The Critical Role of AERONET for Aerosol Modeling and Data assimilation in GEOS

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With contributions from

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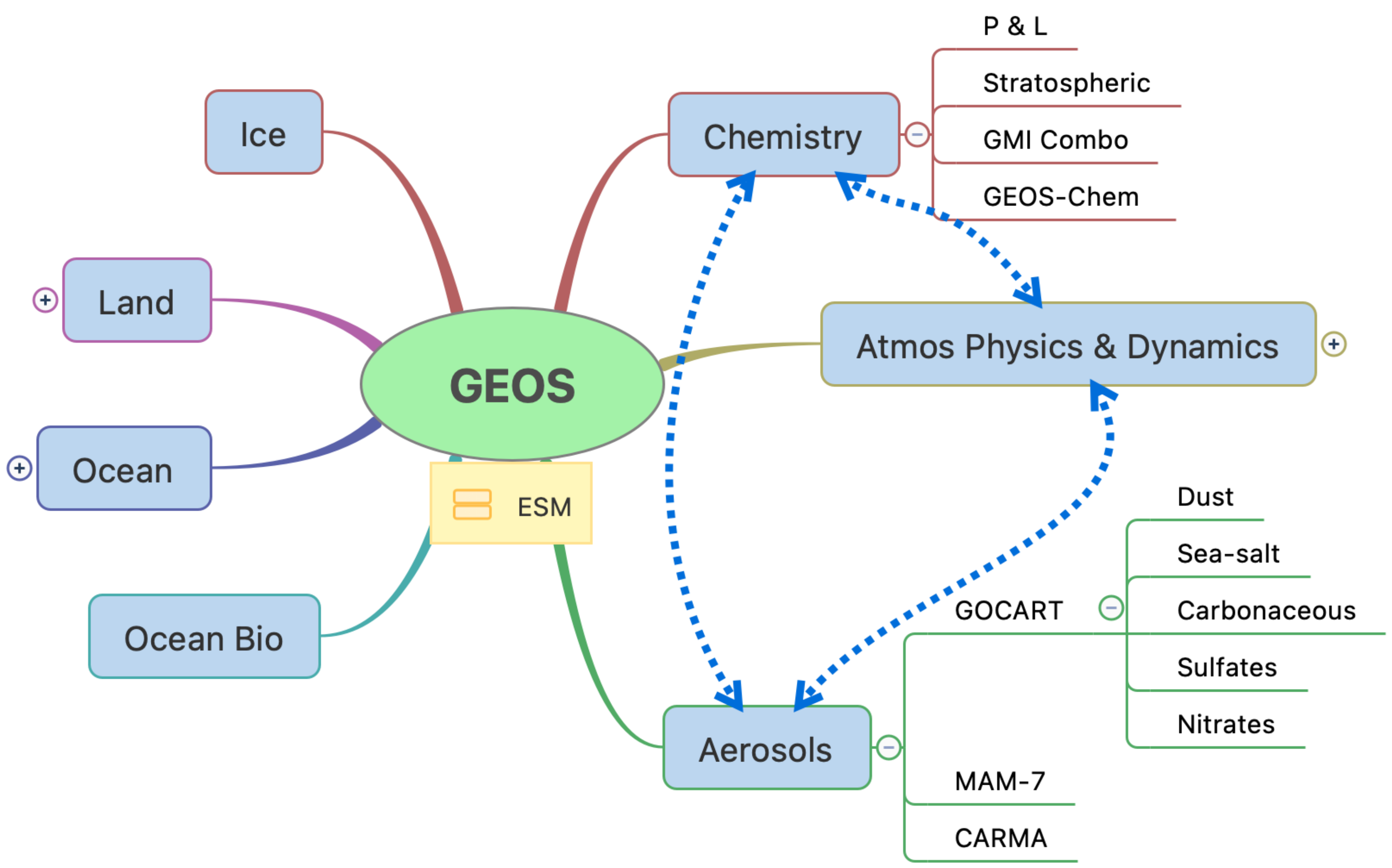
Outline

- Brief introduction to GEOS
  - GEOS Earth System Modeling
  - GEOS Data Assimilation
- GEOS Reanalyzes
- The role of AERONET in GEOS aerosol data assimilation
- Summary

The GEOS Earth System Model

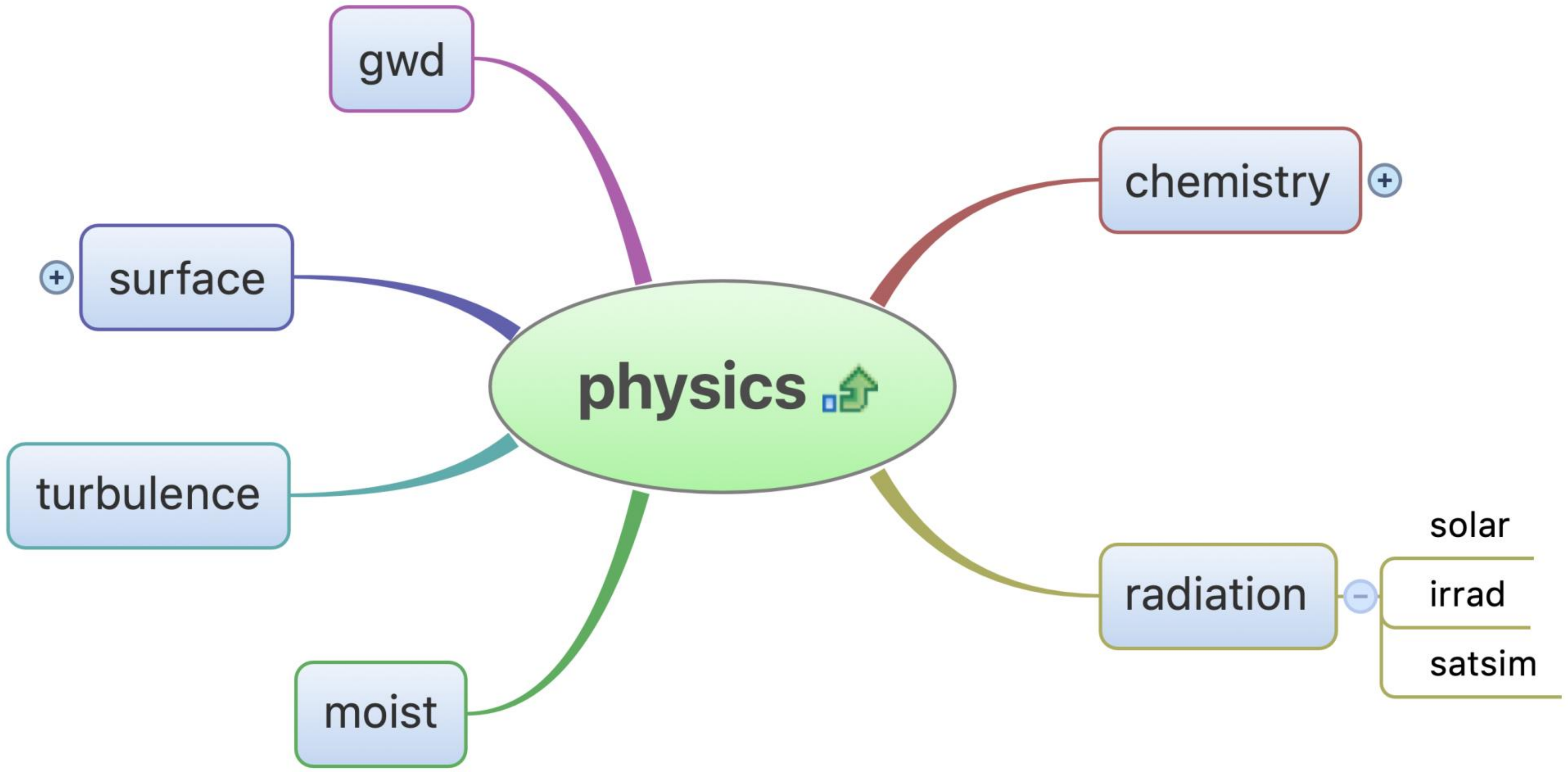
Components, parameterizations and computational implementations

GEOS Earth System Model



- The GEOS-ESM contains all major components of the Earth system
- GEOS is global, running at multiple resolutions
- **Software Architecture**
  - All components coupled with the Earth System Modeling Framework (ESMF), down to physics parameterizations
  - GEOS uses the MAPL usability later for facilitating hierarchical coupling of components
- **Applications of GEOS**
  - NASA reanalyzes
  - Forecasting: NWP, S2S, aerosols, chemistry
  - GEOS analyzes and forecasts provide ancillary information to **NASA instrument teams**
  - GEOS atmospheric composition forecasts play important role in flight planning for **NASA suborbital campaigns**
  - Observation System Simulation Experiments (OSSEs) for support the development of NASA space missions

GEOS Earth System Model



Every entry in this diagram is an ESMF Component

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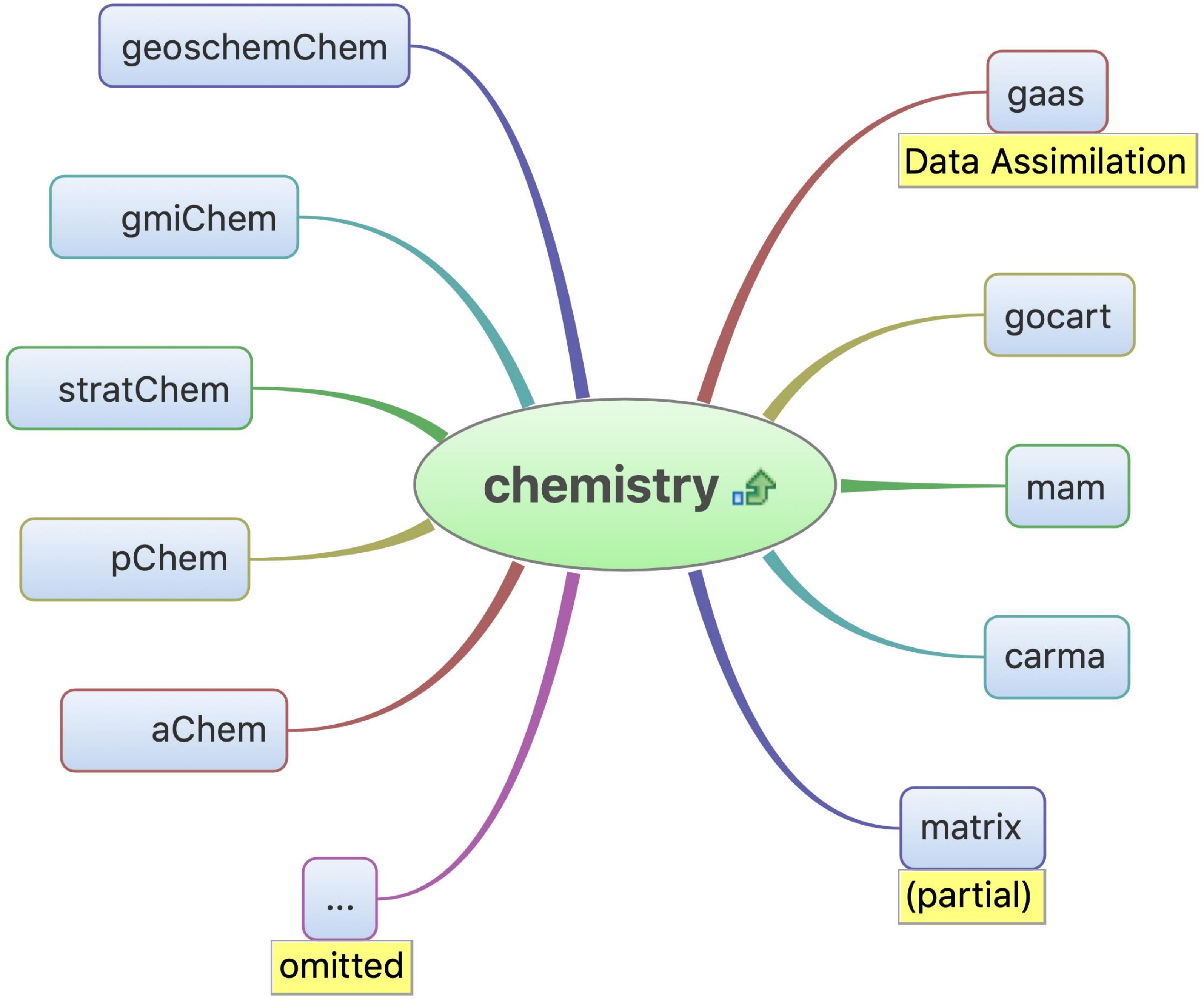

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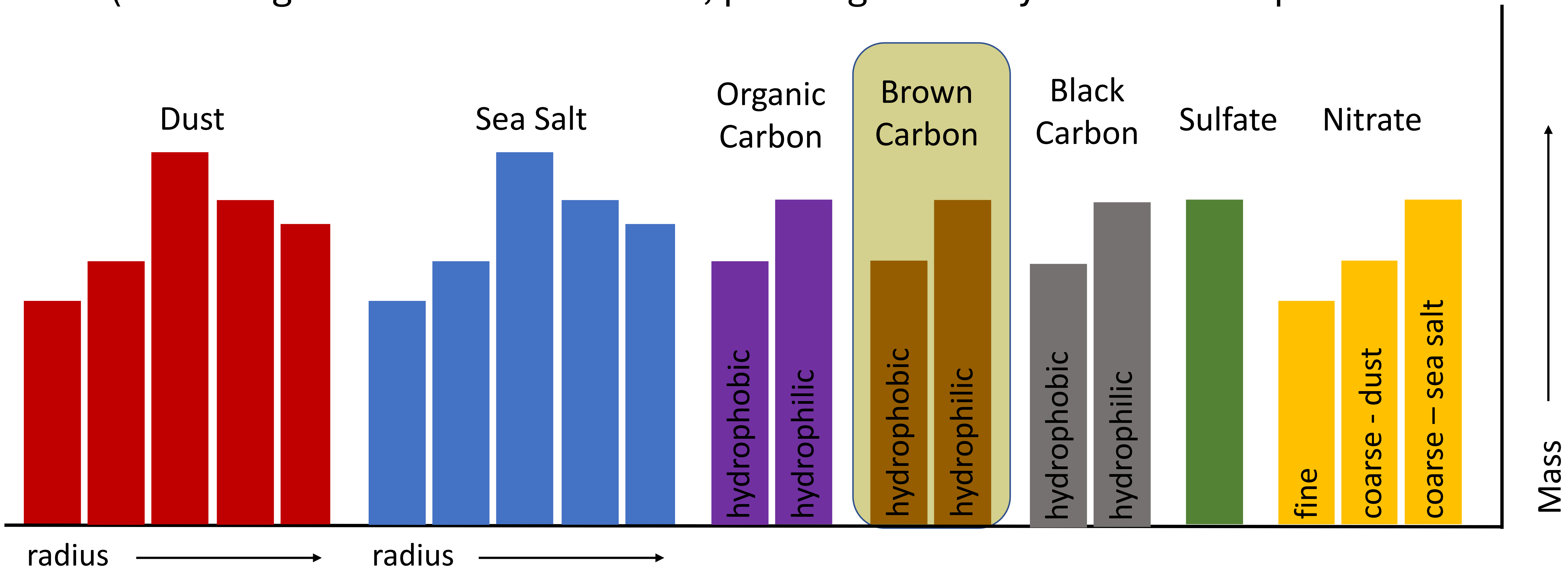
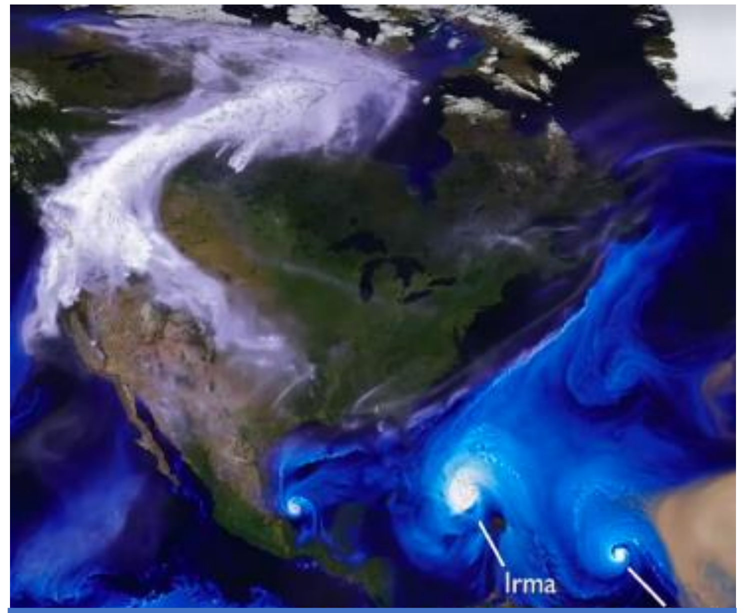
Science Changes Bundled with GOCART-2G

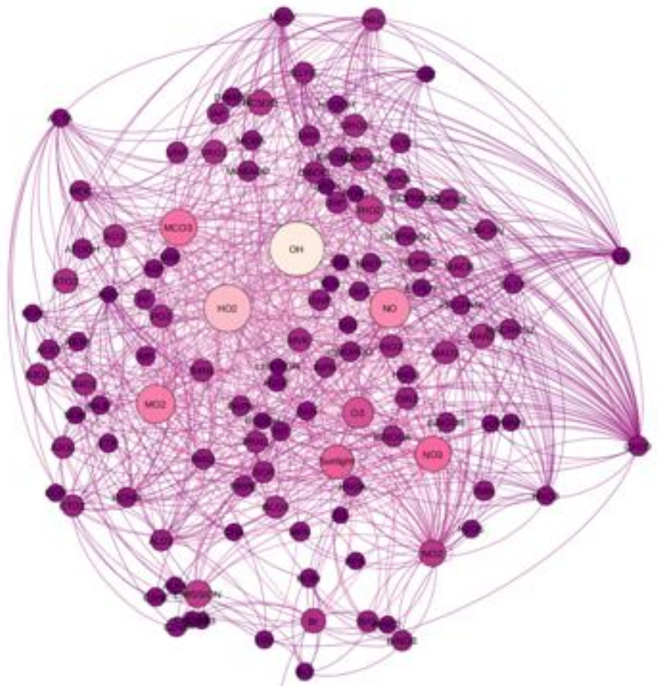
- Separation of organic aerosol into “white” (anthropogenic) and “brown” (biomass burning) components with distinct optical properties
- Increase OA:OC ratio in line with recent airborne measurements
- Inclusion of an ACHEM-driven **SOA scheme** for anthropogenic and biomass burning sources
- Inclusion of a **HEMCO/MEGAN-driven biogenic** SOA scheme
- Introduction of “point wise” source emissions for pyroCb inputs
- Update anthropogenic emissions to downscaled-**CEDS emission** inventory and input oxidant fields to MERRA-2 GMI (valid range of both is 1980 - 2019; padding outside years with endpoints



