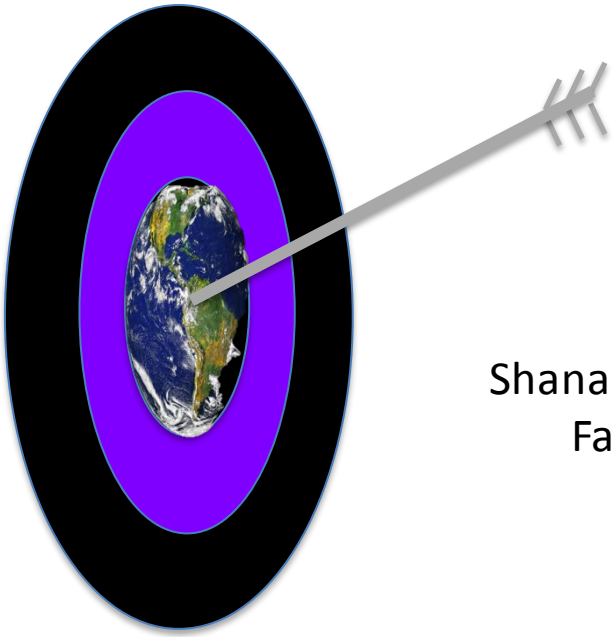
# Creating a long (and wide) -term aerosol climate data record from passive satellite remote sensing

Robert C. Levy (NASA-GSFC)





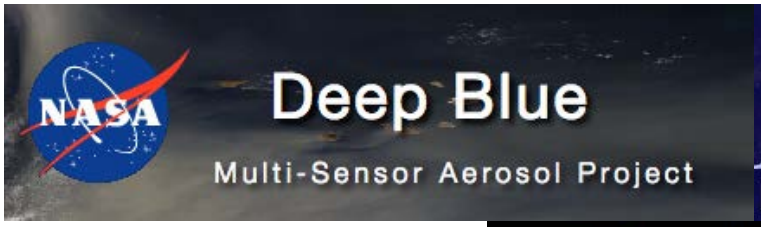



**Current "dark-target" group:** * New in 2016.
Shana Mattoo, Virginia Sawyer* and Richard Kleidman (SSAI/GSFC)
Falguni Patadia and Yaping Zhou* (Morgan State U / GSFC)
Pawan Gupta and Yingxi Shi* (USRA/GSFC)
Lorraine Remer (UMBC/JCET)

AeroCom/AeroSat; Beijing, China; September 2016

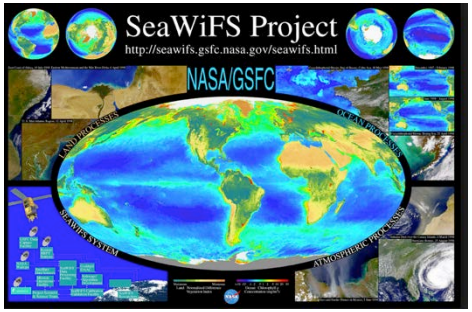
# Its not just dark-target algorithms based on MODIS

**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)<br>Ocean + land (dark) | MODIS → VIIRS | 2000-? | GSFC |
| AOD (Deep-Blue)<br>Land (all) + ocean | SeaWIFs/MODIS<br>→VIIRS | 1997-? | GSFC |
| AOD ()<br>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 |

Let's start with slides from Simon Pinnock from last year's AeroSat

# GCOS Aerosol CDR* Requirements

**Product A.10.1** Aerosol optical depth
**Product A.10.2** Aerosol single scattering albedo
**Product A.10.3** Aerosol layer height
**Product A.10.4** Aerosol extinction profiles from the troposphere to at least 35km

**Product A.10.X** Aerosol "type"

**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 % |

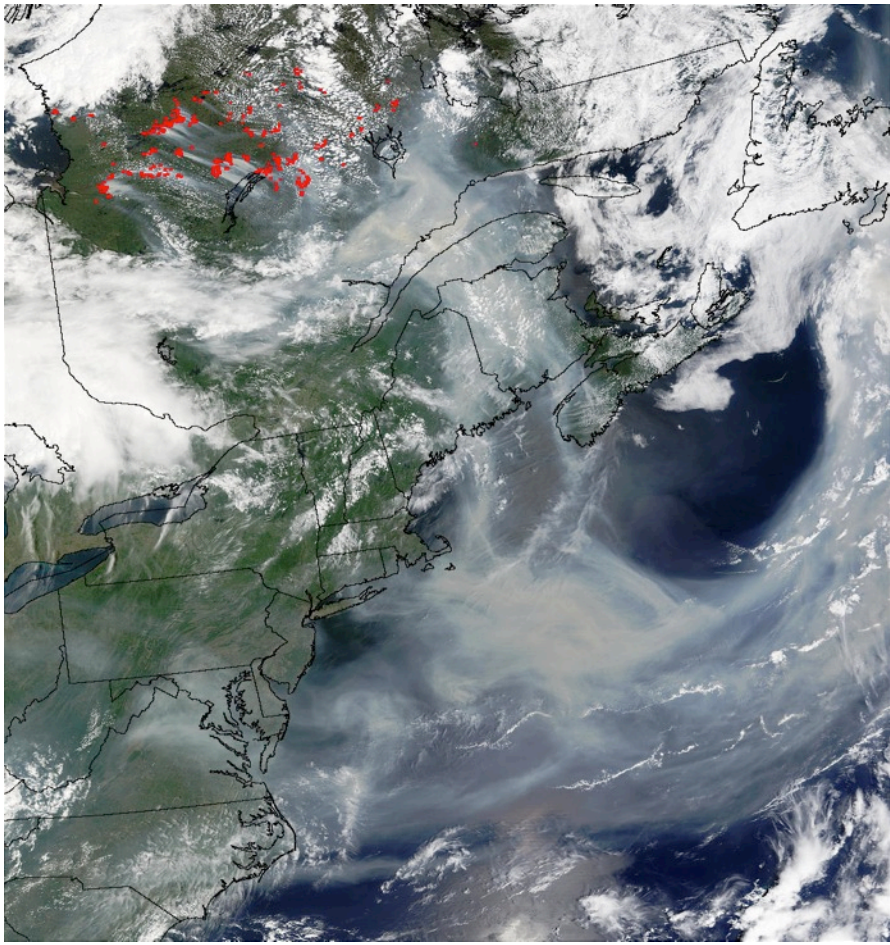


*CDR = Climate Data Record

# Aerosol from space as a climate record

- Multiple aerosol parameters
- Aerosol optical depth (AOD or $\tau$)
- "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**

