The GEOS-5 Aerosol Forecasting and Data Assimilation System

Arlindo da Silva
Arlindo.dasilva@nasa.gov
Global Modeling and Assimilation Office, NASA/GSFC

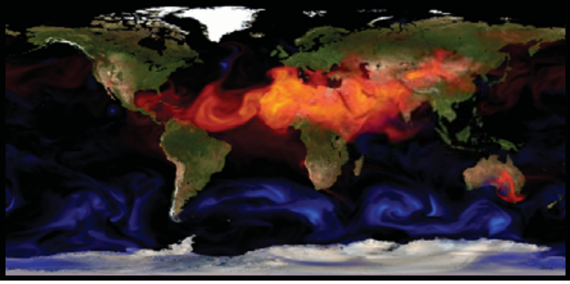
With contributions from Peter Colarco, Anton Darmenov, Virginie Buchard, Gala Wind, Cynthia Randles, Ravi Govindaradju and many others

World Weather Open Science Conference
Montreal, Canada
16-21 August 2014

Outline

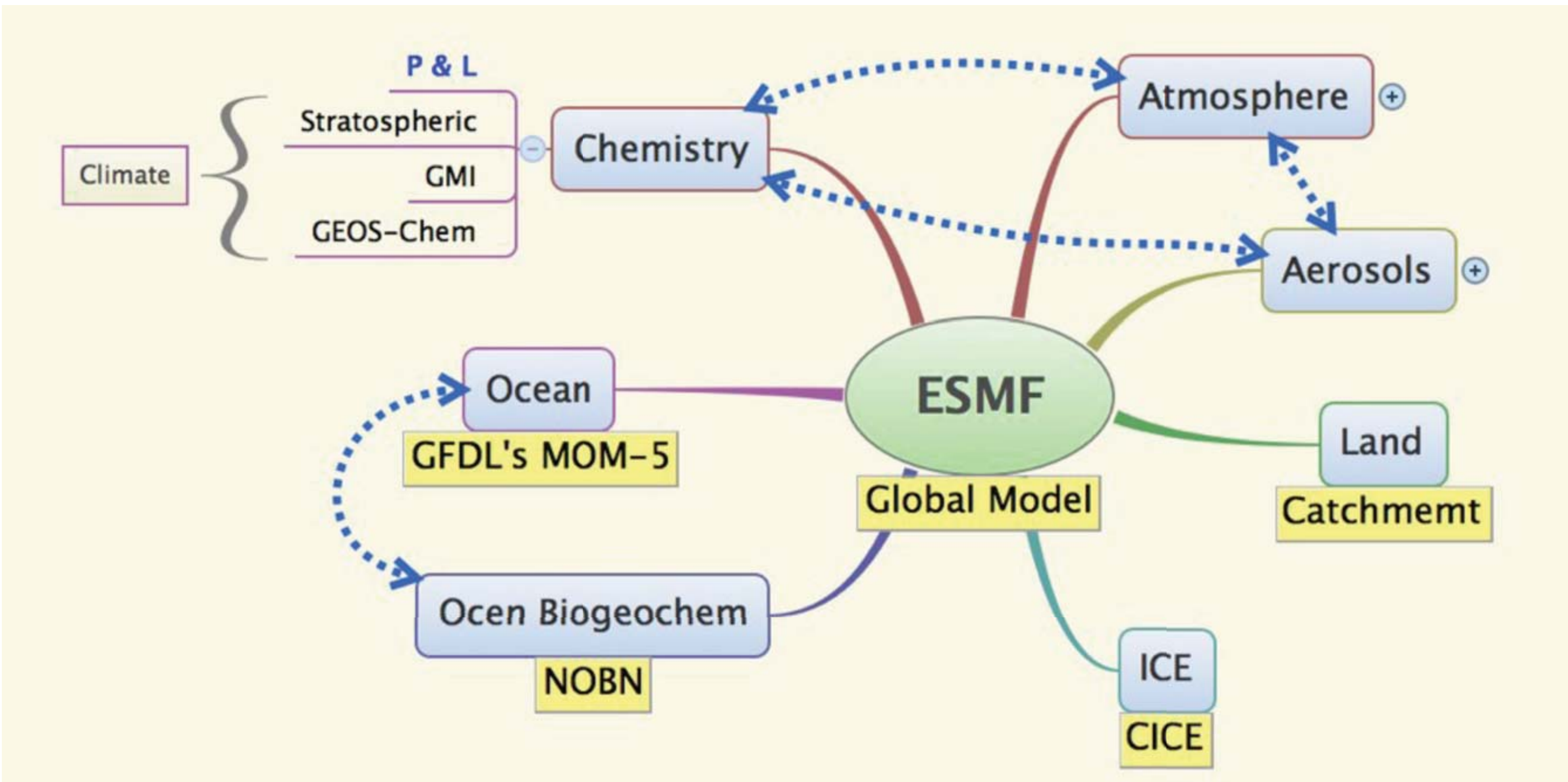
- GEOS-5 Overview
- Current capabilities and future directions
- Highlights:
  - Aerosol forecasting and field campaigns
  - Aerosol Reanalysis
  - OSSEs
- Concluding Remarks

Aerosol activities at GMAO



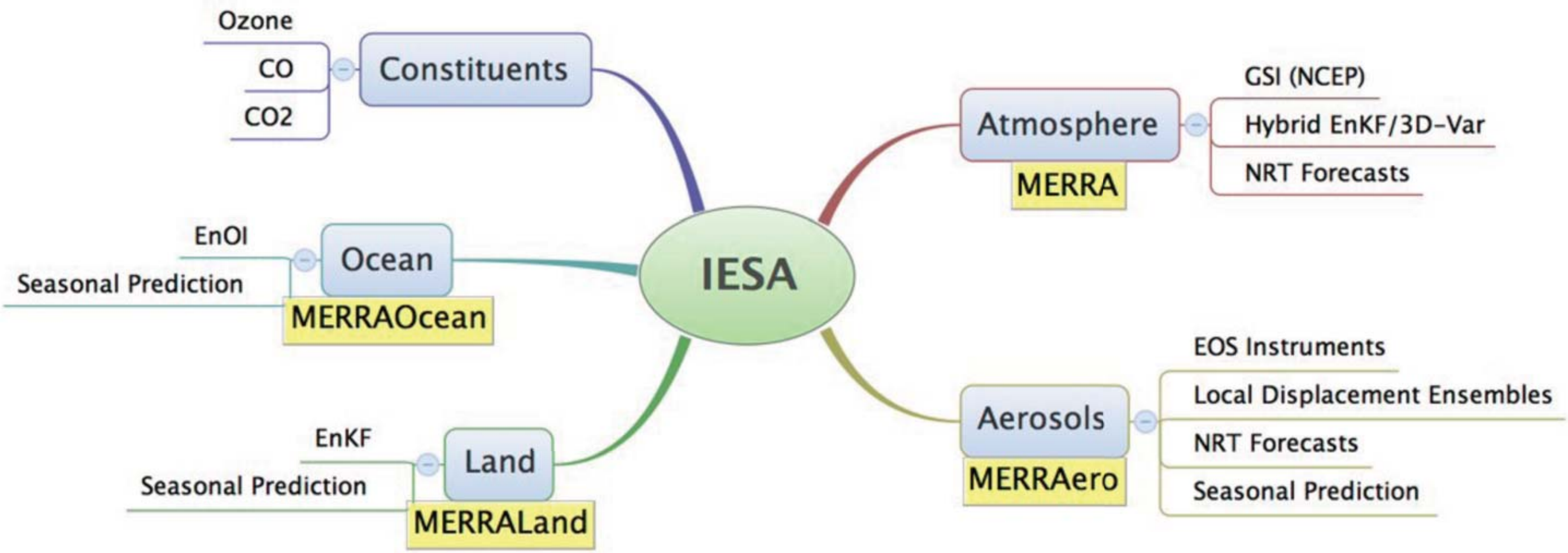
- Developing a **hierarchy of *global* models** capable of skillfully representing
  - the global aerosol distribution as depicted by available in-situ and remotely-sensed measurements
  - the microphysical processes needed for parameterizing cloud/ precipitation-aerosol feedbacks
  - Aerosol interaction with earth-system components
- Developing a comprehensive **aerosol data assimilation capability** for constraining and calibrating aerosol transport models, including the estimation of emissions needed for driving such models
- Developing an **aerosol forecasting capability** in support of NASA field campaigns.
- Developing an **aerosol observing system simulation capability** for aiding planning of future NASA observing missions.

GEOS-5 Earth System Model

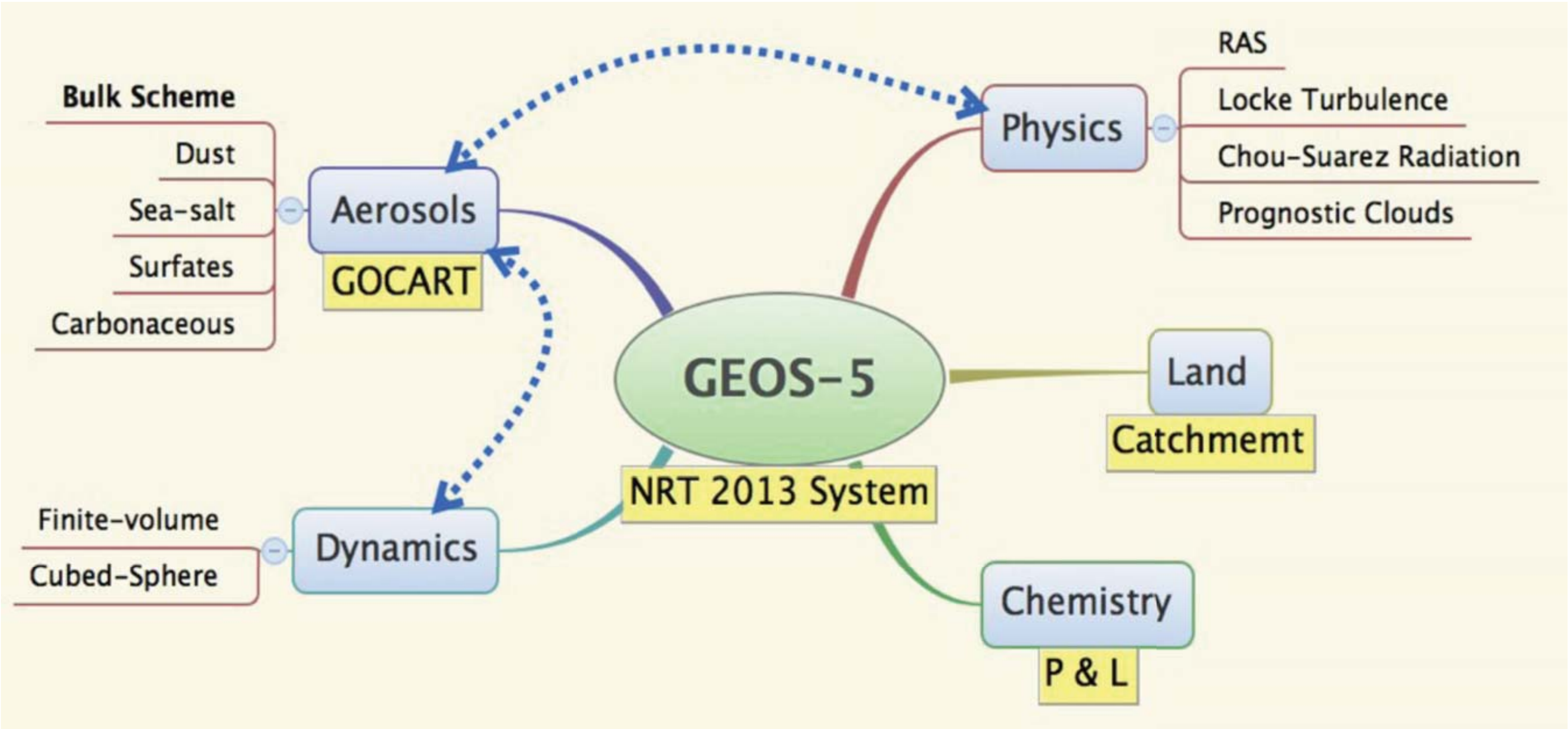


From weather to seasonal to decadal time scales

GEOS-5 Data Assimilation

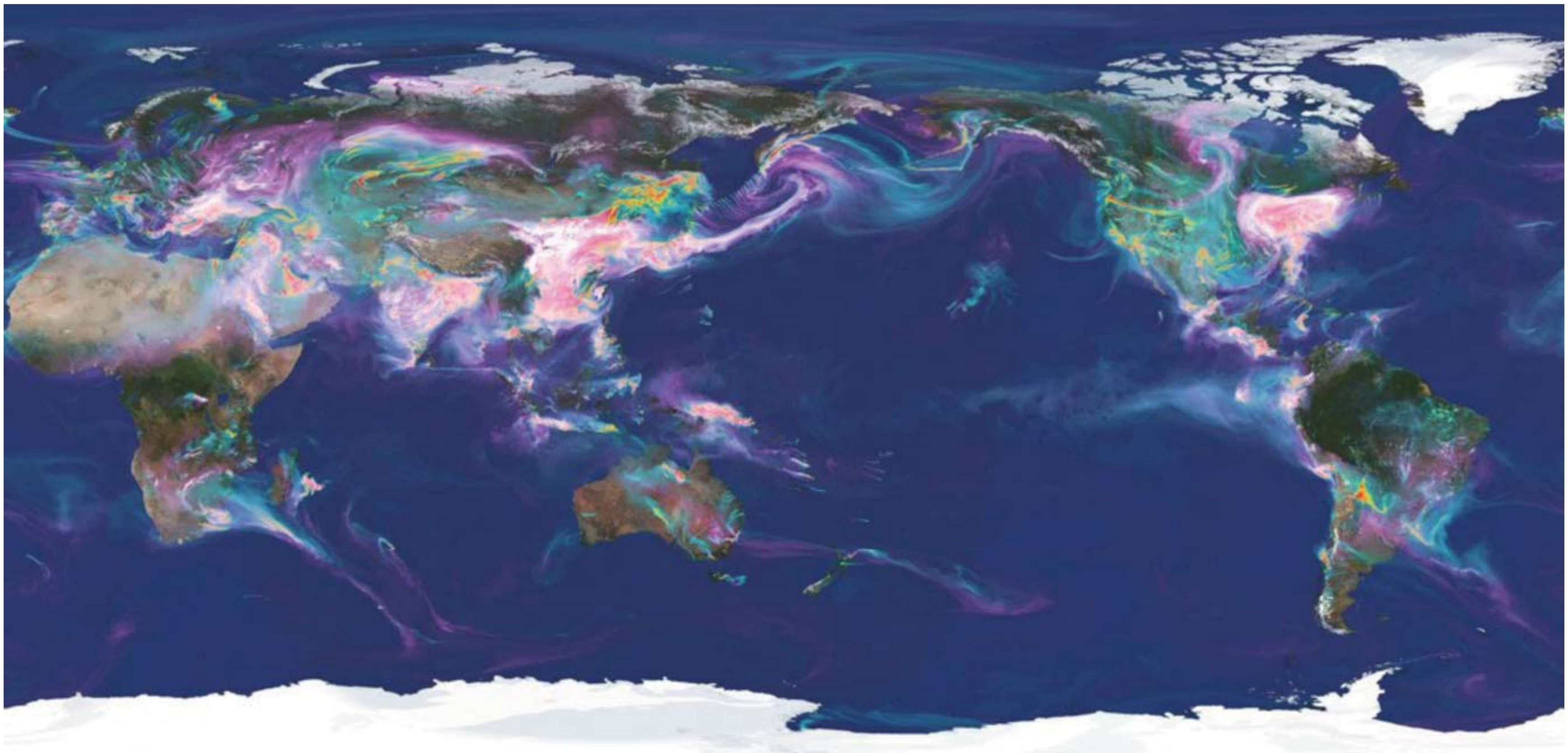


2014 NRT GEOS-5 Model Configuration



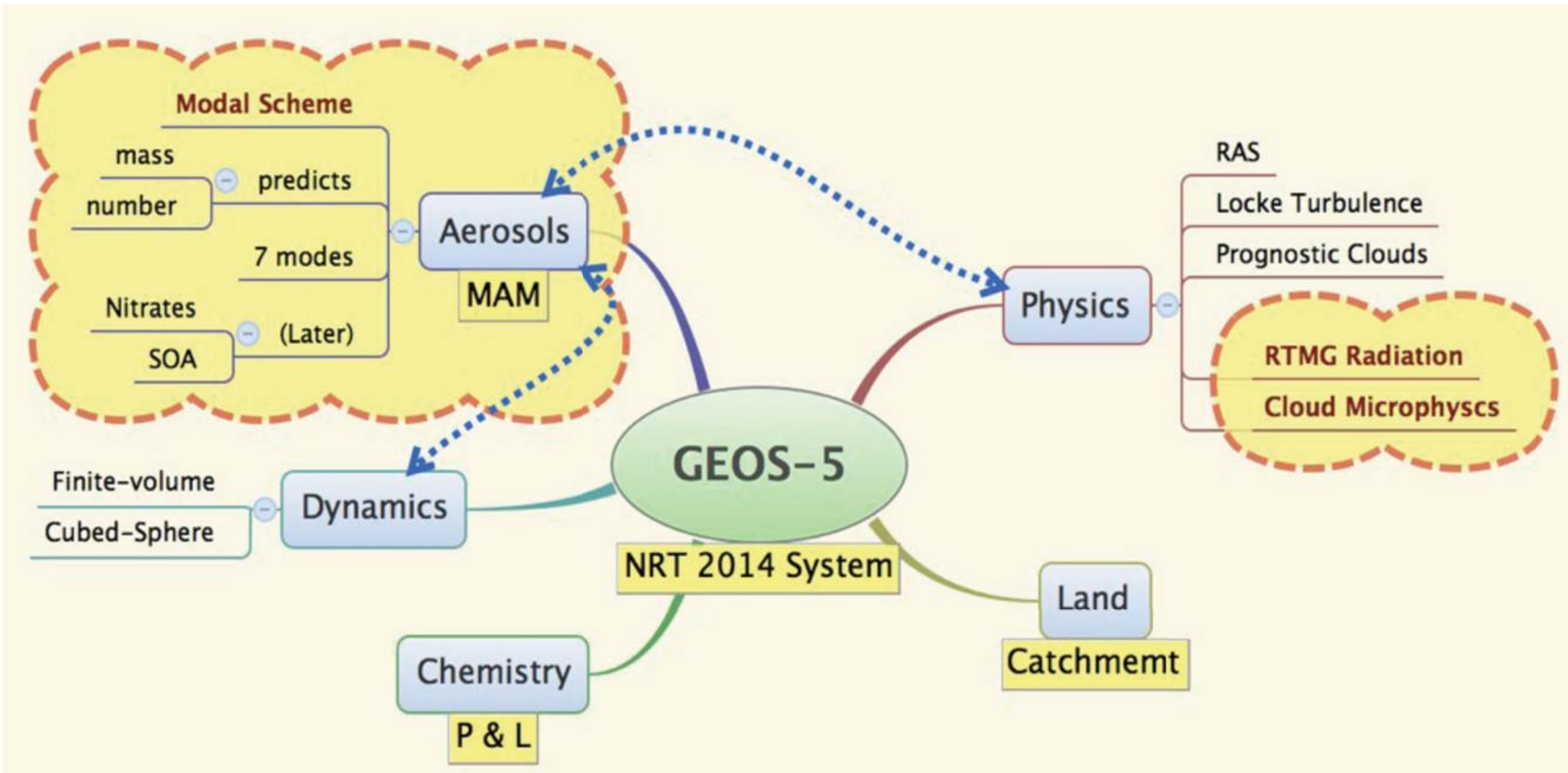
Global, 25 km, 72 Levels, top at 0.01 hPa

