NASA GEOS-5 Aerosol Data Assimilation Update

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

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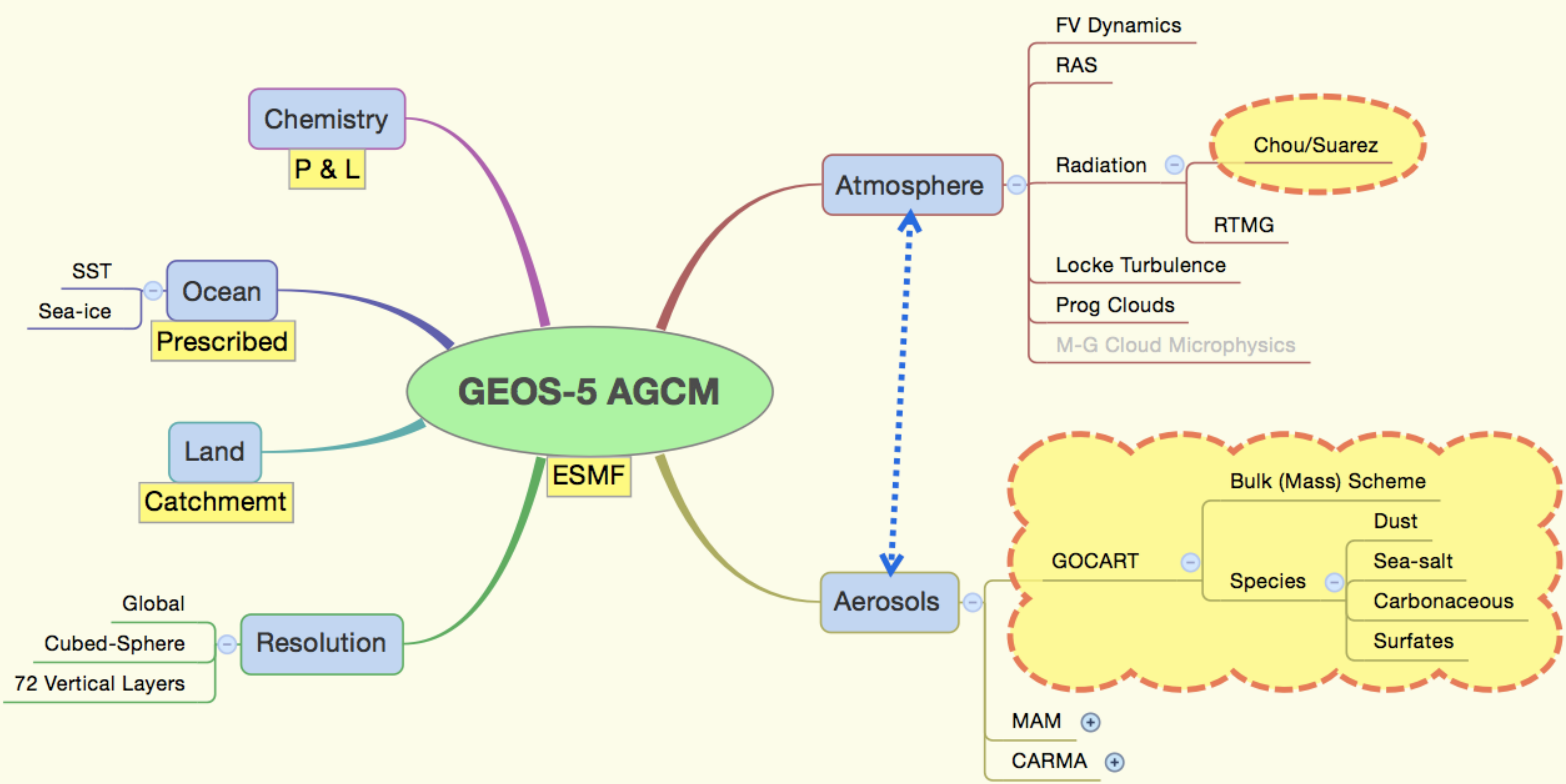
Barcelona, Spain (via WebEx)
June 16-19, 2015

Outline

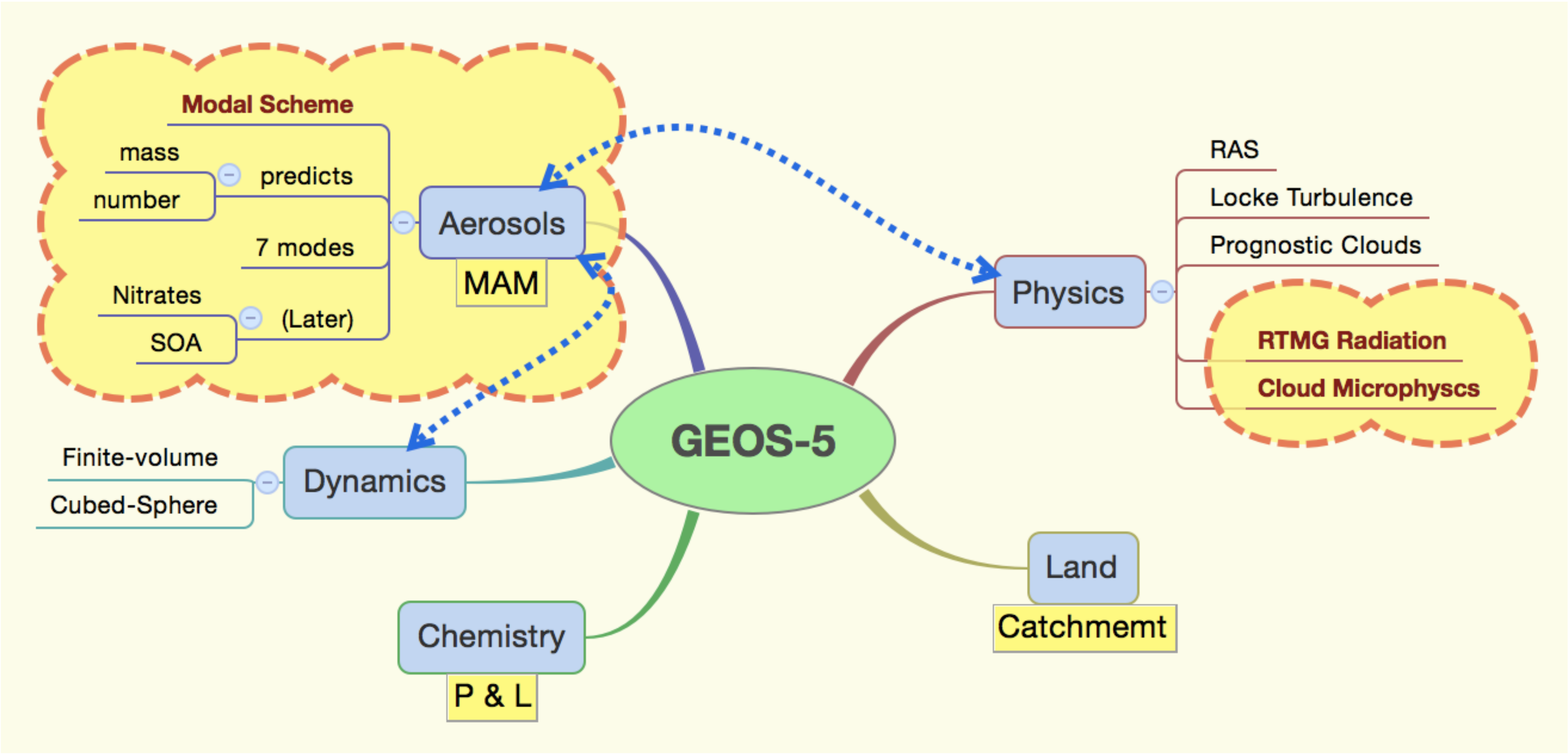
- Development Overview
  - Aerosol modeling evolution
  - Aerosol data assimilation evolution
- Observing system homogenization for reanalyzes
- Data Assimilation & Field Campaigns
- Concluding Remarks

GEOS-5 Model Configuration for and MERR*Aero* MERRA-2



Global, 50 km, 72 Levels, top at 0.01 hPa

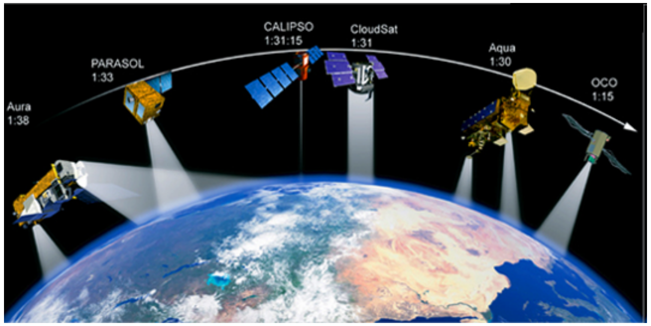
Current GEOS-5 Development: Aerosol & Clouds Microphysics



