# Creating a global aerosol data time series from MODIS, Suomi-NPP VIIRS and beyond:
# **Dark Target**
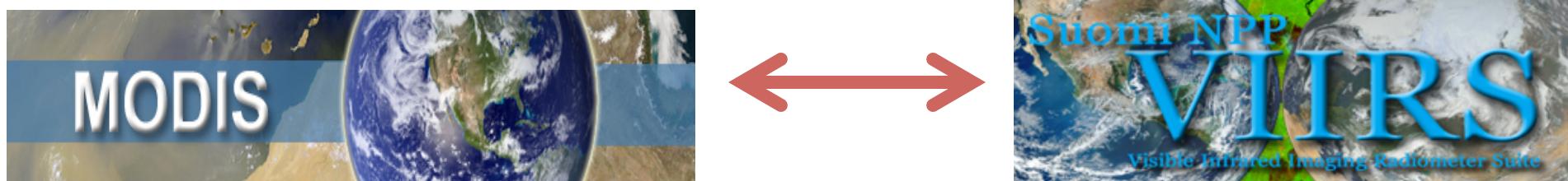
Robert C. Levy (NASA-GSFC)
robert.c.levy@nasa.gov

And the Dark-target aerosol retrieval team:

Shana Mattoo, Leigh Munchak and Richard Kleidman (SSAI/GSFC)
Lorraine Remer (UMBC/JCET), Falguni Patadia (MSU/GSFC),
Pawan Gupta (USRA/GSFC), Robert Holz (SSEC/UWisc), and others

ICAP meeting, Barcelona, 17 June 2015

# Aerosol retrieval from MODIS

## What MODIS observes



May 4, 2001; 13:25 UTC
Level 1 "reflectance"
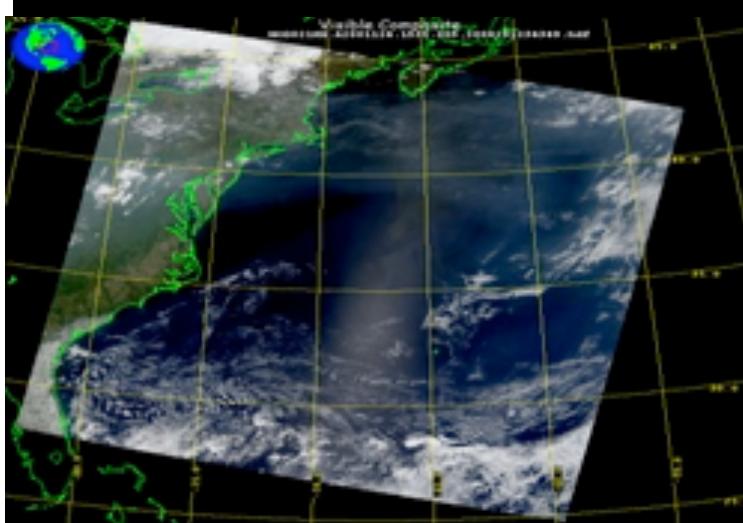
## Attributed to aerosol (AOD)



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

LAND    OCEAN

GLINT

AOD
1.0
0.0
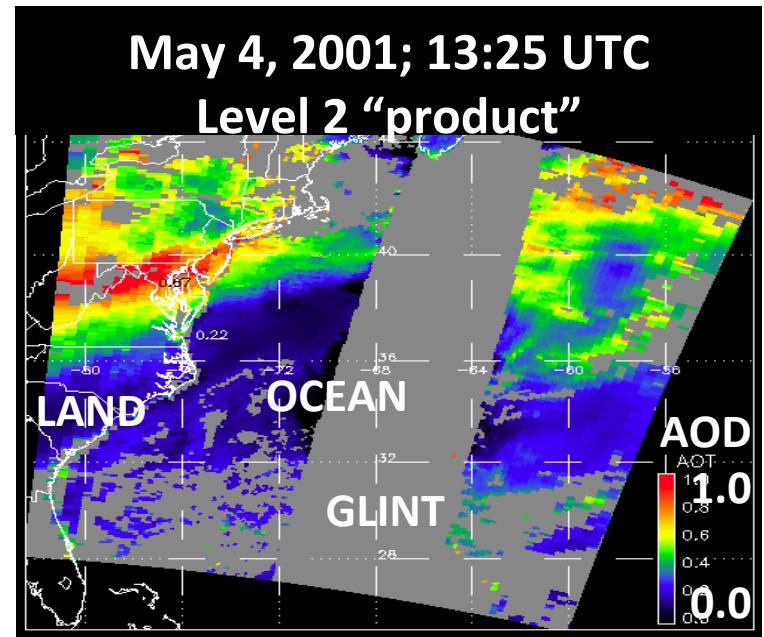
There are many different "algorithms" to retrieve aerosol from MODIS
1. Dark Target ("DT" ocean and land; Levy, Mattoo, Munchak, Remer, Tanré, Kaufman)
2. Deep Blue ("DB" desert and beyond; Hsu, Bettenhousen, Sayer,.. ): Previous talk!!!
3. MAIAC (coupled with land surface everywhere; Lyapustin, Wang, Korkin,…)
4. Land/Atmospheric correction (Vermote, …)
5. Ocean color/atmospheric correction (McClain, Ahmad, …)
5. Etc (neural net, model assimilation, statistical, … )
6. Your own algorithm (many groups around the world)

# Outline

1. MODIS Collection 6 updates (algorithm wise)
   1. DT ocean
   2. DT land
2. Terra vs Aqua (and calibration and trends)
3. Onward to S-NPP VIIRS and climate data records?
4. Summary, challenges, etc

# MODIS Collection 6 updates (Dark target)

- The 10 km standard product (MxD04_L2)

- In addition to improved Deep Blue (DB; previous talk by Andy), there is a DB/DT merge (Sorry, I won't talk about it) .

- And a separate 3 km product (3km: MxD04_3K), aimed at air quality applications (I won't talk about that, either).

# The Dark Target family consists of two separate aerosol optical depth (AOD) retrieval algorithms

**Dark land**

Spectral surface reflectance relationship, which is function of angle and NDVI_SWIR.

aerosol types are prescribed for location/season

Multispectral inversion using 3 wavelengths (0.47, 0.55 and 2.1 µm) and compared to lookup tables

**Water**

Surface BRDF including glint, foam, underlight (function of wind speed)

Aerosol types are not prescribed for season/location

Multispectral inversion using 6 wavelengths (0.55 – 2.1 µm) and compared to lookup tables

Both report the AOD at 550 nm,
Along spectral AOD and/or fine-mode fraction

Slide stolen and modified from A Sayer – ICAP 2015

# Overall changes (C6 vs C5): Aqua, 2008



Jan

C5: Apr 2008 | C6: Apr 2008 | C6-C5 | Added or Deleted coverage

Apr
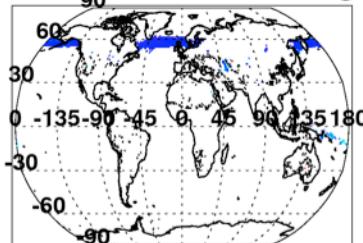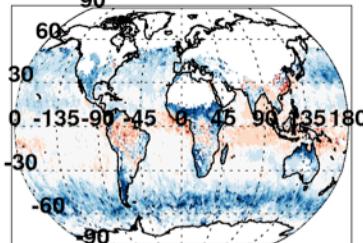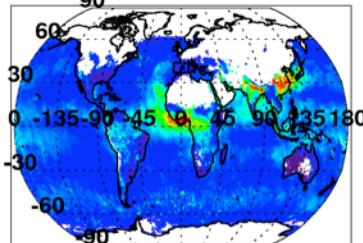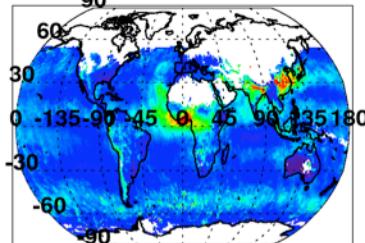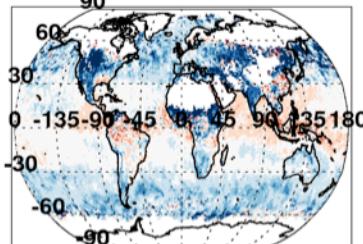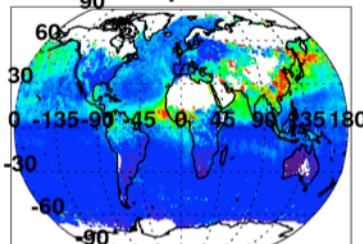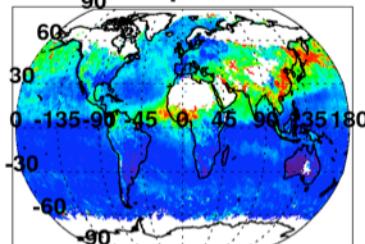
C5: Jul 2008 | C6: Jul 2008 | C6-C5 | Added or Deleted coverage

Jul

C5: Oct 2008 | C6: Oct 2008 | C6-C5 | Added or Deleted coverage

Oct
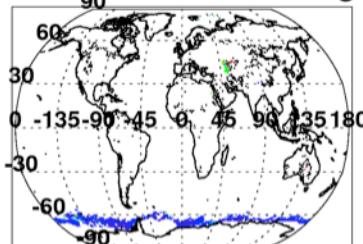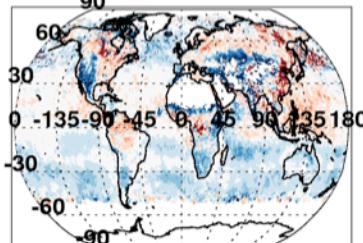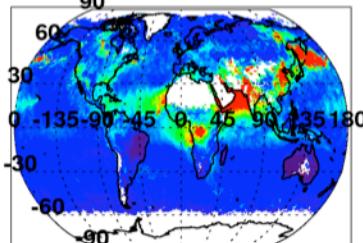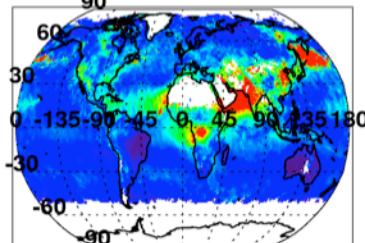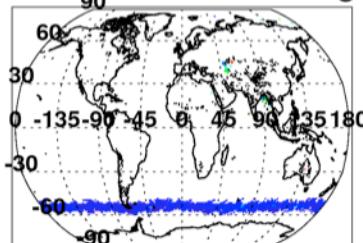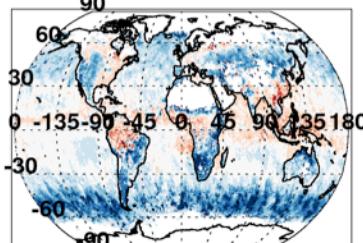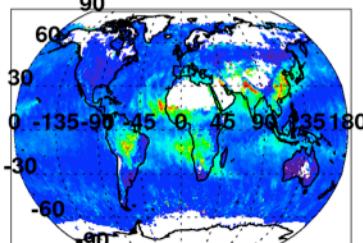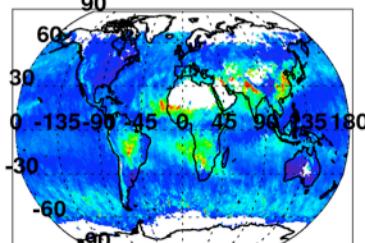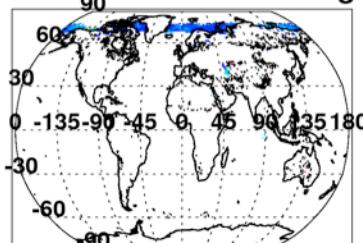
AOD at 0.55 μm
0.0          0.8

AOD Difference
-0.1      0.0      0.1

**DETAILS?? →**

# MODIS (MxD04) Collection 6!

- Levy, R. C., Mattoo, S., Munchak, L. A., Remer, L. A., Sayer, A. M., Patadia, F. and Hsu, N. C.: The Collection 6 MODIS aerosol products over land and ocean, *Atmos Meas Tech,* 6(1), doi:10.5194/amt-6-2989-2013, 2013.