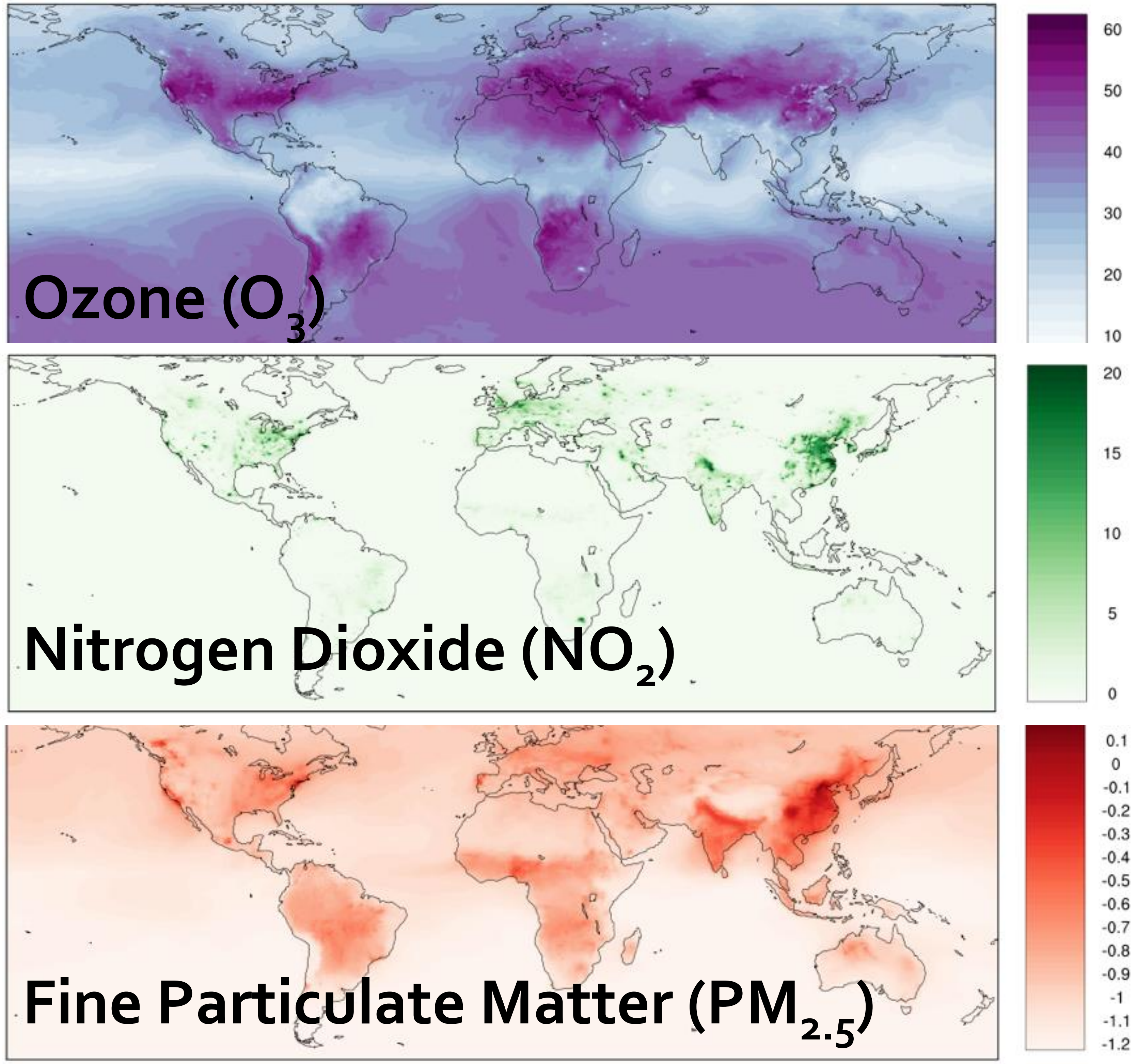
GEOS Composition Forecast (GEOS-CF)



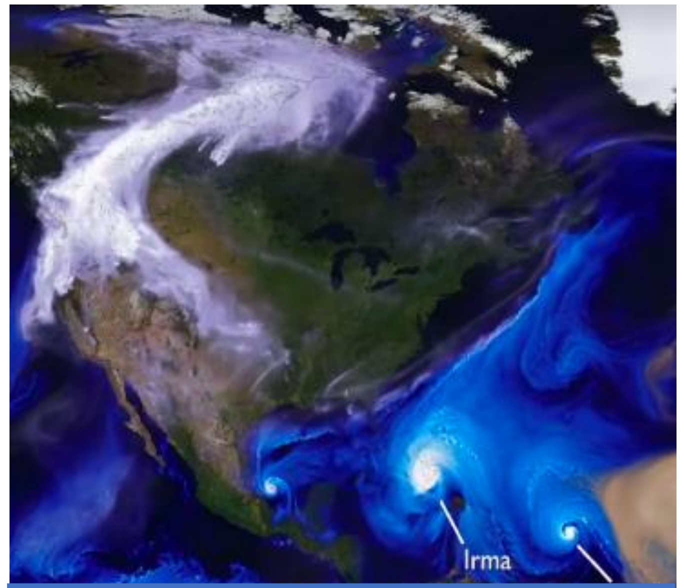
GEOS NWP



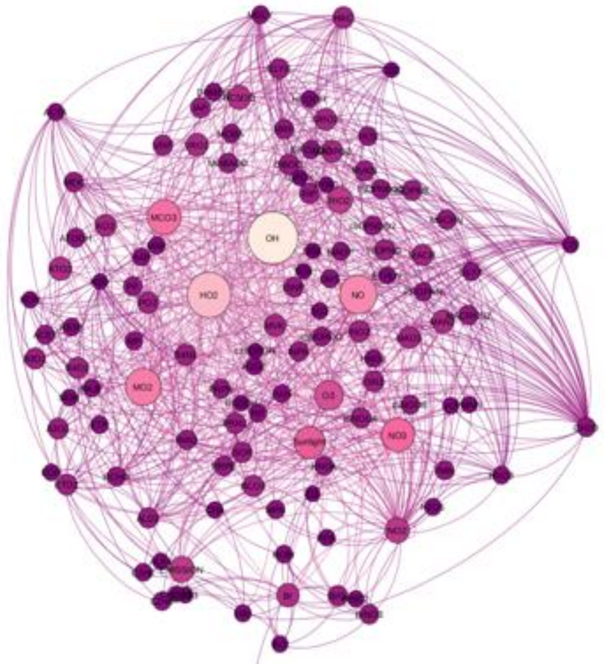
GEOS - Chem



Chemical Data Assimilation System for Reactive Gases



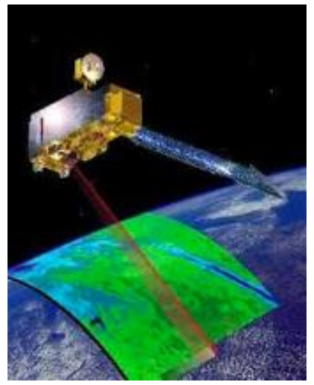
GEOS NWP



GEOS - Chem

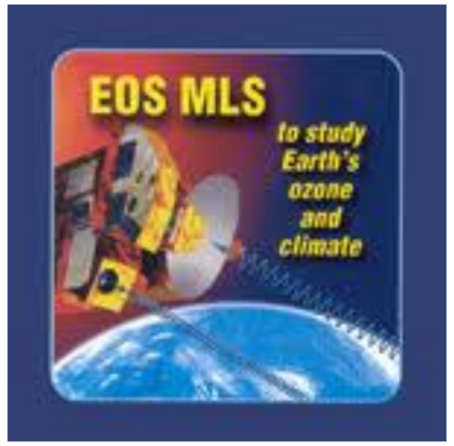
Data Assimilation System
CO, NO_x, O_3

Weakly coupled; 6 hour assimilation window



MOPITT

OMI



MLS

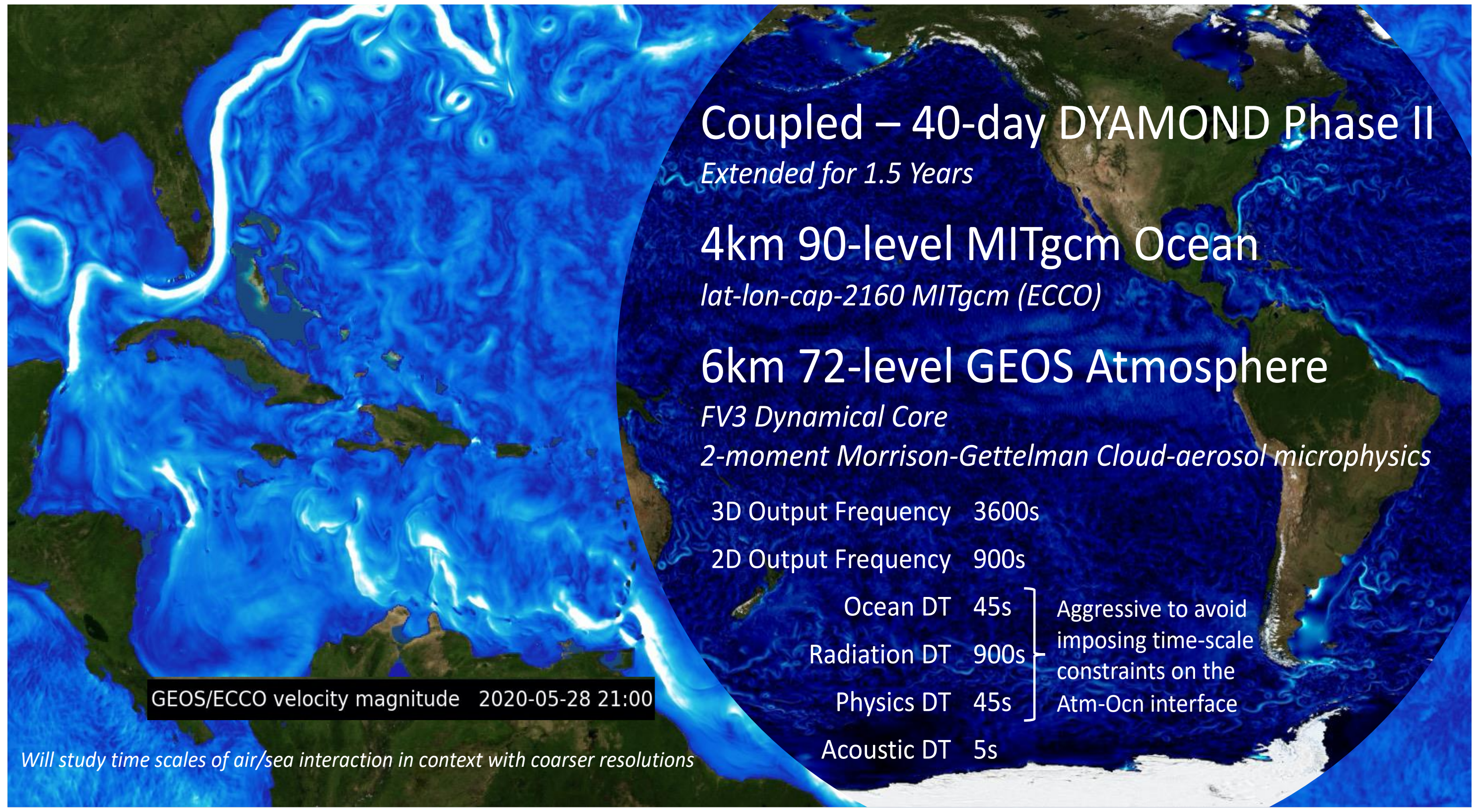
PACE

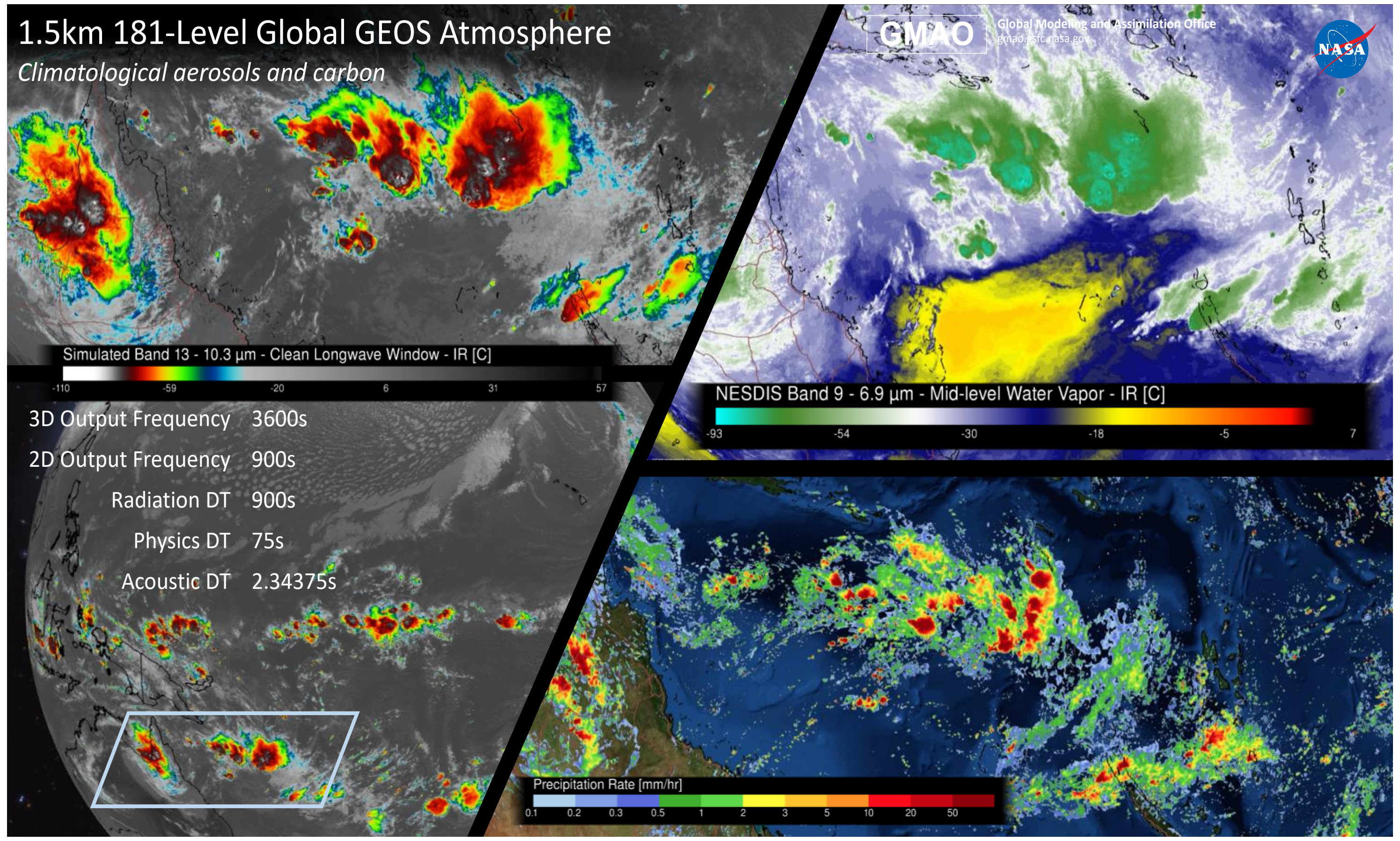
NO_2, O_3?

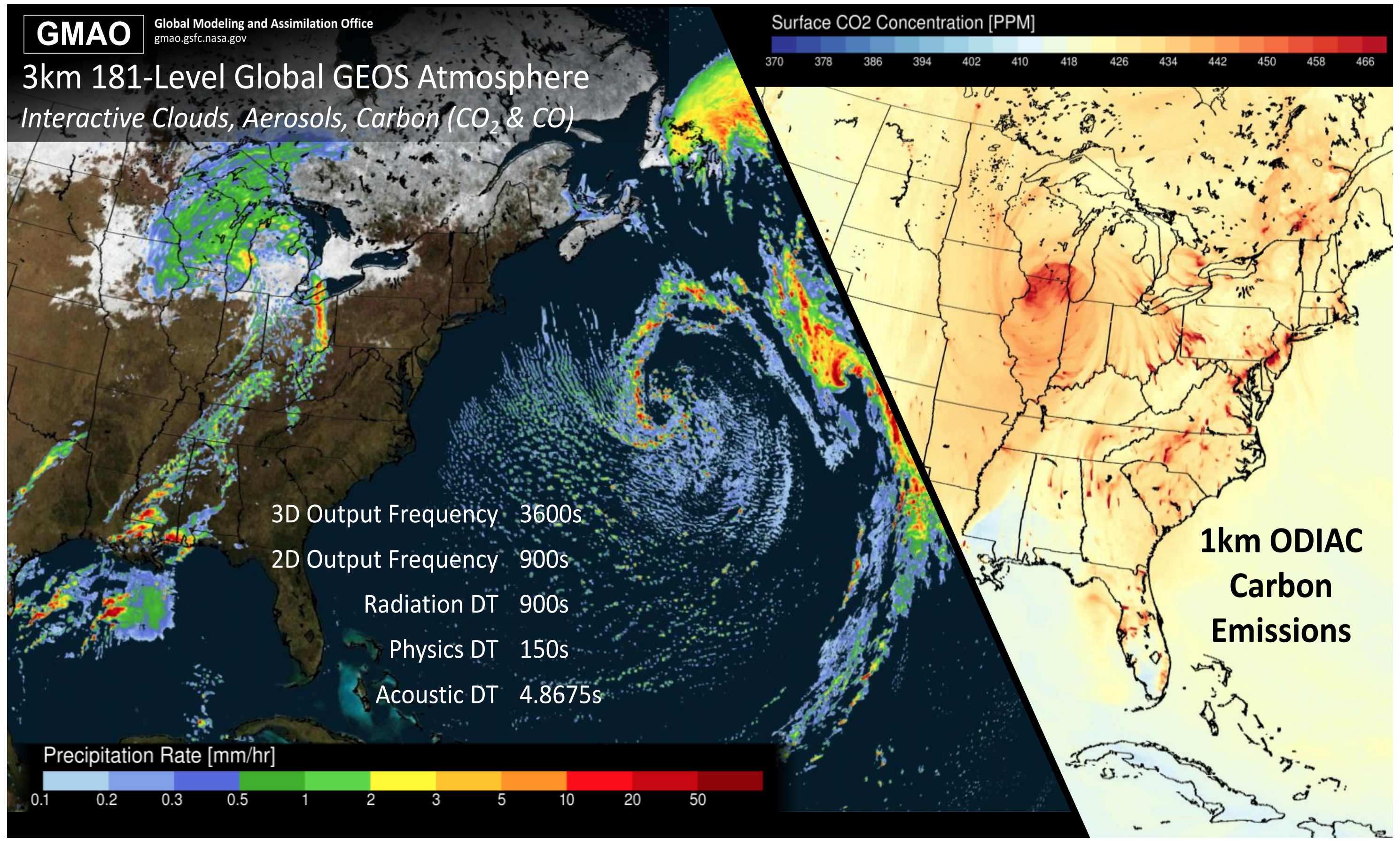
Global km-scale Simulations (GEOS DYAMOND Phase II)

GODDARD EARTH SCIENCES

Configuration	Total Cores - "System"	Throughput	Data Volume
Coupled Atm-Ocn 6km 72-Level Atm 4km 90-Level Ocn	**8,160 Intel Xeon Haswell** processor cores "Pleiades" NASA-NAS	**3 Simulated Days /** Wallclock Day	**0.3 Petabytes**
Atmosphere+Aerosols 3km 181-Level Atm	**39,360 Intel Xeon Skylake** processor cores "Discover" NASA-NCCS	**7 Simulated Days /** Wallclock Day	**2.0 Petabytes**
Atmosphere 1.5km 181-Level Atm	**39,440 Intel Xeon Skylake** processor cores "Discover" NASA-NCCS	**1.5 Simulated Days /** Wallclock Day	**1.3 Petabytes**







