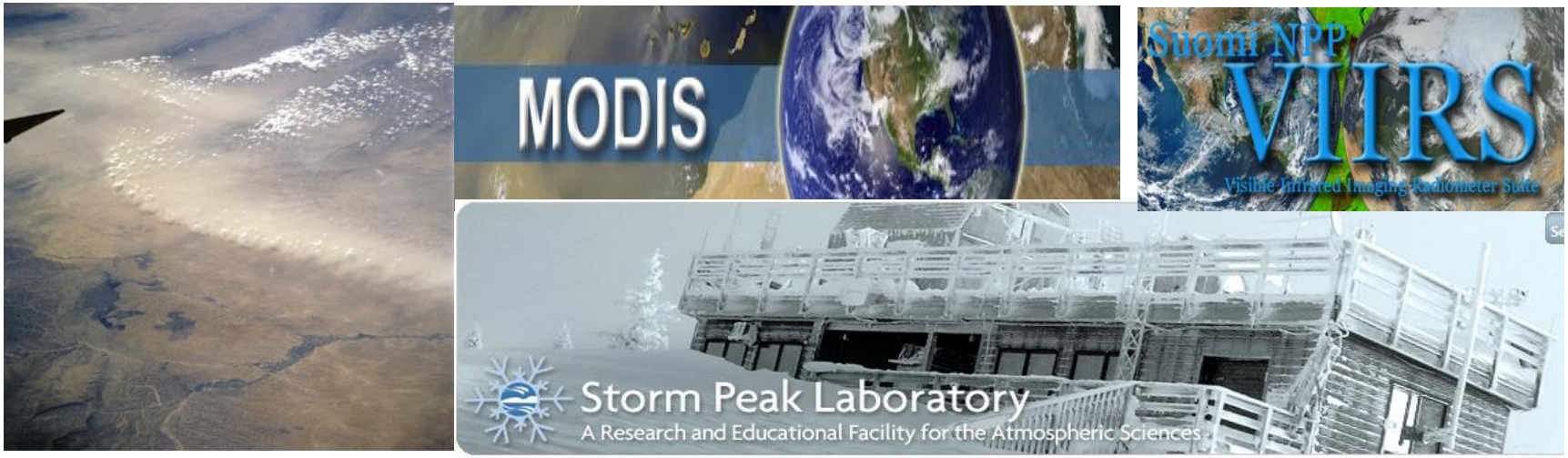
Creating a consistent dark-target aerosol optical depth record from MODIS and VIIRS

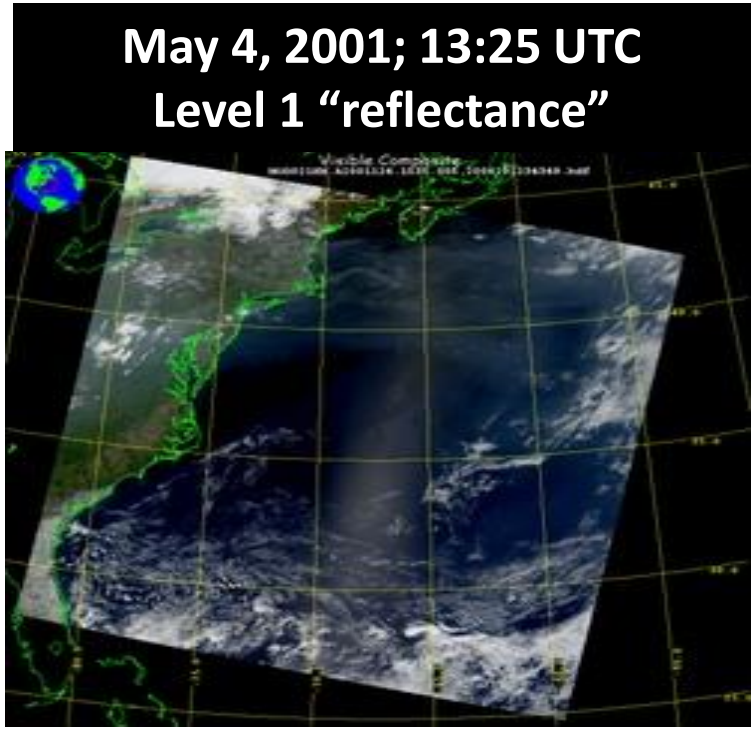
Robert Levy (NASA-GSFC)
Shana Mattoo and Leigh Munchak (SSAI @ NASA-GSFC)
Falguni Patadia (GESTAR/Morgan State @ NASA-GSFC)
Lorraine Remer (UMBC)
Shobha Kondragunta (NOAA/NESDIS/STAR)



AeroCom #14/AeroSat #2 meeting in Steamboat Springs, Colorado: Sep 29, 2014

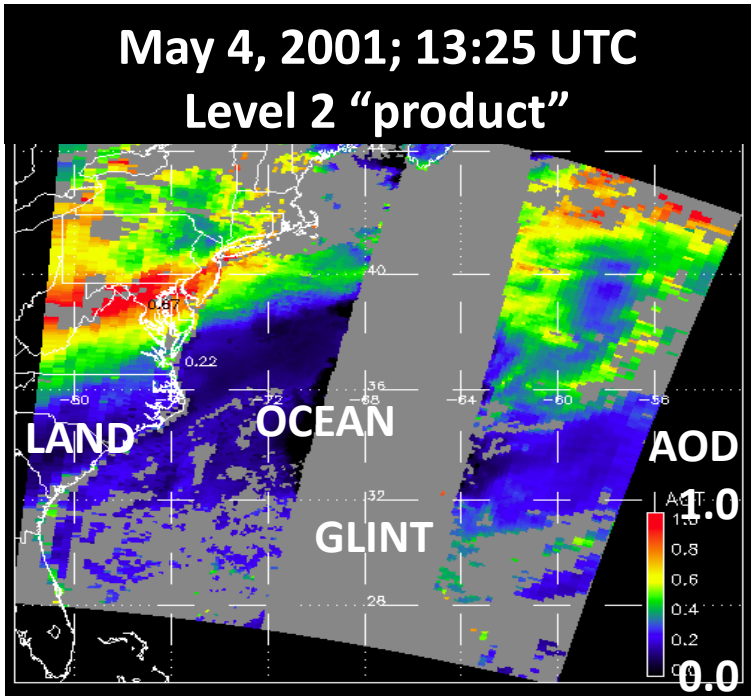
Dark-target aerosol retrieval

Observations (MODIS)



DT algorithm

Attributed to aerosol (AOD)



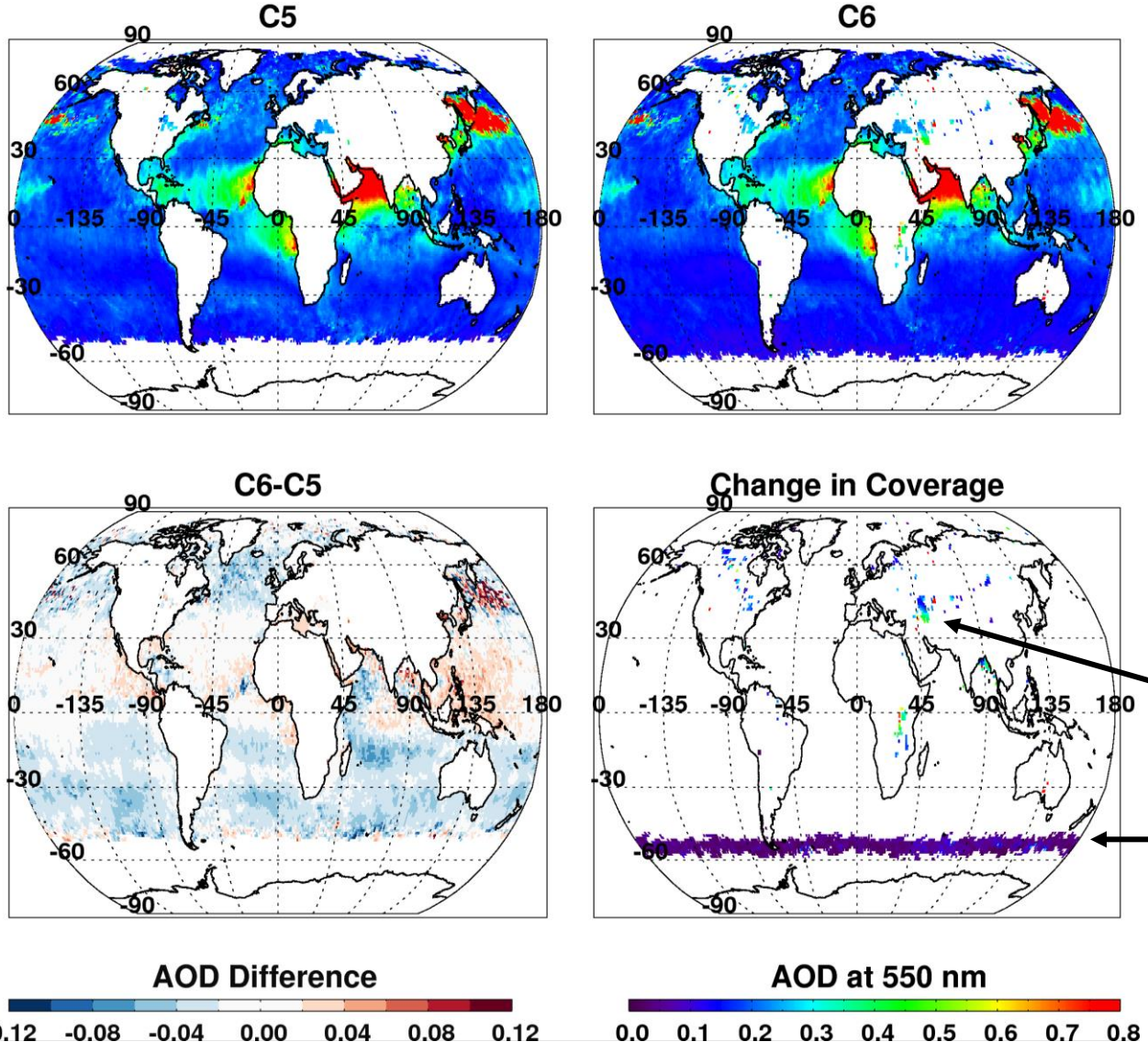
MODIS Collection 6 (C6) in production:

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***, 2989-3034, doi:10.5194/amt-6-2989-2013, 2013.

Outline

- Collection 6 (C6) in production (Aqua complete)
  - Differences from C5 (Level 2)
  - Some preliminary validation (for Aqua)
  - Terra versus Aqua and calibration
- MODIS-VIIRS?
  - VIIRS-IDPS product
  - MODIS-like product on VIIRS
- Towards C7? (If time permits, doubtful)
  - Corrections of urban surfaces
  - New Uncertainty products (per-pixel)

Dark target over ocean
Overall changes to products (Aqua, Jul 2008)

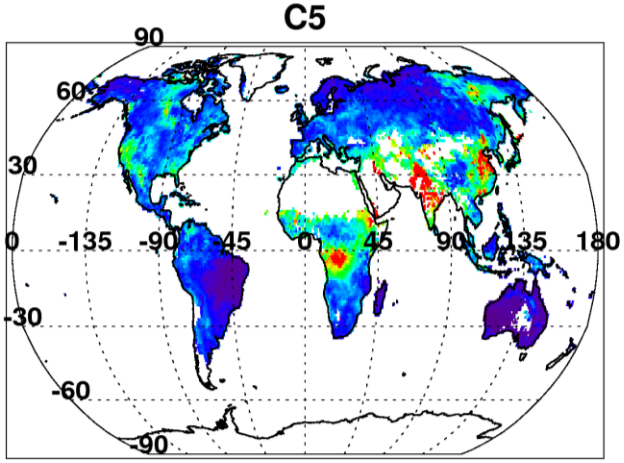


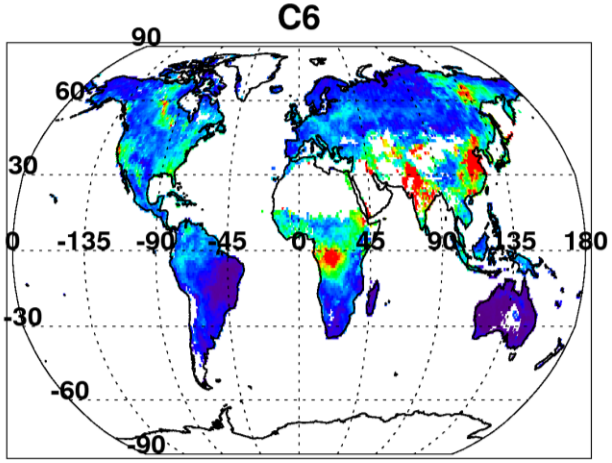
- Overall decrease of AOD in mid-latitudes
- Strong decrease in "roaring 40s" (even stronger in other months)
- Overall increase in tropics

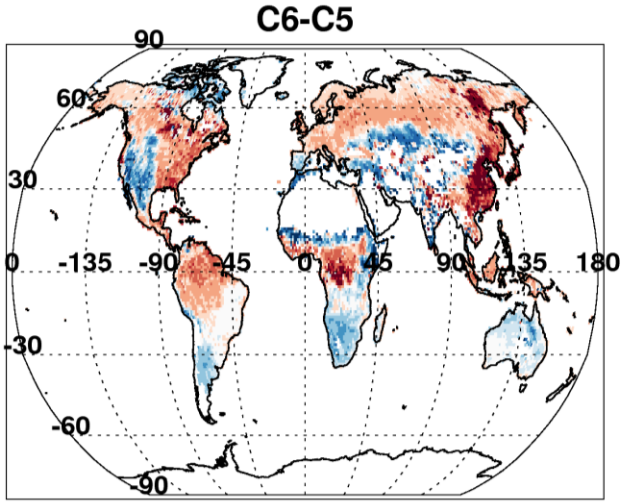
- "New" coverage over inland lakes
- Increase in coverage toward poles