- Sayer, A. M., Munchak, L. A., Hsu, N. C., Levy, R. C., Bettenhausen, C. and Jeong, M. J.: MODIS Collection 6 aerosol products: Comparison between Aqua's e-Deep Blue, Dark Target, and 'merged' data sets, and usage recommendations, *J Geophys Res-Atmos,* doi:10.1002/2014JD022453, 2014.

- Munchak, L. A., Levy, R. C., Mattoo, S., Remer, L. A., Holben, B. N., Schafer, J. S., Hostetler, C. A. and Ferrare, R. A.: MODIS 3 km aerosol product: applications over land in an urban/suburban region, *Atmos Meas Tech,* 6(1), doi: 10.5194/amt-6-1747-2013,2014.

- Remer, L. A., Mattoo, S., Levy, R. C. and Munchak, L. A.: MODIS 3 km aerosol product: algorithm and global perspective*, Atmos Meas Tech,* 6(7), doi:10.5194/amt-6-1829-2013, 2013.

Collection 6 "Webinars":  http://aerocenter.gsfc.nasa.gov/ext/registration/
New "dark-target" website:   http://darktarget.gsfc.nasa.gov
MODIS product website:  http://modis-atmos.gsfc.nasa.gov

# Focus on Trends/Calibration: Terra versus Aqua

Terra (since spring 2000)
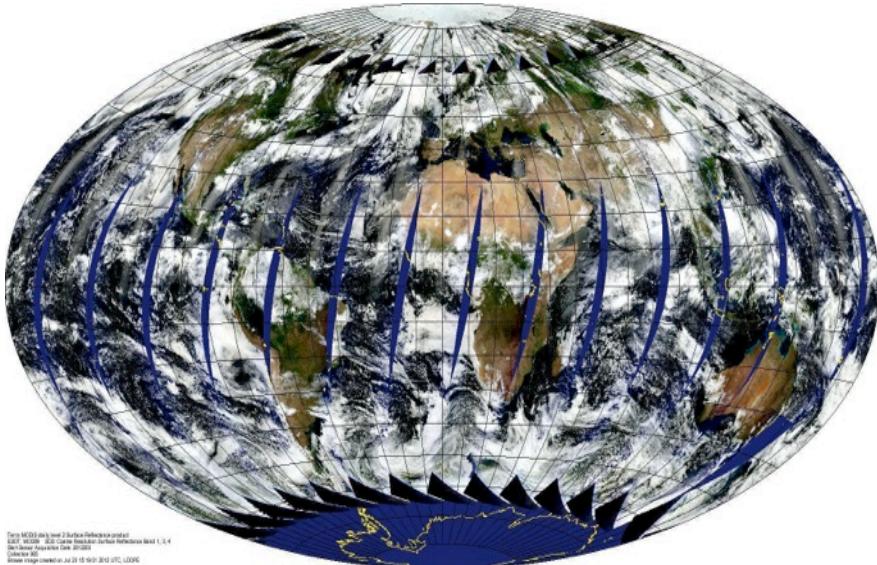
Aqua (since summer 2002)
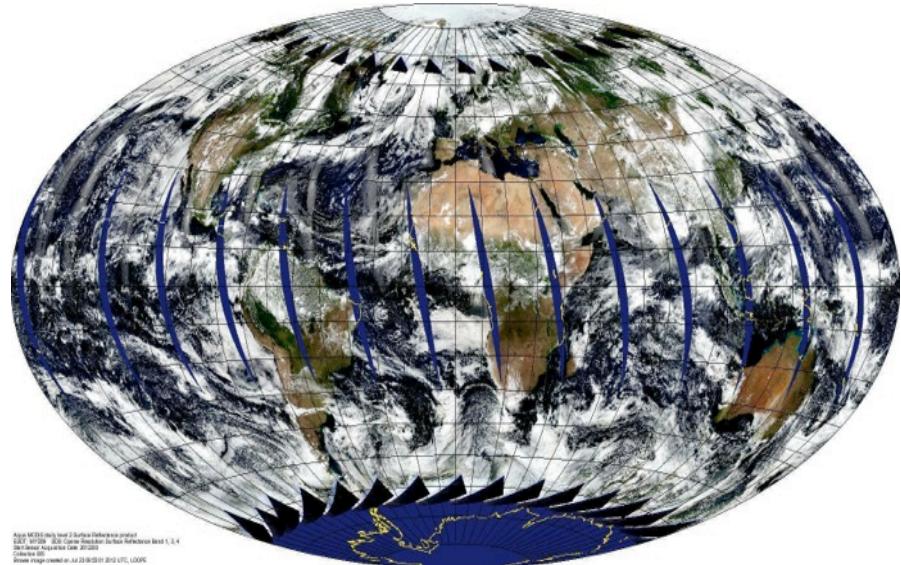


- Same instrument hardware (optical design)
- Same spatial and temporal sampling resolution
- Same calibration/processing teams
- Same aerosol retrieval algorithms
- Identical twins!

# Aerosol Trends:  If based on Collection 5

Aqua:JUL, 2002 to JUN, 2013 ; Terra: JUL, 2002 to JUN, 2013
AREA WEIGHTED = YES, PIXEL WEIGHTED = NO
C5(Aqua & Terra) AOD zonal avg [60S, 60N]

Terra
Aqua

**LAND**

$\beta_B = -0.001/dec$ (abs)
$\beta_R = -0.003/dec$ (rel)

$\beta_B = -0.049/dec$ (abs)
$\beta_R = -0.267/dec$ (rel)

(y-axis) AOD at 550nm (zonal avg): 0.12, 0.16, 0.20, 0.24, 0.28

(x-axis) Jan 2003, Jan 2004, Jan 2005, Jan 2006, Jan 2007, Jan 2008, Jan 2009, Jan 2010, Jan 2011, Jan 2012, Jan 2013
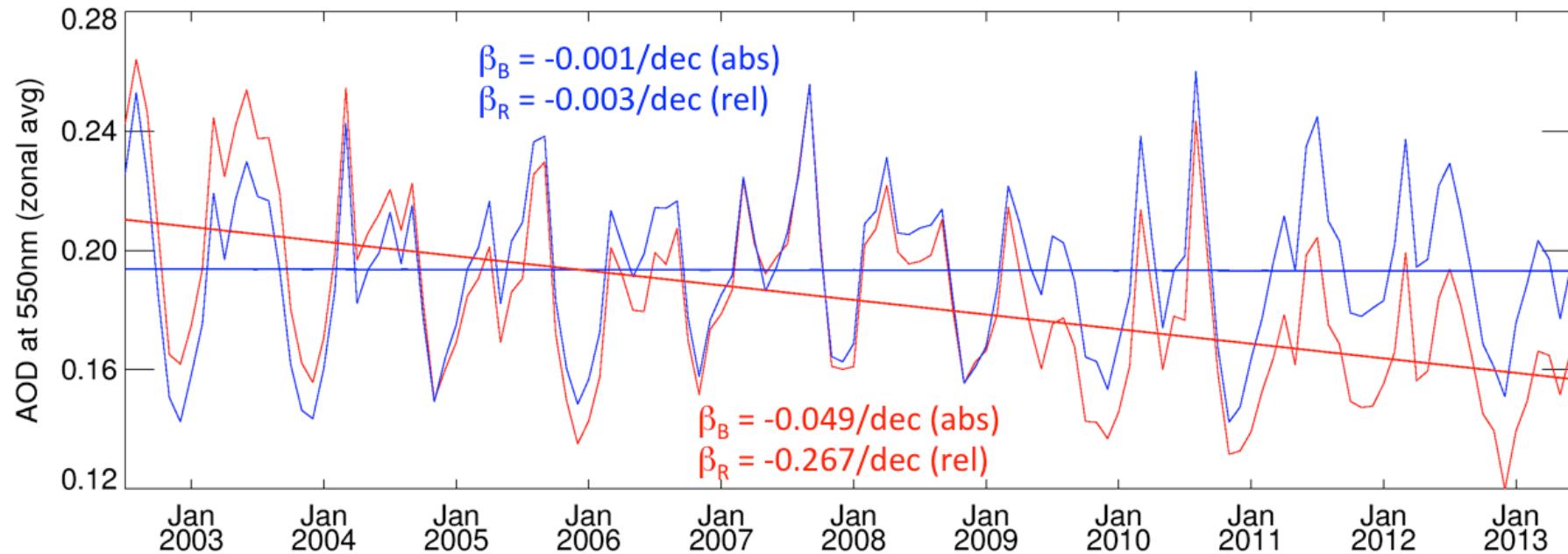
- Over land, Terra *decreased* (-0.05/decade), Aqua *constant*
- Terra / Aqua divergence was similar everywhere on the globe!

- Like identical human twins, the twin MODIS sensors aged differently.

# Tracking MODIS RSB radiometric stability from reflectance trends over CEOS desert sites



29-Sept-2002
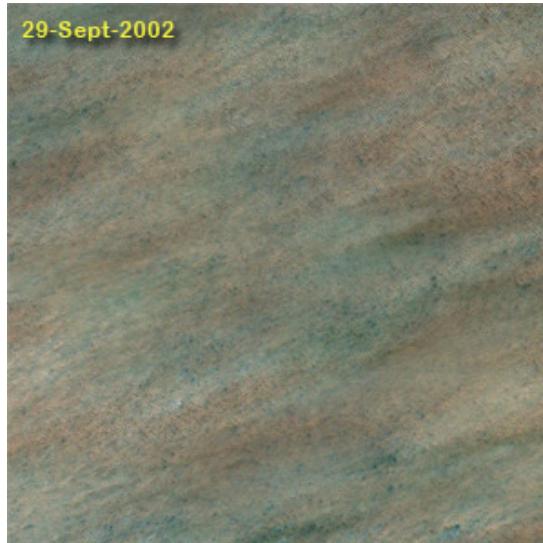
**CEOS desert test sites**



28-Sept-2002

(1) Collect clear-sky MODIS data over desert sites
(2) Develop site-specific BRDF from first 3 years of mission
(3) Over time, compare "observed" reflectance with BRDF modeled reflectance, for different view angles
(4) Trends in Band #3 (0.47 $\mu$m) are consistent with Terra's AOD trends over LAND!
(5) → NEW CALIBRATION METHOD applied to Terra!