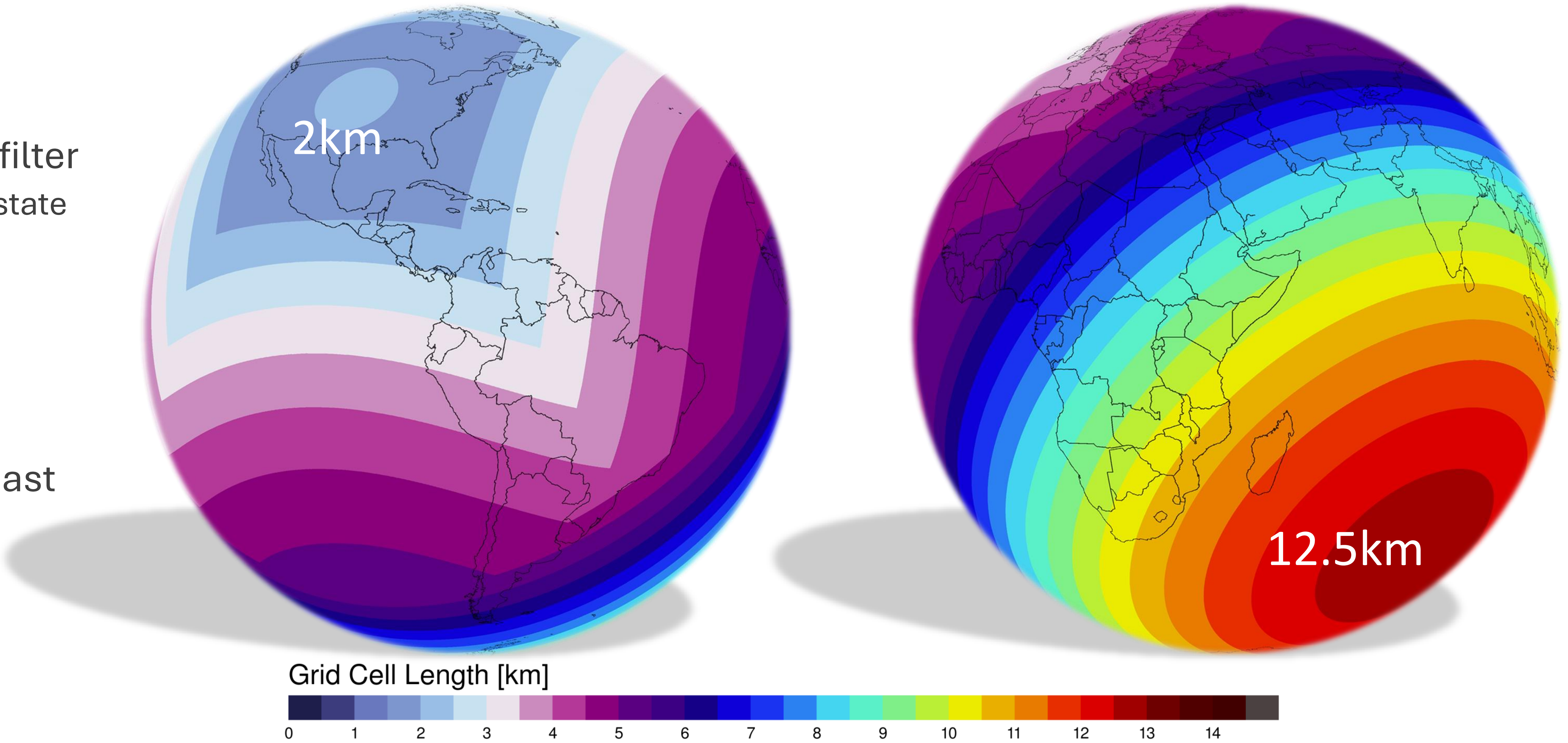
May 2024 NOAA-HWT Spring Forecast Experiment

- c2160 stretched grid
  - ~2km over CONUS
- 137 vertical levels
- Replay to GEOS-FP
  - c720 12.5km L72
- T106 spectral increment filter
  - Constrain the large-scale state
- 72-hr forecasts
  - 00z and 12z daily
- 660 AMD Milan Nodes
- 13 days/day throughput
- 5.5 hours per 3-day forecast

c2160 stretch_fac=2.5

2 km CONUS Grid

Antipole matches GEOS-FP 12.5 km Resolution



Slide Courtesy: Bill Putman (NASA/GMAO)

US Tornado Outbreak

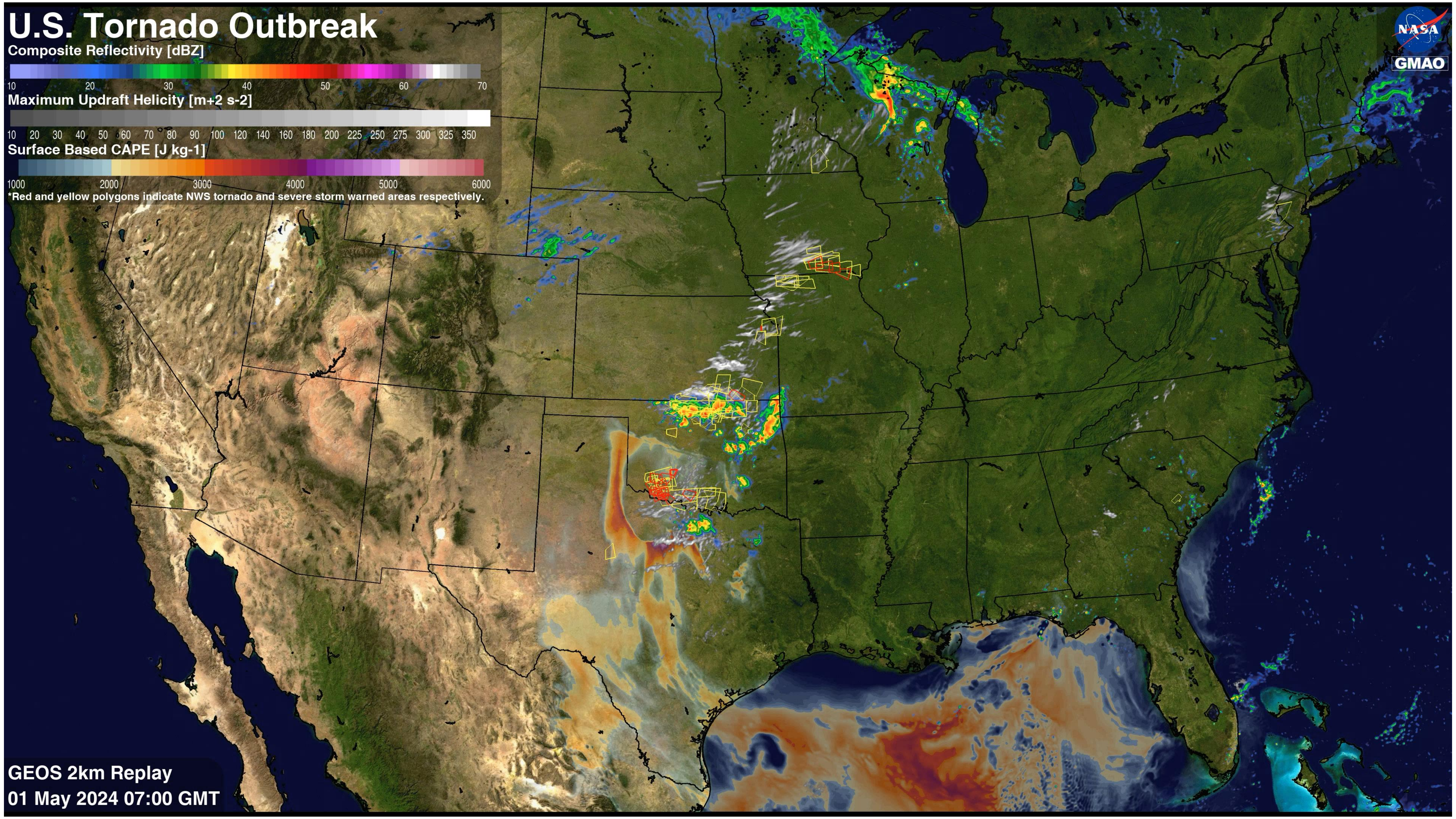
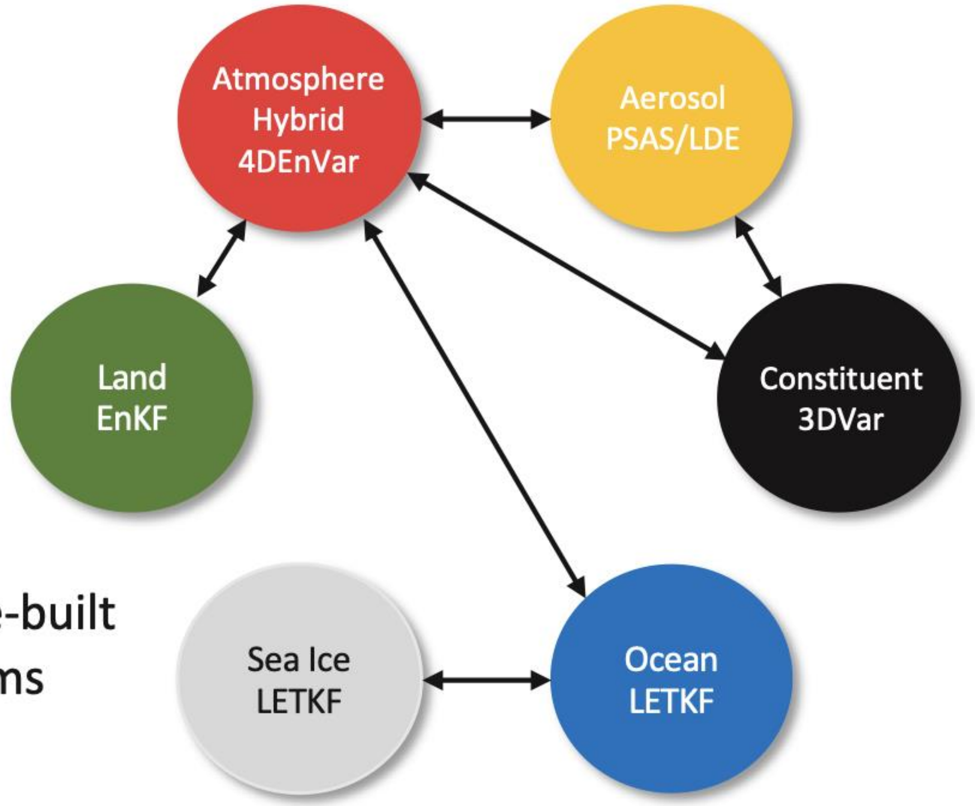


Image Courtesy: Bill Putman (NASA/GMAO)

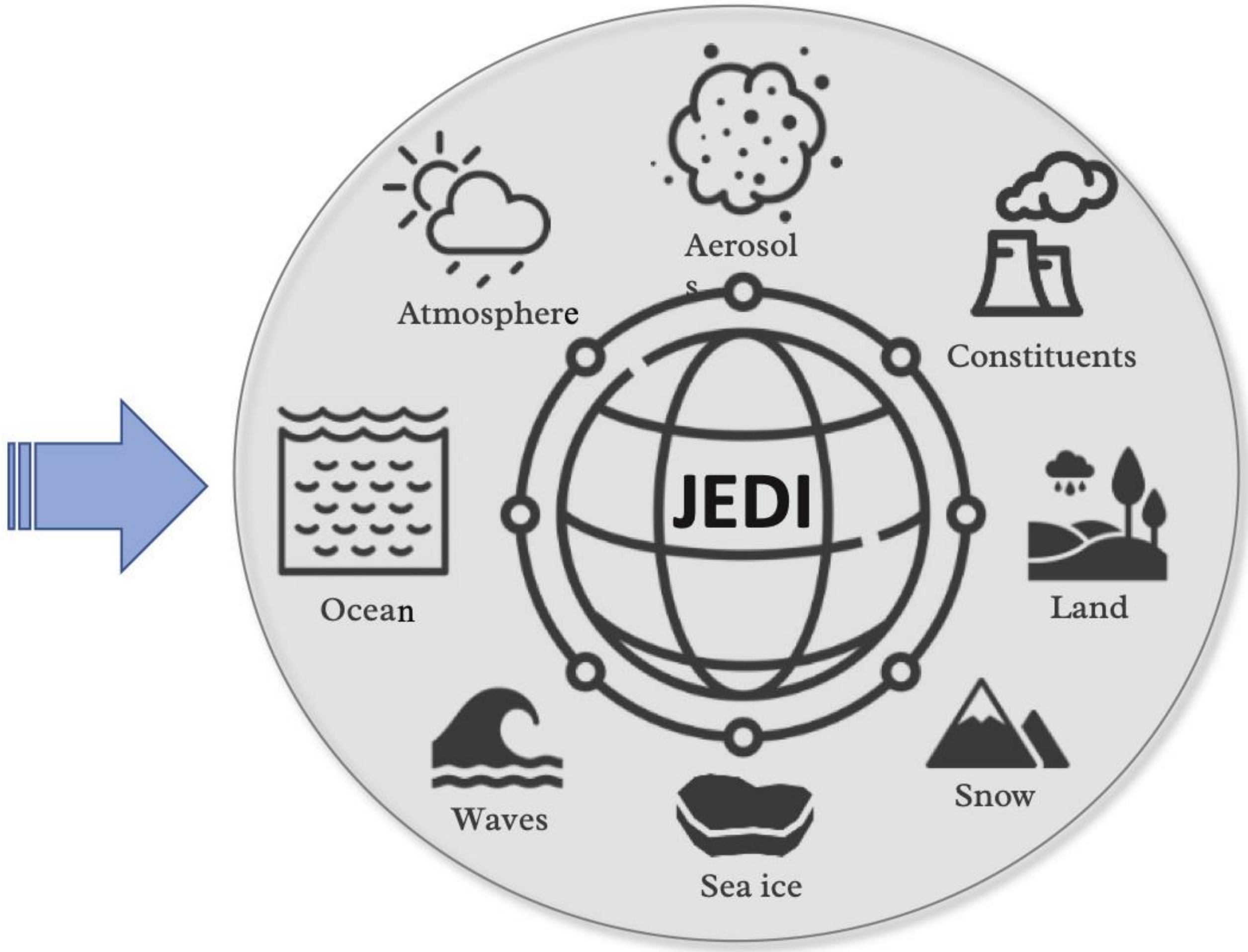
Data Assimilation

Joint Effort for Data assimilation Integration (JEDI)

An open-source, state-of-the-art, data assimilation infrastructure for all Earth system components developed by JCSDA and its partners (NASA, NOAA, DoD, academia...)



Current purpose-built legacy DA Systems



- Eliminate GMAO's dependence on legacy, purpose-built assimilation systems
- Modern software design will enable interdisciplinary science using coupled models *and* assimilation
- Multi-agency adoption will help expand use of NASA observations and accelerate their R2O transition

Slide Courtesy: Ron Gelaro (NASA/GMAO)

JEDI Development Thrusts at GMAO

Atmospheric DA

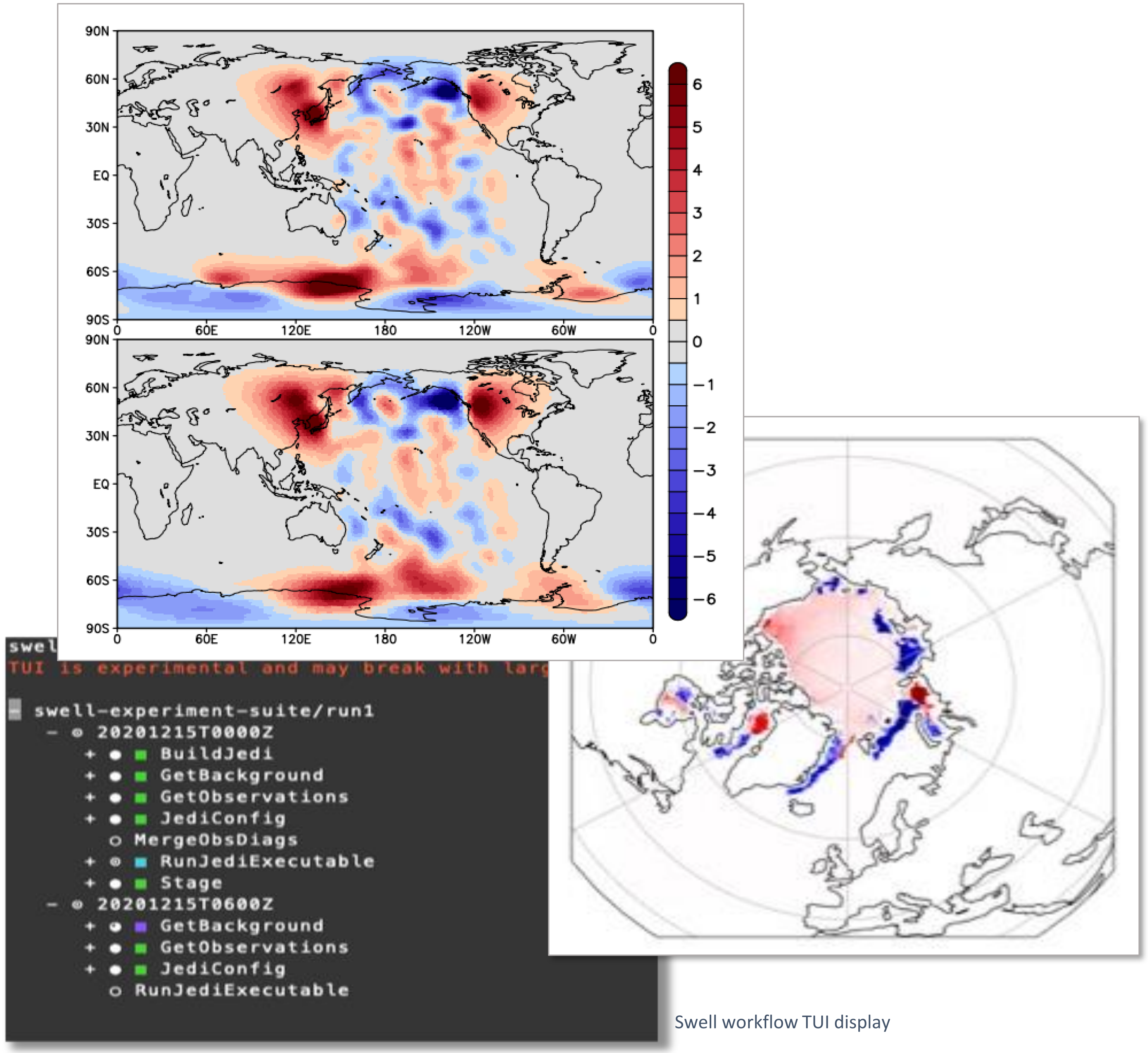
- Phased implementation of JEDI Var and **aerosol DA** into the existing GEOS-FP scripting to expedite operational transition
- Accommodation of other high-priority GEOS-FP plans including increased vertical resolution, updated physics

Coupled Marine DA

- Ground-up development of JEDI-based ocean and sea-ice DA using GEOS-MOM6 within a new workflow ecosystem
- Coordinated development with JEDI atmospheric DA components for transition to coupled atmosphere-marine DA.