GEOS-5 SO_2 & Sulfates



Non-hydrostatic 7km global meso-scale simulation

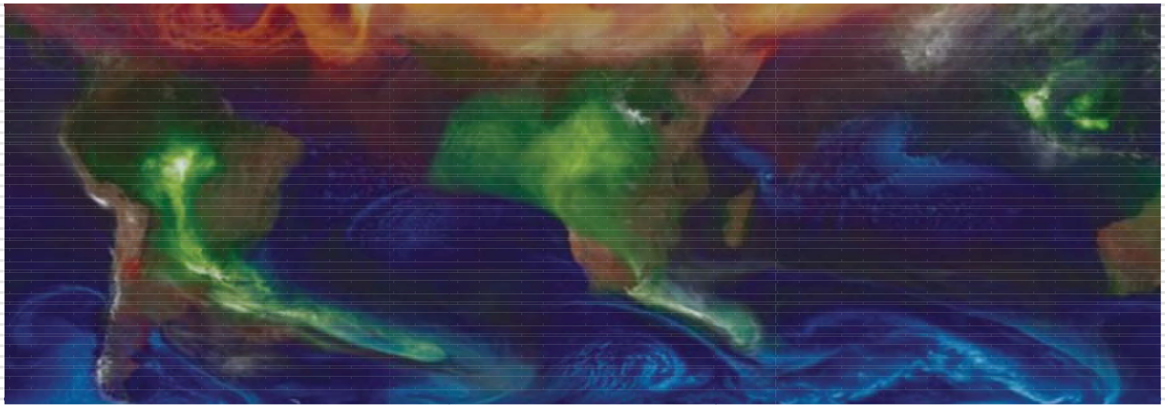
2015 NRT GEOS-5 Configuration



Global, **14 km**, **137** Levels, top at 0.01 hPa

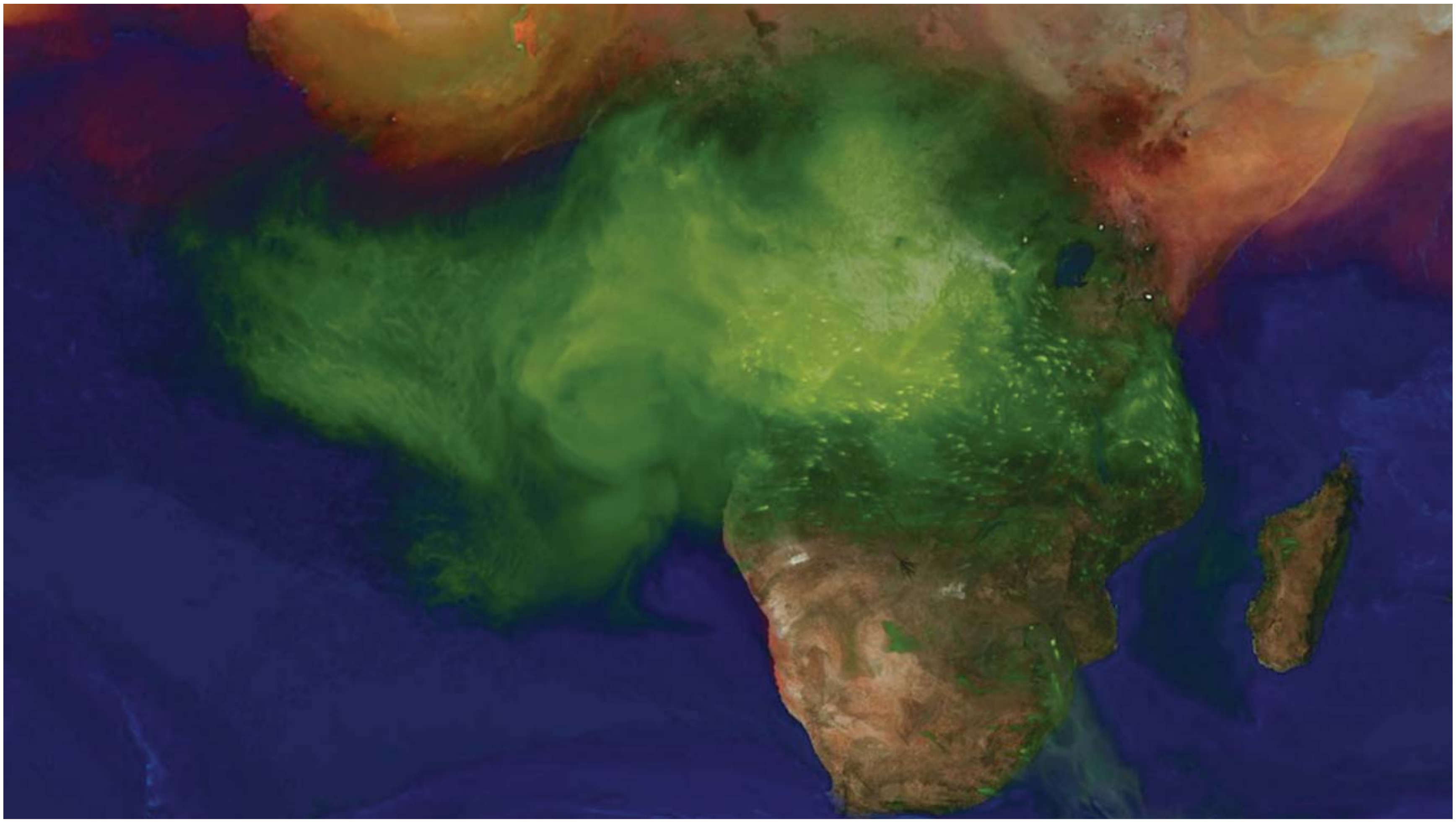
QFED: Quick Fire Emission Dataset

- Top-down algorithm based on MODIS Fire Radiative Power (AQUA/TERRA)
- FRP Emission factors tuned by means of inverse calculation based on MODIS AOD data.
- Daily mean emissions, NRT
- Prescribed diurnal cycle



JCSDA: inclusion of geo-stationary information

GEOS-5 Biomass Burning Aerosols



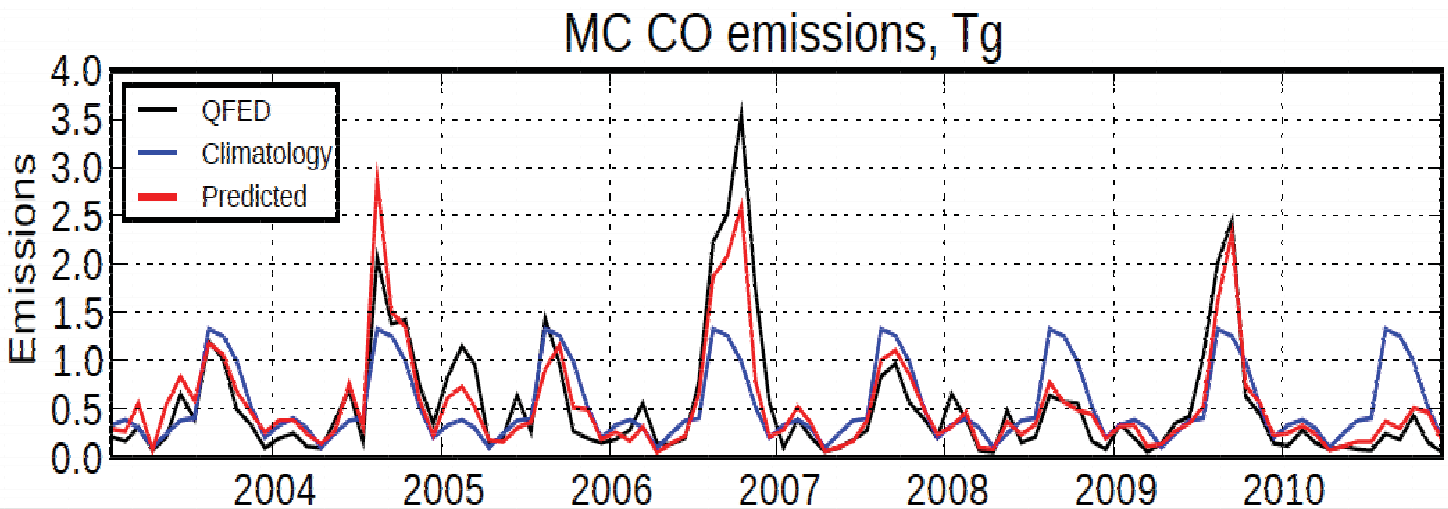
Non-hydrostatic 7km global meso-scale simulation

Modeling Interannual Variability of Biomass Burning Emissions

- BB emission anomalies respond directly to precipitation and surface humidity conditions
- The normalized Canadian Fire Weather Index captures the *fammability* conditions as a function of surface meteorology

- Parameterization:

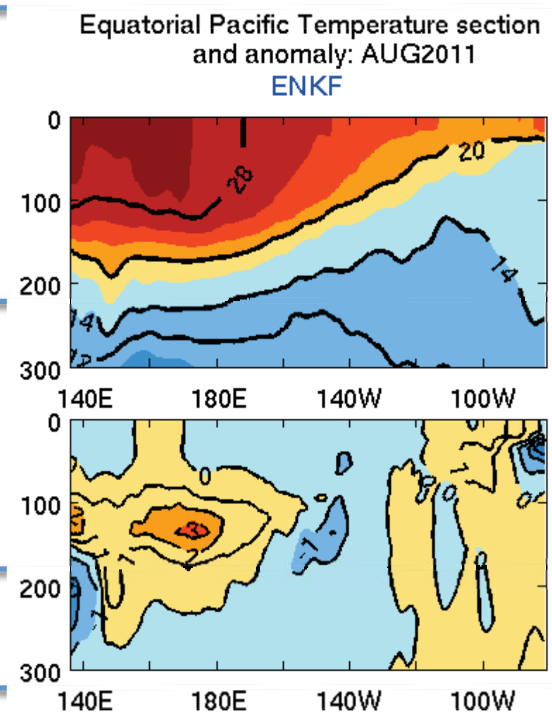
$$E = \mathcal{E}\left(\frac{I}{I_{clm}}\right)^{\alpha_b} E_{clm}$$

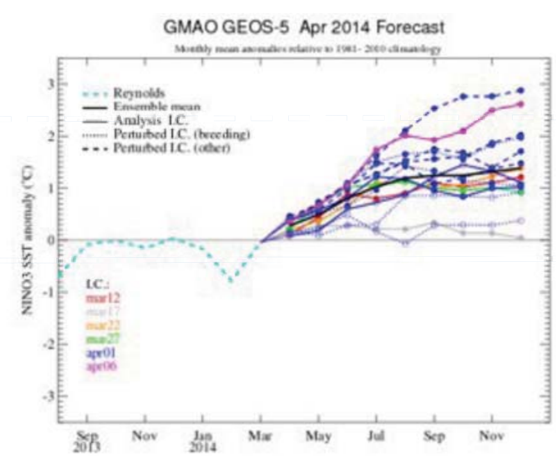


Maritime Continent Example

Current Status of GEOS-5 Seasonal Prediction

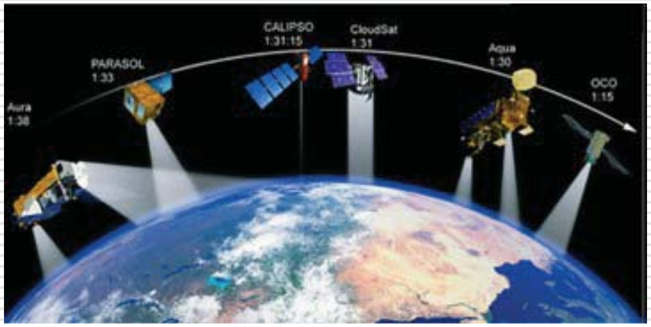
Application	***System Characteristics***
Decadal, IPCC (1960-2009)	2 deg atmos, 1 deg ocean MOM4, Fortuna 2.5, specified aerosols (PCHEM), EnOI/SAFE(sea ice) with scout and MERRA forcing; original run in several streams, lost water – sea level problem due to precip correction, new run one stream/no correction
S-I, NMME (1979 – present),	1 deg atmos, ½ ocean, MOM4, Fortuna 2.5, specified aerosols (PCHEM), EnOI, EnKF, with MERRA forcing, altimeter assim.
IESA (2013/14)	¼ deg atmos, 1/10 deg MOM5, Latest Ganymed, using FAST (EnOI with time lagged estimates of cov)
Current tuning coupled model	2 deg atmos, 1 deg ocean, MOM5, latest Ganymed
ODAS dev. Aquarius salinity analysis	1 deg atmos, 1/2 deg ocean, MOM5, latest Ganymed
Next S-I System	½ deg atmos. Ganymed, ¼ (1/5) MOM5, interactive aerosols, new diurnal layer, updated sea ice model, wave model, force with MERRA2, dynamic vegetation, EnOI, Aquarius SSS, new synthetic salinity prior to Argo (2004/5), GRACE ocean mass anomalies, sea level from TOPEX, Poseidon, Jason





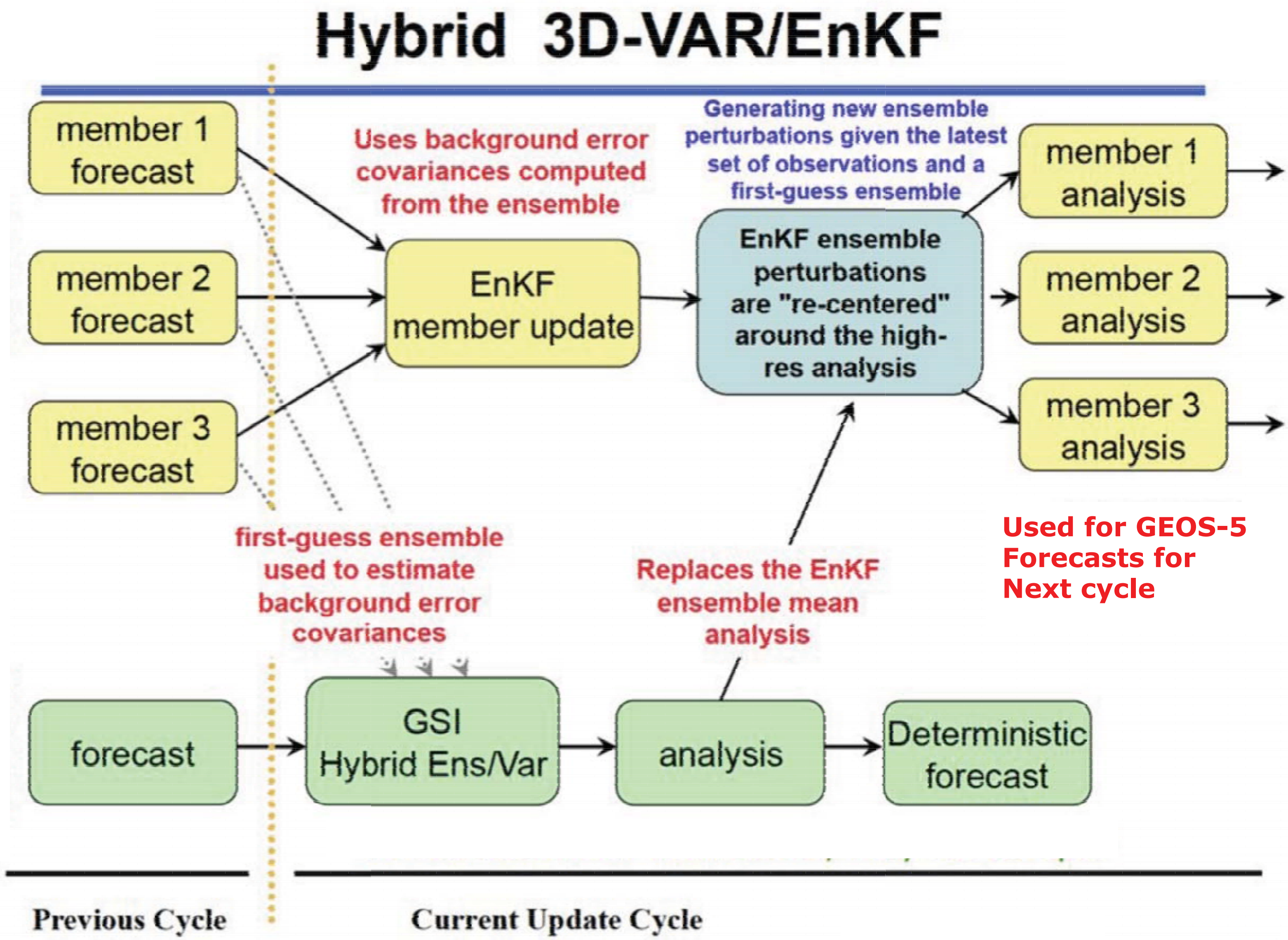
Aerosol Data Assimilation
2014 NRT Configuration