Global, **12.5 km**, **72** Levels, top at 0.01 hPa

Current GEOS-5 Aerosol Data Assimilation

- 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

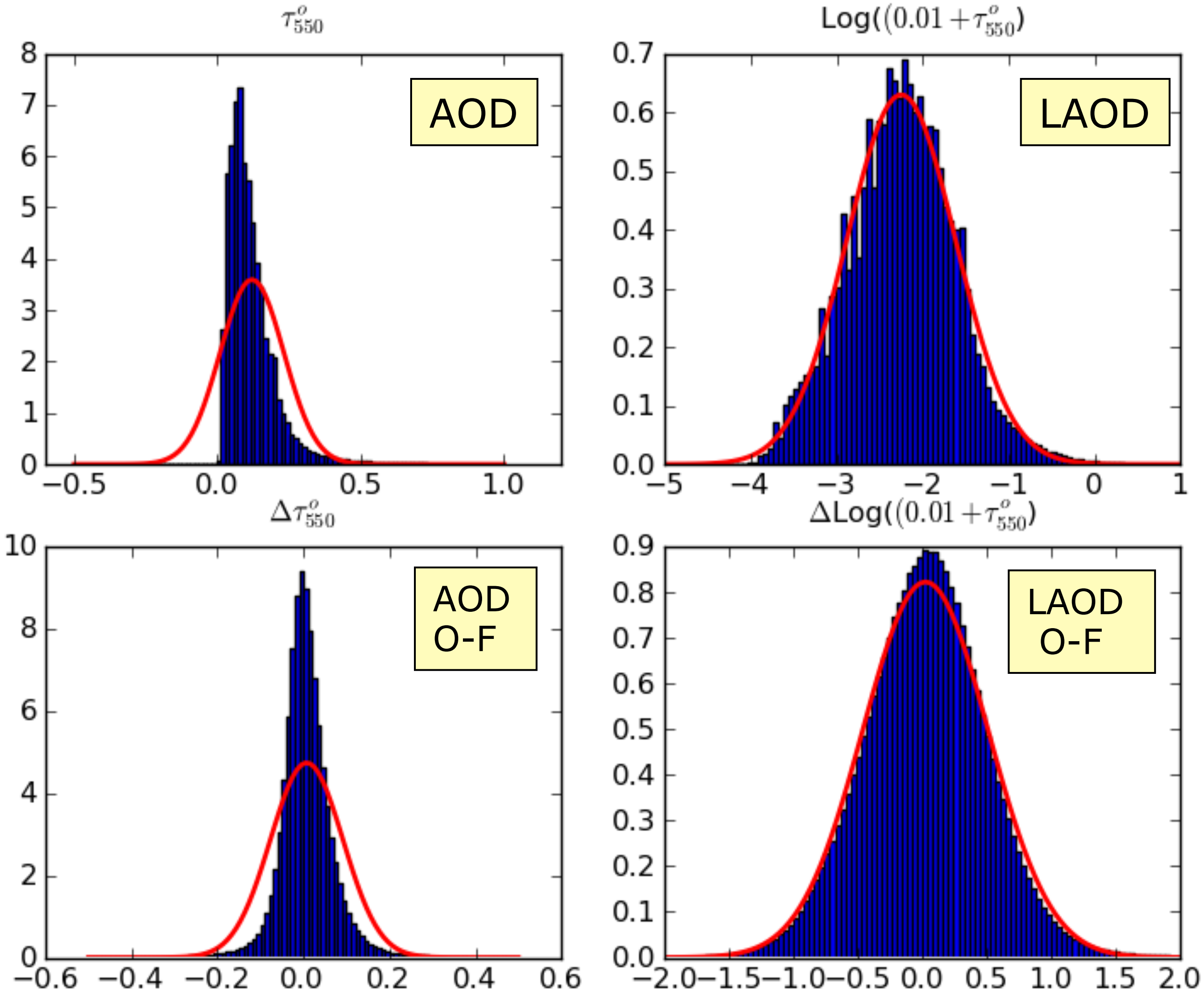
Data Type

- Quality control and Data Assimilation methodologies assumes Gaussian statistics
- AOD (and errors) is not normally distributed
- *Log-transformed* AOD has better statistical properties:

$$\text{Log}\,(\,0.01 + \text{AOD})$$

- This 0.01 factor is determined from *goodness-of-fit* considerations

Analysis Variable: $\eta = \log(\tau + 0.01)$



MODIS/TERRA Ocean

Analysis Splitting

3D Aerosol Concentration Analysis

$$x^a = x^f + P^f H^T \left(H P^f H^T + R\right)^{-1} \left(y^o - H x^f\right) \equiv x^f + \delta x^a$$

where y is AOD, and x is aerosol concentration.

2D AOD Analysis

Since the AOD observable is 2D is common to solve the AOD analysis equation:

$$y^a \equiv H x^a = y^f + H P^f H^T \left(H P^f H^T + R\right)^{-1} \left(y^o - H x^f\right) \equiv y^f + \delta y^a$$

Projecting AOD into Concentration Increments

The 3D concetration increments is related to the 2D AOD increments by:

$$\delta x^a = P^f H^T \left(H P^f H^T\right)^{-1} \delta y^a$$

For efficiency, this last equation can be solved in 1D (vertical).

Analysis Splitting with Ensembles

If the background error covariance P^f is parameterized in terms of ensemble perturbations, say

$$\begin{aligned} X &= \begin{pmatrix} x_1 & x_2 & \cdots & x_E \end{pmatrix} \\ Y &= HX \\ &= \begin{pmatrix} Hx_1 & Hx_2 & \cdots & Hx_E \end{pmatrix} \\ &= \begin{pmatrix} y_1 & y_2 & \cdots & y_E \end{pmatrix} \end{aligned}$$

so that

$$P^f \sim XX^T$$

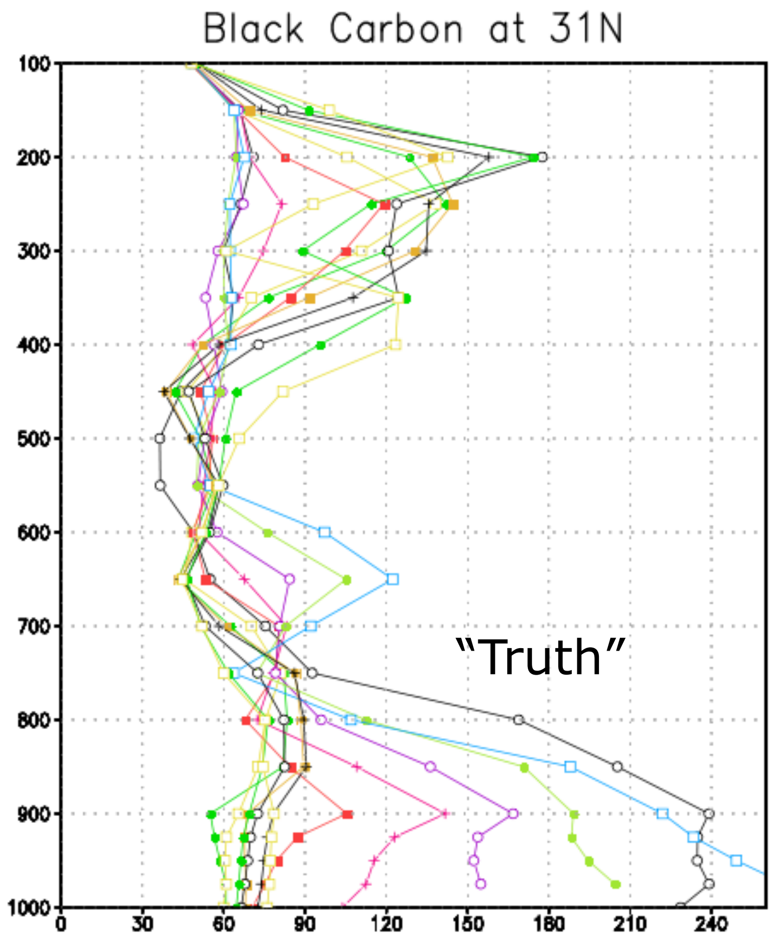
it follows that

$$\delta x^a = XY^T \left(YY^T\right)^{-1} \delta y^a$$

This is the well known (unbiased) linear regression equation.

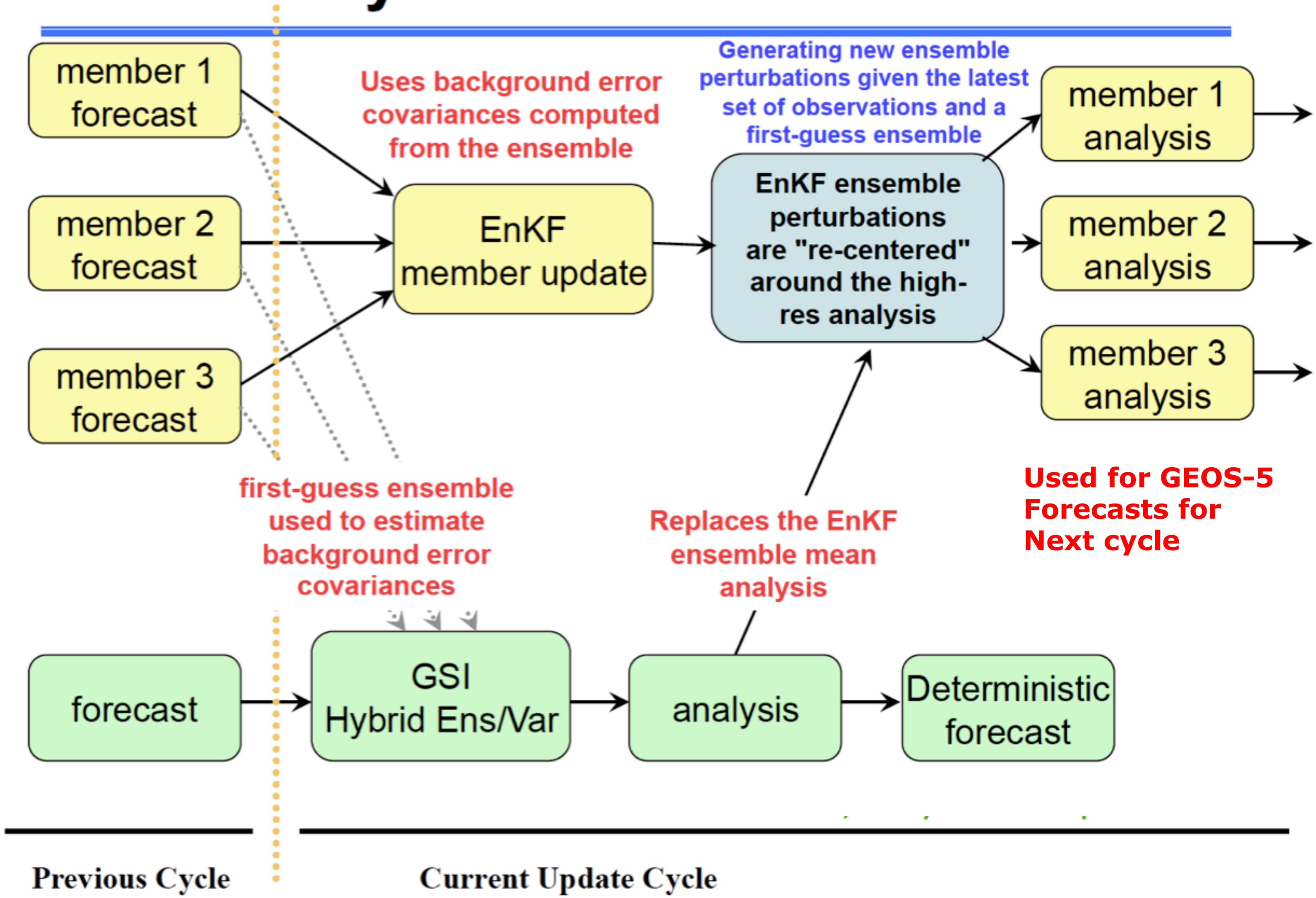
Local Displacement Ensembles (LDE)

