The development of OMI aerosol index assimilation capability for aerosol analyses over bright surfaces

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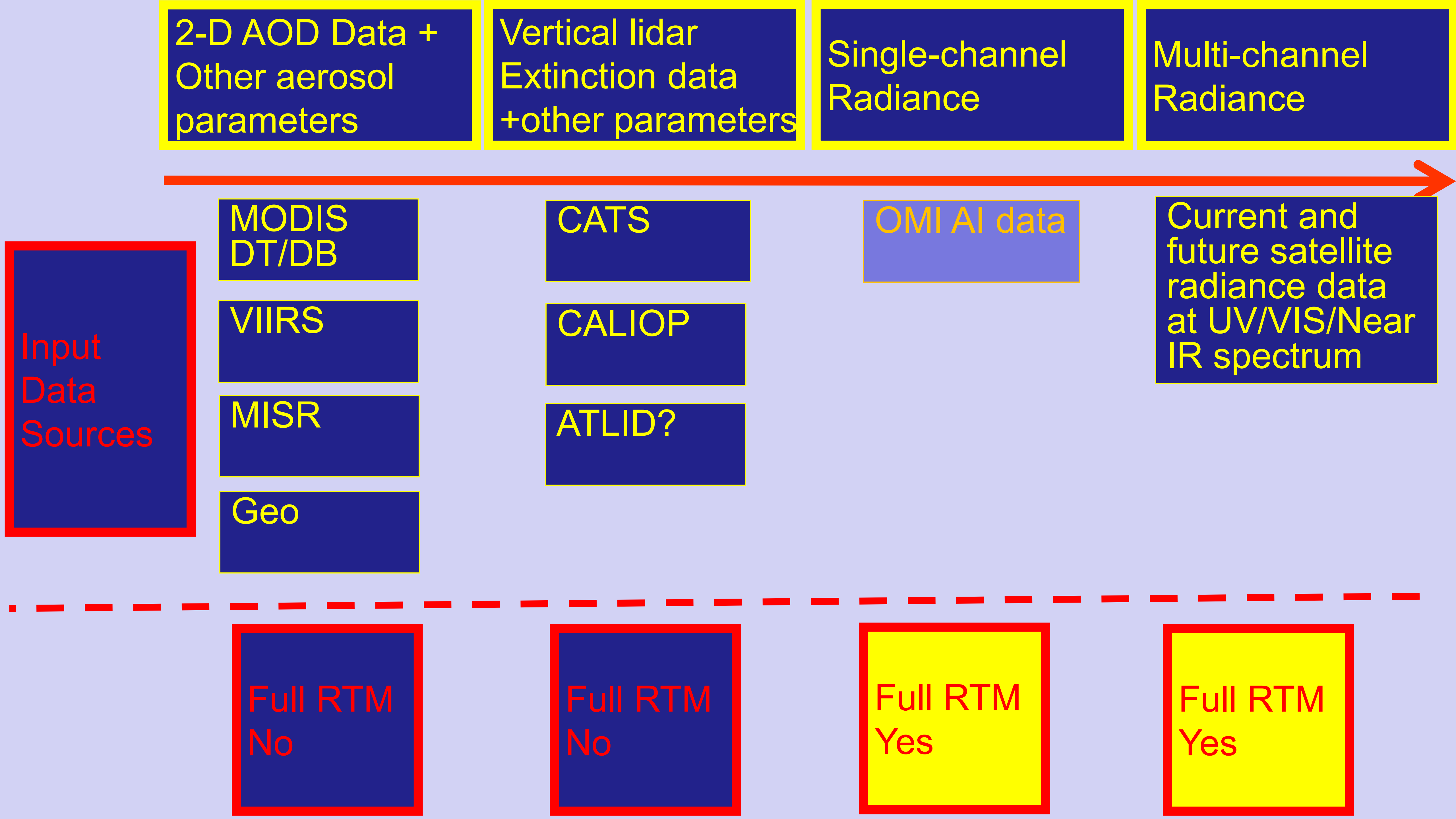


2-D AOD Data + Other aerosol parameters
Vertical lidar Extinction data +other parameters
Single-channel Radiance
Multi-channel Radiance
Input Data Sources
MODIS DT/DB
VIIRS
MISR
Geo
CATS
CALIOP
ATLID?
OMI AI data
Current and future satellite radiance data at UV/VIS/Near IR spectrum
Full RTM No
Full RTM No
Full RTM Yes
Full RTM Yes

Required ingredients for radiance assimilation at the UV/VIS spectrum

- A forward model that simulates TOA UV/VIS/Near IR radiances. Needs wavelength dependent information of:
  - Surface BRDF or non-BRDF reflectance as a function of geo-location
  - Aerosol physical and optical properties
    - Vertical distributions
    - Absorbing and scattering coefficients
    - Phase function / scattering matrices
  - Molecular absorption & scattering
  - A full-blown radiative transfer model for forward modeling + Jacobian calculations
- Aerosol transport model
- Assimilation system

Advantages of OMI AI data assimilation

- Satellite retrieved aerosol properties are routinely used operationally for improving aerosol analysis and forecasts.
  - Limited data are available over other bright surfaces such as desert and cloudy regions
  - Over the Arctic region, however, there is no data for AOD assimilation from either passive- or active-based sensors.
- Observations from OMI have been used to derive aerosol related quantities such as aerosol index over bright surfaces.
- Thus, a radiance-based data assimilation system has been developed that is capable of directly assimilating OMI AI over data-denied bright surfaces (desert and snow/ice covered regions) for NAAPS

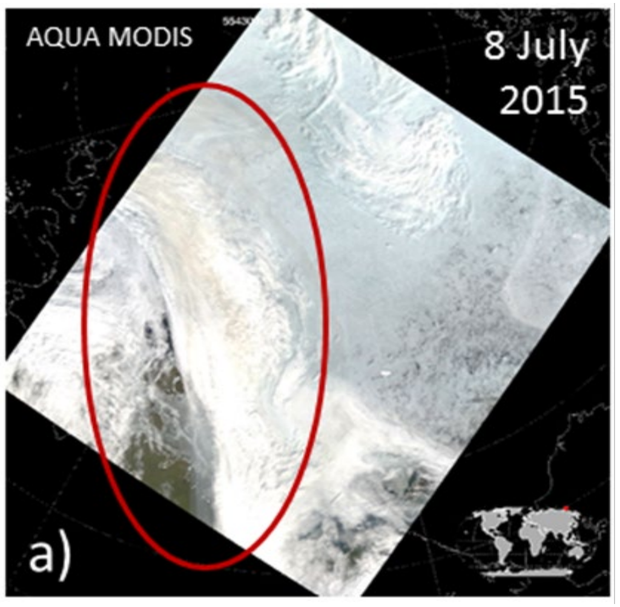
- It is also among the first attempts at radiance assimilation in the UV spectrum

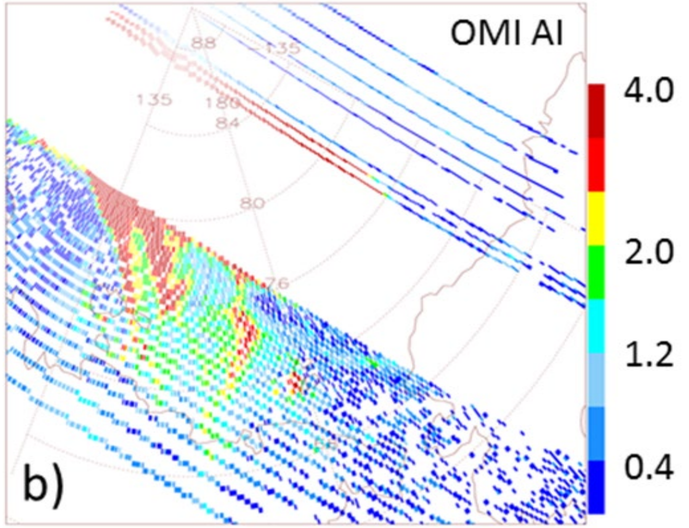
Use OMI aerosol index as an alternative data source for aerosol modeling over bright surfaces

- Aerosol index is defined by the ratio of observed radiance at 354 nm (I_{obs354}) and calculated radiance (I_{cal354}) at 354 nm for a Rayleigh (no aerosol) atmosphere (e.g. Torres et al., 2007).
- AI is sensitive to UV absorbing aerosols over dark and bright surfaces.

$$AI = -100\, log_{10} \frac{I_{obs354}}{I_{cal354}}$$

- Developed a radiance-assimilation-based AI data assimilation system for directly assimilating OMI AI into NAAPS over bright surfaces (e.g. deserts and the Arctic region). Tested over the North Africa region (Zhang et al., 2021) and conducted preliminary studies over the Arctic region.
- Additional data streams can be added, inducing data from TROPOMI, OMPS, and the PACE mission.





Datasets and models

— **Radiative transfer for the forward model:**

Vector LInearized Discrete Ordinate Radiative Transfer (VLIDORT)

— **Aerosol transport model:**

Naval Aerosol Analysis and Prediction System (NAAPS)

V1 NAAPS reanalysis

— **Assimilation system:**

Modified from the 3-D version of the Navy Variational Data Assimilation System for Aerosol (NAVDAS-AOD)

— **Satellite/ground-based data:**

OMI Level 2 UV aerosol products (OMAERUV)

Version 3, level 2 AERONET data

— **Study period:**

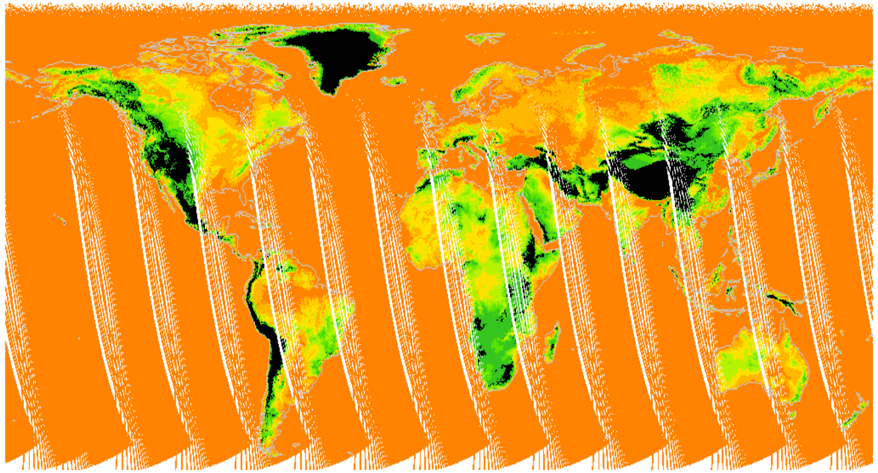
July and August of 2007 (Africa region – desert and cloudy regions)

April 01 – May 20 2008 (Arctic region)

