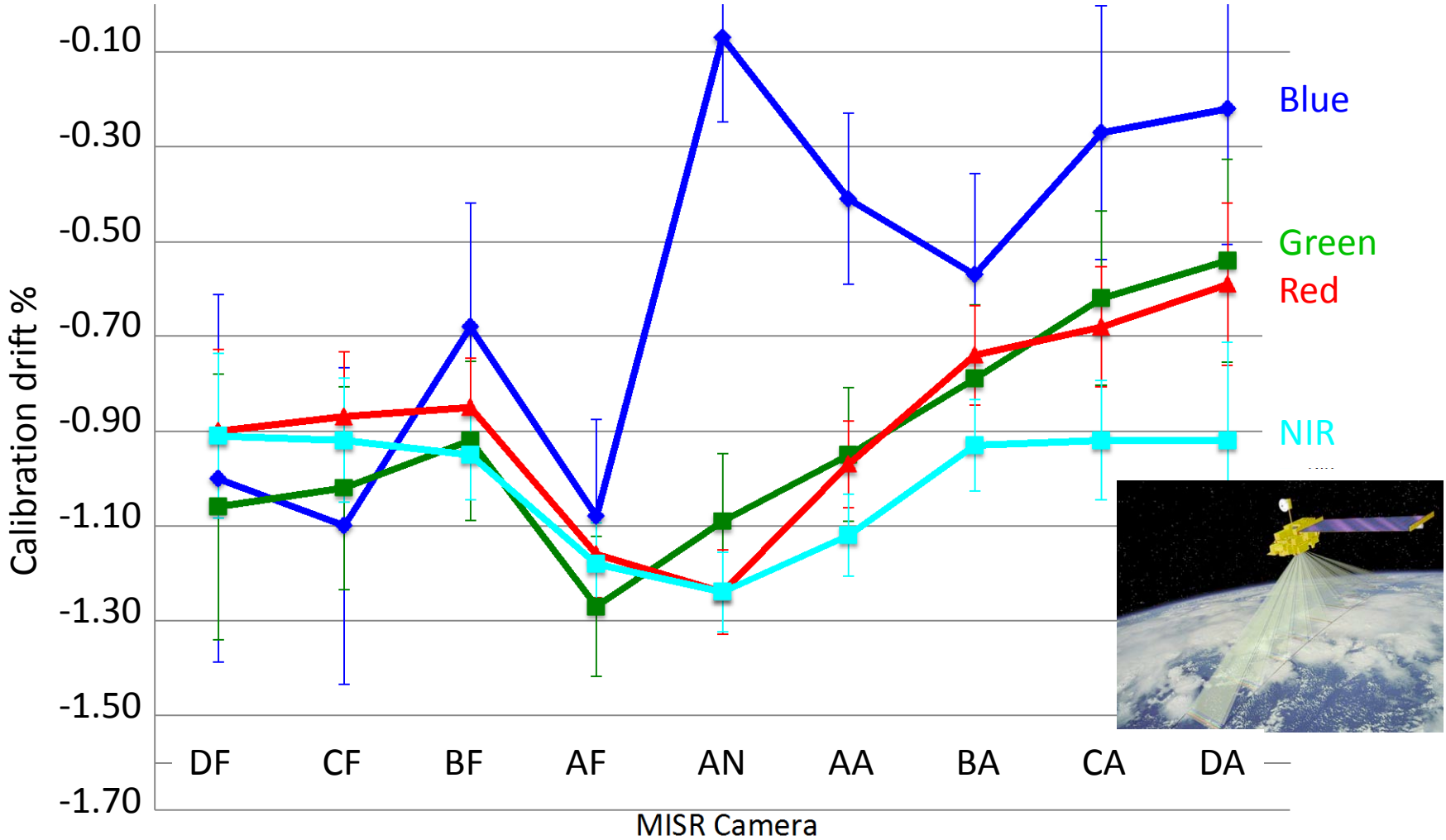
9 Cameras x 4 Spectral Bands, Assessed over 2002-2014
Based on time-series imagery of three relatively stable desert sites

1% of "typical" is approximately 0.001 in radiance, which is 0.01 in AOD

Sampling Issues: Equatorial Crossing Time (MISR)

MISR Block Center Time for Block 90, Path 084

More sunglint before 2002, due to later equatorial crossing (closer to local noon)

From Mike Garay, JPL

The equatorial crossing time of Terra has changed. Between 2000-2002 it changed by 15 minutes, then has been mostly stable since. This affects the statistics of scattering angles observed and sunglint patterns. For this particular MISR observation "block", there was more sunglint (fewer observations) in 2000

Long satellite records
Main Issues

1. Consistency of **subsequent instruments**
   MODIS-Terra vs MODIS-Aqua

MODIS-Terra vs MODIS-Aqua

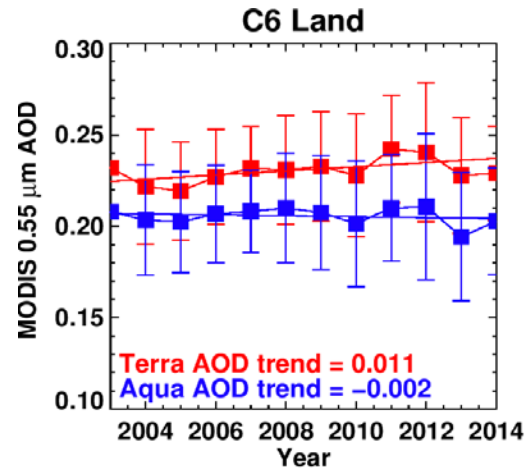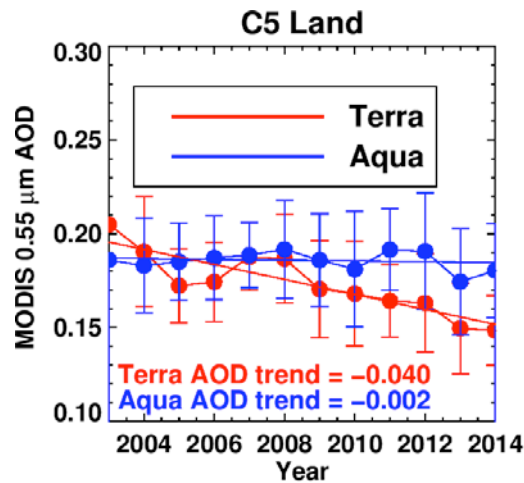Terra (10:30, Descending)
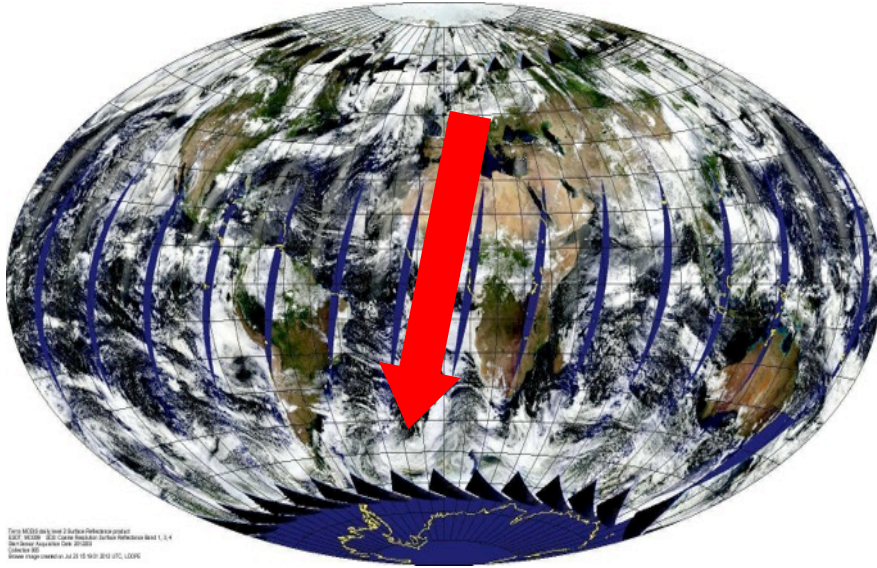
Aqua (13:30, Ascending)
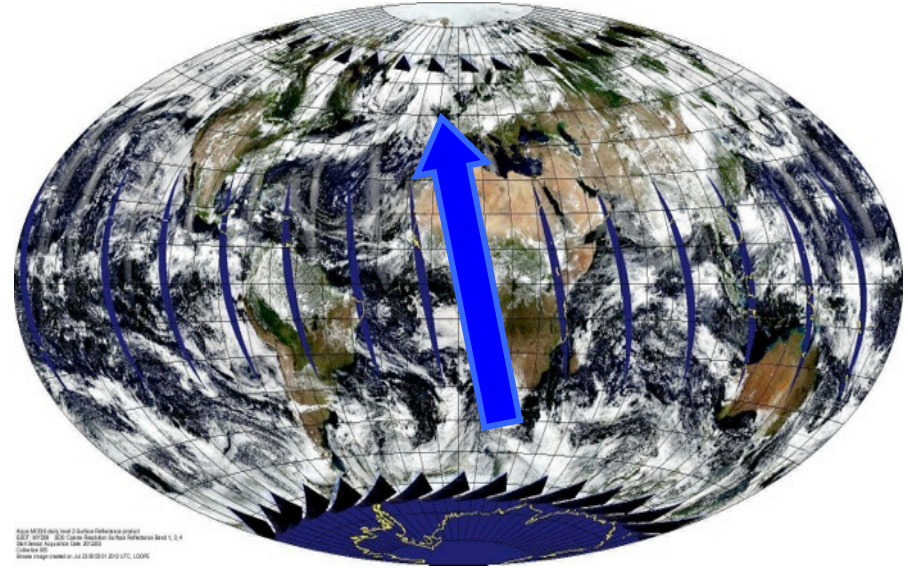
The two MODIS instruments are **<u>INDENTICAL TWINS!</u>**
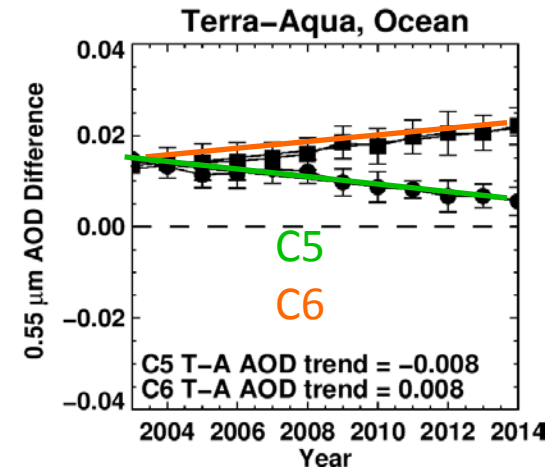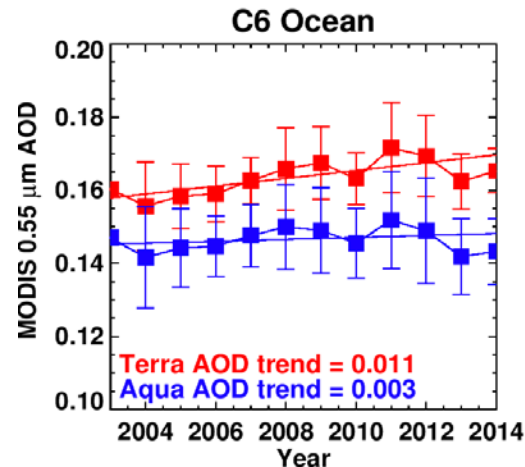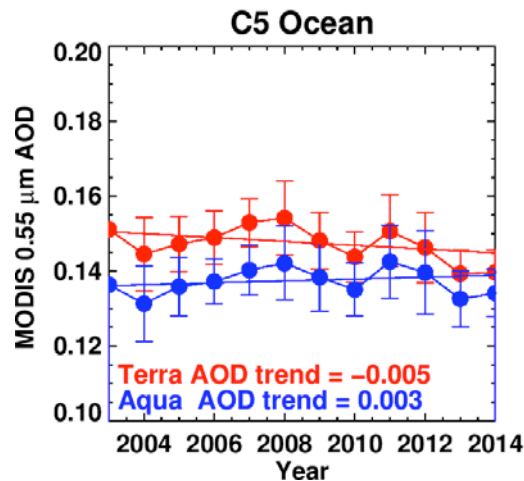Do they observe the world in the same way?