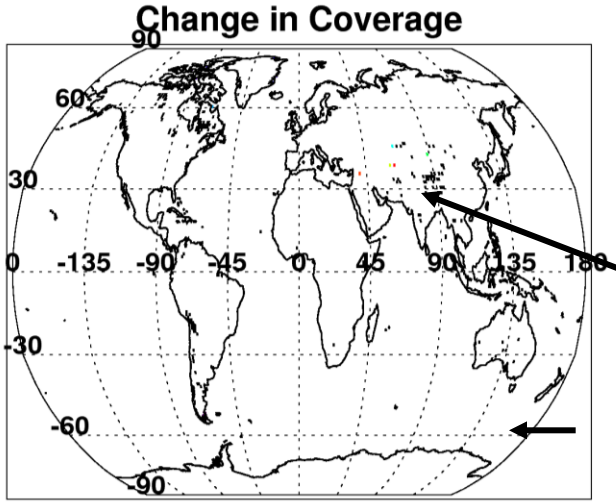
See Munchak poster

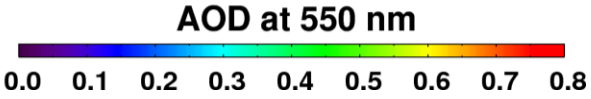
Dark target over land
Overall changes to products (Aqua, Jul 2008)









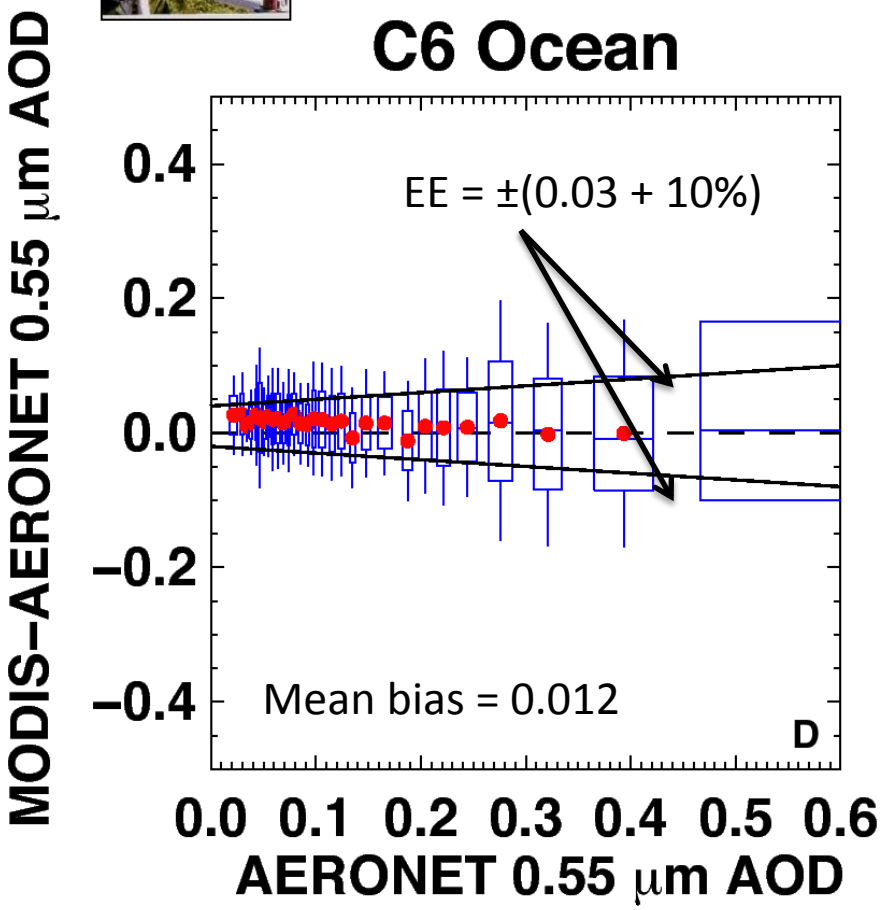


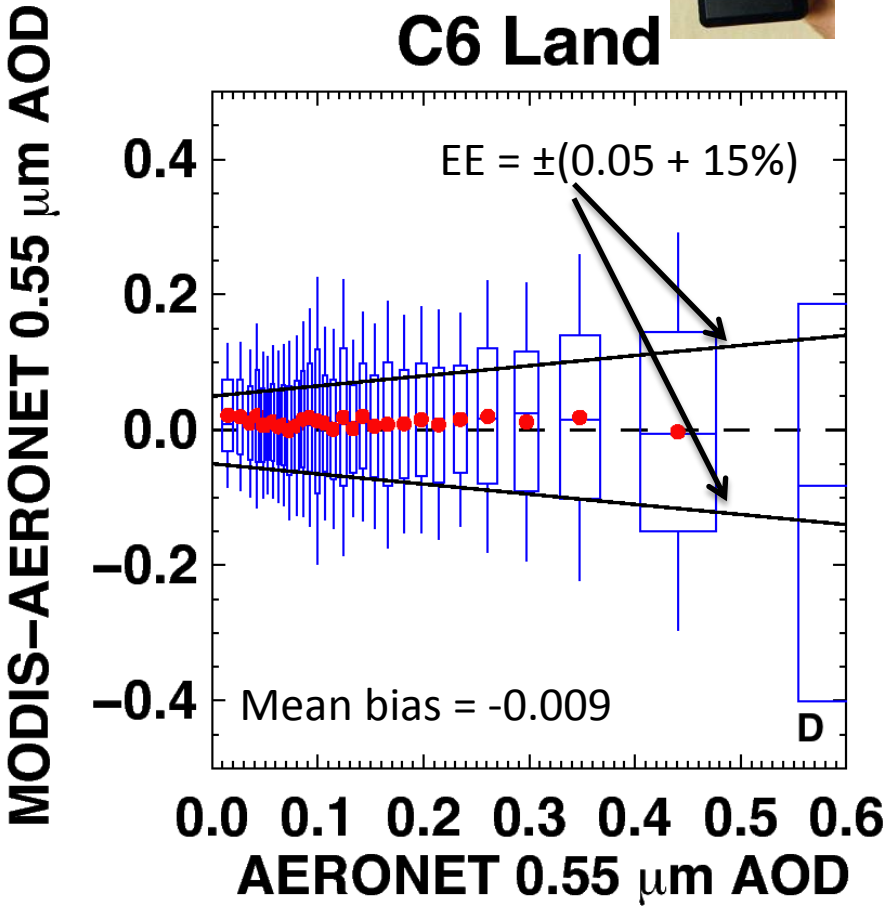
- Overall decrease of AOD in semi-arid
- Overall increase over vegetation
- Strong increase over Eastern Asia

- Slight change in coverage here and there

See Munchak poster

C6: Aqua MODIS compared to AERONET (based on 8 months of test data)

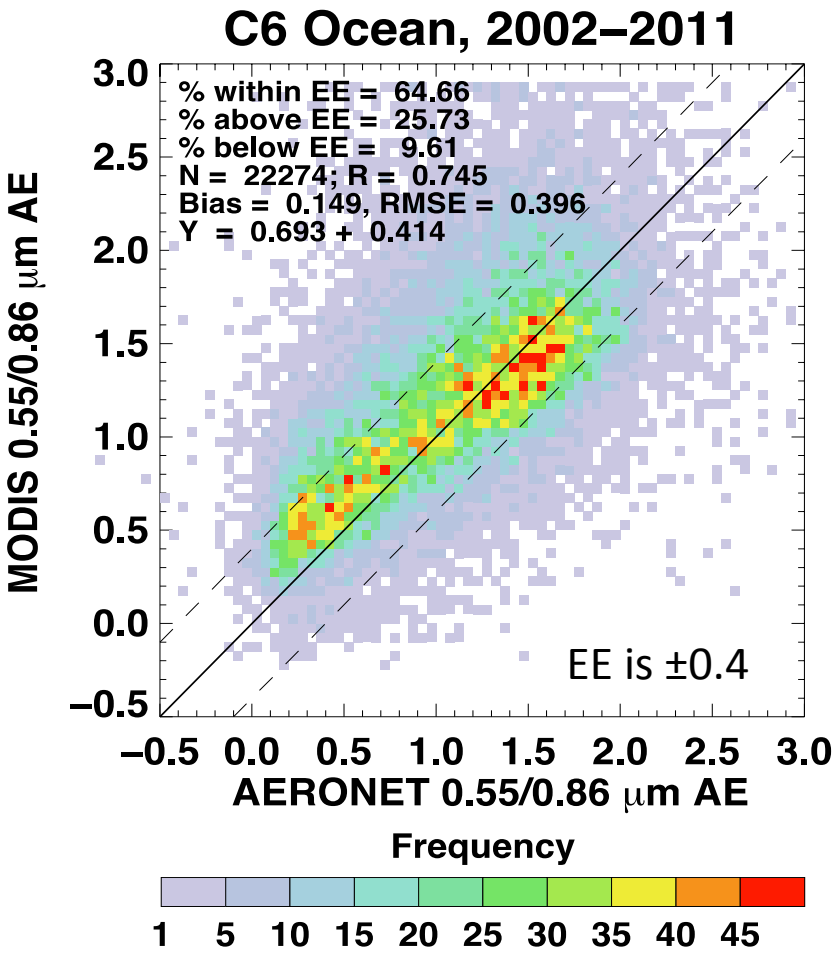


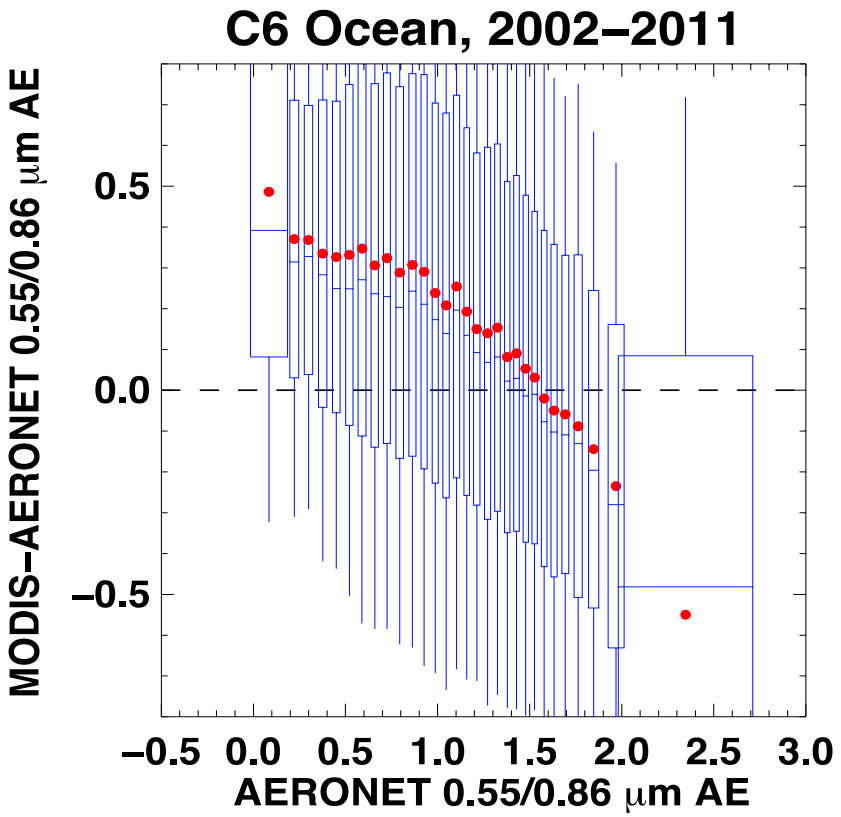


- Larger uncertainty for individual Aqua-MODIS retrievals
- Where collocated, global MODIS mean agrees to AERONET within ±0.015 over both land and ocean

Figs from Levy et al., AMT 2013

Reasonable match of AE within ±0.4 (Ocean)





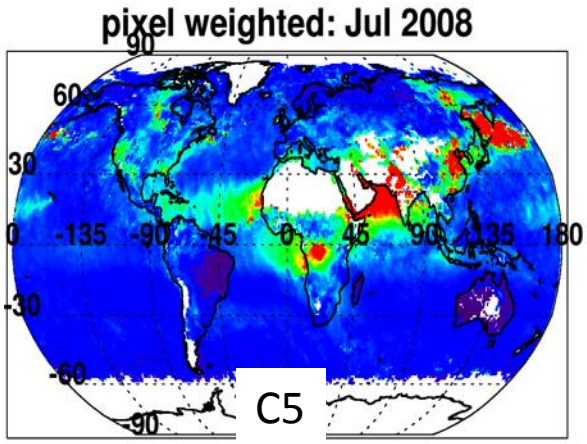
AE reported when AOD > 0.15

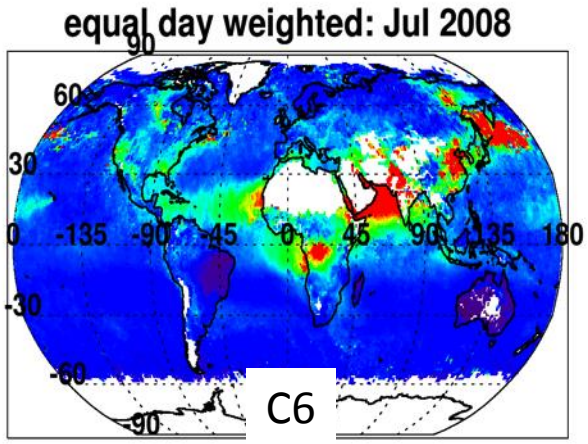
MODIS "range" is less than AERONET
This has a been problem for ever.
There is no easy fix.