- Construct perturbation ensembles by means of isotropic displacements around gridbox
- Weigh each ensemble member by its fit to 2D AOD analysis
- For efficiency, perform the AOD-to-mixing ratio calculation in 1D



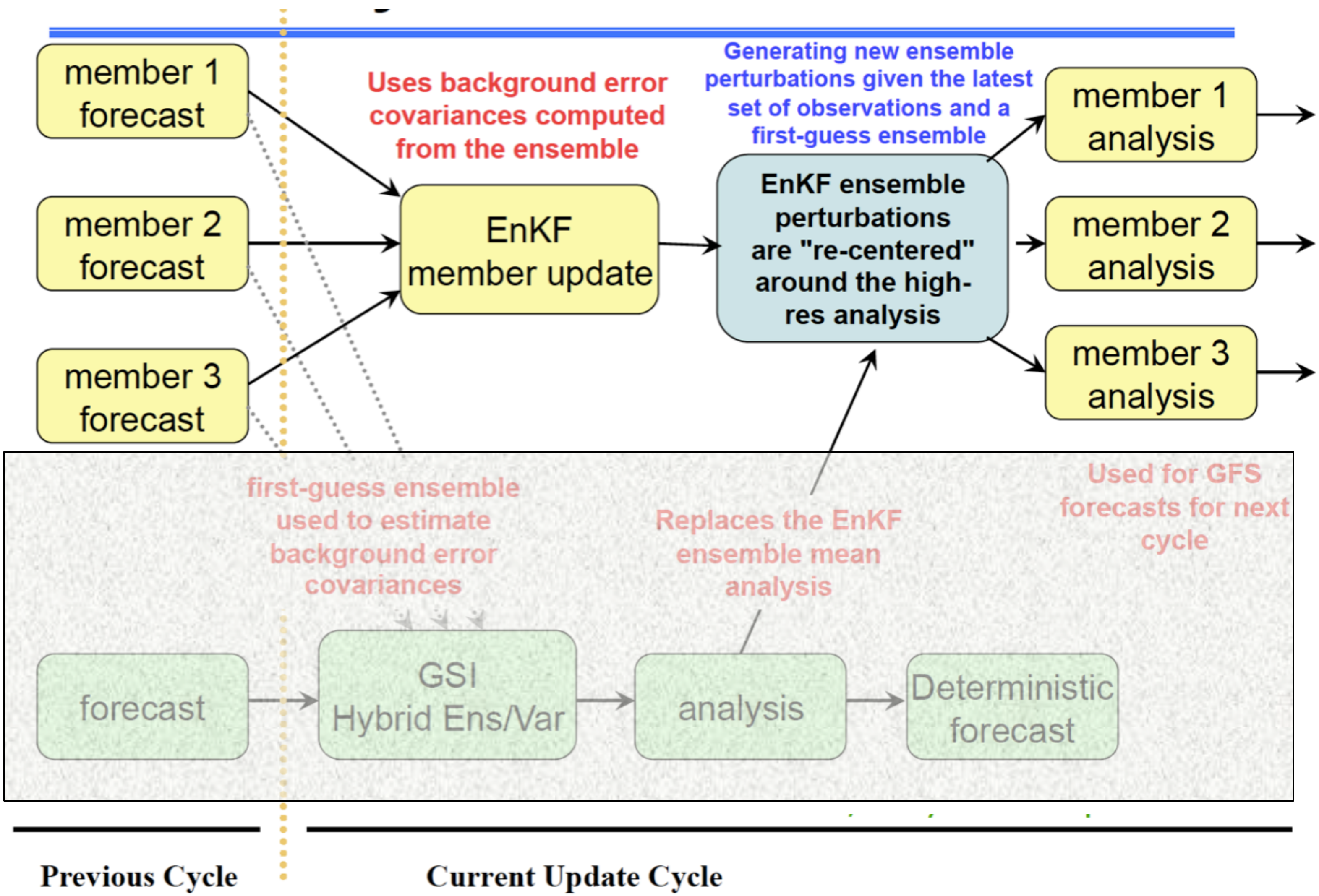
GEOS-5 **Meteorological** DAS

Hybrid 3D-VAR/EnKF



In collaboration with NOAA NCEP, ESRL

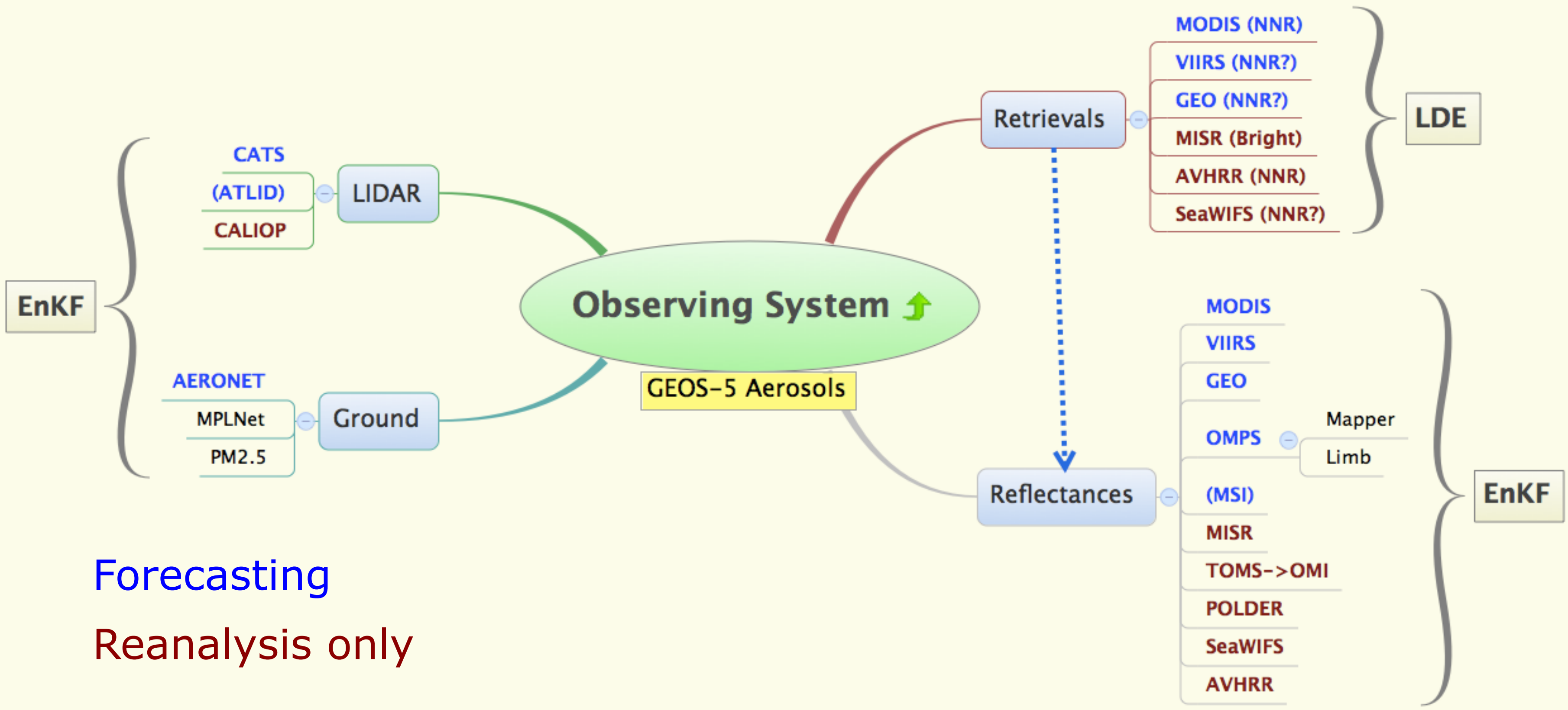
GEOS-5 **Aerosol** Assimilation
Phase I: EnKF Only



In Development: GEOS-5 Aerosol EnKF

- Based on Whitaker & Hamill (2002) formulation
  - Same codebase as GEOS-5 EnsVar System
- Aerosol ensembles
  - produced by GEOS-5 EnsVar system
  - 32 or 64 members
  - ~ **50 or 25 km** resolution (central analysis: **12.5 km**)
- Aerosols impact GSI observation operators (for IR channels) but no aerosol increments produced.
- *Adaptive maximum-likelihood estimation of error variances and localization functions*