Time series of MODIS-derived AOD (DT algorithm)

$\Delta\tau = $ Terra - Aqua

LAND
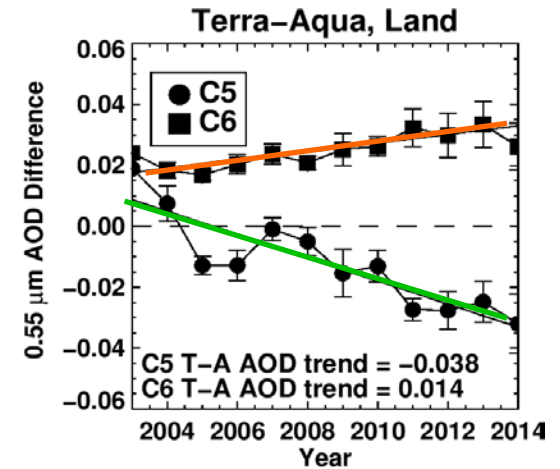
OCEAN

MODIS C6 calibration also tied to "bright surface"

Good news: Strong $\Delta\tau$ negative "trending" is reduced in C6

Bad news: 1) $\Delta\tau$ offset increases, and 2) there is now a positive trend

Should we expect an 0.02 offset between AM and PM?

# "Expected" $\Delta\tau$ differences due to AM/PM? What can model tell us?

- Motivated by Nick Schutgen's experiment
- For Terra and Aqua separately,
  - Create two "empty" grids (hourly and 0.5° x 0.625°)
  - Perform hourly aggregations of MODIS AOD
  - If valid MODIS pixels, populate one grid with MODIS data, and the other with GEOS-5 AOD.

- Compute:
  - $\Delta\tau$ for satellite (MODIS = Terra-Aqua)
  - $\Delta\tau$ for model (Model= AM-PM)

- Model version includes assimilation of meteorological variables and infrared /Microwave radiances, but not MODIS (no Terra or Aqua radiances)

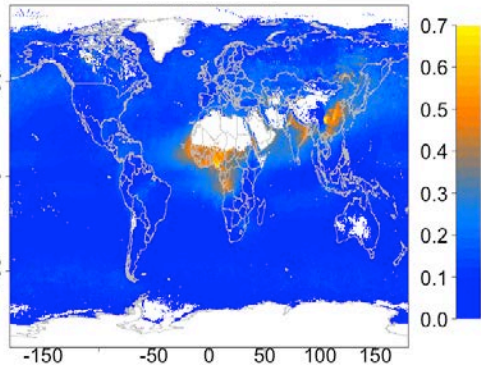Aggregated Dark Target 550nm AOD 2006-01-01 00:15:07

Pete Colarco and Virginia Sawyer
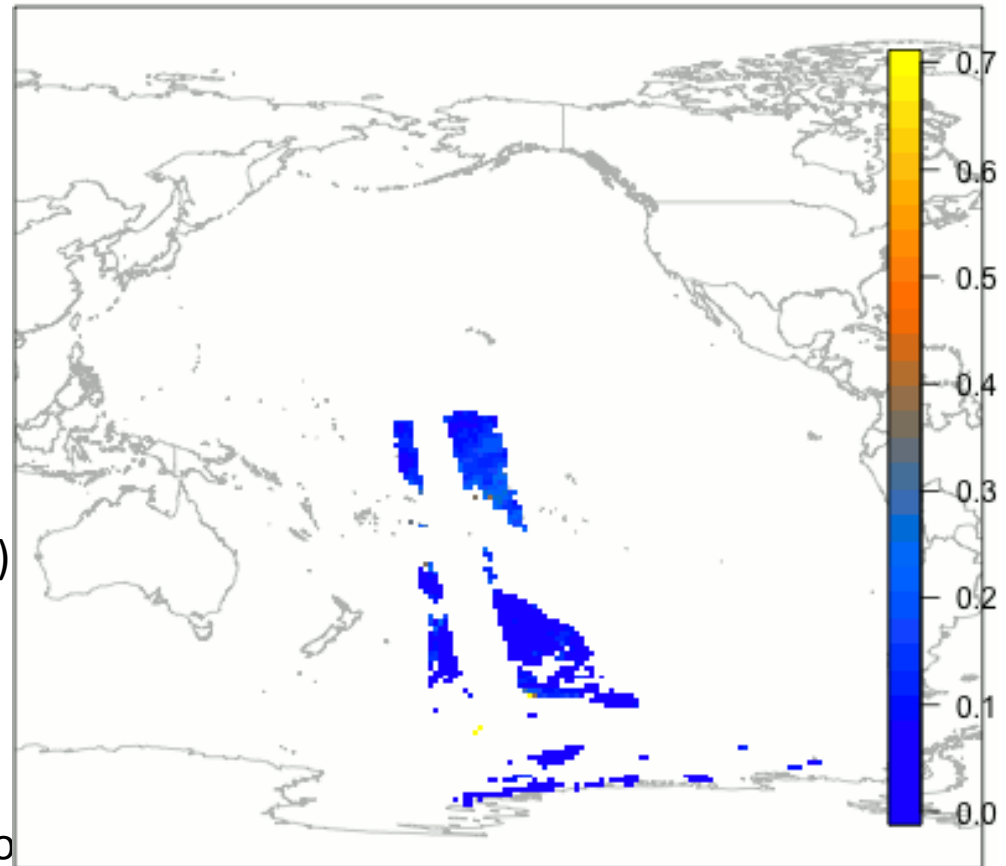
Δτ differences (AM-PM) during 2008
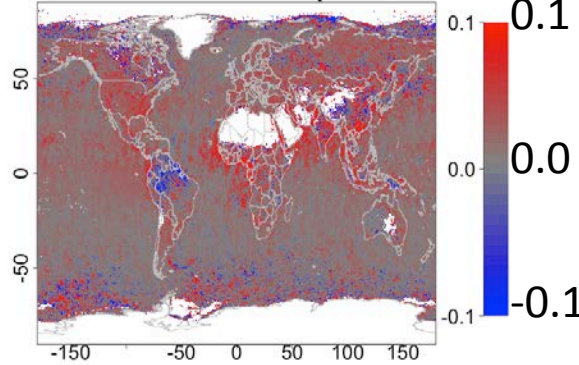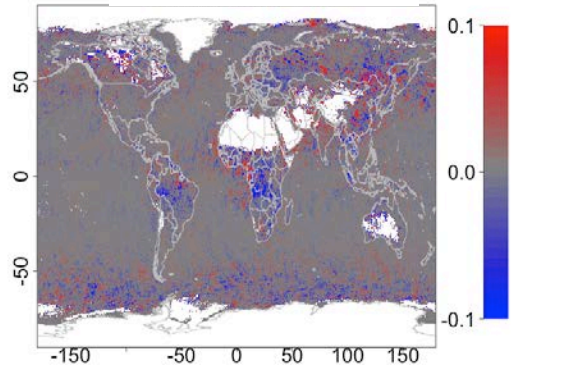

MODIS Aqua
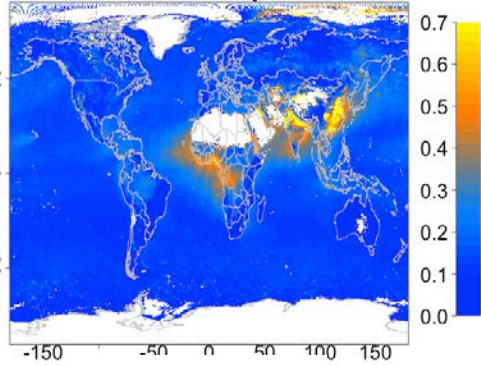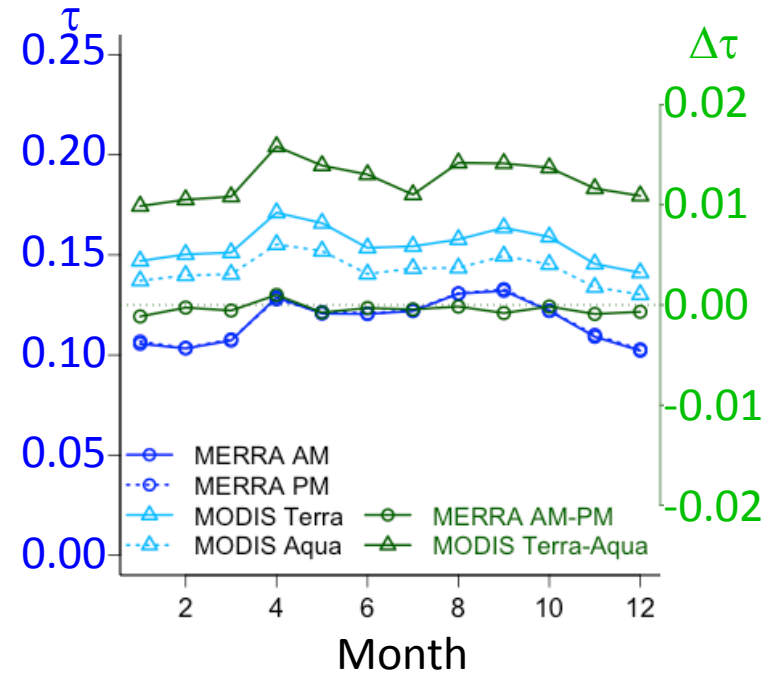
MODIS Terra-Aqua

MODEL PM

MODEL AM-PM

MODEL vs MODIS over Ocean

Land: Δτ for MODEL is both + and - (clouds?), while MODIS is mostly +,

Ocean: Δτ for MODEL is mostly zero, while MODIS is mostly +

→ AM-PM for MODIS is greater than AM-PM expected by MODEL

Presumably, we have run out of physical reasons for differences…

When all else fails.
Focus on the calibration → (C6+)?