New Workflow Ecosystem (Swell)

- Python-based system for constructing, configuring and deploying workflows using Cylc, plus diagnostics
- Comprehensive on-premises CI featuring multi-tiered nightly testing of GMAO and JCSDA developments



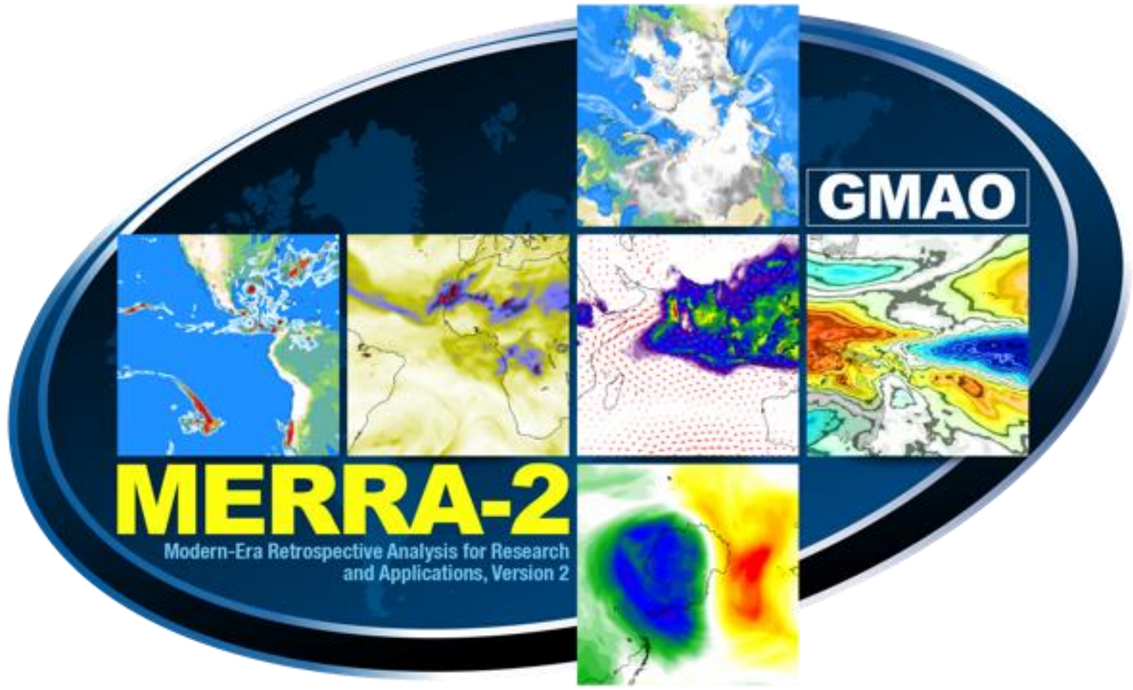
Swell workflow TUI display

Slide Courtesy: Ron Gelaro (NASA/GMAO)

GMAO Global Products

GEOS

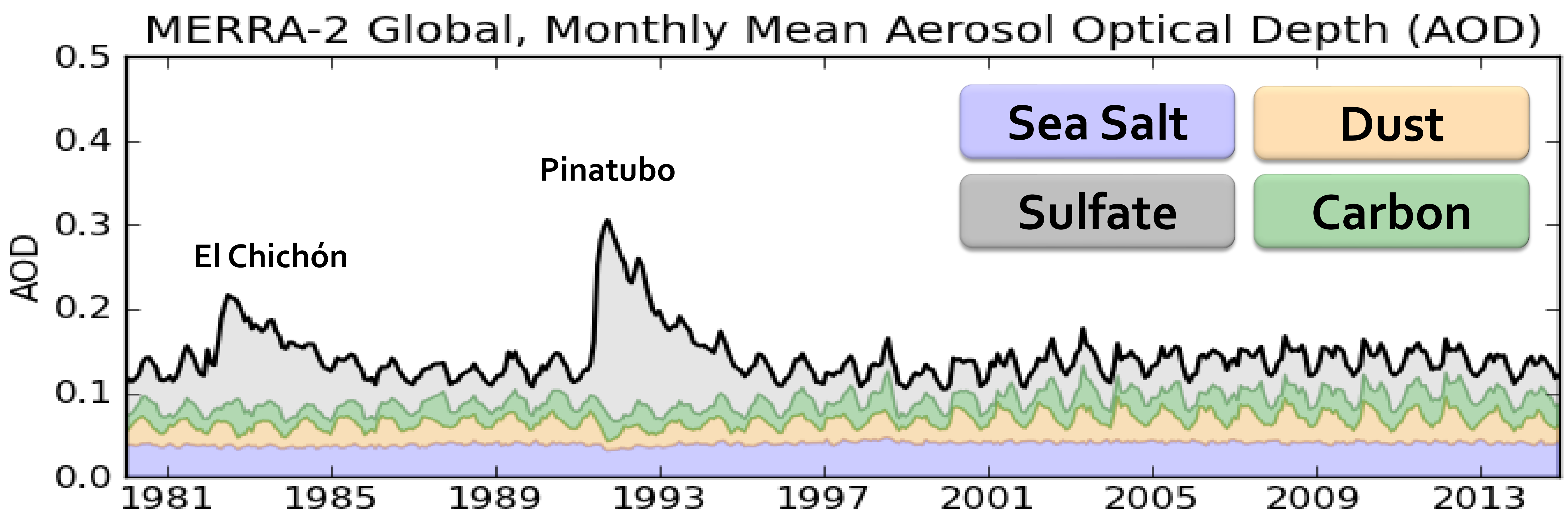
- Forecasting
  - GEOS-S2S — Seasonal (Coupled)
  - GEOS-FP — NWP+Aerosols
  - GEOS-IT
    - GEOS-CF — Reactive Gases
- Reanalysis
  - MERRA-2
    - MERRA-21C



Case Study: Role of AERONET for MERRA-2

MERRA-2 Global Mean AOD Analysis: 1980 - Onward

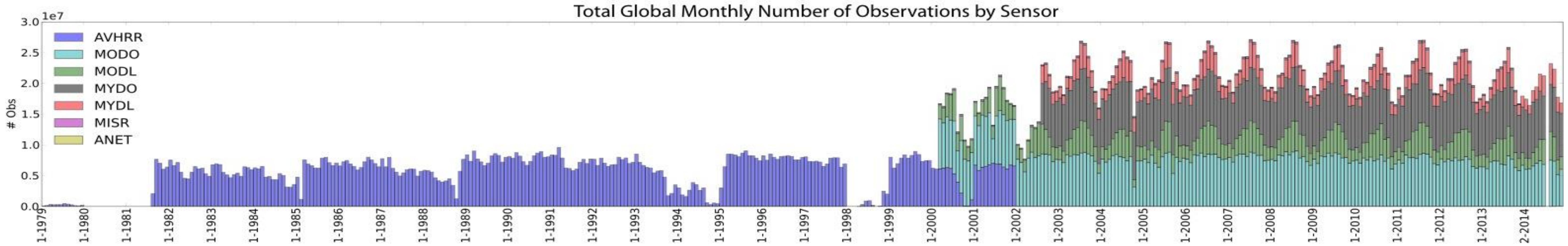
- Unique amongst its peers then, the MERRA-2 reanalysis includes an aerosol reanalysis for the modern satellite era (1980 – onward).
- Aerosols are ***coupled*** to the meteorological reanalysis (both radiatively and through emissions/loss processes).



Aerosol Observing System

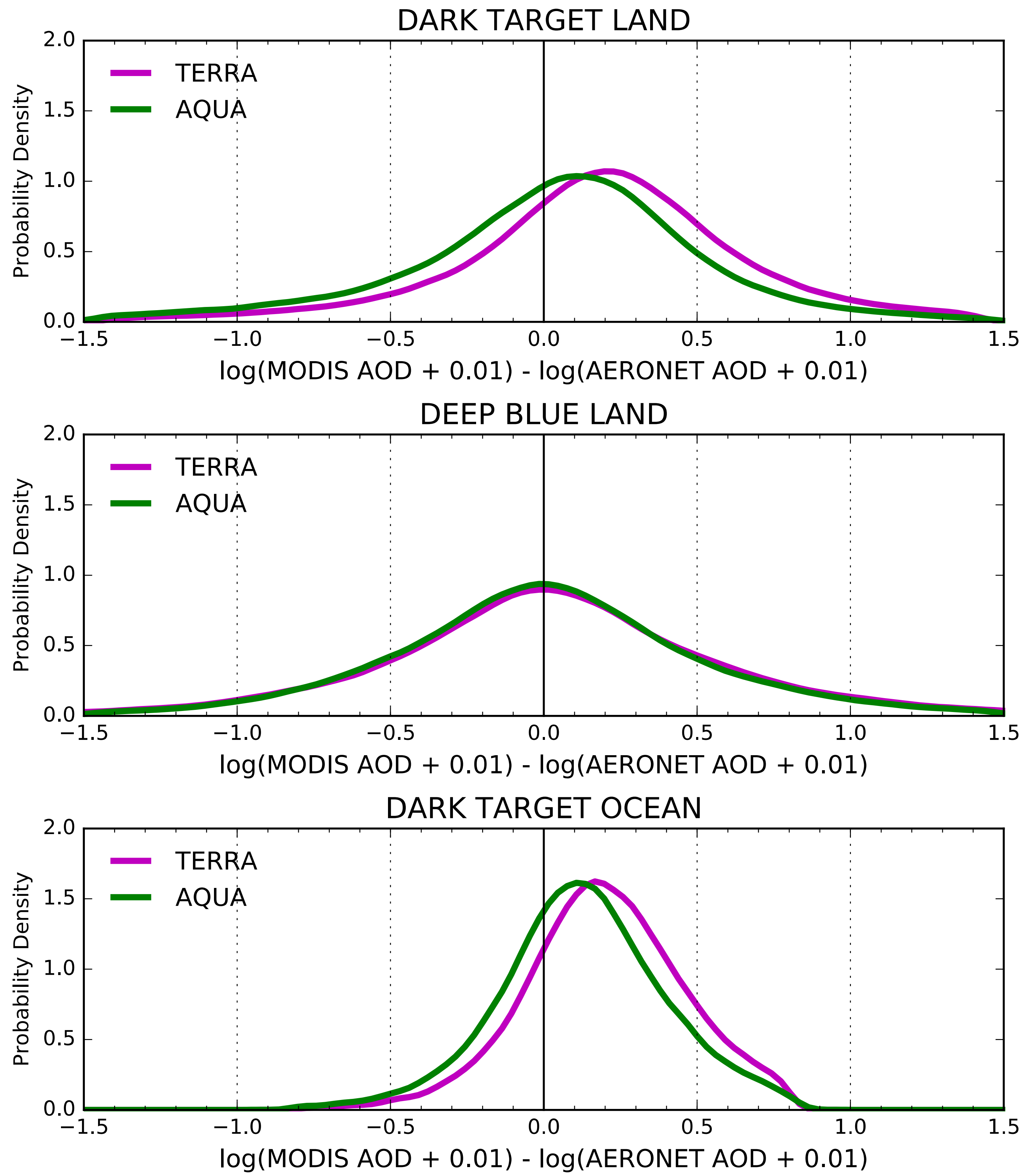
Sensor	Period	Remarks
AVHRR*	1979 – 2002	PATMOS-x; NNR; Ocean Only
AERONET	1999 – 2015	Ground-based stations
MODIS Terra*	2000 – Onward	C5; NNR; Separate land & ocean
MODIS Aqua*	2002 – Onward	C5; NNR; Separate land & ocean
MISR	2000 – 2014	Bright surfaces (albedo > 0.15)

TOTAL GLOBAL MONTHLY NUMBER OF AOD OBSERVATIONS (× 10^7) BY SENSOR



Biased Aerosol Observing System

National Aeronautics and Space Administration



- The aerosol data assimilation problem requires a homogenized AOD observing system across different platforms
- Biases between datasets can propagate in the model forecast and lead to artificial time variability.

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NRL Empirical AOD Corrections

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D22207, doi:10.1029/2005JD006898, 2006

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MODIS aerosol product analysis for data assimilation: Assessment of over-ocean level 2 aerosol optical thickness retrievals

Jianglong Zhang[1,2] and Jeffrey S. Reid[1]

Received 16 November 2005; revised 1 March 2006; accepted 10 July 2006; published 18 November 2006.

[1] Currently, the Moderate-resolution Imaging Spectroradiometers (MODIS) level II aerosol product (MOD04/MYD04) is the best aerosol optical depth product suitable for near-real-time aerosol data assimilation. However, a careful analysis of biases and error variances in MOD04/MYD04 aerosol optical depth product is necessary before implementing the MODIS aerosol product in aerosol forecasting applications. Using 1 year's worth of Sun photometer and MOD04/MYD04 aerosol optical depth (τ) data over global oceans, we studied the major biases in MODIS aerosol over-ocean product due to wind speed, cloud contamination, and aerosol microphysical properties. For τ less than 0.6, we found similar uncertainties in the mean MOD04/MYD04 τ as suggested by the MODIS aerosol group, while biases are nonlinear for τ larger than 0.6. We showed that uncertainties in MOD04/MYD04 data can be reduced, and the correlation between

An over-land aerosol optical depth data set for data assimilation by filtering, correction, and aggregation of MODIS Collection 5 optical depth retrievals

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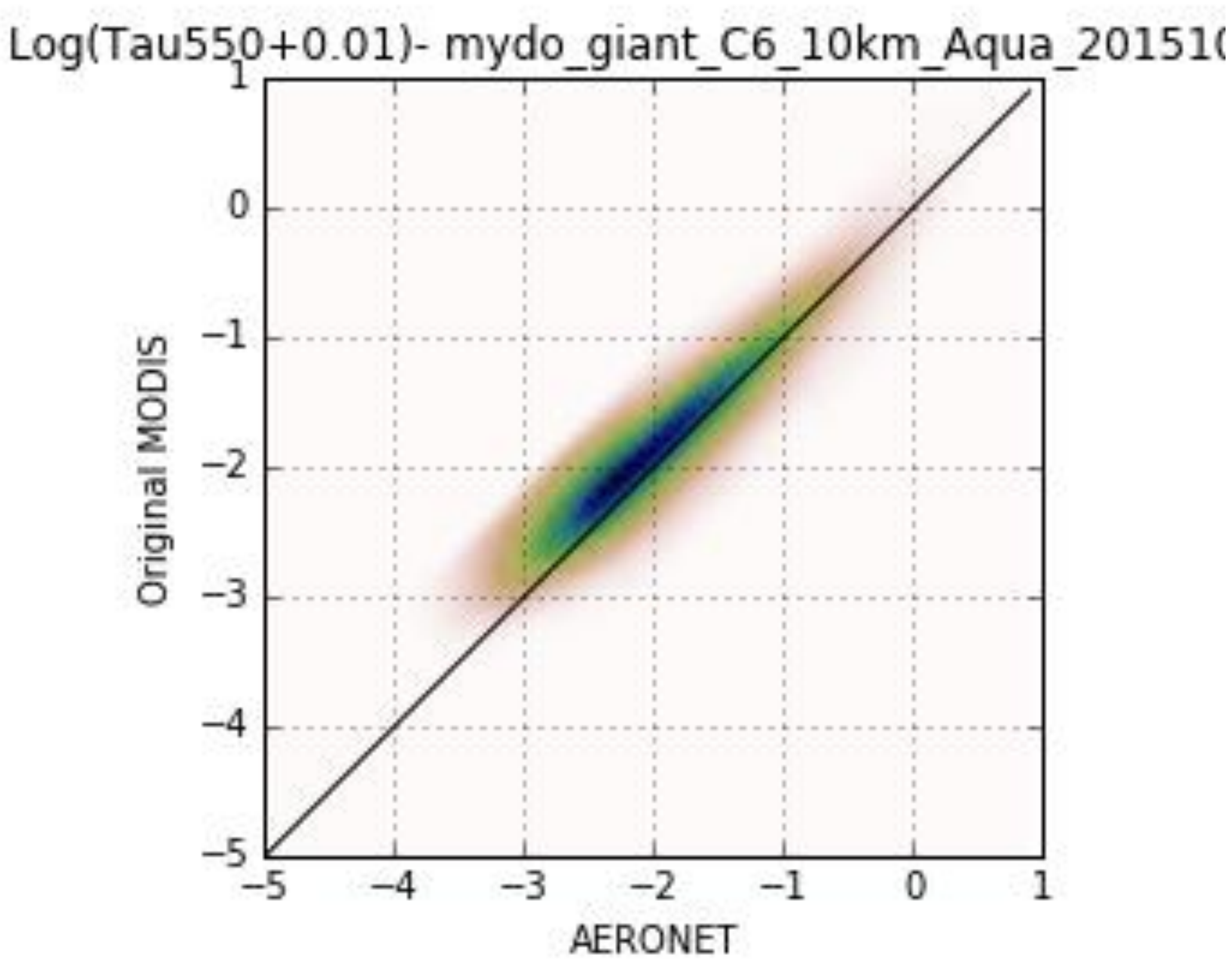
Neural Net for MODIS C5 AOD Empirical Retrievals

- **Ocean Predictors**
  - Multi-channel
    - TOA Reflectances
    - ~~Retrieved AOD~~
  - Angles
    - Glint
    - Solar
    - Sensor
  - Cloud fraction (<70%)
  - Wind speed
- **Target: AERONET**
  - Log(AOD+0.01)