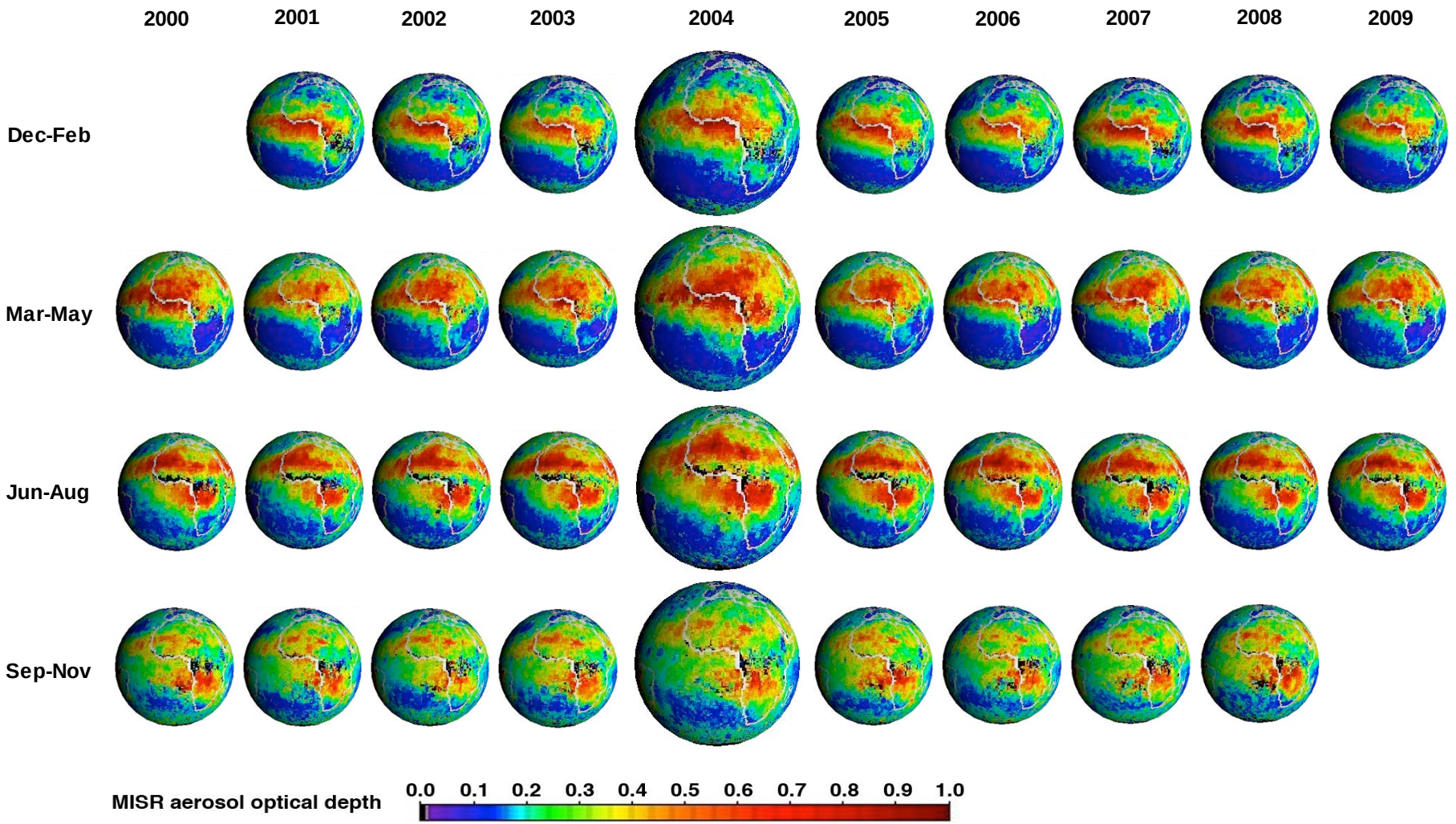
# Long satellite records

## *Main Issues*

**0.** Consistency of **single instrument**

**MISR-Terra (calibration)**

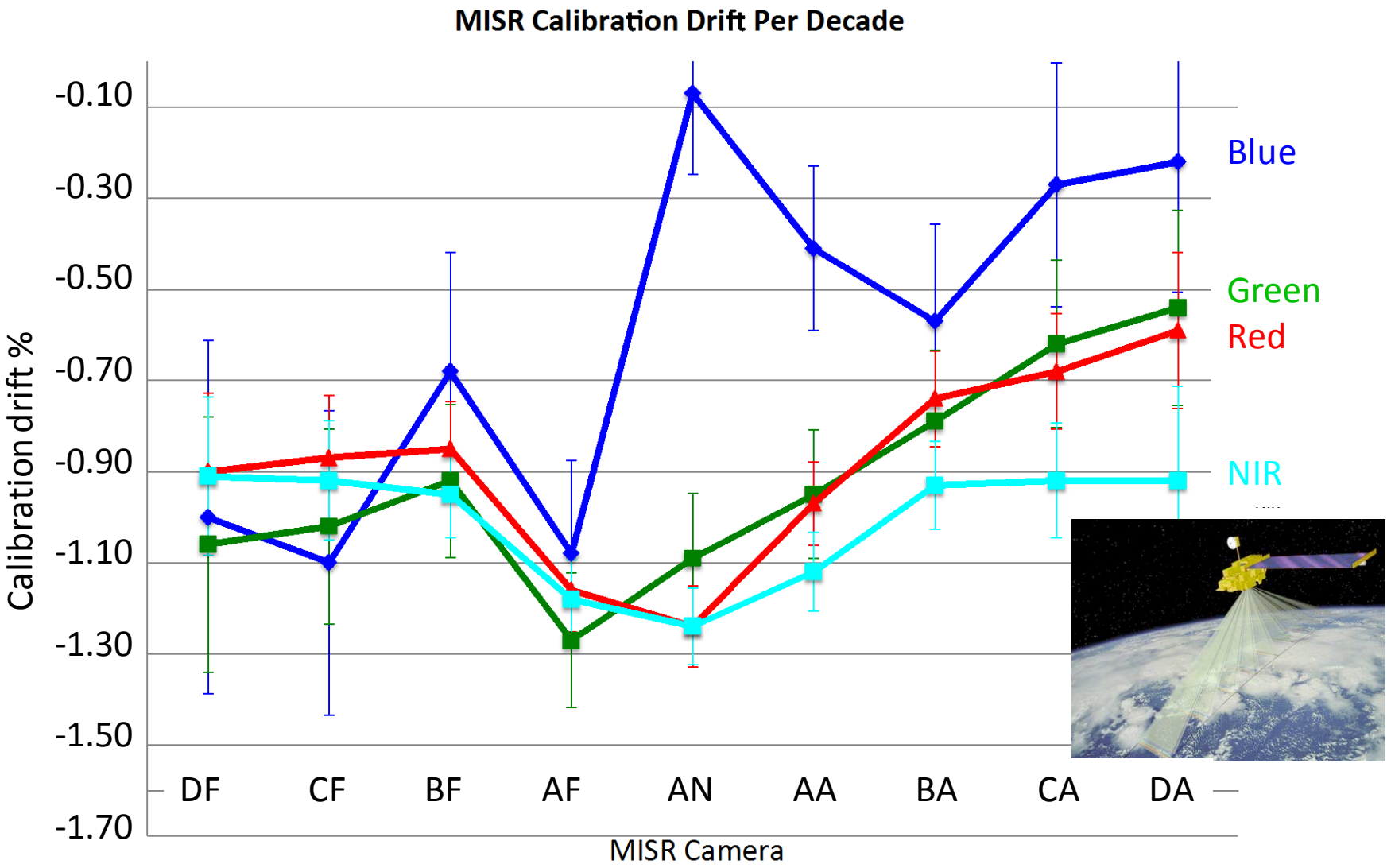
# *Ten* Years of Seasonally Averaged Mid-visible Aerosol Optical Depth from **MISR**




***…Could this be a CDR? Can we detect AOD trends with confidence?***

*MISR Team*, JPL and GSFC

# ***But for accuracy (±0.01/decade),*** must

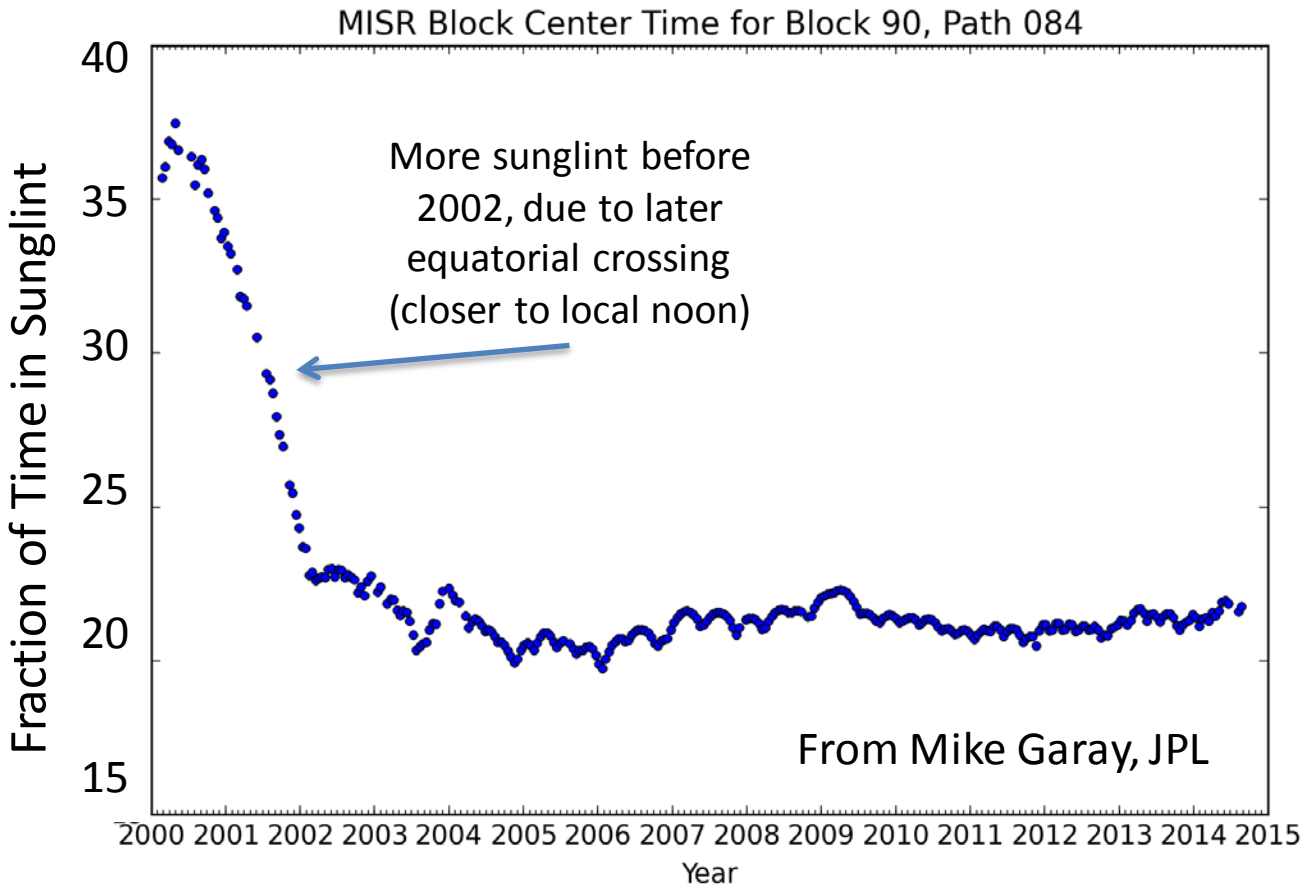



9 Cameras x 4 Spectral Bands, Assessed over 2002-2014
Based on time-series imagery of three relatively stable desert sites

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

*Limbacher & Kahn*, AMTD *in prep.* 2016

# Sampling Issues: Equatorial Crossing Time (MISR)




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

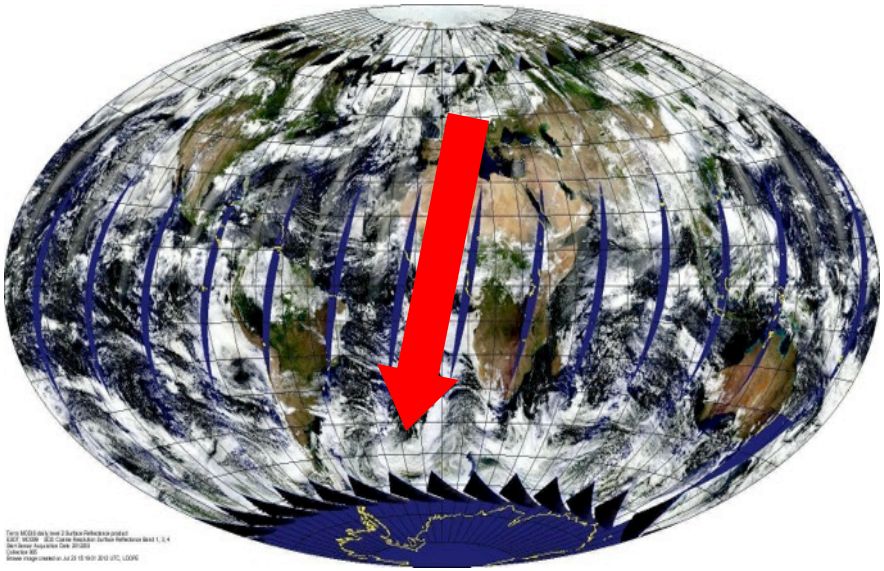
# Long satellite records

## *Main Issues*

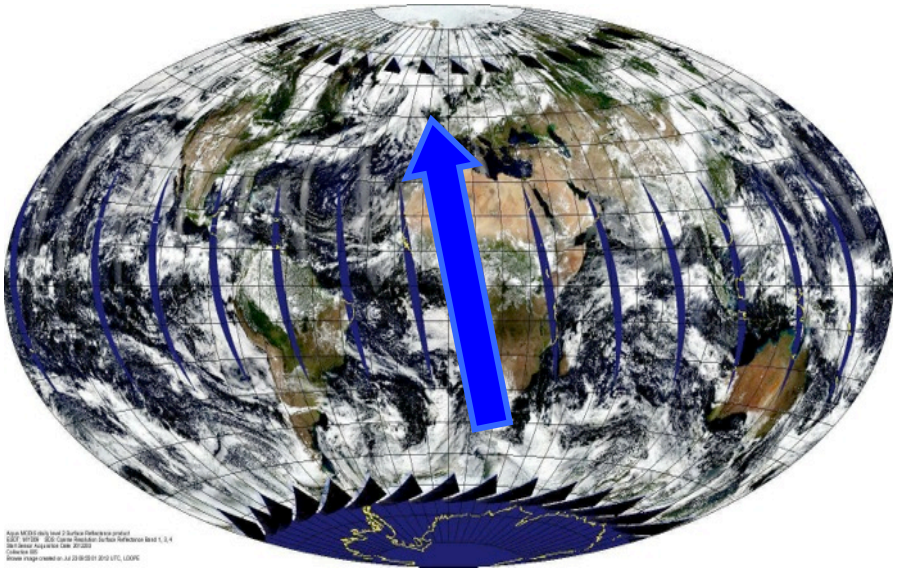
1. Consistency of **subsequent instruments**
   **MODIS-Terra vs MODIS-Aqua**

# MODIS-Terra vs MODIS-Aqua

Terra (10:30, Descending)



Aqua (13:30, Ascending)



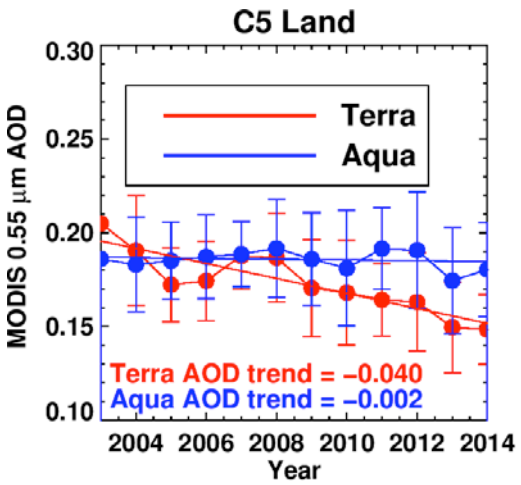
The two MODIS instruments are **INDENTICAL TWINS!**

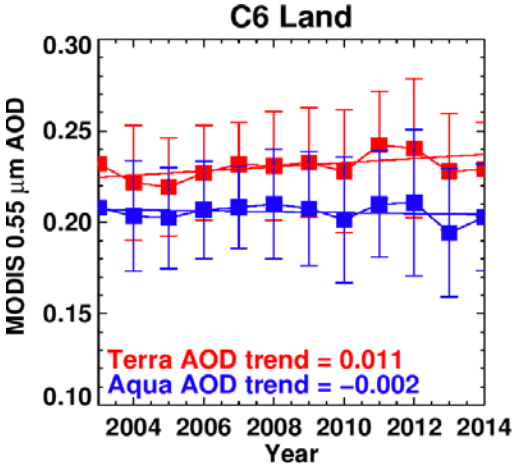
Do they observe the world in the same way?