- Focus on NASA EOS instruments, MODIS for now



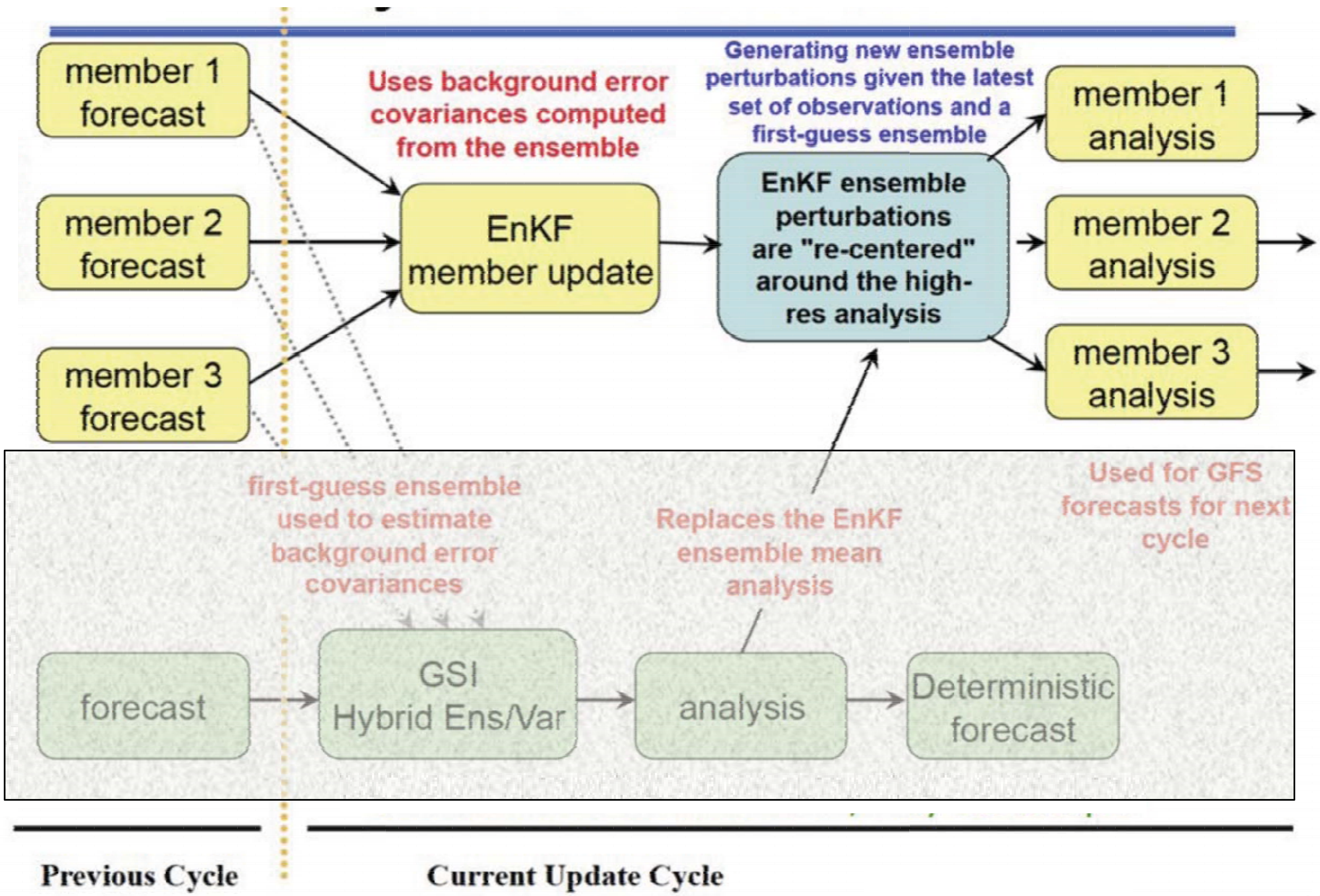
- Global, high resolution 2D AOD analysis
- 3D increments by means of Local Displacement Ensembles (**LDE**)
- Simultaneous estimates of background bias (*Dee and da Silva 1998*)
- Adaptive Statistical Quality Control (*Dee et al. 1999*):
  - State dependent (adapts to the error of the day)
  - Background and Buddy checks based on log-transformed AOD *innovation*
- Error covariance models (*Dee and da Silva 1999*):
  - Innovation based
  - Maximum likelihood

GEOS-5 **Meteorological** DAS

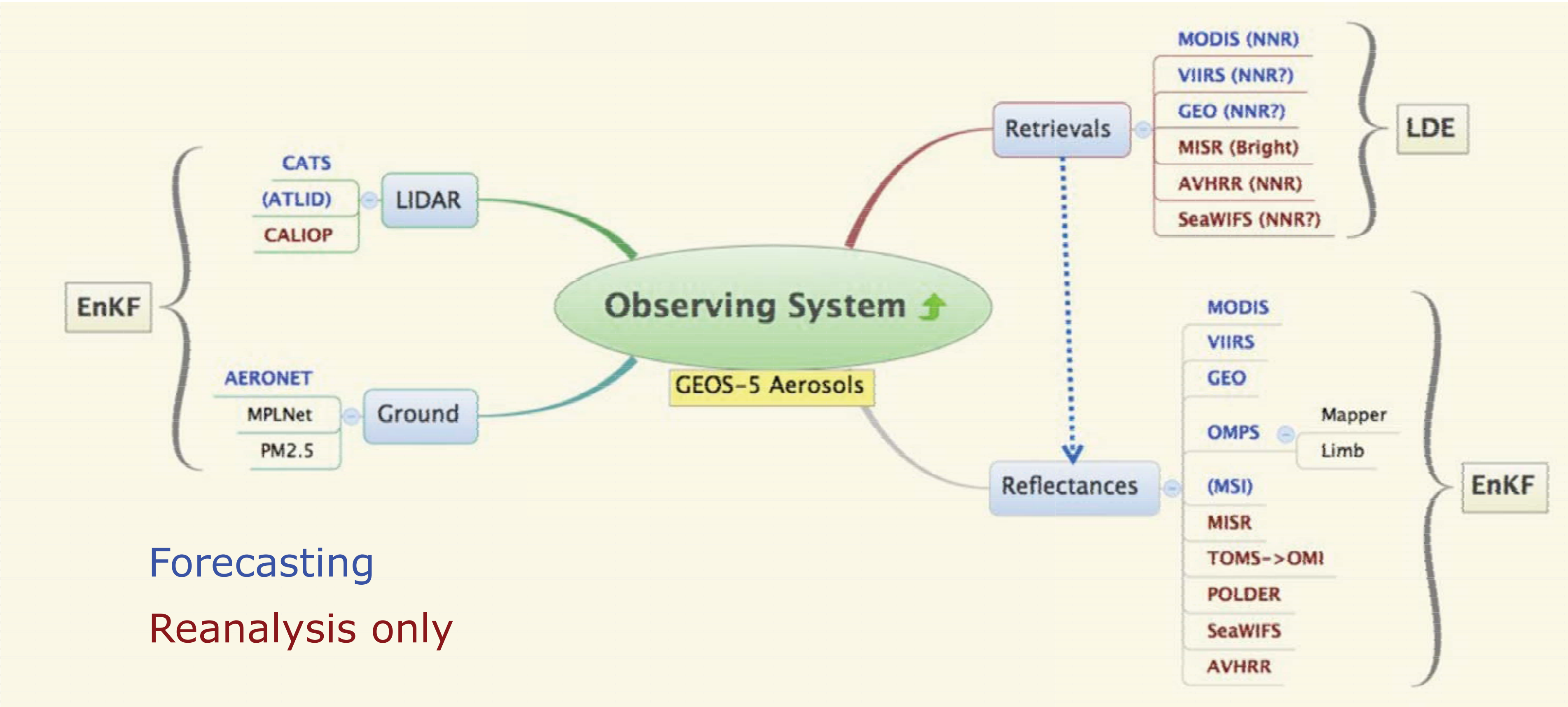


In collaboration with NOAA NCEP, ESRL

GEOS-5 **Aerosol** Assimilation
Phase I: EnKF Only



Aerosol Observing System



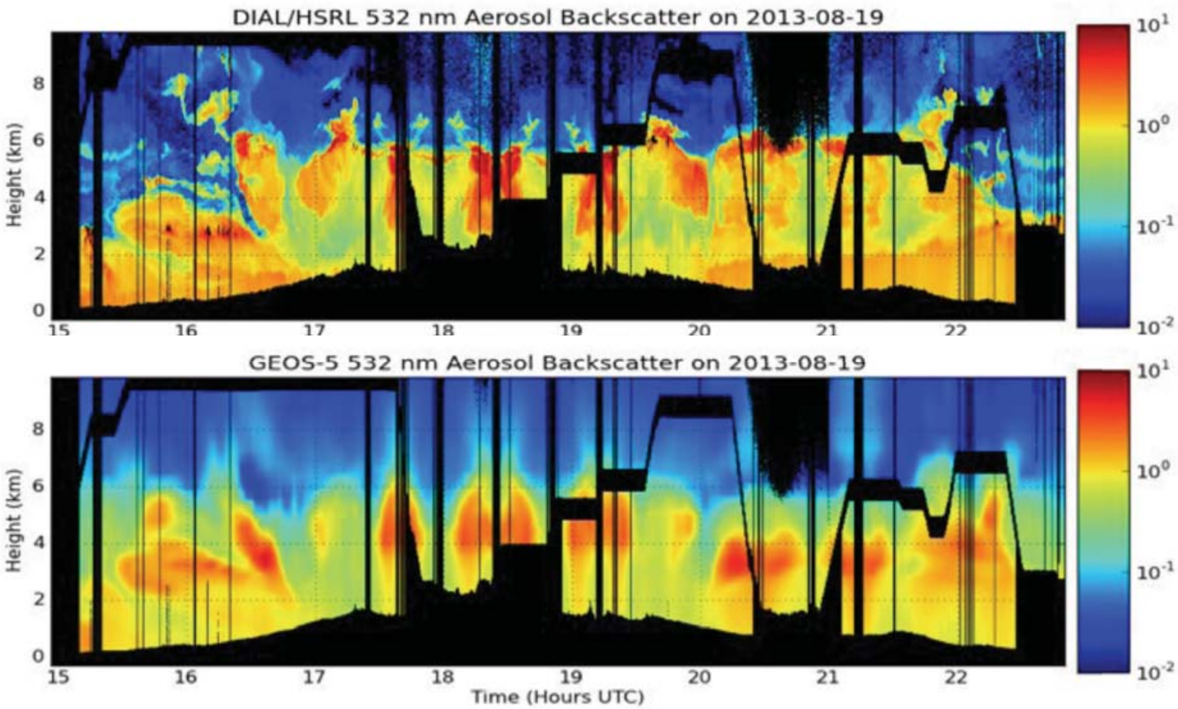
Aerosol Data Assimilation in GEOS-5

Outline

- GEOS-5 Overview
- Current capabilities and future directions
- Highlights:
  - Aerosol forecasting and field campaigns
  - Aerosol Reanalysis
  - OSSEs
- Concluding Remarks

Field Campaign Support

- Global 5-day chemical forecasts
  - O3, aerosols, CO, CO2, SO2
  - Nominally 25 km
- Driven by real-time biomass emissions from MODIS FRP (QFED)
- Constituents transported on-line, interactively
- Since 2007 supported several field missions including TC4, ARCTAS , GloPac, ATTREX, DISCOVER-AQ, HS3 ,SEAC4RS, etc.

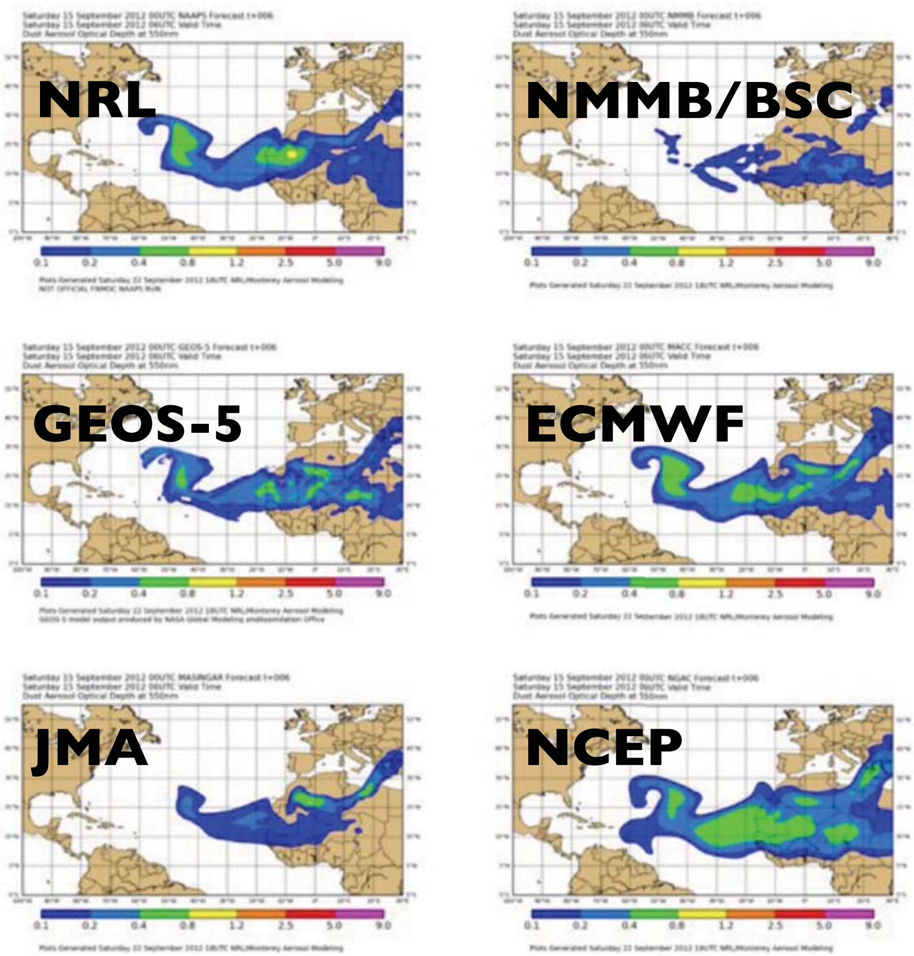


Comparison of observed (top) and simulated (bottom) aerosol backscatter for a slight during the 2013 SEAC4RS campaign.

http://gmao.gsfc.nasa.gov/forecasts/

International Cooperative for Aerosol Prediction (ICAP)

ICAP is an international forum for aerosol forecast centers, remote sensing data providers, and lead systems developers to share best practices and discuss pressing issues facing the operational aerosol community.



ICAP Multi-Model Ensemble Dust Forecast

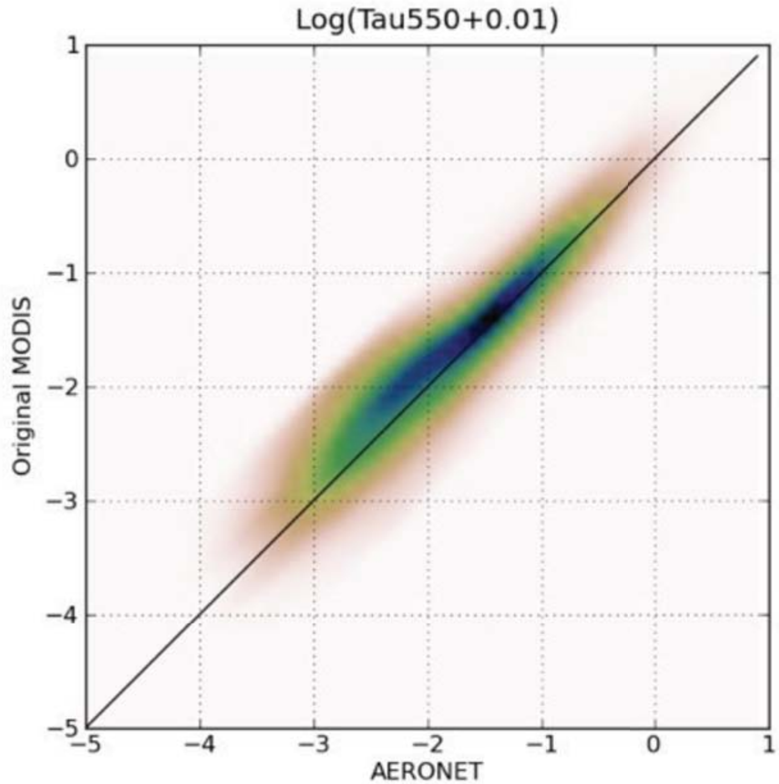
Sessions et al., ACPD, 14, 14933–14998, 2014