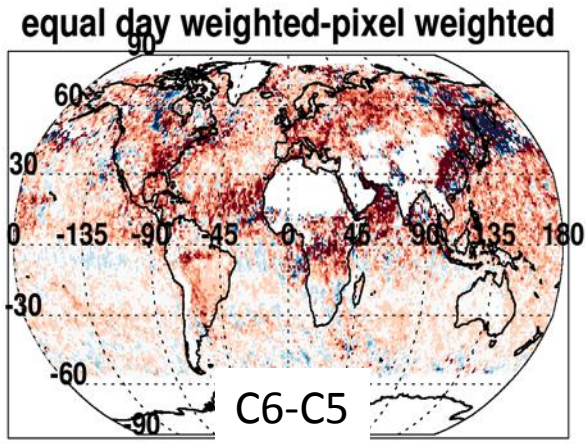
What else for C6 Level 2?

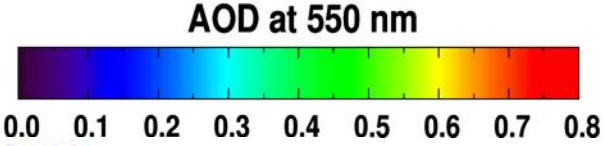
- Diagnostic SDSs (wind speed, integer QAC, topographic elevation, etc)
- “Cloud mask”, “distance to nearest cloud”
- Deep Blue/Dark Target Merge
- Changes to SDS names

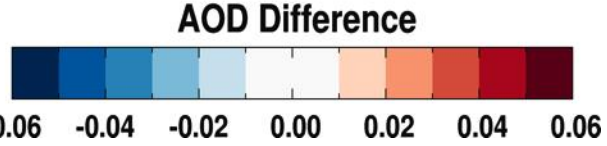
Changes to Level 3 (MxD08_M3)

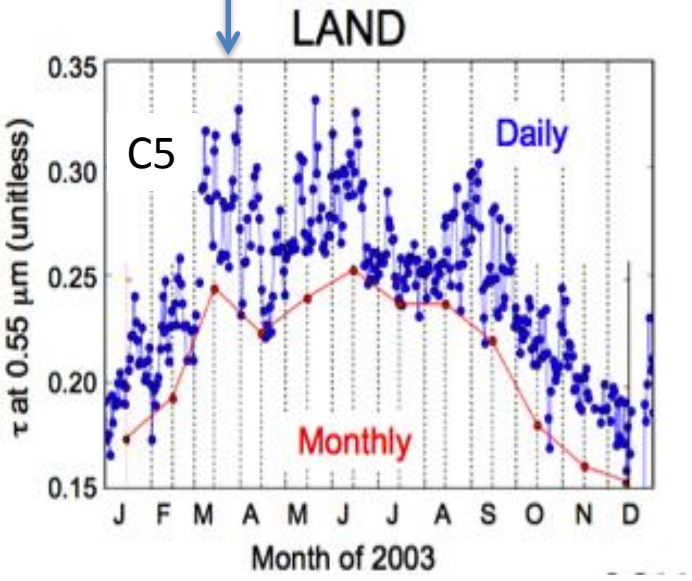












- In C5, averaging daily data did not look like monthly data (left, from Giovanni web application)
- C5 monthly was "pixel weighted". A day with 100 retrieved pixels was worth 10 times more than one with 10. It was clear-sky biased.
- C6 monthly is "equal day" weighted. If at least five pixels in a day, than that day counts.
- → Increases monthly mean AOD over land, and ocean. Less clear sky biased?

Changes to Level 3 (MxD08)

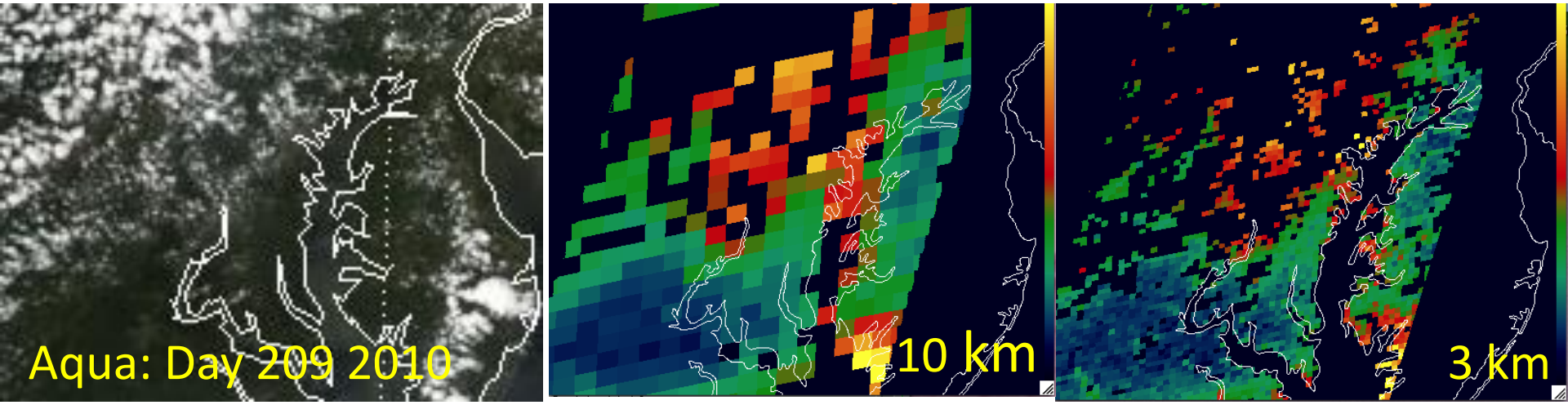
- Angstrom Exponent and size parameters removed, but users can create their own. (i.e. compute AE from mean 0.55 and 0.86 channels)

- MODIS Level 3 also includes minimum, maximum, median, standard deviation and other statistics.

- New for Collection 6 = JOINT HISTOGRAMS of AOD and AE!

MxD04_3K (a new 3 km aerosol product)

- Driven by air quality community,
- Maybe also some applications to aerosol/clouds.
- Currently Dark target only



Munchak, L., R.C. Levy, S. Mattoo, L.A. Remer, B.N. Holben, J.S. Schafer, C.A. Hostetler, and R.A. Ferrare (2013). MODIS 3km Aerosol Product: applications over land in an urban/suburban region *Atmos. Meas. Tech*, *6*, 1747-1759, doi:10.5194/amt-6-1747-2013

Remer, L., S. Mattoo, R.C. Levy, and L. Munchak (2013). MODIS 3km Aerosol Product: Algorithm and Global Perspective *Atmos. Meas. Tech*, *6*, 1829-184, doi:10.5194/amt-6-1829-2013

J. M. Livingston, J. Redemann, et al, (2013). Comparison of MODIS 3-km and 10-km resolution aerosol optical depth retrievals over land with airborne Sunphotometer measurements during ARCTAS summer 2008, Atmos. Chem. Phys. Disc,

MxDATML2 product

- Combines the “best of” MxD04_L2 (10 km) aerosol, MxD06_L2 (5 km) cloud products, and other atmosphere prods
- For joint analyses of aerosols and clouds (at granule level

From MxD06 (clouds) 5 km:

- Latitude
- Longitude
- Cloud_Optical_Thickness
- Cloud_Optical_Thickness_Uncertainty
- Cloud_Optical_Thickness_PCL
- Cloud_Optical_Thickness_16
- Cloud_Optical_Thickness_16_PCL
- Cloud_Optical_Thickness_37
- Cloud_Optical_Thickness_37_PCL
- Cloud_Optical_Thickness_Uncertainty_16
- Cloud_Optical_Thickness_Uncertainty_37
- Cloud_Effective_Radius
- Cloud_Effective_Radius_Uncertainty
- Cloud_Effective_Radius_PCL
- Cloud_Effective_Radius_16
- Cloud_Effective_Radius_16_PCL
- Cloud_Effective_Radius_37
- Cloud_Effective_Radius_37_PCL
- Cloud_Effective_Radius_Uncertainty_16
- Cloud_Effective_Radius_Uncertainty_37
- Cloud_Water_Path
- Cloud_Water_Path_Uncertainty
- Cloud_Water_Path_PCL
- Cloud_Water_Path_16
- Cloud_Water_Path_16_PCL
- Cloud_Water_Path_37
- Cloud_Water_Path_37_PCL
- Cloud_Water_Path_Uncertainty_16
- Cloud_Water_Path_Uncertainty_37
- Cloud_Optical_Thickness_1621
- Cloud_Optical_Thickness_Uncertainty_1621
- Cloud_Effective_Radius_1621
- Cloud_Effective_Radius_Uncertainty_1621
- Cloud_Water_Path_1621
- Cloud_Water_Path_Uncertainty_1621
- Cloud_Phase_Optical_Properties
- Cloud_Quality_Assurance
- Cirrus_Reflectance
- Cloud_Top_Pressure
- Cloud_Top_Temperature
- Cloud_Top_Height
- Cloud_Height_Method
- Cloud_Top_Pressure_1km
- Cloud_Top_Temperature_1km
- Cloud_Top_Height_1km
- Surface_Temperature_1km
- OS_Top_Flag_1km
- Infrared_obs_minus_calc
- Cloud_Mask_SPI
- Cloud_Multi_Layer_Flag
- Cloud_Fraction
- Cloud_Phase_Infrared
- Cloud_Phase_Infrared_1km

From MxD04 (aerosol) 10 km:

- Latitude_10km
- Longitude_10km
- Solar_Zenith_10km
- Viewing_Zenith_10km
- Relative_Azimuth_10km
- Aerosol_Optical_Depth
- Aerosol_Angstrom_Exponent_Ocean
- Aerosol_Land_Sea_Flag
- Aerosol_Cloud_Pixel_Distance_Land_Ocean
- Aerosol_Cloud_Fraction_Ocean
- Aerosol_Cloud_Fraction_Land
- Aerosol_Land_Ocean_Quality_Flag
- AOD_550_Dark_Target_Deep_Blue_Combined
- AOD_550_Dark_Target_Deep_Blue_Combined_QA_Flag
- AOD_550_Dark_Target_Deep_Blue_Combined_Algorithm_Flag
- Deep_Blue_Aerosol_Optical_Depth_550_Land
- Deep_Blue_Angstrom_Exponent_Land
- Deep_Blue_Single_Scattering_Albedo_412_Land
- Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate
- Deep_Blue_Aerosol_Optical_Depth_550_Land_QA_Flag
- Deep_Blue_Aerosol_Optical_Depth_550_Land_Uncertainty
- Aerosol_Quality_Assurance_Land
- Aerosol_Quality_Assurance_Ocean

From MxD05 (precip water) 10 km:

- Precipitable_Water_Infrared_ClearSky
- Precipitable_Water_Near_Infrared_ClearSky

From MxD35 (Cloud Mask) 5 km:

- Cloud_Mask

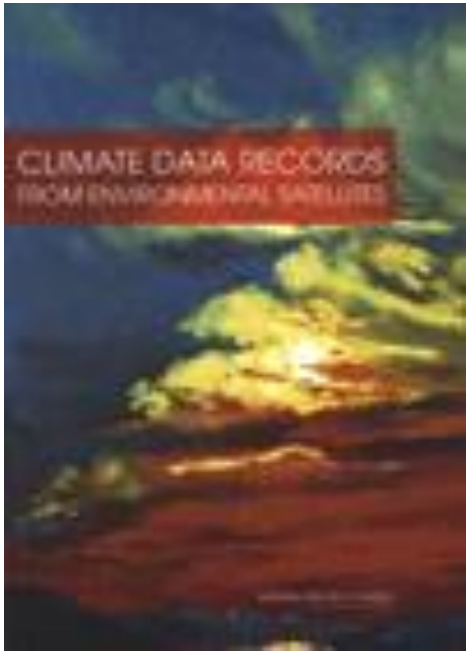
From MxD07 (Profiles) 5 km:

- Total_Ozone
- Lifted_Index
- K_Index
- Total_Totals_Index

Platnick, King, Hubanks,..

Aerosol Climate Data Records (CDRs)?

"A time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change."



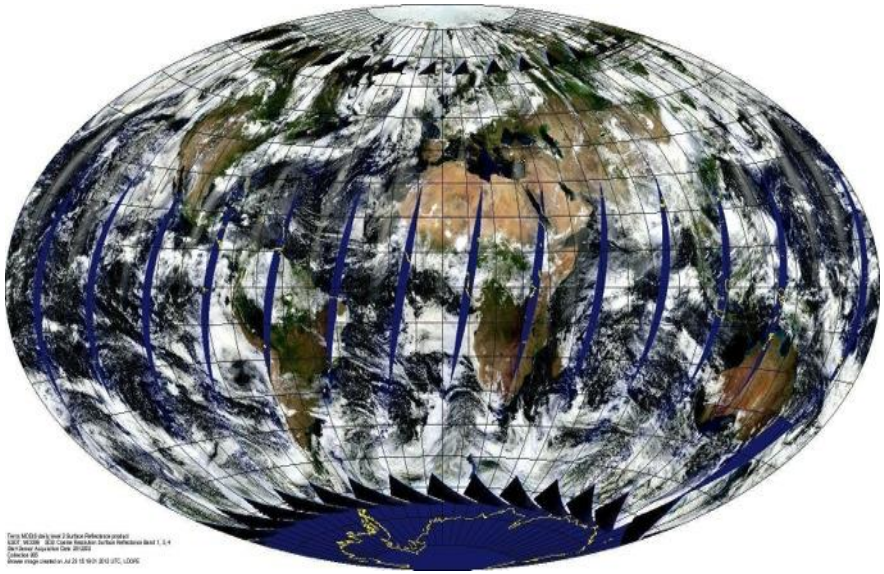
Some requirements

- Measurements sustained over decades
- Measurement of measurement performance (e.g. calibration, stability)
- Acquired from multiple sensors / datasets