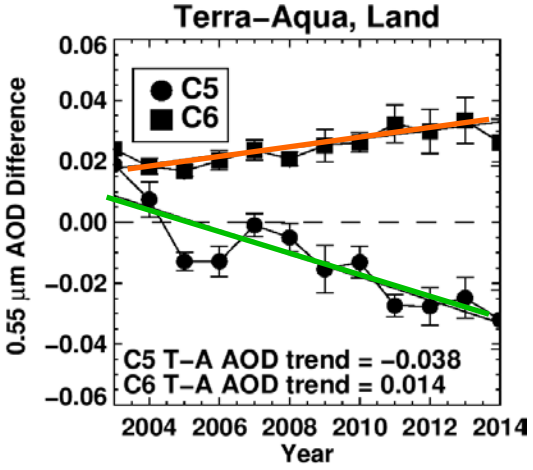
# Time series of MODIS-derived AOD (DT algorithm)

## $\Delta\tau$ = Terra - Aqua

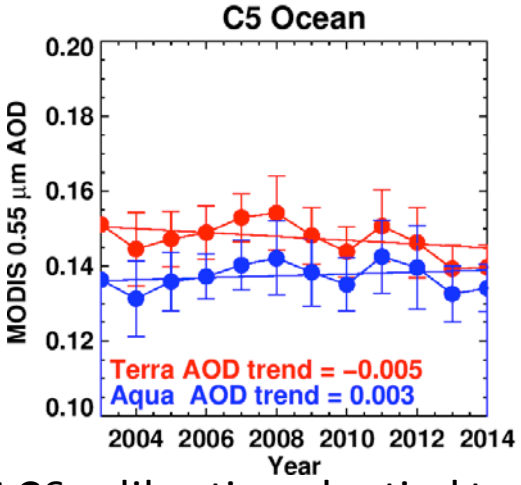
LAND

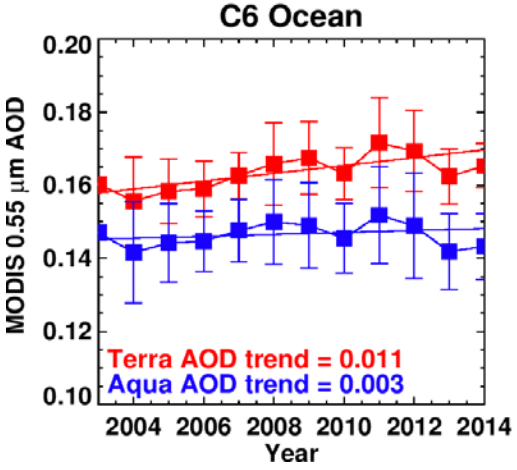


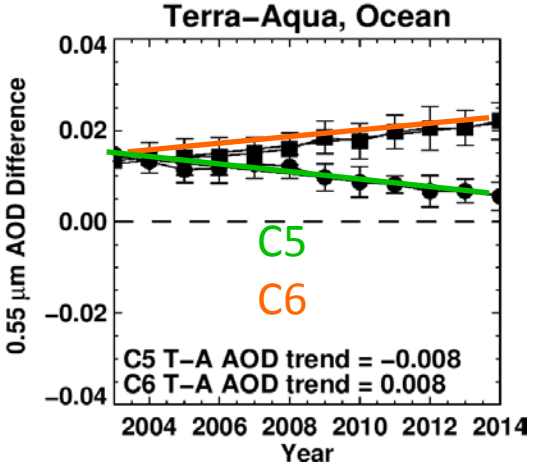




OCEAN




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

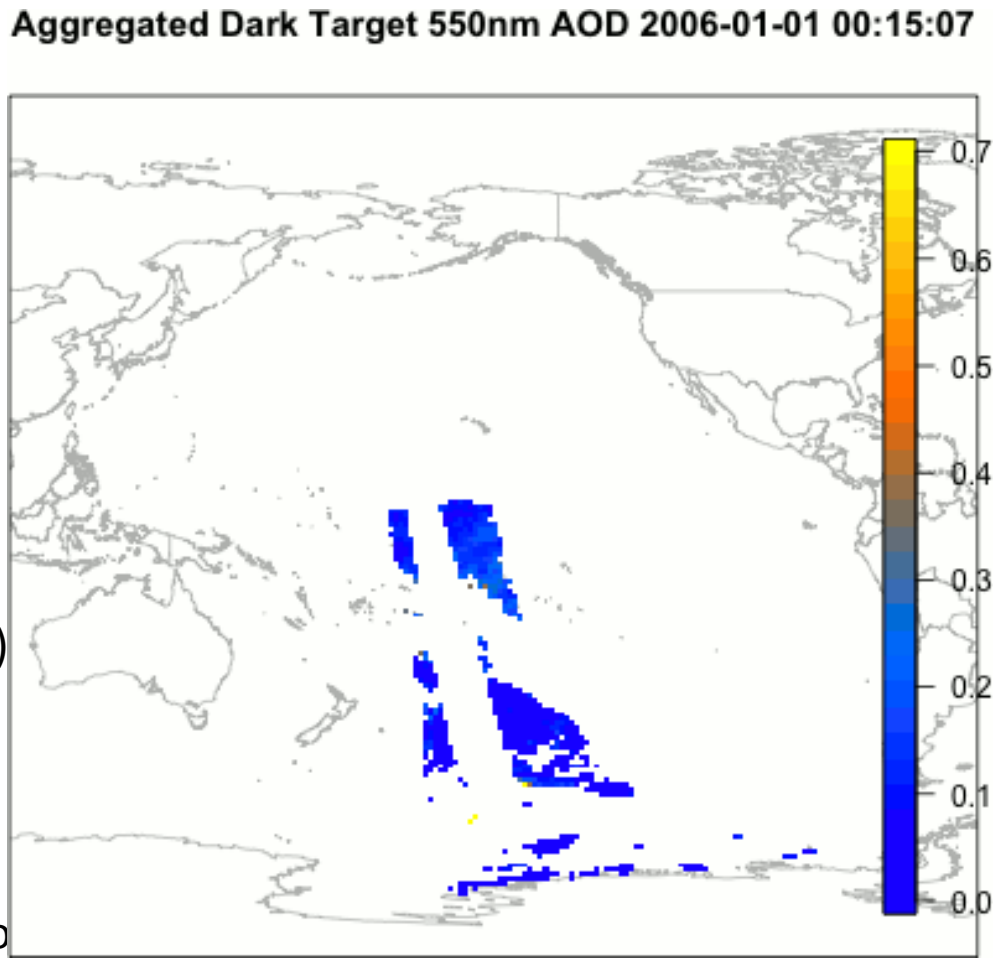
**Should we expect an 0.02 offset between AM and PM?**

# "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.

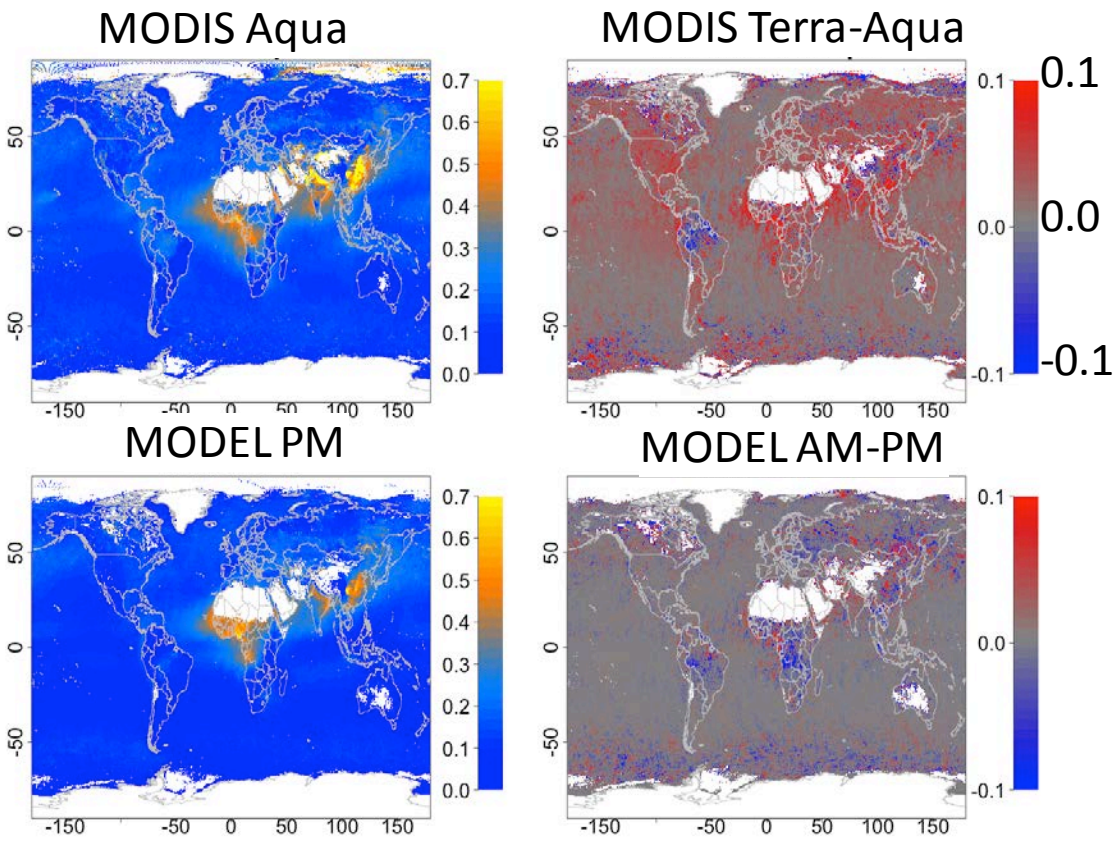
- Compute:
  - $\Delta\tau$ for satellite (MODIS = Terra-Aqua)
  - $\Delta\tau$ for model (Model= AM-PM)