GEOS-5 Reanalysis Activities

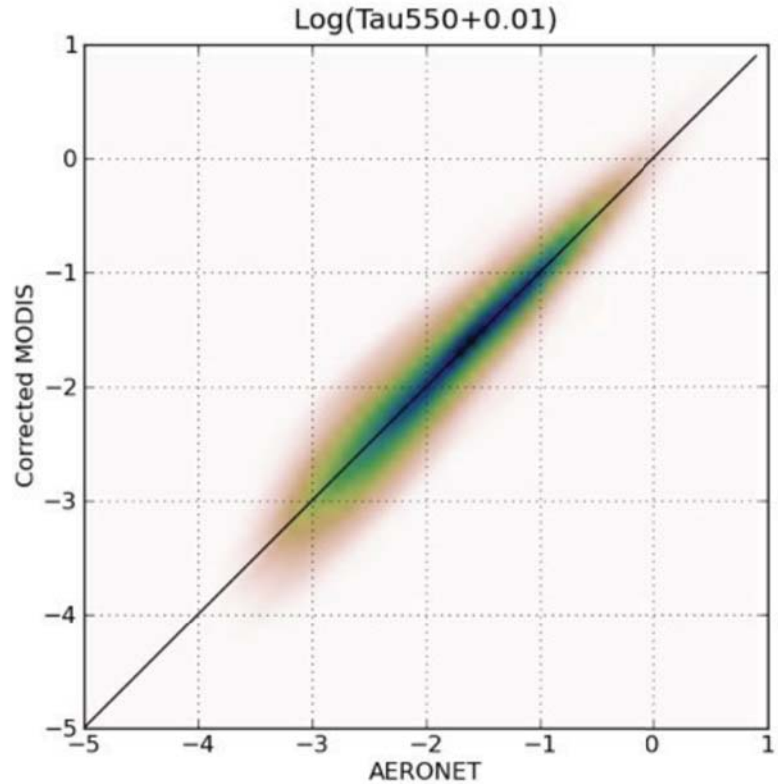
Name	Nominal Resolution	Period	Aerosol Data	Available
MERRA-1	50 km	1979-present	NONE	now
MERRAero	50 km	2002-present	MODIS C5	now
FP for Inst. Teams	50 km	1997-	MODIS C5	In progress
NCA	25 km	2010-11	MODIS C5, MISR	Now
MERRA-2	50 km	1979-present	AVHRR, MODIS C5, MISR, AERONET	Q1 2015

Observational Bias

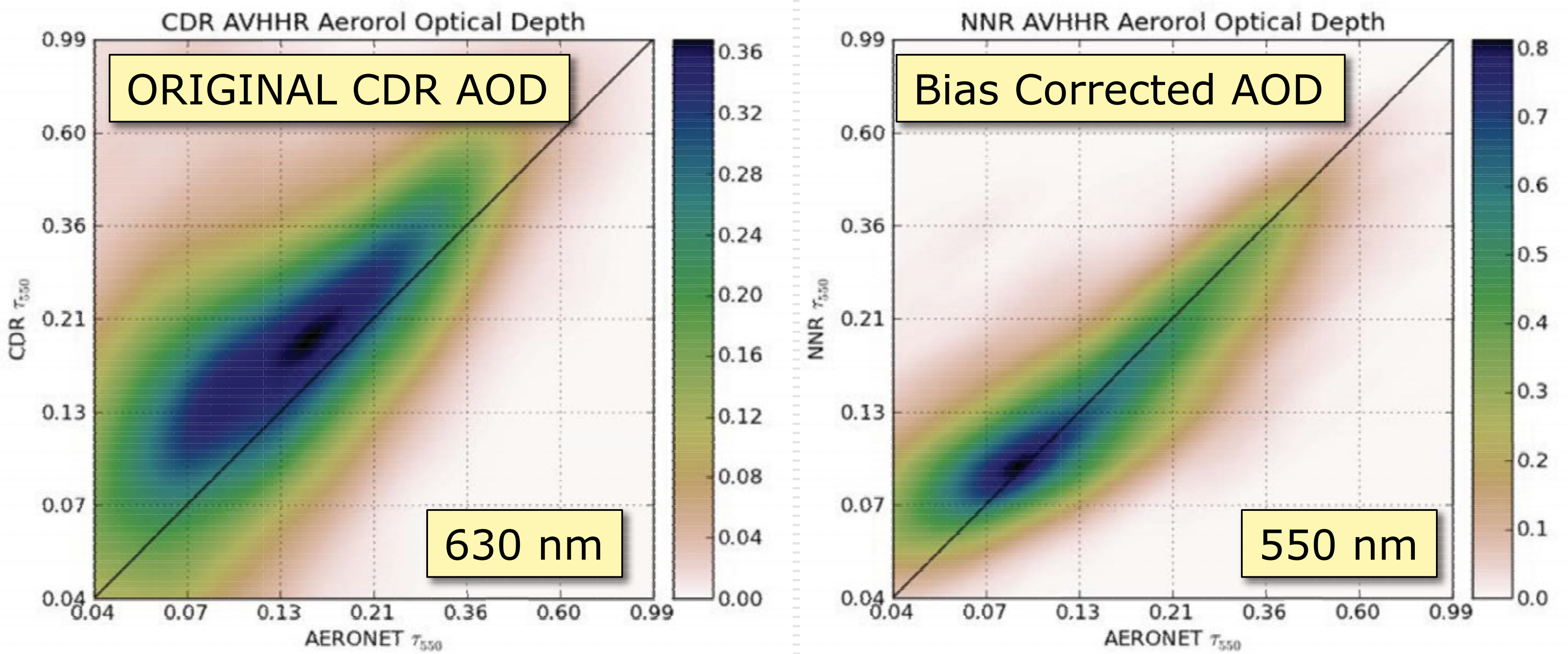
ORIGINAL MODIS AOD



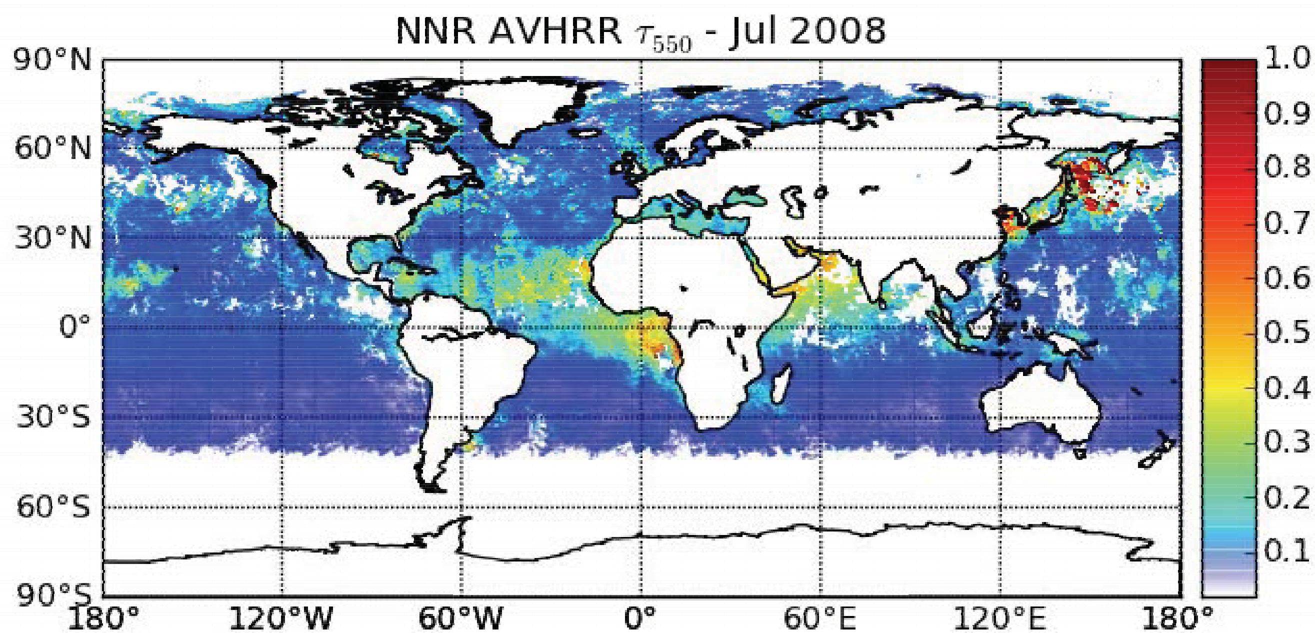
BIAS CORRECTED AOD

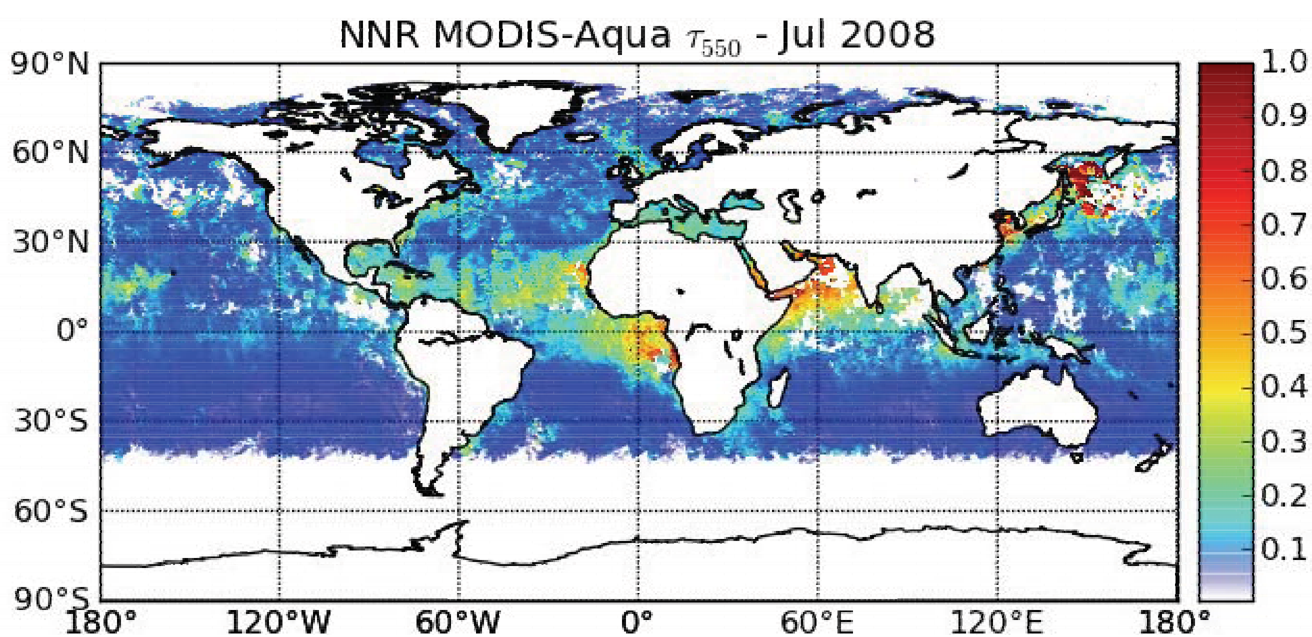


AVHRR NOAA CDR AOD *AERONET Comparison*

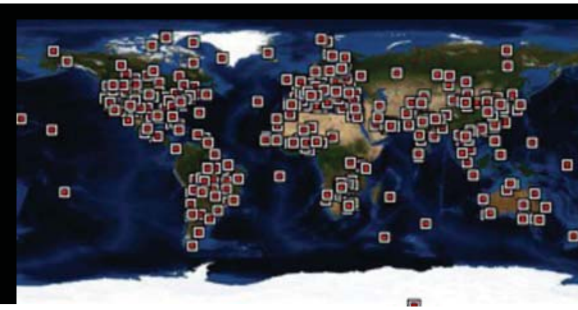


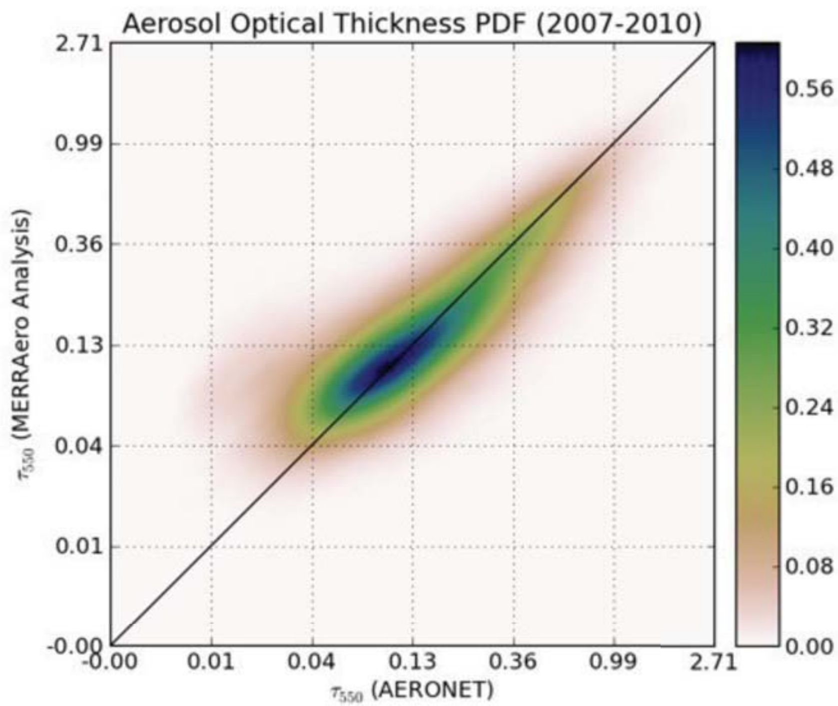
Coastal and Island Stations for 2003-2009

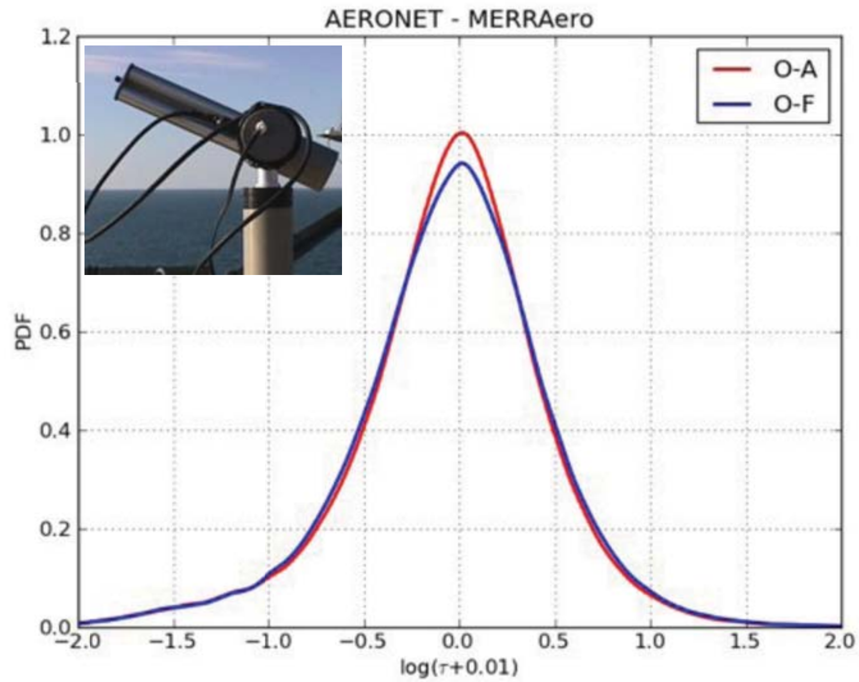

NNR AVHRR τ_{550} - Jul 2008
90°N
60°N
30°N
0°
30°S
60°S
90°S
180°
120°W
60°W
0°
60°E
120°E
180°
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1


NNR MODIS-Aqua τ_{550} - Jul 2008
90°N
60°N
30°N
0°
30°S
60°S
90°S
180°
120°W
60°W
0°
60°E
120°E
180°
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