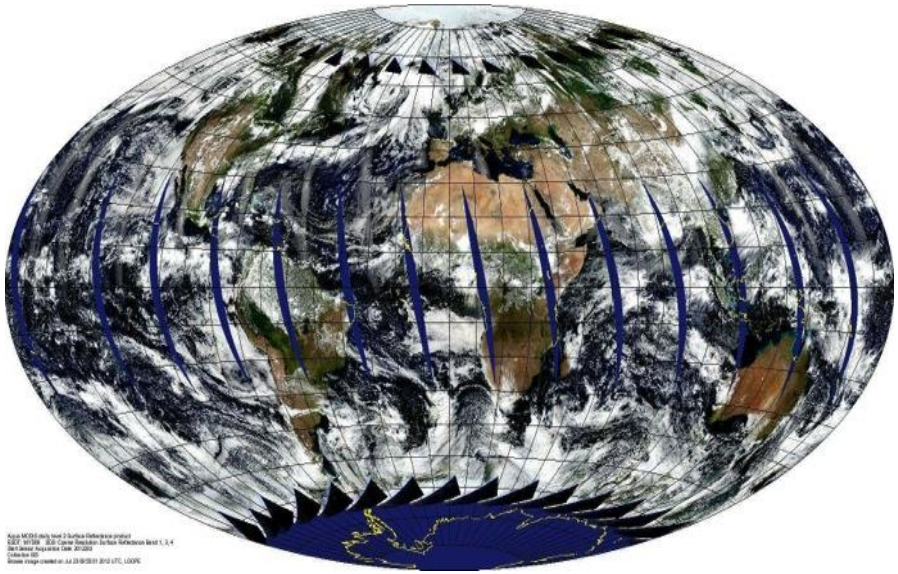
Let's start with MODIS

Two MODIS instruments = "identical twins"

Terra (since spring 2000)

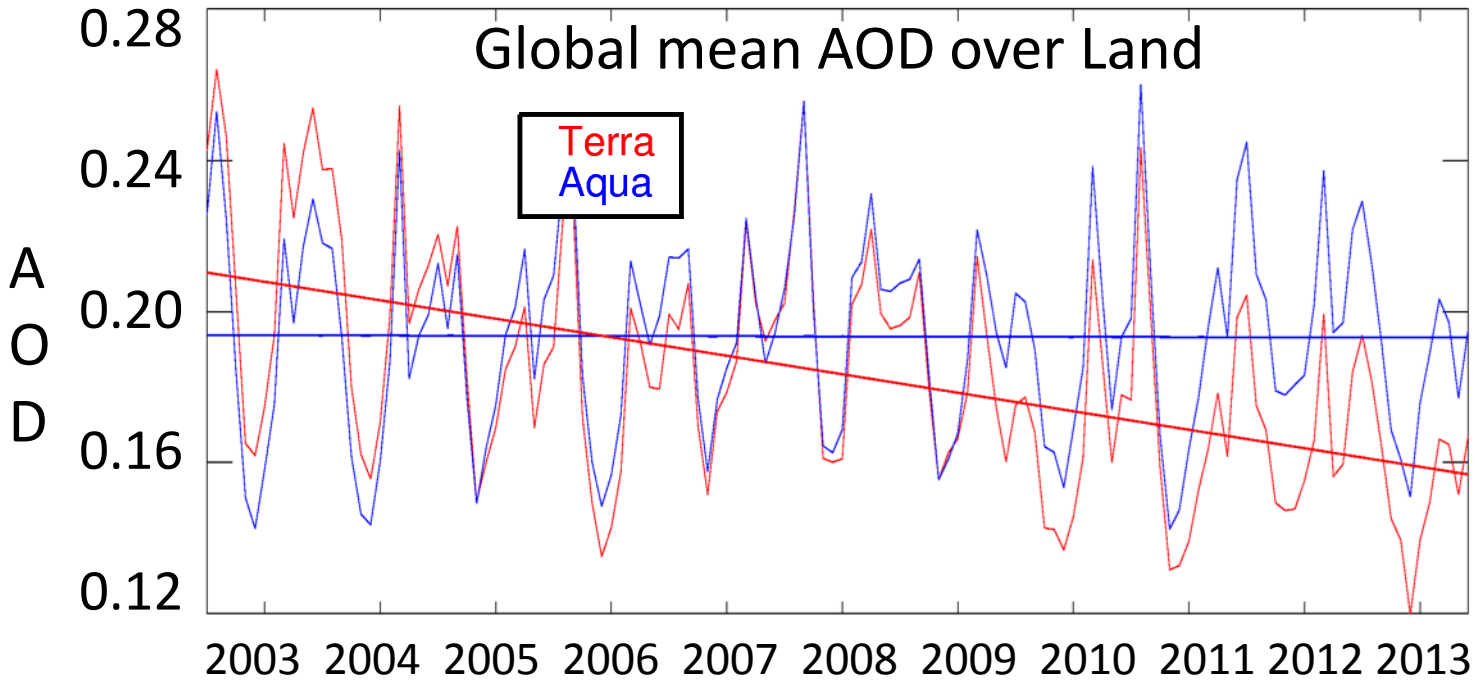


Aqua (since summer 2002)



- Same instrument hardware (optical design)
- Same spatial and temporal sampling resolution
- Same calibration/processing teams
- Same aerosol retrieval algorithms
- "Collection 6" is now available for Aqua.
- Terra processing is beginning soon! (famous words)

Collection 5 AOD Trends: Terra ≠ Aqua

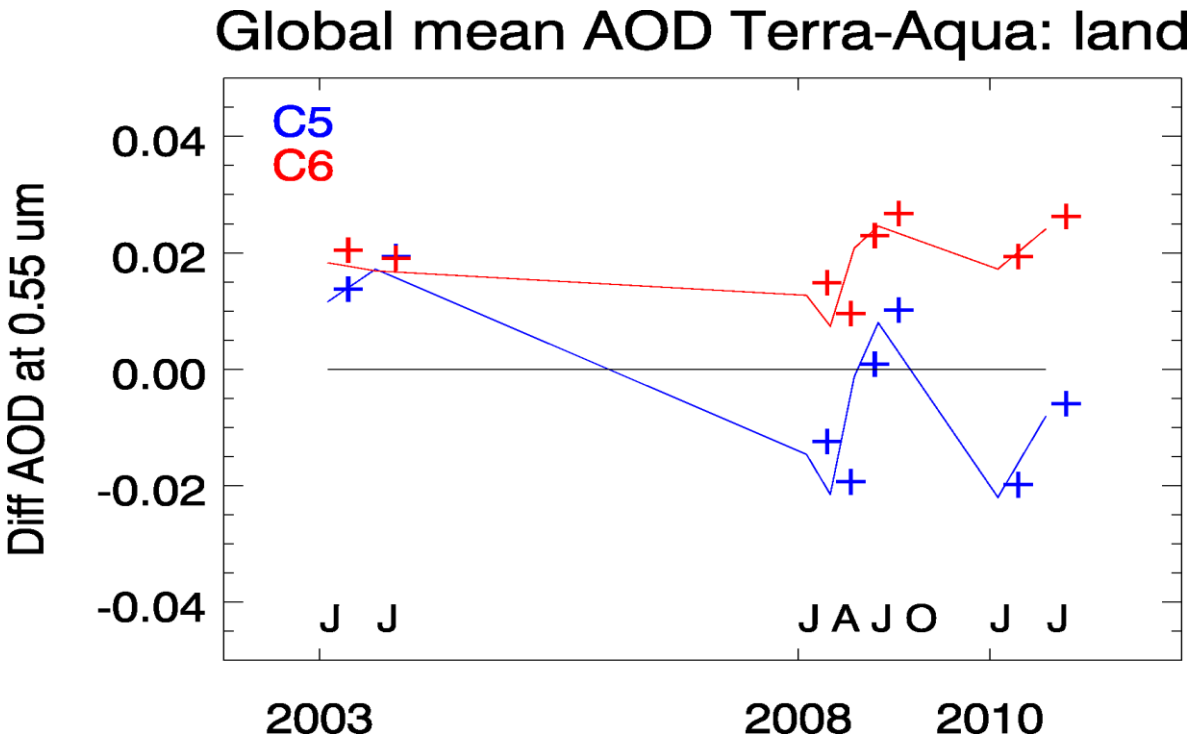


- Collection 5, same calibration and aerosol retrieval algorithms
- Over land, Terra's AOD *decreased* (-0.04/decade), Aqua *constant*
- Terra vs Aqua divergence was the same everywhere on the globe!

→ Terra's calibration had drifted!

Mostly corrected for Collection 6

C6 calibration reduces trend divergence…



- 8 months processed with same dark-target aerosol algorithms
- **New calibration → Terra/Aqua divergence removed**
- **Terra and Aqua should show same trends (still to be processed)**

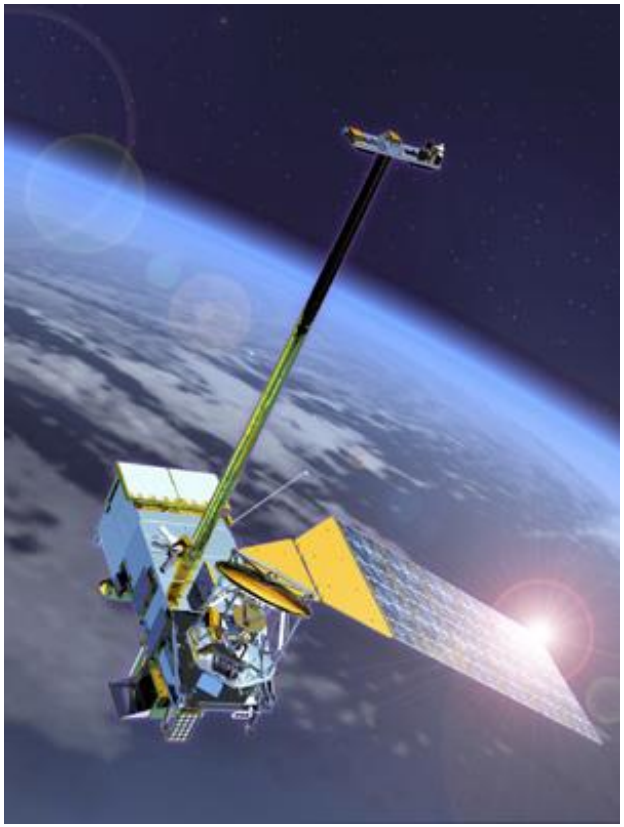
- **… But leaves offset of 0.015 (land) and 0.01 (ocean)**

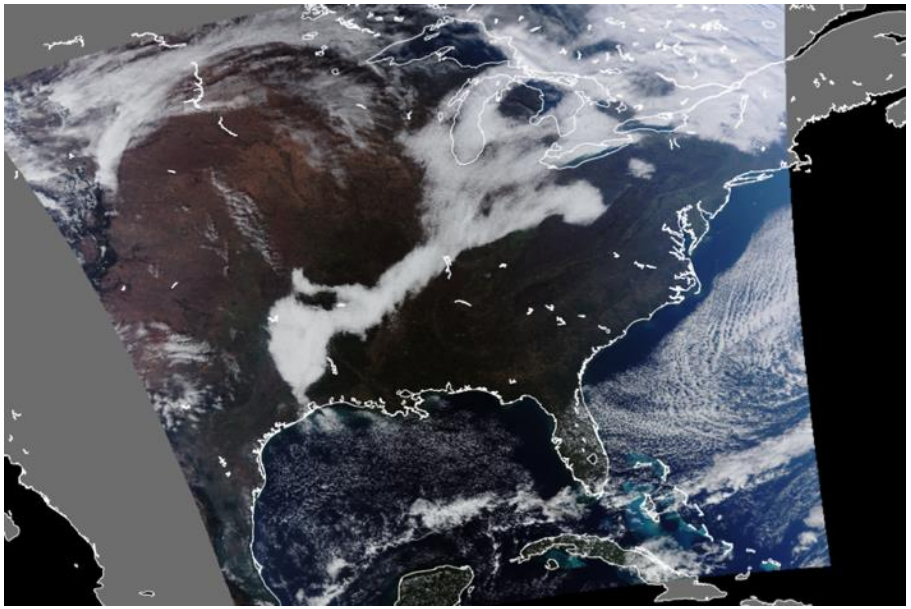
C006

- While C005 was “validated”…
  - The C005 data record did not agree for Terra and Aqua trends
  - Divergence was traced to calibration ***trending***, which is mostly fixed.
- C006 has remaining Terra/Aqua ***offsets*** (~0.015 or 10%) that we are working to understand.
  - Are these real AOD differences and how much?
  - Are these due to cloud differences (and aerosol sampling) between morning and afternoon?
  - Are these due to calibration offsets? We think mostly; Lyapustin et al., suggests how to normalize TOA reflectance from Terra to that of Aqua. But this is asking much better than stated 2% accuracy of MODIS.
- Note that Terra and Aqua (at 15 and 12 years) are 2-3 times mission life. Won’t be here forever.