Aerosol Observing System



Forecasting

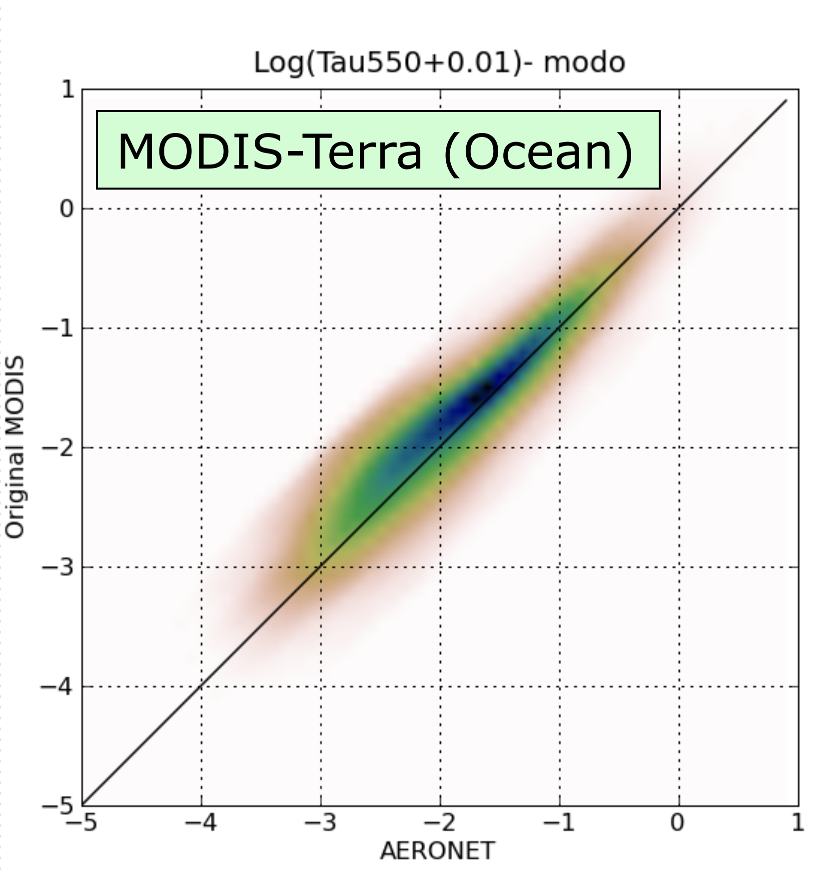
Reanalysis only

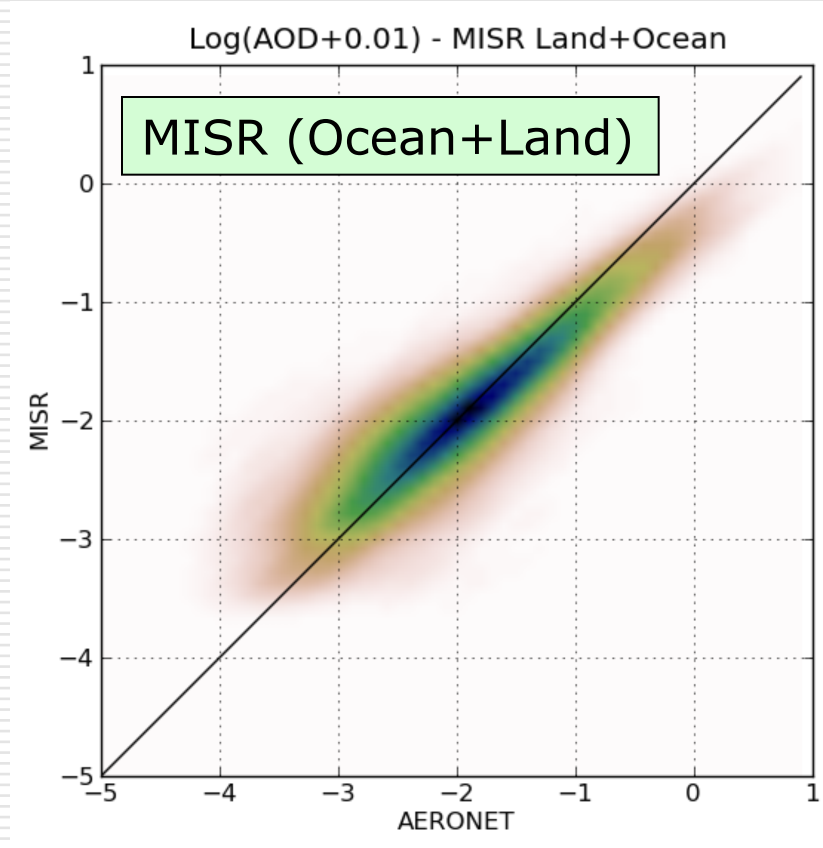
Aerosol Data Assimilation in GEOS-5

Summary of 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	Summer 2015
MERRA-2 Dynamical Downscaling	12.5 km	2000-2015	AVHRR, MODIS C5/C6, MISR, AERONET	Q4 2015

AERONET-MODIS/MISR Joint PDF





Observation bias correction is necessary.

NRL Empirical AOD Corrections

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

Click Here for Full Article

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 20

[1] Currently, the Moderate-resolution Imaging Spect
aerosol product (MOD04/MYD04) is the best aerosol
near-real-time aerosol data assimilation. However, a c
variances in MOD04/MYD04 aerosol optical depth p
implementing the MODIS aerosol product in aerosol
1 year's worth of Sun photometer and MOD04/MYD
over global oceans, we studied the major biases in MO
to wind speed, cloud contamination, and aerosol micr
than 0.6, we found similar uncertainties in the mean M
the MODIS aerosol group, while biases are nonlinear f

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

E. J. Hyer[1], J. S. Reid[2], and J. Zhang[3]

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[2]Naval Research Laboratory, 7 Grace Hopper Avenue, Monterey, CA 93943, USA
[3]University of North Dakota, 4149 University Avenue Stop 9006, Grand Forks, ND 58202, USA

Received: 12 August 2010 – Accepted: 14 August 2010 – Published: 14 September 2010

Correspondence to: E. J. Hyer (edward.hyer@nrlmry.navy.mil)

Published by Copernicus Publications on behalf of the European Geosciences Union.

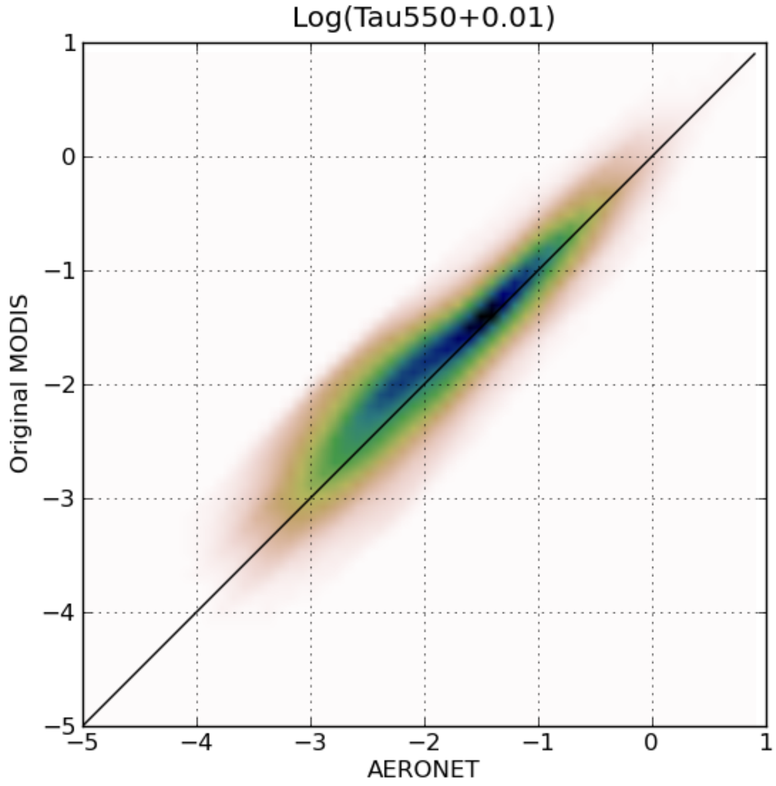
Neural Net for AOD Empirical Retrievals

- Ocean Predictors
  - Multi-channel
    - TOA Reflectances
    - ~~Retrieved AOD~~
  - Angles
    - Glint
    - Solar
    - Sensor
  - Cloud fraction (<85%)
  - Wind speed
- Target: AERONET
  - Log(AOD+0.01)

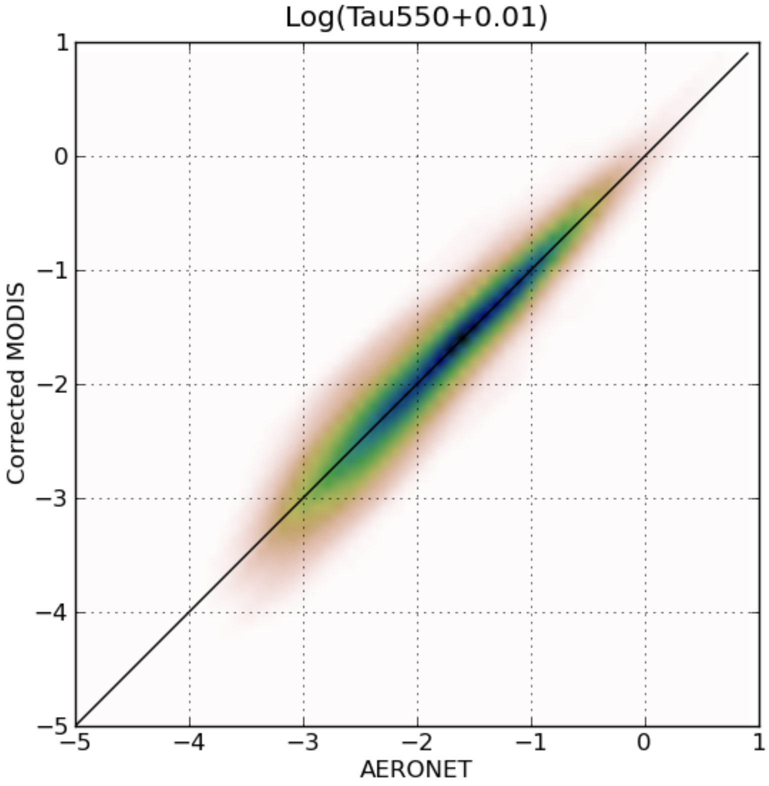
- Land Predictors
  - Multi-channel
    - TOA Reflectances
    - ~~Retrieved AOD~~
  - Angles
    - Solar
    - Sensor
  - Cloud fraction (<85%)
  - Climatological albedo
    - < 0.25
- Target: AERONET
  - Log(AOD+0.01)

