Assimilation of aerosol optical depth data from NPP VIIRS in a global aerosol model

Edward J. Hyer[1]

Peng Lynch[2]

Min Oo[3]

Yingxi Shi[4]

Ted McHardy[4]

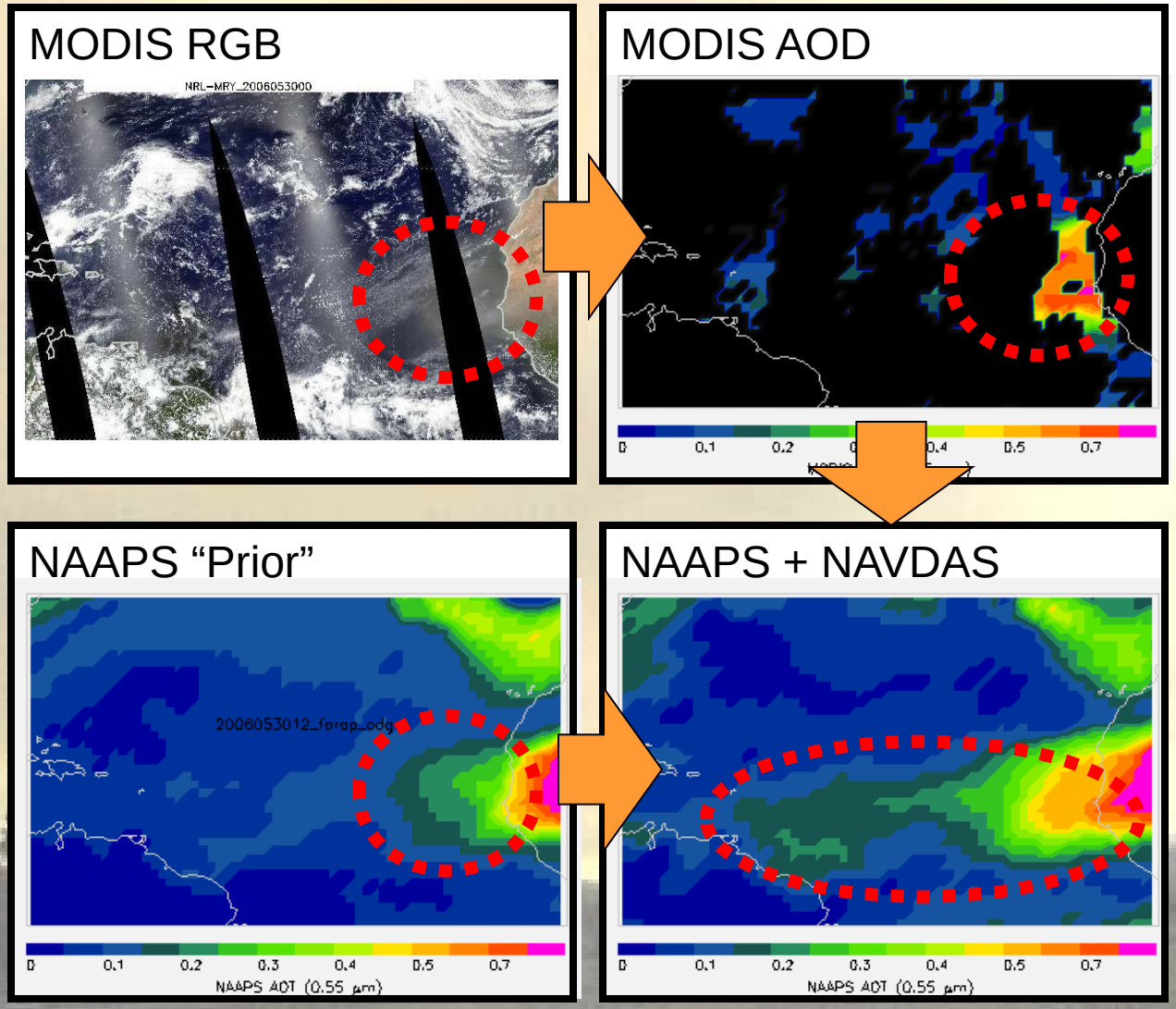
Jianglong Zhang[4]

1. NRL, Monterey, CA
2. Computer Science Corporation
3. University of Wisconsin CIMSS
4. University of North Dakota

In This Talk

- Data Requirements for Aerosol Assimilation
- Preparation of NPP VIIRS products for assimilation
- Assimilation Results
- Conclusions / Prospects

Navy Global Aerosol Forecasting



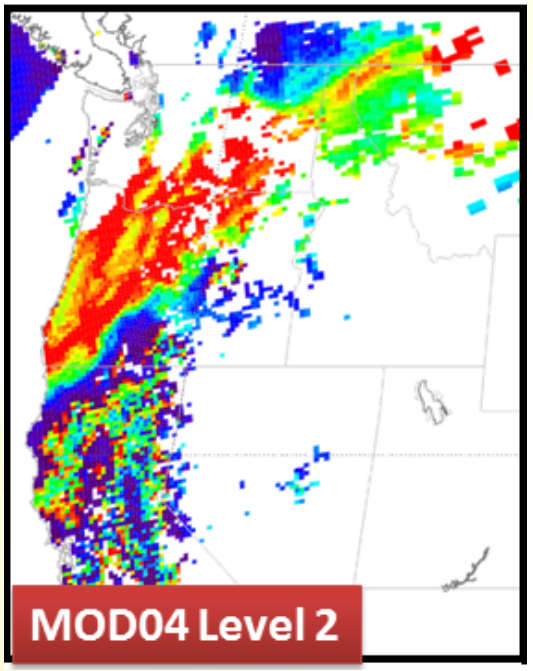
- **Navy Aerosol Analysis and Prediction System (NAAPS) operational since 2005**
- **Navy Variational Data Assimilation System for AOD (NAVDAS-AOD) Operational at FNMOC from September 2009 (MODIS over ocean)**
- **Global MODIS is assimilated operationally as of February 2012**
- **J.L. Zhang et al., "A System for Operational Aerosol Optical Depth Data Assimilation over Global Oceans", JGR 2008.**

Why Does Assimilation-Grade AOD Matter?

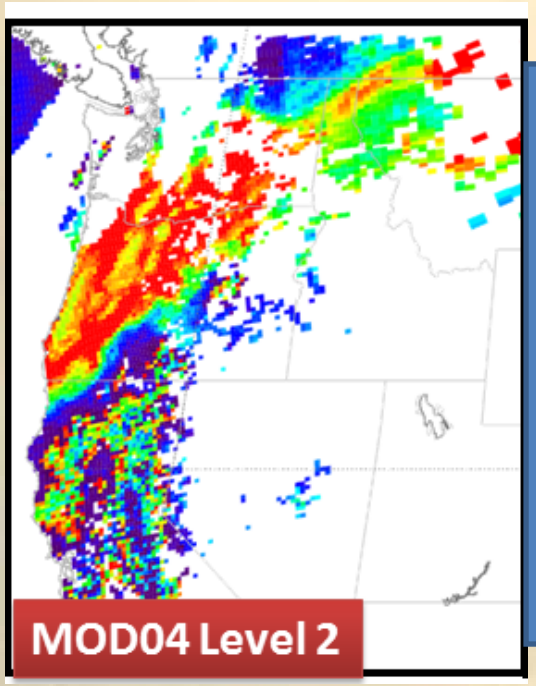
- Aerosol analysis and forecasting requires AOD for assimilation
- Assimilation has specific requirements
  - Minimize outliers
  - Correct persistent bias
  - Quantify residual uncertainty
- Level 2 AOD products are not good enough
  - Correlated bias
  - Limited error characterization

Preparation of Satellite Data for Assimilation

Level 2 MOD04 (NASA) or VAOOO EDR (JPSS) data is generated by upstream data centers – spatial resolutions of a few km



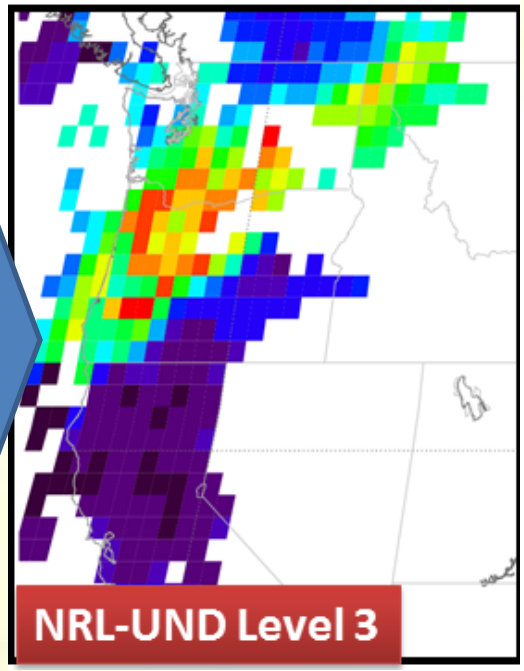
Preparation of Satellite Data for Assimilation



AOD data process developed by NRL and UND, includes

- **Aggressive cloud filtering**
- **Ocean wind speed correction**
- **Land albedo correction**
- **land surface and snow filters**
- **Microphysical AOD bias correction**

0.5 degree product distributed to public via NASA LANCE (MxDAODHD)



- Developed by NRL/UND for MODIS Collection 4&5
- 0.5 degree product distributed to public via NASA LANCE (MxDAODHD)

NRL's process for QA/QC of new satellite AOD products: 5 stages

Starting with a multi-month record of L2 data…

1. L2/L2 comparison to AERONET at full resolution
2. L2/L2 comparison to MODIS

Generation of candidate L3 AOD…

3. L3/L3 comparison to currently assimilated datasets

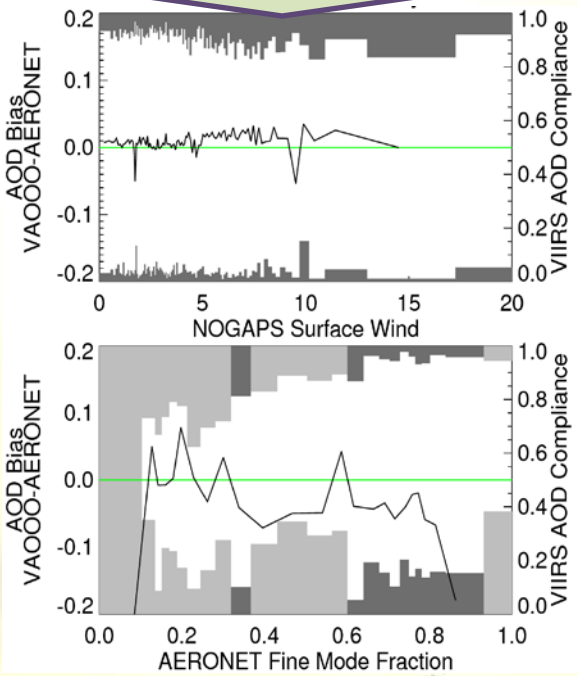
Test runs of NAAPS+NAVDAS-AOD using new data…

4. Model/Model comparison of analyzed aerosol fields using different AOD inputs
5. Model/AERONET comparison and model verification

Stage 1: L2 comparison to AERONET

- Utility:
  - Diagnosis of retrieval behavior
  - Understanding sources of retrieval uncertainty

Stable performance over a wide range of wind speed.