- Trending issues reduced with MODIS DT C6 product, but:
  - Still significant offsets (13%) and
  - Still residual co-trending (<0.01 / decade)
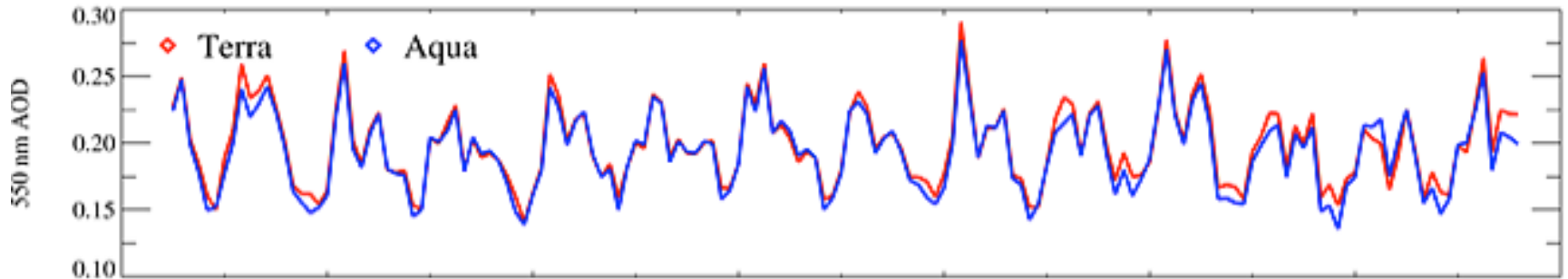
- **Calibration?**
  - Specs = ±2% (±0.002 reflectance)
  - ±0.002 reflectance → ±0.02 in AOD.
  - This is not good enough
  - Try: "C6+" of Lyapustin et al.,
    - (based on deserts, not Dark Targets)
    - Seems to halve the offset
    - C6+ only a few wavelengths → C6++

June 2013, land grid cells
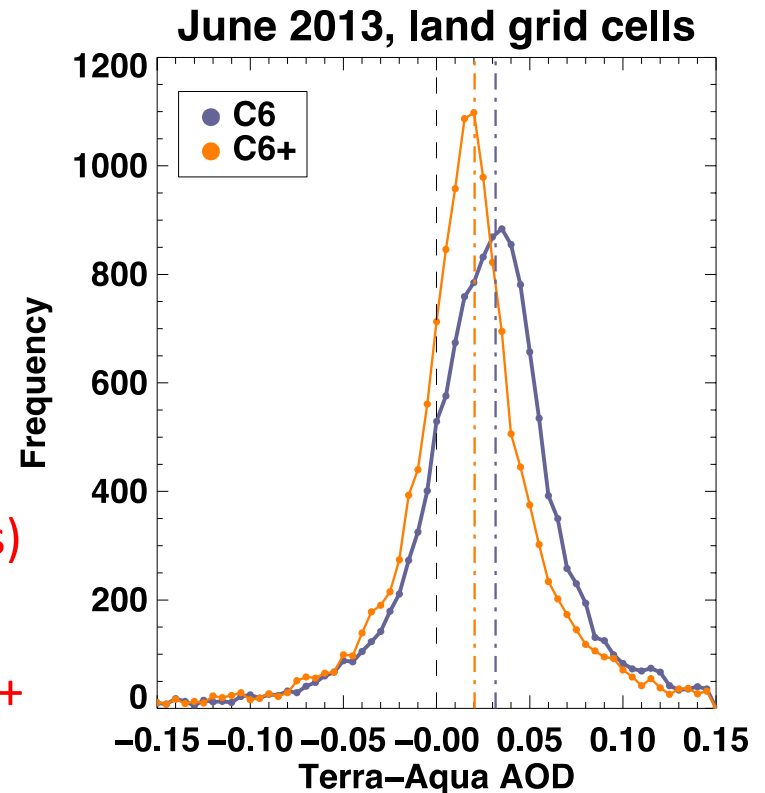
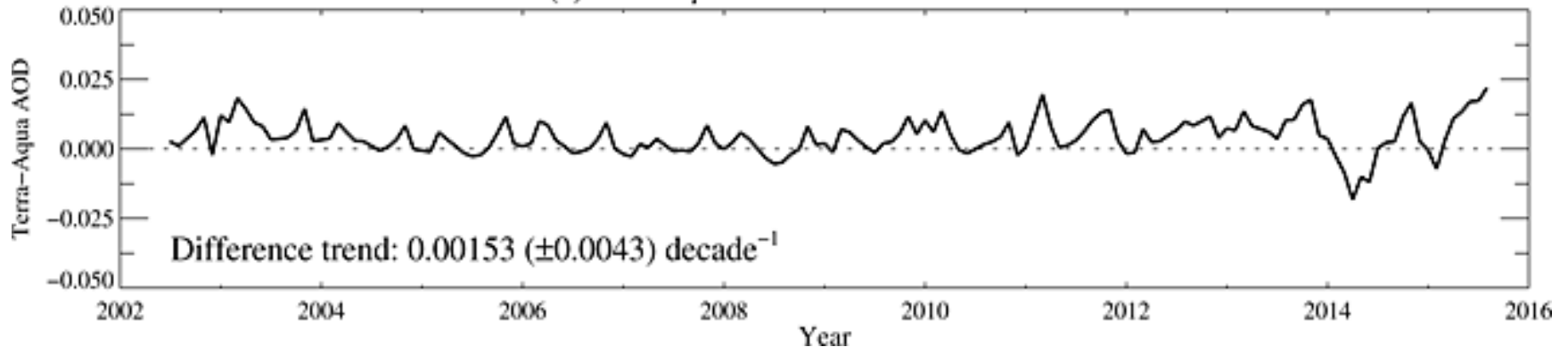# Effect of MODIS Terra radiometric calibration improvements on Collection 6 Deep Blue aerosol products: Validation and Terra/Aqua consistency

(a) Global area–weighted mean AOD

(c) Terra–Aqua AOD difference and decadal trend

Difference trend: 0.00153 (±0.0043) decade^{-1}

- DB already has some calibration improvements
- So that differences are less than half of DT
- But some increase in later years

Session 14
Long satellite records
Main Issues

3.   Consistency of **similar but differing instruments**
       SNPP VIIRS vs MODIS-Aqua
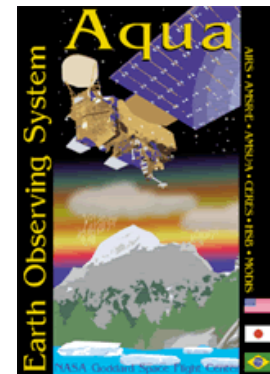   **AVHRR (super super long term!)**

VIIRS versus MODIS

Orbit: 825 km (vs 705 km)

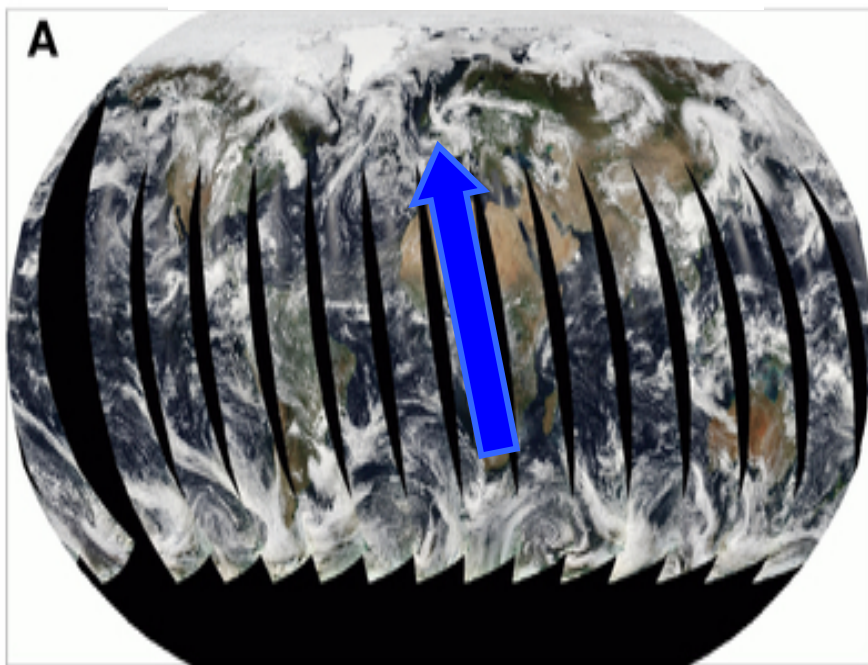**Swath**: 3050 km (vs 2030 km)

Spectral Range: 0.412-12.2μm (22 bands versus 36 bands)

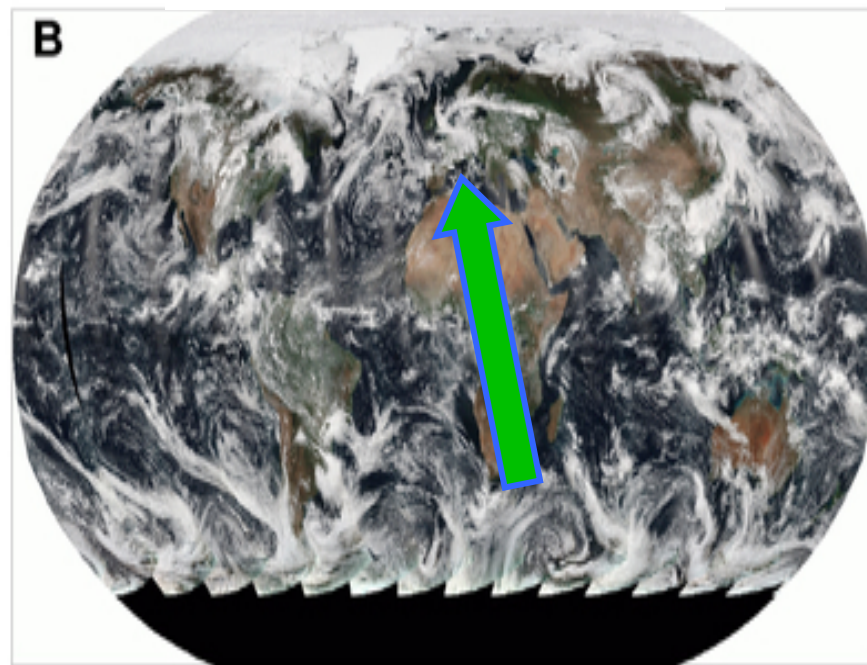**Spatial Resolution**: 375m (5 bands) 750m (17 bands): versus 250m/500m/1km

Wavelength bands (nm) / DT aerosol retrieval: 482 (466), 551 (553) 671 (645), 861 (855), 2257 (2113) → differences in Rayleigh optical depth, surface optics, gas absorption.