Beyond MODIS

Suomi-NPP 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)

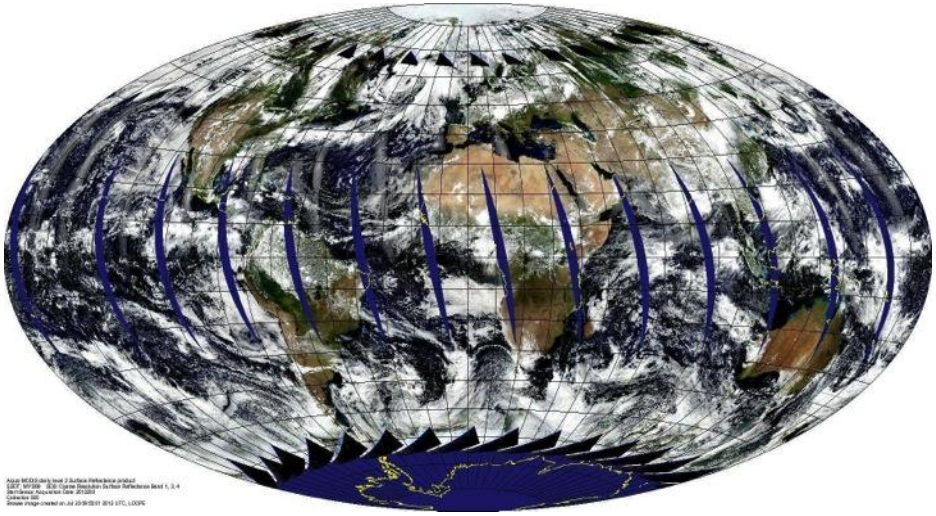
Spectral Range: 0.412-12.2μm (22 bands versus 36 bands)

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

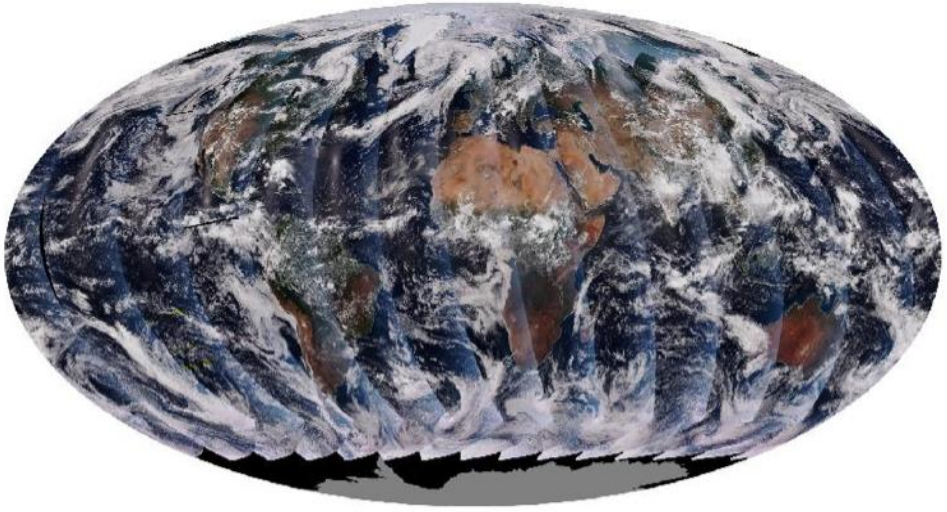
Aerosol retrieval algorithms: "Physics" similar, but different strategies

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);

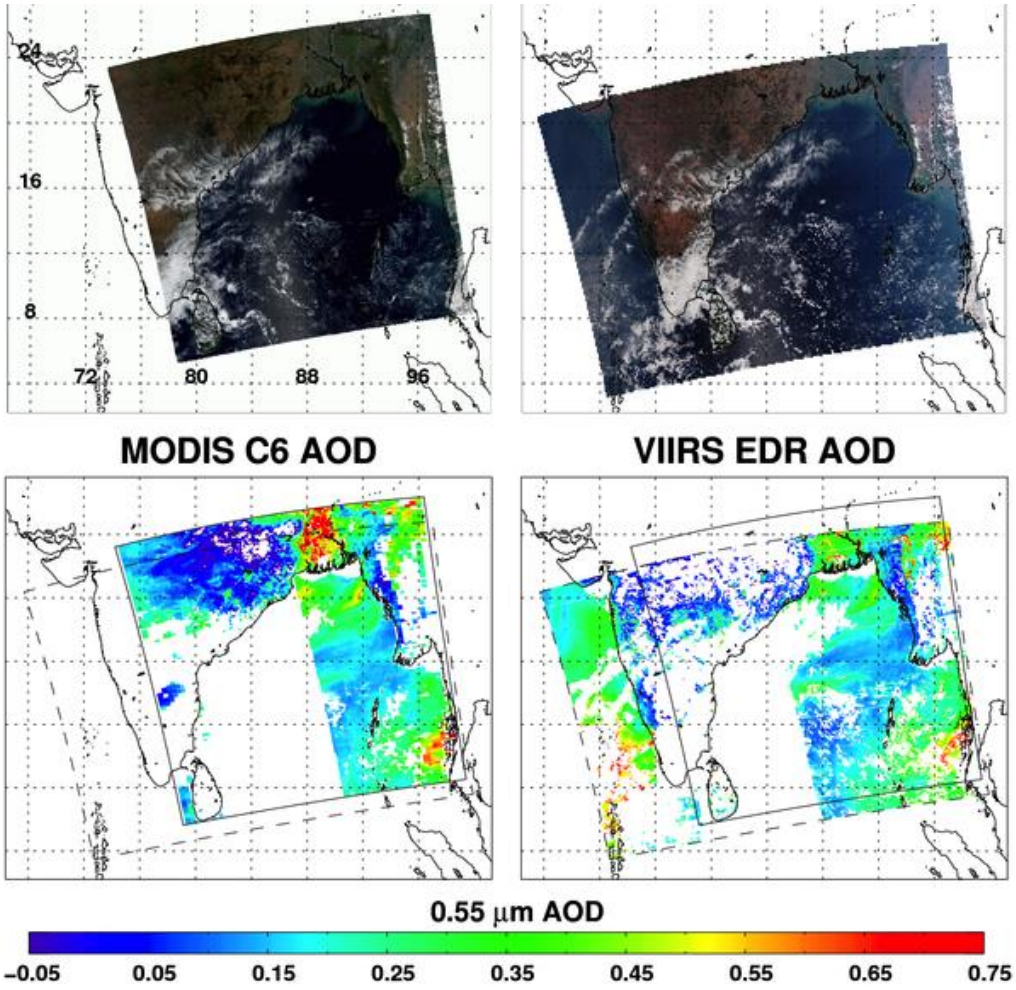


VIIRS Aerosol Algorithm (NOAA)

- Multi-spectral over dark surface
- Separate algorithms used over land and ocean
- 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 μm and spectral), Ångström Exponent (AE), Suspended Matter (aerosol classification), etc
- NOAA CLASS: The Primary Gateway for the VIIRS Data Distribution
- "Provisional" product (published evaluation) 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

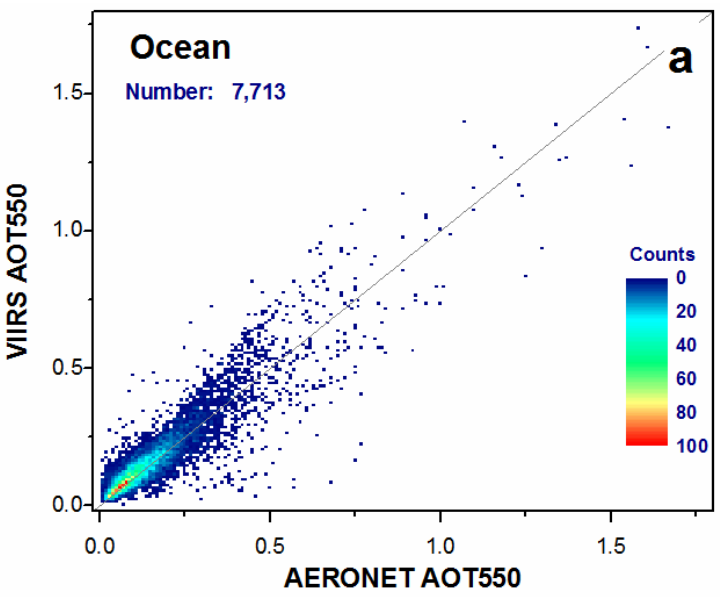
- "heritage" circa 1997

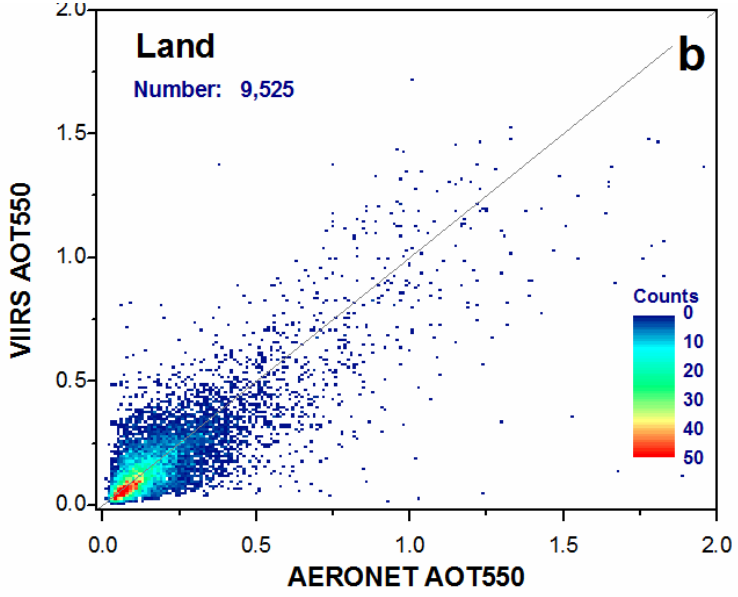
(Kaufman, Tanré, Vermote,…)

- 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.

VIIRS Validation: Comparisons with AERONET





Time period is Jan-Sept 2013

Table shows similar "validation" with respect to MODIS

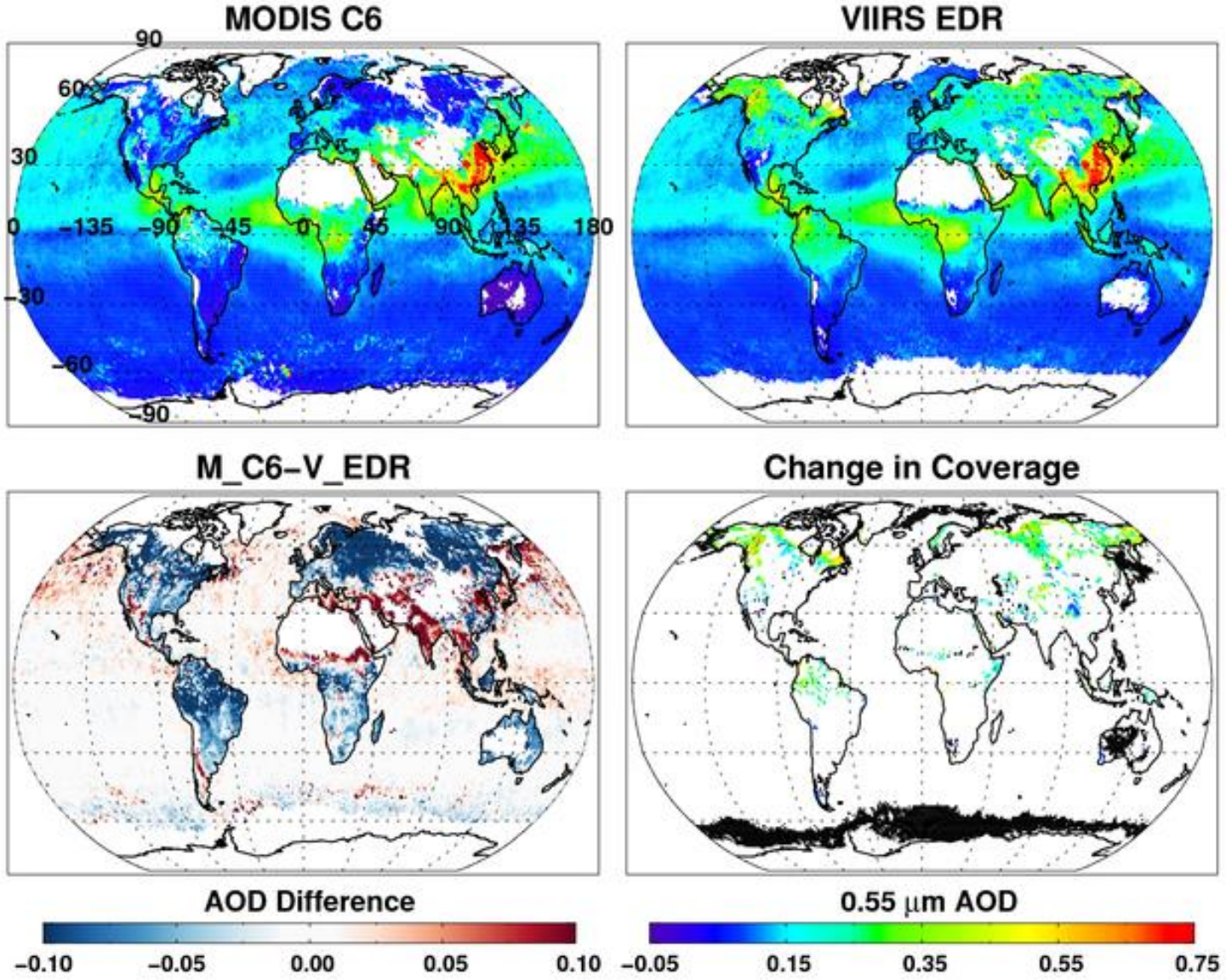
But that VIIRS has many more collocations with AERONET due to wider swath and other reasons

	Ocean				Land			
	MODIS	VIIRS (H)	VIIRS (H + M)	VIIRS (H + M + L)	MODIS	VIIRS (H)	VIIRS (H + M)	VIIRS (H + M + L)
Sample size	1931	7713	10,030	11,133	4990	9525	14,867	18,765
Accuracy	0.001	0.013	0.027	0.050	−0.005	−0.009	0.035	0.063
Precision	0.059	0.061	0.084	0.107	0.106	0.130	0.154	0.195
Uncertainty	0.059	0.062	0.088	0.118	0.106	0.130	0.158	0.205
Correlation	0.909	0.906	0.853	0.792	0.886	0.773	0.666	0.539
Percent within expected MODIS uncertainty range	64.1%	64.1%	54.2%	45.9%	64.7%	71.0%	57.5%	51.7%

[a]There is no requirement that VIIRS and MODIS retrievals occur at the same station and date. The time period is 2 May 2012 to 1 September 2013 (excluding the processing error period of 15 October 2012 to 27 November 2012) over ocean and 23 January 2013 to 1 September 2013 (after PCT update) over land. Three VIIRS results are shown: high-quality retrievals (H); high- or medium-quality retrievals (H + M); and all retrievals with high, medium, or low quality (H + M + L).