High bias for coarse particles

- Plots are based on VIIRS aerosol products from IDPS (only QA='High') and AERONET Level 1.5 for February 2013-November 2014. Solid lines show the mean AOD bias in each bin; gray bars indicate the fraction of retrievals falling outside of an expected error of $0.05+0.2\tau_{AERONET}$.
- (Top) VIIRS EDR shows a small trend of increasing AOD bias with wind speed, with increasing positive errors at high winds.
- (Bottom) Comparison of VIIRS bias as a function of AERONET fire mode fraction (only pairs with tA>0.4 were used) indicates that the VIIRS EDR has better performance retrieving fine-mode aerosols. Extreme high and low values of fine mode fraction are generally in plumes near the source.
  - **NOTE: Negative errors for these plumes have significant representativeness error because of the disparity of scale between the satellite and AERONET**.

Stage 2: L2/L2 comparison to MODIS

VAOOO-MYD04 matchup product from NASA Atmospheres PEATE at U. Wisconsin

- Produced for every overlapping swath
- Packaged as HDF
- Available from UW PEATE
- MODIS Collection 5 only
- Available for 201202-201405

Every MODIS-Aqua scene is checked to see if there is an overlapping VAOOO scene within 15 minutes

For each MYD04 10km Level 2 footprint in the scene, VAOOO footprints whose centers fall within the MYD04 footprint are selected

  - Even if MODIS does not retrieve AOD for that footprint, it is included in the matched product

- Matched product includes all MYD04_L2 SDS
- For VAOOO, product includes:
  - AOT/EPSP for:
    - Mean, all QA
    - Mean, QA = Moderate+|High
    - Nearest EDR retrieval
      - all QA|Moderate|High QA

Questions to address with these data

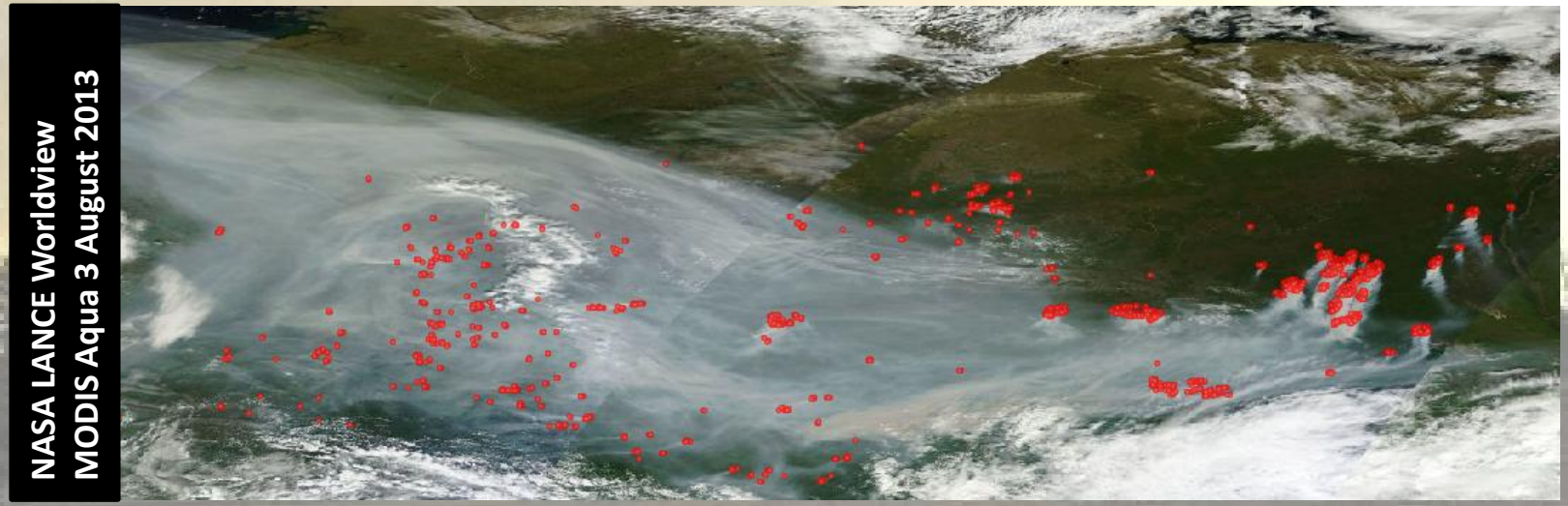
- What is the relative behavior of the two retrievals?
- VIIRS product retrieves limited range of AOD vs MOD04
  - IVAOT retrieves 0 > AOD > 2
  - MOD04 retrieves -0.05 > AOD > 5
  - What is the impact of these limits on matchup data coverage?
  - What is the impact on 1:1 AOD comparisons?
- Is there any discernible cloud contamination bias in VIIRS
  - This would be on top of any MODIS C5 bias

Stage 2 Case Study: Russia Summer 2013

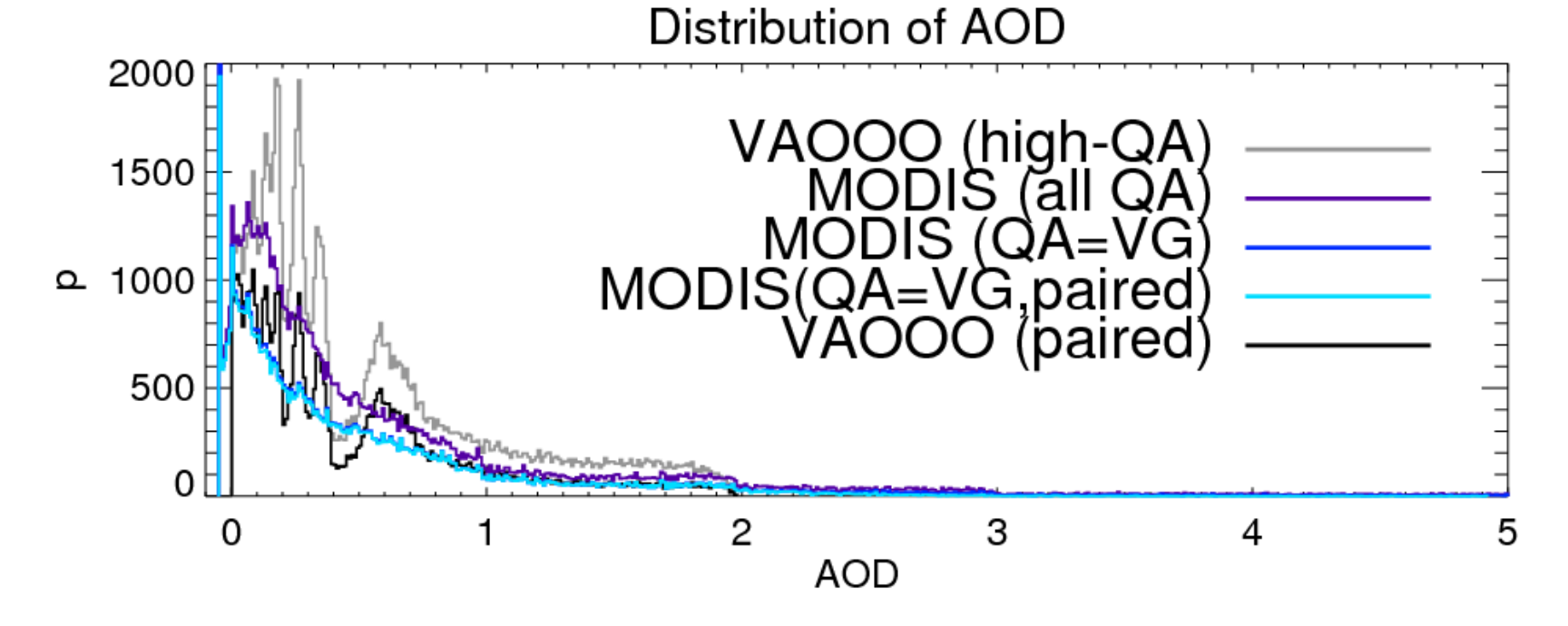
- Russian fires summer 2013
- Bounding box = 50-70N, 75-125W
- 7/23 to 8/23/2013

N=262,825 MODIS footprints

- 77521 valid MODIS (51197 QA=very good)
- 88061 valid VIIRS (QA=high [other QA levels not considered])
- MODIS QA values: 19% very good, 4% good, 3% marginal, 73% not retrieved
- **48,132** footprints with both MYD04 and VAOOO highest QA retrievals



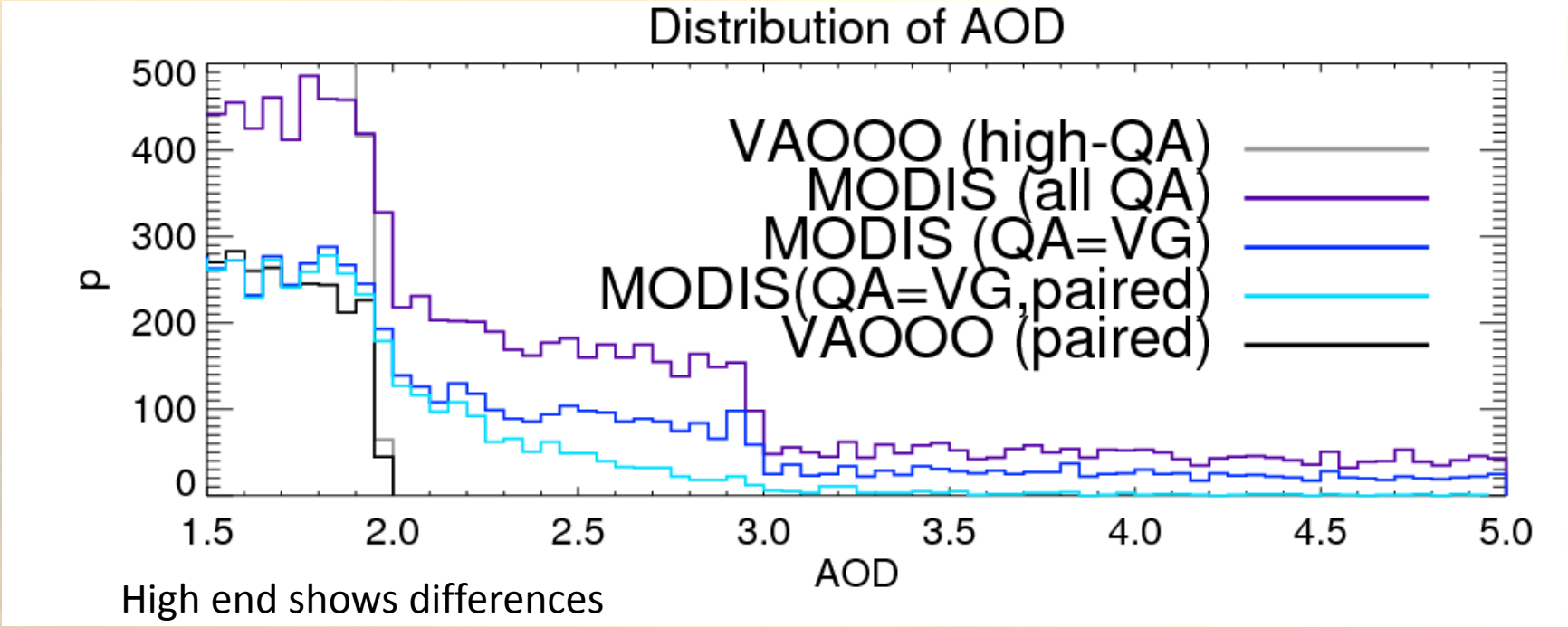
Russia Case – AOD distributions



Giant Smoke Plume = very long tail

- VAOOO AOD distribution is far from smooth
- MODIS is smooth, close to lognormal
- MODIS range = -0.05 to 5.0 VIIRS range = 0.0 to 2.0
- Paired distributions look very different
  - VAOOO = black, MODIS = aqua