Observational Bias

ORIGINAL MODIS AOD



BIAS CORRECTED AOD



PATMOS-x

AVHRR Pathfinder Atmospheres - Extended

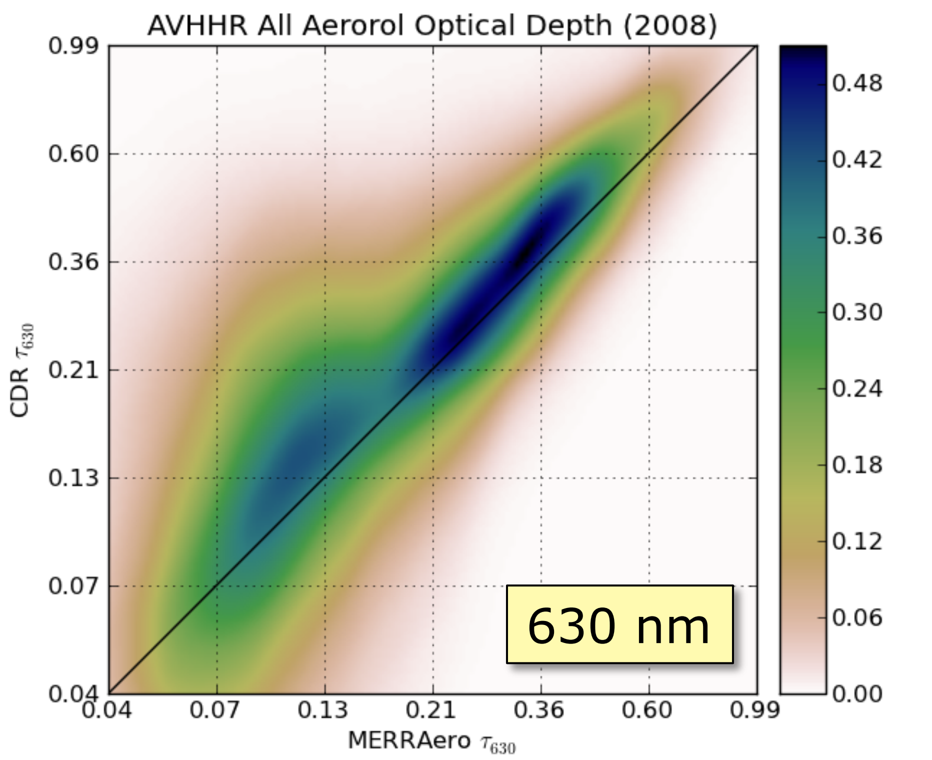
- Overview
- Data
- Documentation
- Monitoring
- Publications
- Contact Us
- Related Links
- Acknowledgments