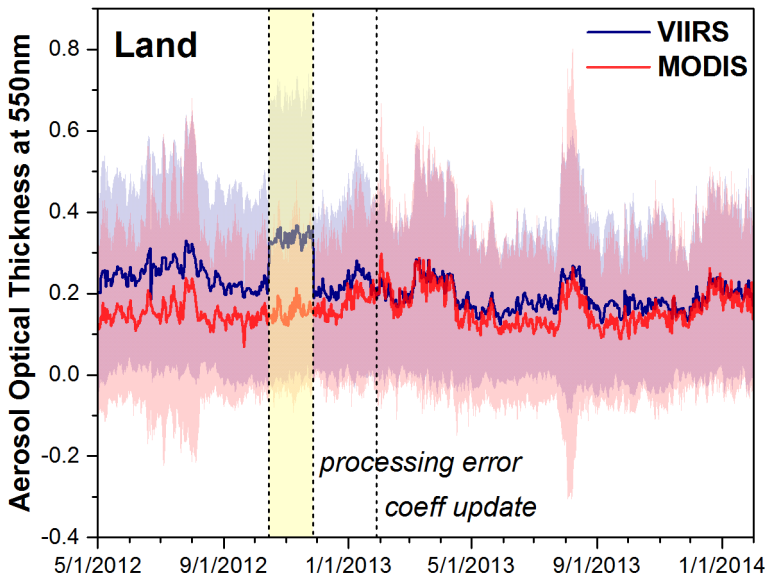
From NOAA/NESDIS/STAR and H. Liu et al., JGR 2014

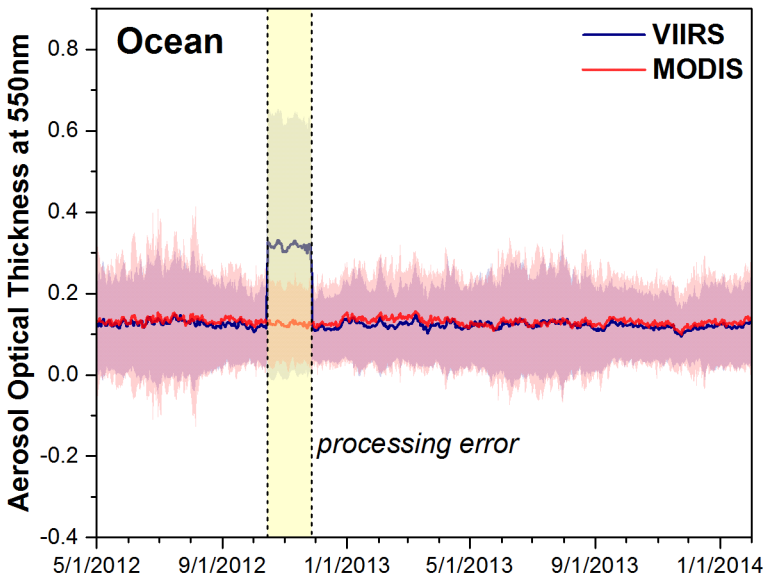
Monthly mean AOD for Spring 2013 (Mar-May)

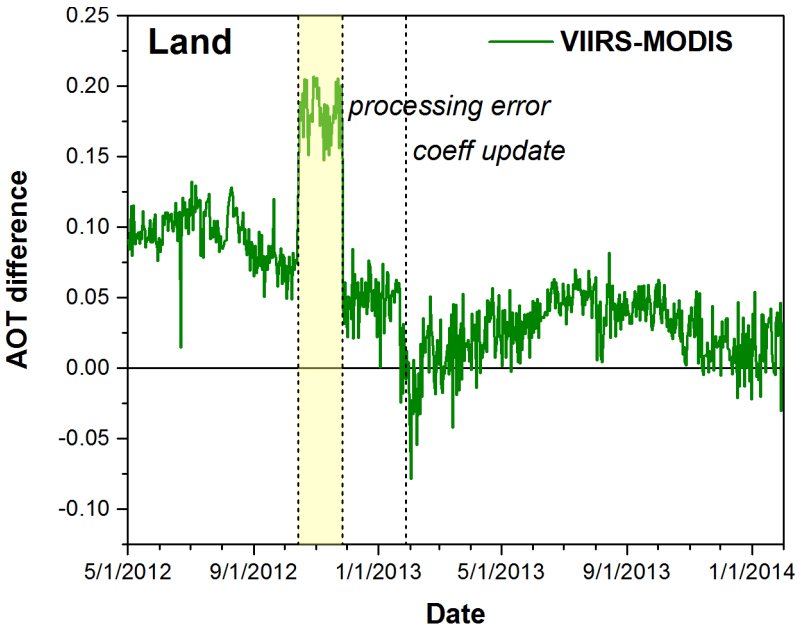


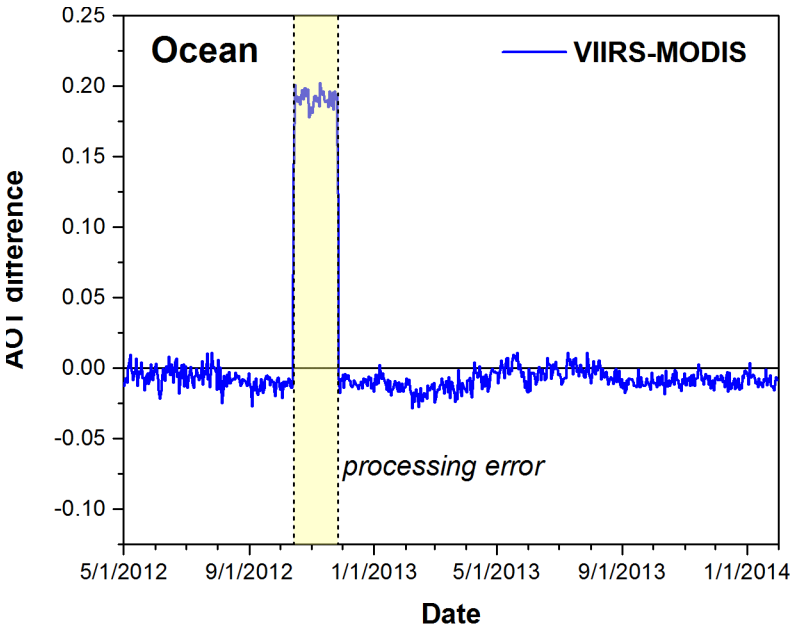
MODIS C6 and VIIRS-EDR are similar, yet different

Time Series of Daily Mean Aerosol Products (non-collocated) (05/02/2012 – 01/31/2014): VIIRS-IDPS









Comparisons with MODIS use MODIS Dark Target Collection 5.1 data

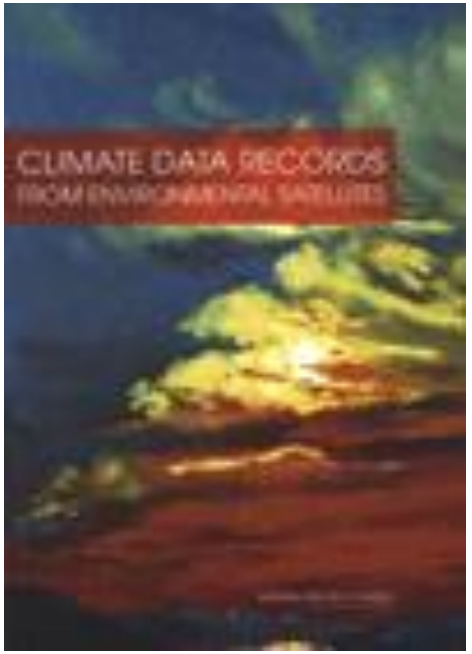
Courtesy of NOAA STAR VIIRS aerosol team

IDP-VIIRS vs MODIS-C6 algorithms

- Both algorithms produce good products (compared to AERONET)
- VIIRS has more coverage than MODIS (# of AERONET collocations)
- “Similar” looking when global gridded, with close global means
- But many differences:
  - Processing stream / granule size / data formatting
  - Cloud mask / pixel selection strategy
  - Aggregation/Averaging
    - VIIRS: Retrieve first (0.75 km) then average to get 6 km AOD
    - MODIS: Compute average reflectance (10 km) then retrieve AOD
  - Bowtie issues
  - Aerosol Retrieval algorithms (inversions, lookup tables, etc)
  - Post-Processing = Assigning Quality Assurance, etc
  - No official plans to reprocess with consistent algorithm.

Aerosol Climate Data Records (CDRs)?

"A time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change."

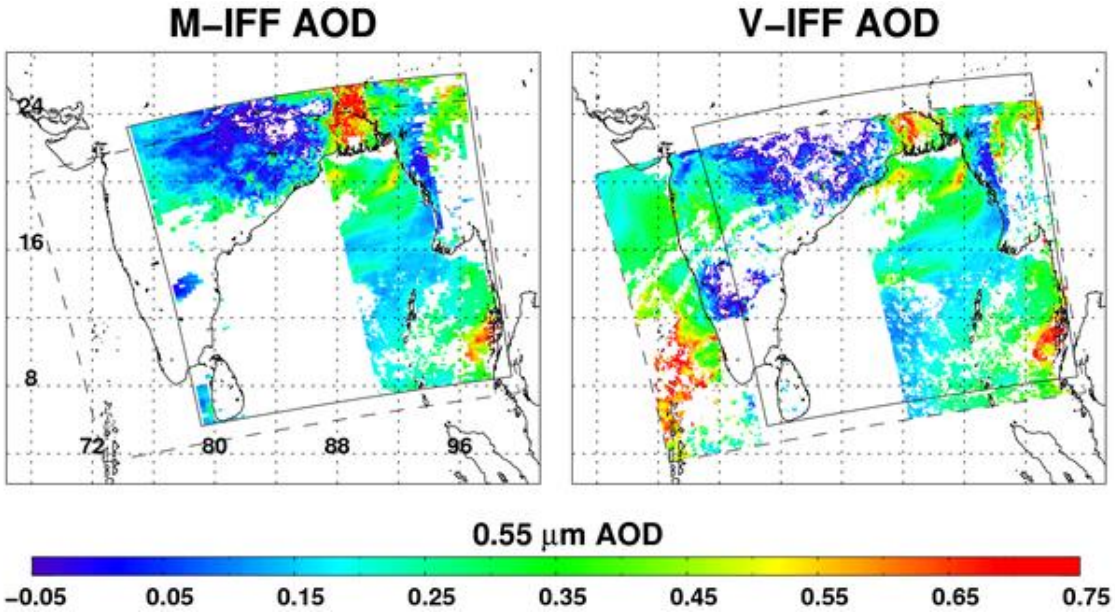


Some requirements

- Measurements sustained over decades
- Measurement of measurement performance (e.g. calibration, stability)
- Acquired from multiple sensors / datasets
- Similar algorithm?

Same algorithm on both platforms?

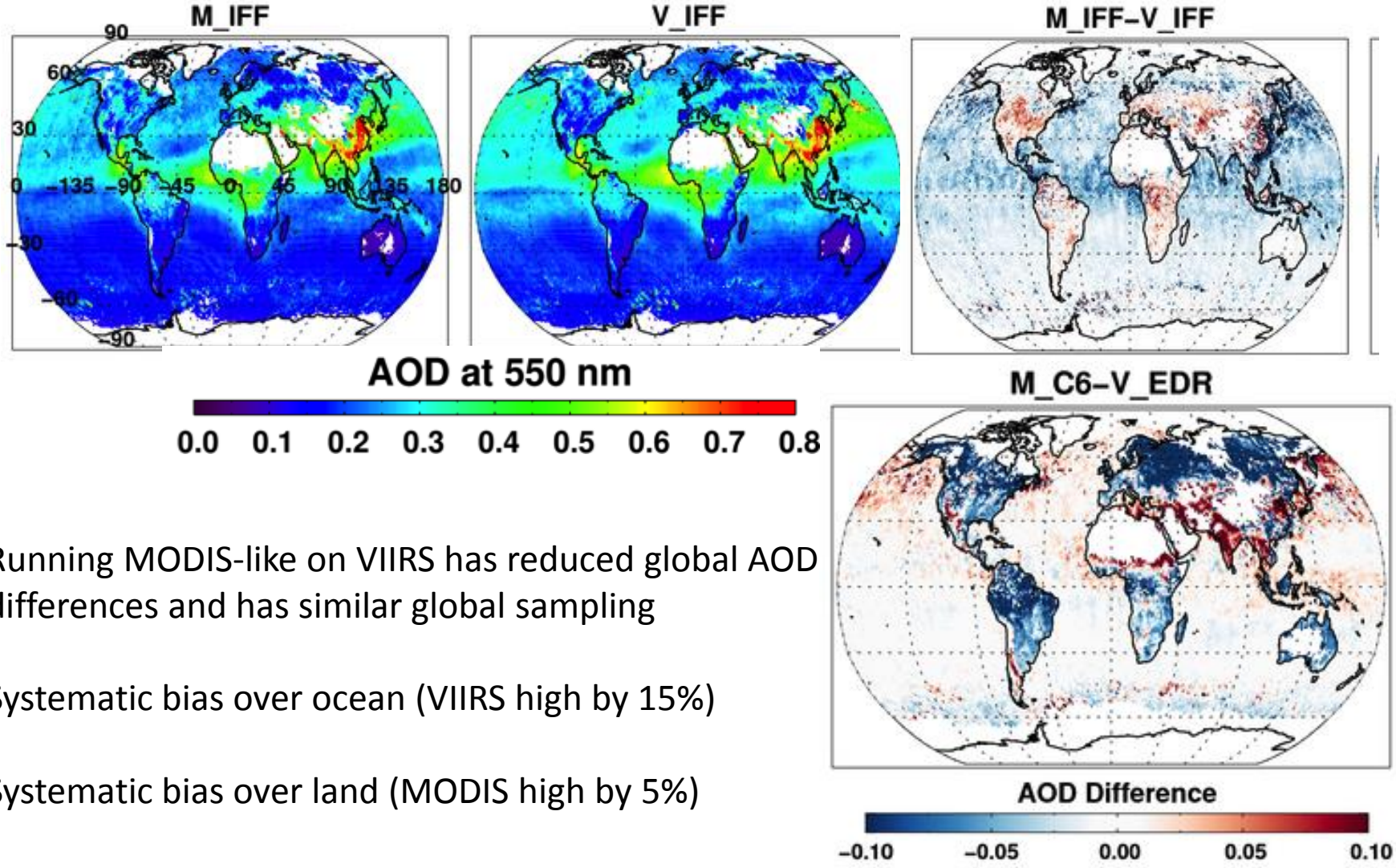
- The Intermediate file format (IFF) is attempt to make MODIS and VIIRS in "same common denominator" (University of Wisconsin)
- MODIS-IFF is 1 km resolution for all bands, VIIRS-IFF is 750 m (no high-resolution bands for either MODIS or VIIRS)
- We can run lookup tables to account for different wavelengths
- 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