**Normalized Reflectance**
**Band #3, Mirror #1, Frame #645 (near nadir)**

Observed Reflectance / BRDF Reflectance

- Terra Reflectance
- Aqua Reflectance

Days since 2000

MCST (Sun, Xiong et al)
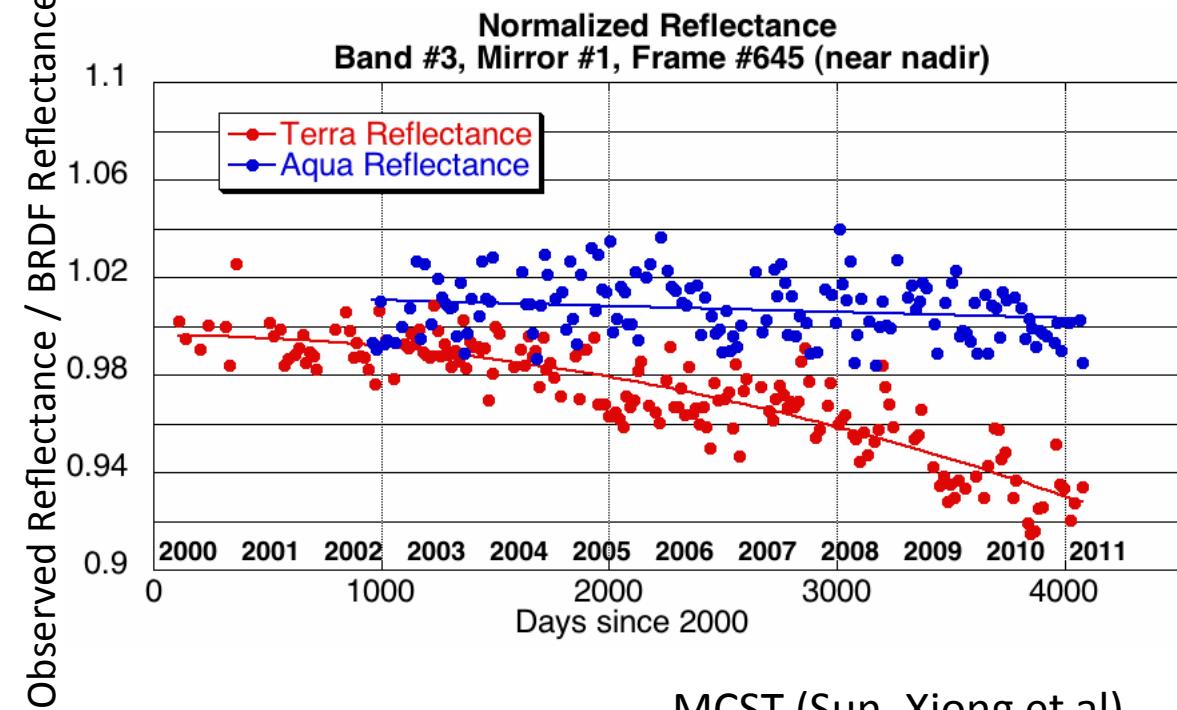
# C6 differences AOD: Terra-Aqua
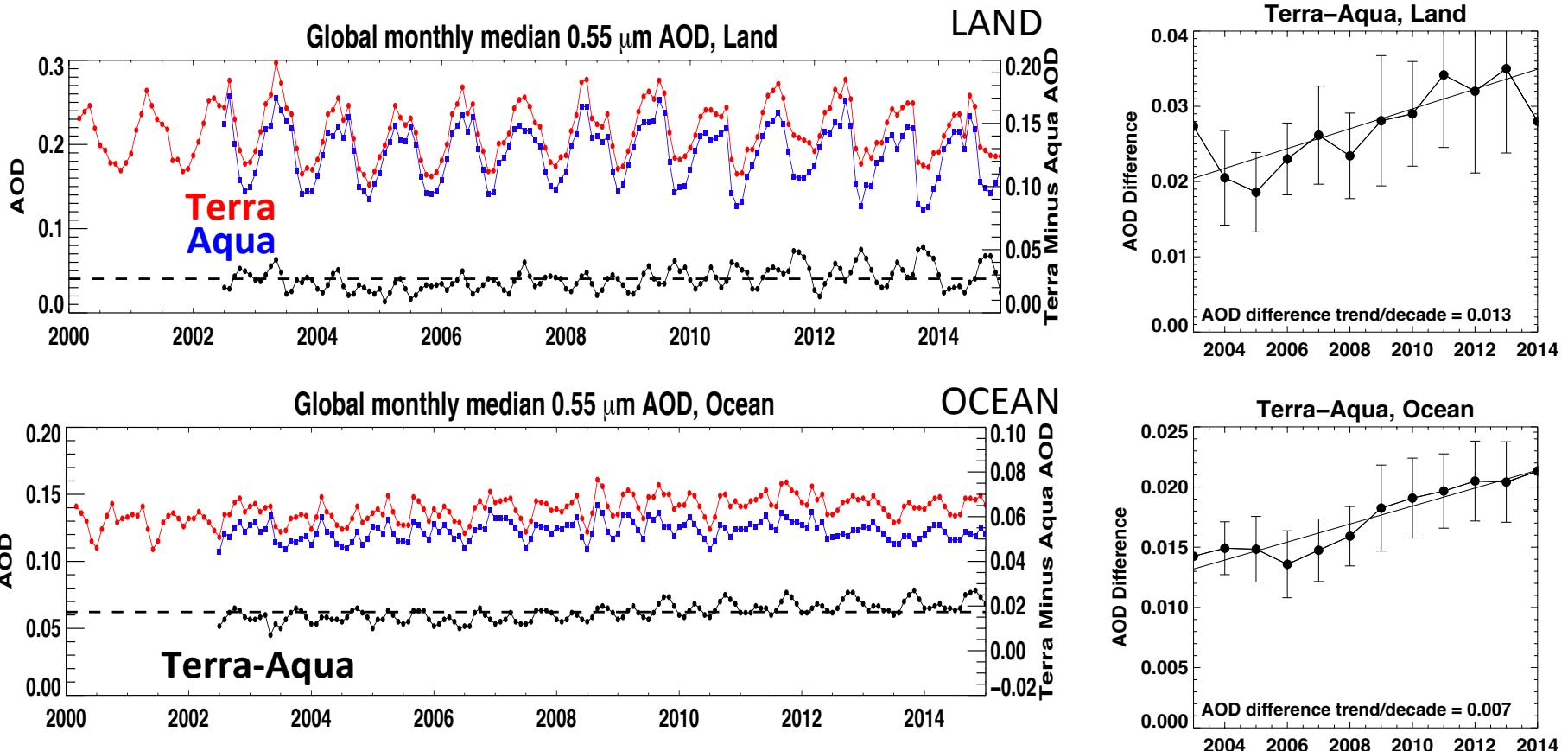


- Terra/Aqua divergence "mostly" removed for C6
- Terra offset by 0.027 land/0.017 ocean), THIS IS >13% of AOD!
- There is still residual trending (Terra-Aqua increasing by ~0.01/decade)
- Bigger-amplitude seasonal cycle to Terra-Aqua after 2011.
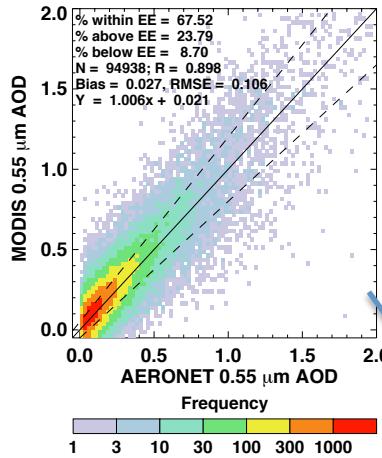
# "Validation": 2003-2013, Land

scatterplots



| Sat | N | Slope | Int | R | RMSE | Bias |
|------|-------|-------|------|-------|-------|-------|
| Terra | 94.9K | 1.01 | 0.02 | 0.892 | 0.106 | 0.027 |
| Aqua | 80.5K | 1.01 | 0.00 | 0.890 | 0.104 | 0.004 |

MODIS vs AERONET: Mar 2003-Feb 2013
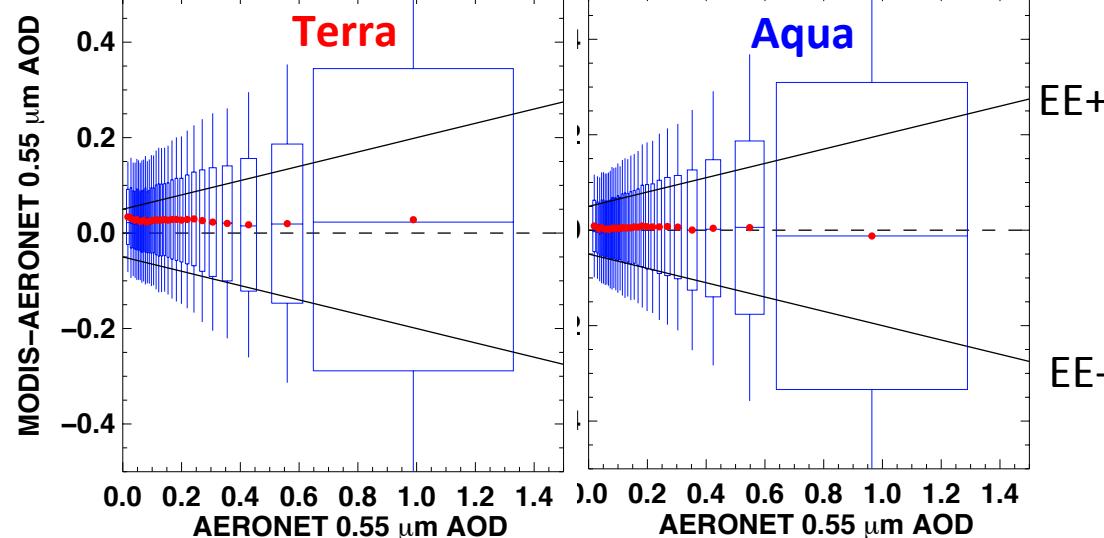


- EE% > 68%: Both Terra and Aqua meet "expected error (EE) " of ±(0.05 + 15%)
- Some metrics nearly identical: Corr = R=0.89, Slope=M=1.01, RMSE=0.10
- Terra is biased high for all AOD (due to **y-intercept**)
- $N_{Terra}$ = 95K versus $N_{Aqua}$=81K. Why? Calibration? Sampling? AM/PM Clouds? Other?
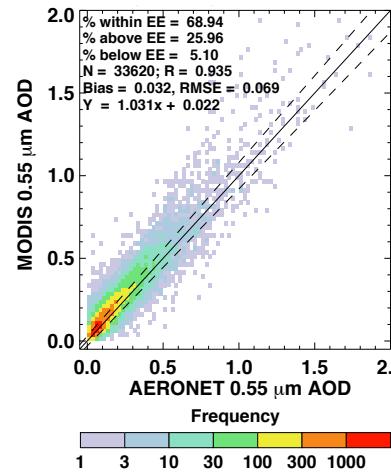
# "Validation": 2003-2013, Ocean

## scatterplots



| Sat | N | slope | Y-int | R | RMSE | Bias |
|---|---|---|---|---|---|---|
| **Terra** | 33.6K | 1.04 | 0.02 | 0.935 | 0.069 | 0.032 |
| **Aqua** | 29.9K | 0.97 | 0.02 | 0.929 | 0.066 | 0.016 |

MODIS vs AERONET: Mar 2003-Feb 2013
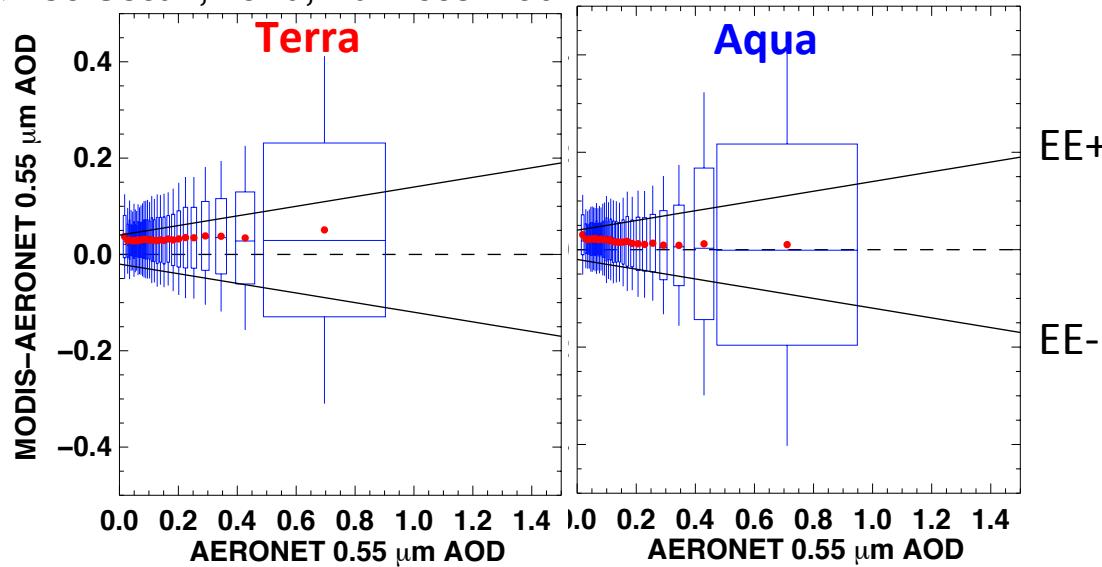


- EE% > 68%: Both Terra and Aqua meet "expected error (EE)" of ±(0.03 + 10%)
- Some metrics nearly identical: Corr = R=0.93, Y-int=0.02, RMSE=0.07
- Terra is biased high, but due to **slope**.
- $N_{Terra}$ = 34K versus $N_{Aqua}$=30K. Why? Calibration? Sampling? AM/PM Clouds? Other?