Last updated 07-Nov-2008 by SSEC Webmaster

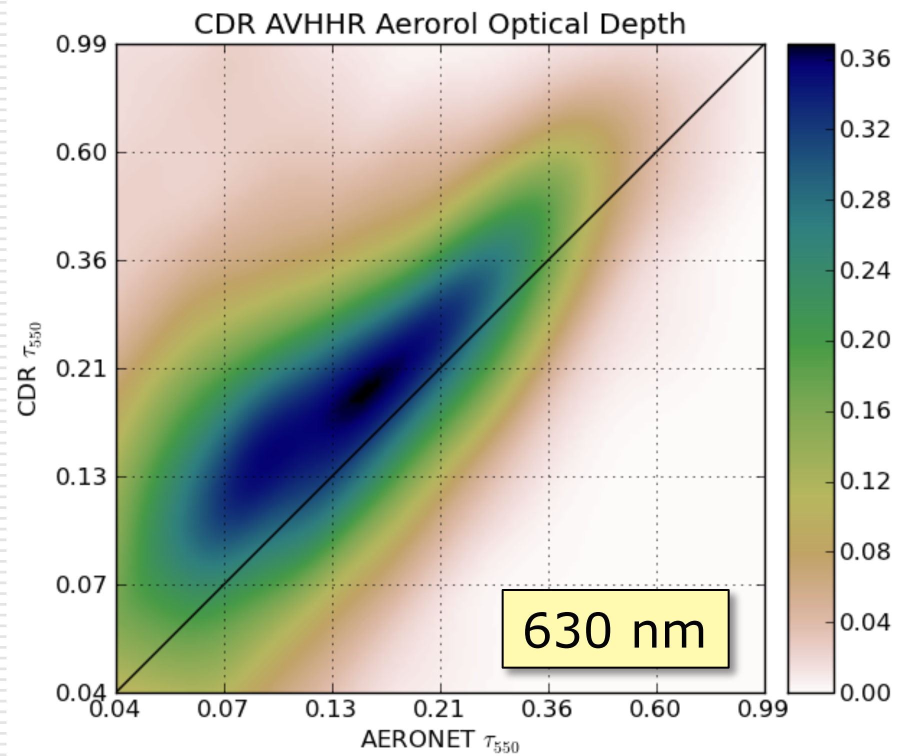
CIMSS SSEC

AVHRR NOAA CDR AOD

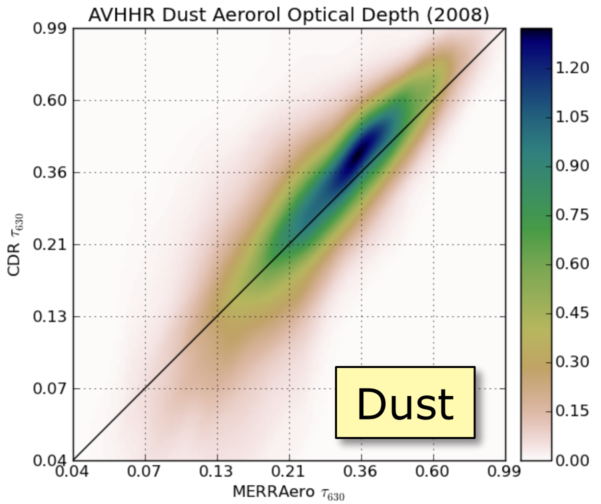
MERRAero, AERONET Comparison



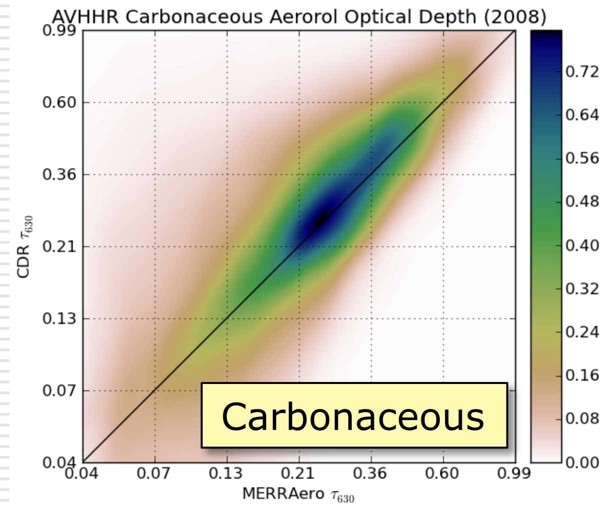
MERRAero

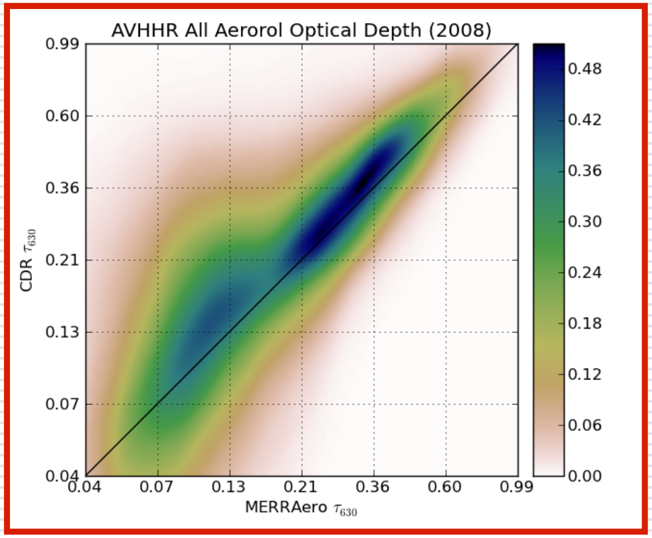


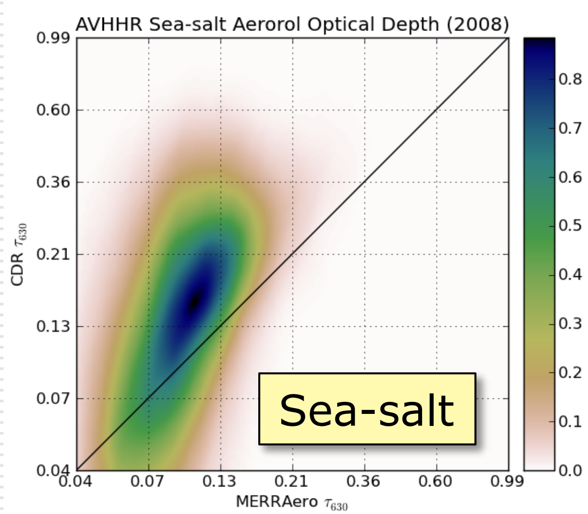
AERONET



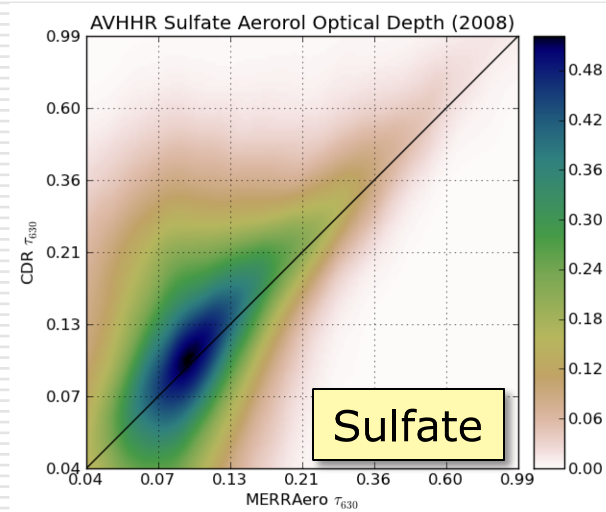
CDR: 2008







Multiple Species



PATMOS-x

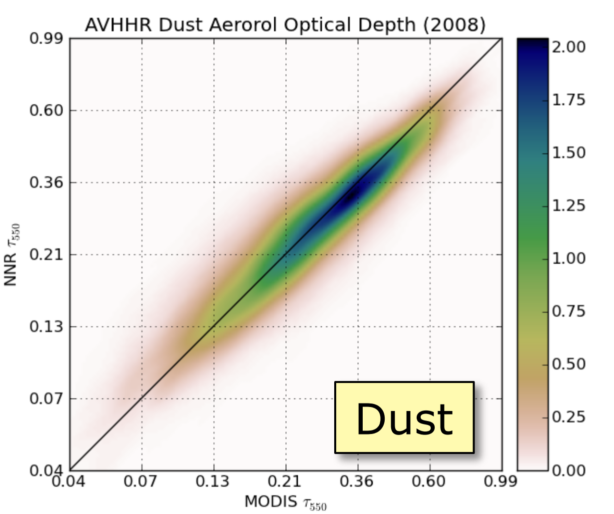
AVHRR Pathfinder Atmospheres - Extended

PATMOS-x Dataset

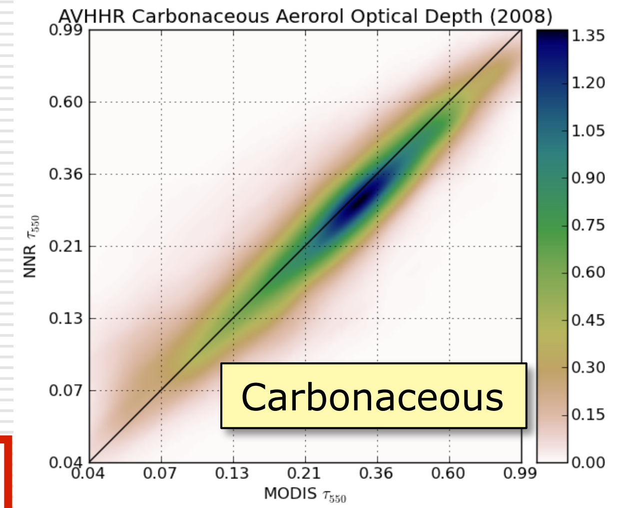
- Version 5 Level 2B
- 0.1 degree sampling (not average)
- Period: 1978-2009
- Inter satellite calibration (MODIS reference)
- Bayesian probabilistic cloud detection (CALIPSO reference)
  - **cpd <0.5%**

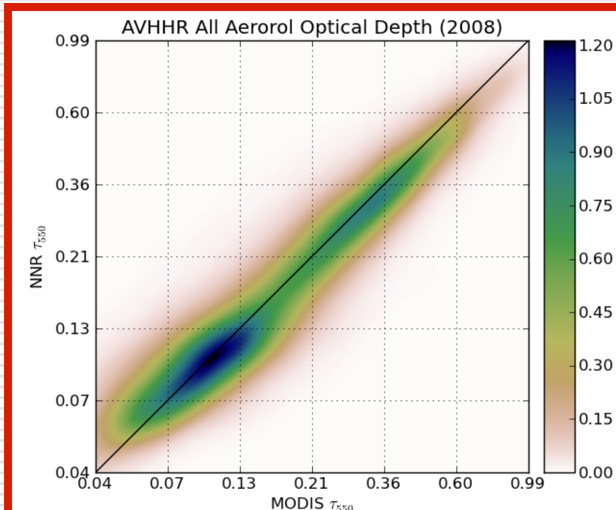
Neural Net Retrival

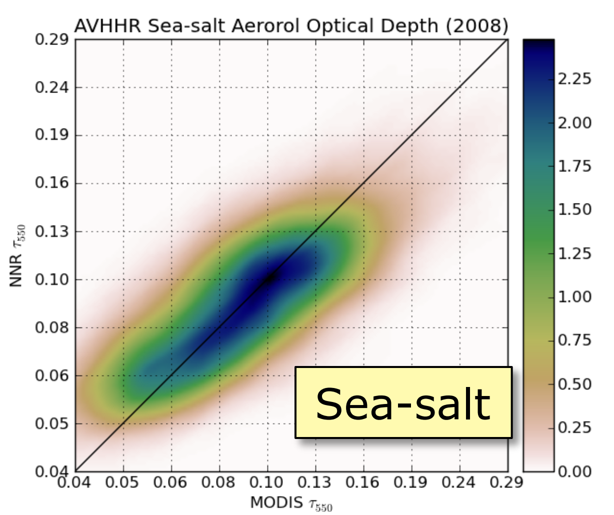
- Ocean Predictors
  - TOA Reflectances
  - 630 and 860 nm
  - TPW
  - Ocean albedo (wind)
  - Solar and sensor angles
  - GEOS-5 fractional AOD speciation
- Target:
  - AOD at 550 nm
  - Balanced MODIS NNR