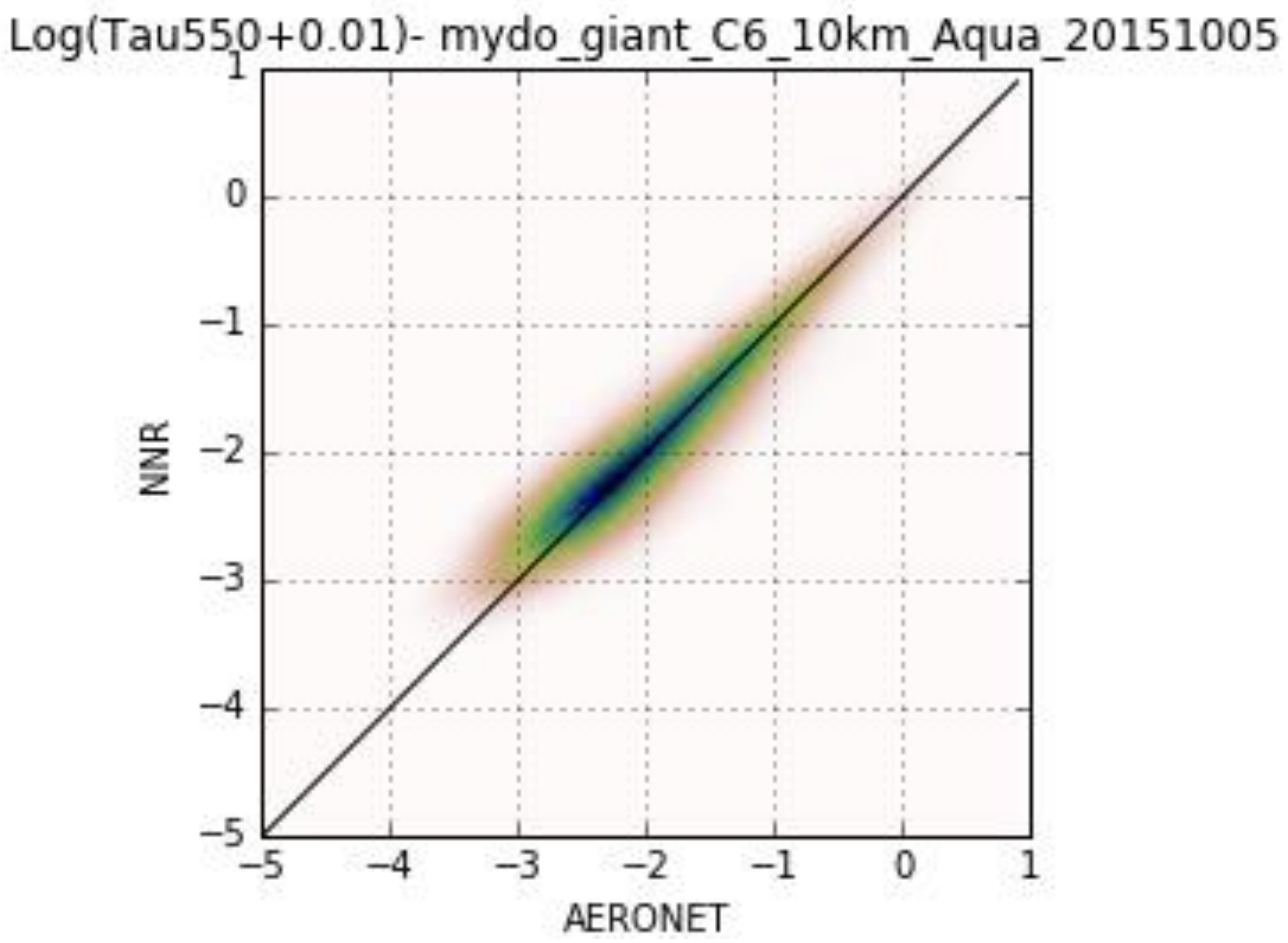
- **Land Predictors**
  - Multi-channel
    - TOA Reflectances
    - ~~Retrieved AOD~~
  - Angles
    - Solar
    - Sensor
  - Cloud fraction (<70%)
  - Surface Albedo or BRDF Kernels
- **Target: AERONET**
  - Log(AOD+0.01)

Observational Bias

ORIGINAL MODIS C6 AOD



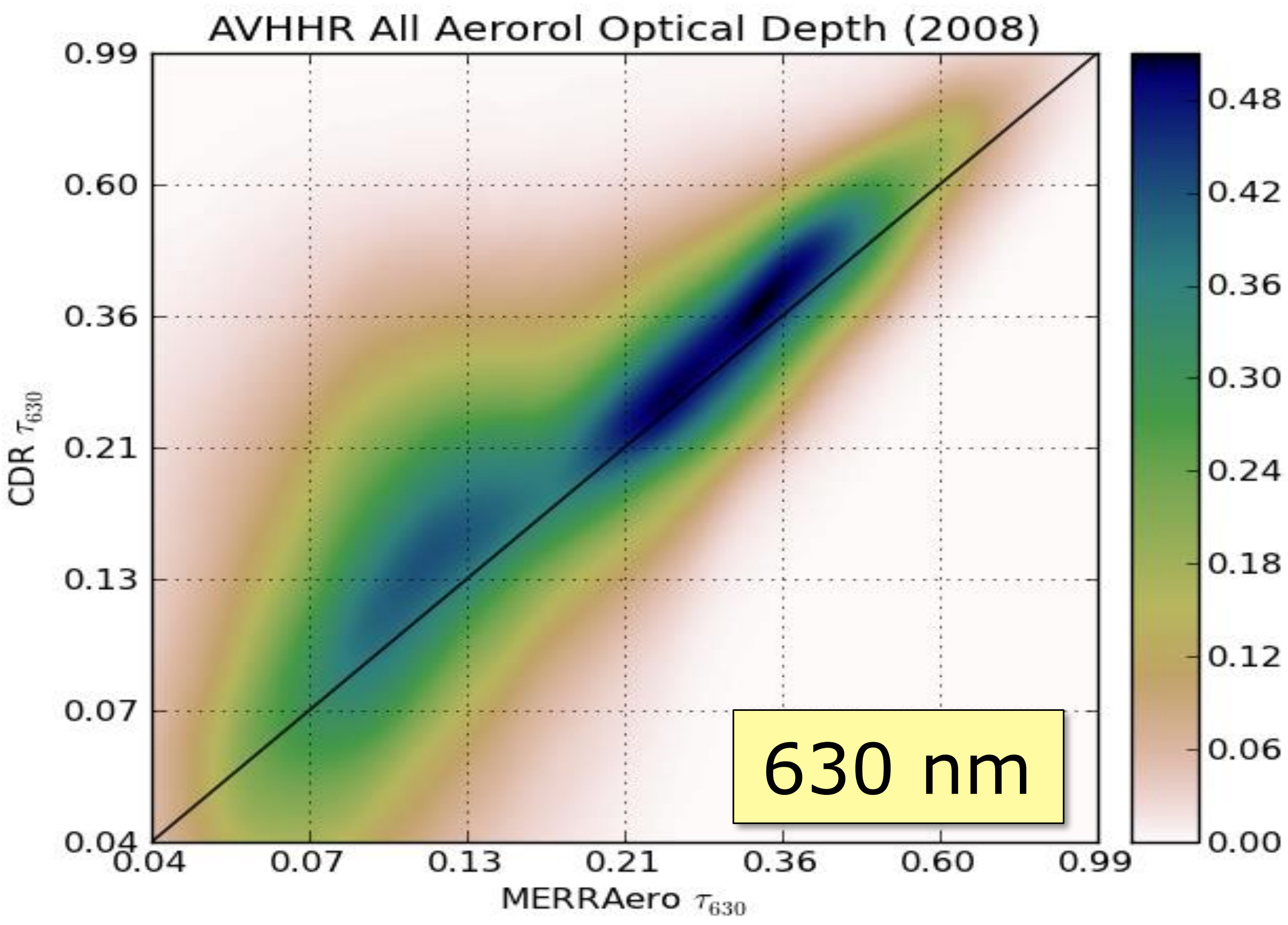
BIAS CORRECTED AOD



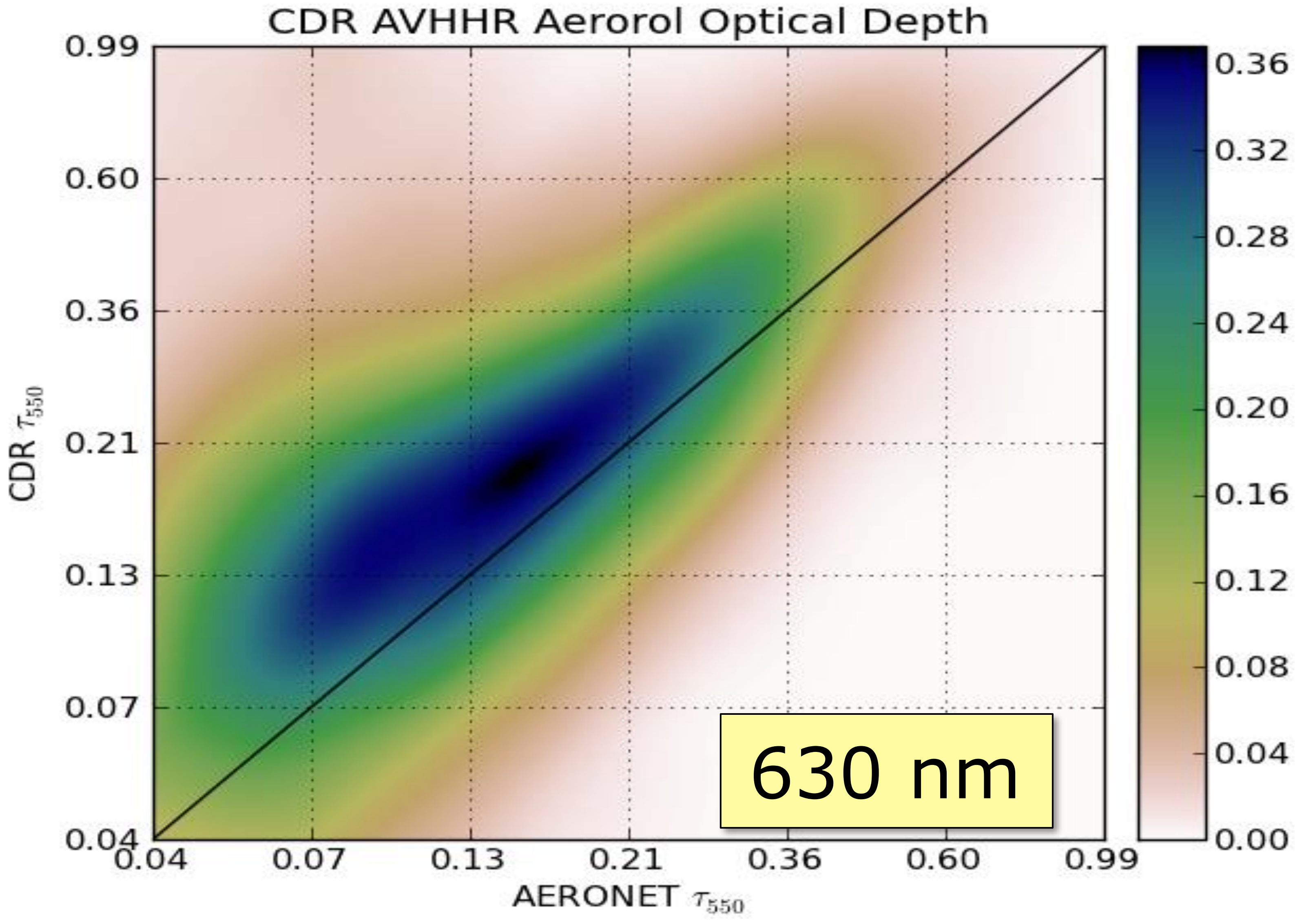
MODIS Neural Net AOD Retrievals trained on AERONET

AVHRR NOAA CDR AOD

MERRAero, AERONET Comparison



MERRAero



AERONET

PATMOS-x

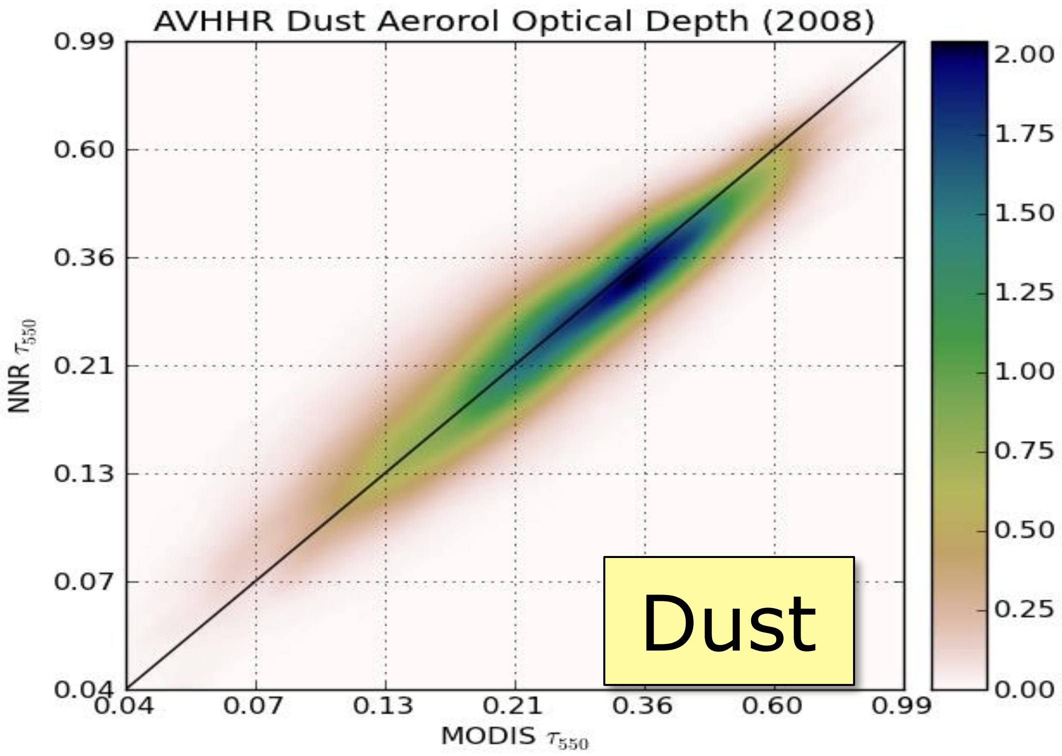
AVHRR Pathfinder Atmospheres - Extended

PATMOS-X DATASET

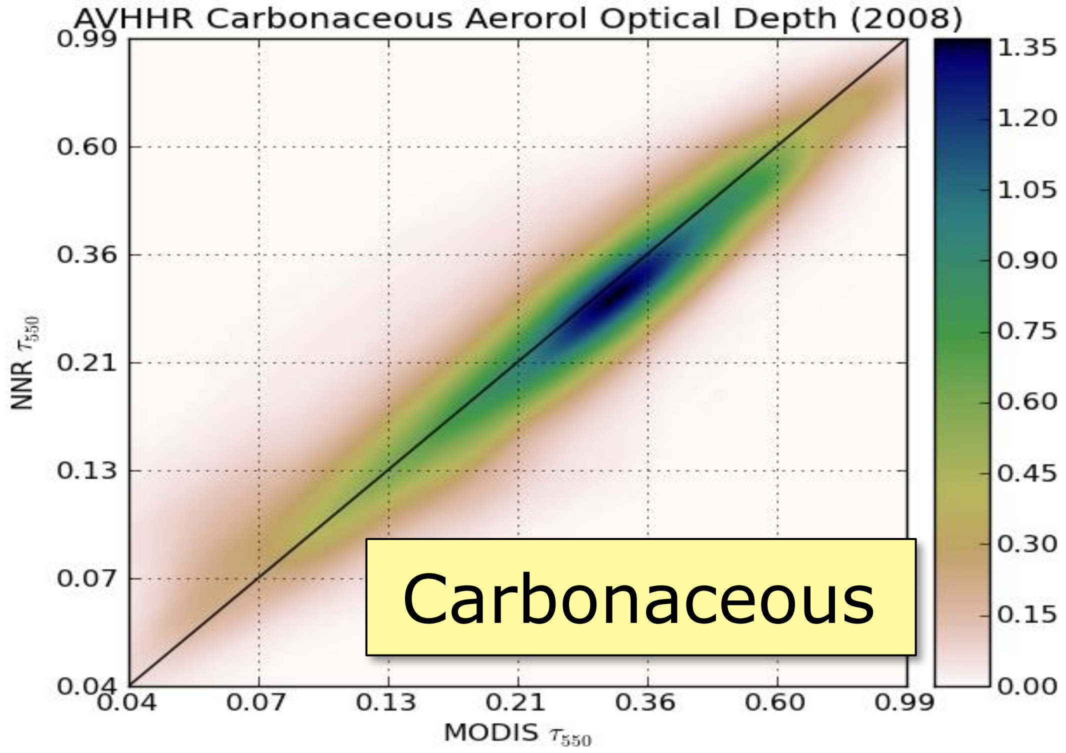
- Version 5 Level 2B
- 0.1 degree sampling (not average)
- Period: 1978-2009
- Inter satellite calibration (MODIS reference)
- Bayesian probabilistic cloud detection (CALIPSO reference)
  - **cpd <0.5%**

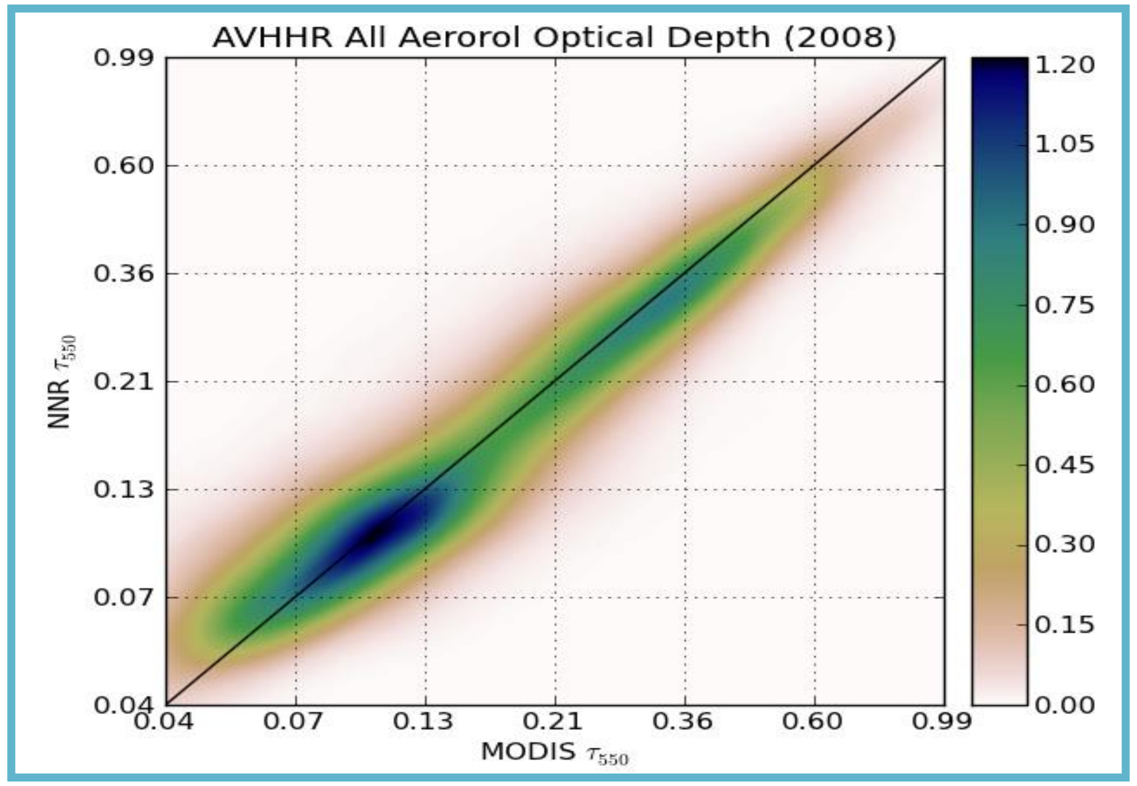
NEURAL NET RETRIVAL

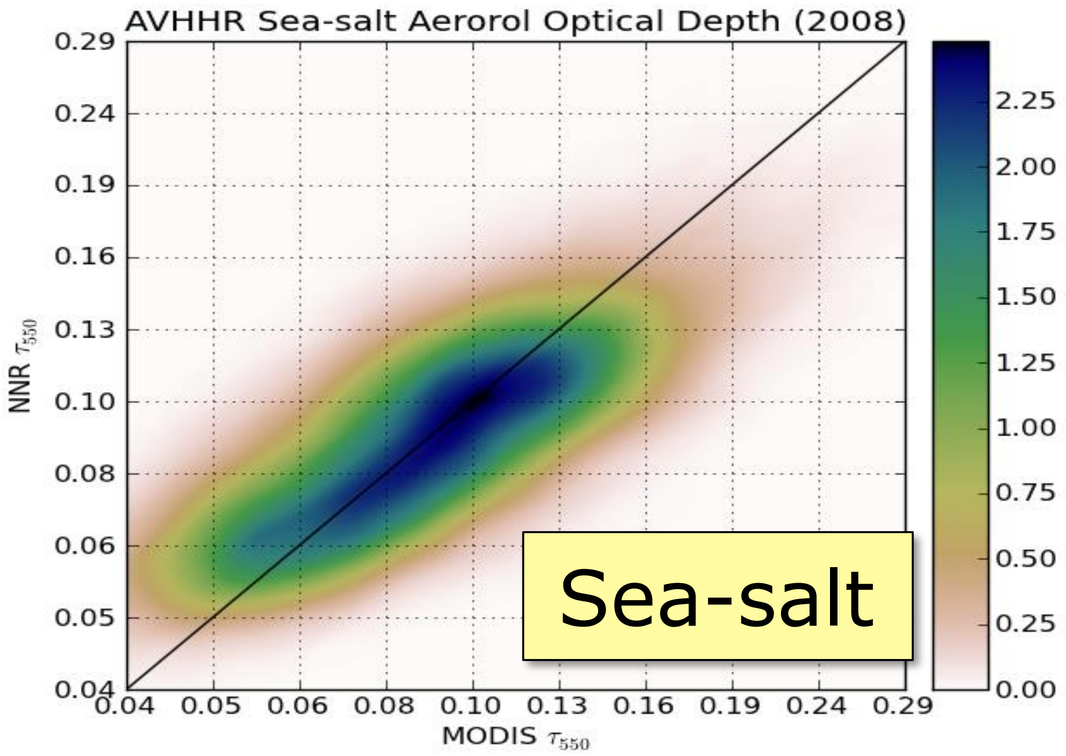
- Ocean Predictors
  - TOA Reflectances
  - 630 and 860 nm
  - TPW
  - Ocean albedo (wind)
  - Solar and sensor angles
  - GEOS-5 fractional AOD speciation
- Target:
  - AOD at 550 nm
  - Balanced MODIS NNR