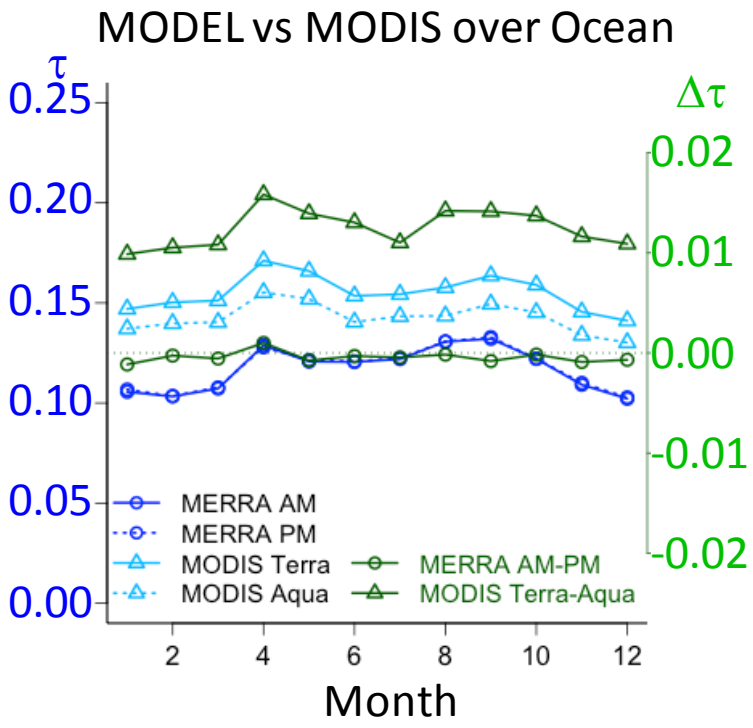
- Model version includes assimilation of meteorological variables and infrared /Microwave radiances, but not MODIS (no Terra or Aqua radiances)




Pete Colarco and Virginia Sawyer

# $\Delta\tau$ differences (AM-PM) during 2008




Land: $\Delta\tau$ for MODEL is both + and - (clouds?), while MODIS is mostly +,

Ocean: $\Delta\tau$ for MODEL is mostly zero, while MODIS is mostly +

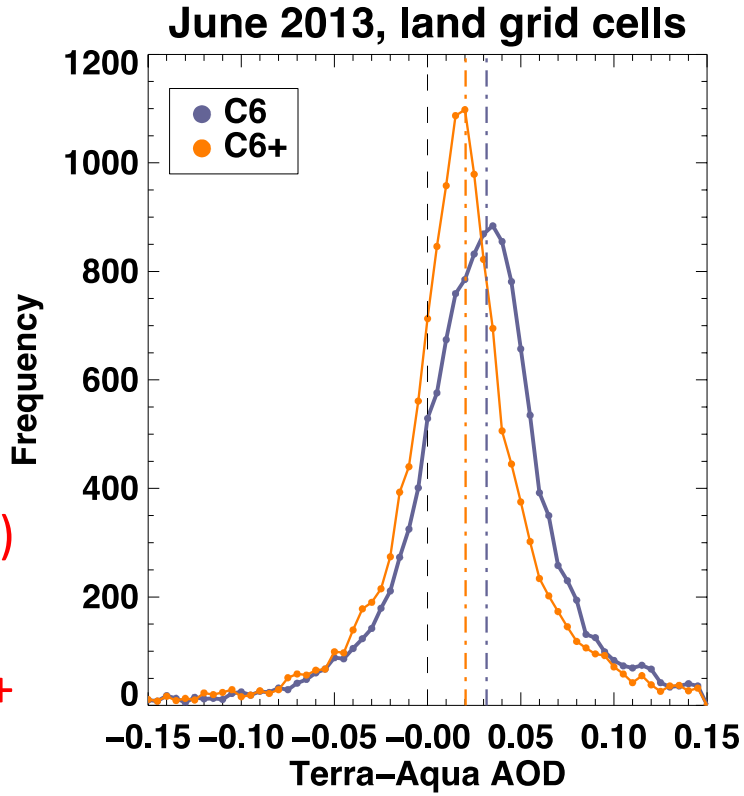
→ AM-PM for MODIS is greater than AM-PM expected by MODEL

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

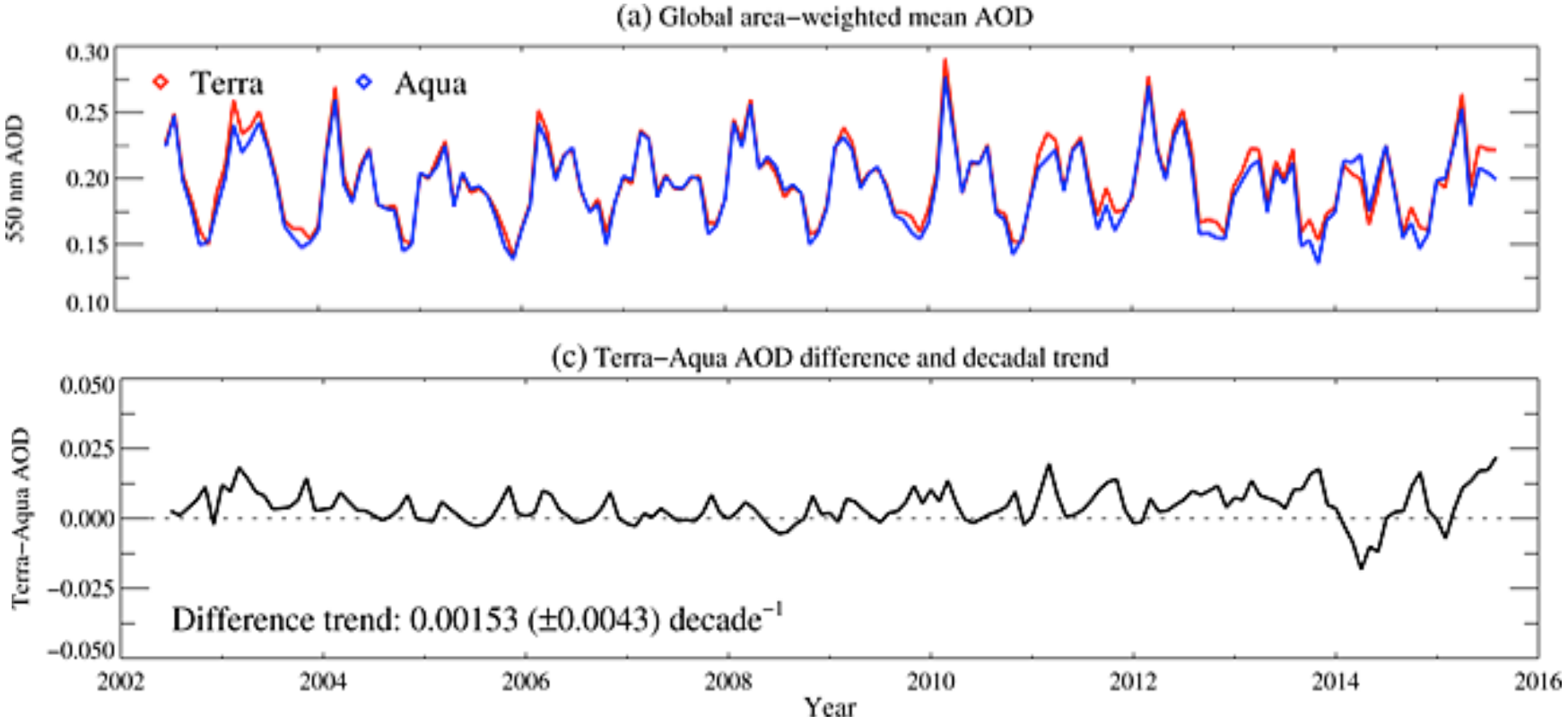
# When all else fails. Focus on the calibration → (C6+)?

- 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++



# Effect of MODIS Terra radiometric calibration improvements on Collection 6 Deep Blue aerosol products: Validation and Terra/Aqua consistency




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

**Sayer et al,. 2015: Journal of Geophysical Research: Atmospheres**
Volume 120, Issue 23, pages 12,157-12,174, 14 DEC 2015 DOI: 10.1002/2015JD023878
http://onlinelibrary.wiley.com/doi/10.1002/2015JD023878/full#jgrd52609-fig-0009

# 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

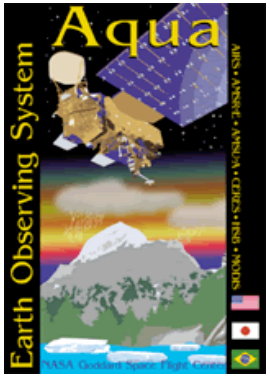

**Orbit**: 825 km (vs 705 km)

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

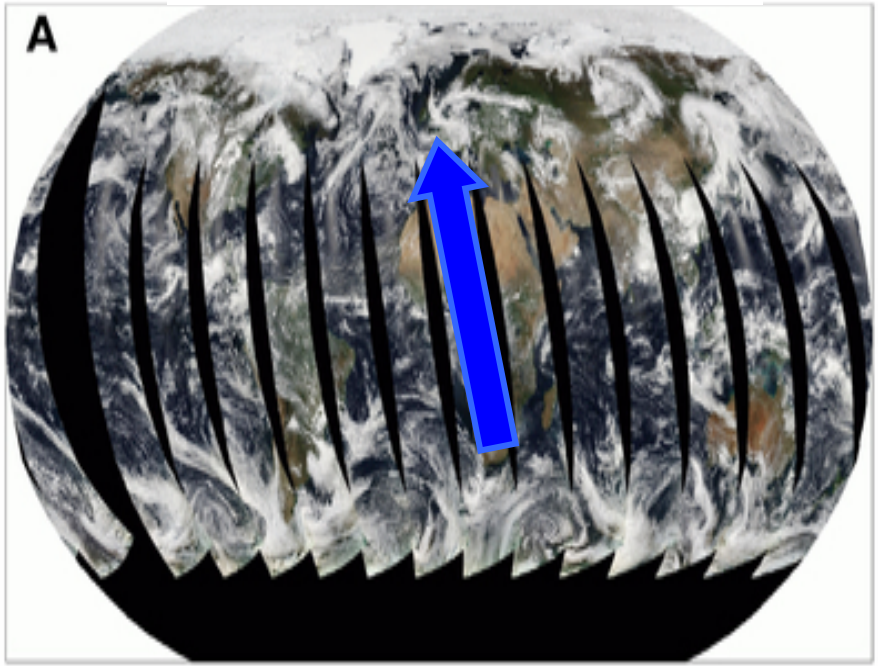
**Spectral Range**: 0.412-12.2μm (22 bands versus 36 bands)

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

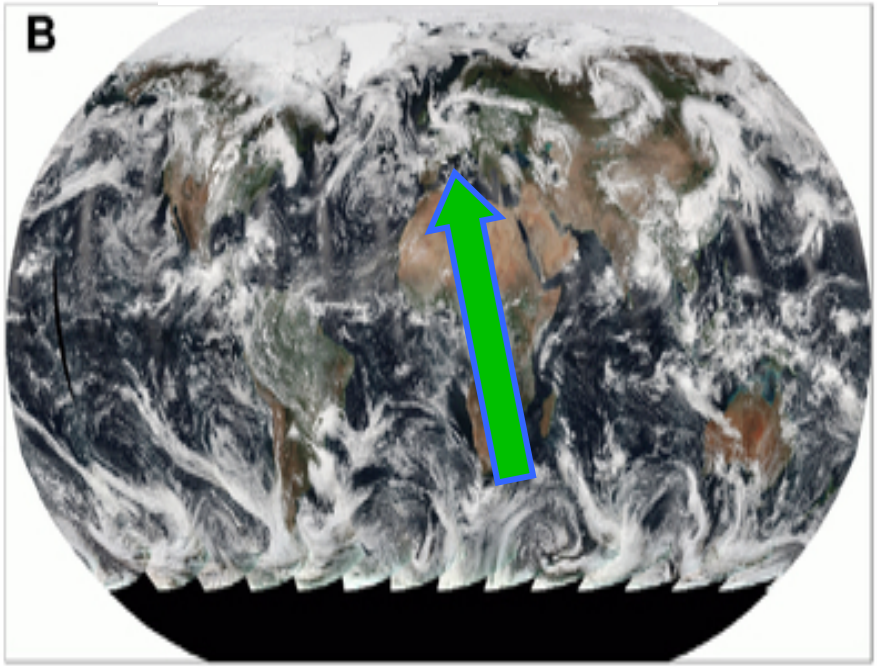
**Wavelength bands (nm) / DT aerosol retrieval**: 482 (466), 551 (553) 671 (645), 861 (855), 2257 (2113) → differences in Rayleigh optical depth, surface optics, gas absorption.