Gridded seasonal AOD (Spring 2013)

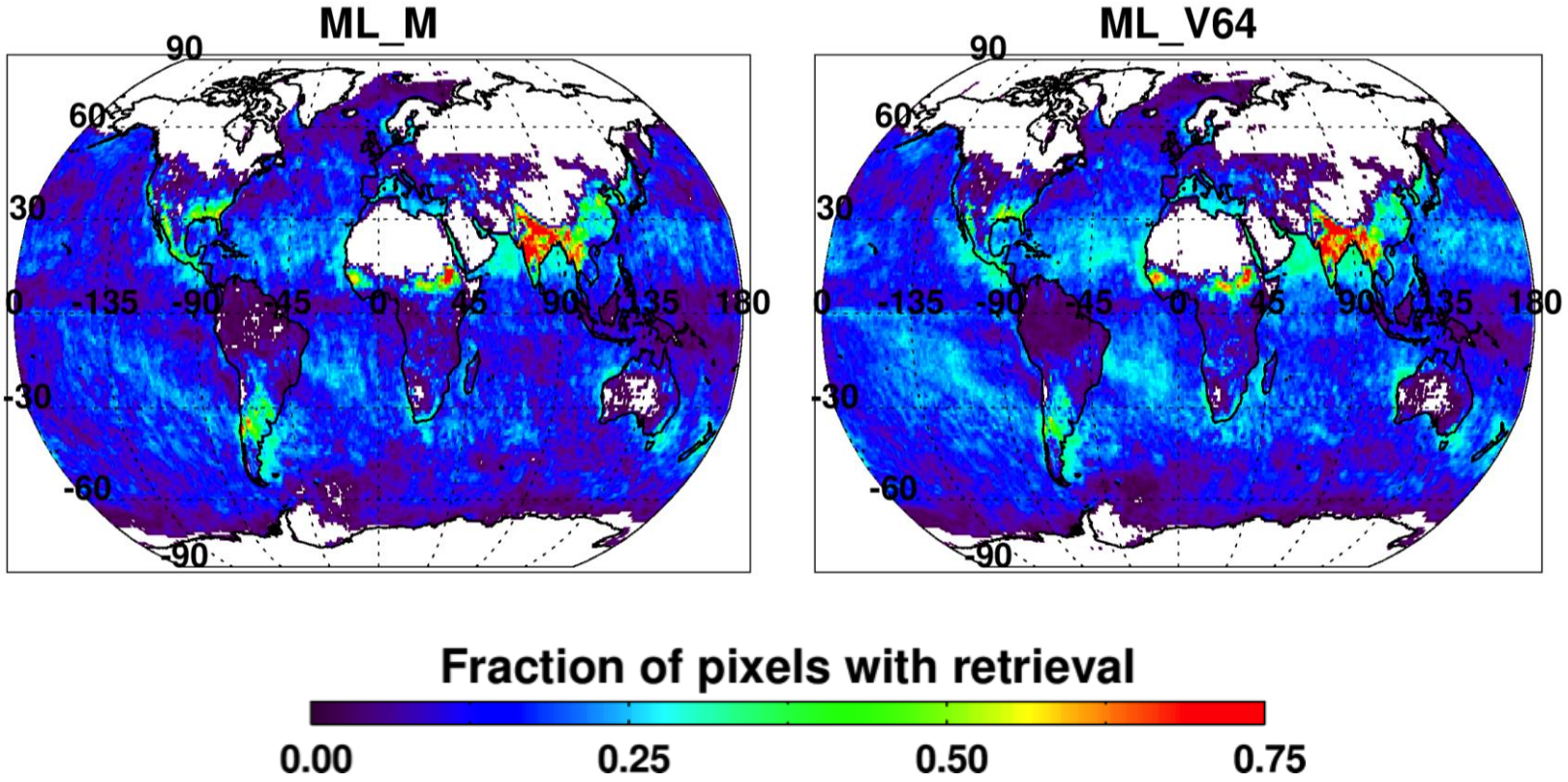


Running MODIS-like on VIIRS has reduced global AOD differences and has similar global sampling

Systematic bias over ocean (VIIRS high by 15%)

Systematic bias over land (MODIS high by 5%)

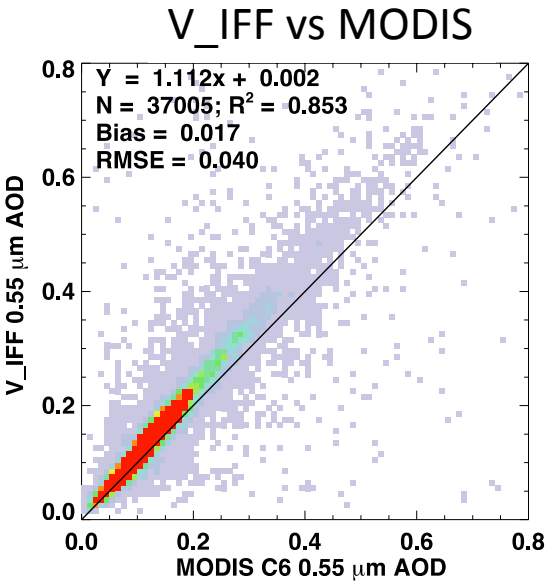
Convergence of “Retrievability”? (Mar 2013)

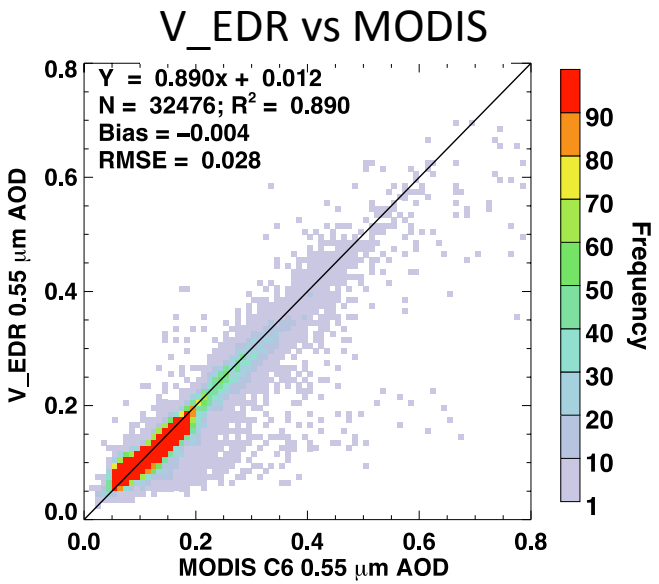


Are there places on the globe that cannot be retrieved by one satellite or another? Will they converge on cloud mask, pixel selection, availability of aerosol retrieval?

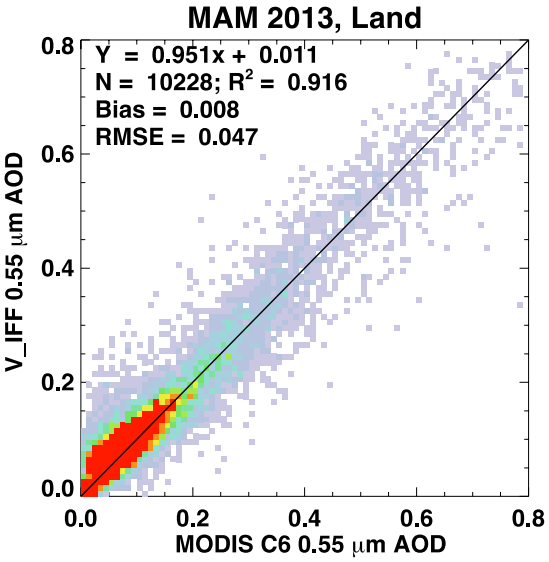
Comparing gridded AOD (Spring 2013)

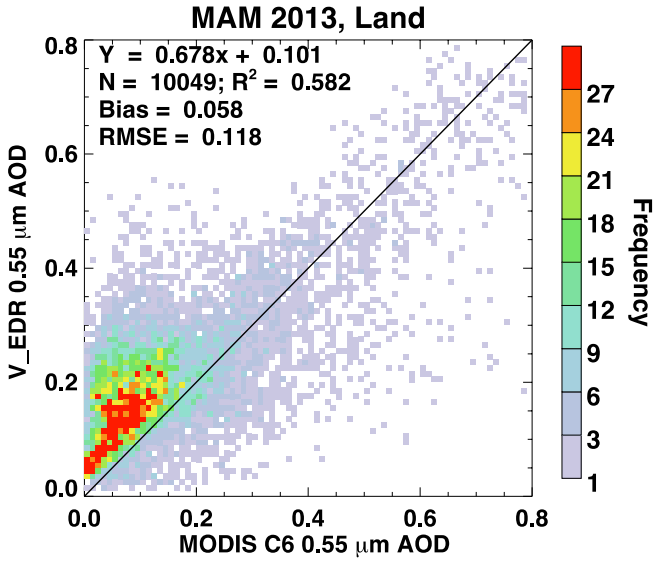
Ocean



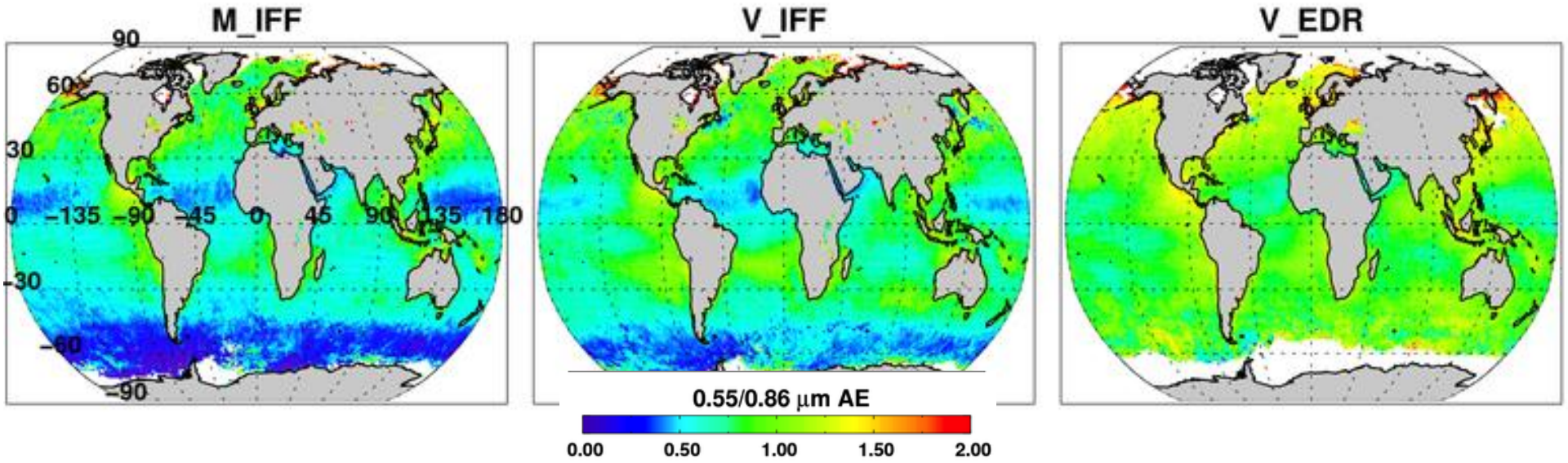


Land





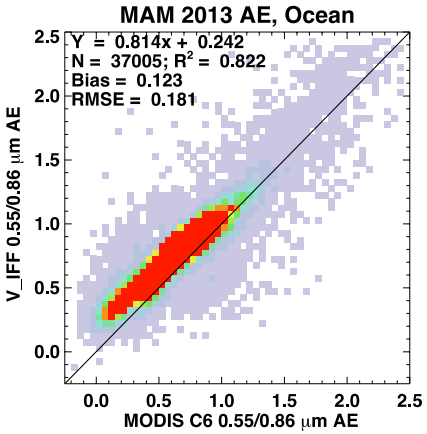
Gridded seasonal AE (Spring 2013)



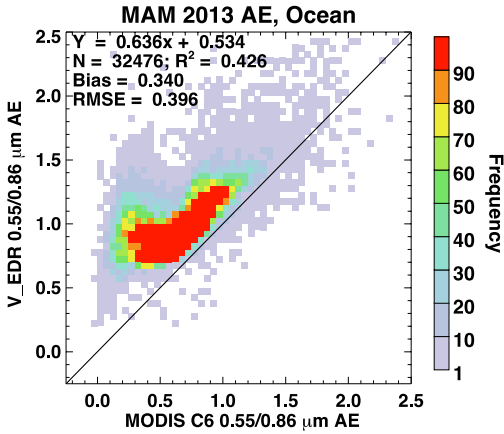
Running MODIS-like on VIIRS has reduced global differences and created maps over the same areas

VIIRS-EDR is just “different” than MODIS

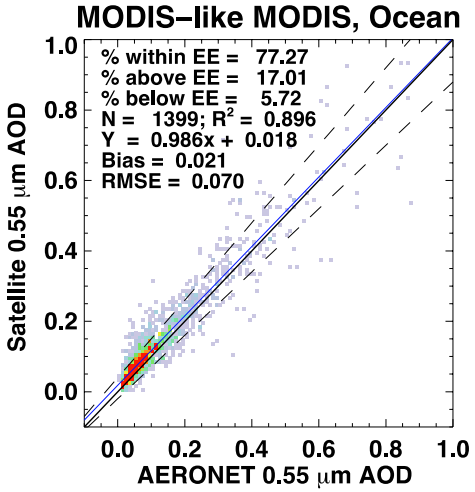
Still a bias with the V-IFF, but looks like the same world.