# Summary (MODIS C6)

- MODIS aerosol retrieval ("MxD04_L2") has many upgrades for Collection 6.

- Aqua/Terra level 2 and 3 are available now

- Trending issues reduced with C6 calibration

- But still significant offsets (~0.02).  Why?

- Still residual co-trending (<0.01 / decade)

- Next step: Consider applying C6+ calibration

Lyapustin, A., Wang, Y., Xiong, X., Meister, G., Platnick, S., Levy, R., Franz, B., Korkin, S., Hilker, T., Tucker, J., Hall, F., Sellers, P., Wu, A. and Angal, A.: Scientific impact of MODIS C5 calibration degradation and C6+ improvements, Atmos Meas Tech, 7(12), 4353–4365, doi:10.5194/amt-7-4353-2014, 2014.

# Beyond MODIS?

- Terra just celebrated its 15$^{th}$ birthday!

- At 12+, Aqua ain't no spring chicken!

- Terra and Aqua MODIS instruments are both >2x original mission lifetimes

- MODIS won't be here forever

- How do we get to 20+ year aerosol data records?

# VIIRS?

## Suomi-NPP (and future JPSS) VIIRS
## Visible Infrared Imager Radiometer Suite
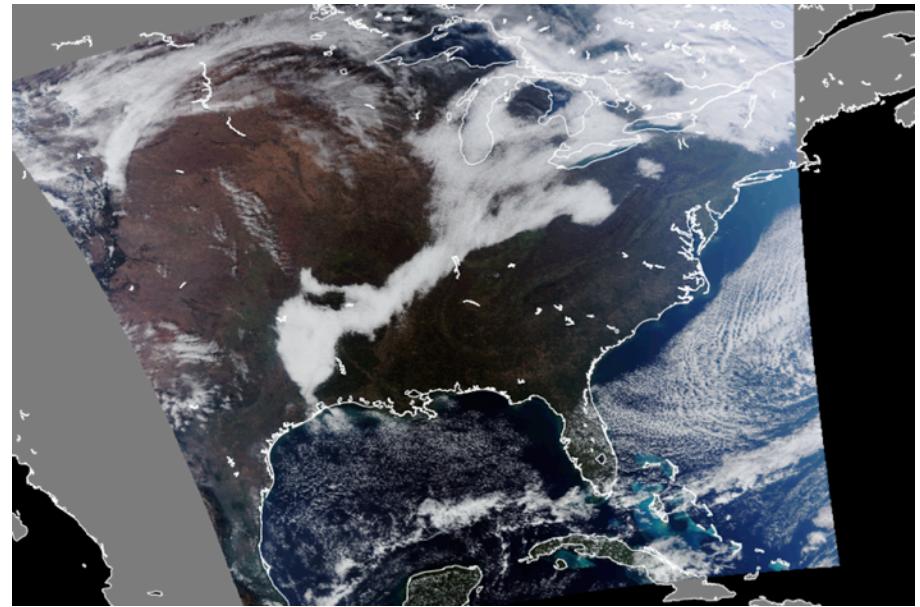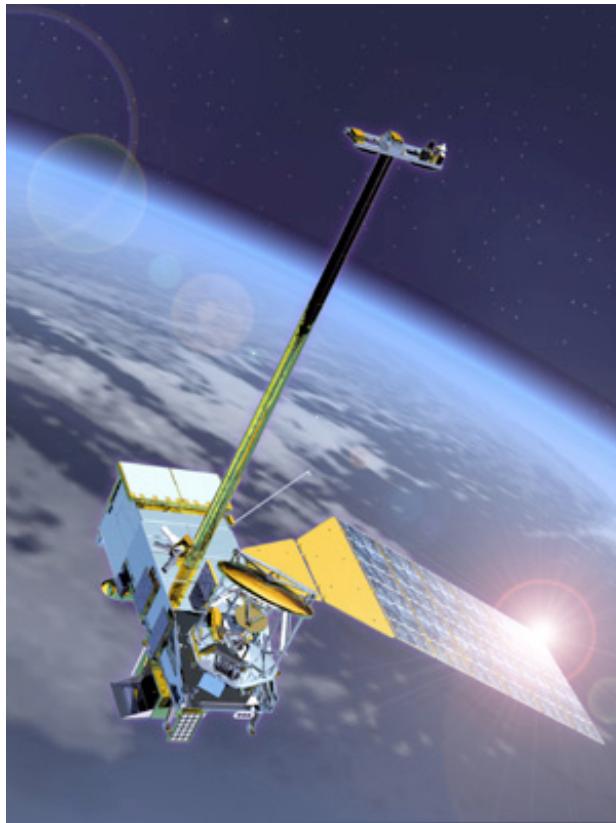


Can VIIRS "continue" the MODIS aerosol data record?

# VIIRS versus MODIS

**Orbit**: 825 km (vs 705 km), sun-synchronous, over same point every 16 days
   Equator crossing: 13:30 on Suomi-NPP, since 2012 (vs on Aqua since 2002)

**Swath**: 3050 km  (vs 2030 km);  Granule size: 86 sec (vs 5 min)

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

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

**Aerosol retrieval algorithms:**  "Physics" similar, but different strategies

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

Aqua (13:30 Local Time, 14.6 revs/day)          Suomi-NPP (13:30 Local Time 14.1 revs/day);



MODIS - 29 May 2013



VIIRS - 29 May 2013
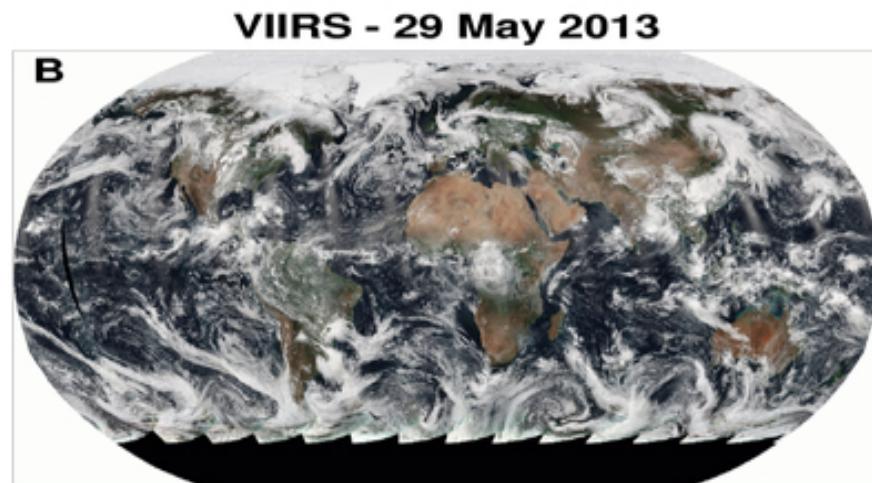
# VIIRS Aerosol Algorithm (NOAA-IDPS)

- Multi-spectral over dark surface
- Separate algorithms used over land and ocean
- 6 km resolution product – an integer multiple of scan lines
- Algorithm heritages
  - over land: MODIS atmospheric correction (e.g. the MOD09 product)
  - over ocean: MODIS aerosol retrieval (MOD04 product)
- Many years of development work:
- Retrieves:  AOD (at 0.55 $\mu$m and spectral), Ångström  Exponent (AE), Suspended Matter (aerosol classification), etc
- NOAA CLASS: The Primary Gateway for the VIIRS Data Distribution
- "Validated Stage 2" (published) since 23 Jan 2013.
- Provides data in HDF5 format (compared to HDF4-ish for MODIS)

# Aerosol retrieval: Different algorithms

Granules over India (Mar 5, 2013, 0735/0740 UTC)
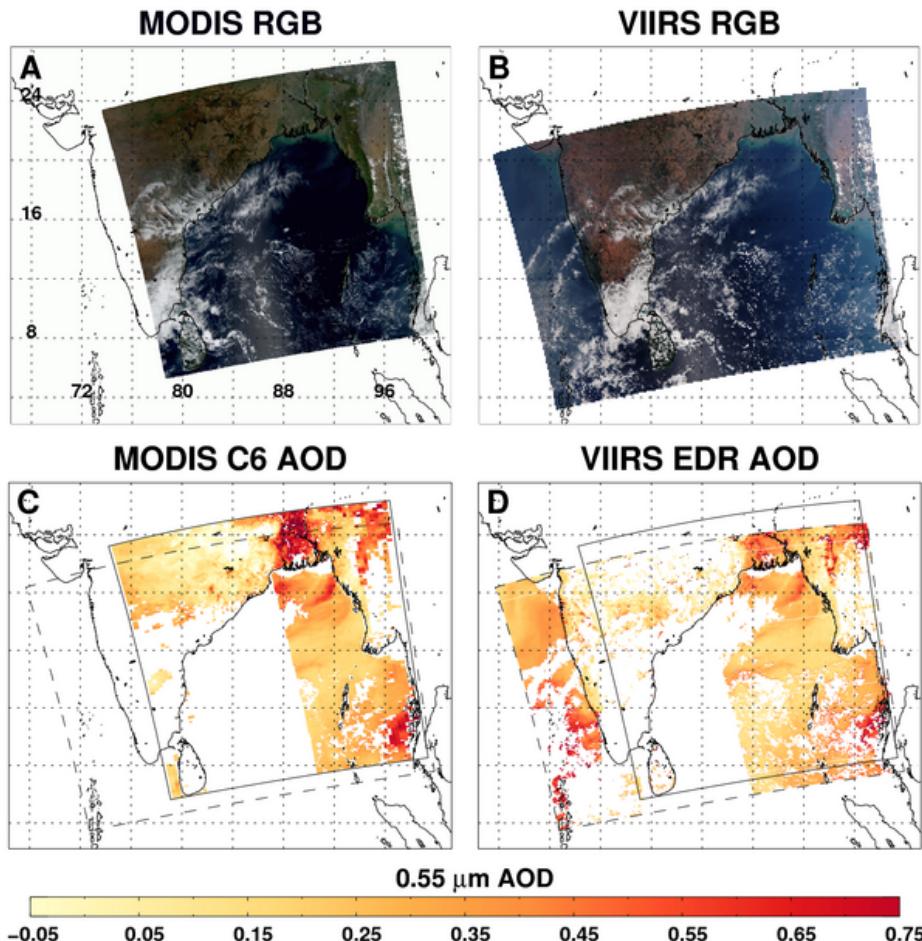


**Ocean retrieval algorithm**
- "heritage" circa 1997 (Tanré, Kaufman, Remer,… )

- MODIS:  C6 assumptions (Levy et al., 2013)
- VIIRS:  C5-like assumptions (Remer et al., 2005)

**Land retrieval algorithm**
- "heritage" circa 1997 (Kaufman, Tanré, Vermote,…)

- MODIS:  C6 "dark-target" (Levy et al., 2007, 2013)
- VIIRS:  C5 "atmos. correction" (Vermote et al., 2008).