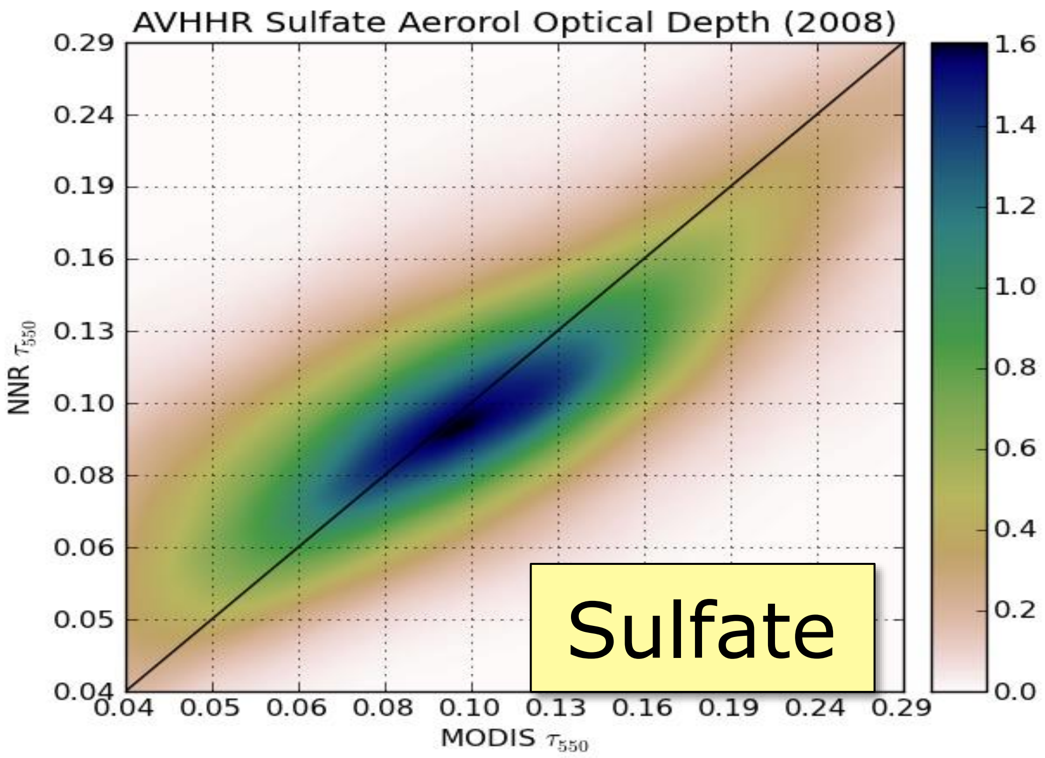
2008







NNR for AVHRR

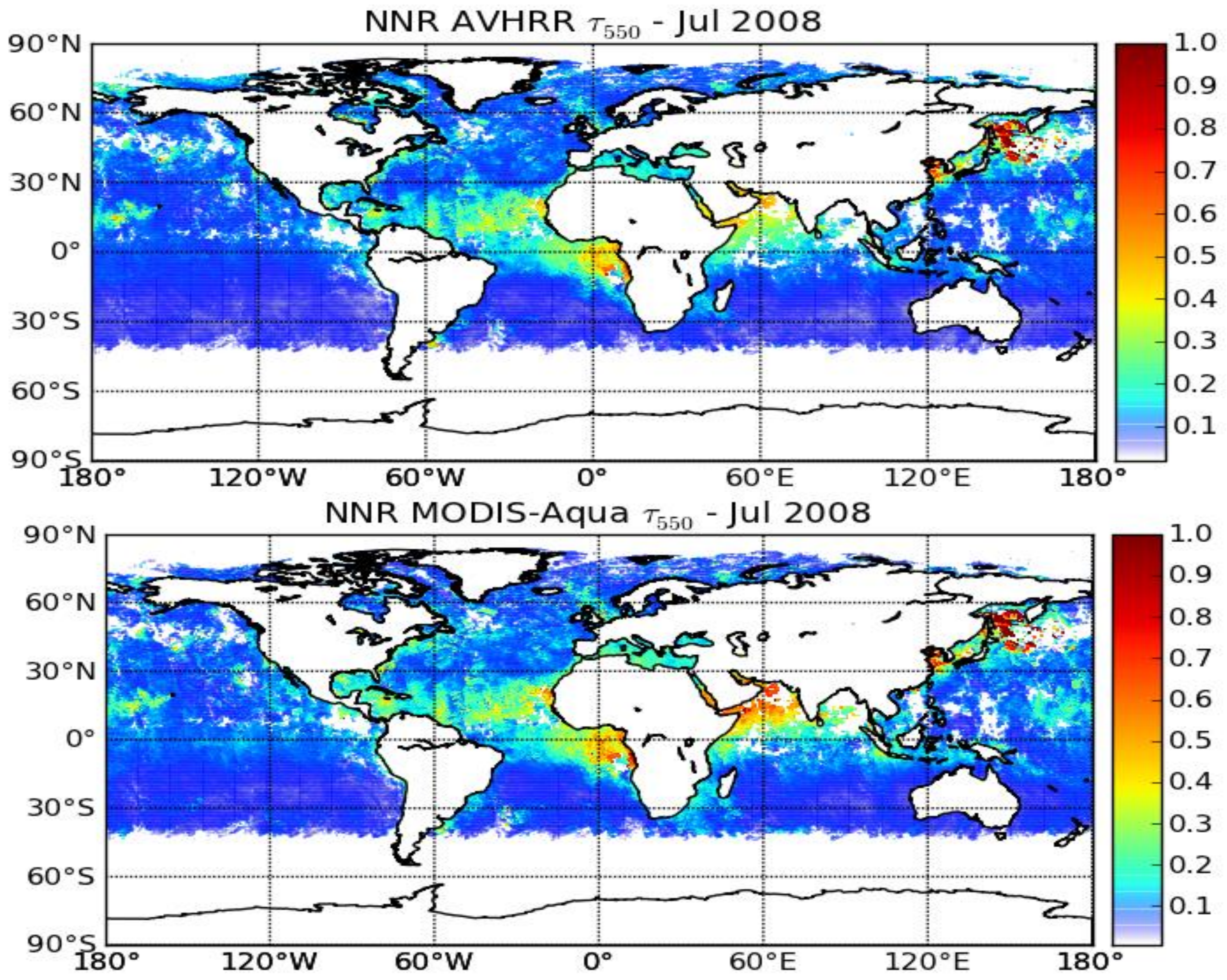


Calibration Transfer: AVHRR before EOS

Observing System Homogenization

In order to minimize spurious jumps due relative instrument biases MERRA-2 uses AERONET as reference in a series of Neural Net Retrievals (NNR) based on reflectances from:

- MODIS Collection 5
- PATMOS/X AVHRR

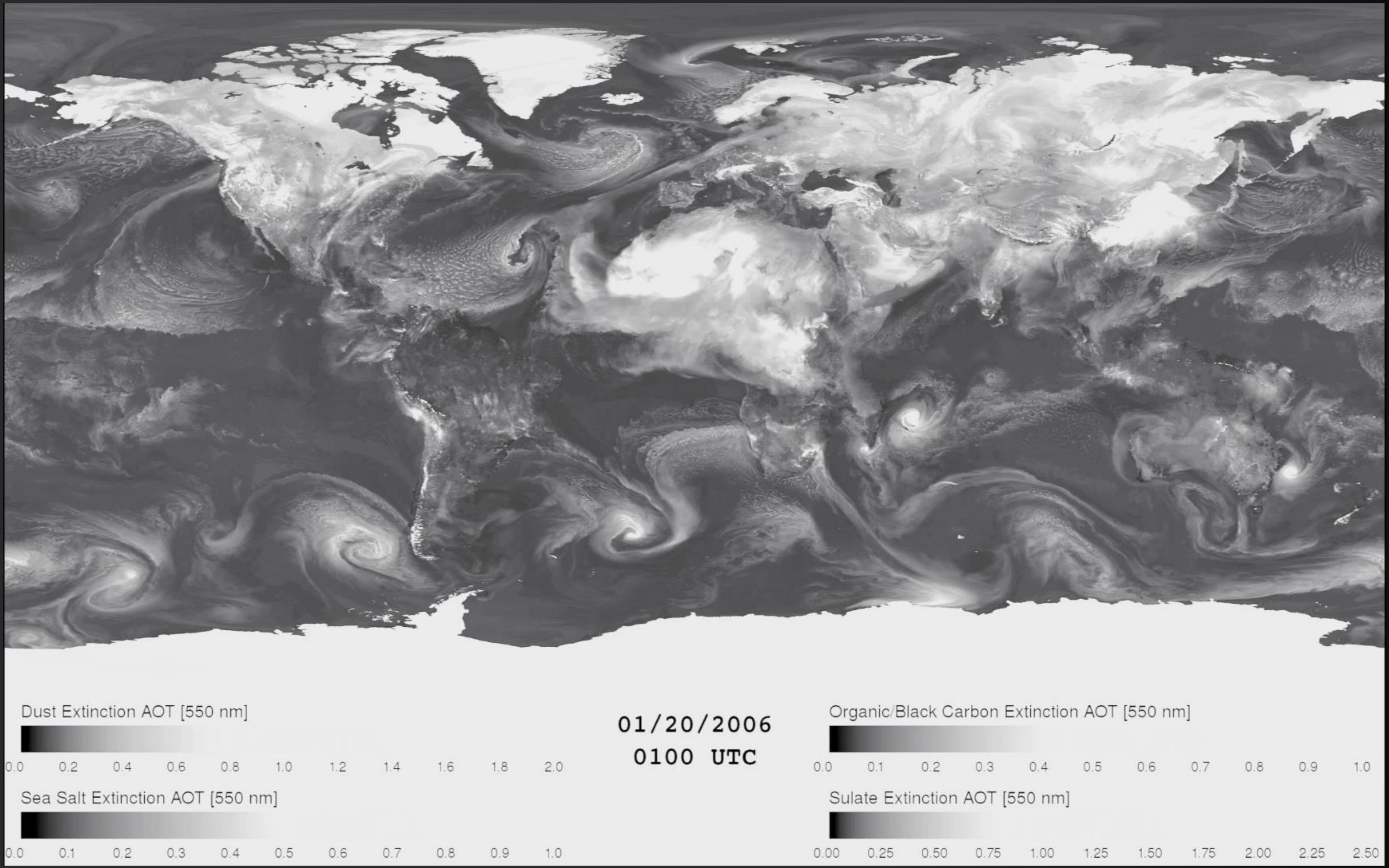


Beyond MERRA-2

Aerosol Speciation

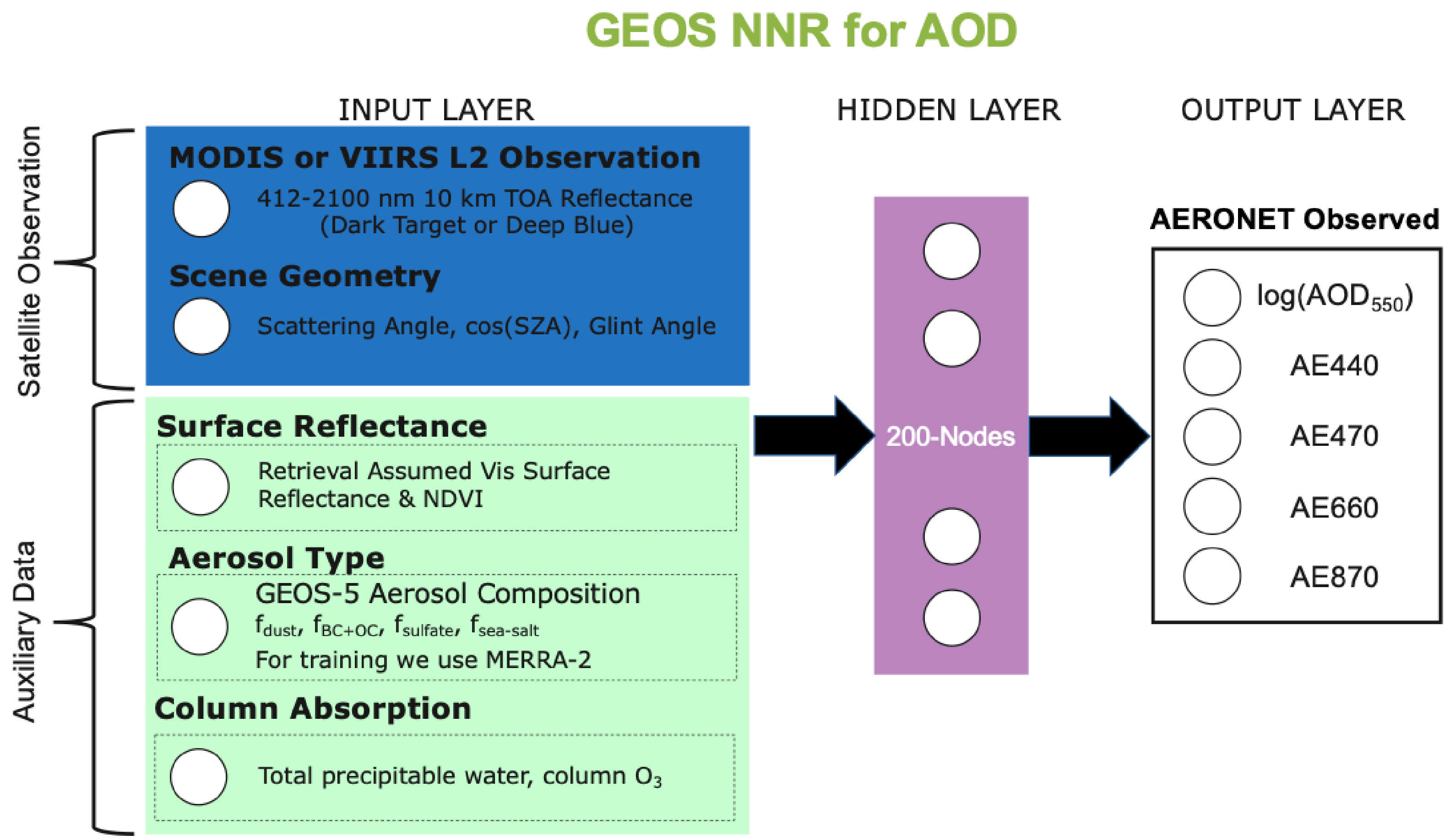
Aerosol Optical Depth (AOD) is the most commonly available observable used for DA

- Vertically integrated mass weighted by extinction coefficient, summed over multiple species: *low observability*
- Single-channel AOD has little impact on speciation
- Multi-spectral AOD measurements (better yet, hyperspectral measurments such as those provided by PACE OCI) permit the DA process to adjust the model speciation
- PACE multi-angle, multi-channel polarimeters will bring much needed information content such as size distribution, index of refraction



Beyond MERRA-2: Role of AERONET

- AERONET continues to provide the *calibration reference for the aerosol observing system*
- The original single wavelength Neural Net retrieval algorithm has been extended to multiple wavelengths allowing Angstrom exponent retrieval
- Multi-channel AOD derived from multi-channel *Level 2 Reflectances:*
  - Generally, can reduces latency for NRT applications
  - No dependency on assumed *aerosol models*
  - Model forecast provides speciation prior