AERONET MERRAero Validation

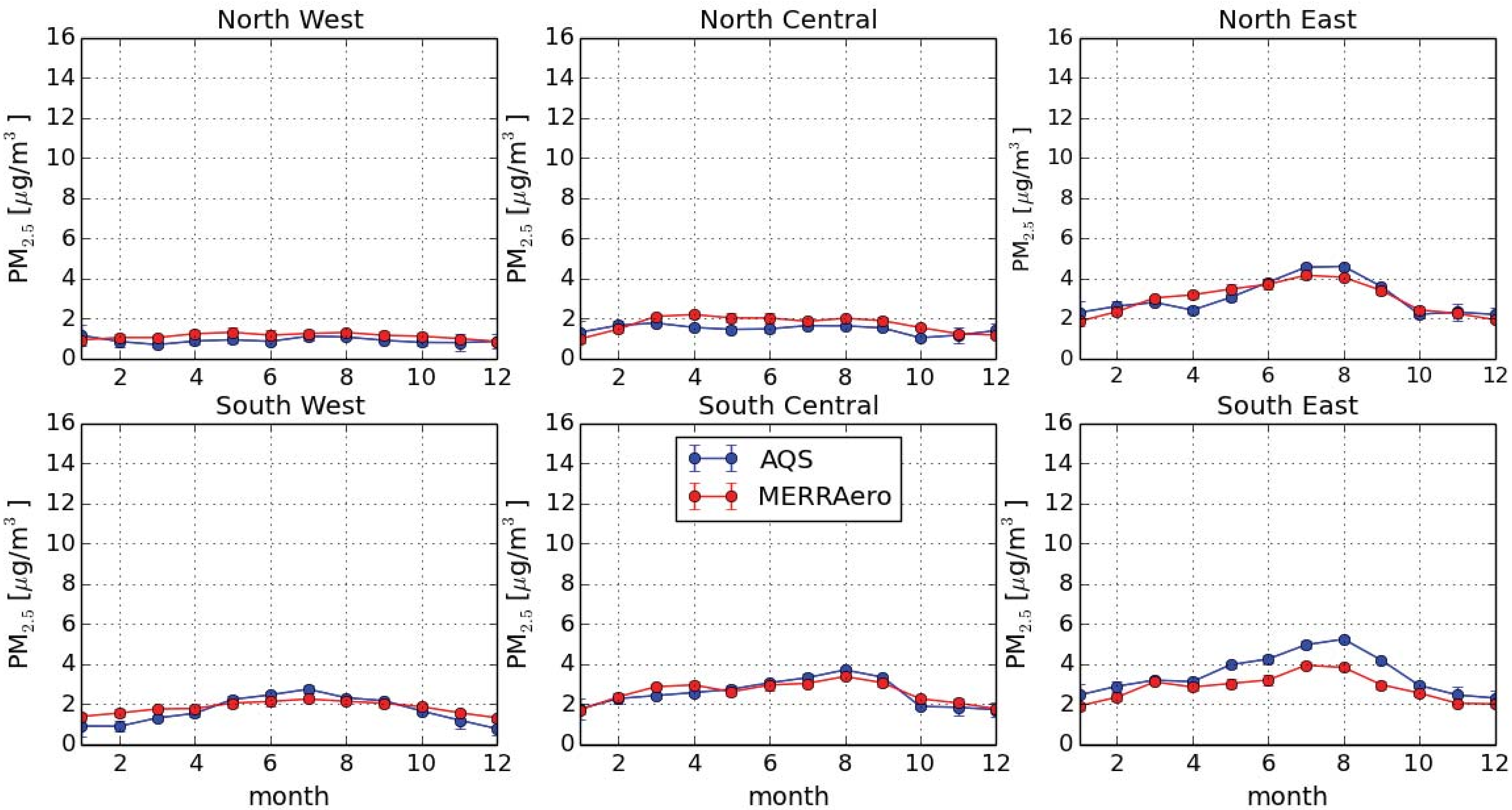




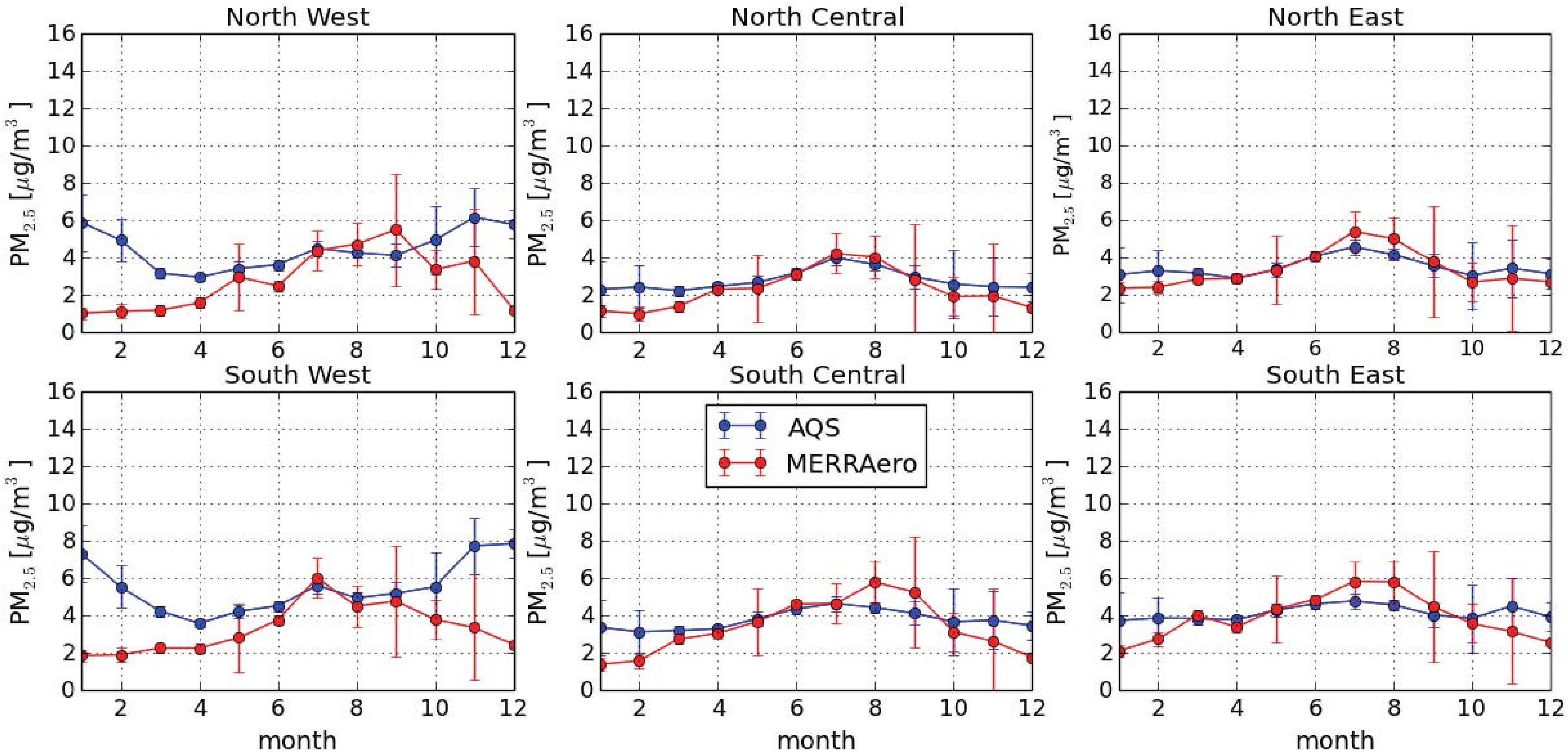


$$\boxed{\eta = \log(\tau + 0.01)}$$

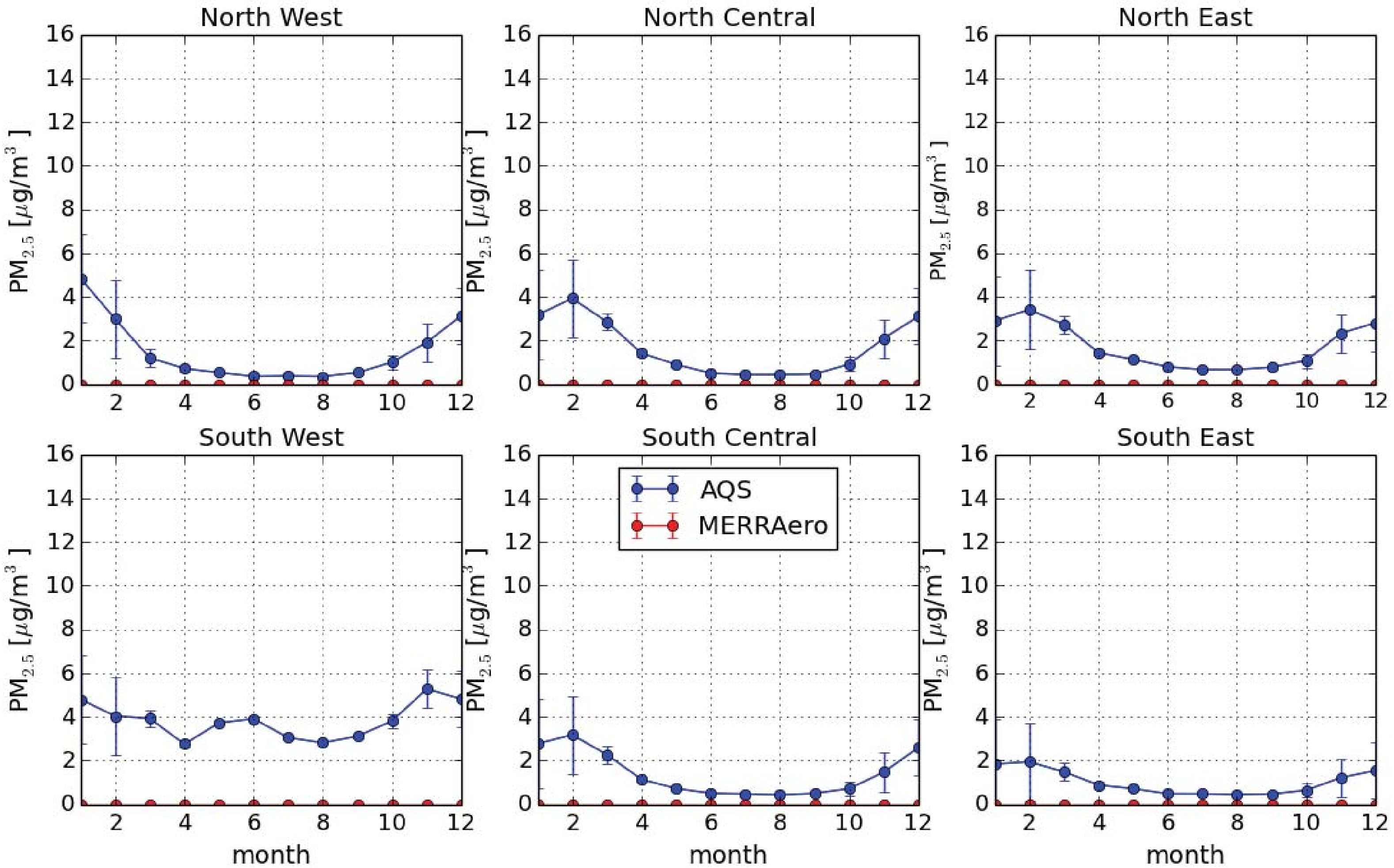
$PM_{2.5}$ (Sulfates) Regional Climatology



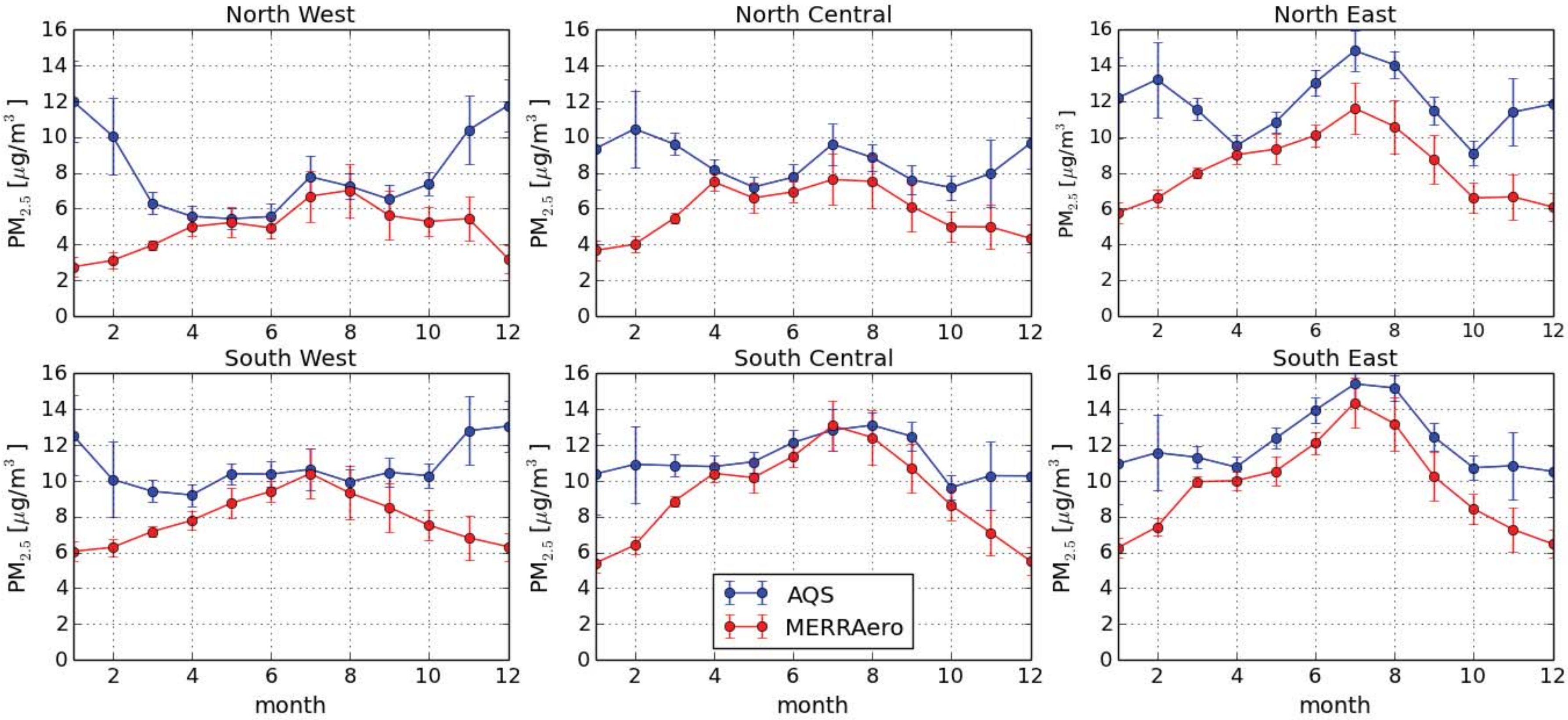
$PM_{2.5}$ (Organic Carbon) Regional Climatology



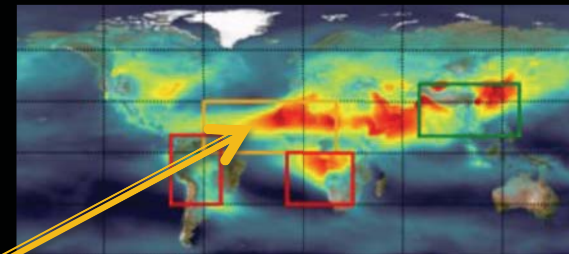
$PM_{2.5}$ (Nitrates) Regional Climatology



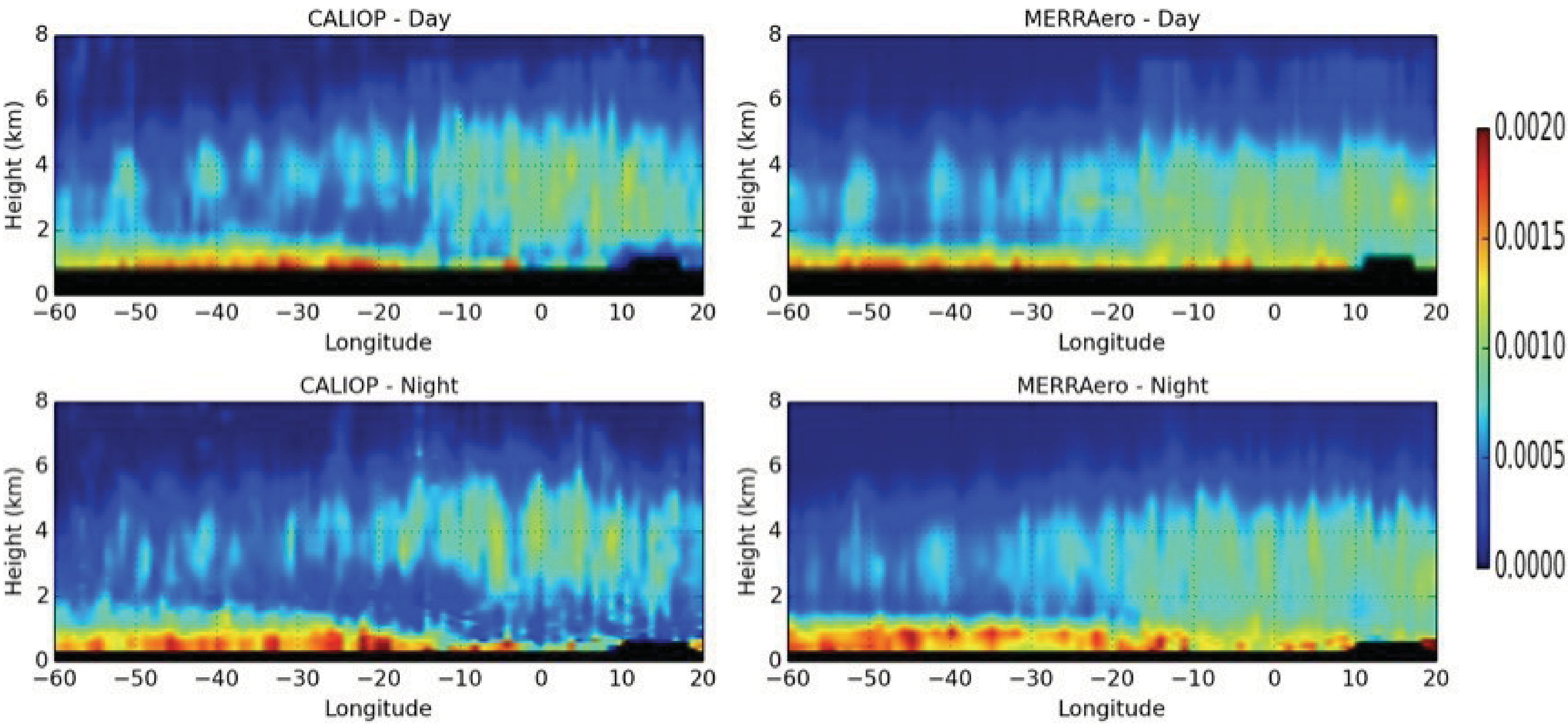
$PM_{2.5}$ (Total) Regional Climatology



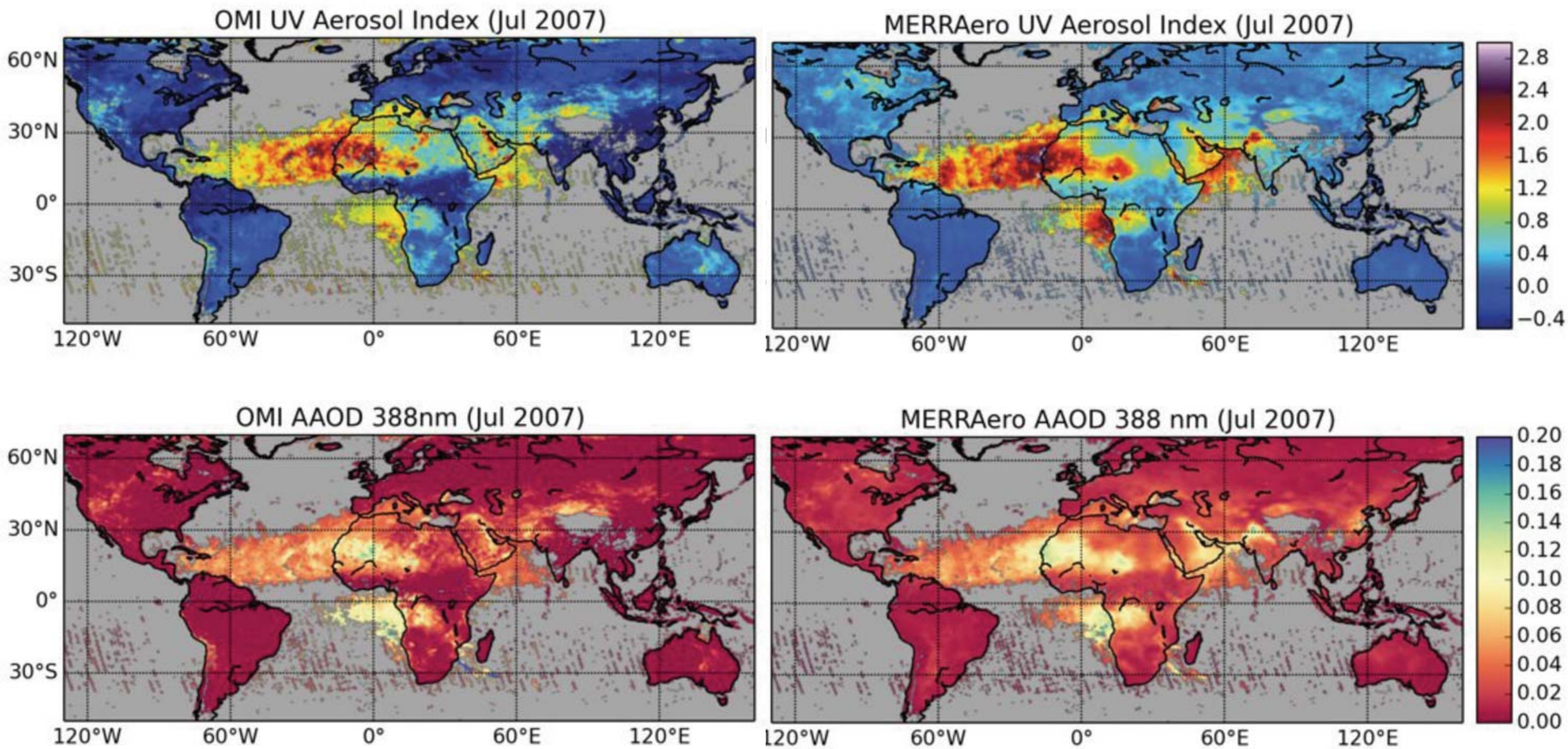
Vertical Structure: Comparison to CALIOP