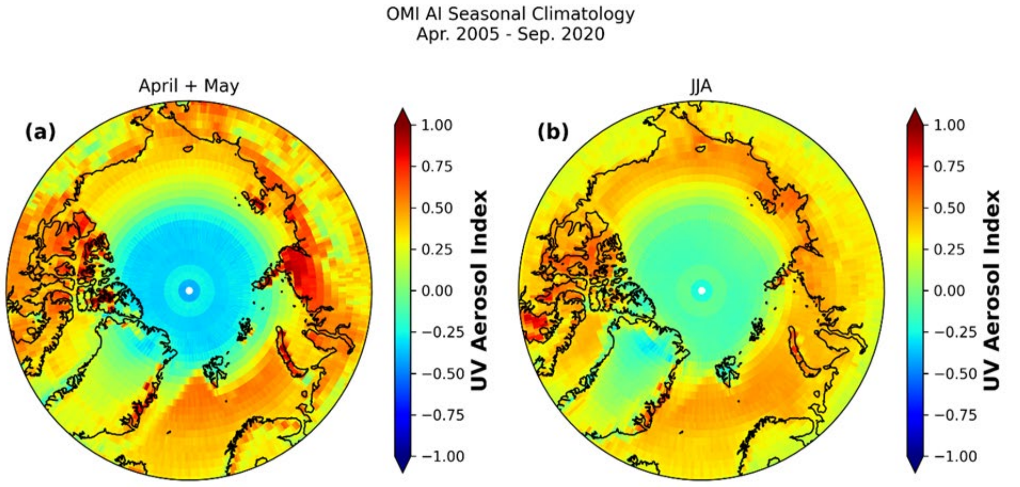
OMI AI data processing

Abnormal high AI values are found over mountainous regions. Also, higher AI values are found near Arctic region. For DA applications, bias reduced and noise removed AI data are needed. QA steps over non-Arctic region include:

- Removal of row anomalies using QA flag
- Pressure > 850 hPa
- AI > 0.1
- Applied low pass filter to remove noisy retrievals
- OMI AI and observing conditions are binned into 1x1° Lat/lon data.
- Additional screening steps were applied for the Arctic region as mentioned later
- **Both cloud free and cloudy retrievals are included.**

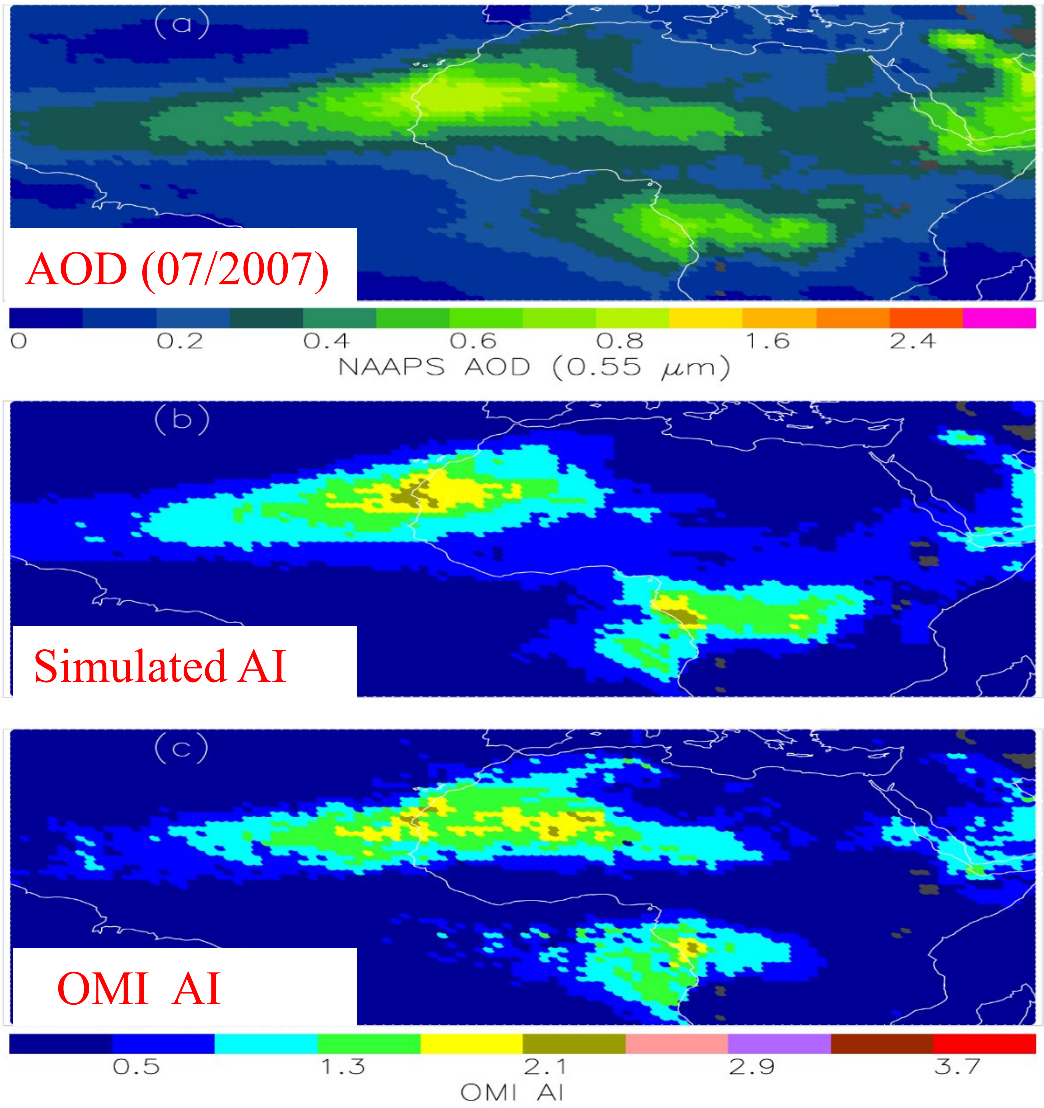


Example of pressure field for April 27, 2008. Regions with surface pressure less than 850 hpa are color in black



Aerosol Index data assimilation system -- Forward model

- A forward model is constructed using the Vector LInearized Discrete Ordinate Radiative Transfer (VLIDORT) to simulate OMI AI using NAAPS aerosol concentrations and surface properties from the OMI dataset.
- VLIDORT is configured to compute OMI radiances and aerosol concentration Jacobians as functions of the observational conditions at 354 and 388 nm.
- The optical properties of ABF, sea salt, dust and smoke aerosols at 354 and 388 nm are adapted from NASA's Goddard Earth Observing System version 5 (GEOS-5) model (e.g. Colarco et al., 2014; Buchard et al., 2015).



Zhang et al., 2021

AI data assimilation system -- Forward model

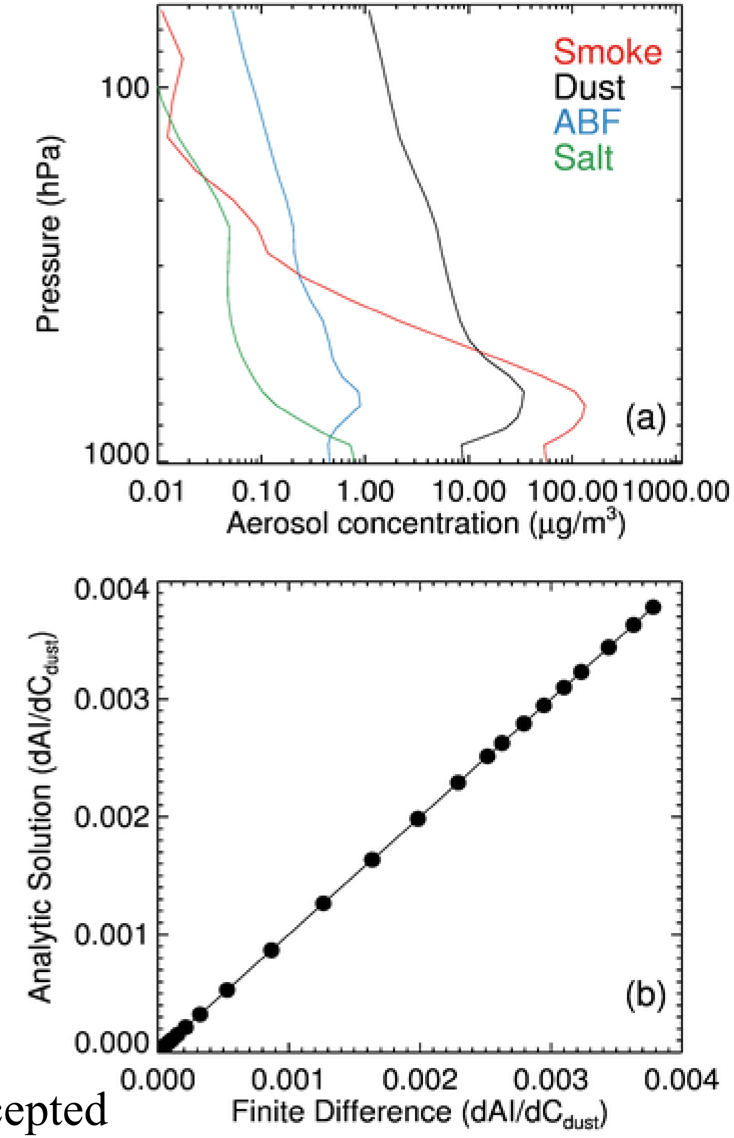
- Jacobians of OMI AI with respect to aerosol mass concentrations are calculated from radiance Jacobians with respect to aerosol mass concentrations for four aerosol species (smoke, dust, ABF/sulfate, sea-salt) at 354 nm ($K_{354,nk} = \frac{\partial I_{aer354}}{\partial M_{nk}}$) and 388 nm ($K_{388,nk} = \frac{\partial I_{aer388}}{\partial M_{nk}}$) wavelengths. The analytic solution is computed by:

$$\frac{\partial AI}{\partial M_{nk}} = \mathcal{A}_1 K_{354,nk}(\rho_{354}) - \mathcal{A}_2 K_{388,nk}(\rho_{388})$$

$$\mathcal{A}_1 = \left(-\frac{100}{I_{aer354}(\rho_{354})\times \ln 10}\right)$$

$$\mathcal{A}_2 = \left(-\frac{100}{I_{ray354}(R'_{388}) \times \ln 10}\right)\frac{\partial I_{ray354}(R'_{388})}{\partial R}\left[\frac{(1-S_b R_{388})^2}{T}\right]$$

- 1 VLIDORT calculation from the analytic solution = near 100 VLIDORT runs from the finite difference method



Zhang et al., 2020; accepted

AI data assimilation system -- The variational OMI AI assimilation system

Two principles underpin the assimilation procedure.

(1) OMI AI is sensitive to UV-absorbing aerosol particles, such as NAAPS smoke and dust.