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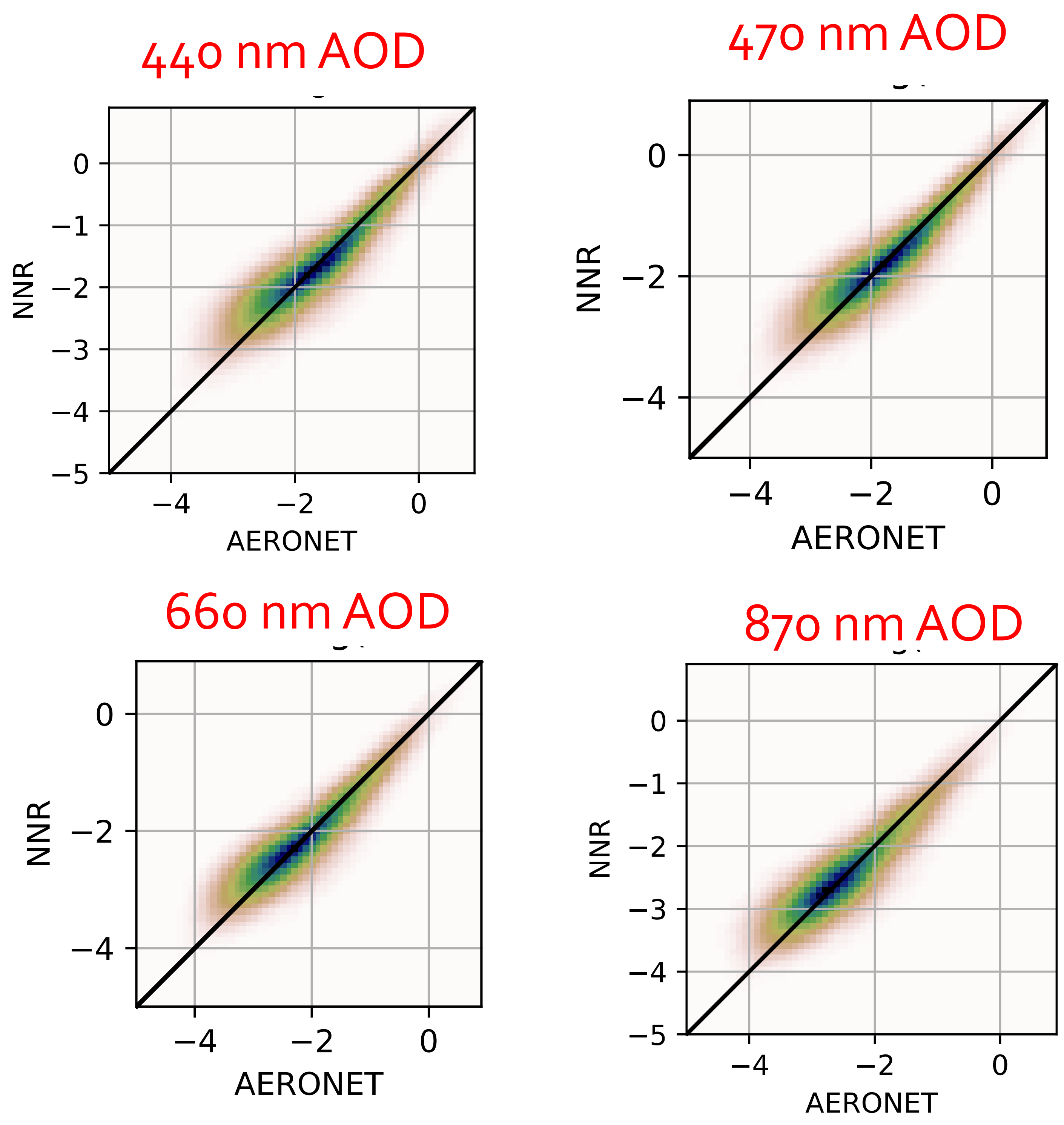
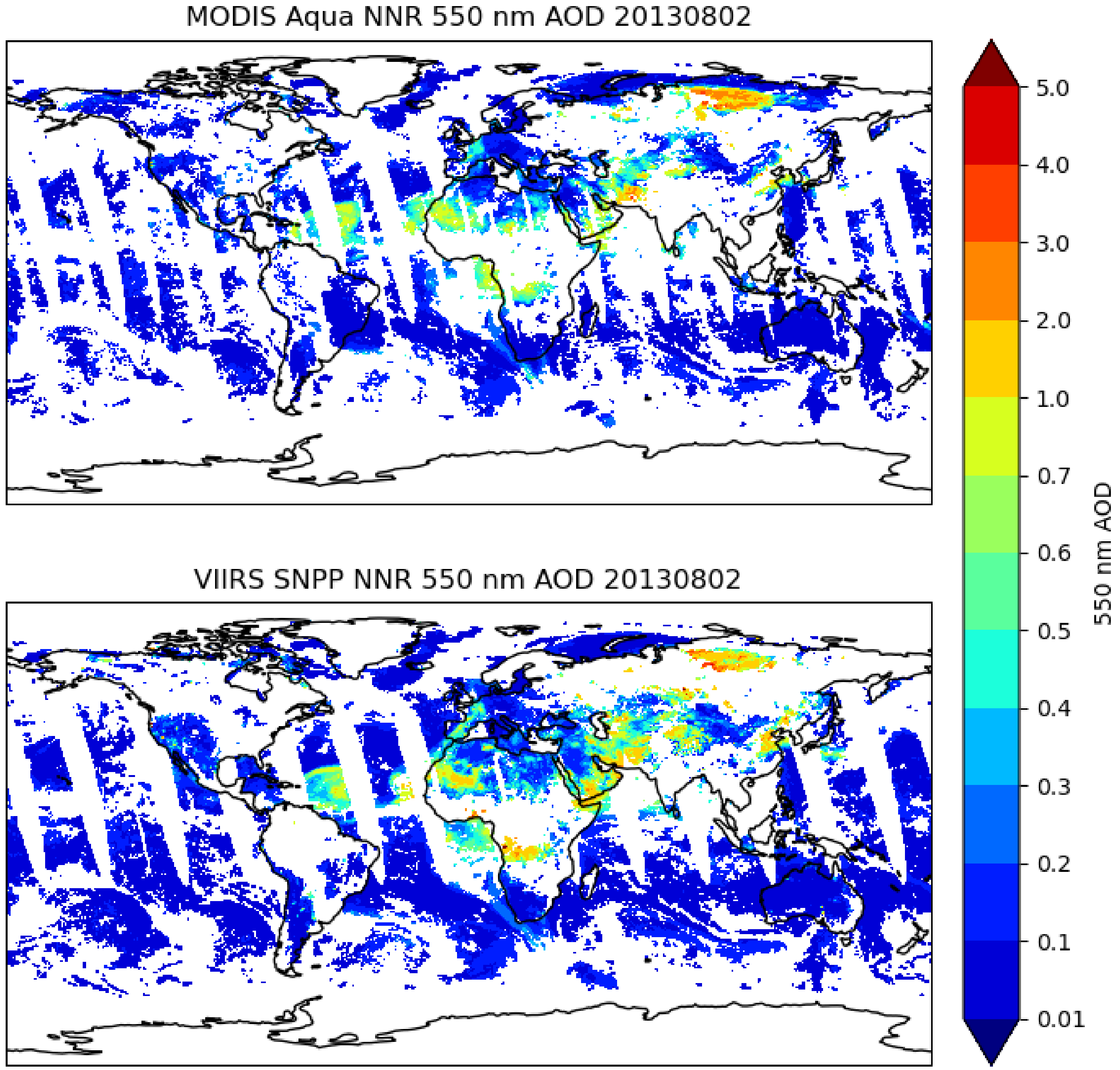
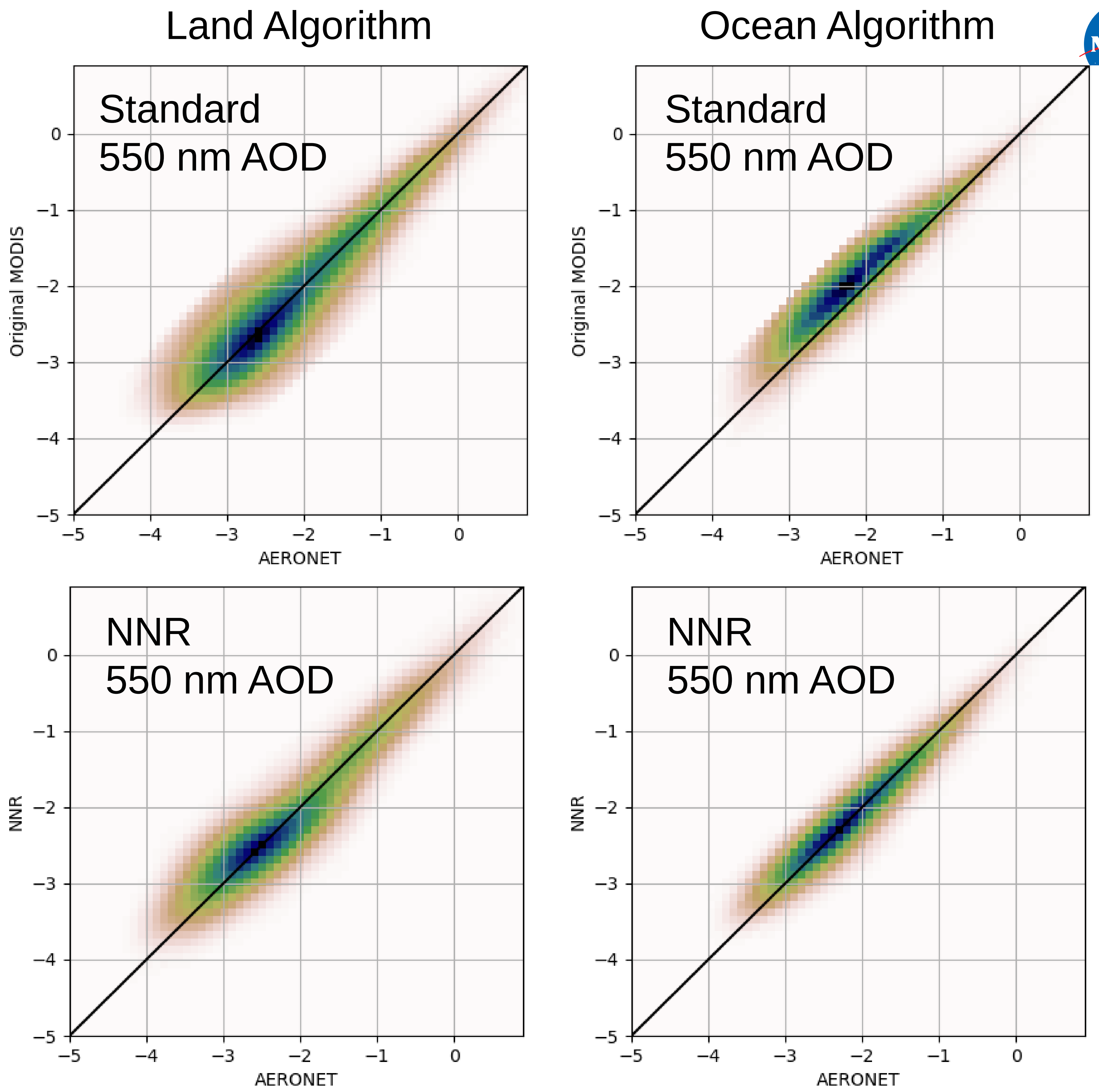
MODIS