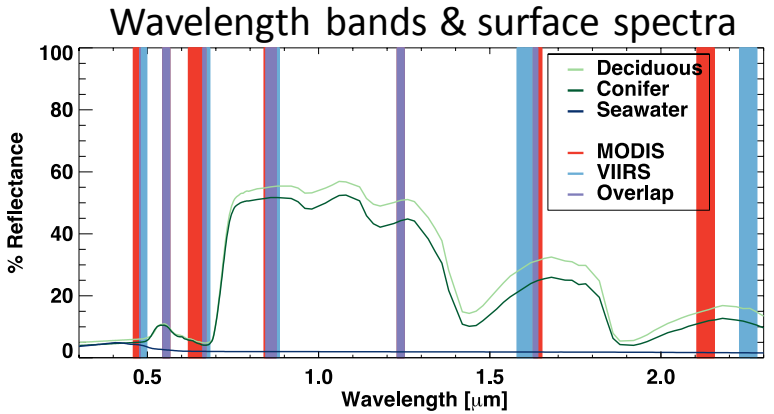

MODIS-Aqua – 29 May 2013




VIIRS-SNPP – 29 May 2013

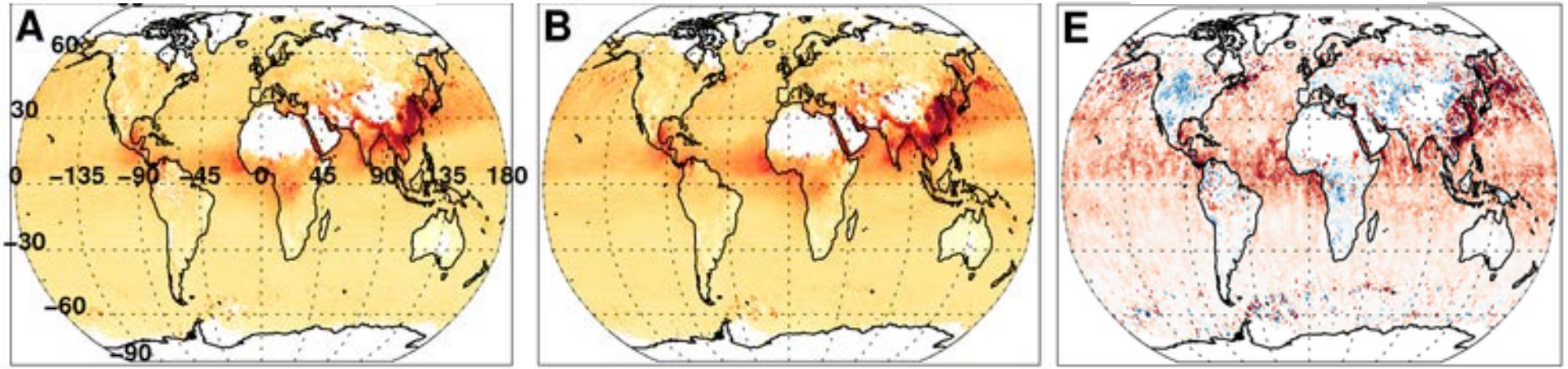


# To develop "continuity" Port algorithms! (Example: DT from MODIS→VIIRS)




- 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%).

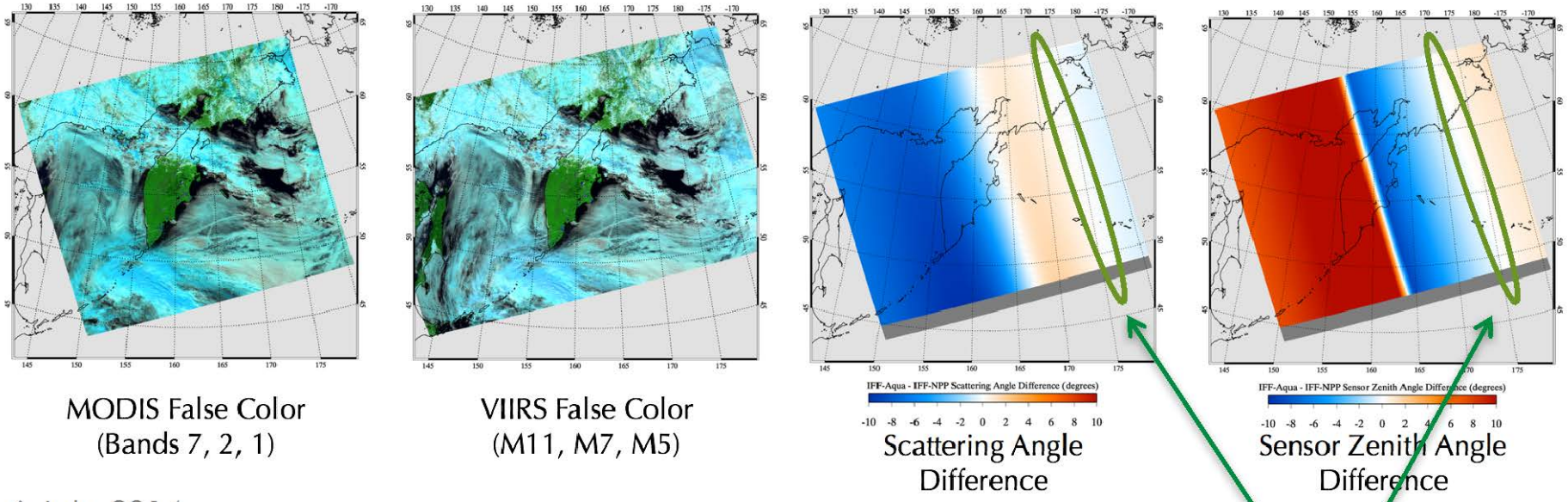


Levy et al., 2015

# 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

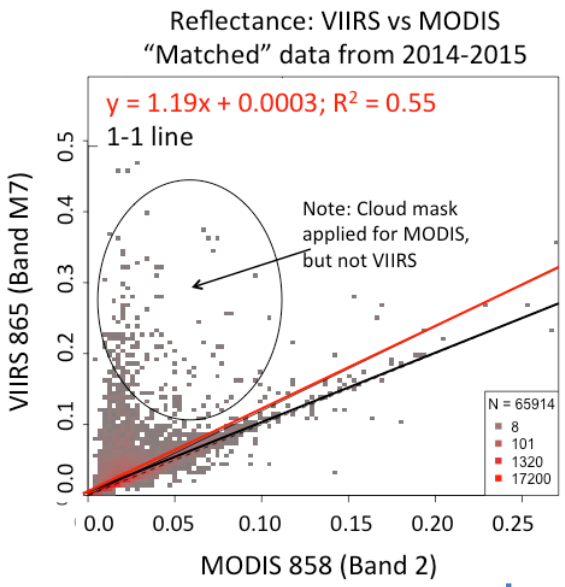
Close overpass (space and time) between Aqua and SNPP near the Kamchatka Peninsula and surrounding waters.



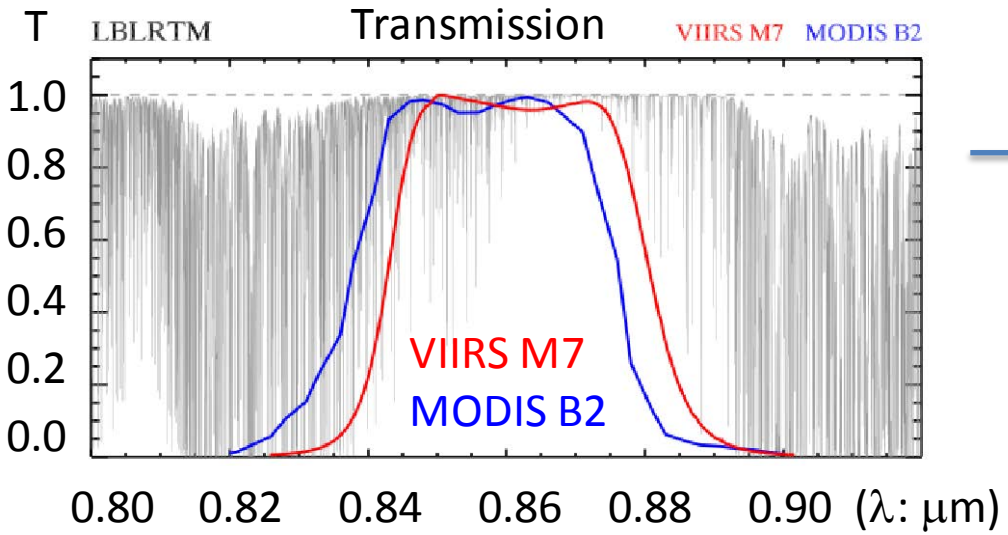

Steve Platnick, Bob Holz, Kerry Meyer, et al

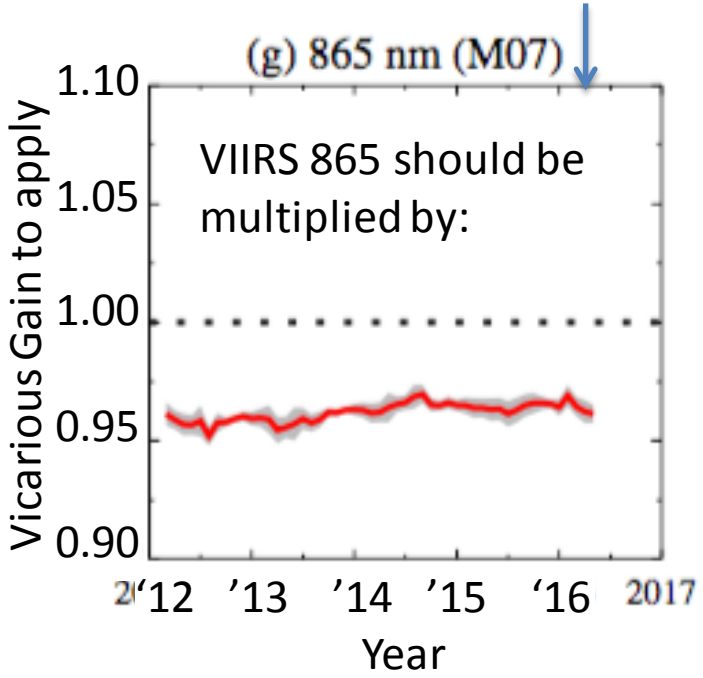
# Calibration: Match files (2)