(2) $AI_{dust} / AI = \Delta AI_{dust} / \Delta AI$

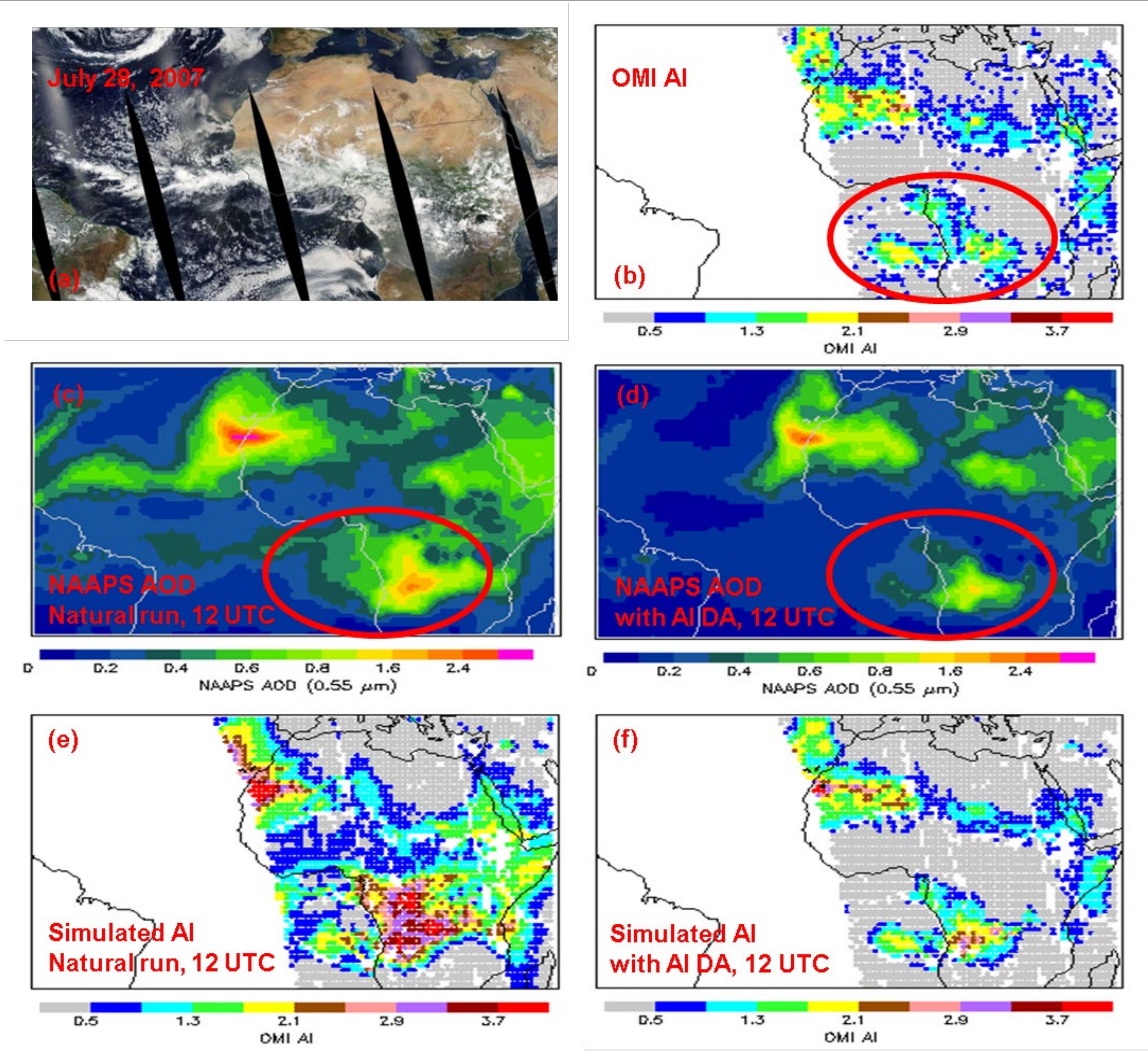
$AI_{smk} / AI = \Delta AI_{smk} / \Delta AI$

Theoretical Basis:

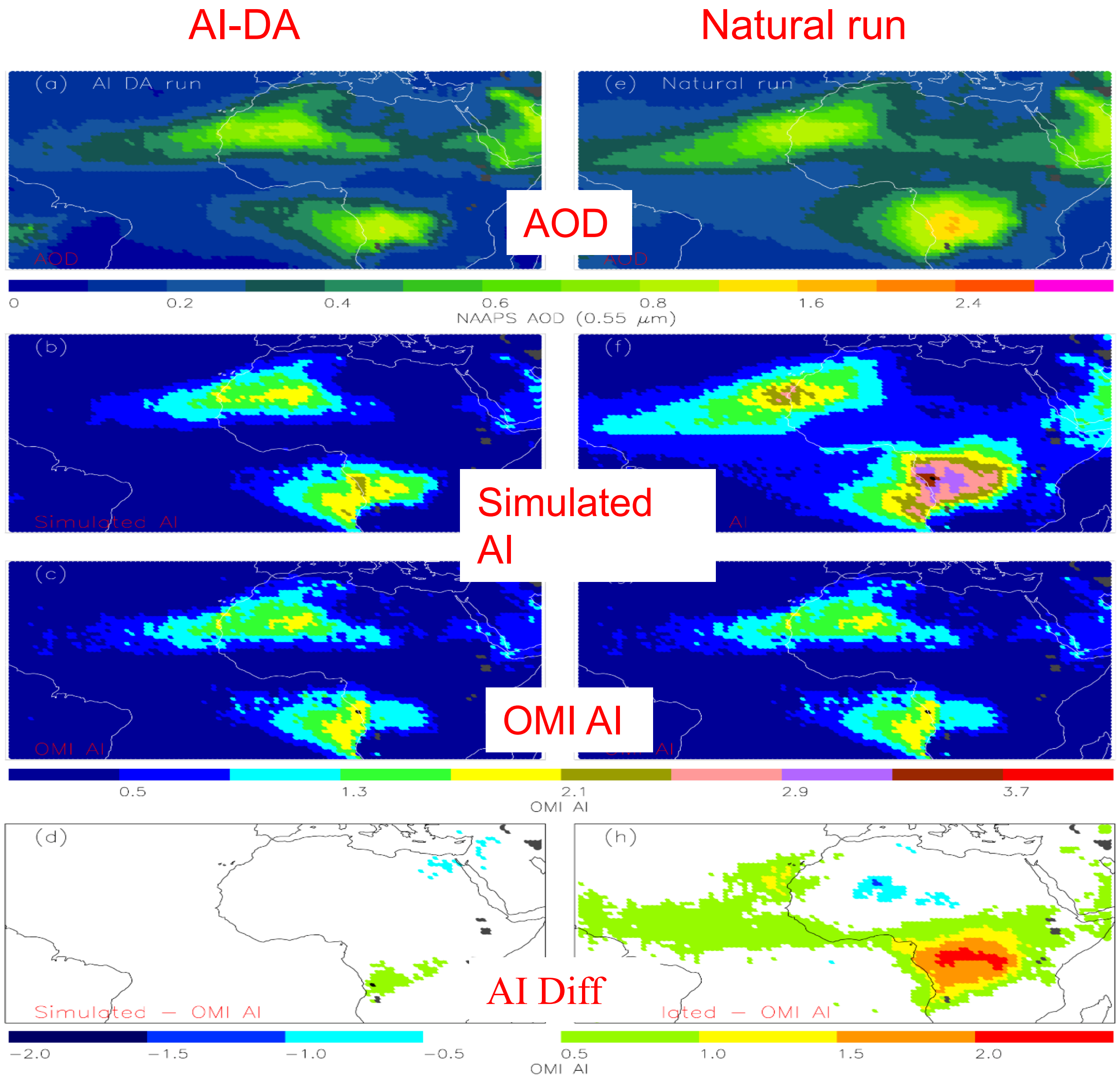
$$C^a = C^b$$

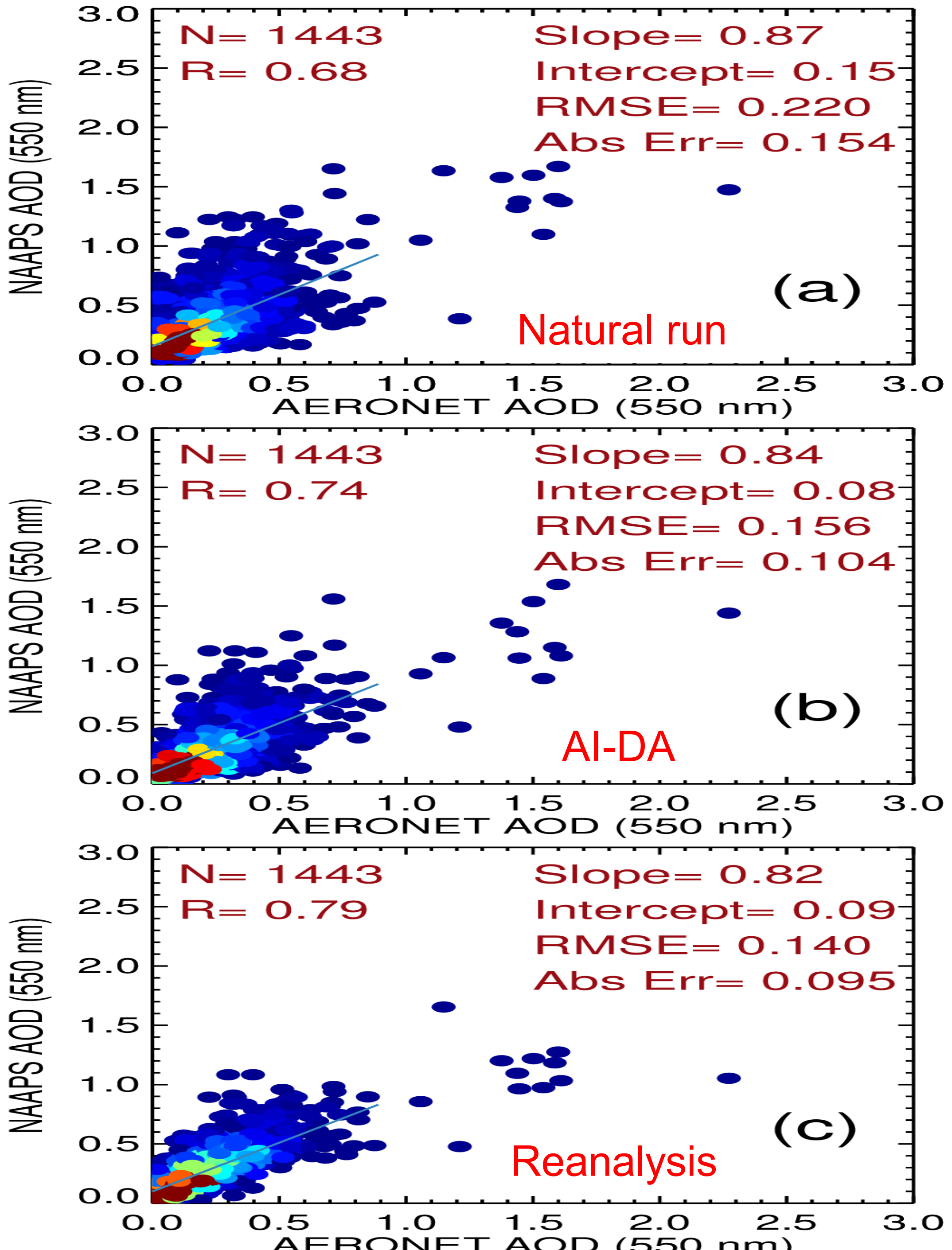
$$+ \frac{P_{dust}\boldsymbol{H}_{dust}^T}{\boldsymbol{H}_{dust}P_{dust}\boldsymbol{H}_{dust}^T + R}[\text{y-H}(C^b)] \times \frac{\boldsymbol{H}_{dust}C_{dust}^b}{\boldsymbol{H}_{dust}C_{dust}^b + \boldsymbol{H}_{smk}C_{smk}^b}$$

$$+ \frac{P_{smk}\boldsymbol{H}_{smk}^T}{\boldsymbol{H}_{smk}P_{smk}\boldsymbol{H}_{smk}^T + R}[\text{y-H}(C^b)] \times \frac{\boldsymbol{H}_{smk}C_{smk}^b}{\boldsymbol{H}_{dust}C_{dust}^b + \boldsymbol{H}_{smk}C_{smk}^b}$$