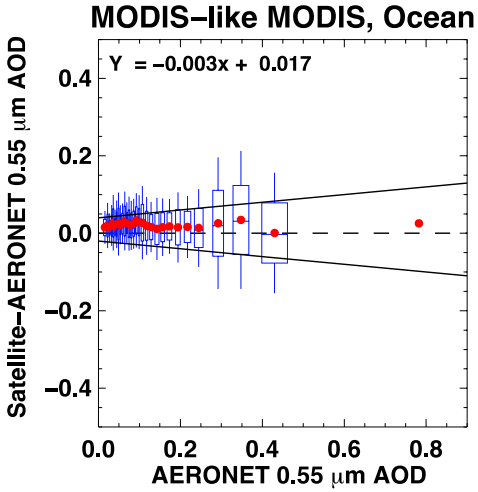


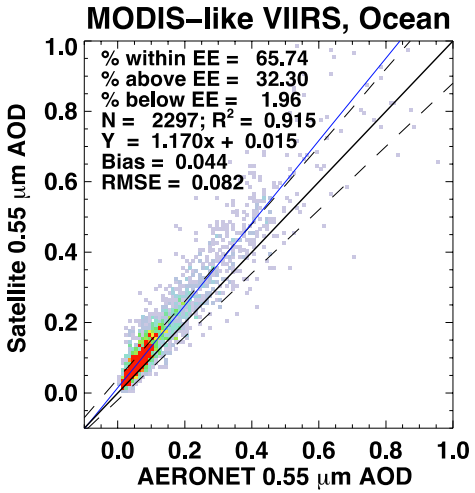
V_IFF vs MODIS

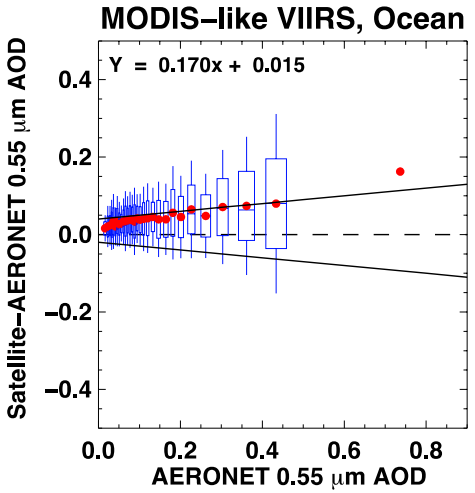


V_EDR vs MODIS







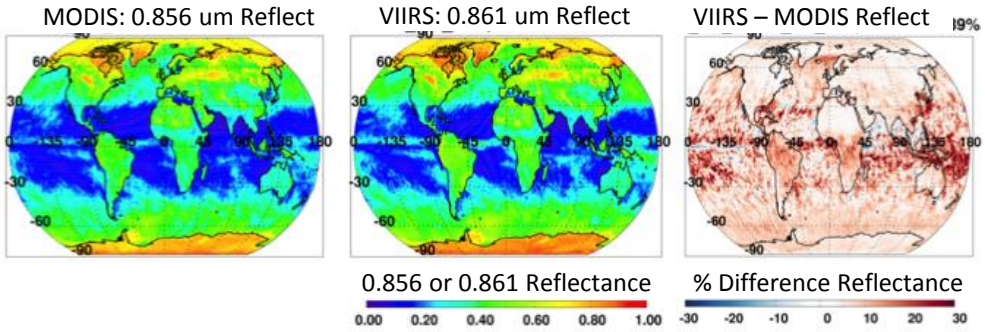


Comparing to AERONET and calibration

Interesting: MODIS-like on VIIRS has great correlation but 1.17 slope!

Studies such as Uprety et al., (2013) do radiometric comparisons between VIIRS and MODIS and find that VIIRS may be 2% high in some bands.

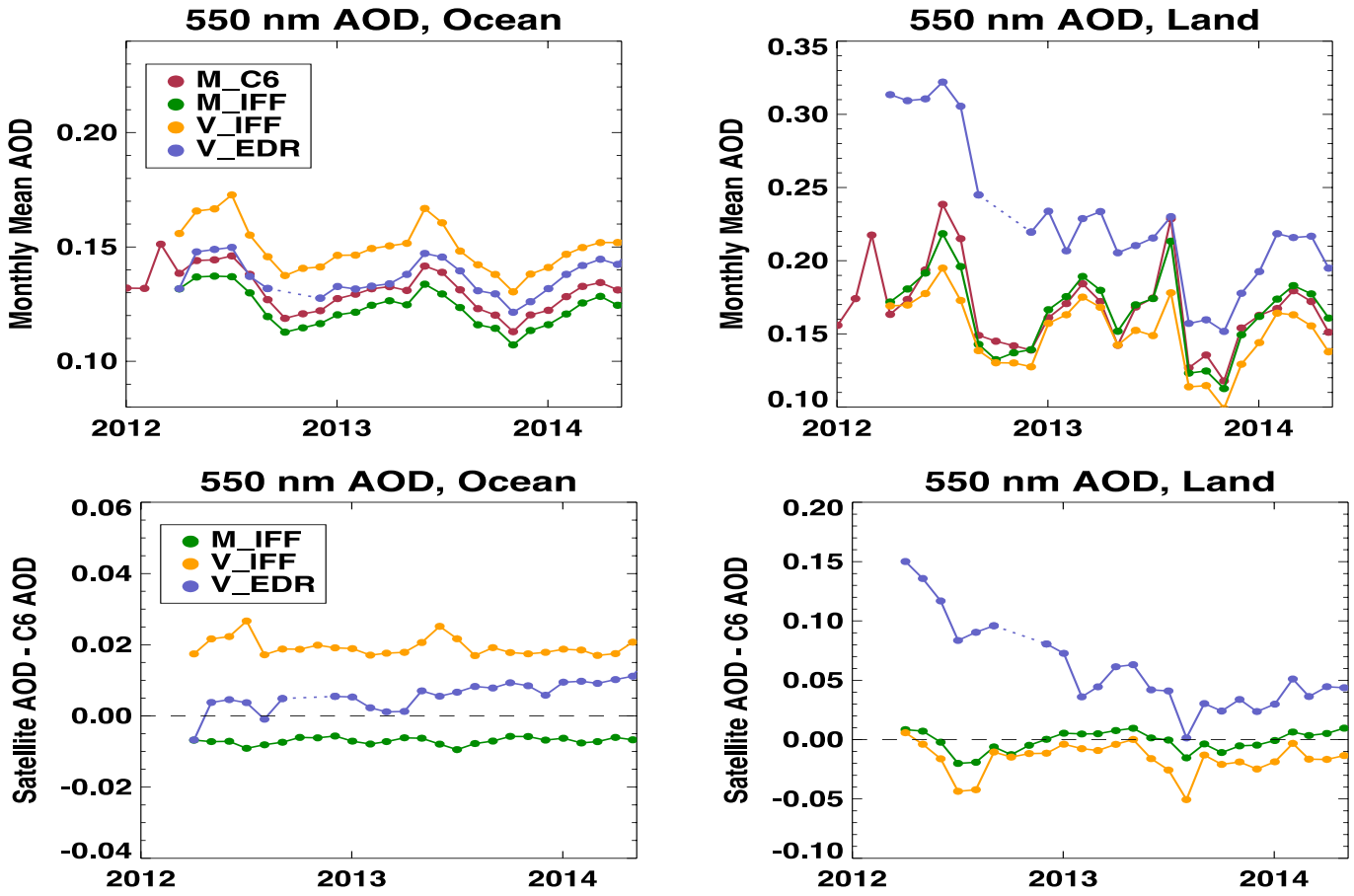
2% high bias is sufficient to give a 1.17 slope over ocean without the adding same bias to land.



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?
- What about "sampling"?
  - Even if the mean, histograms and gridded data looked similar, what about the "retrievability?"
  - Fraction of retrieved pixels / total pixel
- Comparison (validation) with AERONET?

Global Time Series

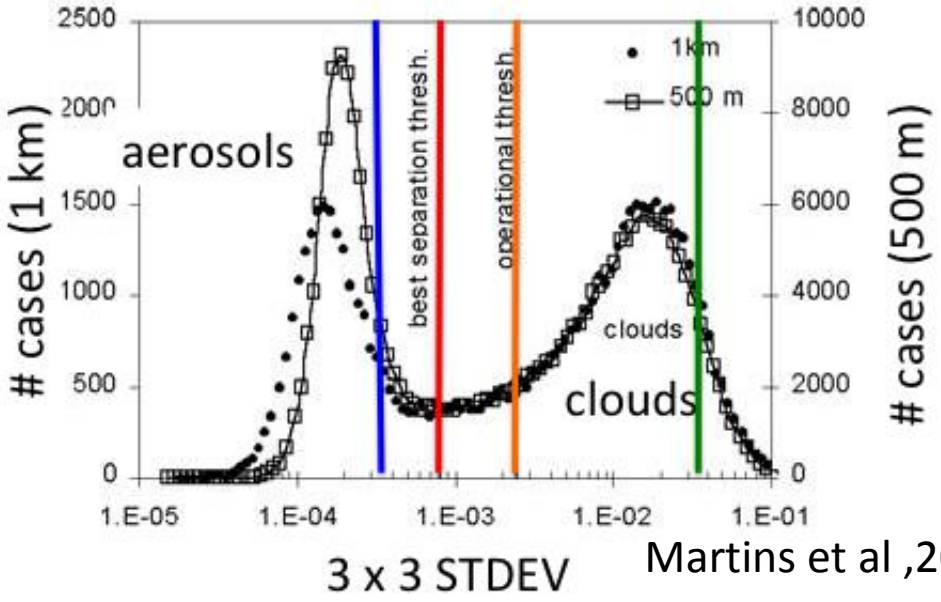


- Yes, AOD is converging.
- Both M-IFF and V-IFF have same seasonal cycle; matches with M-C6
- But, offsets between M-IFF and V-IFF of 0.02 over ocean. (Sound familiar?)
- And, there is offset (0.01) between M-C6 and M-IFF over ocean.
- Cloud masking is still an issue

Still not homogenized yet

More things we realized (or remembered)

- Land/Sea mask are different, even for M-C6 vs MODIS-IFF.
- Large swath of VIIRS may include 2 orbits (3 hours) of MODIS
- Different resolutions really change cloud mask (including M-C6 vs M-IFF)



Martins et al ,2002

"Round 2" of our effort: Can we quantify remaining differences?

Summary (1)

- Creating Climate Data Records is tricky
- We have a mature MODIS algorithm in the Dark-target aerosol retrieval
- The C6 algorithm is good, and we have accounted for trending differences between MODIS Terra and Aqua
- But there are still Terra/Aqua offsets of ±0.015
  - Some of it is due to absolute calibration differences (<2%), which we think we can reduce.

Summary (2)

- NPP-VIIRS is online
  - VIIRS is “similar” instrument, yet different then MODIS
  - The NOAA product is VERY GOOD with similar global EE.
  - With 50% wider swath, VIIRS has daily coverage
  - VIIRS-EDR could be used in AeroCom studies? (starting 2013)
- 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?

- For DARF, we need global (and regional) AOD within ±0.02.
- What about other applications (air quality, aerosol transport)?

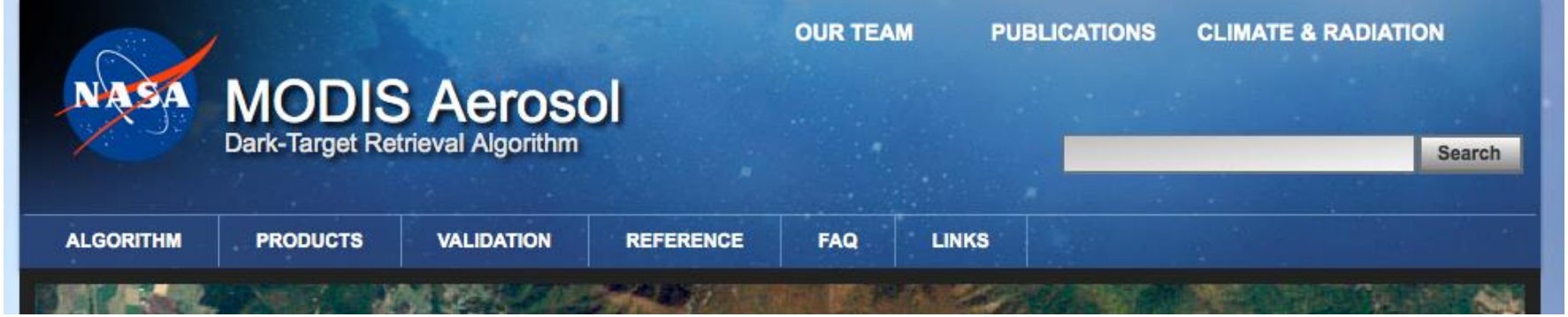
Summary (3)

- We are developing a common algorithm to help create a long term aerosol CDR across these multiple sensors.
  - Can get global mean within ±0.02-ish.
  - Regional means are still too different
- This is a work-in-progress...
  - porting cloud masking and pixel selection is issue
  - Calibration
  - The IFF files do not include high resolution bands.
  - What is good enough for climate applications? (e.g. CERES fluxes?)

Climate Data Records (CDRs)?

- Two MODIS sensors for >12 years (2000/2002-present)
- Suomi-NPP VIIRS is online (2011-present)
- JPSS1 VIIRS (near-future)
- JPSS2 VIIRS (future future)
- Other satellites with dark-target wavelengths

- → Towards multi-decadal AOD!



- Web site in development
- 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