- Differences in wavelengths, cloud masks, pixel selection technique, quality assurance etc:
- Also, not exactly overlapping orbits (note 5 min difference).
- Note, 86 second VIIRS granules aggregated to 5 minutes.

# Monthly mean AOD for Spring 2013 (Mar-May)
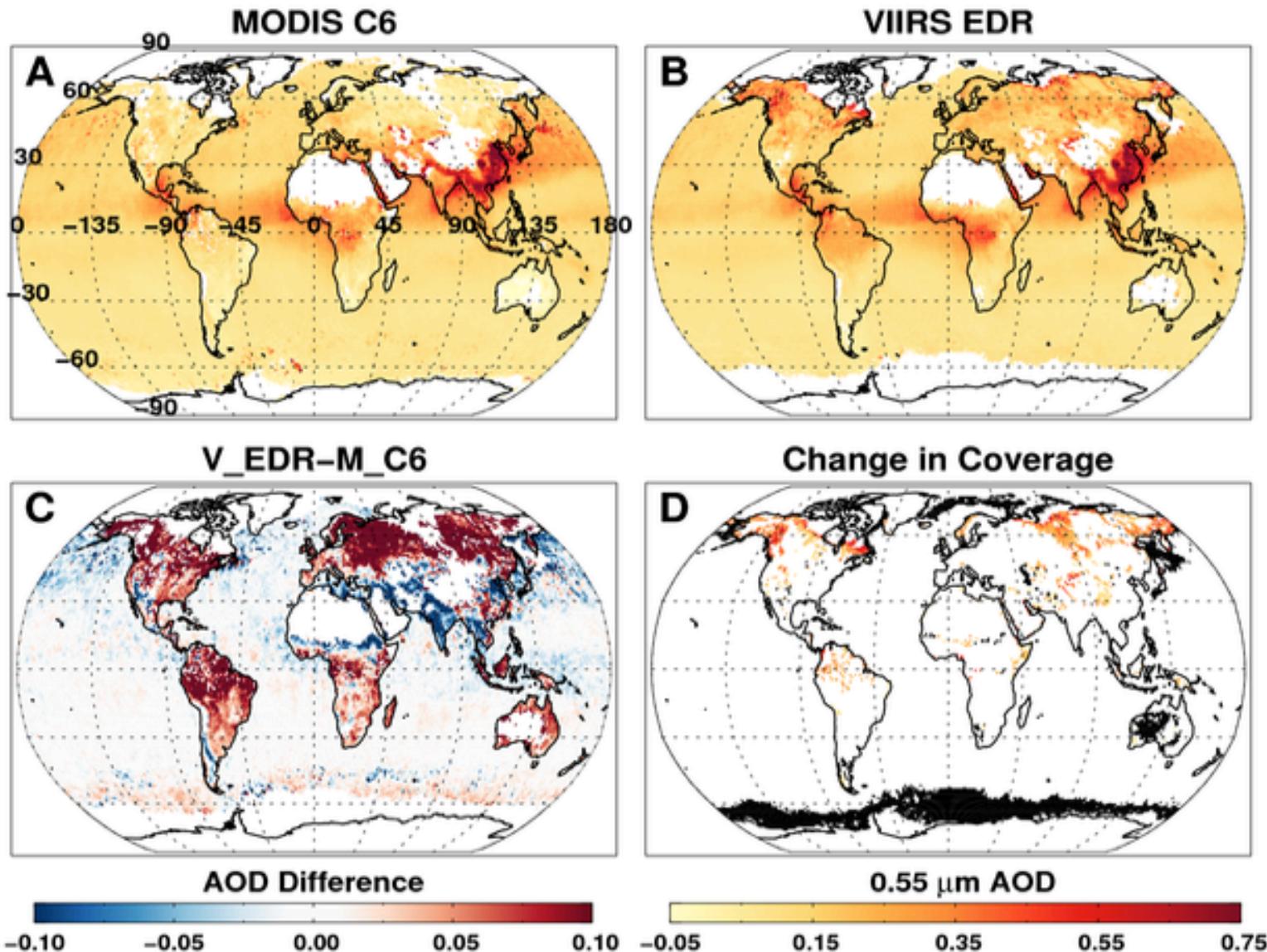


MODIS C6 and VIIRS-EDR are similar, yet too different

# Developing a MODIS-like algorithm for VIIRS

- The Intermediate file format (IFF) puts MODIS and VIIRS in "same common denominator" (University of Wisconsin)
- MODIS-IFF is 1 km resolution for all bands, VIIRS-IFF is 750 m (no high-resolution bands for either MODIS or VIIRS)
- Use 10 x 10 pixel retrieval boxes (so 10 km for MODIS; 7.5 km for VIIRS).
- Run lookup tables to account for different wavelengths
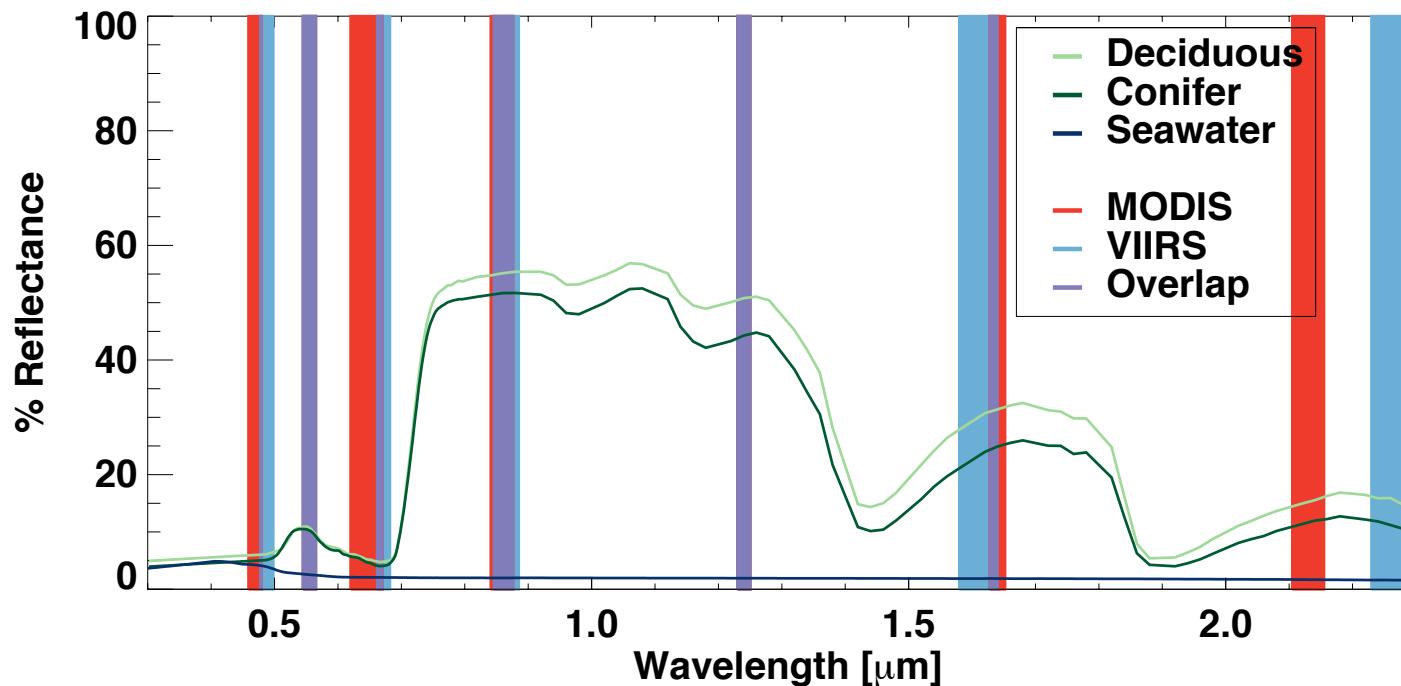
# Same algorithm on both platforms?

- Apply C6-like thresholds for cloud masking, pixel selection and aggregation
- Run "MODIS-like" algorithm on both M-IFF and V-IFF data
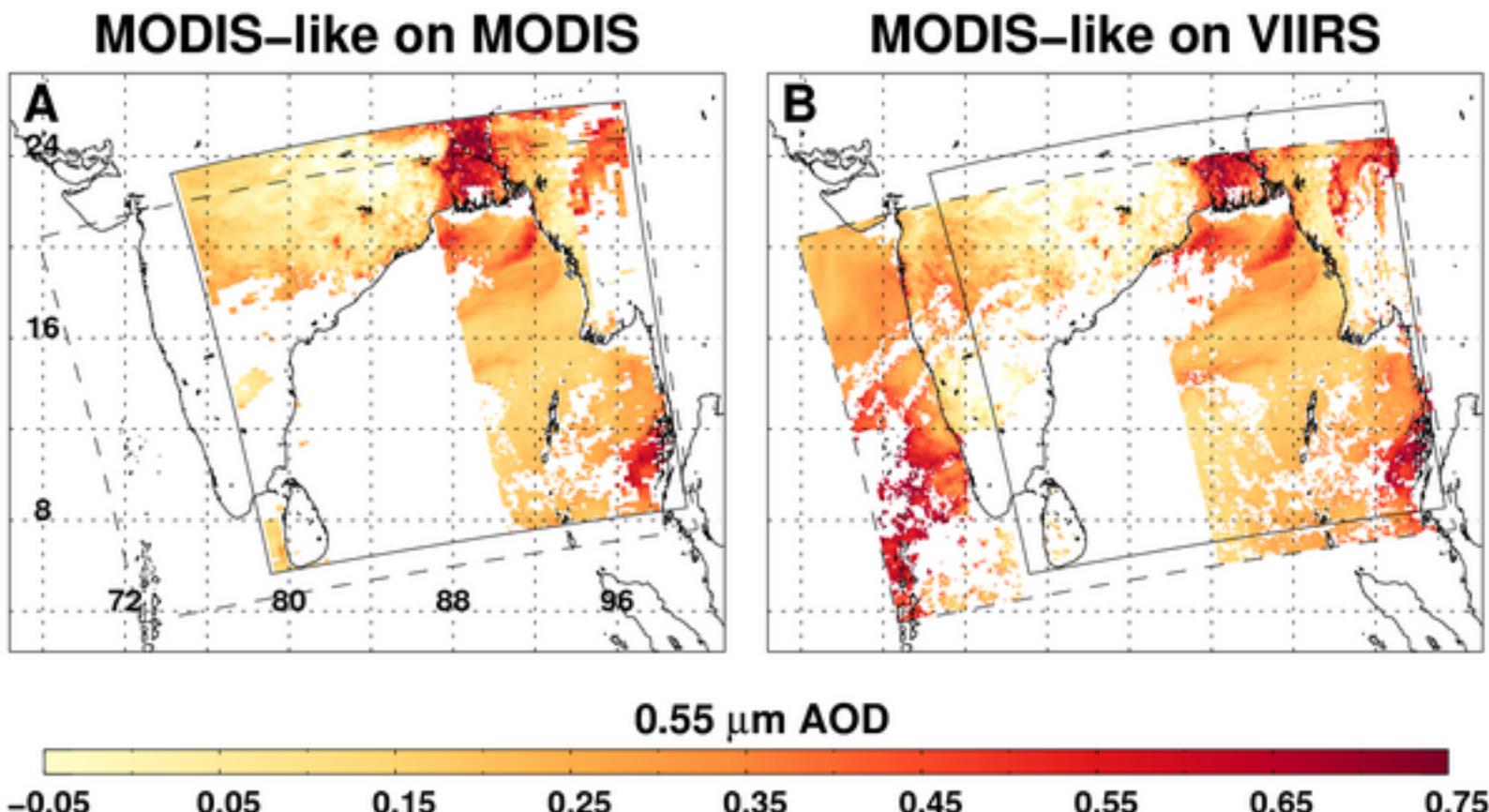


→ Much more similar AOD structure
→ Still differences in coverage and magnitude. We are learning why.
   (Cloud masking/spatial variability thresholds?)