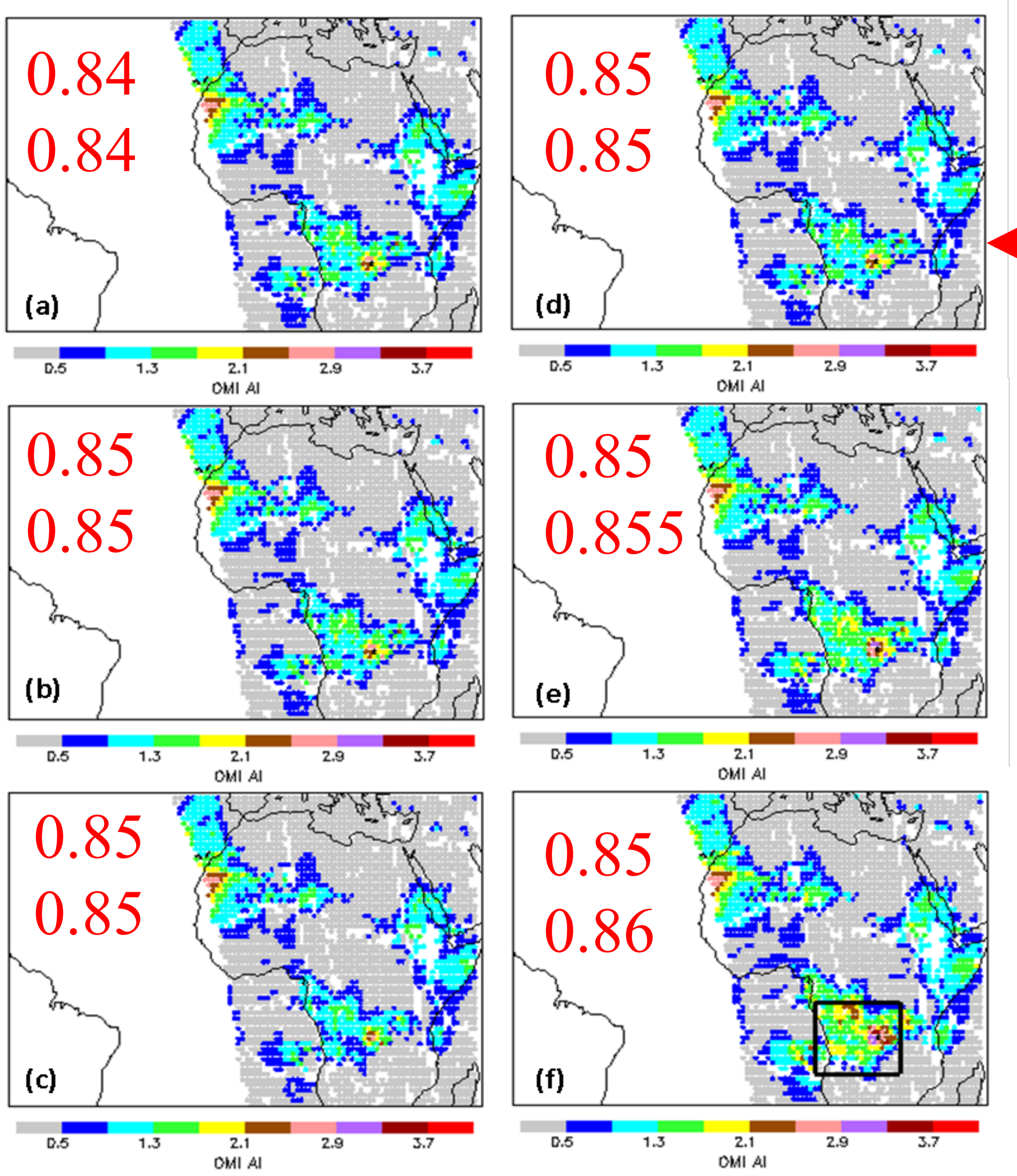


Evaluating the performance of the AI assimilation system over Africa



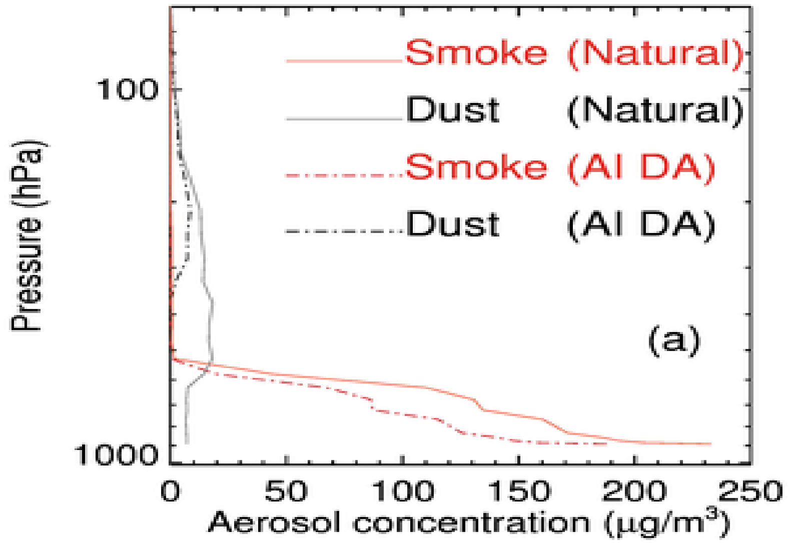


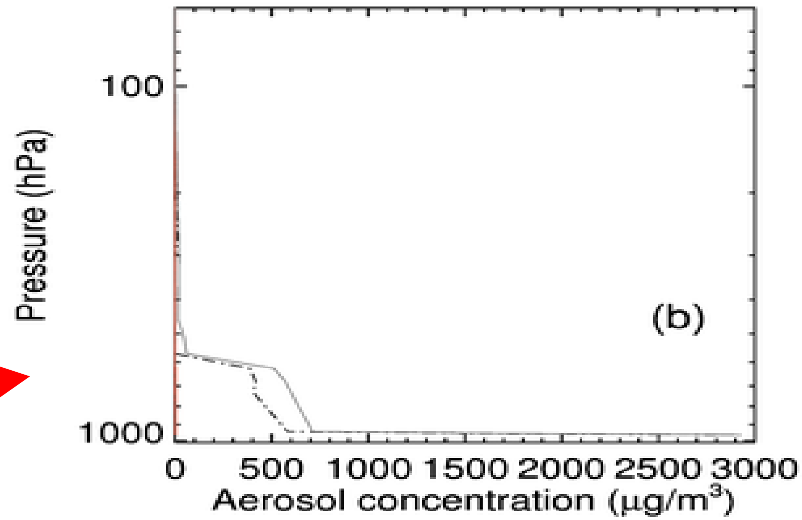
Aerosol Index data assimilation system
Sensitivity test to Single Scattering Albedo (July 28, 12 UTC, 2007)



Fixing the SSA value for the 354 nm channel at 0.85, and perturbing SSA values at 388 nm from 0.85 to 0.86, a ~30% change is found in the value of the simulated OMI AI, but only a ~10% change is found for the NAAPS AOD after OMI AI Data Assimilation.

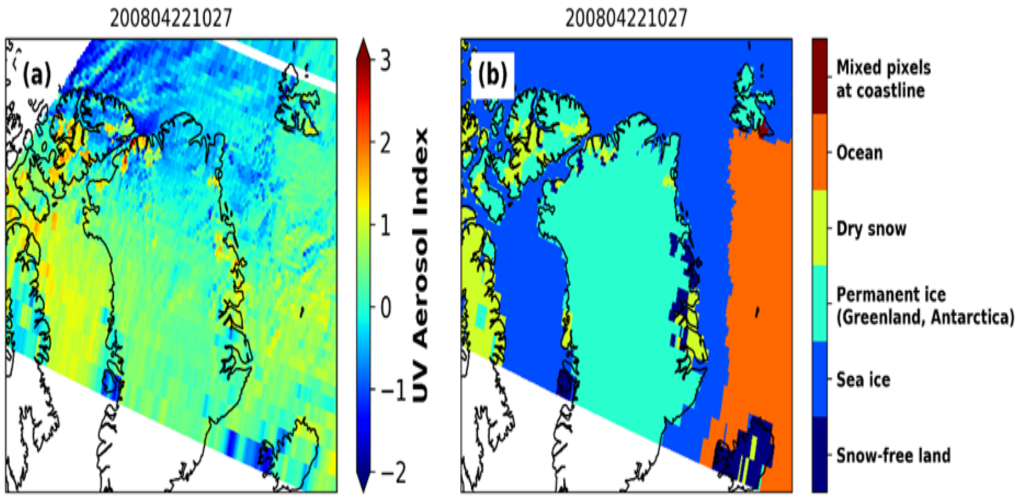
Changes in aerosol vertical distributions due to the OMI AI DA.