- 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




Example: 0.86 μm channel over "clear" sky



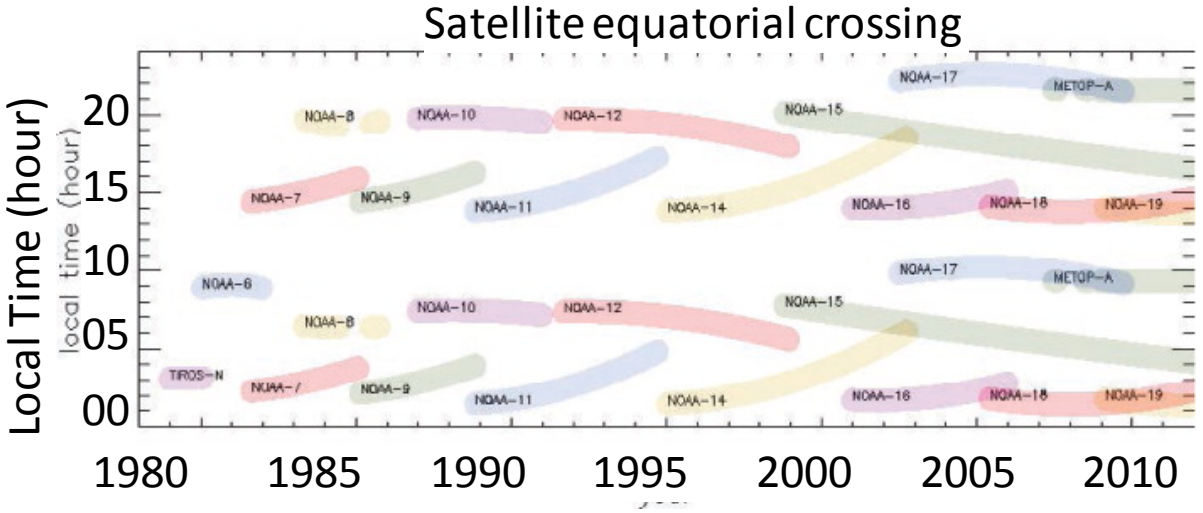



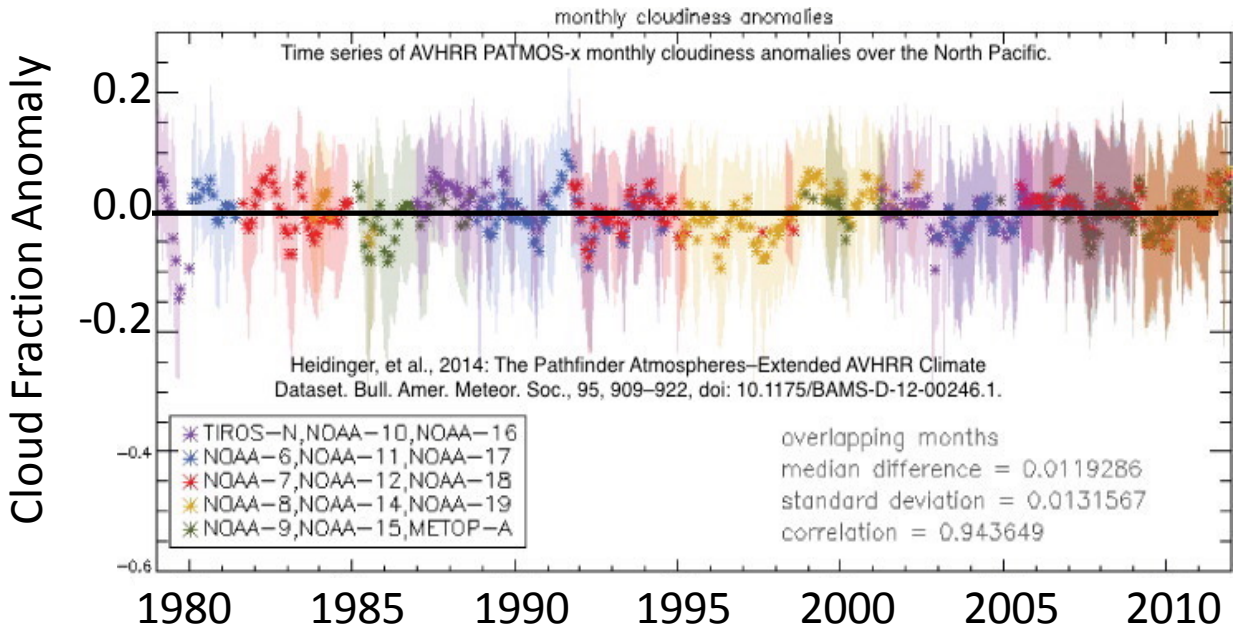

Sayer et al., AMTD 2016

# 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 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

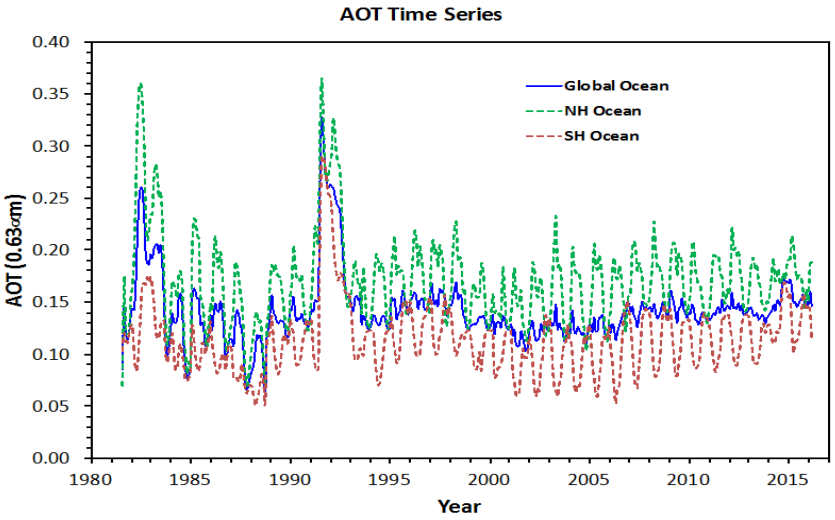
Heidinger et al., 2014.

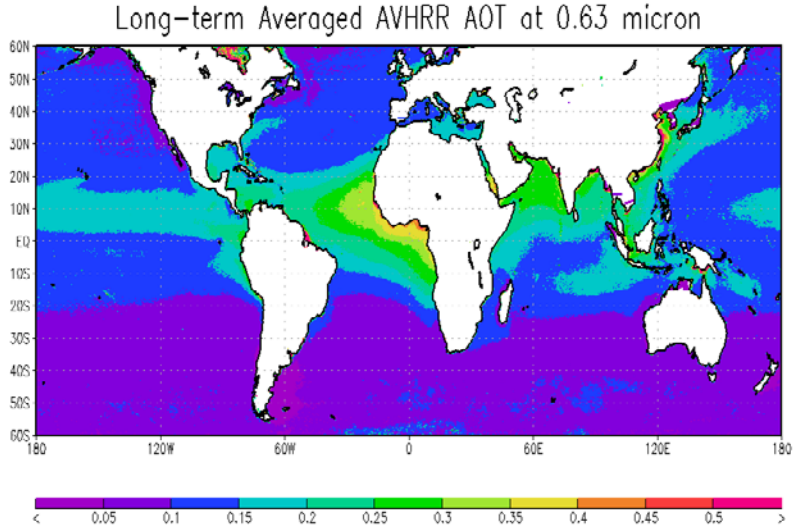
# NOAA AVHRR AOT Climate Data Record (CDR)

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

Tom Zhao, NOAA/NESDIS/NCEI

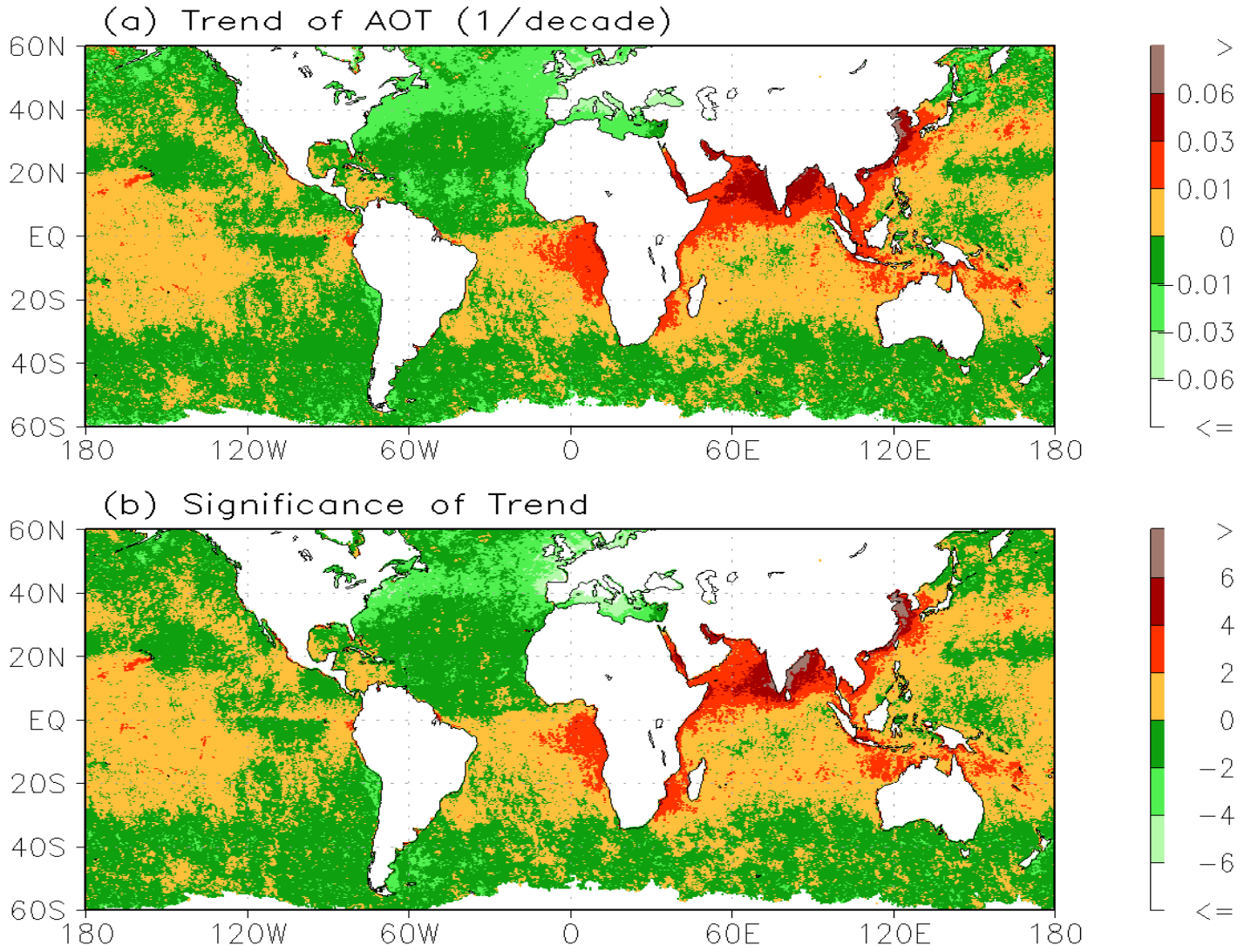
- CDR Product: AOT at 0.63μm
- Spatial coverage: global ocean (-60ºS–60ºN)
- Spatial resolution: 0.1ºx0.1º
- Temporal coverage: 1981-2016
- Temporal resolution: daily and monthly
- Independent 2-channel algorithm
- Retrieval quality is degraded beyond -60ºS–60ºN & AOT will not be considered as CDR