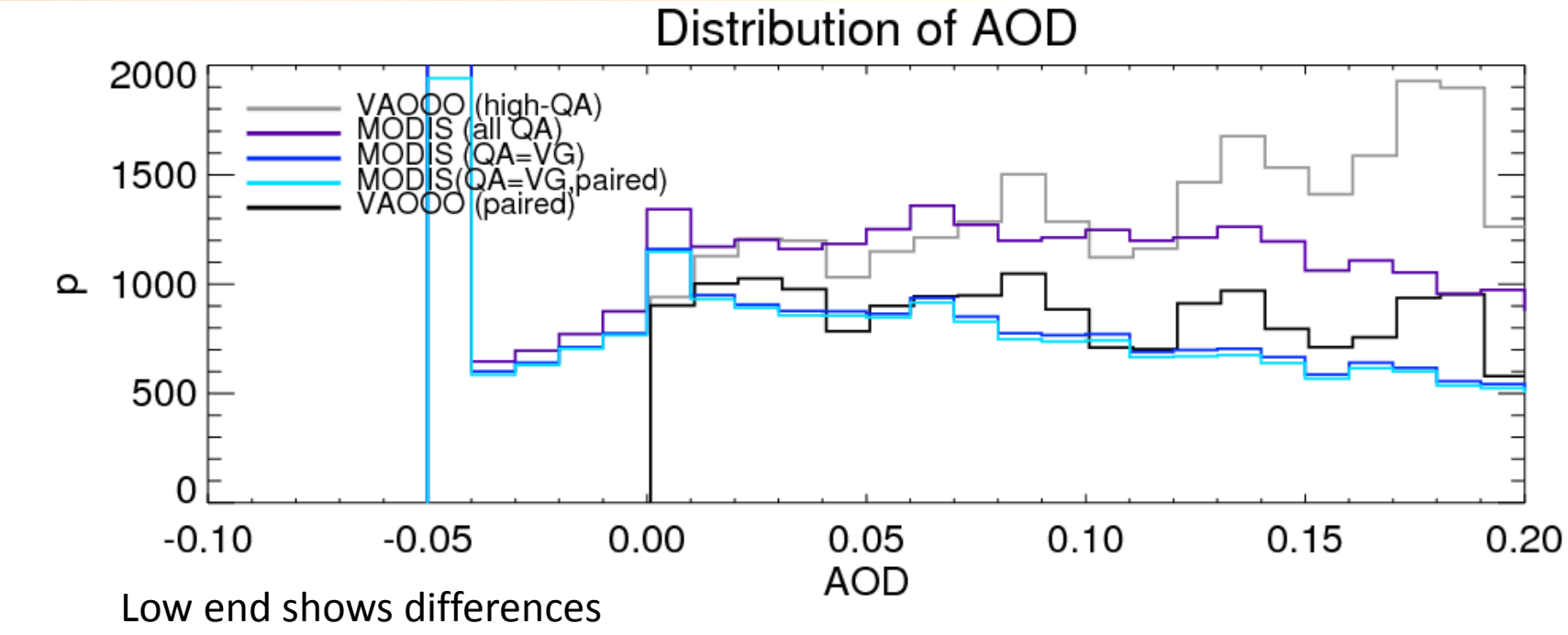
Russia Case – AOD distributions



High end shows differences

- VAOOO cannot retrieve above AOD=2.0
  - QA=VG (blue) and paired (aqua) diverge above AOD=2.0
  - Consistent with positive AOD truncation in VAOOO

Russia Case – AOD distributions

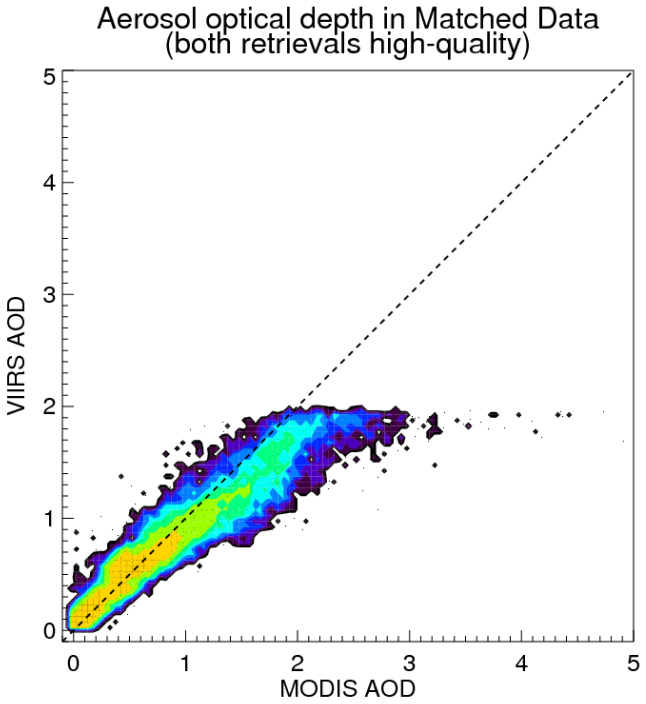


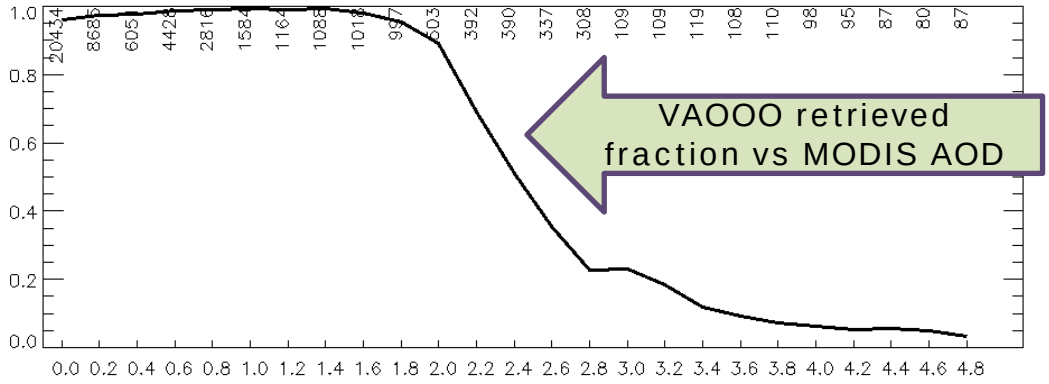
Low end shows differences

- Lots of MODIS negative AOD values
  - QA=VG (blue) and paired (aqua) match, except in lowest bin
  - Consistent with negative AOD truncation in VAOOO?
- Above 0.0, MODIS looks smooth, VAOOO distribution is uneven

Russia case– VIIRS AOD and retrieval success vs MODIS AOD

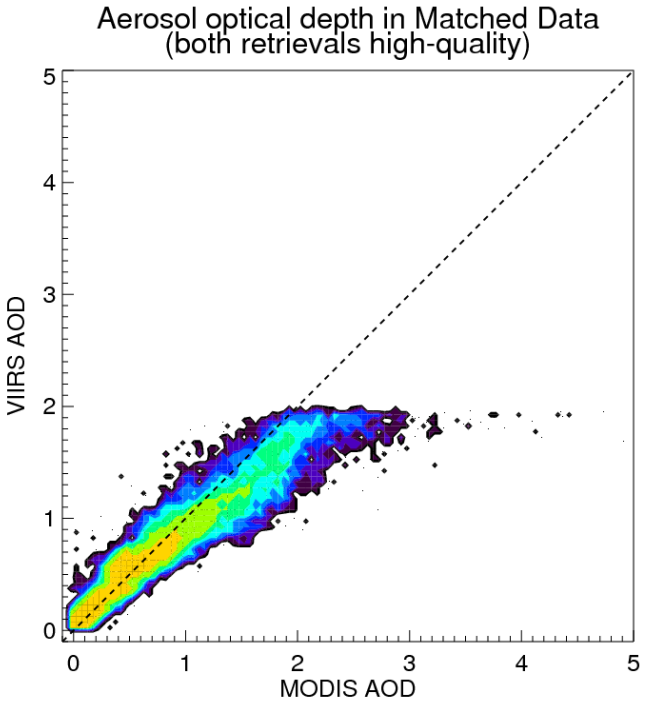
- VIIRS and MODIS have slope close to 1.1 up to VAOOO~1.2
- Truncation effect at high AOD is clearly evident even at single-retrieval level (MODIS retrievals with high AOD paired with nearby successful VIIRS retrievals with AOD<2)