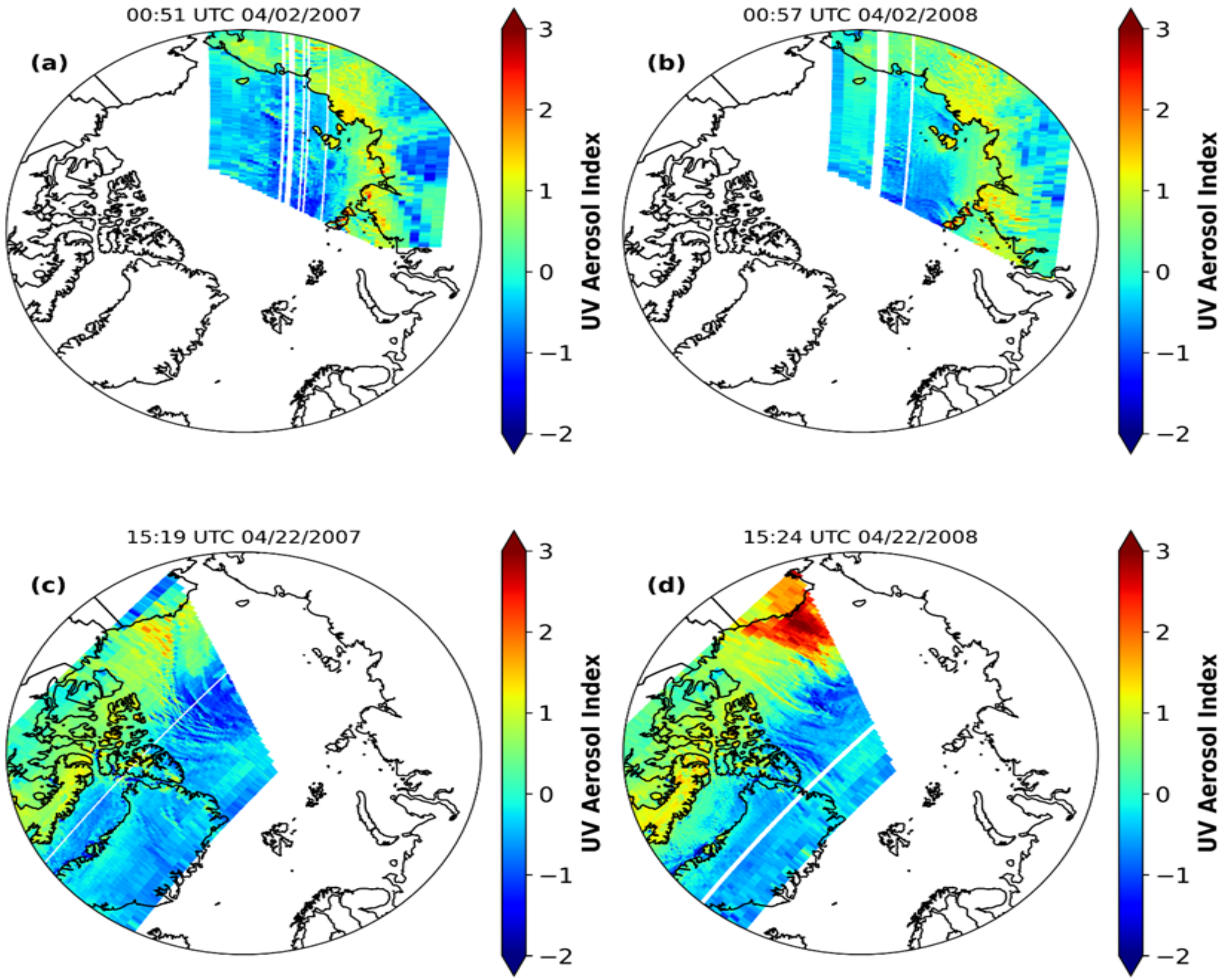




Difficulties faced when using OMI AI data over the Arctic region

- For the same date and similar UTC times, similar high AI (AI > 0.8) patterns are often found over the Arctic region for different years. This indicates that those high AI patterns may not be true UV-absorbing aerosol signals. Those repeatable high AI patterns are strong functions of viewing geometry.

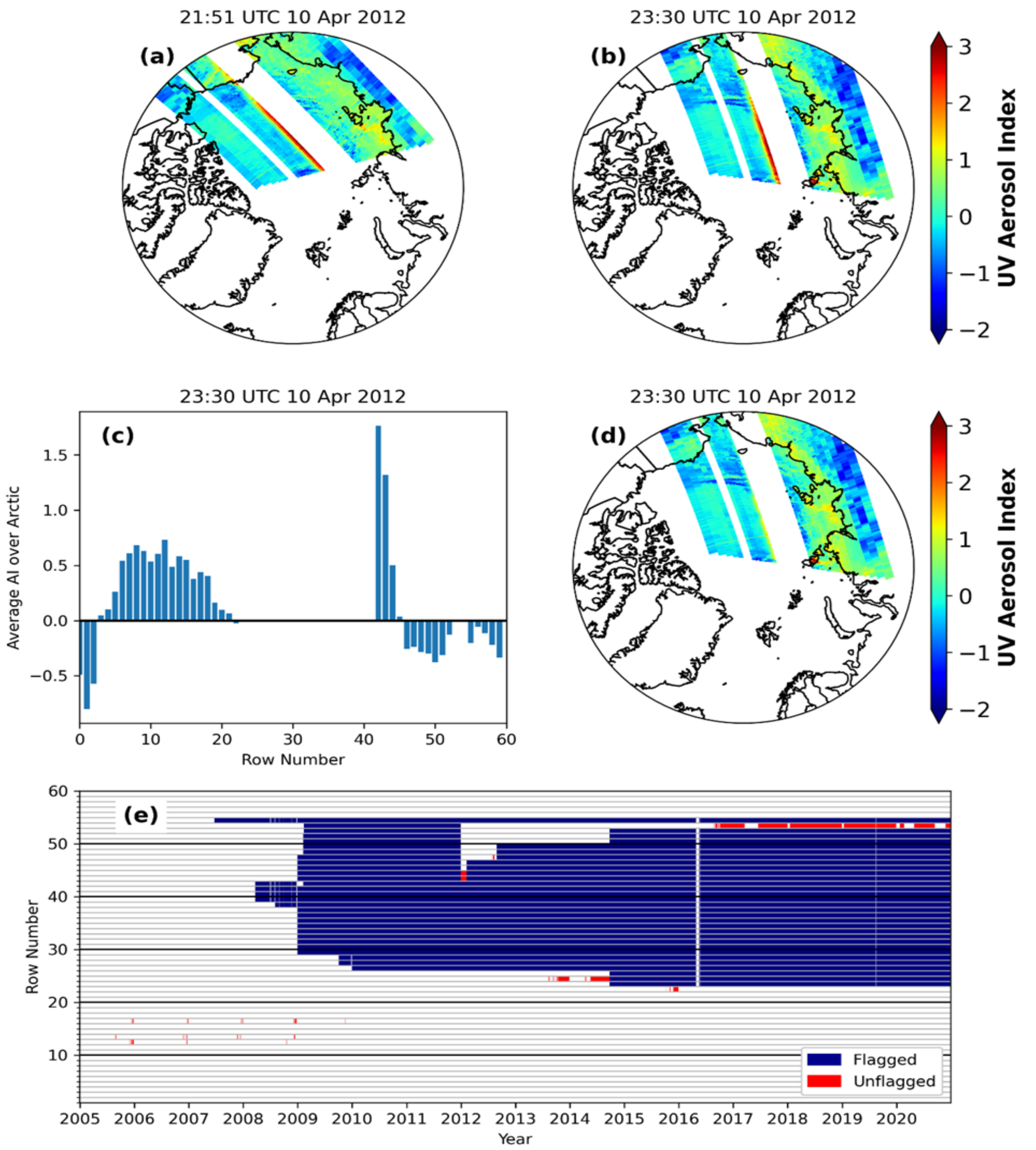




Single swath OMI AI data from a) 00:51 UTC 2 April 2007, b) 00:57 UTC 2 April 2008, c) 15:19 UTC 22 April 2007, d) 15:19 UTC 22 April 2008.

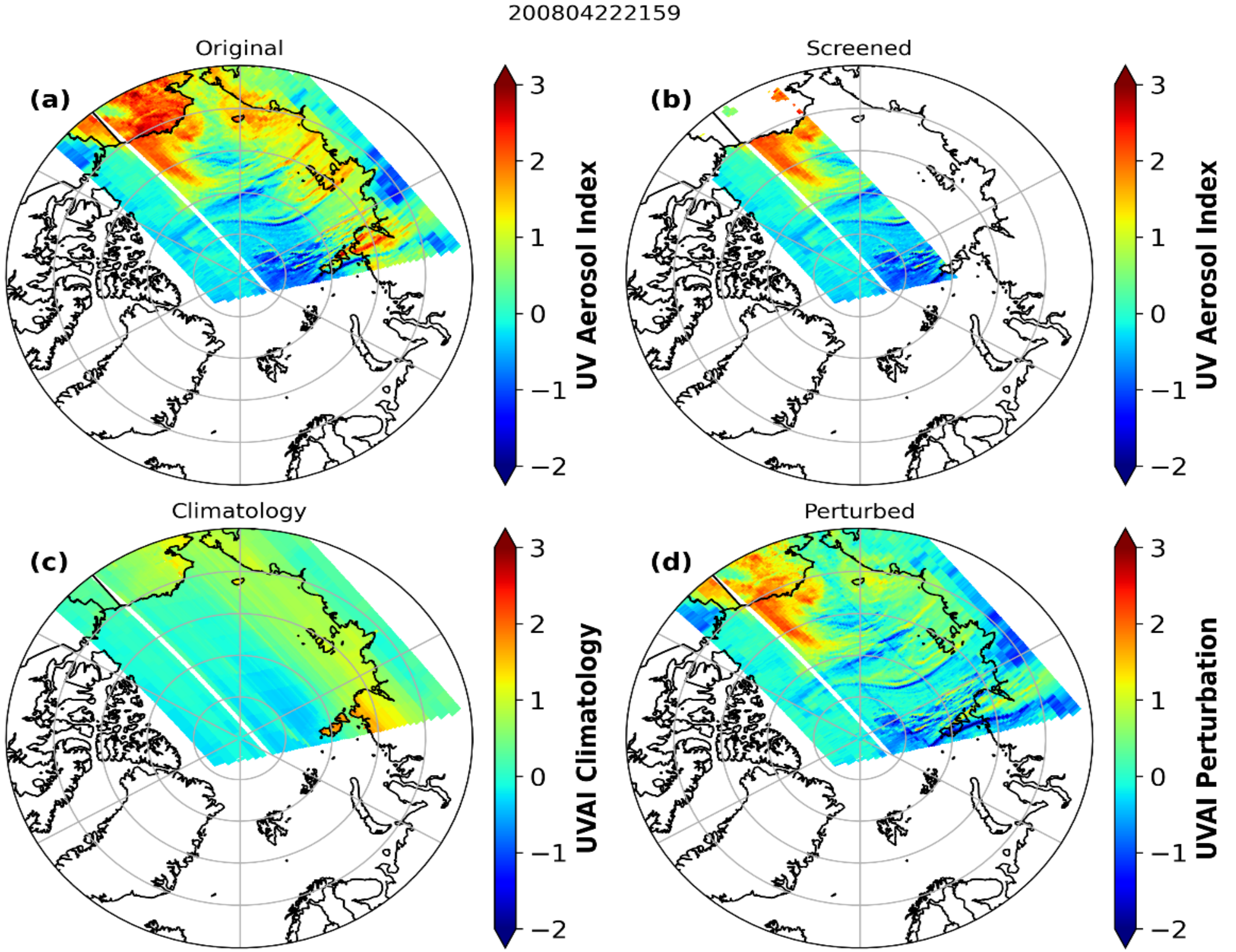
Additional row anomalies

- In the OMI data, row anomalies are highlighted with a quality control flag named the XTrackQualityFlag (Xtrack).
- Over the Arctic region, we found additional row anomalies that are not captured by the Xtrack flag.
- To identify additional bad rows, daily averages of AI from the northern end of all 60 OMI sensor rows over the Arctic are calculated
  - if any one of those 60 row averages is more than two standard deviations away from the mean of all the 60 row averages, it is flagged as a bad row.