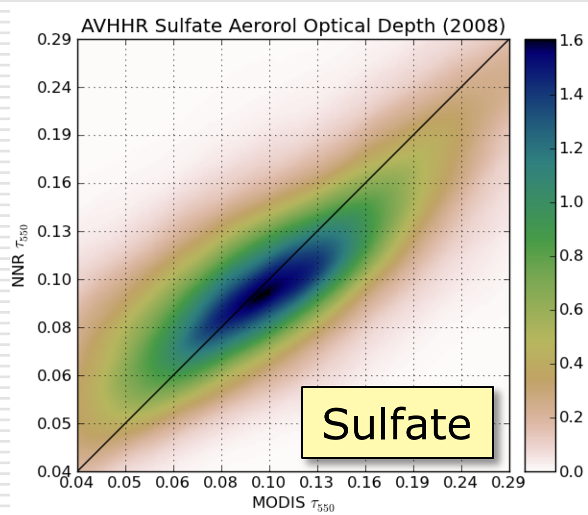
2008

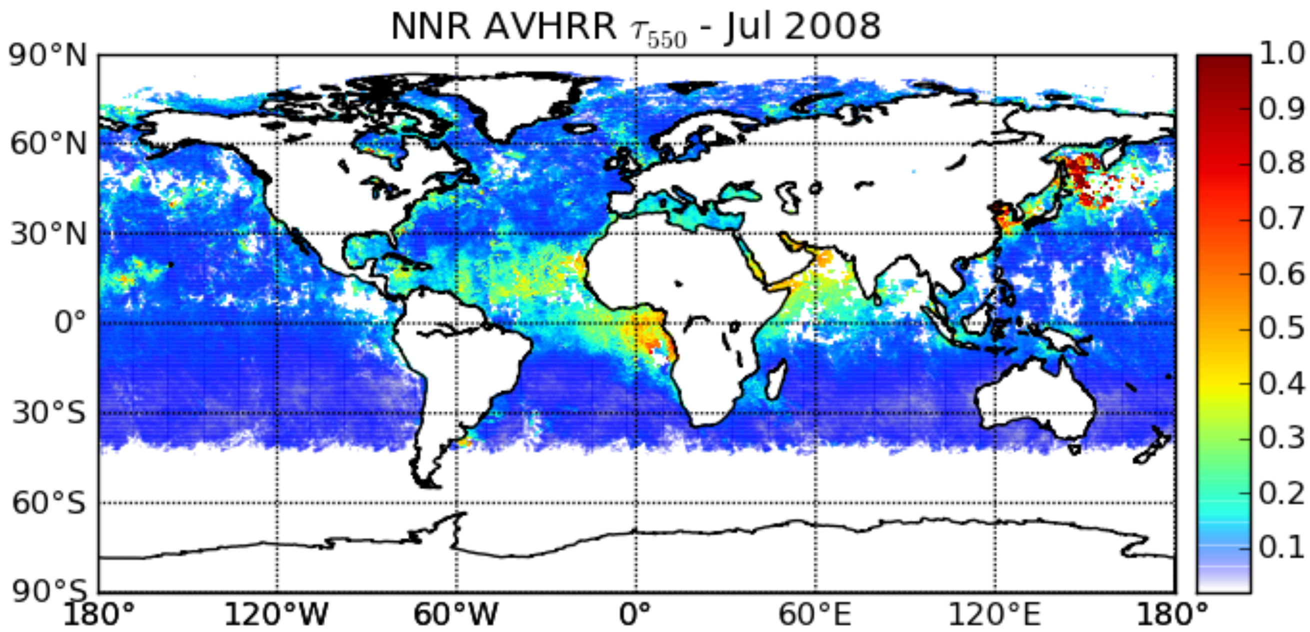


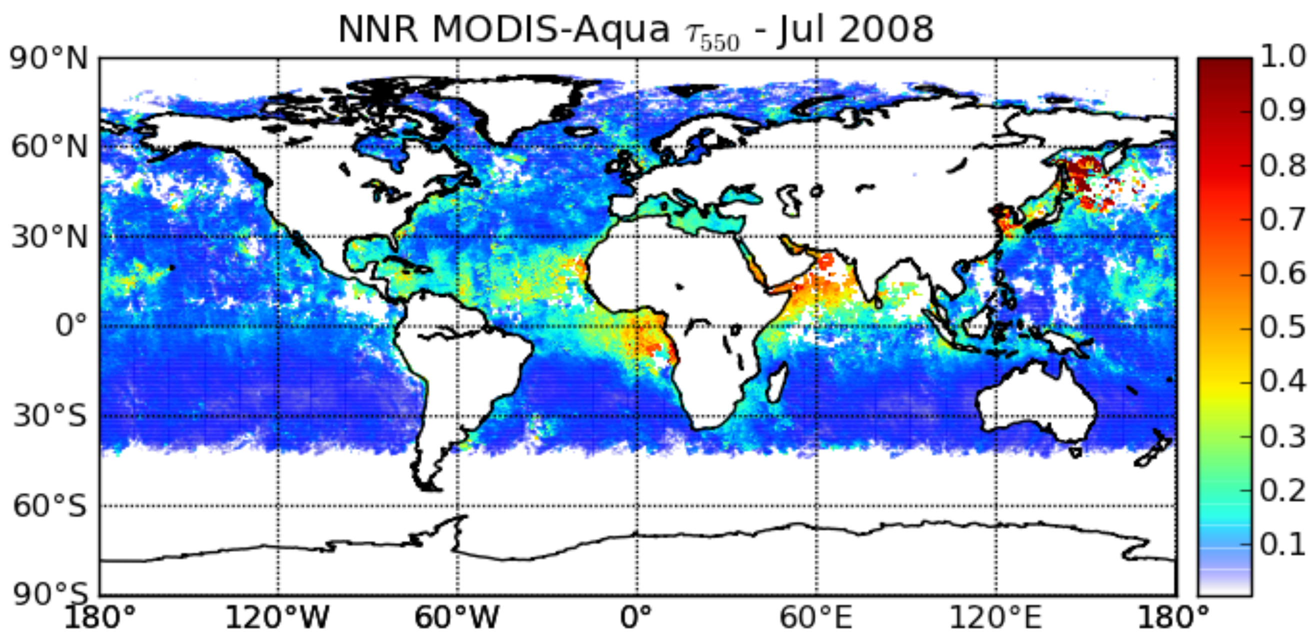




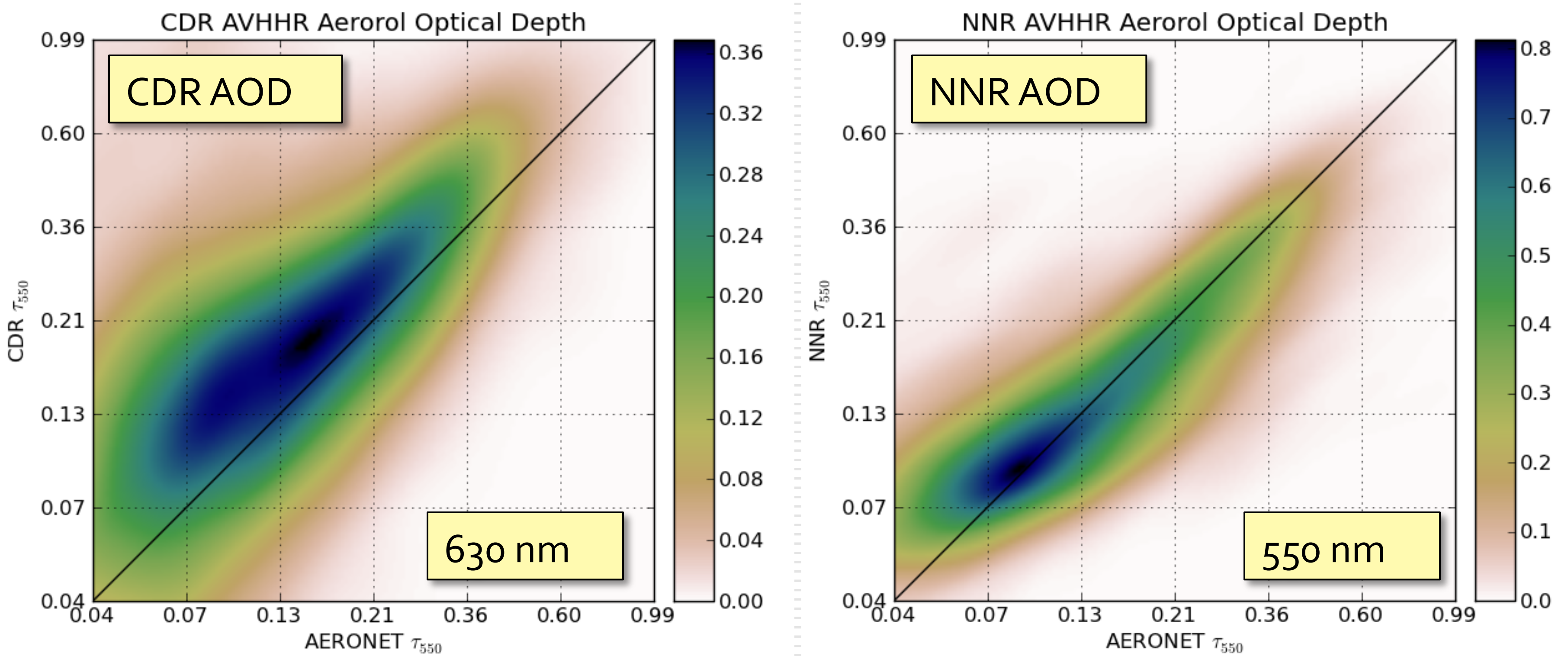
Multiple Species




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

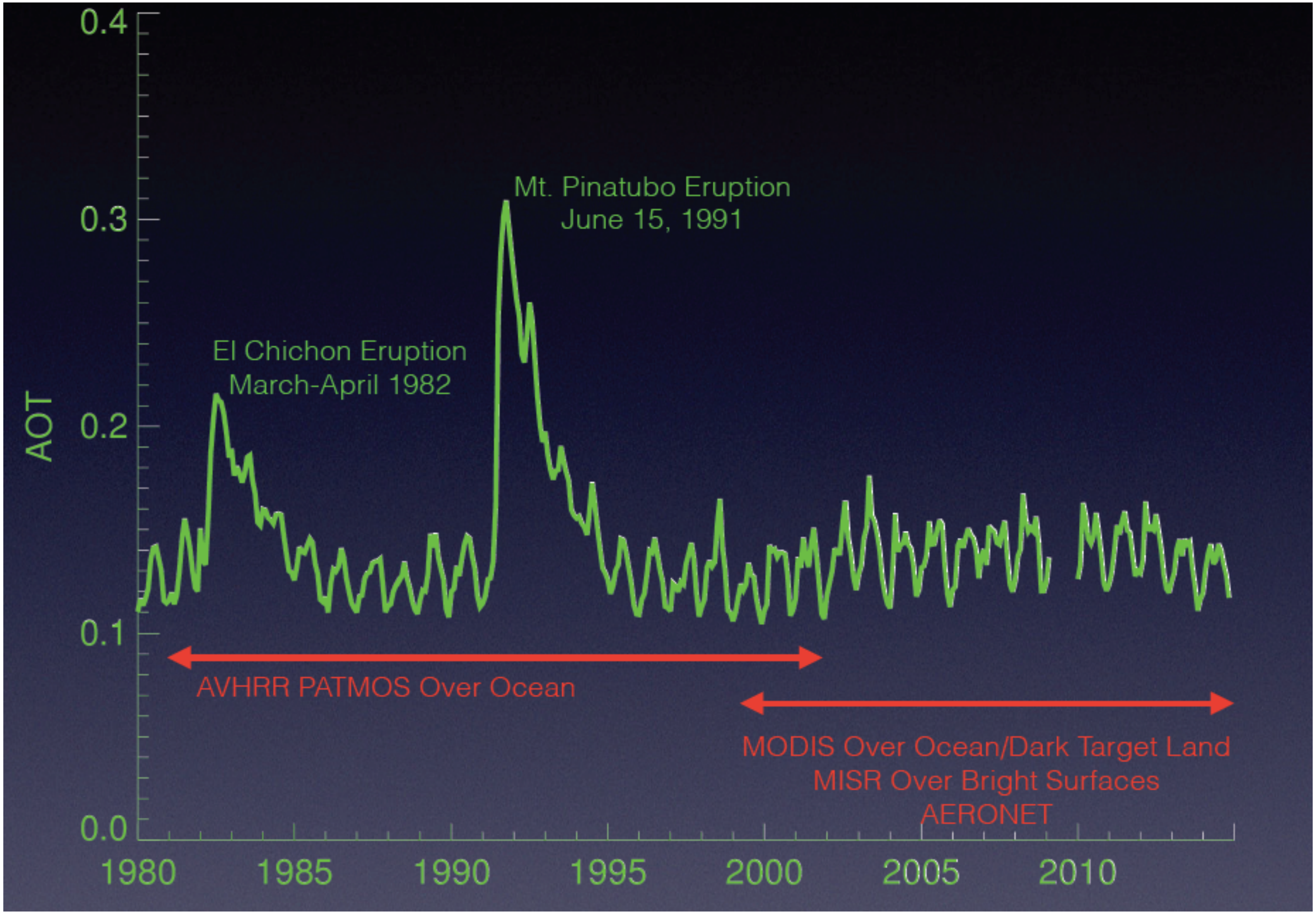

NNR MODIS-Aqua τ_{550} - Jul 2008
90°N
60°N
30°N
0°
30°S
60°S
90°S
180°
120°W
60°W
0°
60°E
120°E
180°
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