# Gridded seasonal AOD (Spring 2013)

MODIS

MODIS-like on VIIRS

Difference M - V



Versus…



M_C6–V_EDR
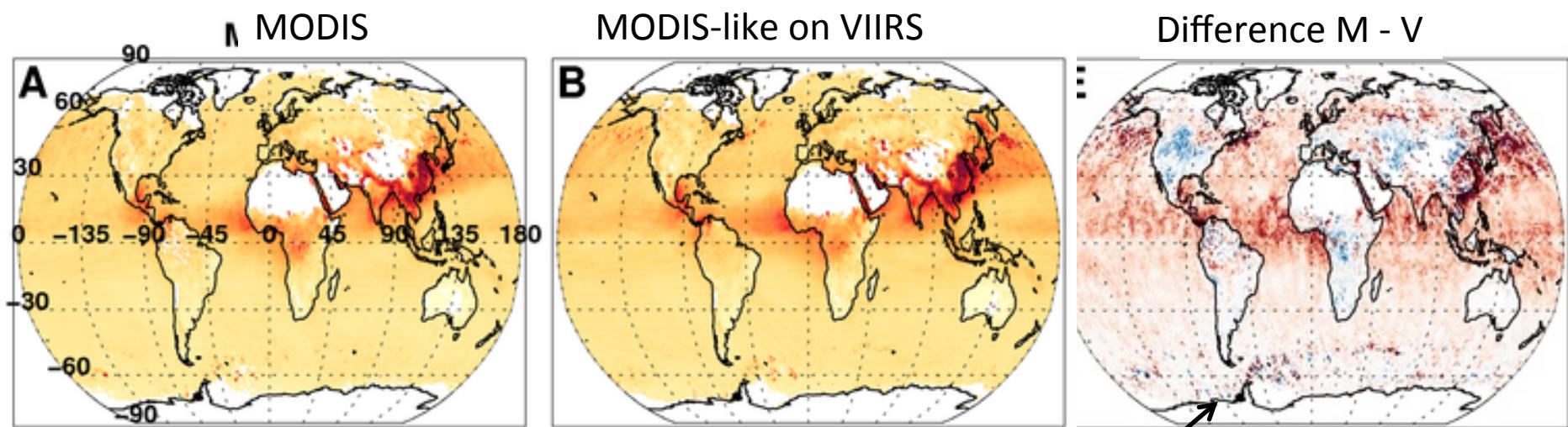
AOD Difference

Running MODIS-like on VIIRS has reduced global AOD differences and has similar global sampling

Systematic bias over ocean (VIIRS high by 15%)

Less systematic bias over land (MODIS high by 5%)
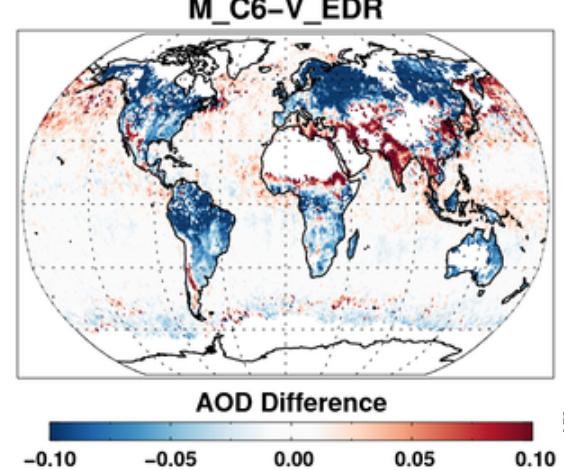
# Comparing gridded AOD (Spring 2013)

VIIRS_EDR vs MODIS
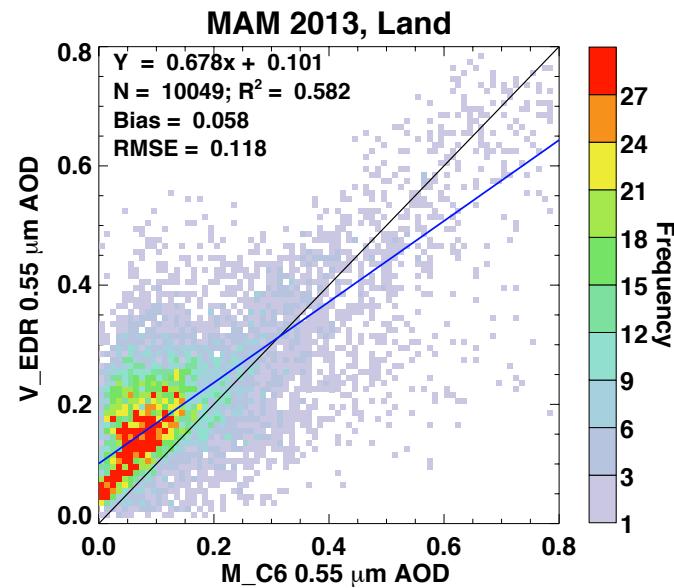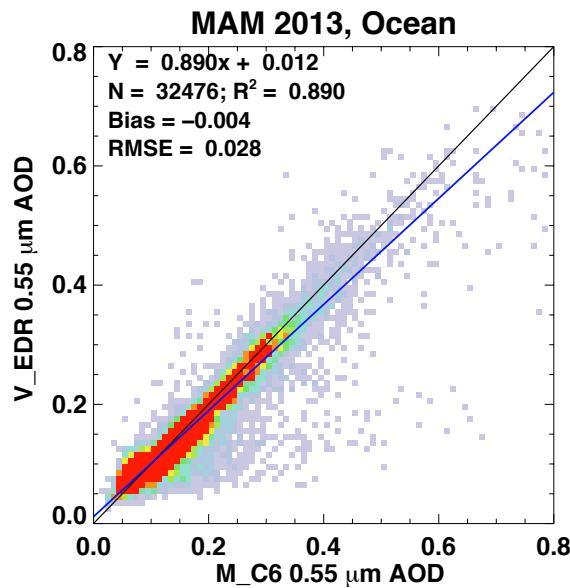
MODIS-like (VIIRS) vs MODIS
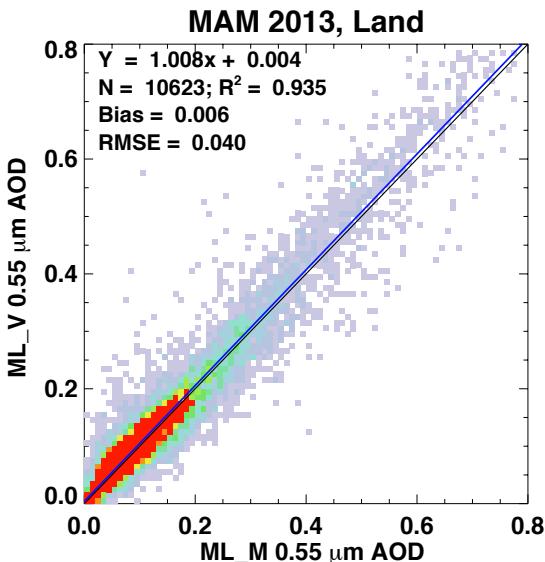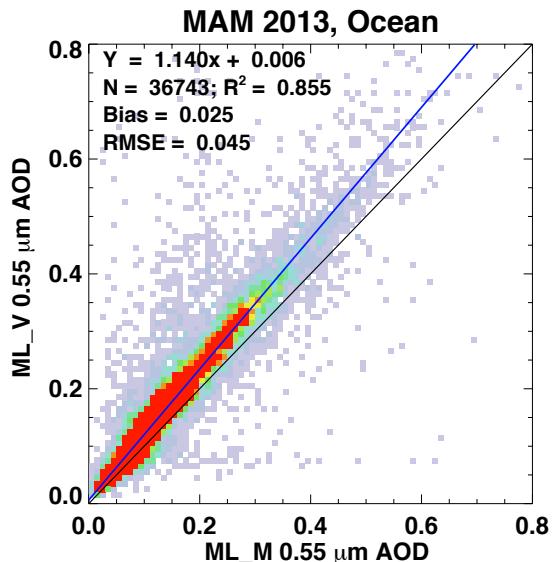
New data
More like MODIS
But 1.15 slope over ocean!



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# Angstrom Exponent (0.55 / 0.86 μm)
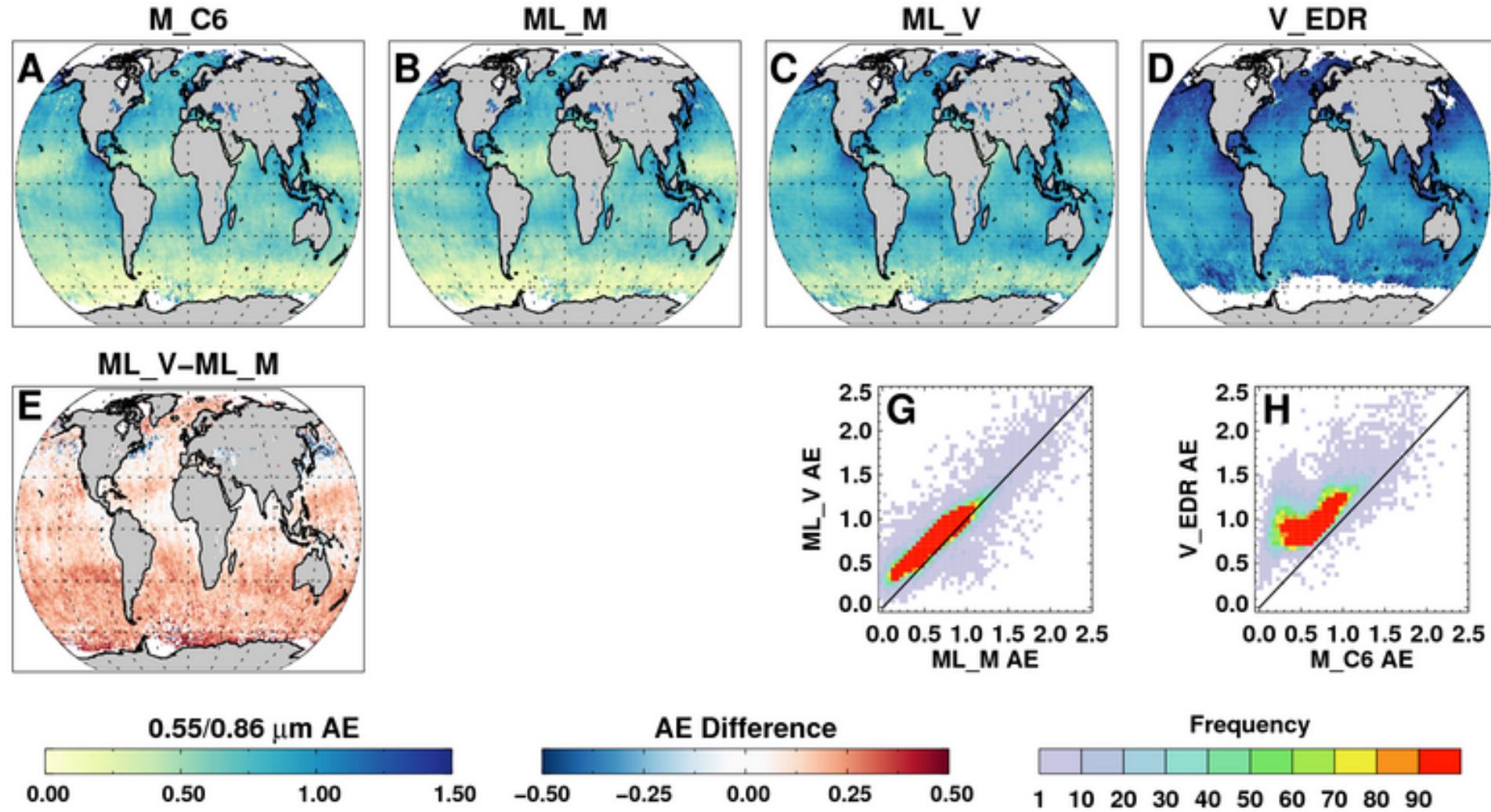