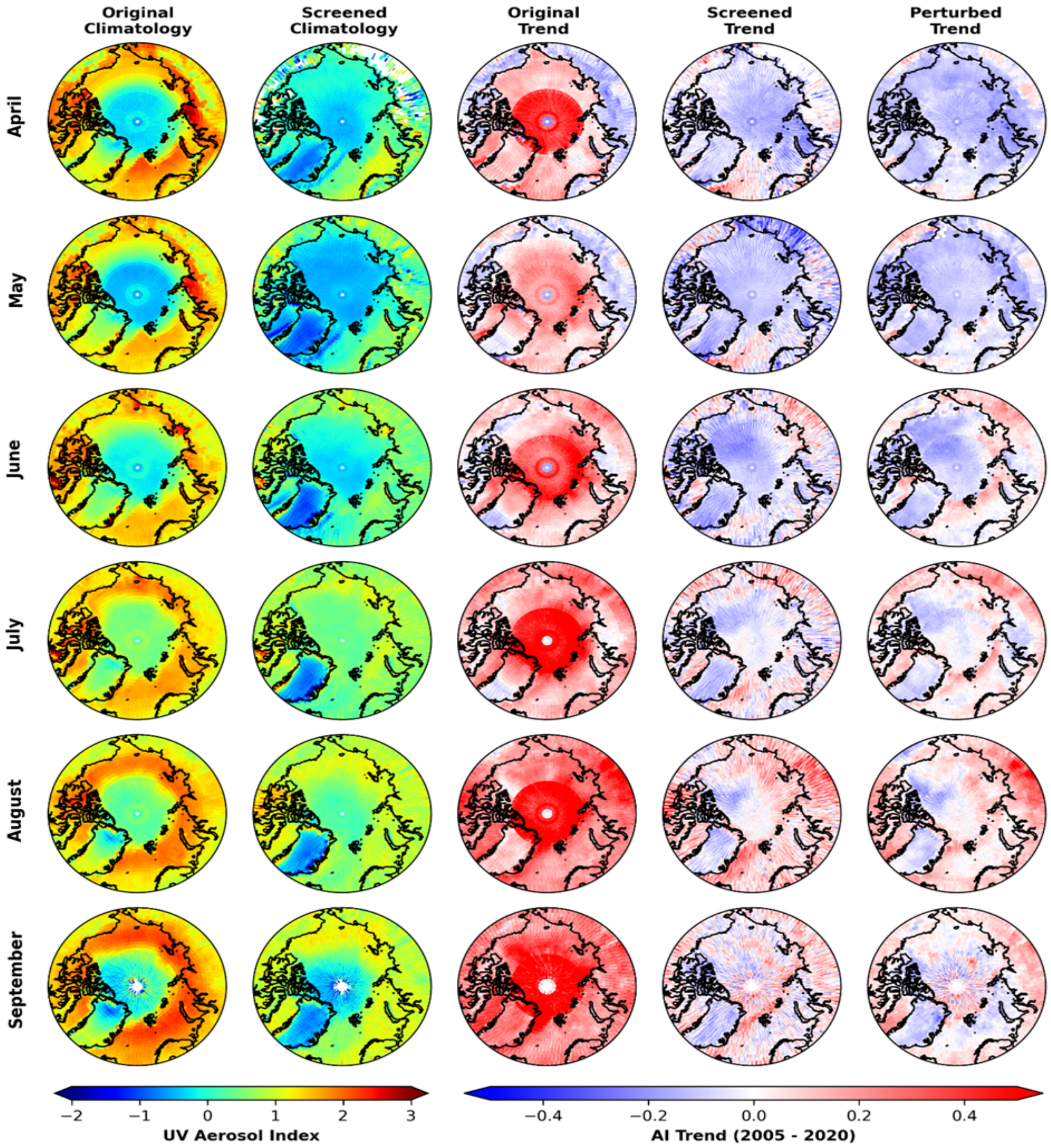


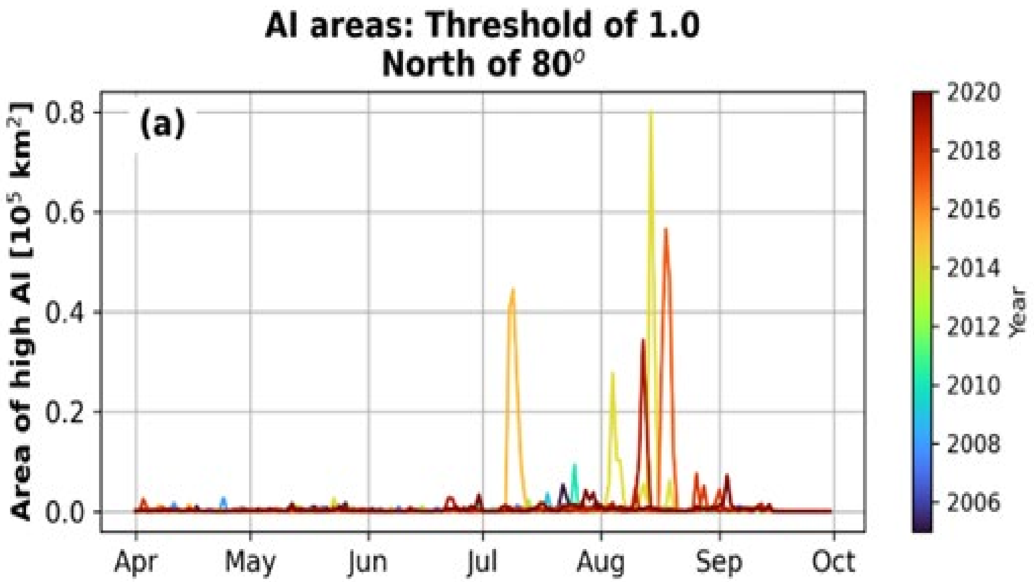
Filtering OMI Aerosol Index data through a climatology and a screened approach

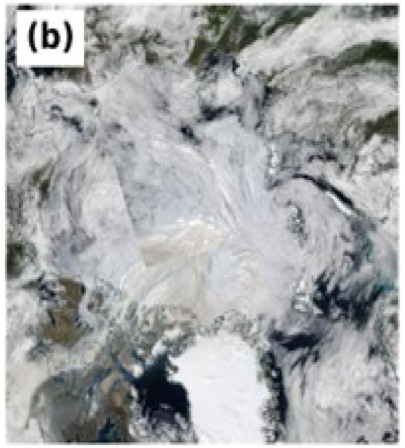
- Perturbing approach: An OMI AI database is constructed as function of viewing geometry and surface albedo over the Arctic region using relatively aerosol- free data from 2007. The newly constructed OMI AI database is used as a filter to distinguish background AI from true aerosol AI signals.
- Screening Approach: only use rows 56-60 after QA steps for climate applications