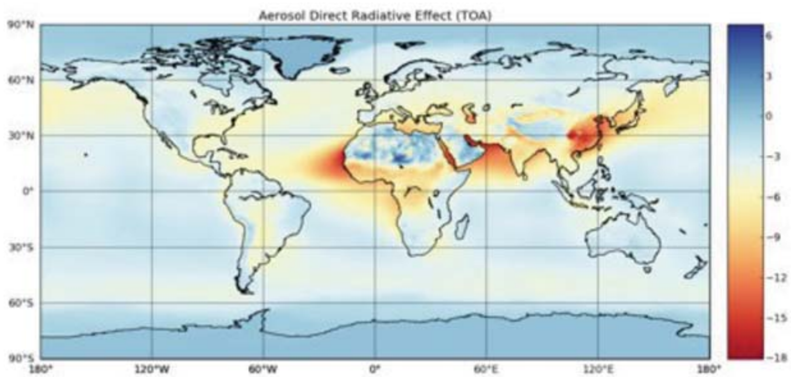
DUST

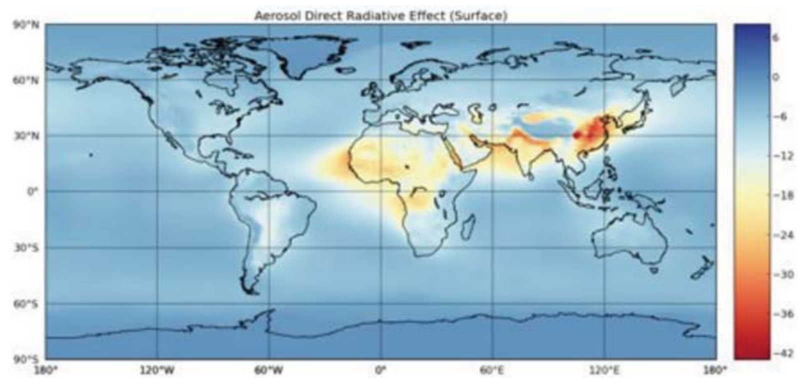


Evaluation of MERRAero Absorption using OMI



Clear-Sky Aerosol Direct Radiative Effect

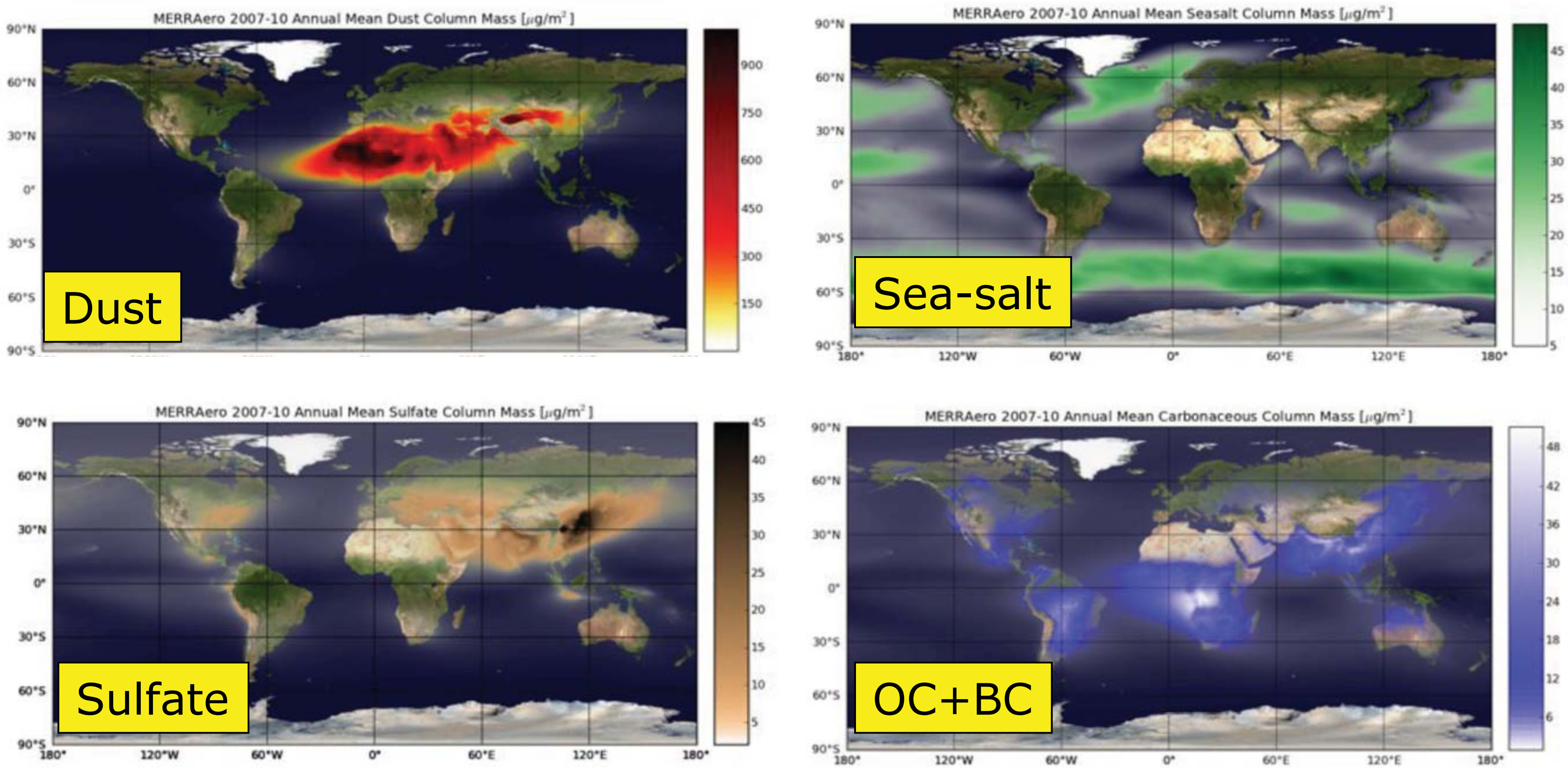




Source	TOA SW DRE Ocean (Land)	Atmos. Ocean (Land)	Surface SW DRE Ocean (Land)
MERRAero	-3.8 (-4.3)	2.8 (6.8)	-6.6 (-11.1)
Other Observational Yu *et al.* (2006)	-5.5 ± 0.2 (-4.9 ± 0.7)	3.3 (6.8)	-8.8 ± 0.7 (-11.8±1.9)
Multi-model Ensemble Yu *et al.* (2006)	-3.4 ± 0.6 (-2.8 ± 0.6)	1.4 (4.4)	-4.8 ± 0.8 (-7.2 ± 0.9)
GEOS-5 (Free)	-3.4 (-2.7)	0.5 (2.8)	-3.9 (-5.5)

$$DRE_{SW} = \left(F_{SW}^{\downarrow} - F_{SW}^{\uparrow}\right)_{Aerosols} - \left(F_{SW}^{\downarrow} - F_{SW}^{\uparrow}\right)_{NoAerosols}$$

Assimilated Aerosol Annual Mean Mass



Speciation potentially adjusted by spectral reflectances

Mass Budget

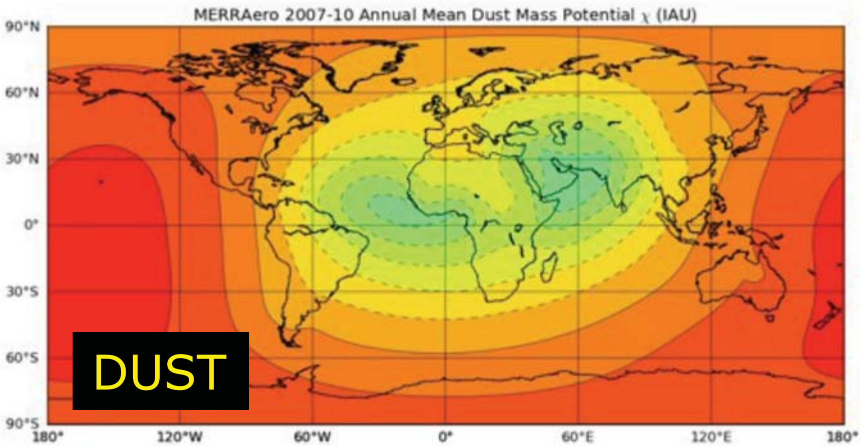
Annual mass budget for an aerosol specie q:

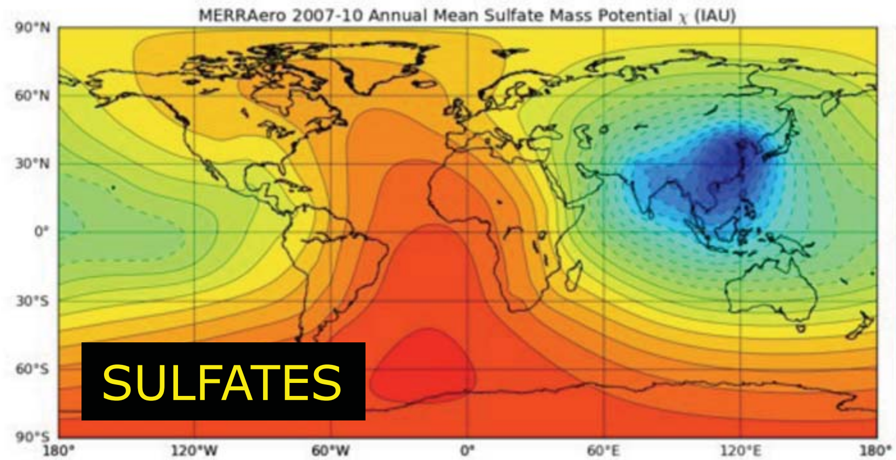
$$\nabla \cdot \overline{\langle \mathbf{u}q \rangle} = \overline{E} + \overline{P} - \overline{L} + \frac{\overline{\langle \Delta q^a \rangle}}{\tau}$$

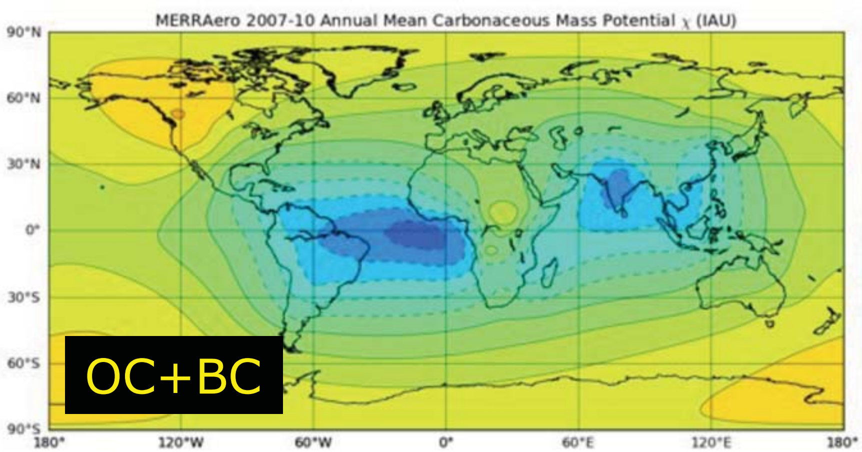
where

$\mathbf{u}q$	Mass flux
E	Emissions
P	Chemical production
L	Loss processes
Δq^a	Anaysis increments
τ	Analysis interval (3 hours)
$\langle \cdot \rangle$	Mass weighted vertical integral
$\overline{(\cdot)}$	Time average

Annual Mean Analysis Increments







$$\chi = \nabla^{-2}\left[(\overline{E} + \overline{P} - \overline{L} + \frac{\langle \Delta q^a \rangle}{\tau}\right]$$

O.S.S.E.

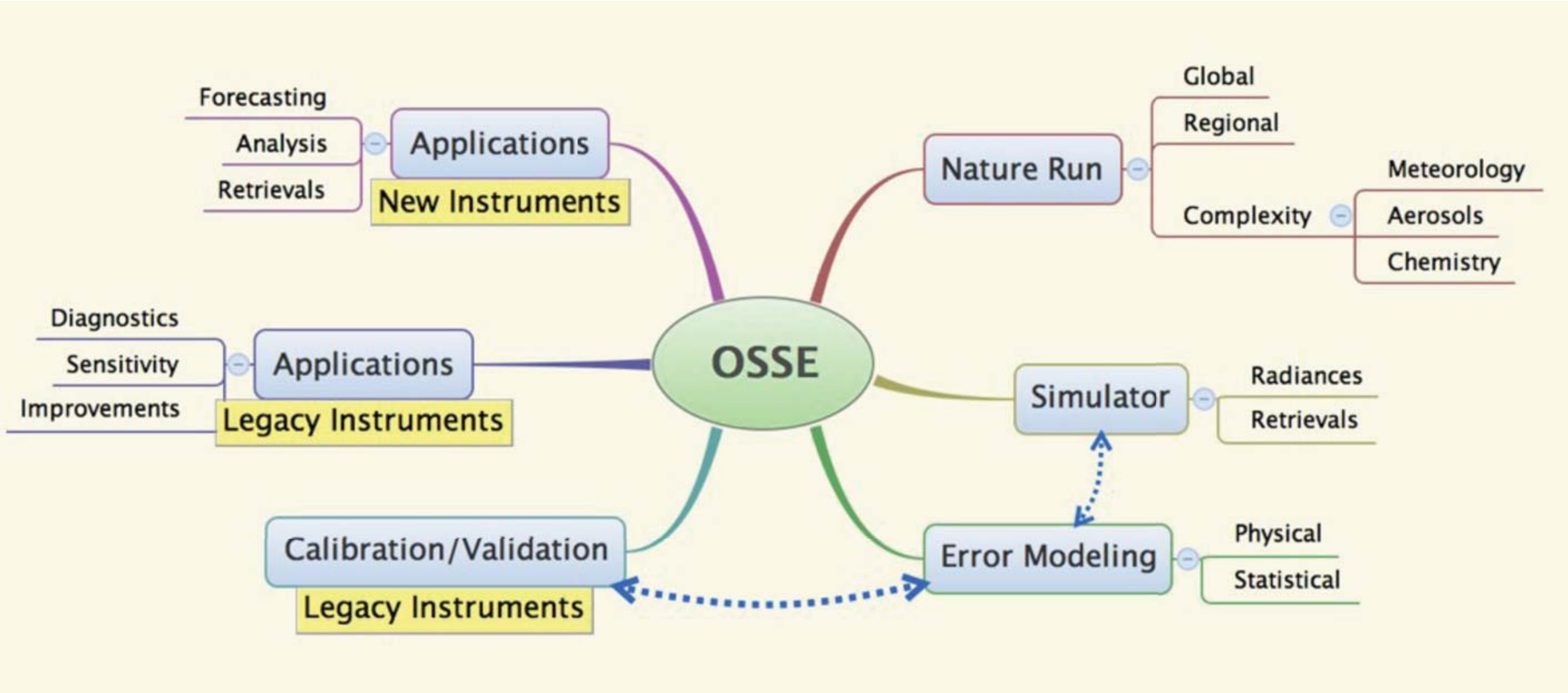
- Observing System
- Simulation
- Experiment

Model-based OSSE

A framework for numerical experimentation in which *observables* are simulated from fields generated by an earth system model, including a *parameterized* description of the *observational error* characteristics.