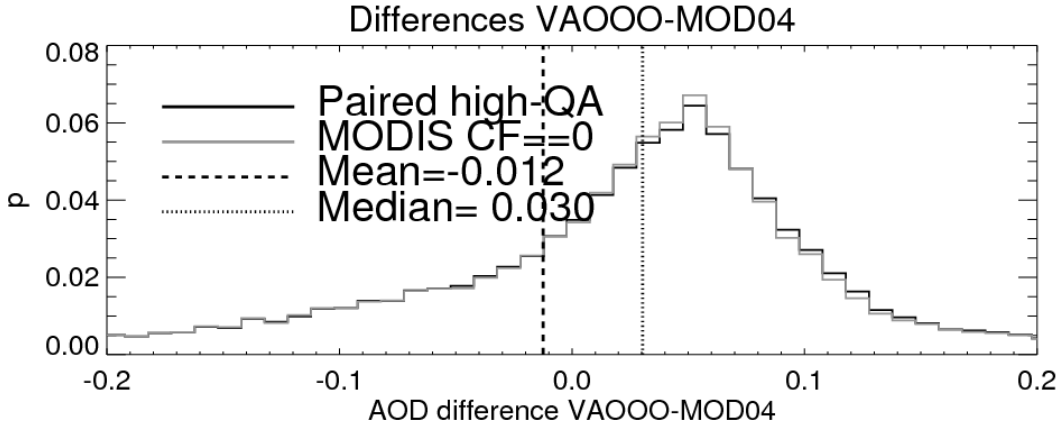




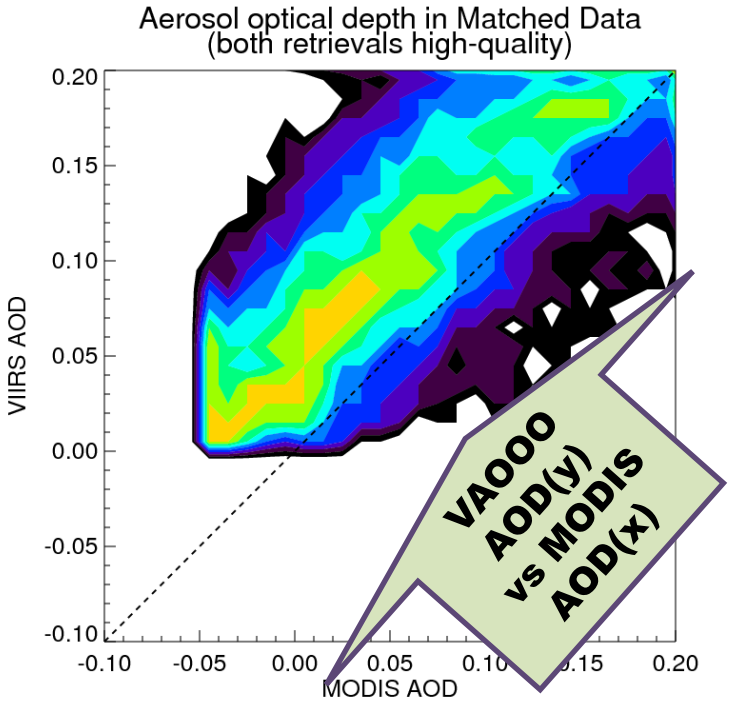
Russia case– VIIRS AOD vs MODIS

- In the mean, MODIS > VIIRS
  - Weighted by high-AOD tail
- In the median, VIIRS > MODIS
  - Weighted by low AODs

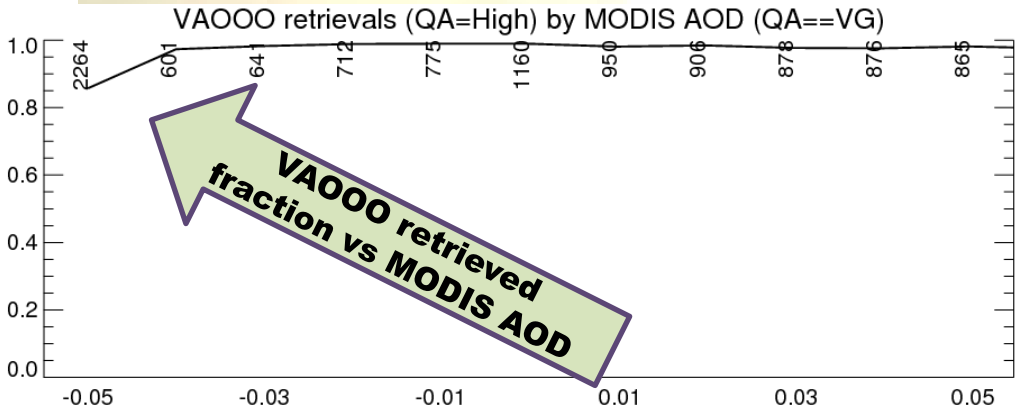




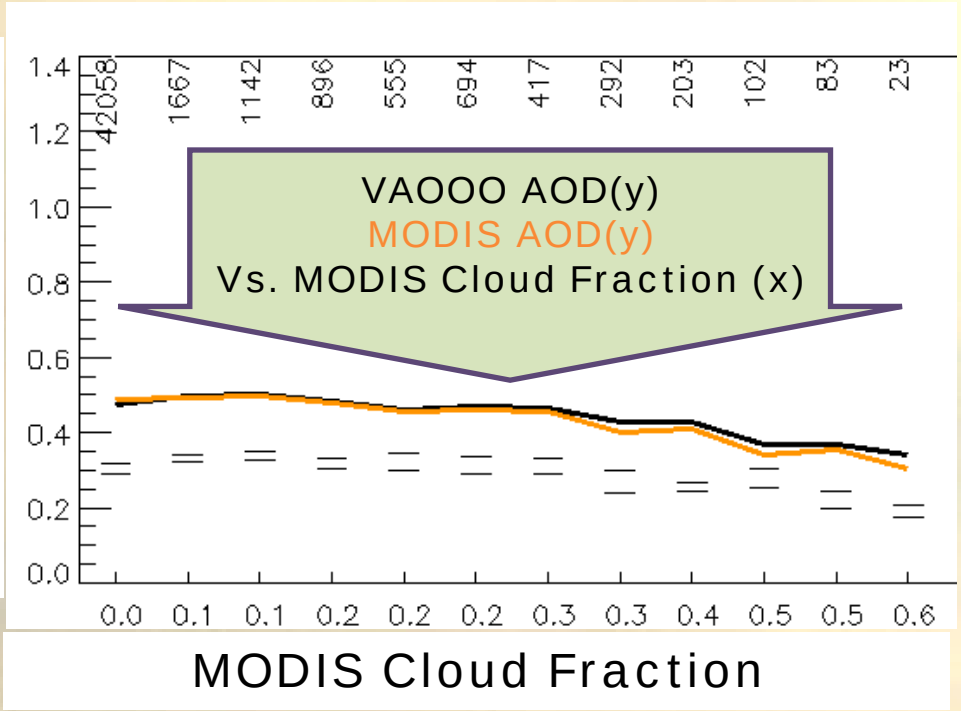
Russia case– VIIRS AOD and retrieval success vs MODIS AOD



- VIIRS has clear positive offset vs MODIS
- MODIS has large fraction of negative AOD retrievals
- Scatter is greater than ocean case
- Significant evidence of truncation at low end
  - MODIS retrieves negative AOD, VIIRS cannot retrieve even nearby
  - This effect is not nearly enough to offset positive bias in unpaired means



AOD vs MODIS Cloud Fraction (sensor comparison)



- Uses only paired retrievals with MODIS QA=='very good' & VAOOO QA==High
- **BLACK:** Median VAOOO AOD (nearest QA==high) as a function of MODIS Cloud Fraction.
- **ORANGE:** Median MODIS AOD (QA=VG only) as a function of MODIS Cloud Fraction.
- Mean AOD is high for this study area
- VAOOO and MOD04 track closely
- VAOOO is very slightly higher at high cloud fraction
- **Not evidence for cloud leakage in VAOOO**

Conclusions from L2/L2 matchup study

- This comparison does not indicate any evidence of cloud leakage in VAOOO
- Major impact of AOD upper limit of 2.0
  - After averaging of data, this will cause significant bias
- Detectable impact of AOD lower bound of 0.0
  - Not likely a large source of bias
- VAOOO is ~0.06 higher than MODIS Collection 5 Dark Target for clean conditions in continental Russia
  - Other validation suggests the answer is in between
  - This large discrepancy complicates combined use of these datasets

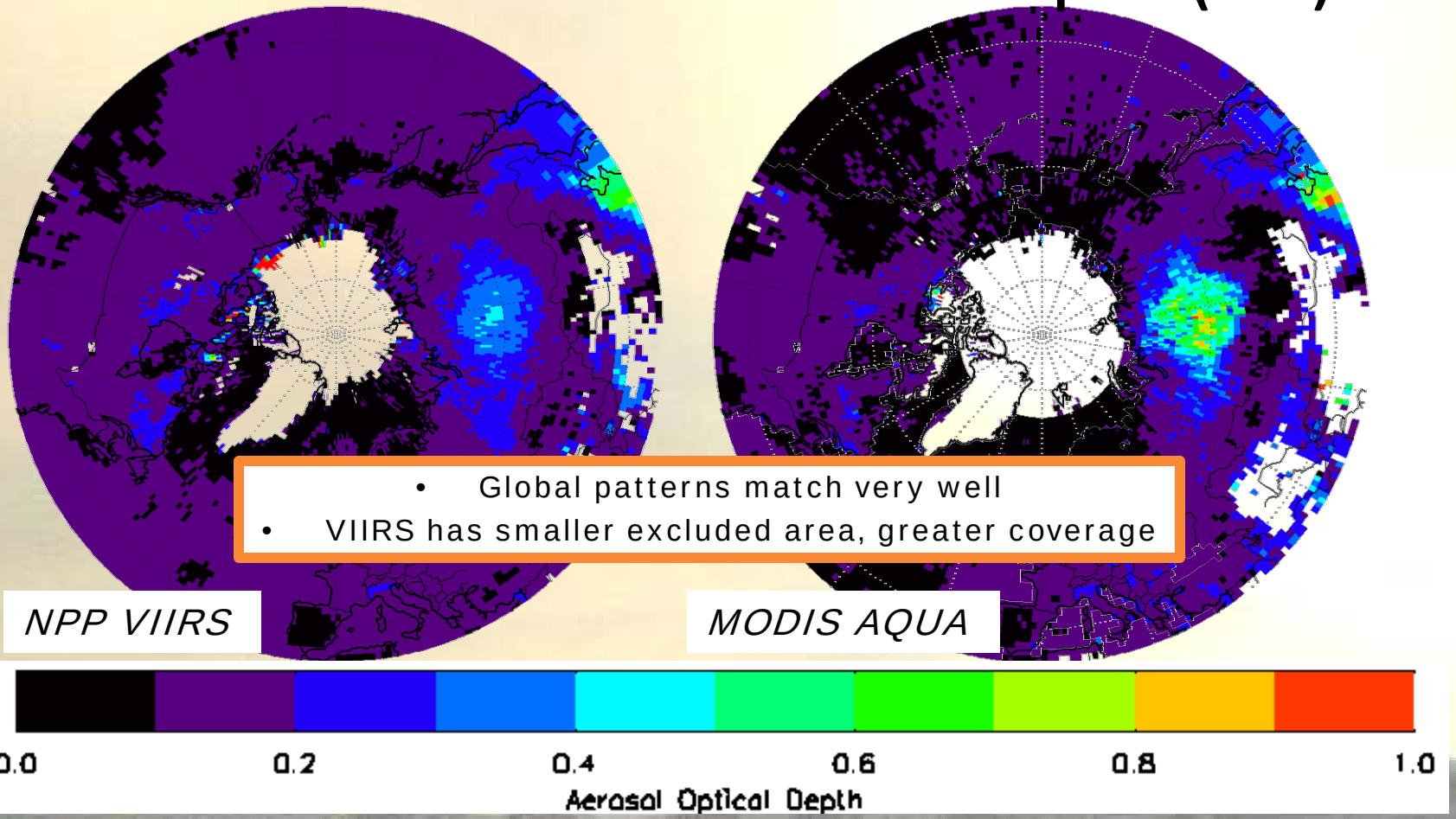
Stage 3: L3 comparisons of gridded AOD products

- Compare VIIRS after QA/QC with MODIS after QA/QC
- Compare VIIRS+MODIS AOD to MODIS-only
- **PROS:**
  - Products can be evaluated separately and jointly
  - Effects on assimilation system can be inferred by directly testing coverage and consistency
  - Effects of data filtering can be quickly examined
- **CONS: No ground truth.**
  - This analysis is less useful for diagnosing the retrievals' behavior.