MODIS-Aqua – 29 May 2013

VIIRS-SNPP – 29 May 2013

To develop "continuity" Port algorithms! (Example: DT from MODIS→VIIRS)

Wavelength bands & surface spectra
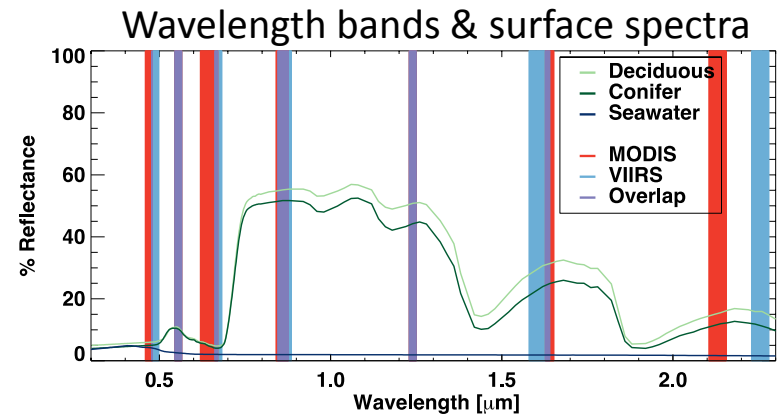
- Deal with differences in wavelengths (gas corrections/Rayleigh, etc)
- Retrieve on VIIRS (compared with retrieval on MODIS):
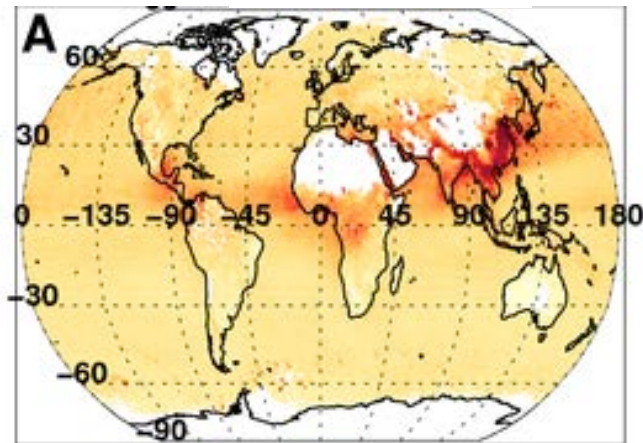
DT on MODIS   DT on VIIRS   Difference M - V

- Darn! There is a systematic bias over ocean (VIIRS high by 20%).

Levy et al., 2015

Calibration: Match files (VIIRS vs Aqua)

- Can we "prove" calibration differences? It's hard!
  - Differences in orbit → no true matches inside ±70° latitude
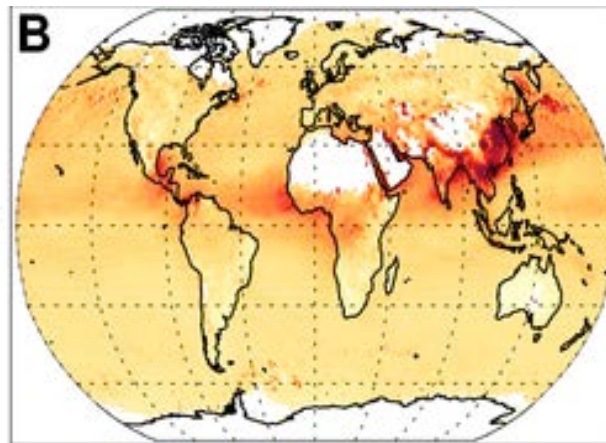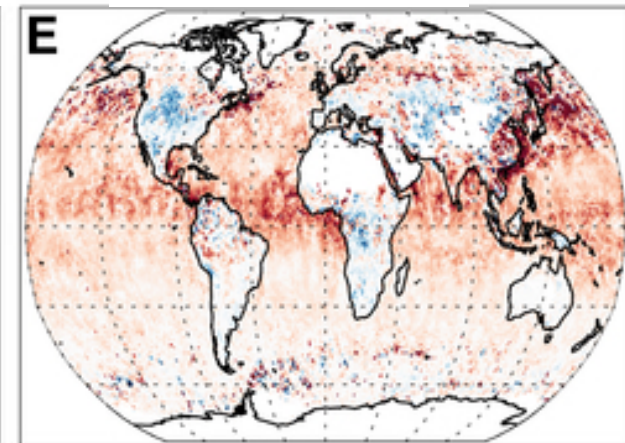 - Common geometry is very limited
  - University of Wisconsin is creating match files to analyze

Close overpass (space and time) between Aqua and SNPP near the Kamchatka Peninsula and surrounding waters.
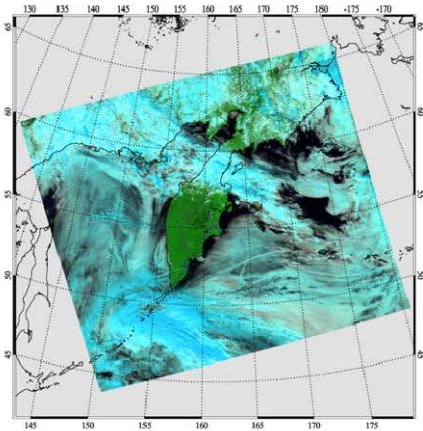
MODIS False Color
(Bands 7, 2, 1)
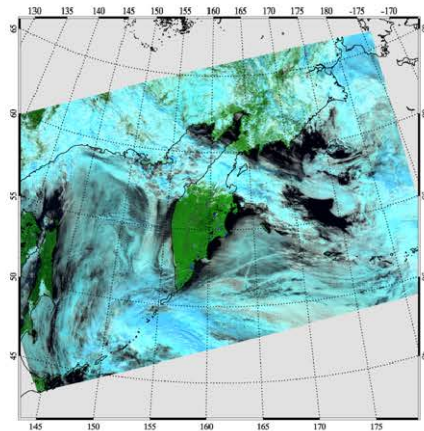
VIIRS False Color
(M11, M7, M5)
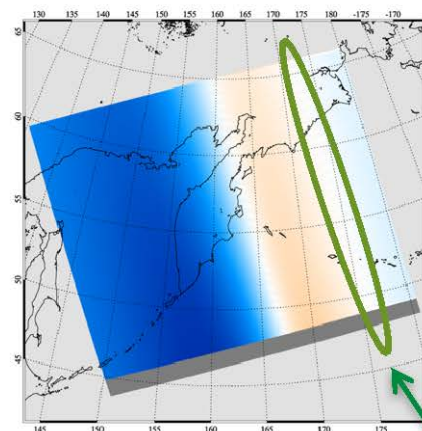
IFF-Aqua - IFF-NPP Scattering Angle Difference (degrees)
-10 -8 -6 -4 -2 0 2 4 6 8 10
Scattering Angle
Difference
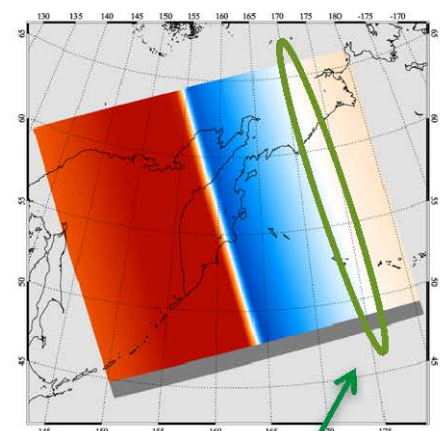
IFF-Aqua - IFF-NPP Sensor Zenith Angle Difference (degrees)
-10 -8 -6 -4 -2 0 2 4 6 8 10
Sensor Zenith Angle
Difference

6 July 2014

"common" geometry/angles

Steve Platnick, Bob Holz, Kerry Meyer, et al

Calibration: Match files (2)

- slight differences in wavelength
- Account for Rayleigh and gas absorption differences
- Clouds everywhere; hard to find mutual cloud free.
- But after careful matching…
- Get new "gain" coefficients for VIIRS
- Andy has already written a paper!!!
- But we still need to test and validate

Reflectance: VIIRS vs MODIS
"Matched" data from 2014-2015

$y = 1.19x + 0.0003; R^2 = 0.55$
1-1 line

Note: Cloud mask applied for MODIS, but not VIIRS

VIIRS 865 (Band M7)

MODIS 858 (Band 2)

N = 65914
8
101
1320
17200

Example: 0.86 μm channel over "clear" sky

T   LBLRTM   Transmission   VIIRS M7   MODIS B2

VIIRS M7
MODIS B2

0.80   0.82   0.84   0.86   0.88   0.90   (λ: μm)

(g) 865 nm (M07)

VIIRS 865 should be multiplied by:

Vicarious Gain to apply

'12   '13   '14   '15   '16   2017
Year

Sayer et al., AMTD 2016
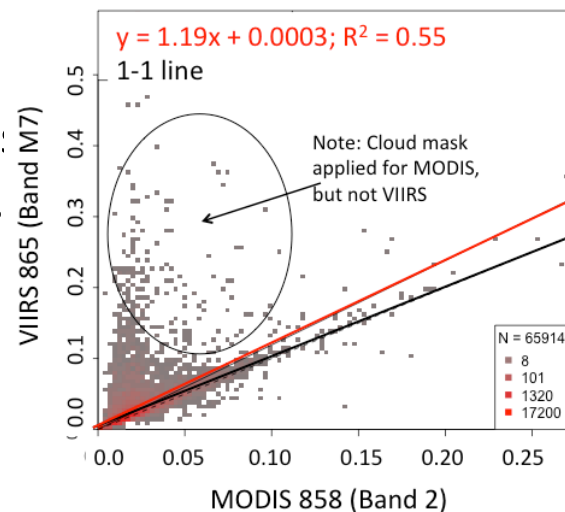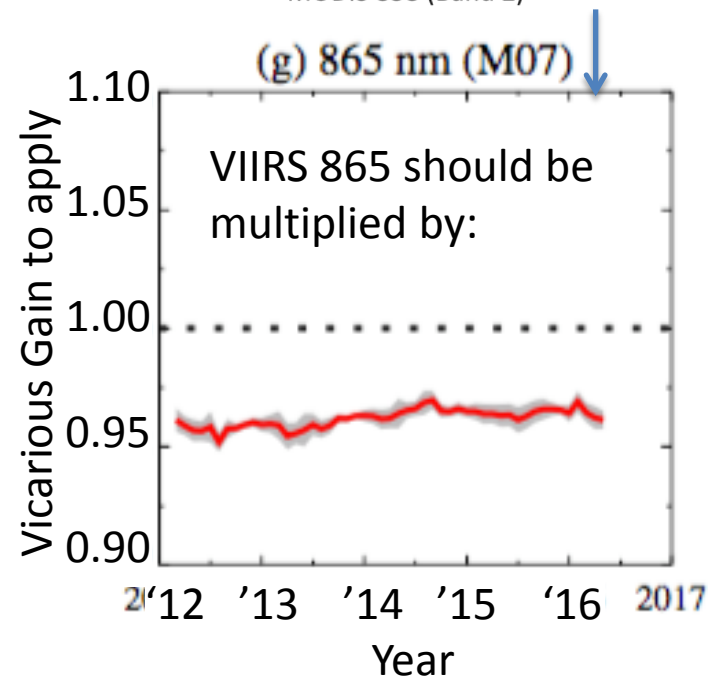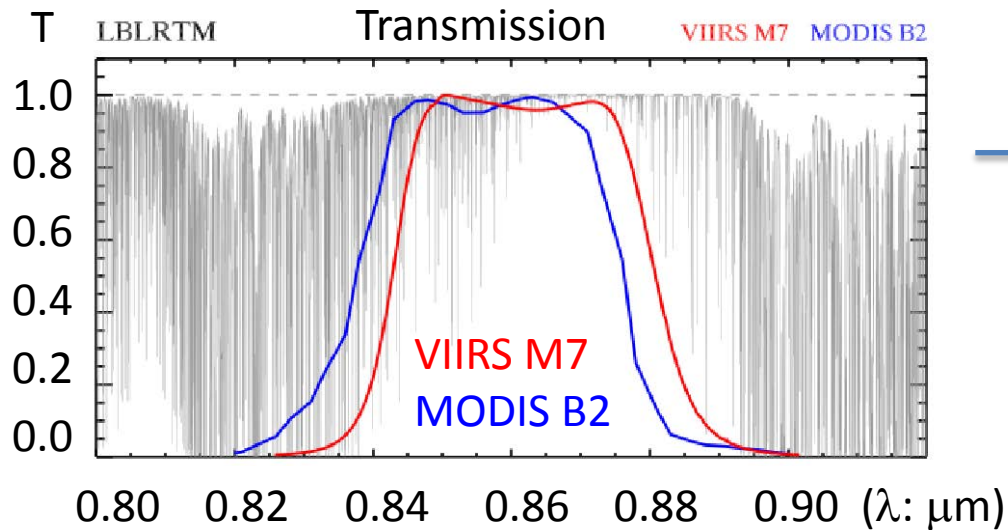
MODIS vs VIIRS (or two similar instruments)

- MODIS-Aqua/NPP-VIIRS = Not identical twins, but
  - At least orbits are "close"
  - The instruments both have calibrations and calibration teams that monitor them.
  - For both DT and DB retrieval algorithms, there is great portability.
- Now, how about three or more instruments!
  - Much harder
  - Also, how do we create datasets back to the 1980s?

Long-long time series from AVHRR
(things to note from PATMOS-x Cloud)

Satellite equatorial crossing

- Satellite crossings all over the place.

- Calibration much less precise than MODIS

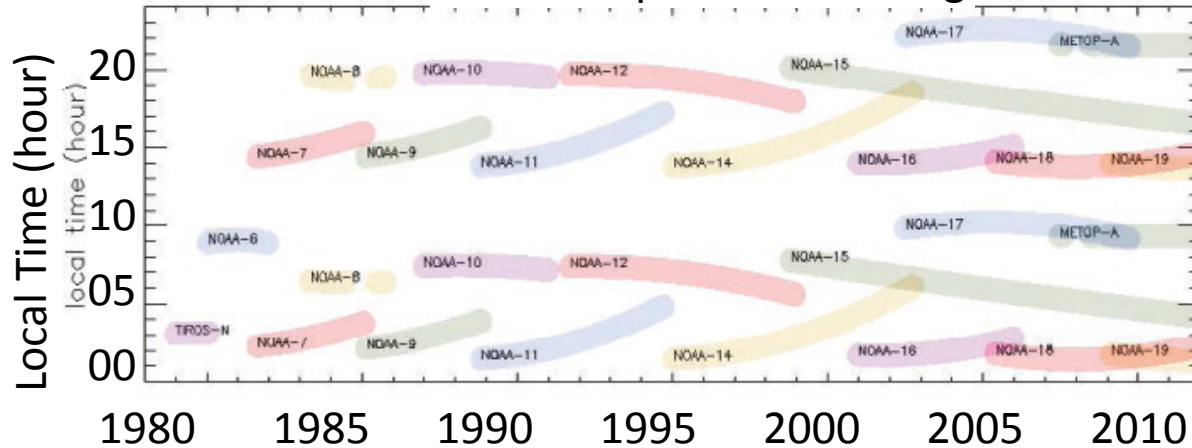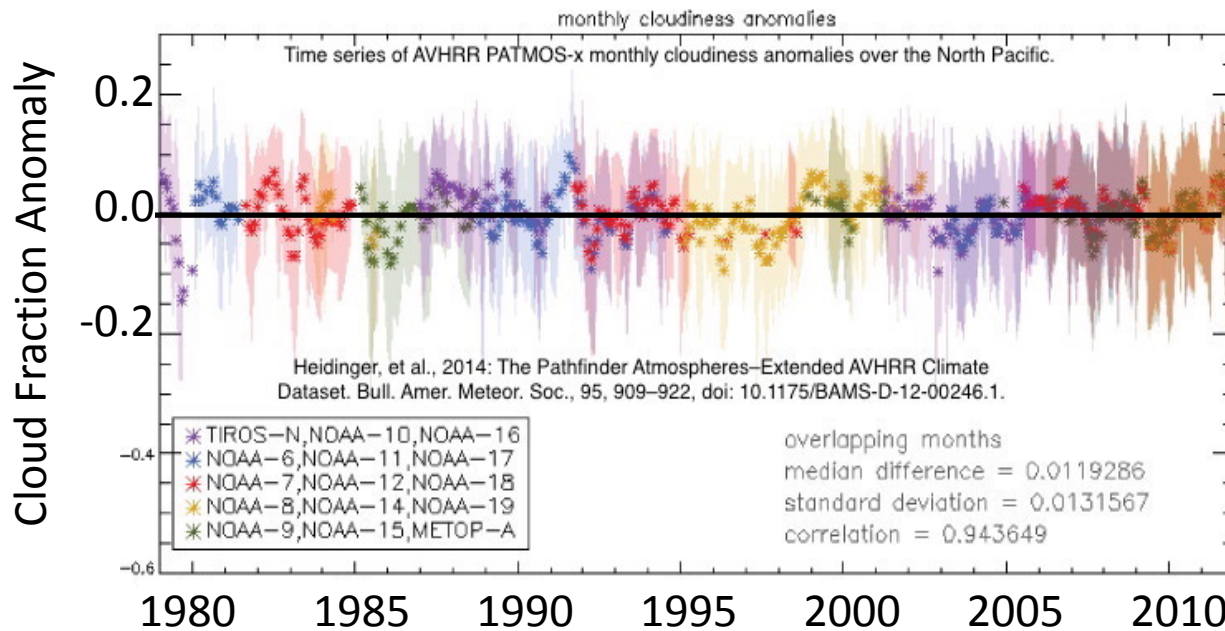- Requires lots of work in homogenizing

- These figures are for deriving long-term cloudiness.

- We can learn from these folks

monthly cloudiness anomalies

Time series of AVHRR PATMOS-x monthly cloudiness anomalies over the North Pacific.

Heidinger, et al., 2014: The Pathfinder Atmospheres–Extended AVHRR Climate Dataset. Bull. Amer. Meteor. Soc., 95, 909–922, doi: 10.1175/BAMS-D-12-00246.1.

* TIROS-N,NOAA-10,NOAA-16
* NOAA-6,NOAA-11,NOAA-17
* NOAA-7,NOAA-12,NOAA-18
* NOAA-8,NOAA-14,NOAA-19
* NOAA-9,NOAA-15,METOP-A

overlapping months
median difference = 0.0119286
standard deviation = 0.0131567
correlation = 0.943649

Heidinger et al., 2014.

NOAA AVHRR AOT Climate Data Record (CDR)

(www.ncdc.noaa.gov/cdr/atmospheric/avhrr-aerosol-optical-thickness)

Tom Zhao, NOAA/NESDIS/NCEI

- CDR Product: AOT at 0.63μm

- Spatial coverage: global ocean (-60ºS–60ºN)

- Spatial resolution: 0.1ºx0.1º

- Temporal coverage: 1981-2016

- Temporal resolution: daily and monthly

- Independent 2-channel algorithm

- Retrieval quality is degraded beyond -60ºS–60ºN & AOT will not be considered as CDR

AOT Time Series

Long-term Averaged AVHRR AOT at 0.63 micron
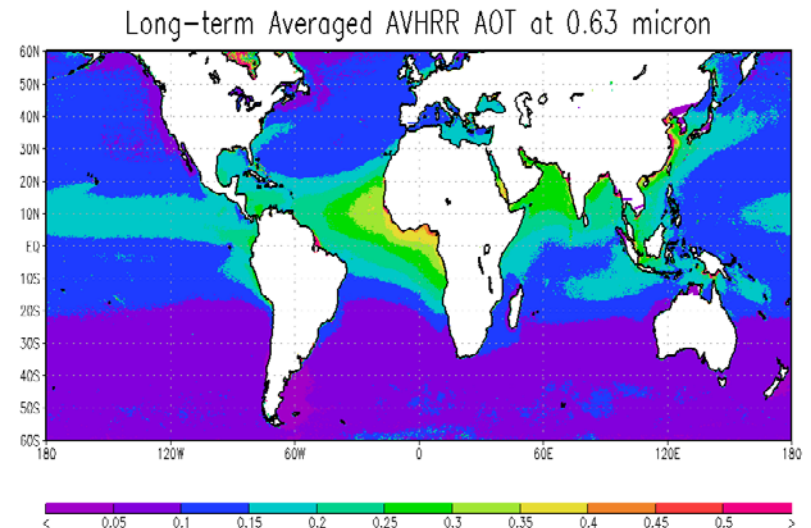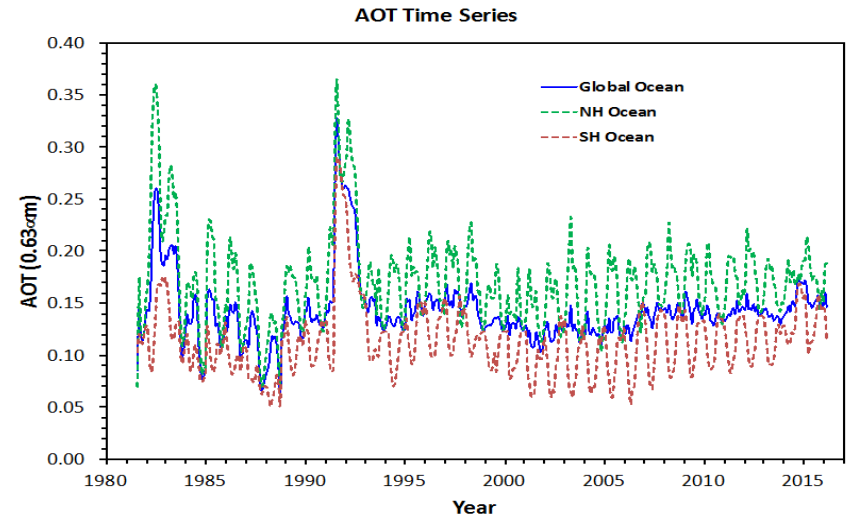
Application Example-1: Trend Detection