MODIS-like on VIIRS has Angstrom Exponent that looks much more like MODIS

# "Validation": 2013-2014, Land

scatterplots

| Sat | N | slope | Y-int | R | RMSE | Bias |
|------|------|-------|-------|-------|-------|-------|
| ML-M | 4128 | 1.00 | 0.003 | 0.901 | 0.101 | 0.012 |
| ML-V | 4989 | 1.01 | -0.007 | 0.902 | 0.111 | 0.005 |

VIIRS vs MODIS (Aqua): March 2013-Feb 2014
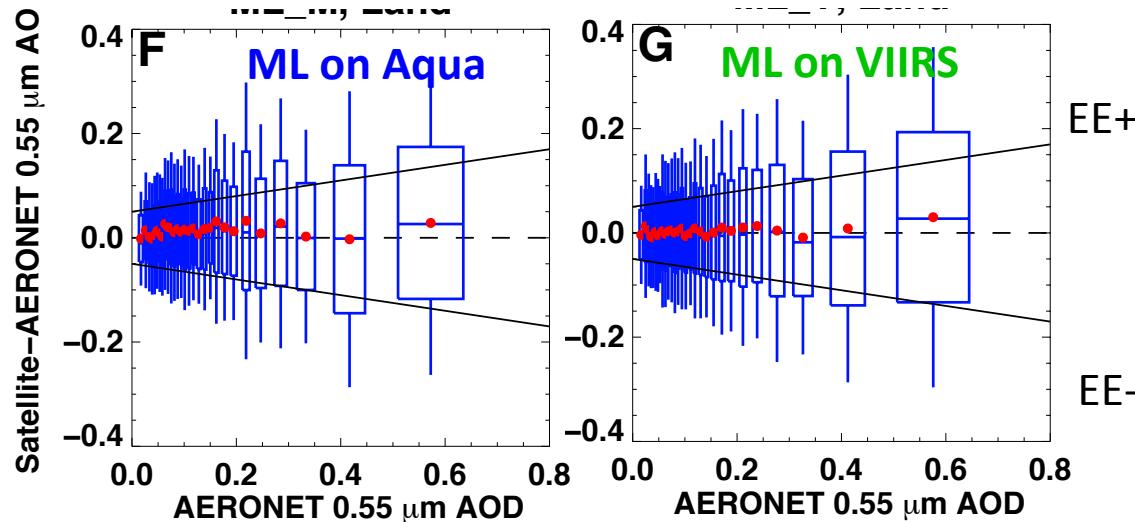


- EE% > 68%:  Both VIIRS and MODIS-Aqua meet "expected error (EE) " of ±(0.05 + 15%)
- Some metrics nearly identical:  Corr = R=0.90, Slope=M=1.01, RMSE=0.10
- VIIRS is has even smaller bias than MODIS (due to **y-intercept**)

# "Validation": 2013-2014, Ocean

scatterplots

| Sat | N | slope | Y-int | R | RMSE | Bias |
|---|---|---|---|---|---|---|
| ML-M | 1399 | 0.98 | 0.02 | 0.931 | 0.070 | 0.021 |
| ML-V | 2297 | 1.17 | 0.02 | 0.949 | 0.078 | 0.044 |

VIIRS vs Aqua: Mar 2013-Feb 2014
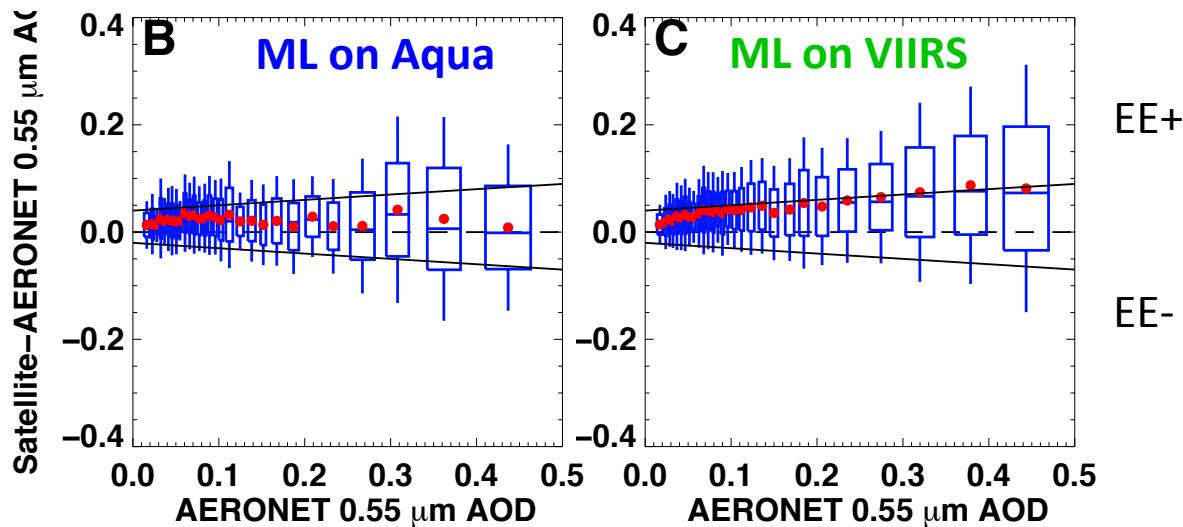


- VIIRS does not quite meet >68% within EE of ±(0.03 + 10%)
- Some metrics nearly identical:  Corr = R=0.93, Y-int=0.02, RMSE=0.07
- VIIRS is biased very high, but due to **slope**.

# Calibration? Again?

- Terra vs Aqua:
  - Ocean: Terra high by +0.017 or 13%;  Driven by slope
  - Land:  Terra high by +0.027 or 13%, Driven by y-offset

- VIIRS vs Aqua:
  - Ocean: VIIRS high by +0.25 or 20%; Driven by slope
  - Land:  VIIRS lower by -0.01 or 5%;  Driven by y-offset



MODIS: 0.856 um Reflect    VIIRS: 0.861 um Reflect    VIIRS – MODIS Reflect    7.39%

0.856 or 0.861 Reflectance    % Difference Reflectance
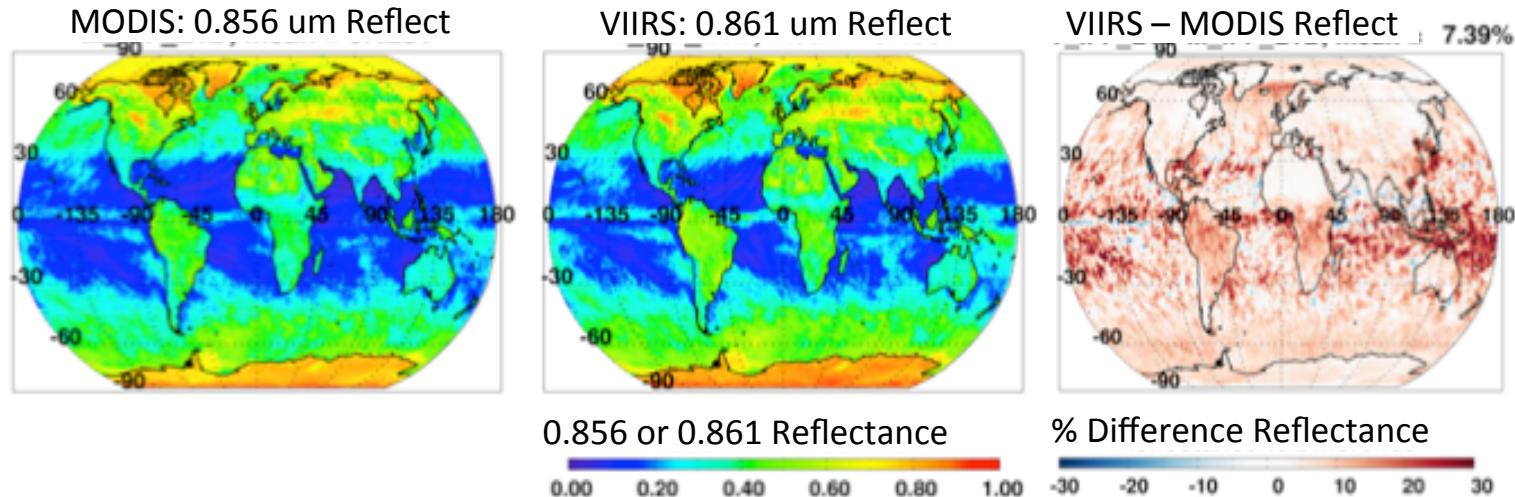
- VIIRS reflectance may be >2% high in some bands?   (e.g. Uprety et al., 2013)
- 2% high bias can give a 1.17 slope over ocean without the adding bias to land.
- Terra-Aqua differences are smaller, but they also to be calibration-driven..

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# Retrievability: To retrieve or not to retrieve?