# Application Example-1: Trend Detection

AOT Long-term Trend and Significance



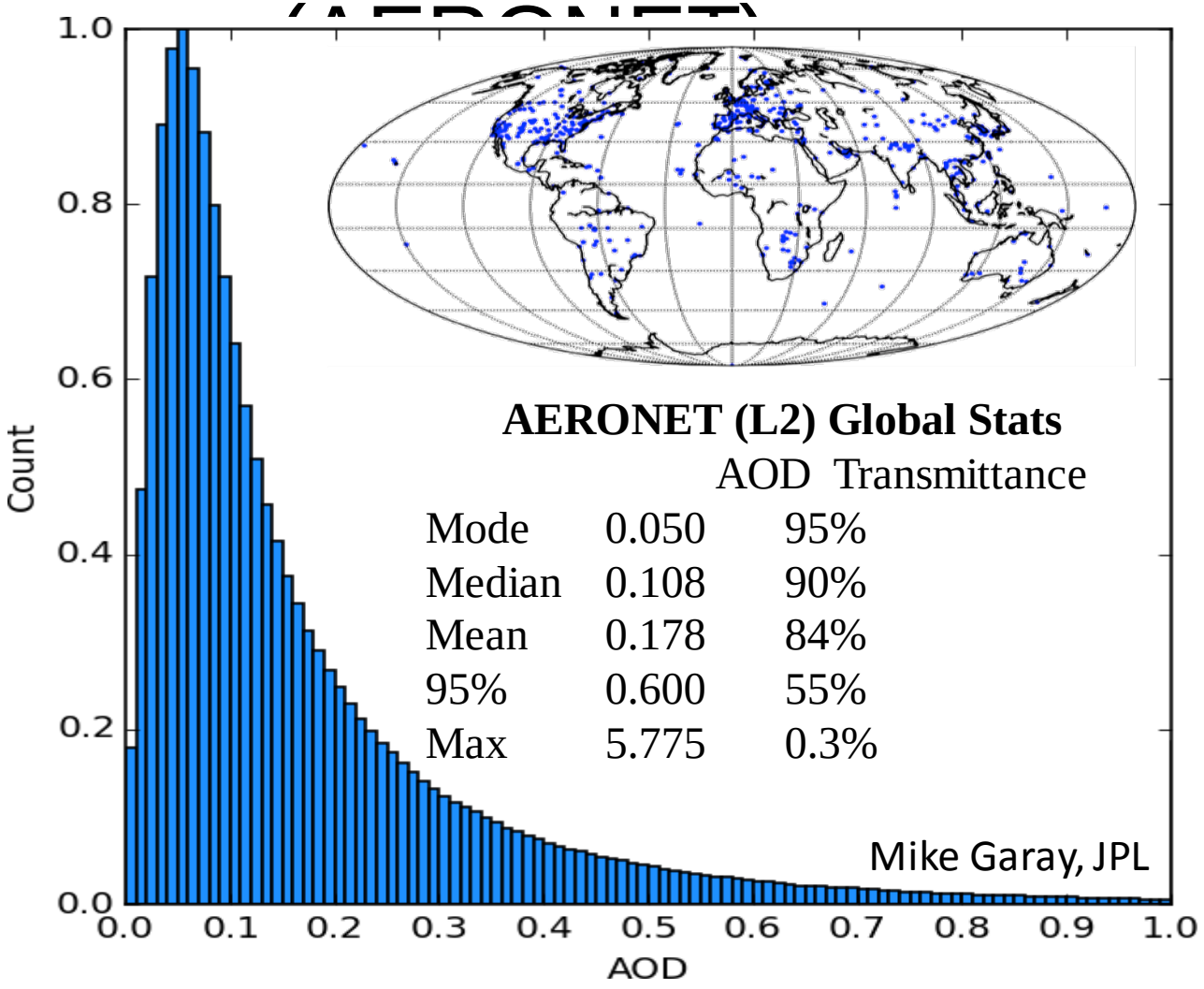
# Long satellite records

## *Main Issues (and examples)*

**4.** Consistency of **reference datasets**
**AERONET**

We would like to think of AERONET as “ground truth”…

# Aerosol Robotic Network (AERONET)

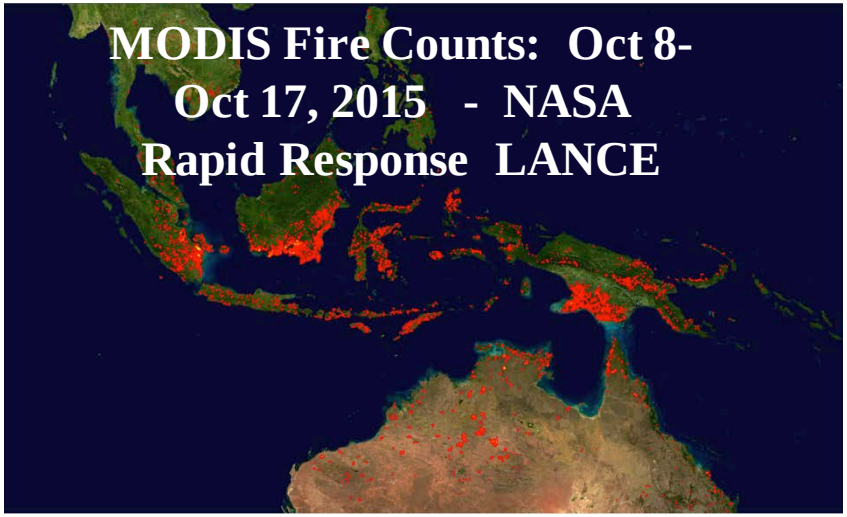



AERONET-observed AOD is extremely lognormal.
Should Satellite data also be? (for that matter, models?)

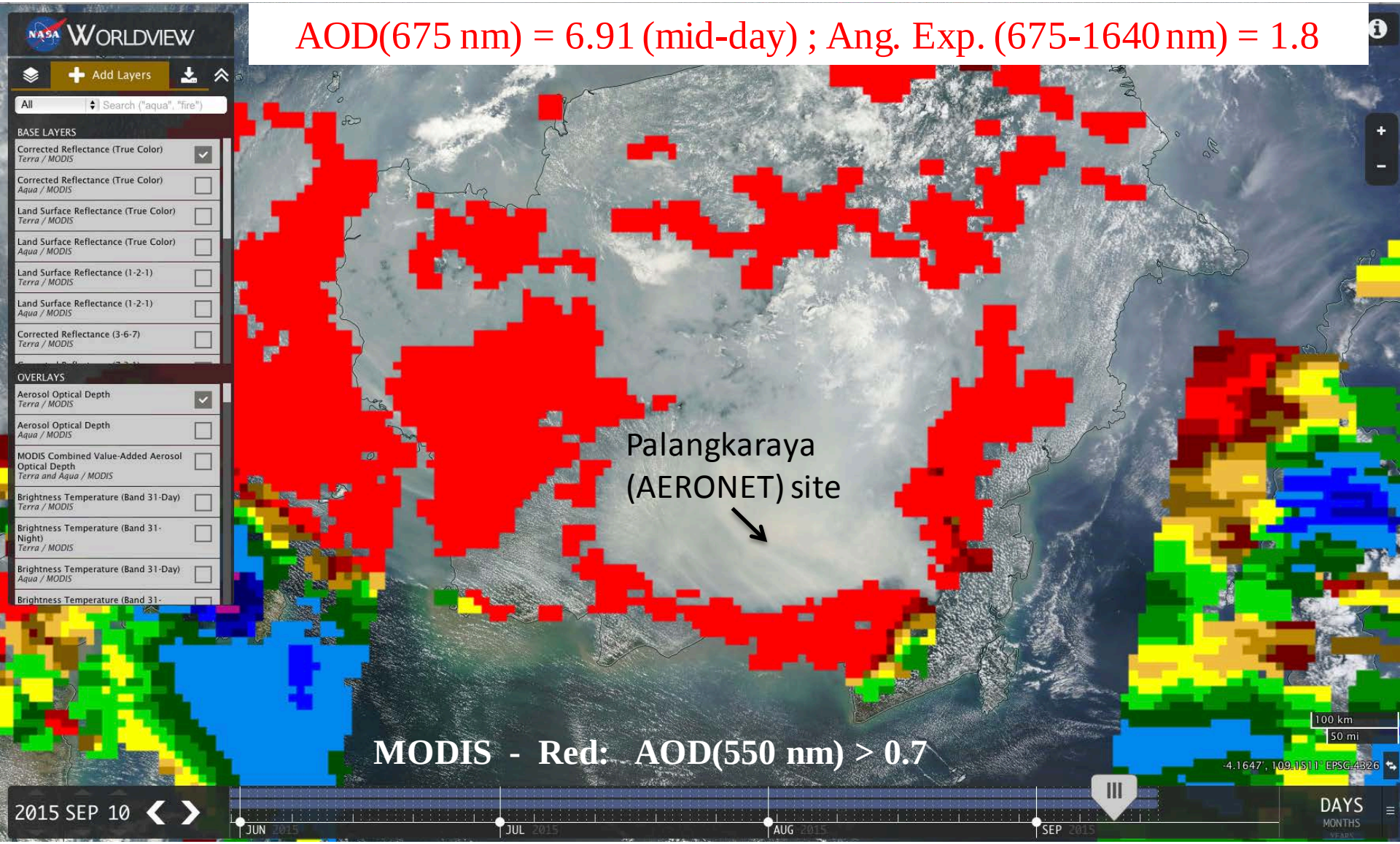
# But we all are missing something…..

**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.,

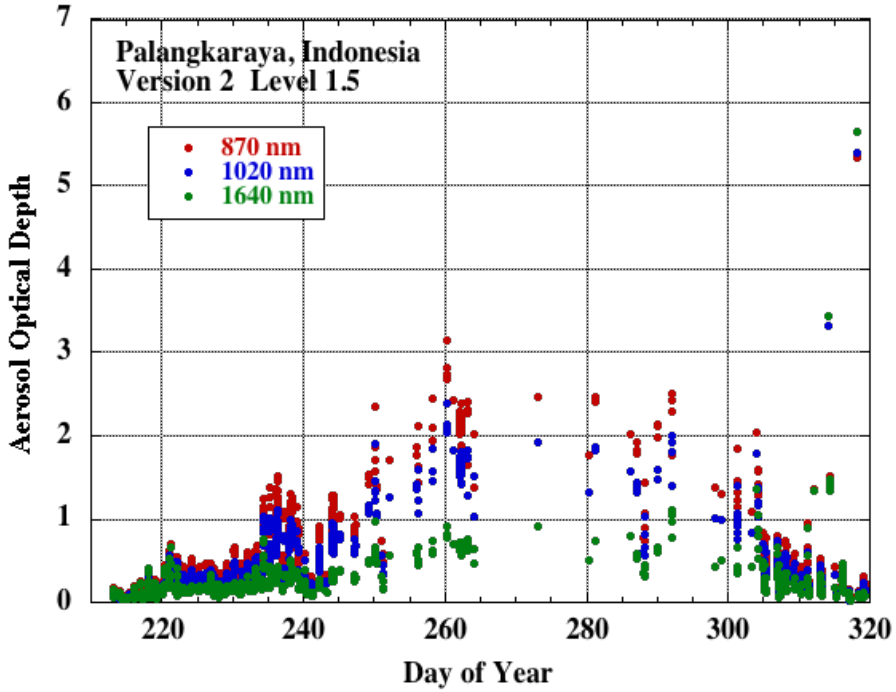
We complain that satellites (e.g. MODIS) can't retrieve these super extreme events!.... (AERONET Level 1 shows AOD ~ 7.0!)