AOT Long-term Trend and Significance

(a) Trend of AOT (1/decade)

(b) Significance of Trend
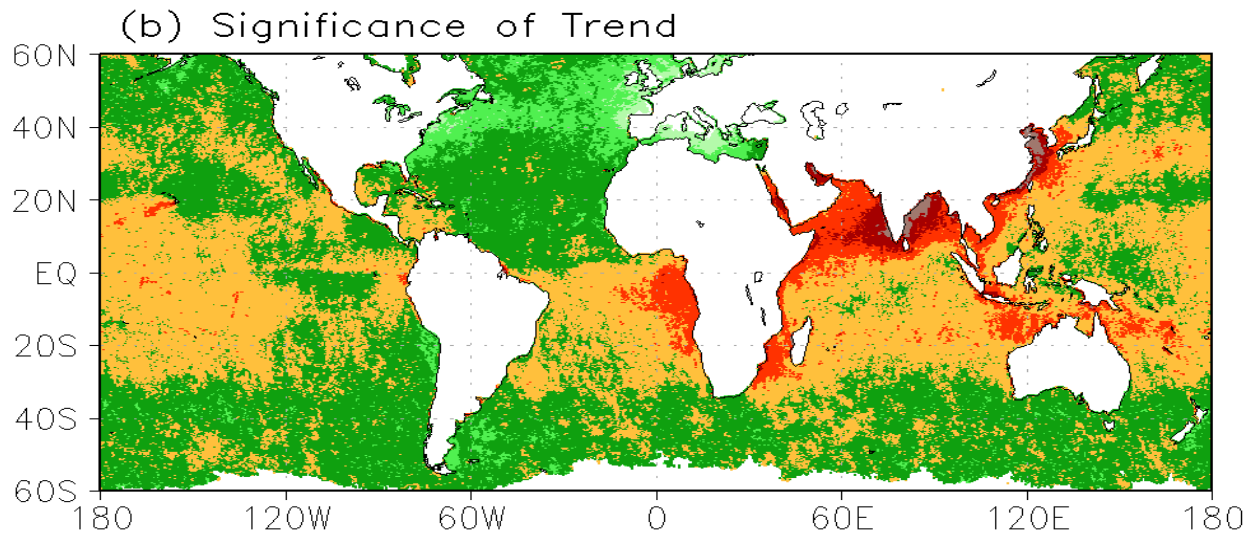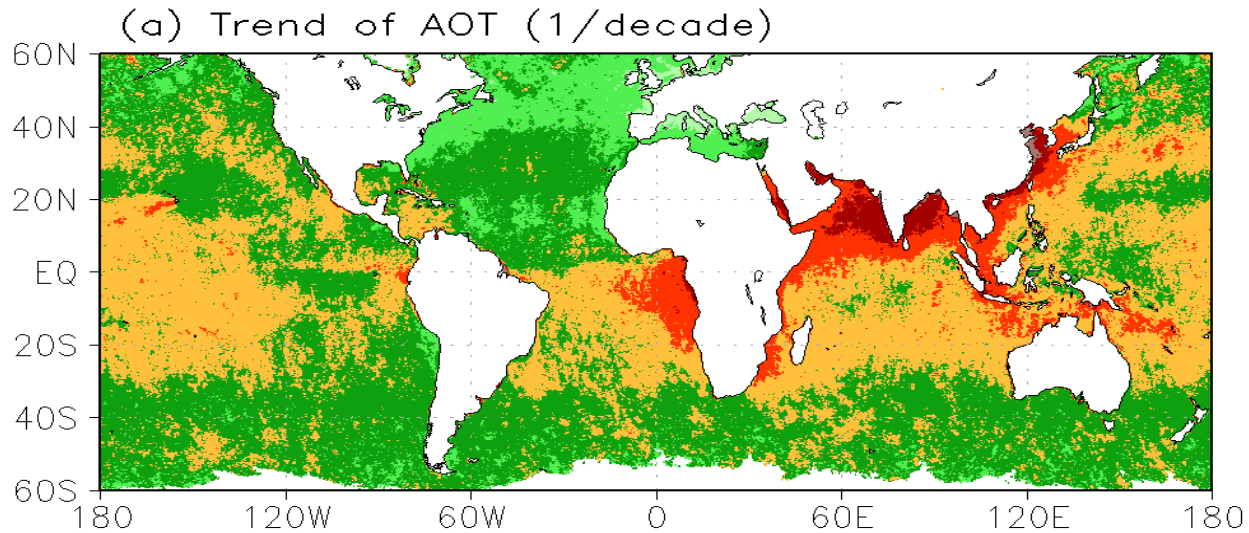
Long satellite records
Main Issues (and examples)

4. Consistency of **reference datasets**
   AERONET

We would like to think of AERONET as "ground truth"...

Aerosol Robotic Network (AERONET)

AERONET (L2) Global Stats

	AOD	Transmittance
Mode	0.050	95%
Median	0.108	90%
Mean	0.178	84%
95%	0.600	55%
Max	5.775	0.3%

Mike Garay, JPL
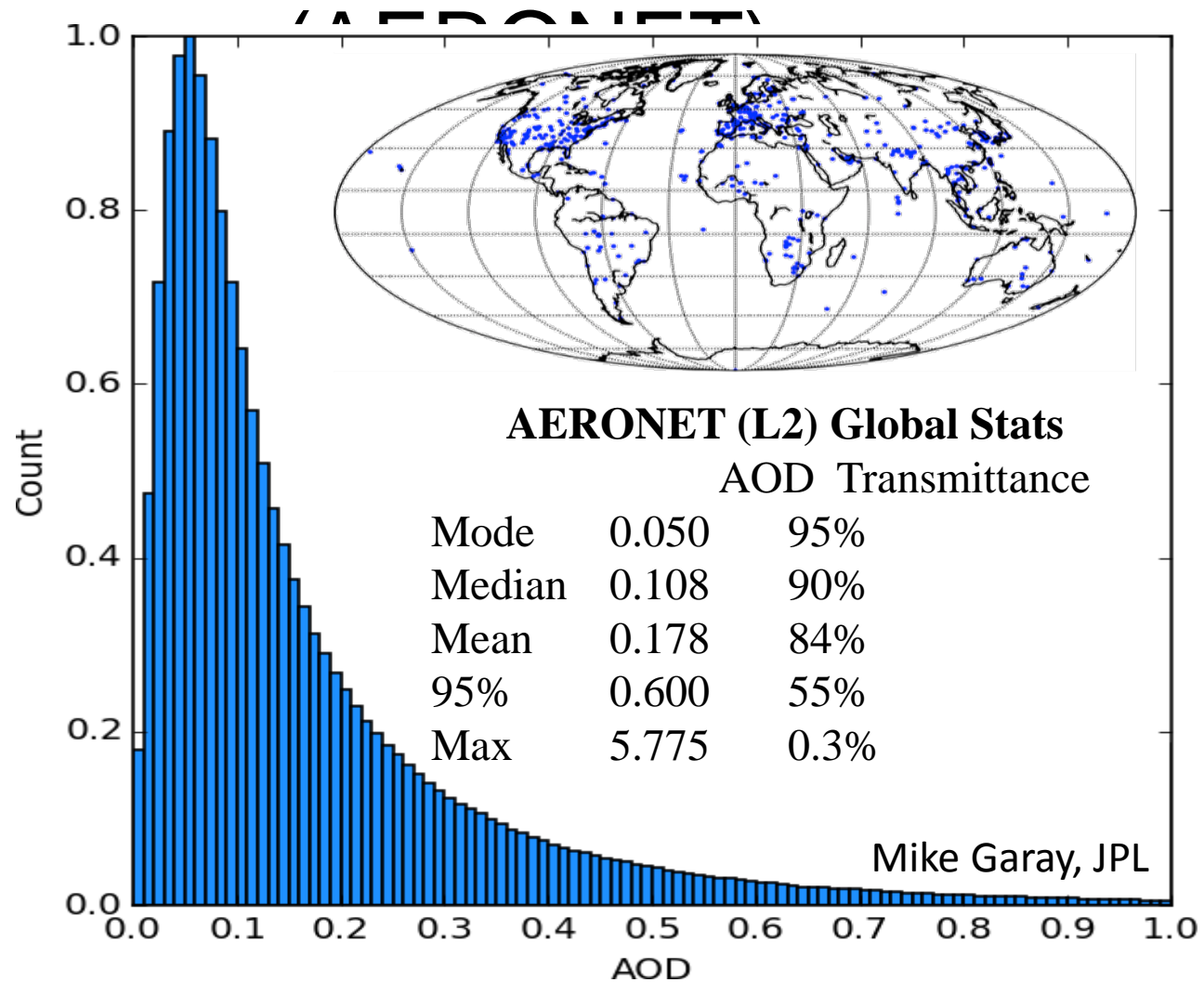
AERONET-observed AOD is extremely lognormal.
Should Satellite data also be? (for that matter, models?)

But we all are missing something…..

Remote sensing measurements of biomass burning aerosol optical properties during the 2015 Indonesian burning season from AERONET and MODIS satellite data

Tom Eck (AERONET team) et al.,

Borneo – Oct 19, 2015 Smoke from Peat Fires

MODIS Fire Counts: Oct 8- Oct 17, 2015   - NASA Rapid Response LANCE
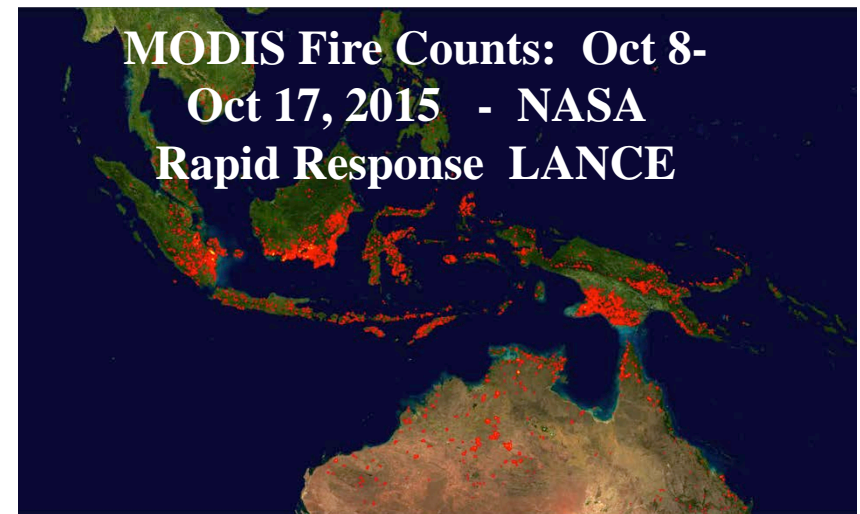
We complain that satellites (e.g. MODIS) can't retrieve these super extreme events!.... (AERONET Level 1 shows AOD ~ 7.0!)