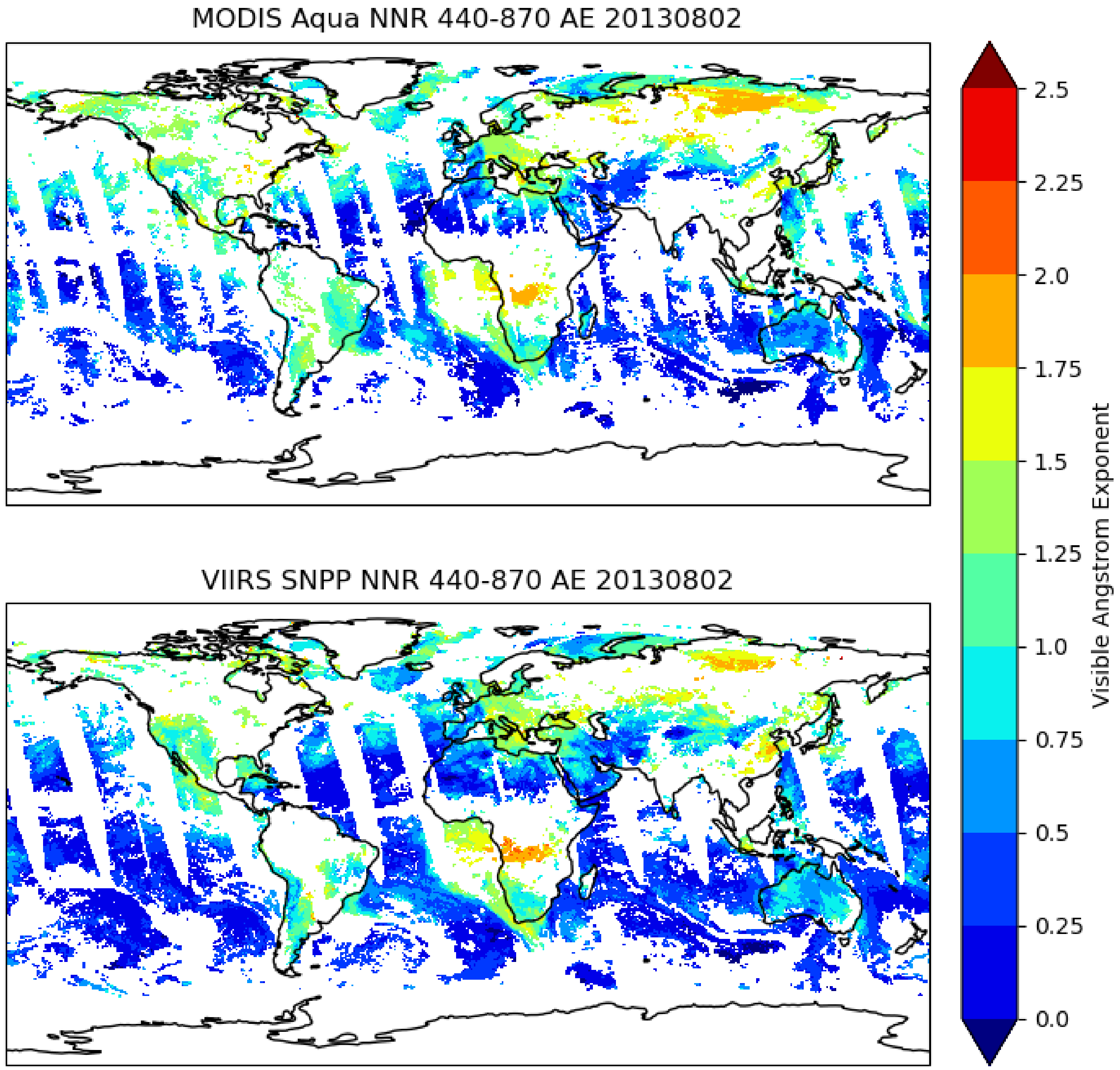


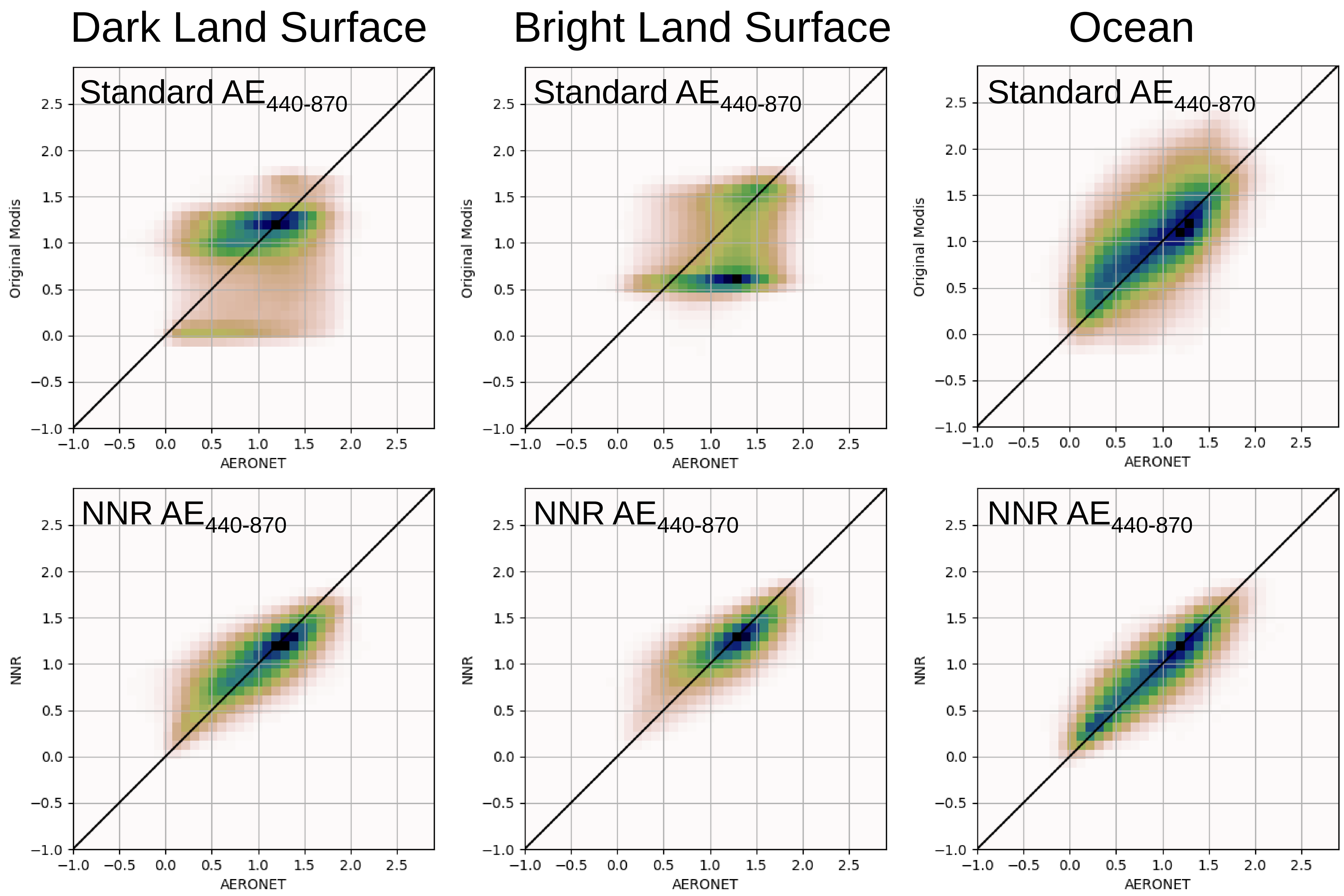
NNR Implemented on VIIRS-SNPP





NNR Algorithm Modified to Predict Visible Angstrom Exponent





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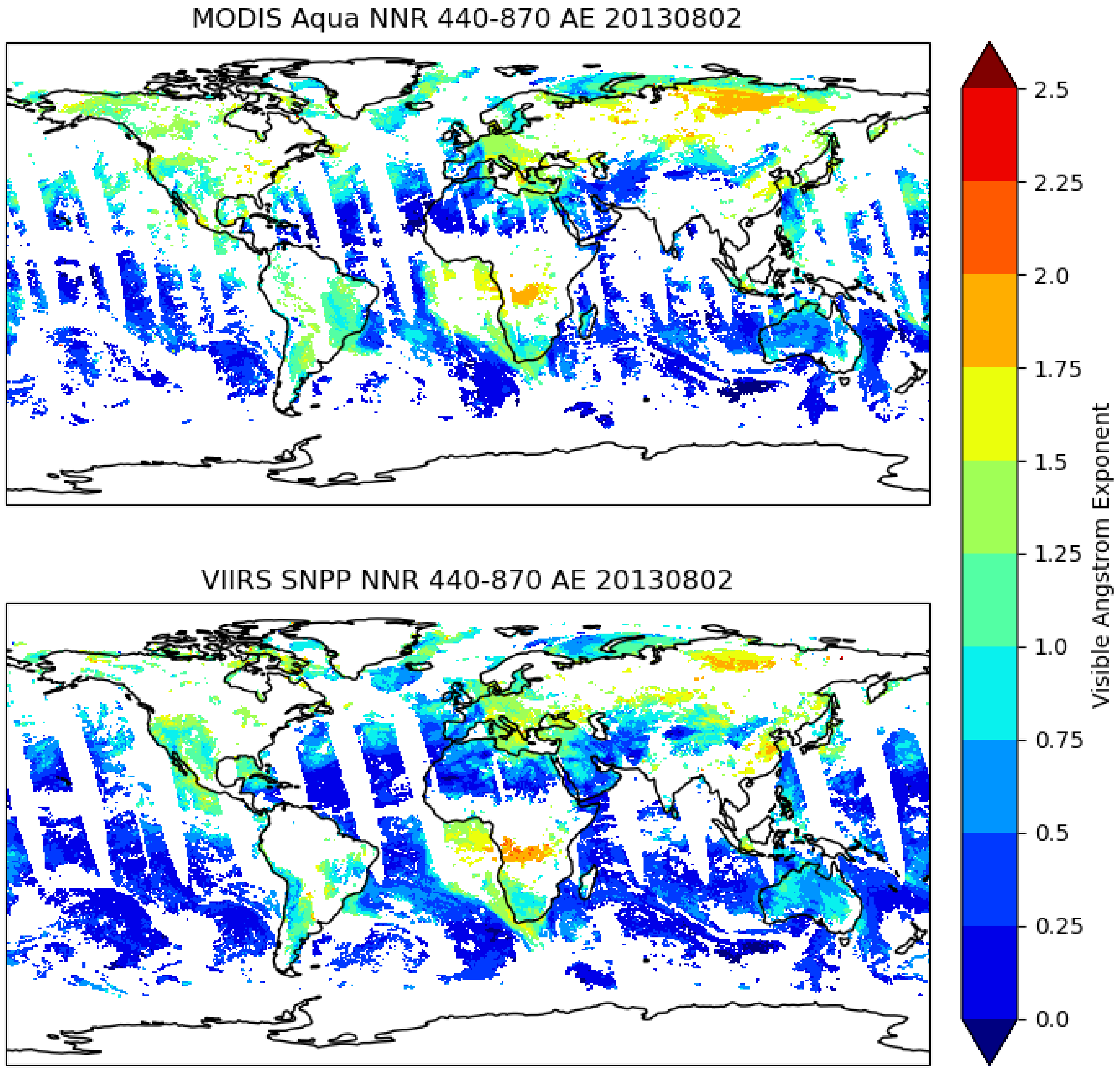
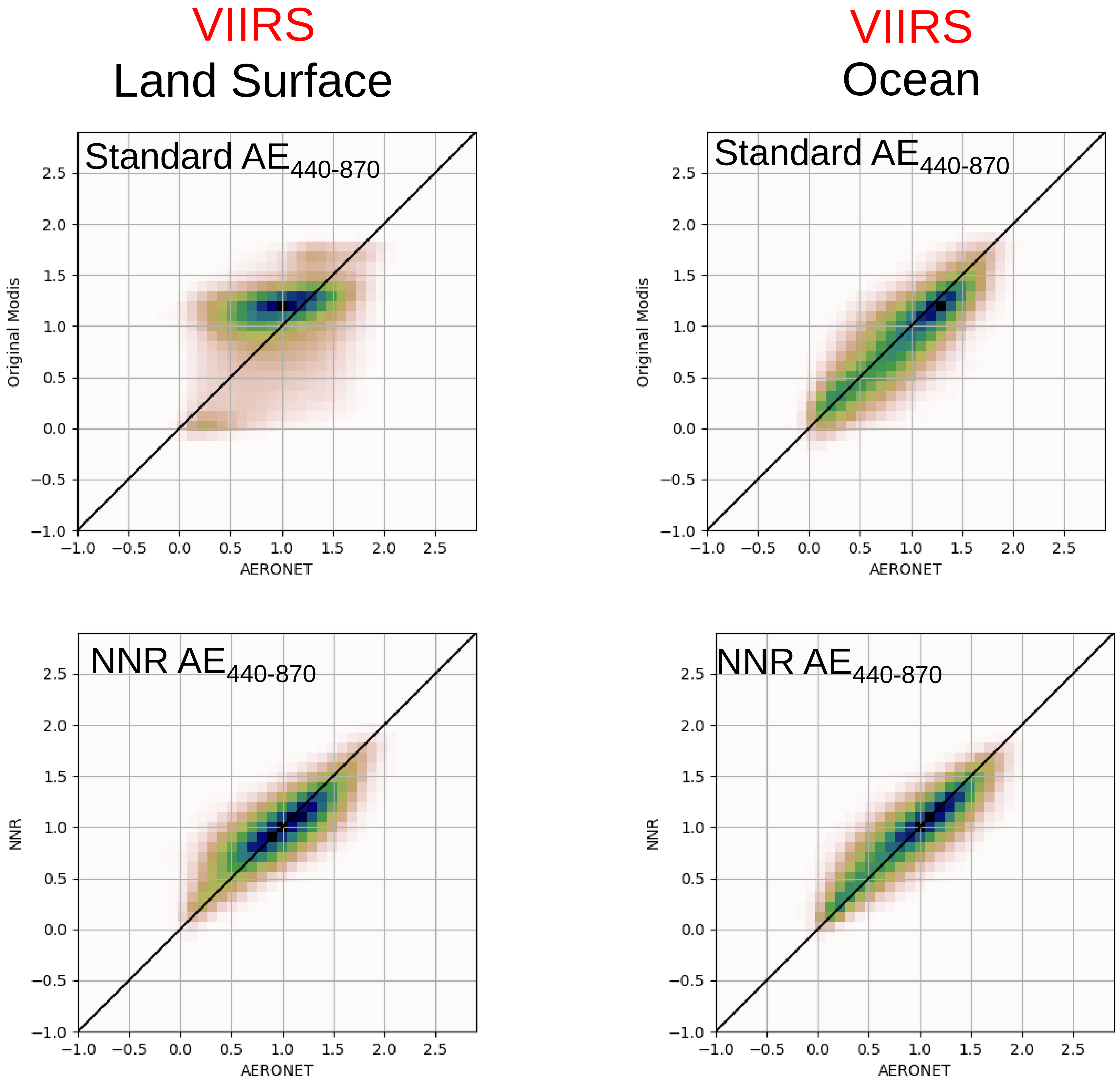
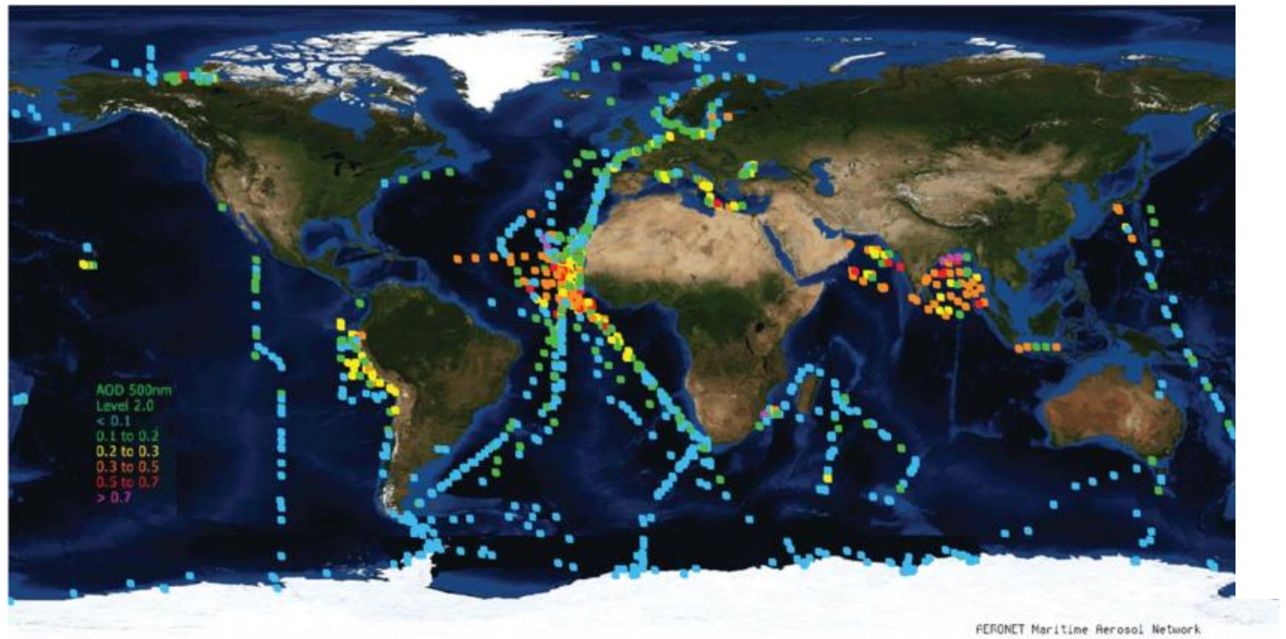


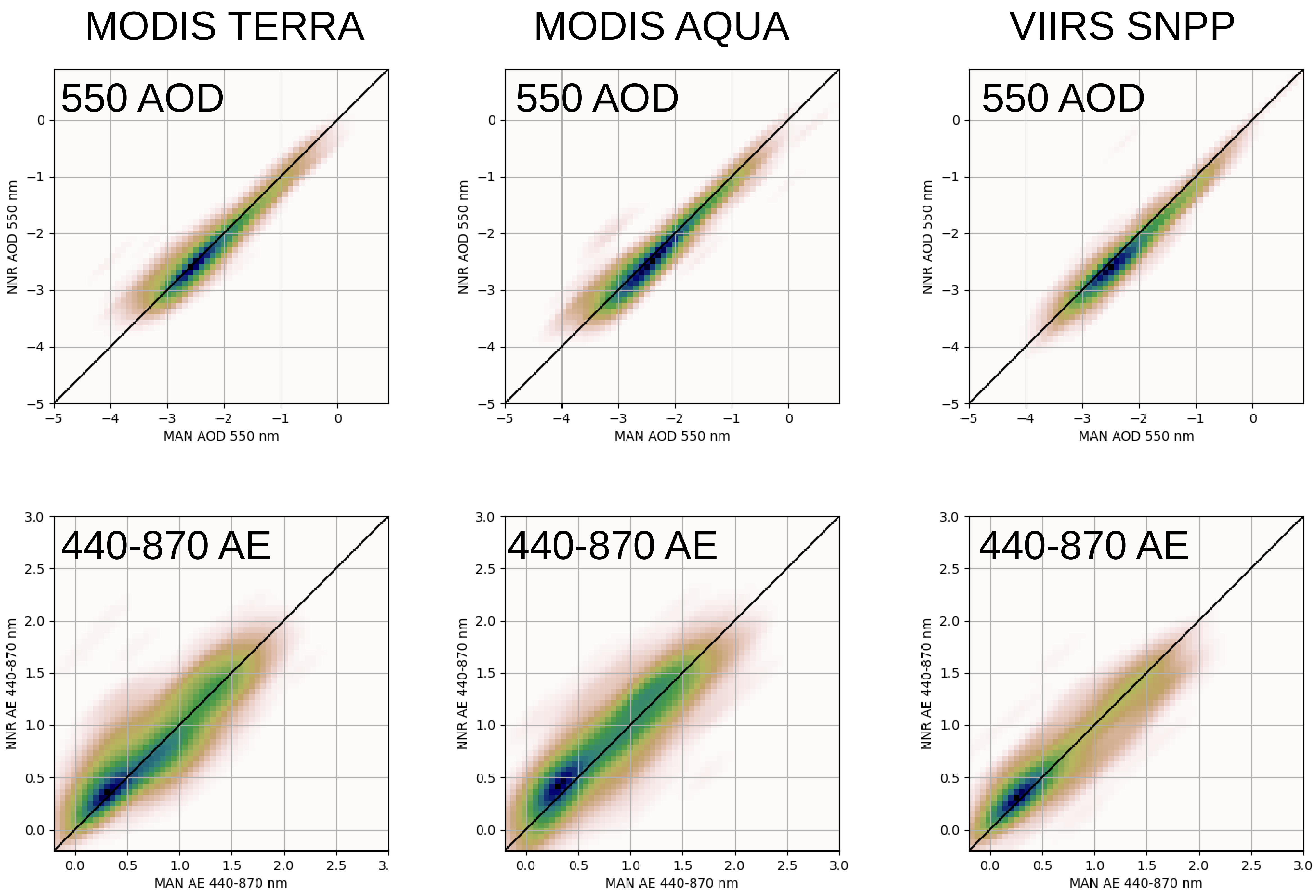


Validation: Comparison to Maritime Aerosol Network

Handheld sun photometers are deployed during research cruises

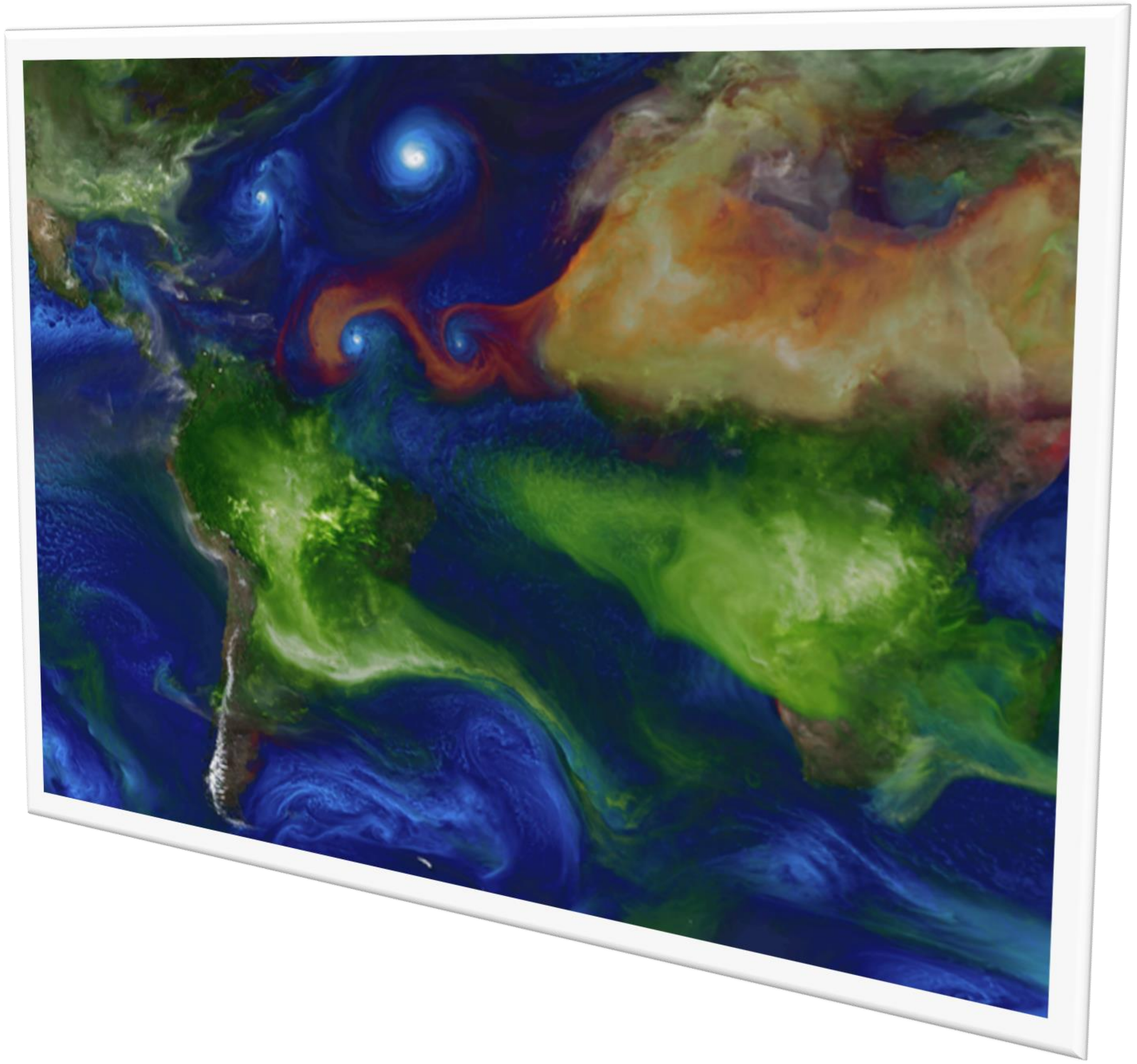
MAN Cruise Tracks



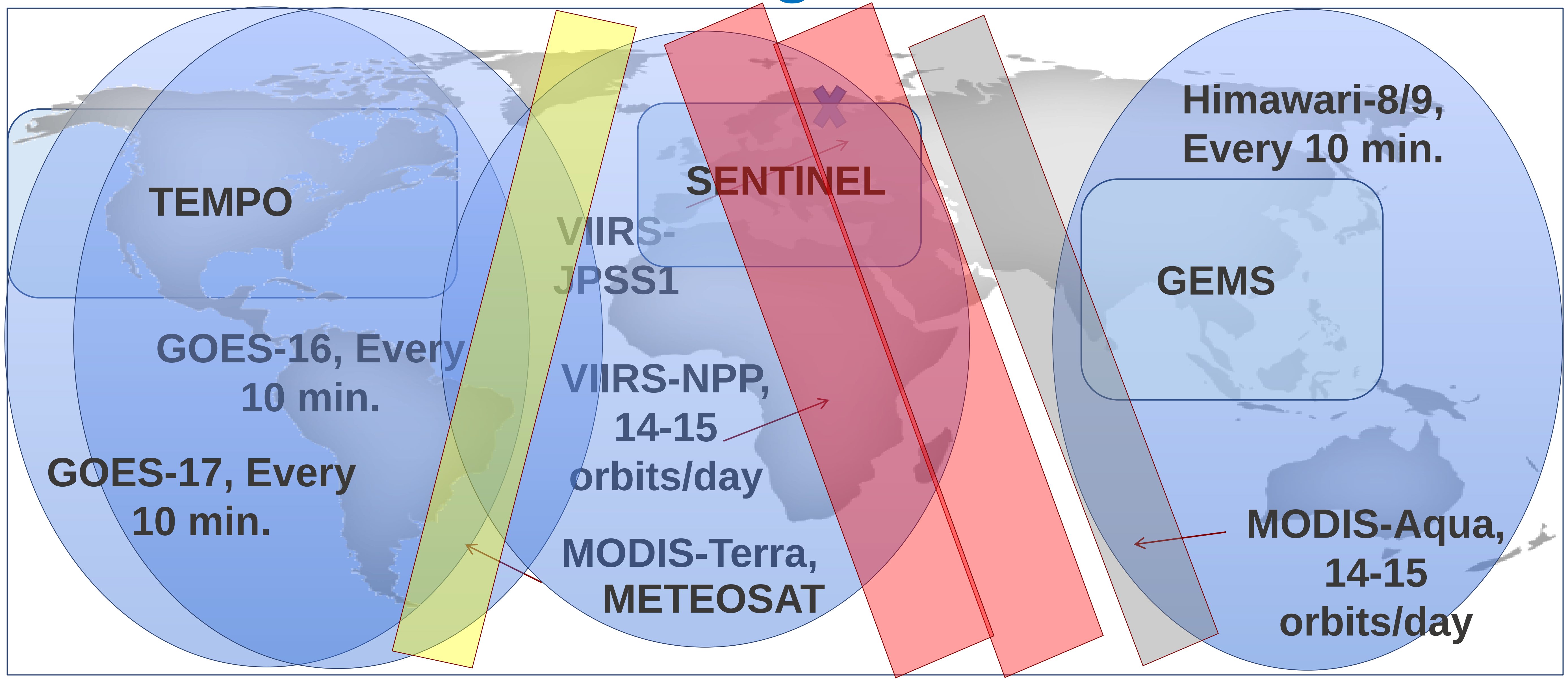


Summary

- GEOS is a flexible **global** Earth System model and data assimilation system in support of NASA applications
- All GEOS systems include aerosols coupled to radiation and cloud microphysics
- AERONET has played a critical role is GEOS aerosol data assimilation
  - Homogenization of the current observing system (MODIS, VIIRS)
  - Calibration transfer to historical AVHRR observations.
- AERONET has enabled NNR of visible Angstrom Exponent over land



Target Aerosol Observing System in GEOS: LEO & GEO Program of Record



- Current GEOS-FP system assimilates MODIS and AERONET observations
- Assimilation of geostationary GOES and Himawari data are in implementation and testing phases
- Assimilation of VIIRS planned after geostationary data have been implemented.

Extra Slides