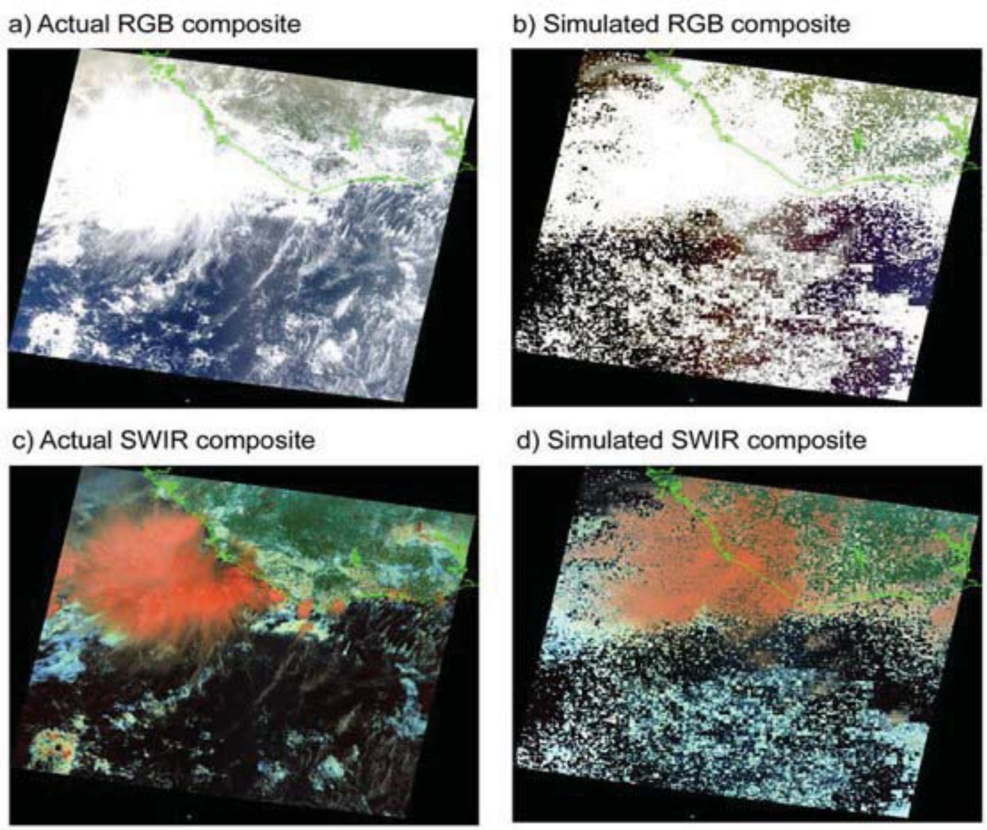
Simulations are performed in support of an experimental goal.

Elements of an OSSE System



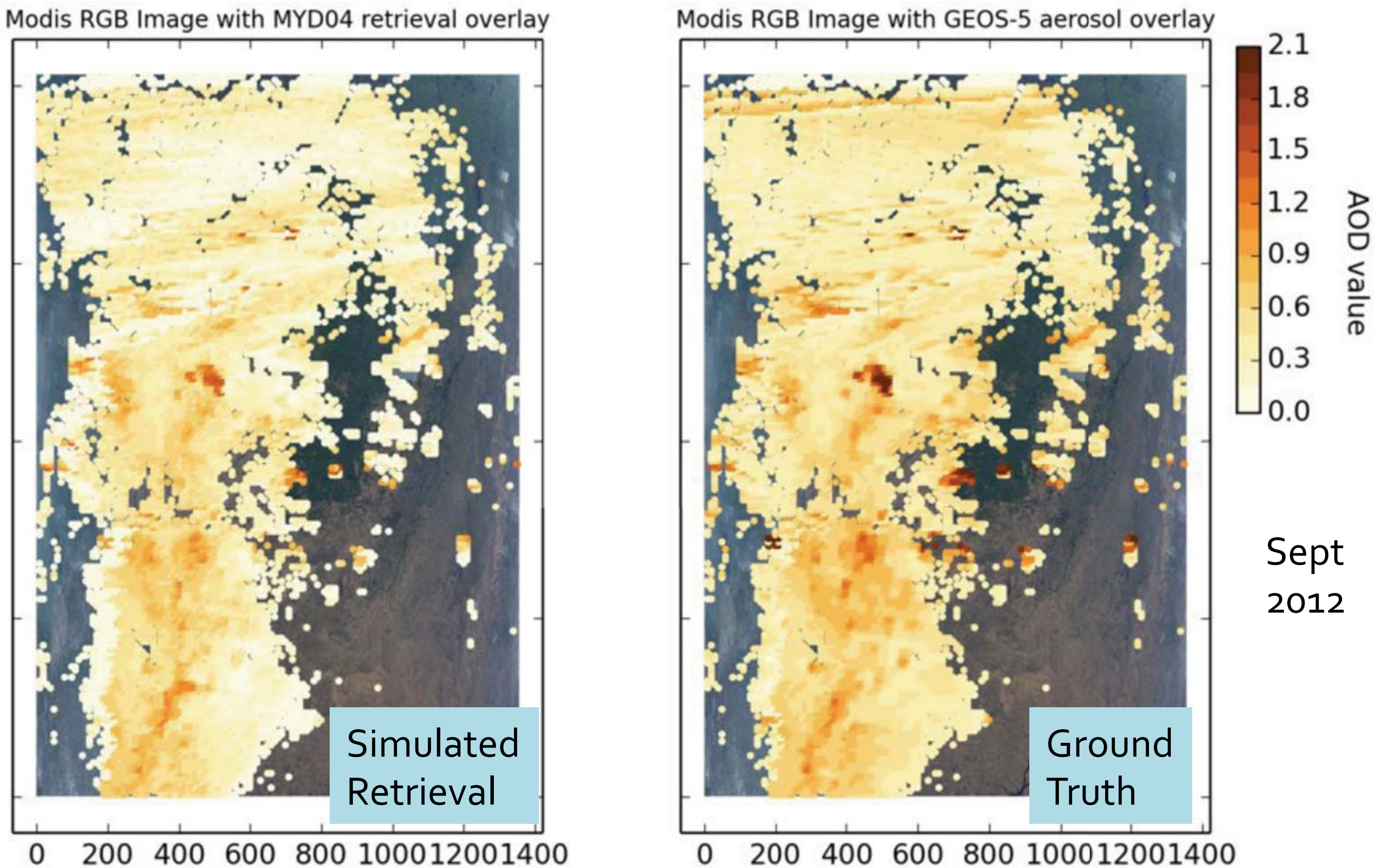
MODIS Cloud & Aerosol Retrieval Simulator

- PDF based sub-grid sampling of GEOS-5 fields (ICA)
- Spatial "clumping"
- Radiances for 27 MODIS channels
- Cloud and aerosol extinction, ssa, phase function
- Operational Retrievals
  - Clouds: MOD06
  - Aerosols: MOD04



Wind et al., 2013, GMD

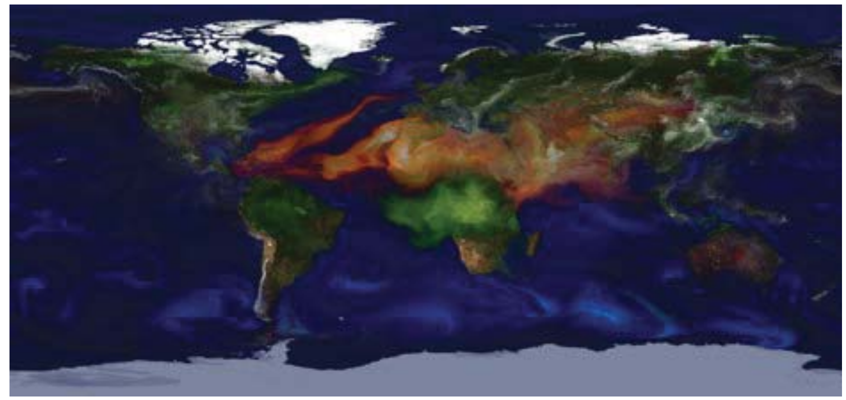
MODIS Retrieval Simulator Biomass Burning in Brazil

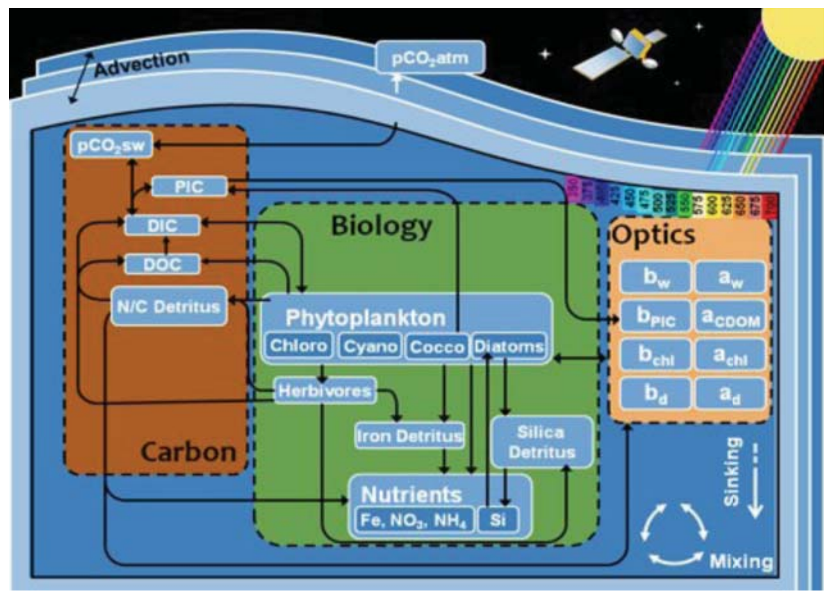


Sept 2012

PACE Simulator

- GEOS-5 non-hydrostatic 7 km atmosphere with GOCART aerosols
- Coupled to GEOS-5 10 km ocean component with biogeochemistry
- Simulation of
  - Water leaving radiances
  - t.o.a. reflectances





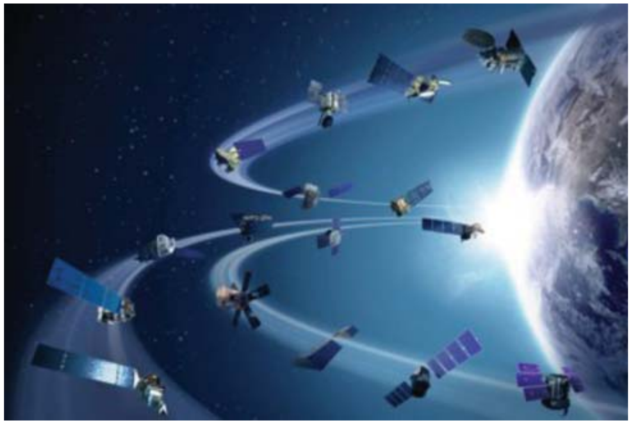
Concluding Remarks

AEROSOLS IN GEOS-5

- The GEOS-5 Earth Modeling System includes data assimilation of its major components
- Aerosols are an integral part of the GEOS-5 NRT and re-analysis systems
- GEOS-5 OSSE activities in support of new NASA observing missions
  - Builds on NWP capabilities, extends it to constituents and other components

GEOS-5 EVOLUTION

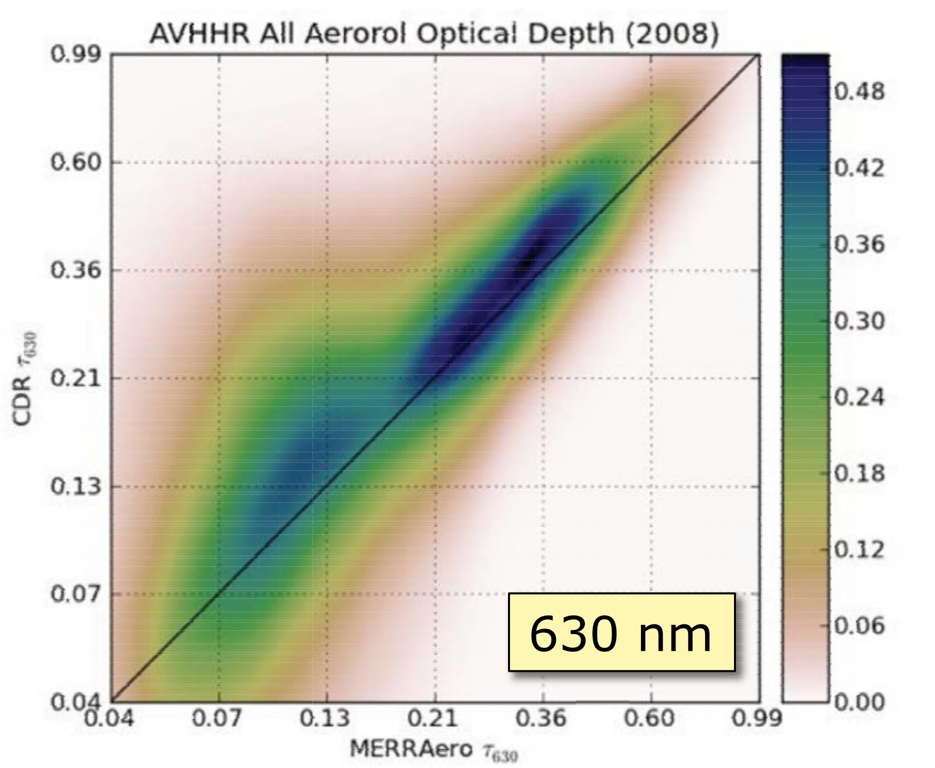
- Aerosol/cloud processes evolving from bulk to modal/2-moment schemes
- Aerosol assimilation evolving into a EnKF sub-system within the atmospheric 4D-EnVar



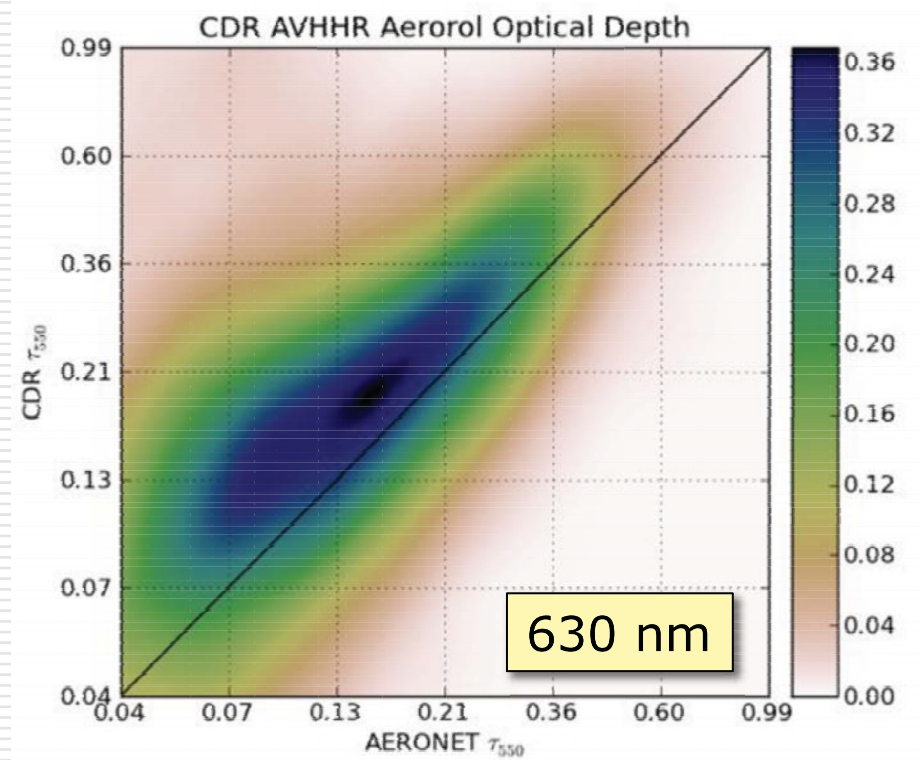
Extra Slides

AVHRR NOAA CDR AOD

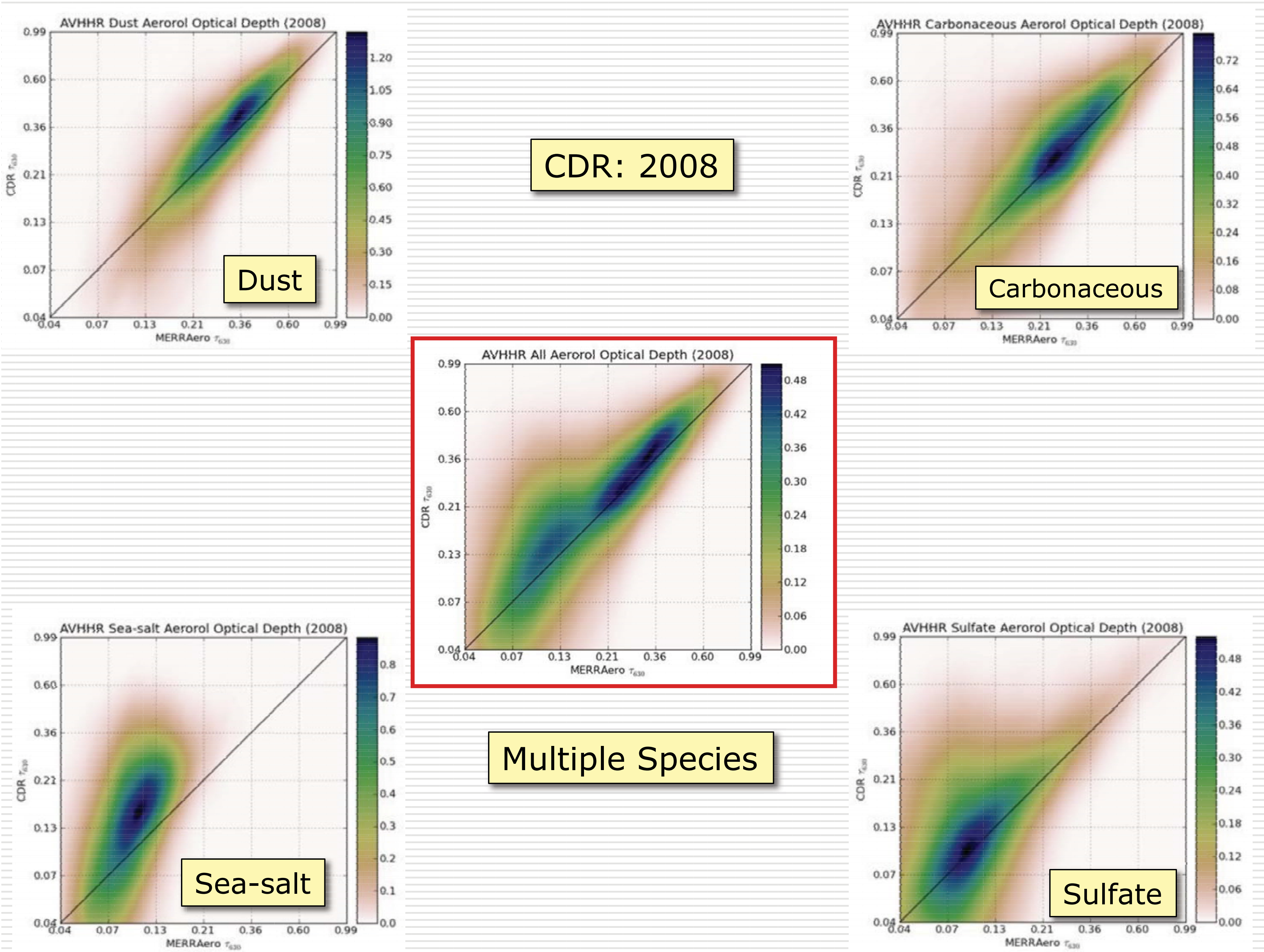
MERRAero, AERONET Comparison



MERRAero



AERONET


CDR: 2008
AVHHR Dust Aerorol Optical Depth (2008)
Dust
AVHHR Carbonaceous Aerorol Optical Depth (2008)
Carbonaceous
AVHHR All Aerorol Optical Depth (2008)
Multiple Species
AVHHR Sea-salt Aerorol Optical Depth (2008)
Sea-salt
AVHHR Sulfate Aerorol Optical Depth (2008)
Sulfate
MERRAero τ_{630}
CDR τ_{630}