AOD(675 nm) = 6.91 (mid-day) ; Ang. Exp. (675-1640 nm) = 1.8

Palangkaraya (AERONET) site

MODIS - Red: AOD(550 nm) > 0.7

2015 SEP 10
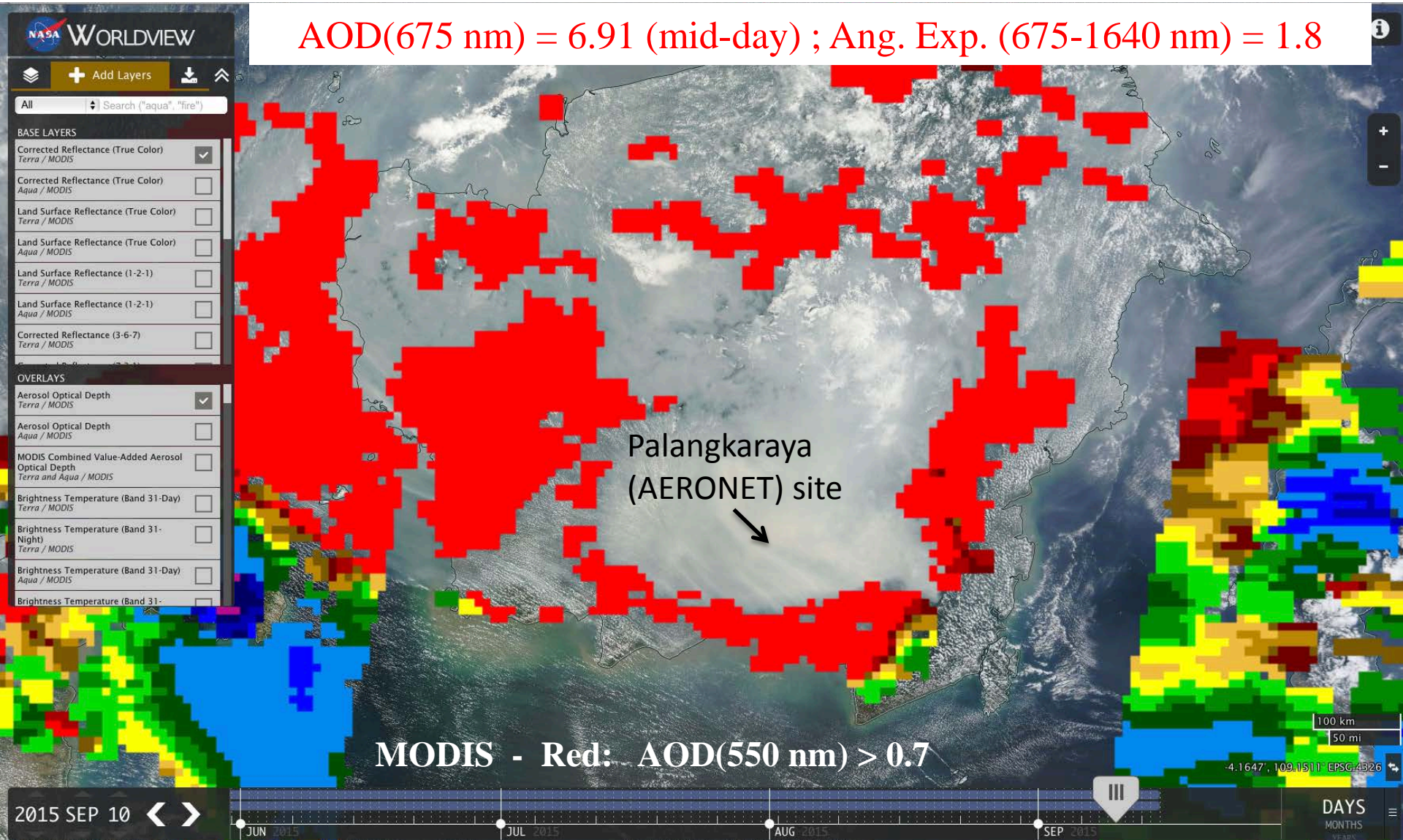
…But neither can AERONET (until now, Version 3)

Palangkaraya, Indonesia   Aug 01- Nov 15, 2015
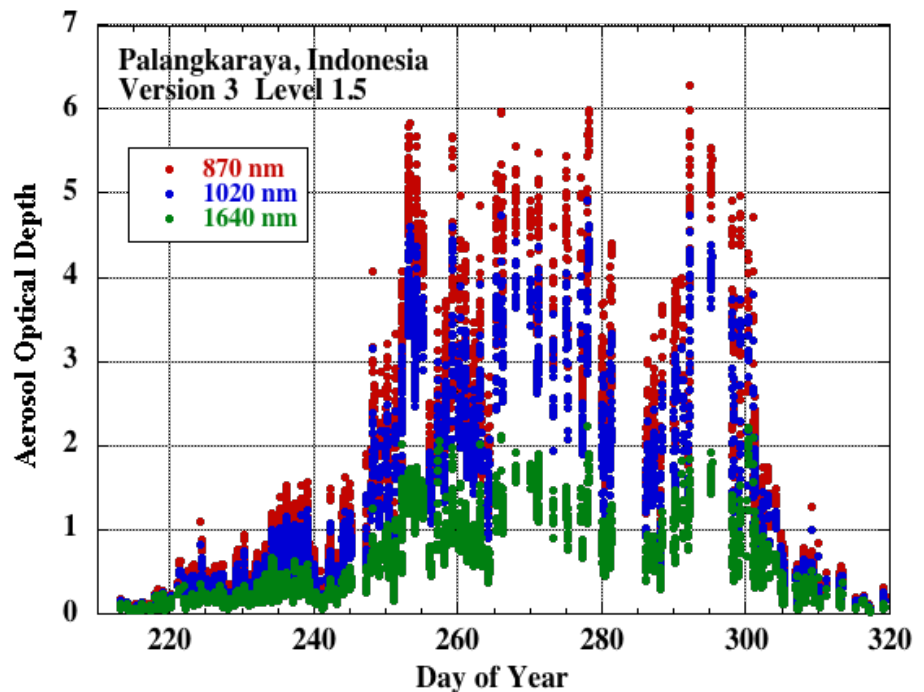
- V2: Very heavy smoke missed due to insufficient direct sun signal (in UV/VIS)
- V3: But, at least for smoke (large AE), there is enough direct sun signal in SWIR!
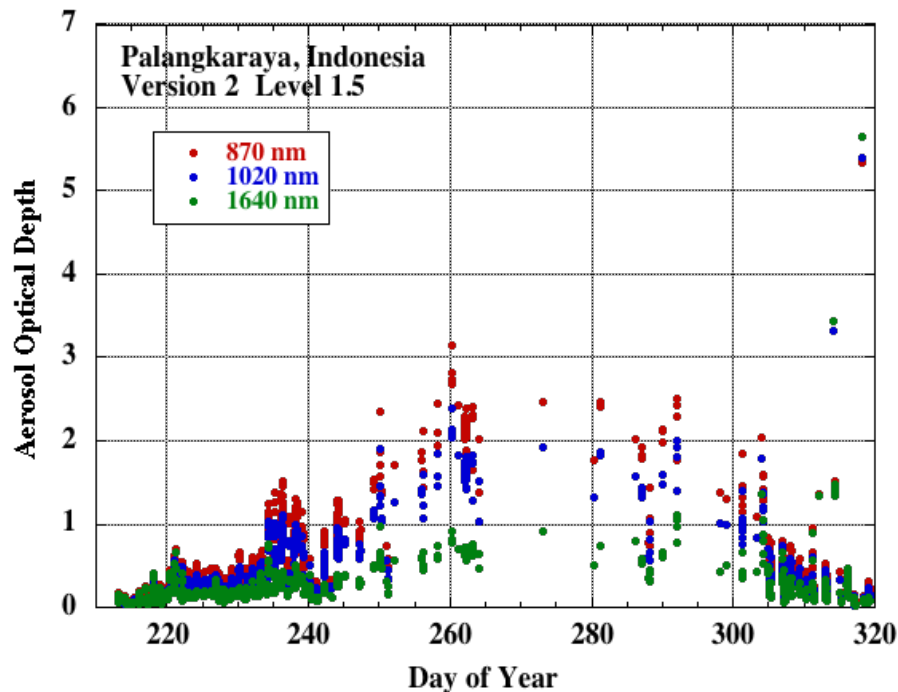
New V3 Algorithm Restores AOD data for longest wavelengths when signal strength is sufficient

Version 3 is not yet "validated", but when do we start using it to validate satellite/model data?
If there are now lots of new "big" events, will this again throw climatology into turmoil?

We know these high AOD events exist

- If we could retrieve them….