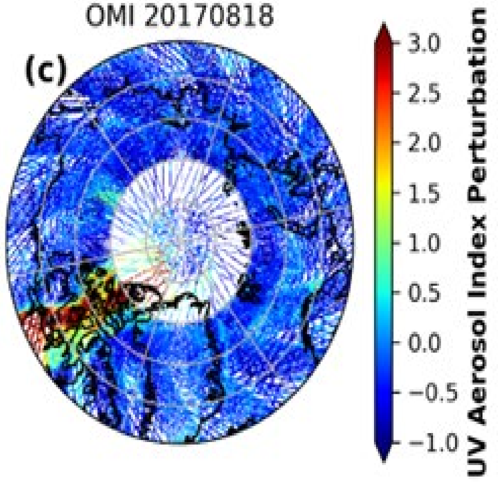


Climate applications





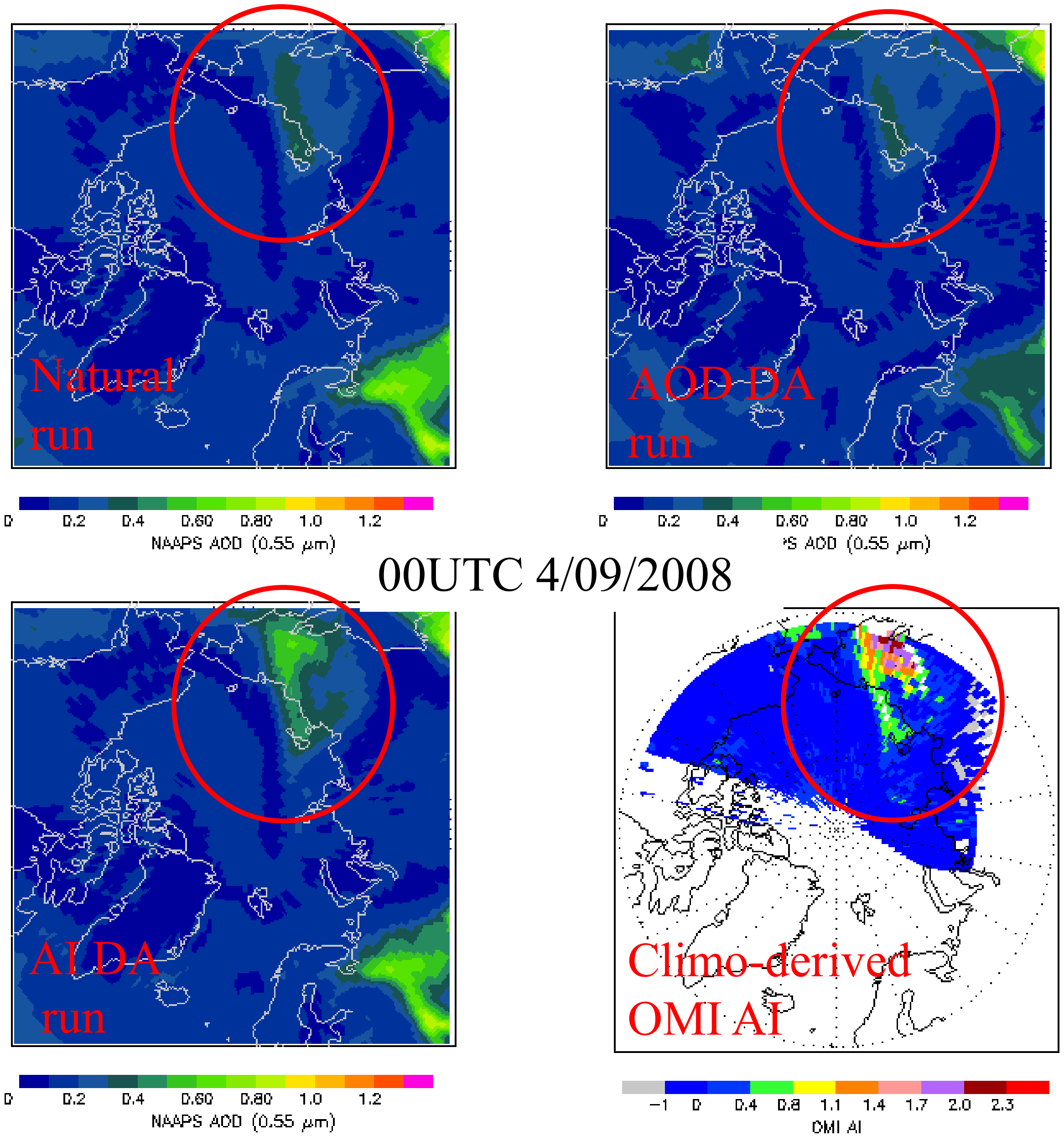




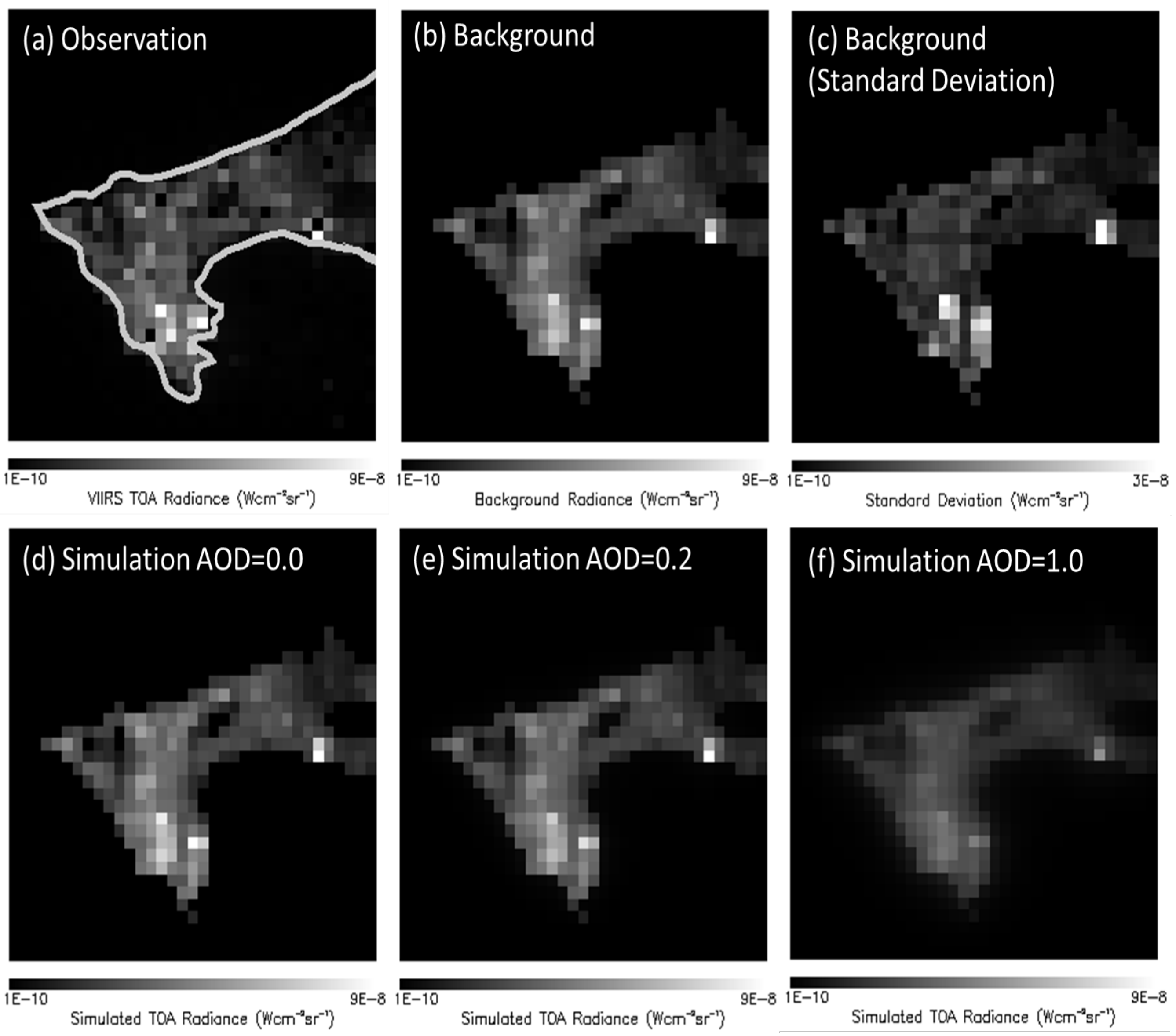
Preliminary results over the Arctic region

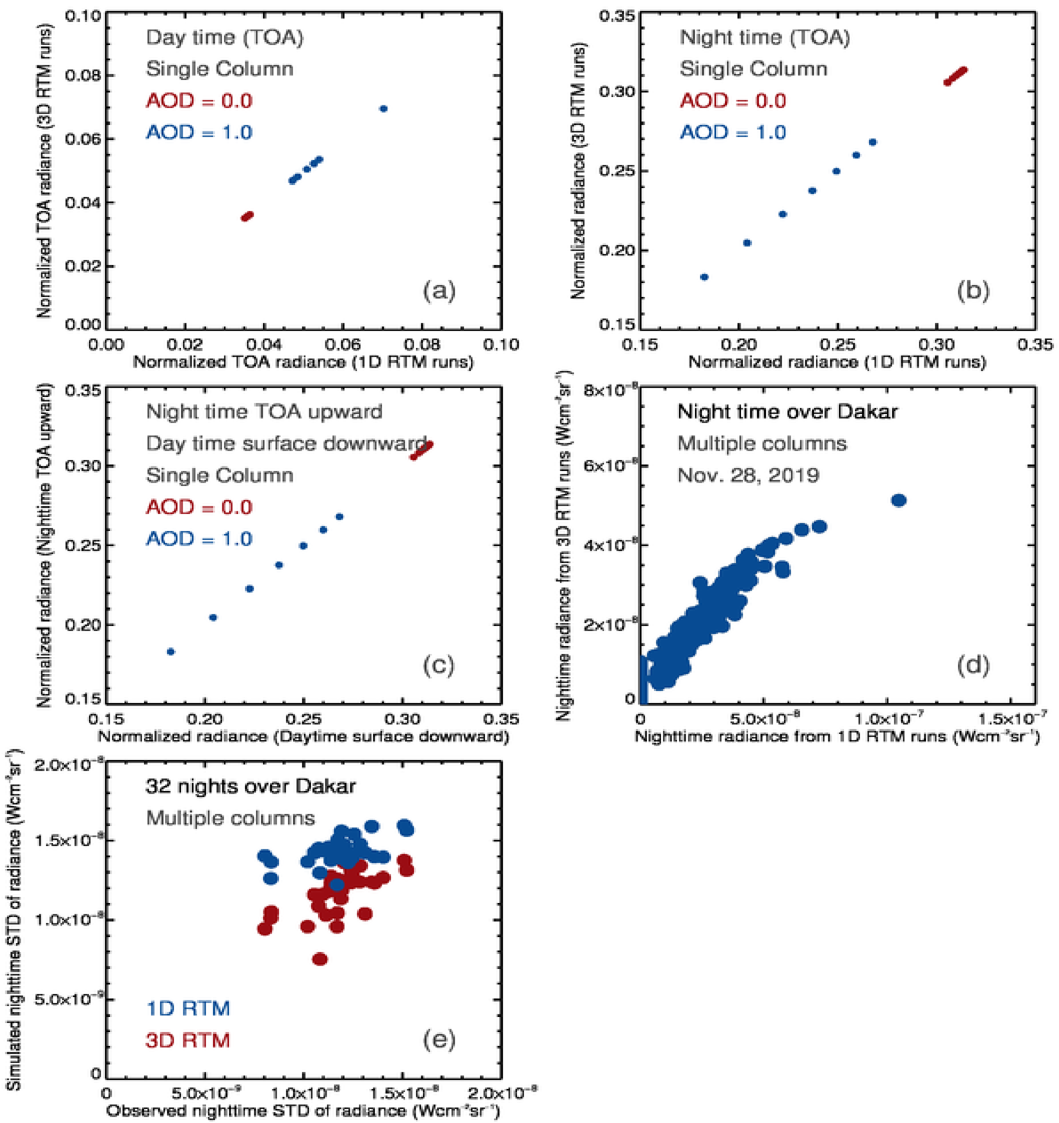
- OMI AI data are gridded (1x1° Lat/Lon) for every 6 hours. Data thinning is applied

- Preliminary results suggest that aerosol plumes, as indicated by OMI AI, are better represented in NAAPS AOD fields with the use of OMI AI data assimilation. Both absolute and RMS errors are reduced by 10-20% by OMI AI DA.



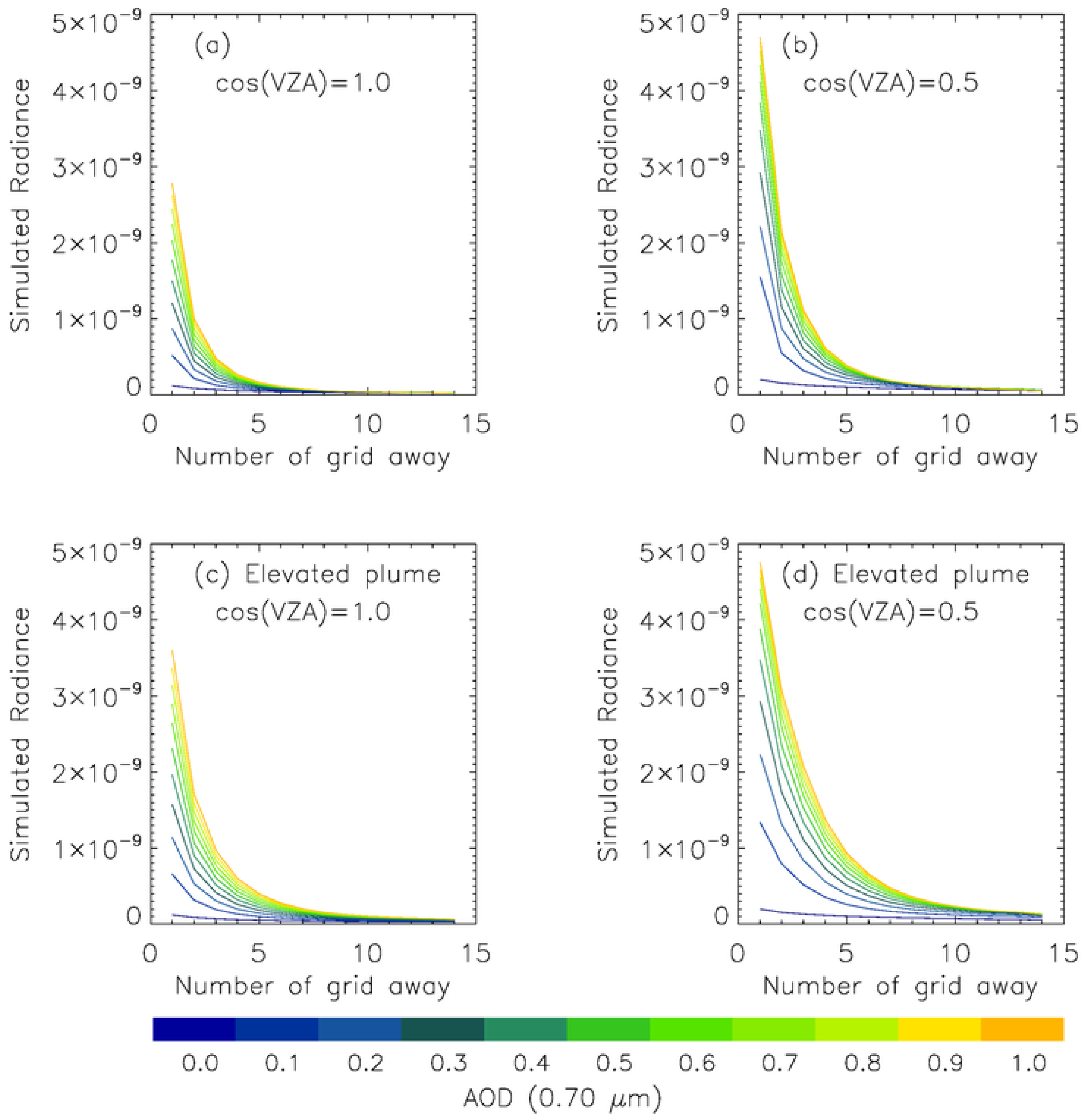
A nighttime 3-D RTM capability (a new data source for aerosol DA?)