PATMOS-x

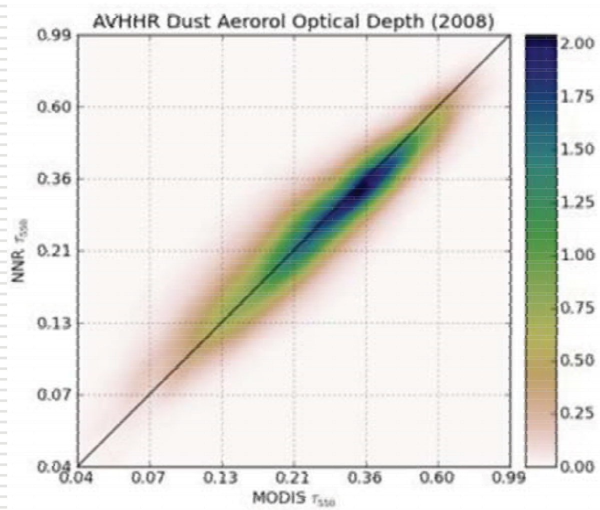
AVHRR Pathfinder Atmospheres - Extended

PATMOS-x Dataset

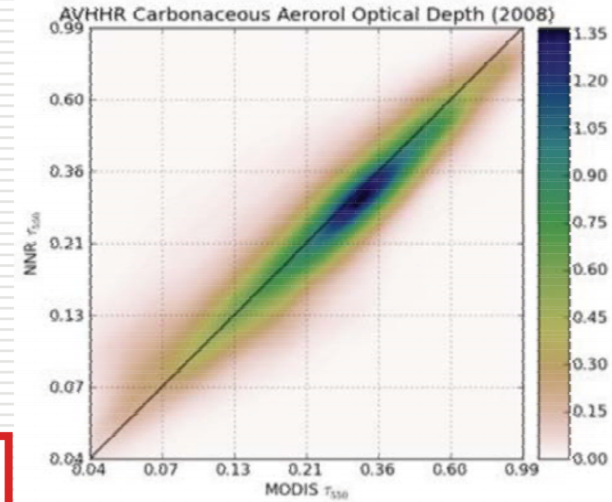
- Version 5 Level 2B
- 0.1 degree sampling (not average)
- Period: 1978-2009
- Inter satellite calibration (MODIS reference)
- Bayesian probabilistic cloud detection (CALIPSO reference)
  - **cpd <0.5%**

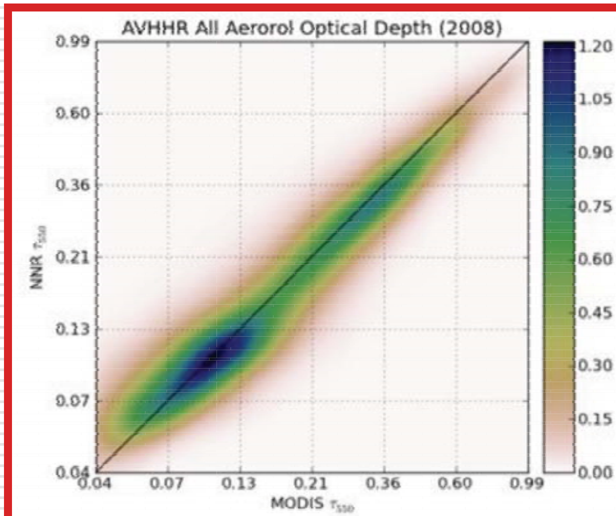
Neural Net Retrival

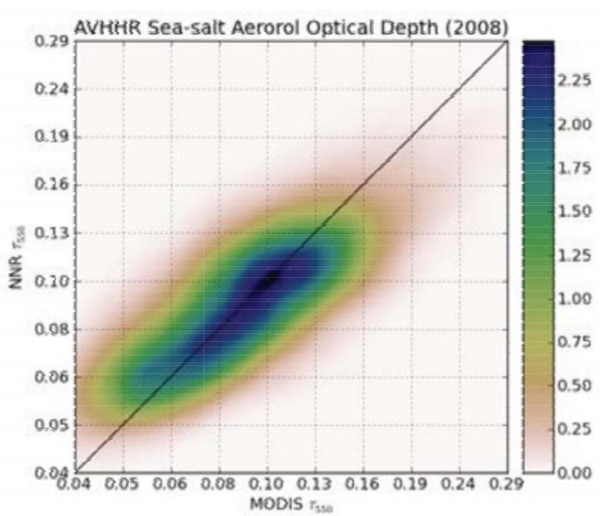
- Ocean Predictors
  - TOA Reflectances
  - 630 and 860 nm
  - TPW
  - Ocean albedo (wind)
  - Solar and sensor angles
  - GEOS-5 fractional AOD speciation
- Target:
  - AOD at 550 nm
  - Balanced MODIS NNR



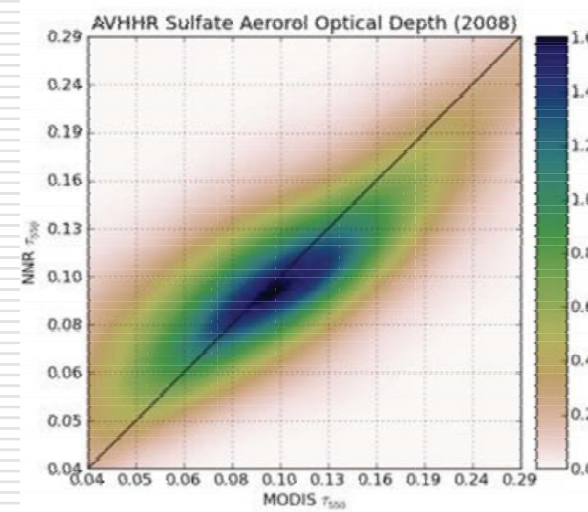
2008



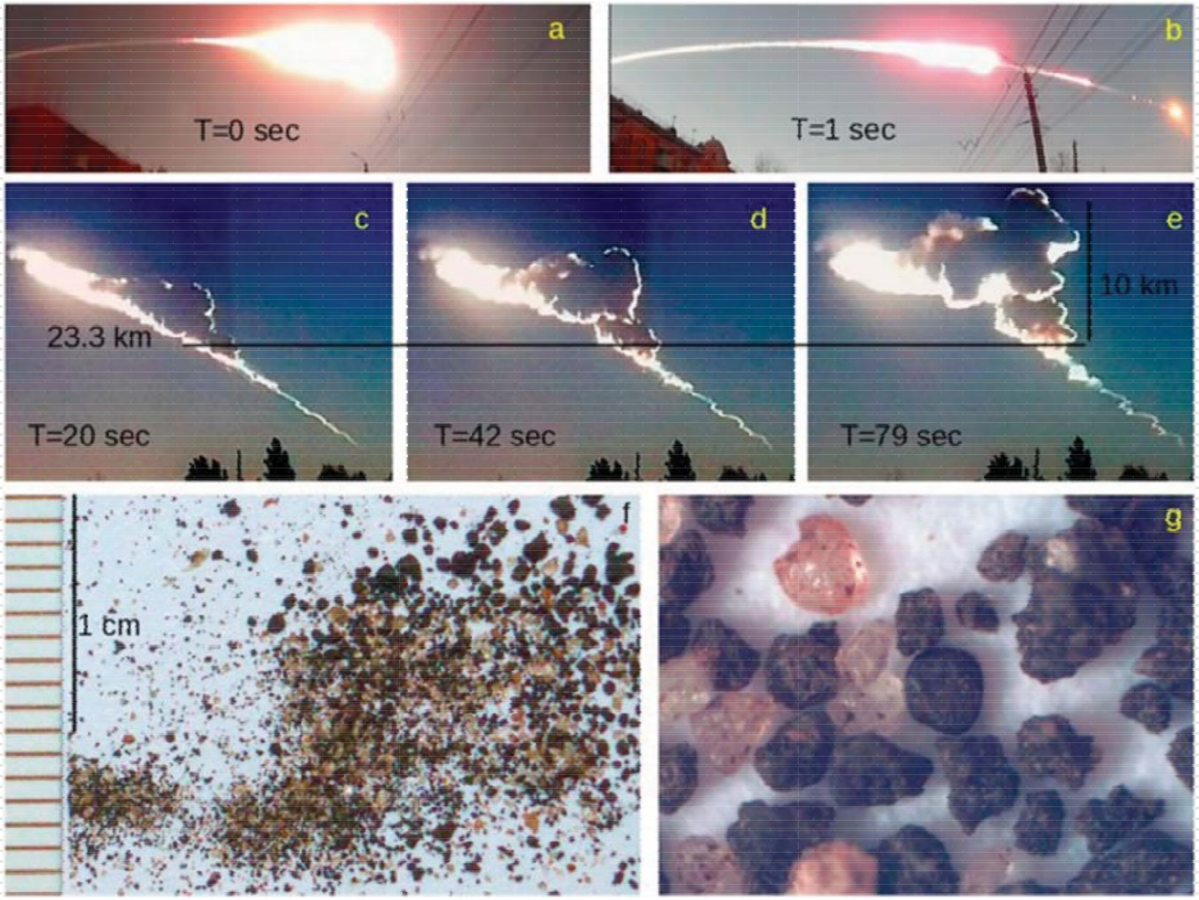




Multiple Species



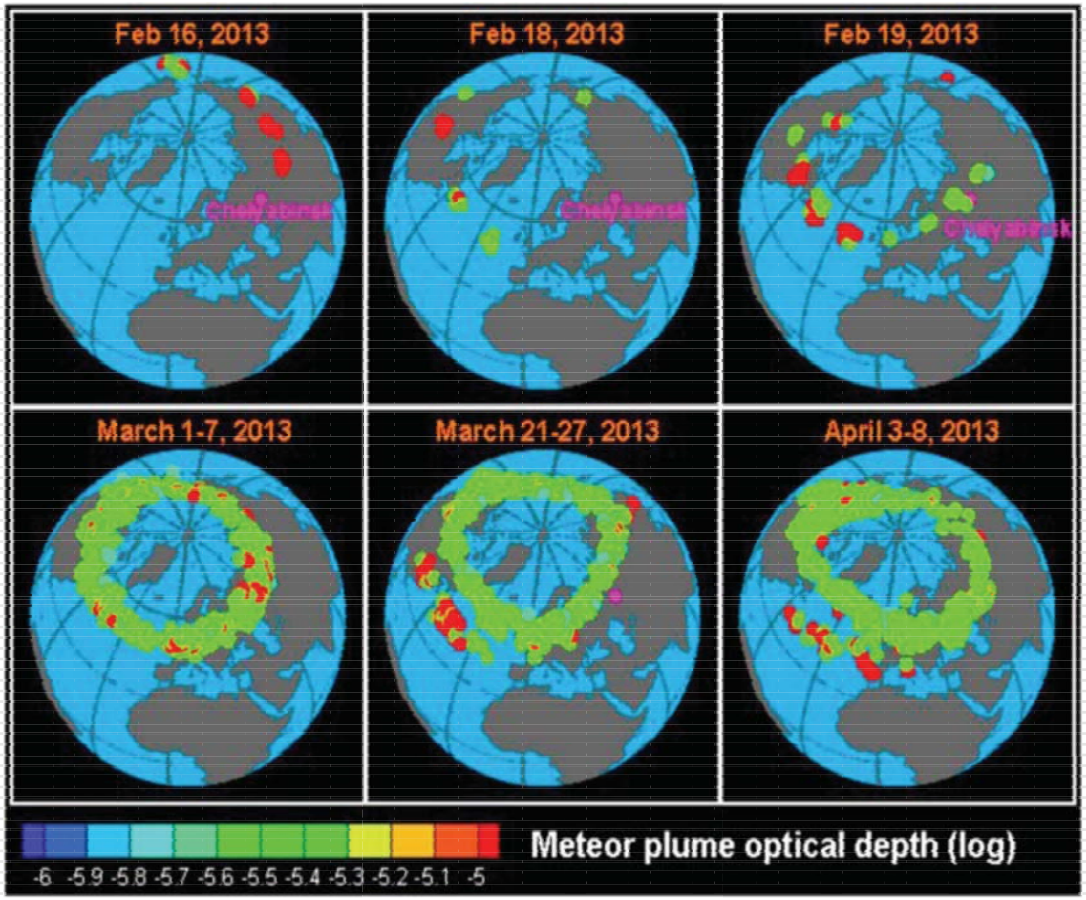
Russian Super Bolide of 2013



Gorkavyi et al., 2013 (2013)

3:20 UTC 15 February 2013

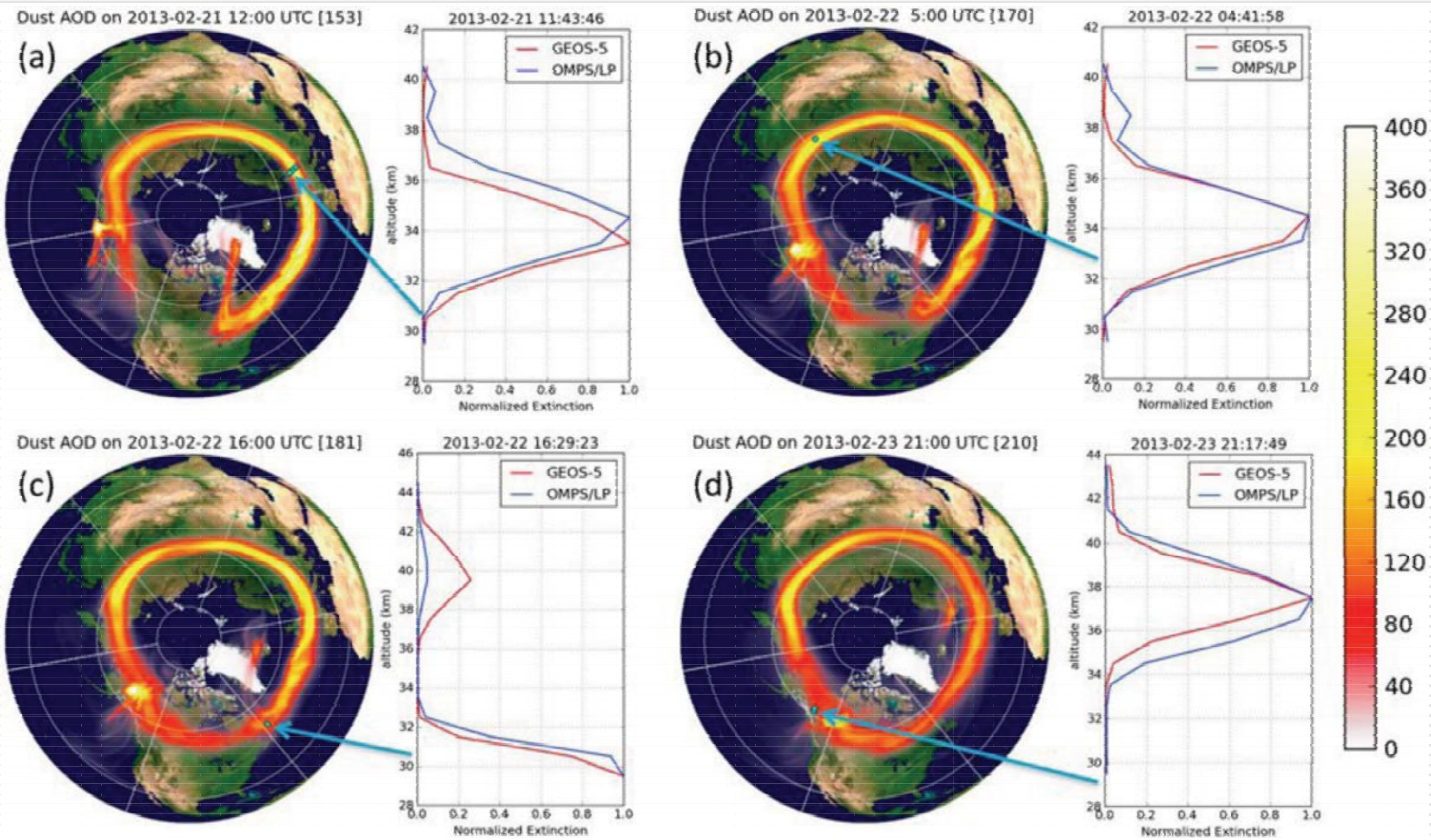
Chelyabinsk Meteor Dust Plume



Gorkavyi et al., 2013 (2013)

As seen by OMPS Limb Profiler

Chelyabinsk Meteor Dust Plume



Gorkavyi et al., 2013 (2013)

As simulated by GEOS-5