NPP VIIRS pre-processor

- 1-degree, 6-hour
  - **Operational NAAPS now 1/3°**, 1° used for testing
- "fullQA" uses information packaged with EDR granules
  - QA = 'Good' (highest EDR QA value)
  - Cloud mask, cloud proximity, snow flags, glint flags
  - No textural filtering (this is a cal/val experiment, not an operational candidate)
- Results shown using 12 months of data
  - 2013.01.24.00 to 2014.01.12.00

VIIRS ‘fullQA’ AOD vs NRL-UND Level 3 MODIS-Aqua (C5)



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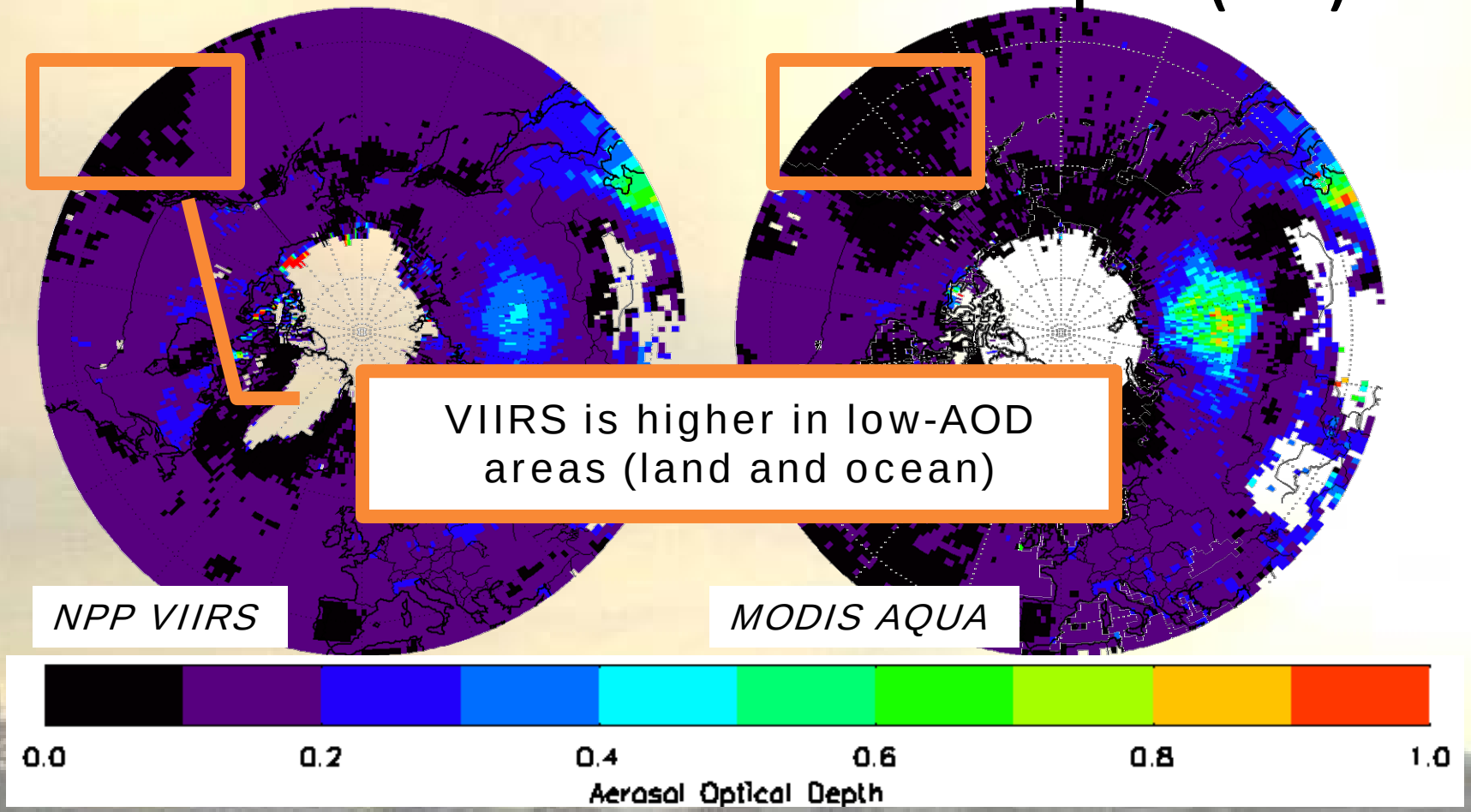

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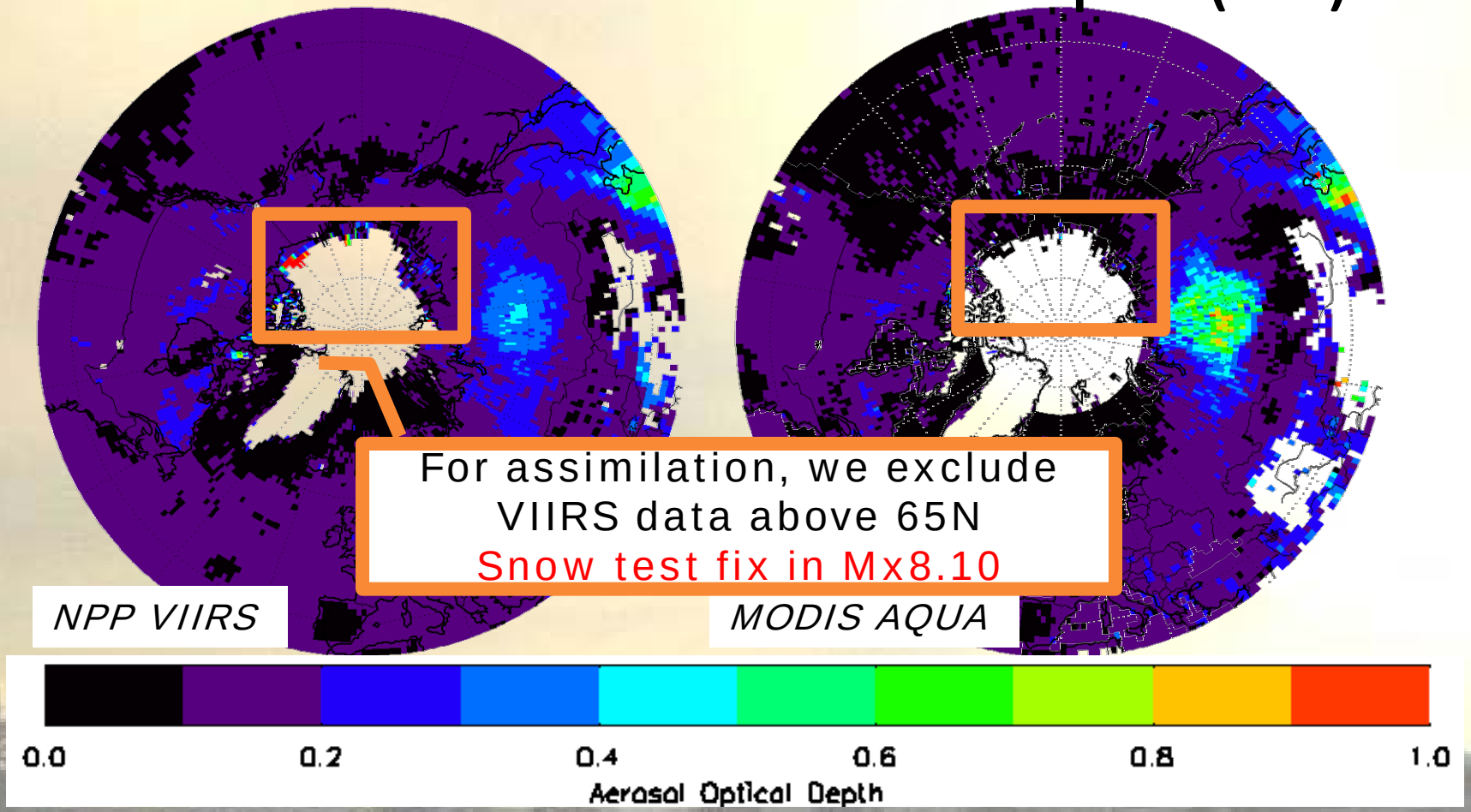