- How would the regional aerosol climatology (and estimates of climate effects) be altered
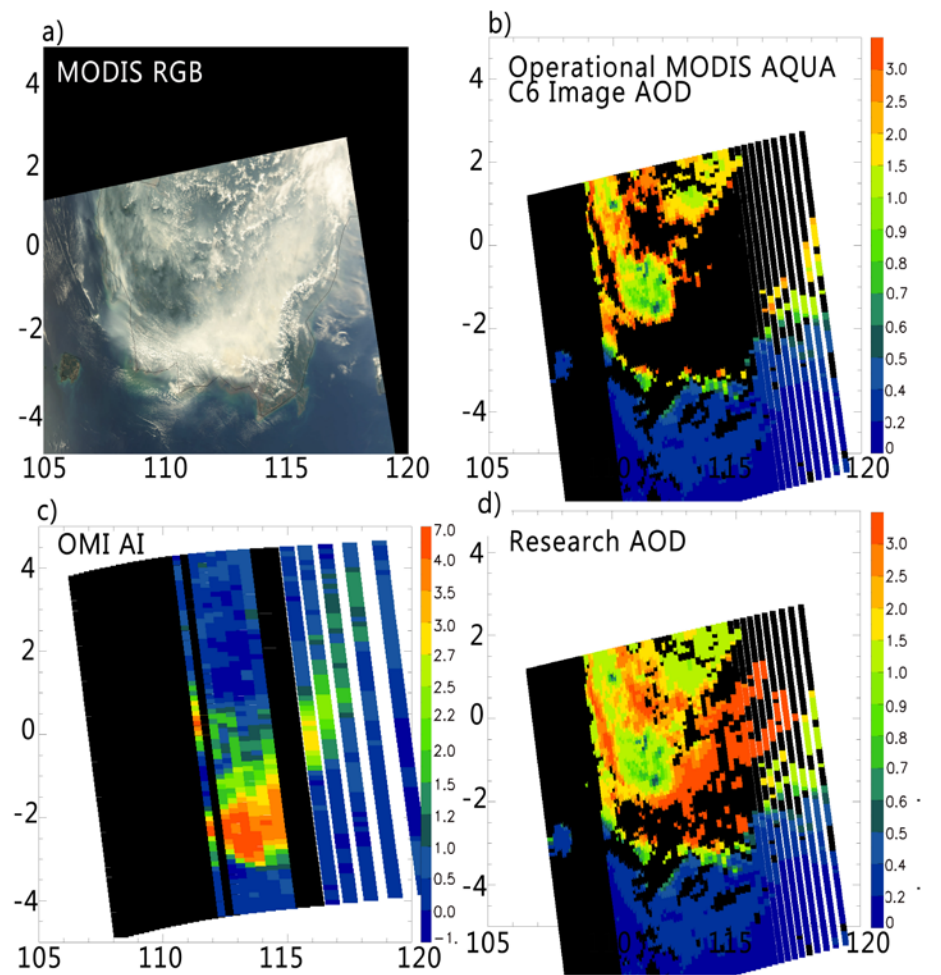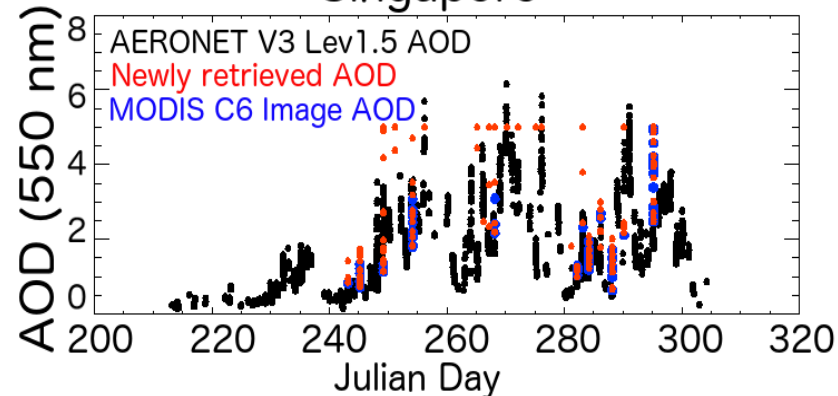
Yingxi Shi et al. (Look for purple poster)

Session 14
Long satellite records
Thomas's Seed Questions

Producing Satellite Climate Data Records (CDR)

1. How much do we need to do to produce climate quality?

Some of metrics for assessing continuity (of overlapping time series)

- Convergence: of gridded (Level 3 –like) data
  - For a day? A month? A season?
  - What % of grid boxes must be different by less than X?
    - in AOD?   In Angstrom Exponent?   Size parameters?

- Validation: Comparison with AERONET, etc?

- "Retrievability":

Do algorithms/products make same choices under same conditions?

- Other metrics??

- Andy?

MODIS (Aqua): MAM 2013
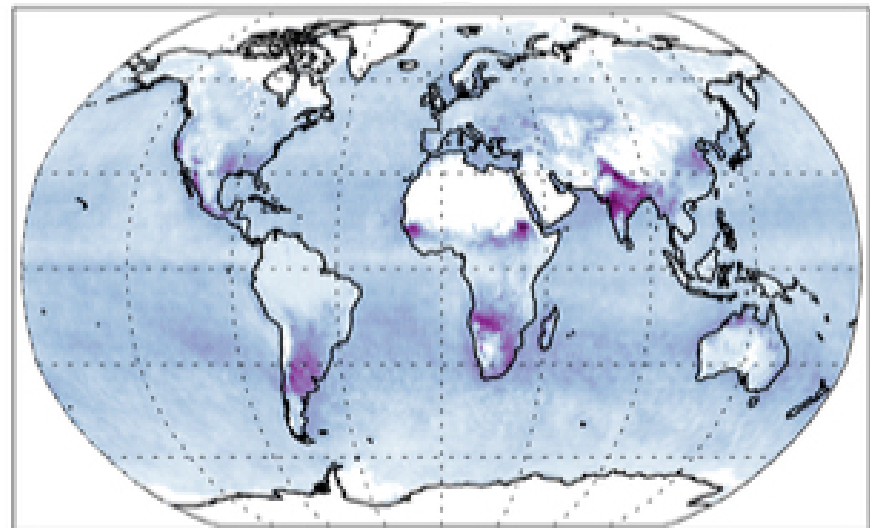
Fraction of pixels with retrieval

0.00   0.25   0.50   0.75

Aerosol retrieval: Other things to think about (from my MODIS/DT perspective)

- Improving coverage ?
- Removing bias over urban areas ?
- A (non-spherical) dust retrieval over ocean ?
- Fill in missing retrievals at coastlines ?
- Accounting for 3D radiation effects ?
- Sub pixel clouds?
- Developing Uncertainty "products" ?

"whack-a-mole"

- Which updates will be in "forward" stream (e.g. a Collection 6.1), and which can go into reprocessing? (Wait for Collection 7?)
- Which will go into VIIRS? Etc? What versions will be used for ECVs?
- How will we apply to future missions? To Geostationary?
- And of course, how will that affect the long-term record?

Or, throw up our hands and be "assimilated"?

WHY AEROSOL REANALYSES?

- Like meteorological reanalyses, we expect aerosol and chemistry reanalyzes to be a dominant data source for most earth system science applications.

- While standalone satellite and model aerosol products see wide utilization, there is a significant need in climate and applied applications for a best available, contiguous, fused product on a regular grid.

- Aerosol reanalyses combine advantages of data accuracy from satellite products and data consistency from modelling. The data is gridded and has good spatial and temporal coverage.

- Weighting and error can be controlled, or at least characterized relative to the environmental state.

- Aerosol reanalysis are being pursued at nearly all major NWP centers because of the ability to integrate meteorological analyses and thus context.

But there is a lot to do!
Lets start with simple AOT
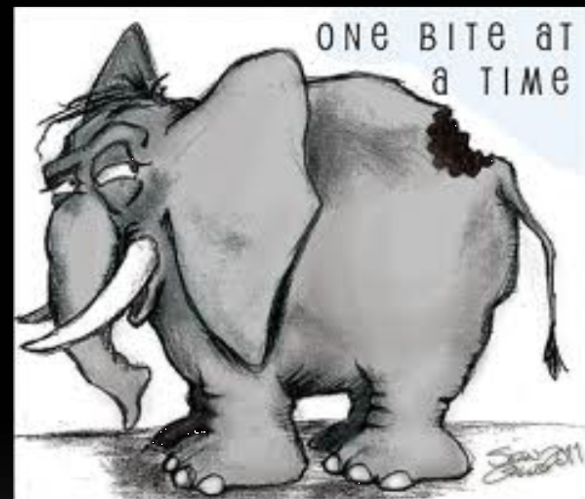
ONE BITE AT A TIME

Abrams's Advice: When eating an elephant, take one bite at a time.

Peng Lynch/NRL
(AeroSat 2015)

Some thoughts from Ed Hyer
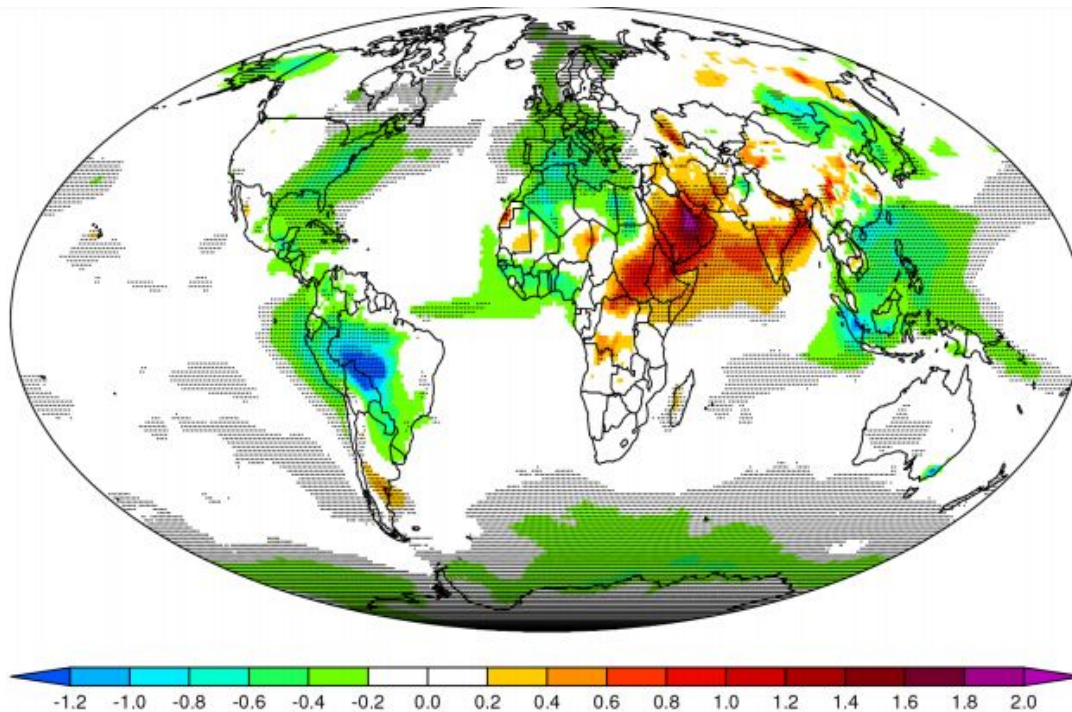# Lynch et al. 2016 reanalysis trend

Figure 13. Trends of the deseasonalized reanalysis total AOT at 550 nm over 2003–2013 (unit: $100 \times AOT\,year^{-1}$). The dotted areas have passed the 95 % statistical significance level (see text and Zhang and Reid, 2010, for details).

- NAAPS model reanalysis
- 2003-2013 (11yr)
- Constrained by MODIS DT + MISR
- Significance of trend evaluated using Weatherhead method
- Trend in SE Asia would not be significant, and would probably not be down, if run was to 2015
- **Point: this is a short time series relative to interannual variation in burning regions**
  - **Q: What about dust sources?**
- Trends in ECONUS, Europe, China probably more stable

Session 14
Long satellite records
Another Set of Questions?
Producing Satellite Climate Data Records (CDR)

1. Should it be based on a simple algorithm that can be used on many sensors? (e.g. a single channel algorithm?)
2. Should it based on doing the best you can with each individual sensor? (sophisticated retrieval?)
3. Should it involve model assimilation? (seems not fair)
4. What should my job be as a data provider?
    Should I provide a version 1, 2 and 3?

5. Or do I want to always work to provide something new?
6. How do we not turn into „calibration engineer" instead of aerosol scientist?