**MODIS (Aqua): MAM 2013**



**MAM 2013, Ocean**

$Y = 1.163x + -0.004$
$N = 37741; R^2 = 0.901$
Bias = 0.030
RMSE = 0.049

E

**MAM 2013, Land**

$Y = 0.956x + 0.005$
$N = 11514; R^2 = 0.963$
Bias = −0.000
RMSE = 0.024

H
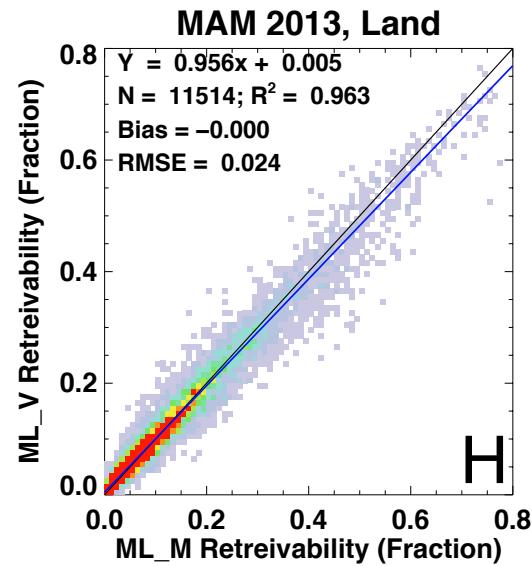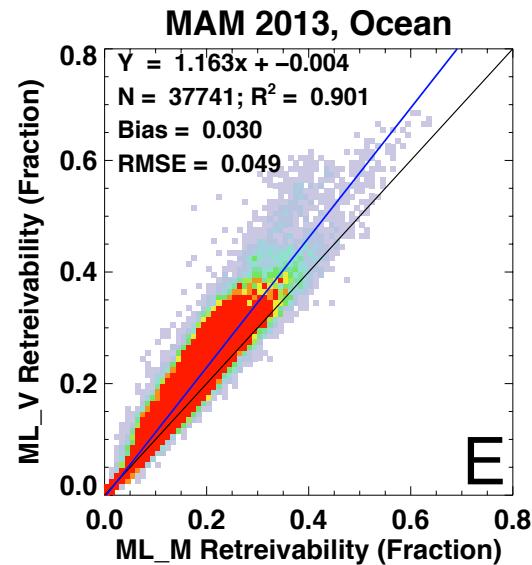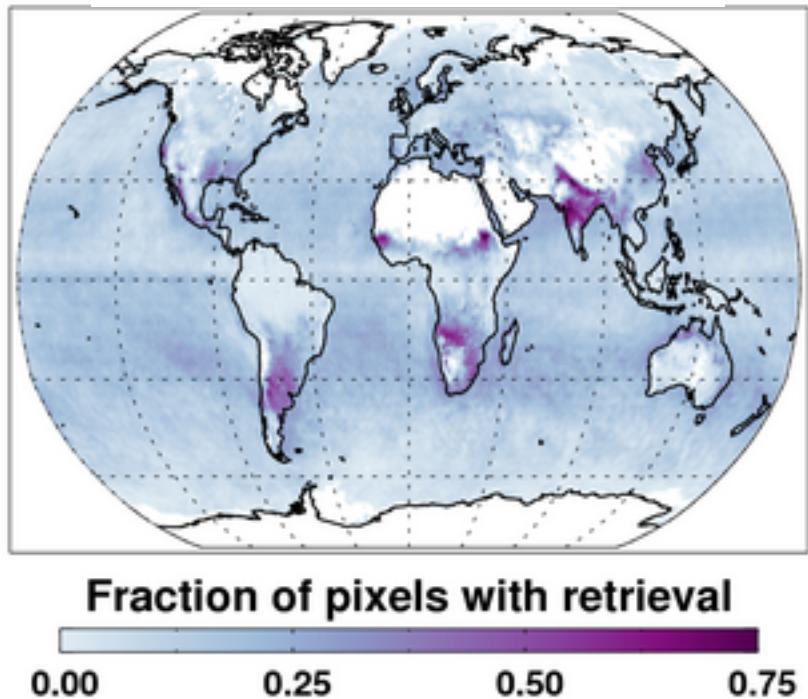
1°x1° retrieval fractions provided by the ML_V versus ML_M products during Spring 2013.

# Will VIIRS continue MODIS? How would we know?

- 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?


- Sampling: Do instruments observe similar conditions?

- Retrievability: Do algorithms make same choices?

- Validation: Comparison with AERONET, MAN, etc?

# A time series (of sorts) so far
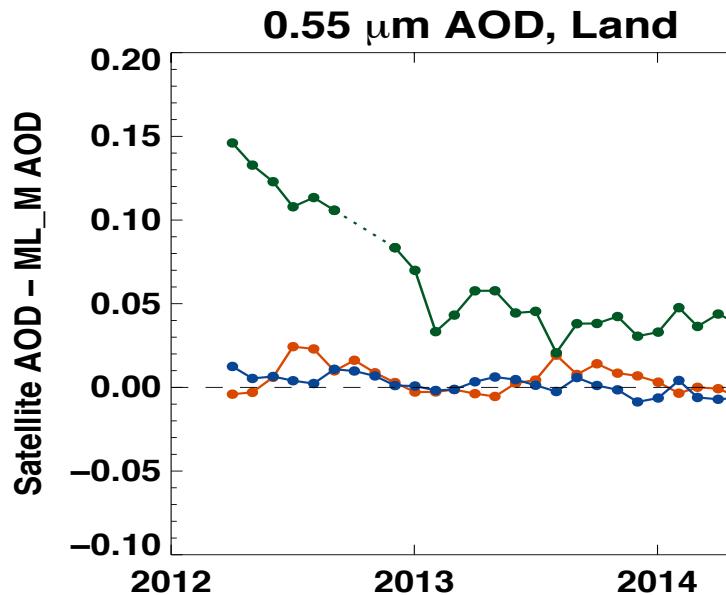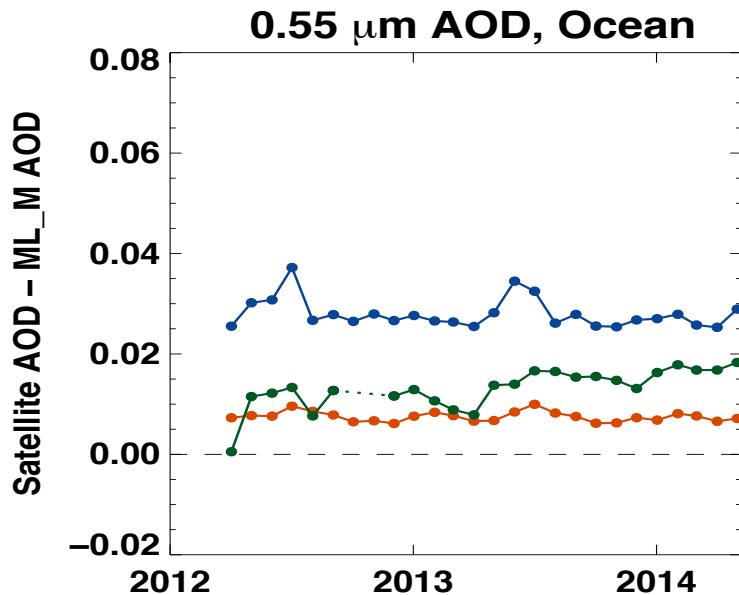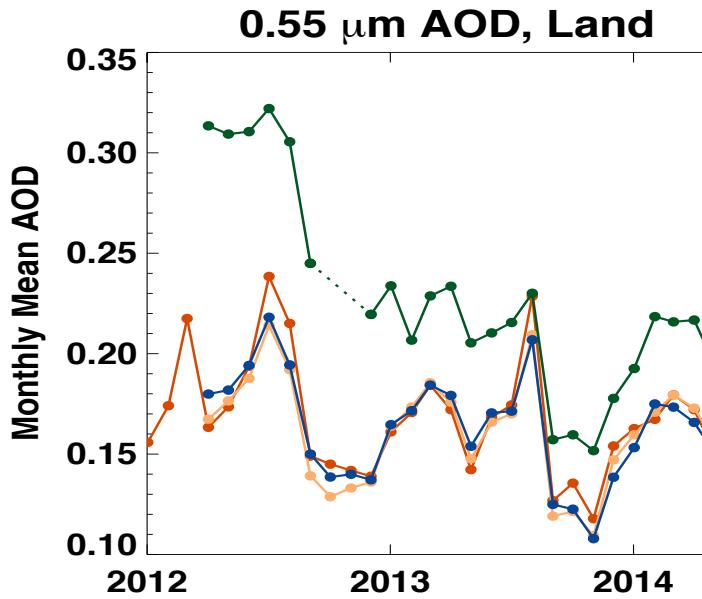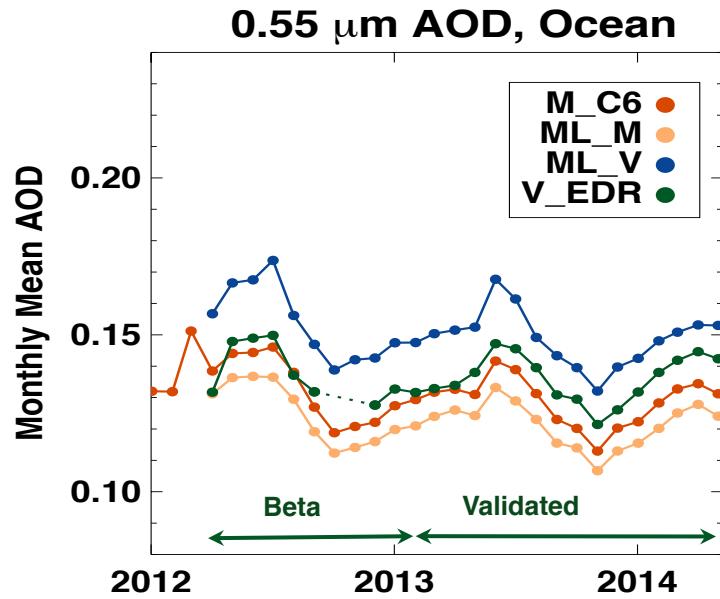
# Greater community-wide VIIRS plans

- Some highlights from the recent "joint" MODIS-VIIRS Science team meeting in Maryland (early May 2015).
    - Our VIIRS-DT processing will be handled by University of Wisconsin
    - Formats will likely be NetCDF4. Level 1 "granule" size will likely be 6 minutes (collocation with CrIS sensor)
    - MODIS-VIIRS "Continuity" cloud mask (MOD35-like) is under development
    - NASA-led "calibration" effort is underway, and will be different than the NOAA-led calibration
    - We are required to post something resembling an ATBD and/or a user guide for VIIRS products.
    - Many more issues to work out. For example, will new products on VIIRS be back-produced on MODIS? What will happen to Level 3?
    - Another issue: retrieval pixel size versus original pixel size: # scan lines
    - Discussions over how algorithms will be implemented after Suomi-NPP (e.g. JPSS 1 and JPSS 2 satellites).
- We will continue to retrieve IFF-based MODIS-like aerosol products, and provide to the ICAP community (please ask) until "official" products are released

# Summary

- MODIS-DT Collection 6 –
  - Aqua/Terra level 2, 3 available now;
  - Extended diagnostics, DT/DB merge, science improvements
  - "Trending" issues reduced, but 15% or 0.02 Terra/Aqua offset remains .
- VIIRS-IDPS (MODIS-ish over ocean; not over land)
  - VIIRS is "similar" instrument, yet different then MODIS
  - The NOAA product has similar global EE to MODIS (over ocean).
  - With 50% wider swath, VIIRS has daily coverage
- VIIRS-DT – now,
  - Ensures *algorithm* consistency with MODIS DT.
  - IFF-based granules are being processed now (we are sharing)
  - 20% NPP/Aqua offset over ocean.
  - Paper was submitted May 31 to AMTD ! (Some of you may review it?)
- VIIRS-DT - future,
  - We don't have "continuity" yet.
  - Move towards full resolution (includes I-bands)
  - Discussion here at MODIS-VIIRS Science Team meeting (formats, delivery, ATBDs, documentation, etc…)

# Summary (cont)

- Can VIIRS continue the MODIS record?
  - We believe we need to apply the same algorithm
  - Calibration is a concern.
- We still need to define "how similar is good enough"?
- Which statistics must converge?
  - Expected error (validation)
  - Sampling
  - Means/variance
  - At 0.55 μm only? At other wavelengths?
  - Etc
- Keep open discussion with our "super-users" (ICAP modelers, assimilators, etc). What do **YOU** need?
- Improvements for "Collection 7", which would be a joint MODIS/VIIRS product.

NASA
MODIS Aerosol
Dark-Target Retrieval Algorithm

OUR TEAM    PUBLICATIONS    CLIMATE & RADIATION

Search

ALGORITHM    PRODUCTS    VALIDATION    REFERENCE    FAQ    LINKS

- Web site in development/ATBDs being updated
- Reference for all things "dark target"
  - The algorithms and assumptions
  - Examples
  - Validation
  - Primary publications
  - Educational material
  - FAQ
  - Links to data access
  - Considering a "forum"

http://darktarget.gsfc.nasa.gov