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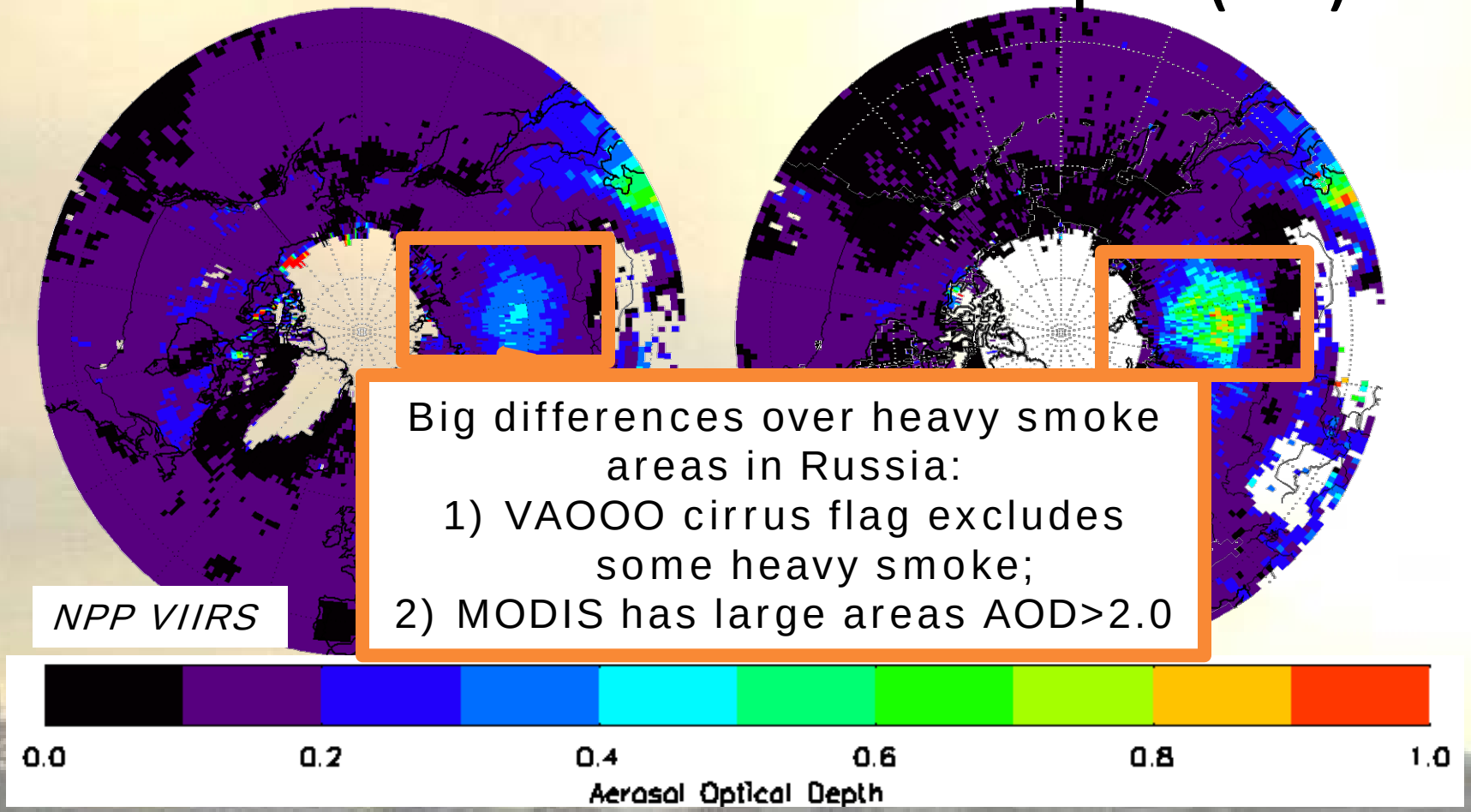
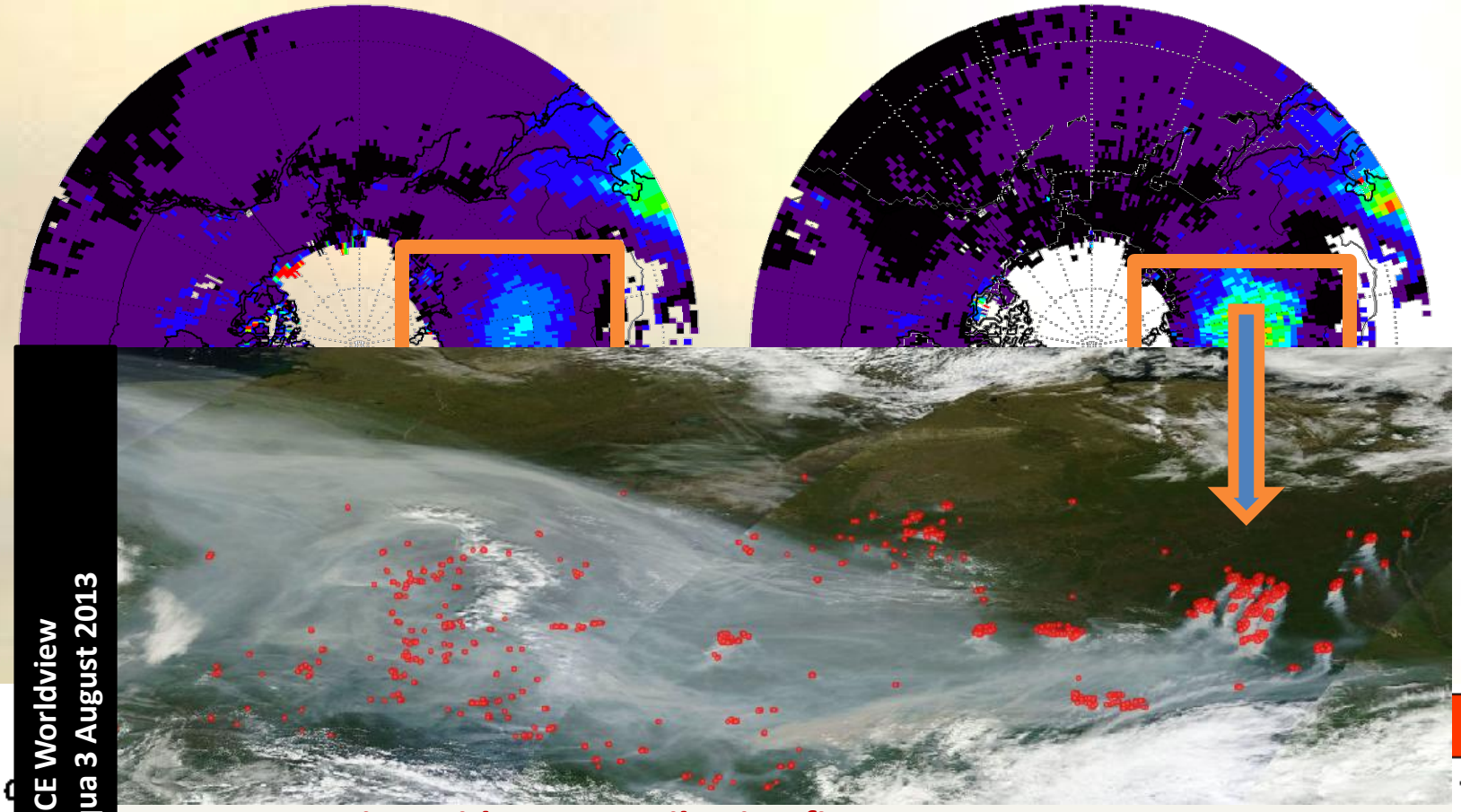
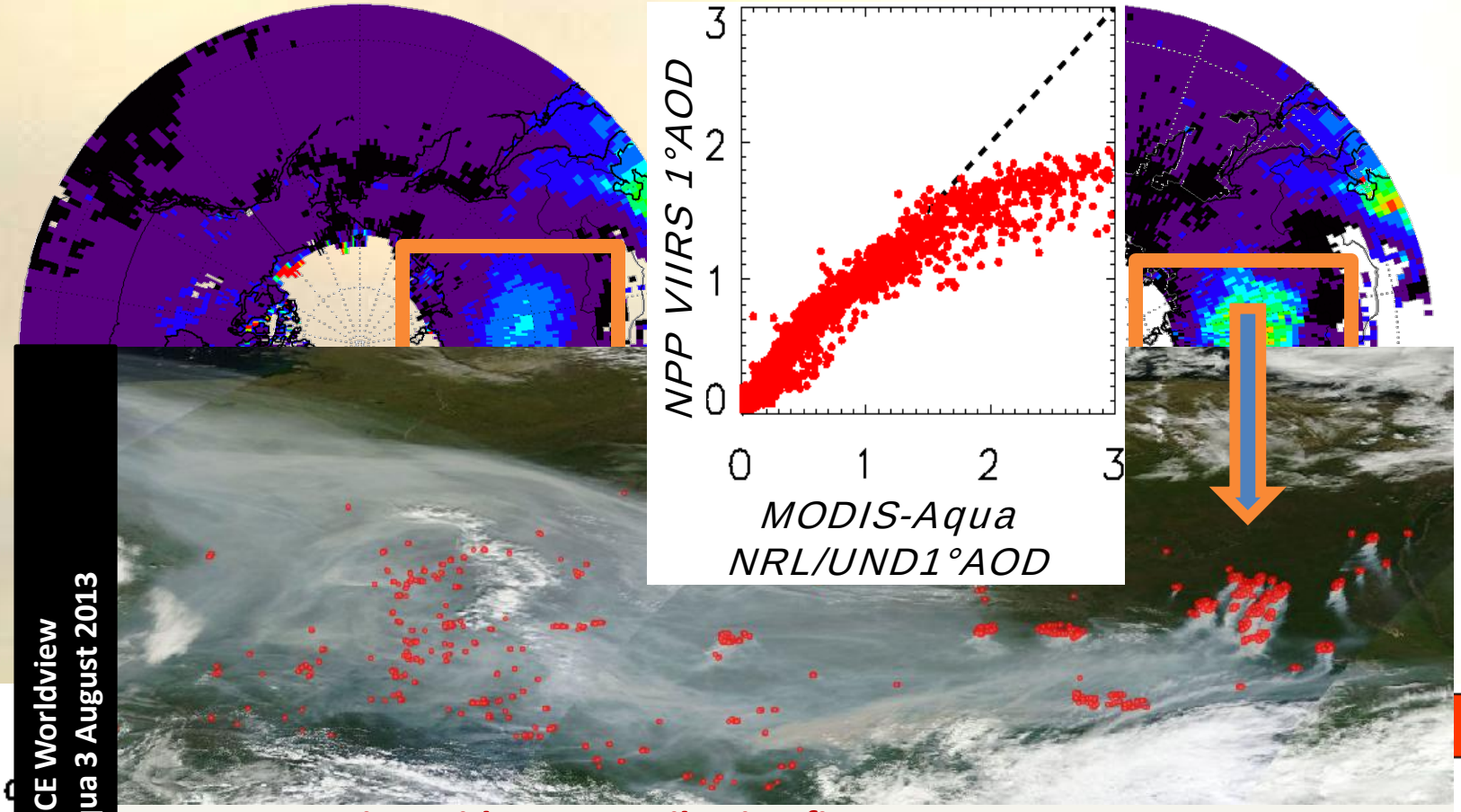


Differences over heavy smoke



- **Massive midsummer Siberian fires**
- **Episodic, intense plumes**
- **VIIRS truncation causes big differences**

Differences over heavy smoke

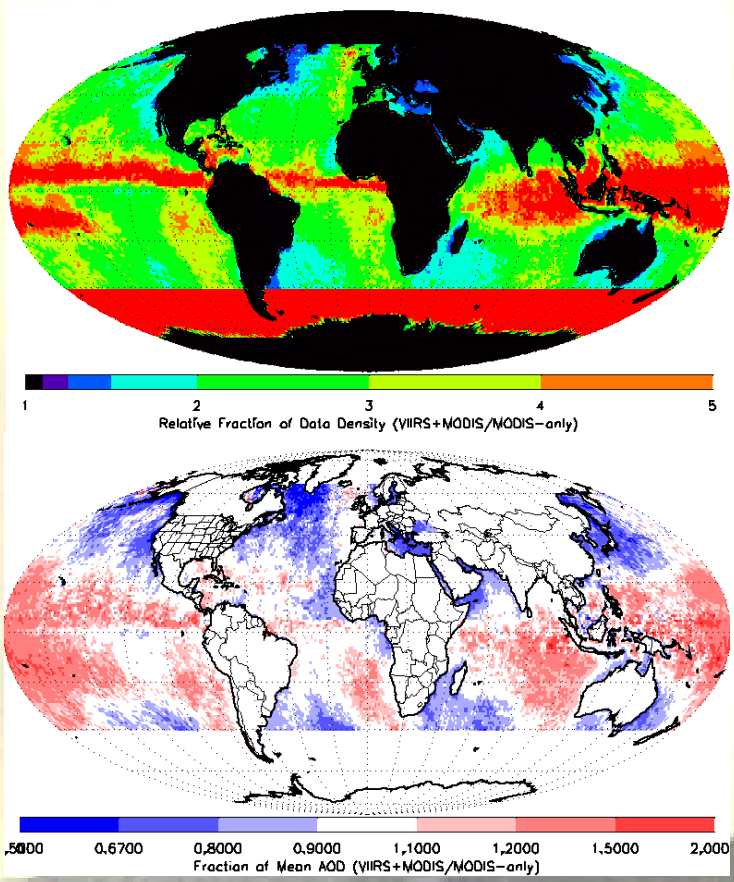


- **Massive midsummer Siberian fires**
- **Episodic, intense plumes**
- **VIIRS truncation causes big differences**

Stage 3: L3 comparisons of gridded AOD products (ocean-only)

- (Top) Data density of VIIRS+MODIS/MODIS shows dramatic increases in data availability near the ITCZ. Solid red area below 40S reflects exclusion of that area in NRL/UND MODIS AOD product.
- (Bottom) Fractional change in mean observed AOD for VIIRS+MODIS/MODIS
  - decreased AOD over high-latitude oceans
  - increased AOD near the equator.