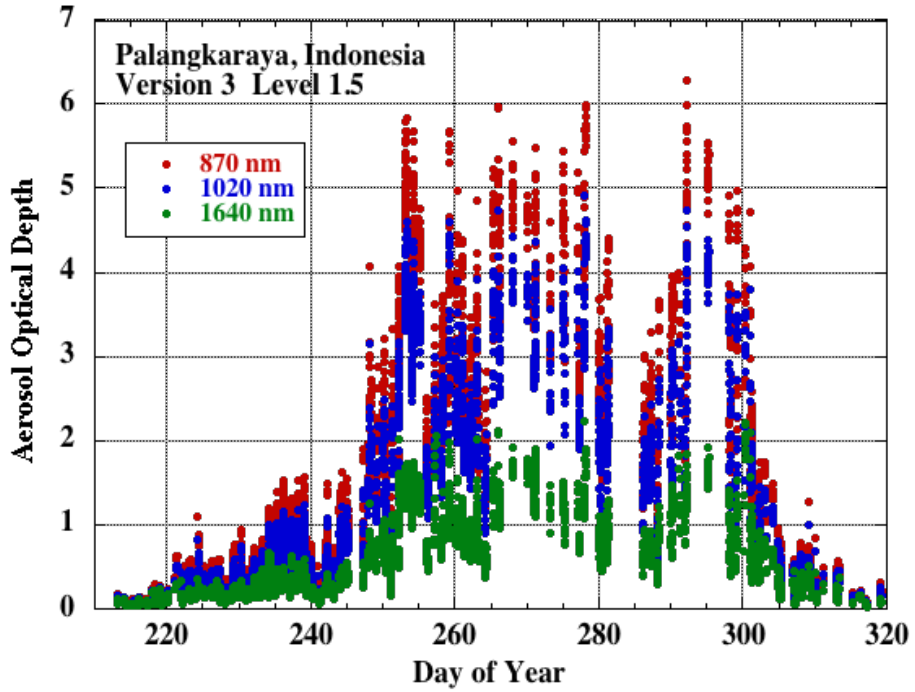


# …But neither can AERONET (until now, Version 3)

**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!



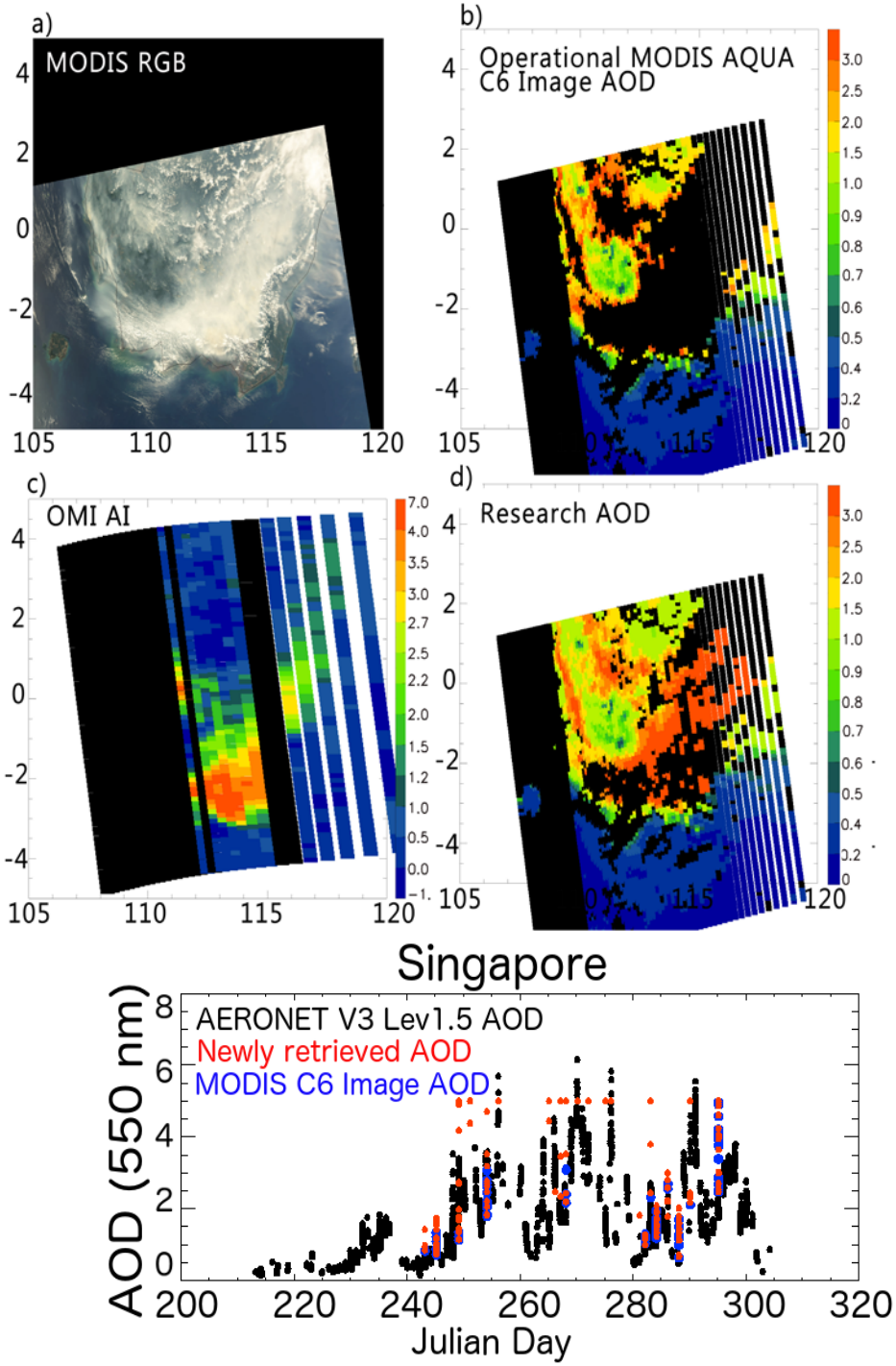

New V3 Algorithm Restores AOD data for longest wavelengths when signal strength is sufficient

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)

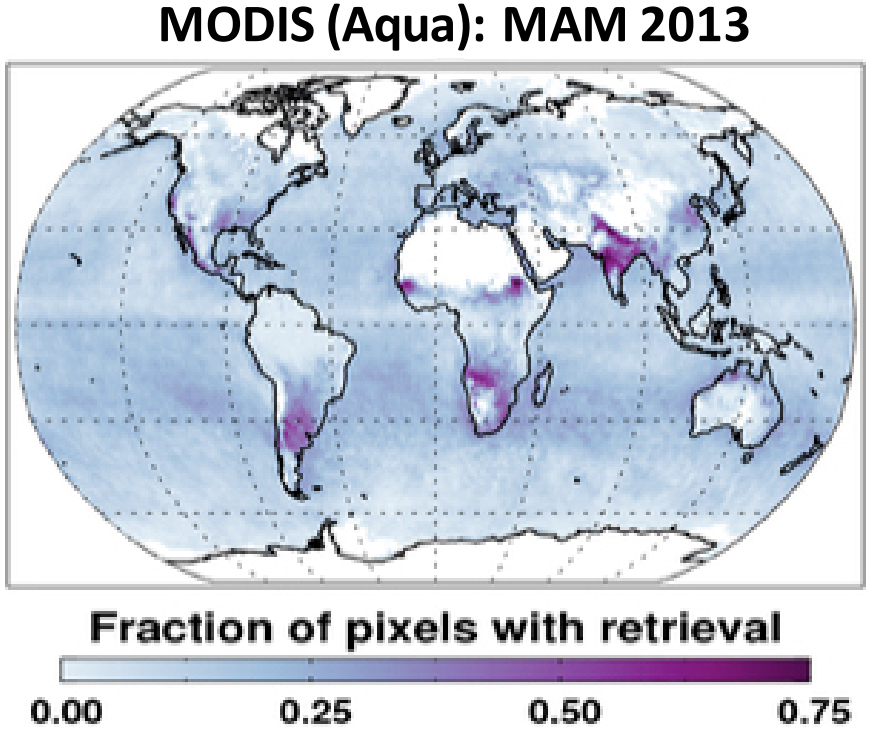
1. How much do we need to do to produce climate quality?

# 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?



# 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


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

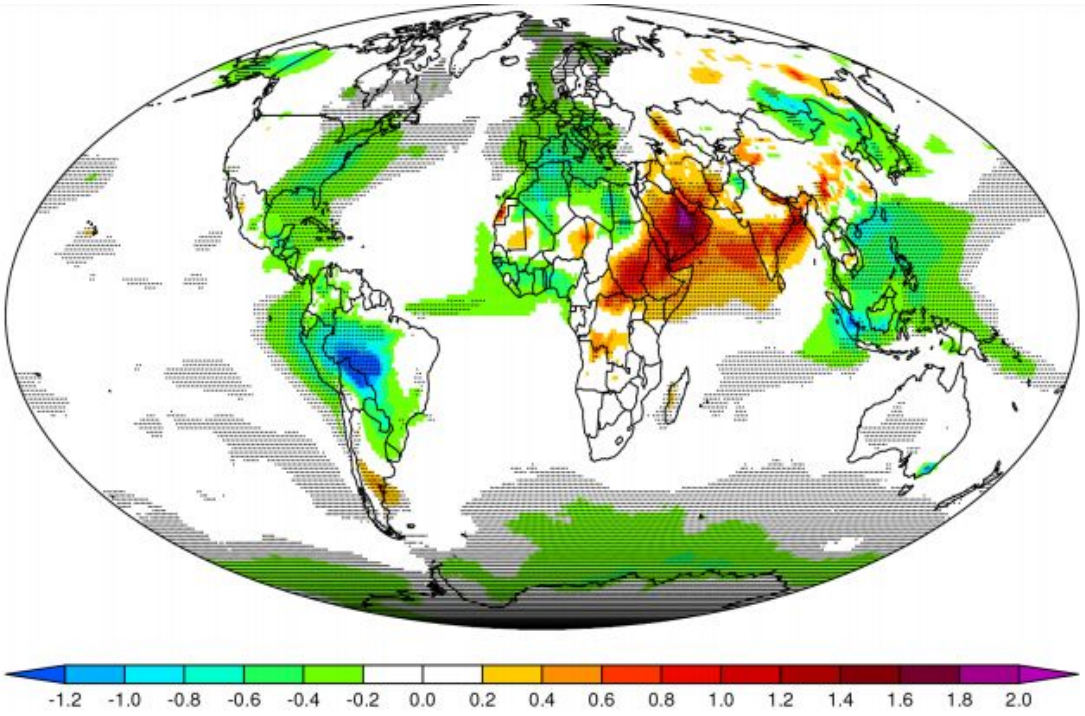



**Figure 13.** Trends of the deseasonalized reanalysis total AOT at 550 nm over 2003–2013 (unit: 100 × AOT year$^{-1}$). The dotted areas have passed the 95 % statistical significance level (see text and Zhang and Reid, 2010, for details).

- 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?