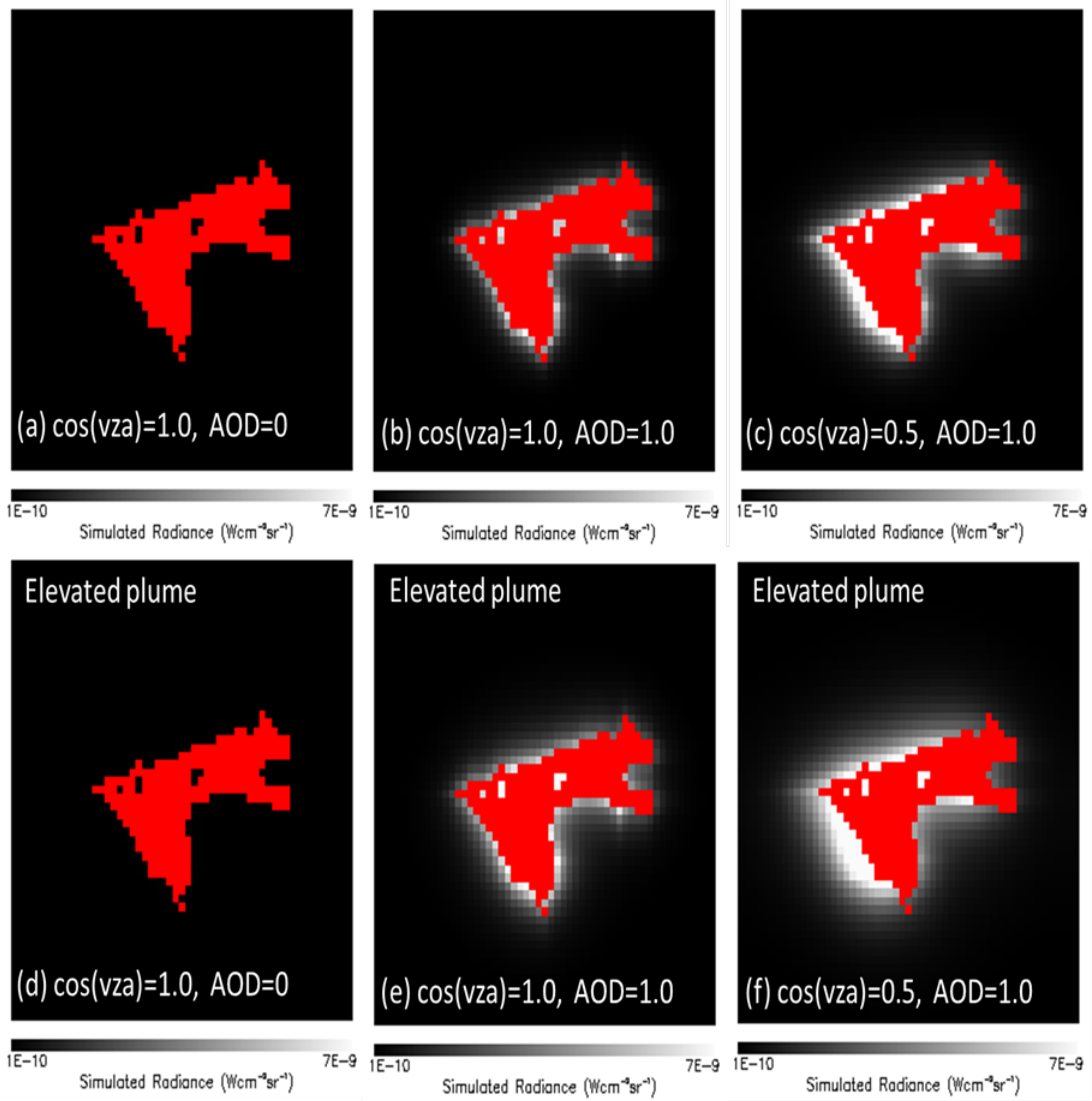




Zhang et al., 2022, submitted

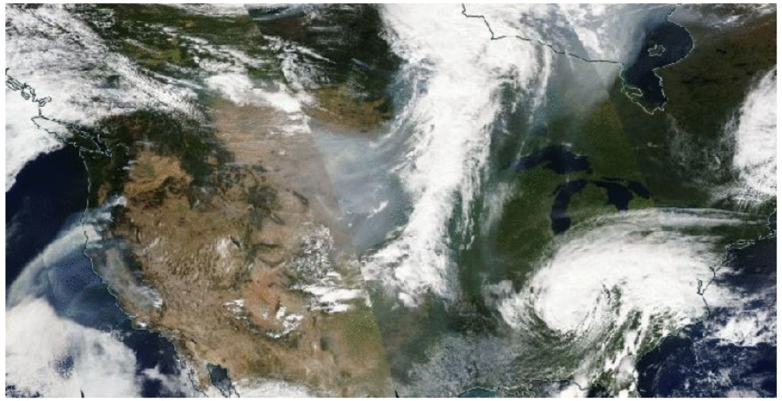
May be a new nighttime AOD dataset for aerosol DA?

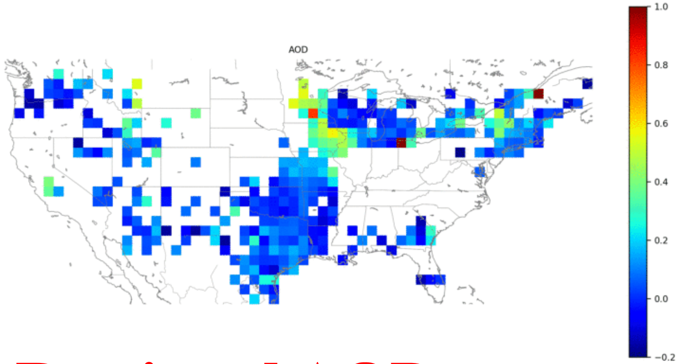




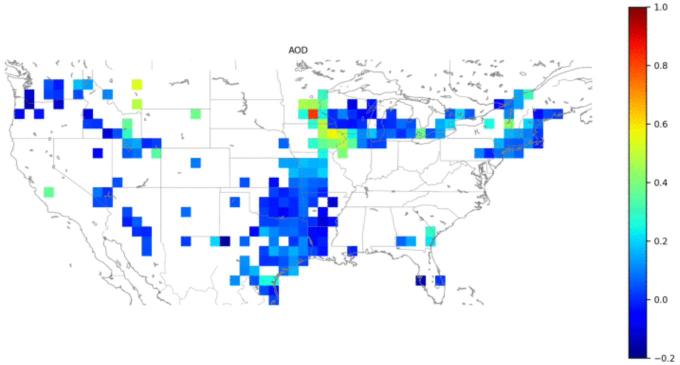
Aqua MODIS

2017/09/01



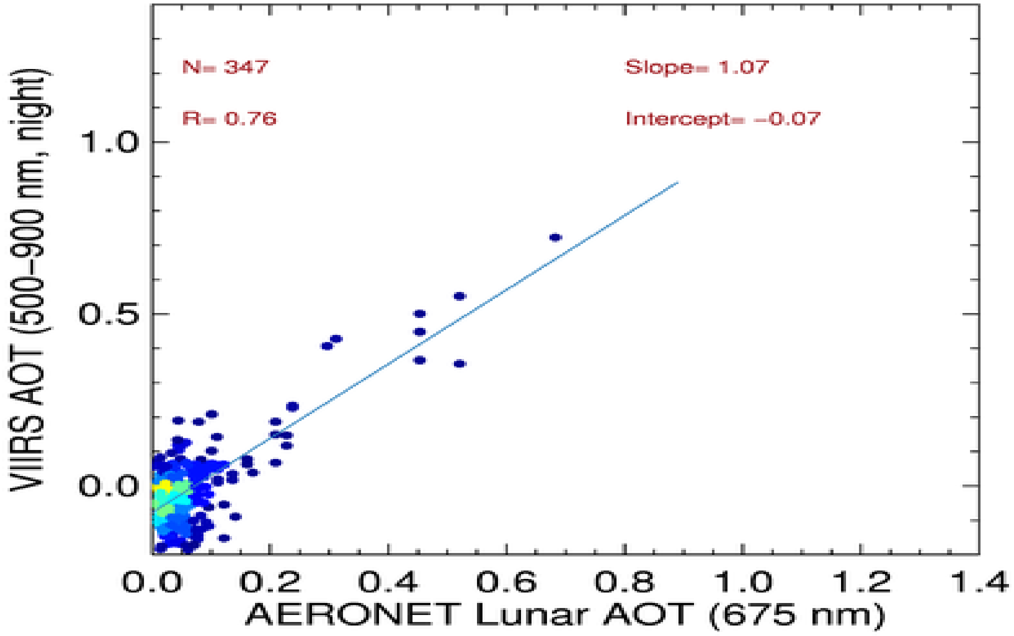


Retrieved AOD, nighttime



Retrieved AOD, nighttime Improved QA

- Developed a regional nighttime AOD retrieval capability using VIIRS DNB data (Zhang et al., 2019)
- New changes included the use of NASA's Black Marble data as the low boundary condition
- Results are promising
- Cloud contamination remains an issue



Conclusions

- We have constructed a new assimilation system for the direct assimilation of OMI AI. The aim is to improve the accuracy of aerosol analyses over bright surfaces such as cloudy regions and deserts.
- The performance of the OMI AI data assimilation system was evaluated over South-Central and Northern Africa for the period of 01 July to 31 August 2007. A total of ~30% reduction in Root-Mean-Square-Error and absolute error was found for NAAPS analyses with the use of OMI AI assimilation, when compared with nature runs. This shows that our OMI AI data assimilation system works as expected.
- This study also suggests that NAAPS analyses with OMI AI data assimilation cannot out-perform NAAPS reanalysis data that were incorporated with MODIS and MISR AOD assimilation over cloud free regions.
- Promising results were found by applying the newly developed AI assimilation system over the Arctic region.