Increased availability of data in partially cloudy regions is an expected consequence of higher spatial resolution; however, the cloud filtering in the NRL-UND MODIS L3 product is very strict, and it is likely that cloud proximity effects contribute to the VIIRS AOD in the ITCZ region.



After Stage 3, an aerosol analysis is generated with NAVDAS-AOD

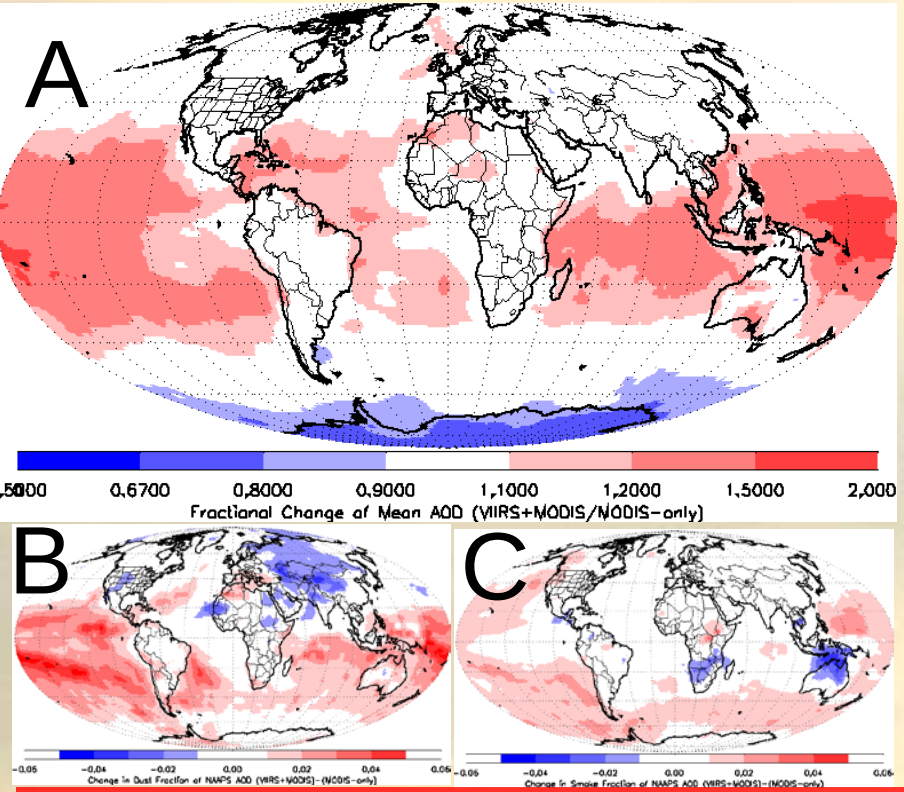
- Cycling runs combine 6-hour NAAPS forecasts with NAVDAS-AOD analysis
- Can be easily run for multiple months/years
- All run properties are identical except AOD data input to NAVDAS-AOD
  - MODIS-only (current NAAPS operational setup)
  - MODIS+VIIRS
  - These results use only over-ocean VIIRS AOD

Stage 4: comparison of analyzed aerosol fields from NAAPS

An aerosol re-analysis is generated using NAAPS including cycling assimilation of one or both AOD datasets. This results in a continuous global field of aerosol properties reflecting the information content of the AOD datasets.

- **PROS:**
  - Allows examination of spreading of information in space and time
  - Allows examination of model consequences of AOD data choices
- **CONS:**
  - Analysis is weakly linked to AOD retrieval.
  - Analysis contaminated by biases in underlying model sources/sinks.
  - Effects of AOD values and AOD observation density convolved.

Stage 4: comparison of analyzed aerosol fields from NAAPS



(A) Fractional change of mean NAAPS AOD, (MODIS+VIIRS)/(MODIS-only)

- VIIRS observations near the equator are clearly seen to increase optical depths throughout the tropical oceans.
- VIIRS observations in the southern oceans reduce analyzed AOD values over Antarctica
  - Note: absolute concentrations are low over Antarctica in all analyses.

(B-C) Effect of VIIRS data on the fraction of NAAPS AOD from dust (B) and smoke (C).

- Addition of aerosol mass in tropical ocean manifests as increase in dust fraction

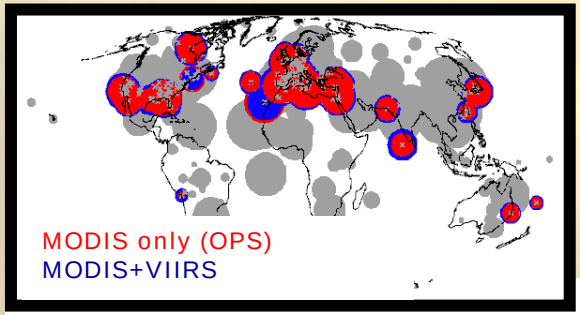
Interactions between the assimilated AOD observation density and the biases of the native NAAPS model source functions result in imbalances in aerosol composition. **For instance, a greater number of observations during the burning season in southern Africa, which is overestimated by the FLAMBE smoke source used in NAAPS, will bring down the AOD in that region and reduce the smoke AOD contribution in the annual average.**

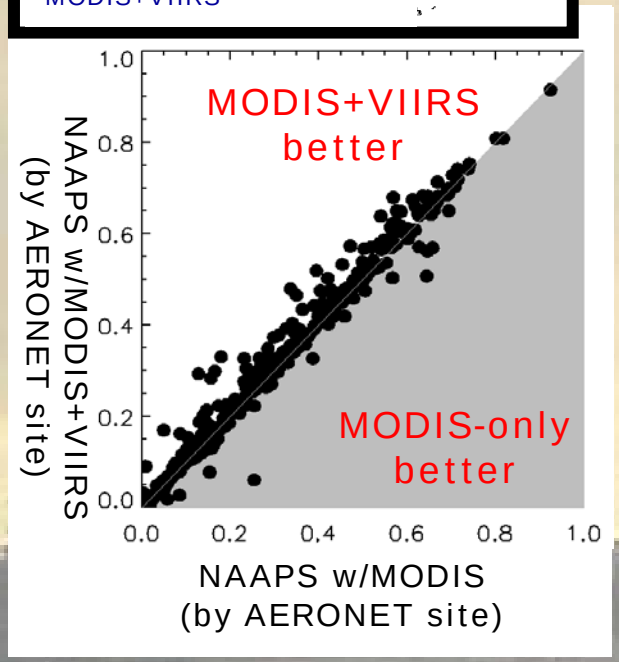
Stage 5: Comparison of NAAPS analyzed AOD to AERONET

- NAAPS analyzed AOD is compared to AERONET for model verification
- This is our final determination if assimilation of AOD data is making NAAPS “better” or “worse”
- **PROS:**
  - Ground truth—a better match to AERONET is a better analysis/forecast
    - (assuming you are not assimilating AERONET)
- **CONS:**
  - This analysis does not provide much insight into the details of the model processing and the AOD data.

VIIRS Over-ocean NAAPS assimilation test results

AOD Correlation (r^2) at AERONET stations





VIIRS over-ocean AOD assimilation tests

- VIIRS processing
  - All in-granule quality flags
  - Buddy check
  - Cloud proximity check
  - Textural filtering
- NAAPS AOD analysis results:
  - VIIRS+MODIS better than MODIS only
  - RMSE reduced at 234 of 399 AERONET stations (not shown)
  - correlation (r2) vs AERONET L1.5 increased at 272 of 399 stations
    - Colored symbols on map indicate stations where r2 differed by more than 0.05
  - VIIRS data have positive bias, driving up NAAPS AOD
    - Sites that had low bias got better, sites with high bias got worse
    - With stronger filtering, it should be possible to reduce this effect

Results and Next Steps

- Operational implementation of VIIRS assimilation
- Testing of new VIIRS data products, especially over land
- Thank you!!
  - Sponsors: JPSS, NASA AQAST, NRL
  - JPSS Aerosol Cal/Val Team

Backup Slides

VIIRS Aerosol Products (1)

- **Aerosol Optical Thickness (AOT)**
  - for 11 wavelengths (10 M bands + 550 nm)
- **APSP (Aerosol Particle Size Parameter)**
  - Ångström Exponent derived from AOTs at M2 (445 nm) and M5 (672 nm) over land, and M7 (865 nm) and M10 (1610 nm) over ocean
  - qualitative measure of particle size
  - over-land product is not recommended!
- **Suspended Matter (SM)**
  - classification of aerosol type (dust, smoke, sea salt, volcanic ash) and smoke concentration
  - currently, derived from VIIRS Cloud Mask (volcanic ash) and aerosol model identified by the aerosol algorithm
- **Only day time data**
- **Only over dark land and non-sunglint ocean**

VIIRS Aerosol Products (2)

At NOAA Comprehensive Large Array-data Stewardship System (CLASS):

- **Intermediate Product (IP)**
  - 0.75-km pixel
    - AOT, APSP, AMI (Aerosol Model Information)
      - land: single aerosol model
      - ocean: indexes of fine and coarse modes and fine mode fraction
    - quality flags
- **Environmental Data Record (EDR)**
  - 6 km aggregated from 8x8 IPs filtered by quality flags
    - granule with 96 x 400 EDR cells
    - AOT, APSP, quality flags
  - 0.75 km
    - SM

At NOAA/NESDIS/STAR:

- **Gridded 550-nm AOT EDR**
  - regular equal angle grid: 0.25°x0.25° (~28x28 km)
  - only high quality AOT EDR is used

VIIRS EDR vs MODIS L2 Aerosol Products

	Aqua-MODIS	Suomi NPP-VIIRS
Swath Width	2330 km	3000 km
Sensor bands used for aerosol retrieval.	0.411, 0.466, 0.554, 0.646, 0.856, 1.242, 1.629, 2.114 µm	0.412, 0.445, 0.488, (0.550), 0.555, 0.672, 0.746, 0.865, 1.24, 1.61, 2.25 µm
Pixel size, nadir	0.5 km	0. 75 km
Pixel size, edge of scan	2 km	1.2 km
Product resolution, nadir	10x10 km (20x20 500m pixels)	6x6 km (8x8 750m pixels) (AOT and Angstrom exponent)
Product resolution, scan edge	40x20 km	12.8x12.8 km

Compared with MODIS, VIIRS has:

- Improved coverage: gap-free daily observation around the globe
  - enabled by the wider swath
- Improved spatial characteristics Swath-edge pixels are 2x nadir, vs 4x for MODIS

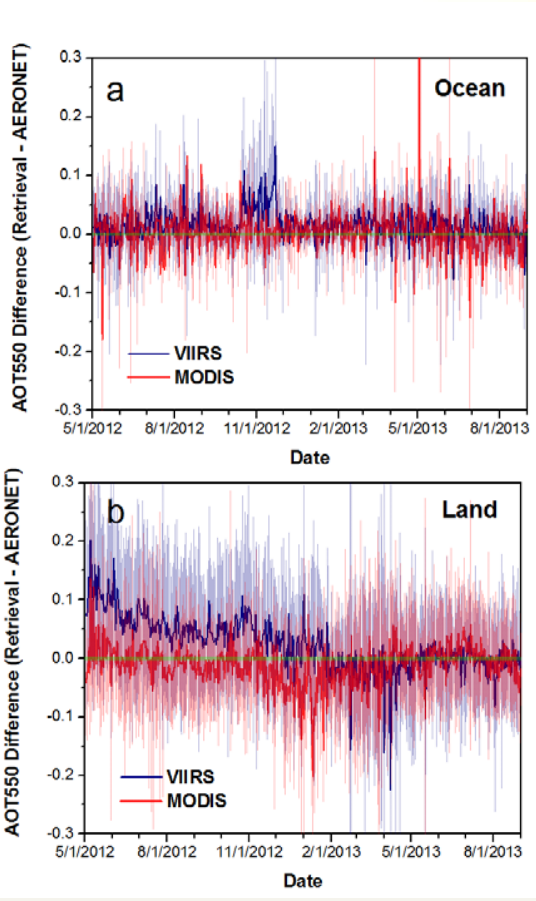
- Algorithm Differences:
- Retrieval of AOD is done at the pixel level: aggregation of AOD values is done to produce the EDR product.
- Over-land algorithm (like MOD09 atmospheric correction) retrieves a single aerosol model, a mix of fine and coarse; over-ocean algorithm (like MOD04) retrieves fine and coarse mode properties separately.

VIIRS Aerosol Resources

- **Two peer-reviewed publications**
  - Jackson et al. JGR 2013
  - Hongqing Liu et al. JGR 2014
- **NOAA VIIRS Air Quality Workshop (from 2013):** http://alg.umbc.edu/aqpg/viirs_workshop/
  - Many useful talks, special notice to talk by Rohit Mathur (EPA) on satellite products and AQ models
- **VIIRS aerosol user's guide and fully revised ATBD** (technical description): http://www.star.nesdis.noaa.gov/smcd/emb/viirs_aerosol/documents.php

VIIRS Aerosol Cal/Val

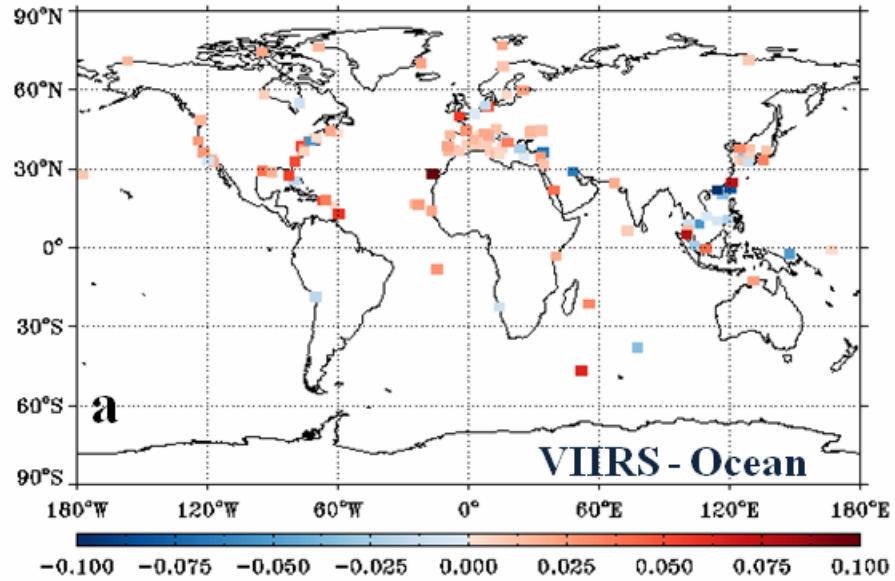
- AERONET sun photometers are the gold standard
  - Accuracy and precision exceed what is expected even from the best satellite products
  - Data should not be used uncritically in regions with thin cirrus (Chew et al. *Atm. Env* 2011; Huang et al. *JGR* 2011*)*
- Right: time series of AERONET vs VIIRS AOD (blue) and MODIS-Aqua C5 AOD (red) over ocean (top) and land (bottom).
  - Evolution of VIIRS algorithm (blue) can be seen
  - MODIS Collection 5 (red) and VIIRS have similar accuracy after 1/24/2013

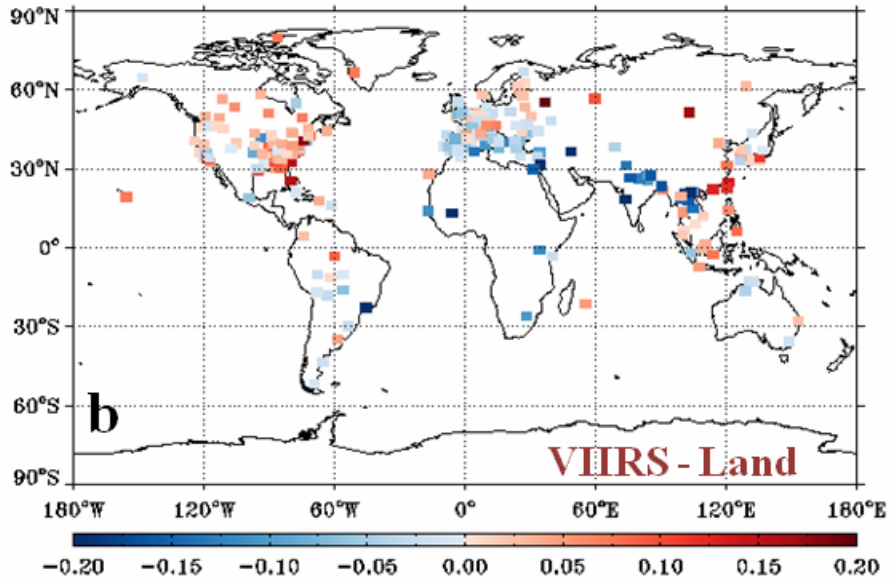


Hongqing Liu et al., *JGR* 2014

VIIRS Aerosol Cal/Val

- VIIRS and MODIS ocean retrievals have similar errors vs AERONET
- Pattern of biases over land is very different for VIIRS vs MODIS Collection 5
- MODIS Collection 6 (now in production) has reduced biases over land (Levy et al. *ACP* 2013), different patterns from VIIRS





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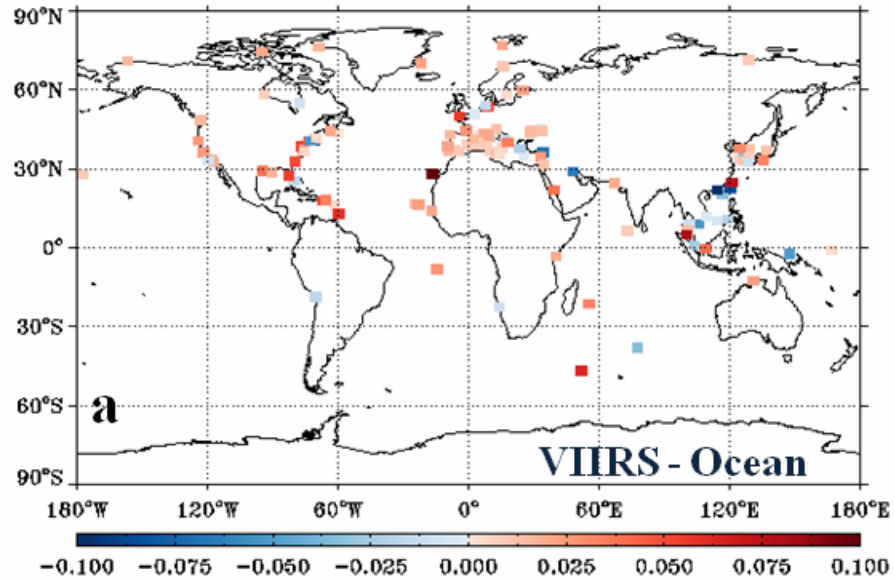

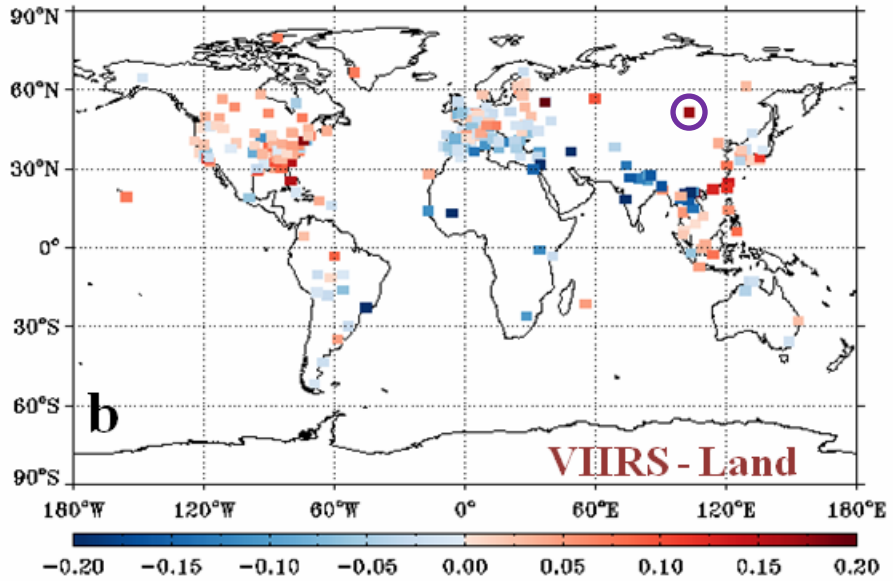

Hongqing Liu et al., *JGR* 2013