AERONET Validation

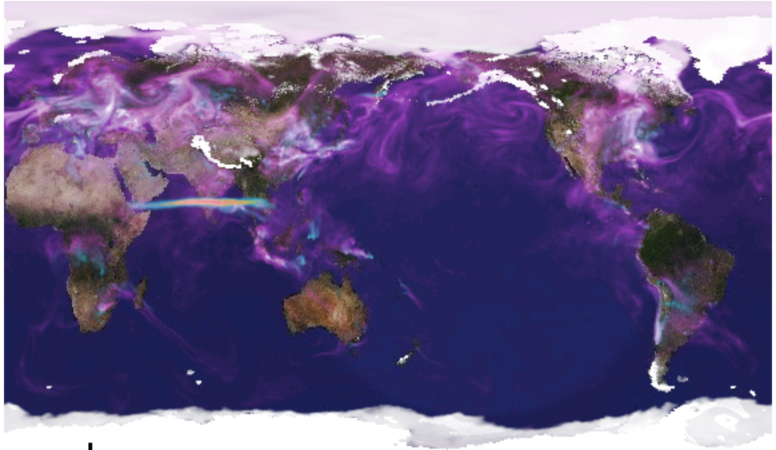


Coastal and Island Stations for 2003-2009

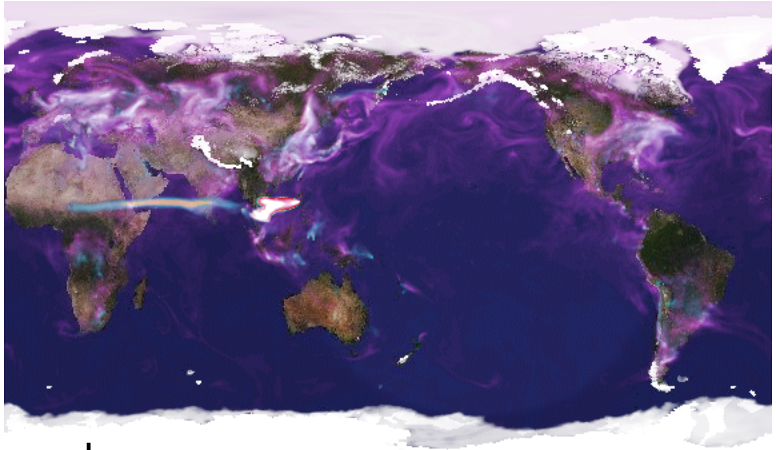
MERRA-2 Global AOD



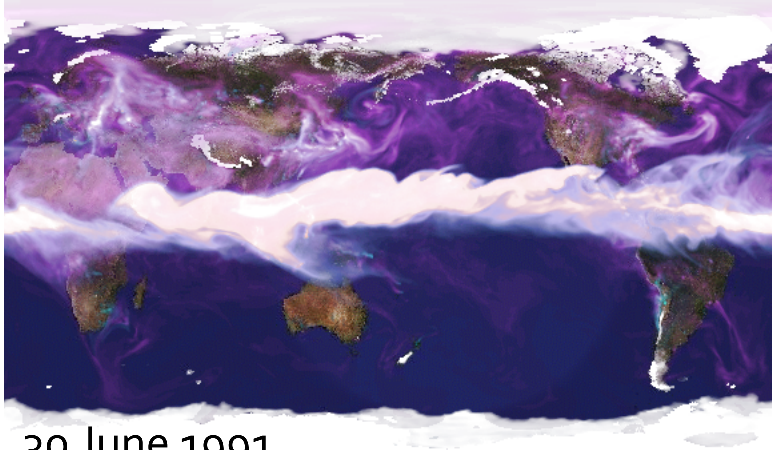
Pinatubo Eruption:
15 June 1991



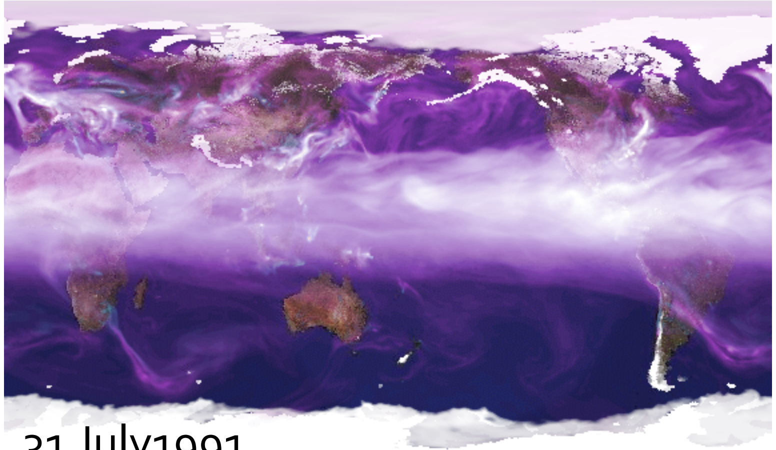
14 June 1991



15 June 1991



30 June 1991



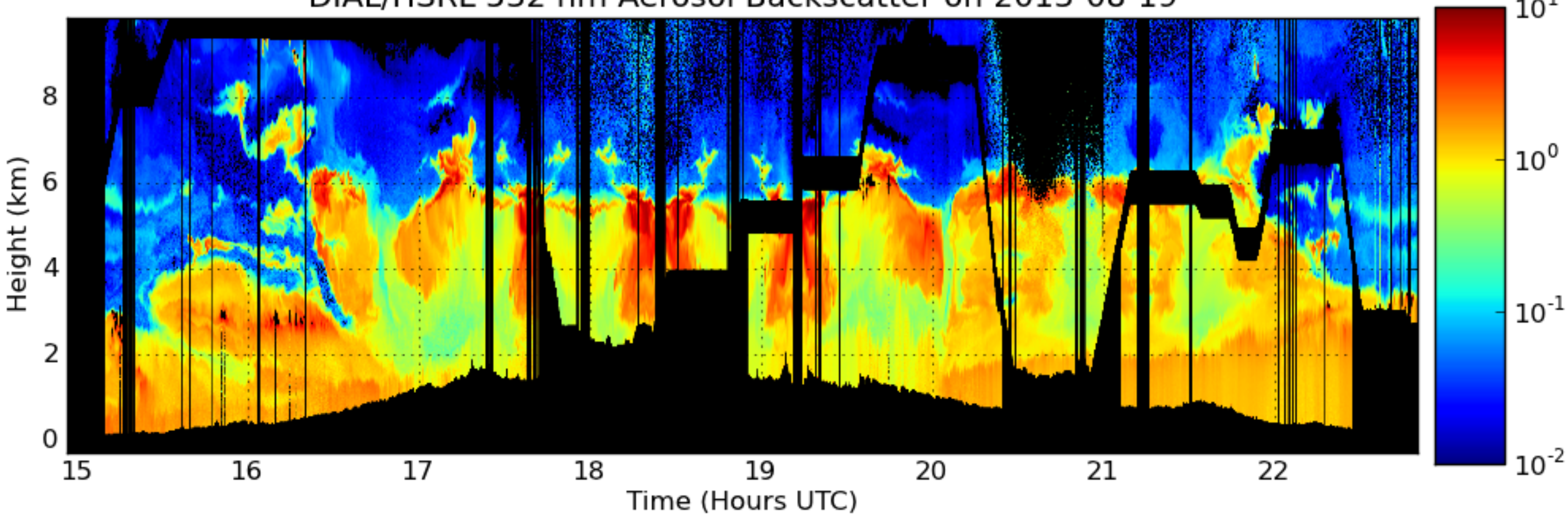
31 July1991

Data Assimilation and Field Campaigns

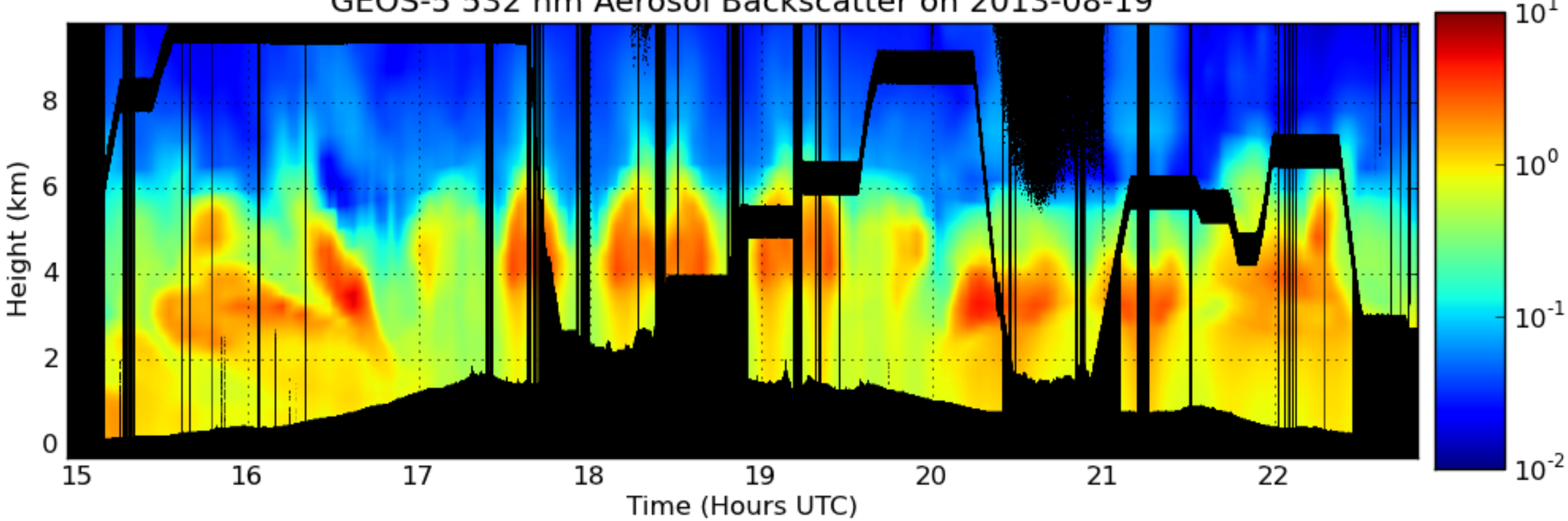
- Assimilation of localized field campaign data in a global model is of limited utility
  - Impact is often downstream of measurement
- However, field campaign data provide a great opportunity for DA algorithm development
  - Produce analysis along a flight curtain
  - Use model state sampled at curtain as prior
  - Include measurements from multiple sensors polarimeters, radiometers, LIDAR
  - Update model state, verify against in-situ payload

HSRL/Dial & GEOS-5 During SEAC4RS

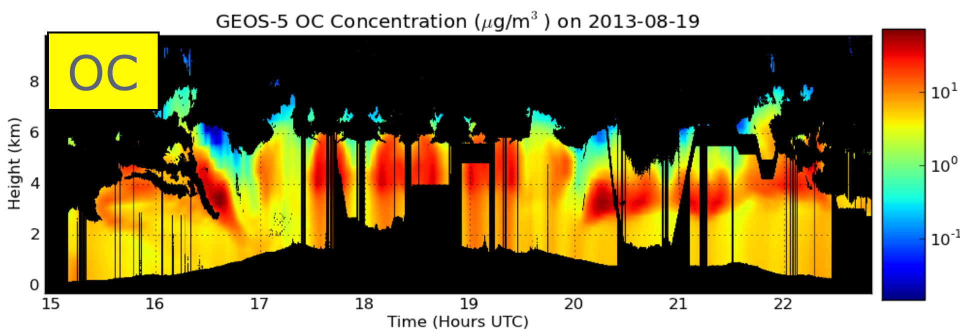
DIAL/HSRL 532 nm Aerosol Backscatter on 2013-08-19

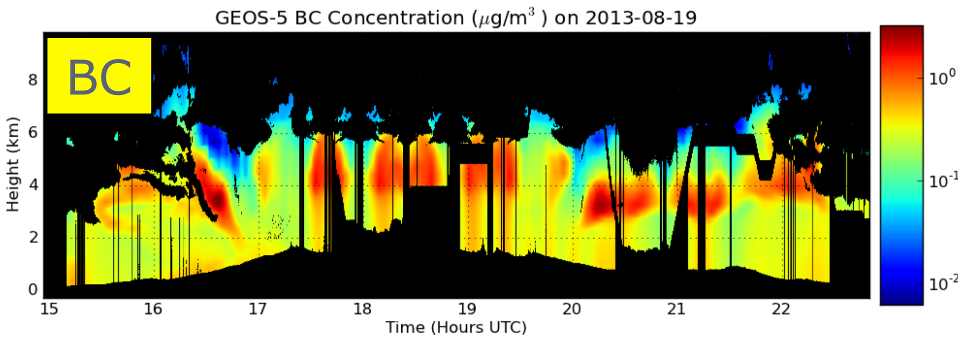


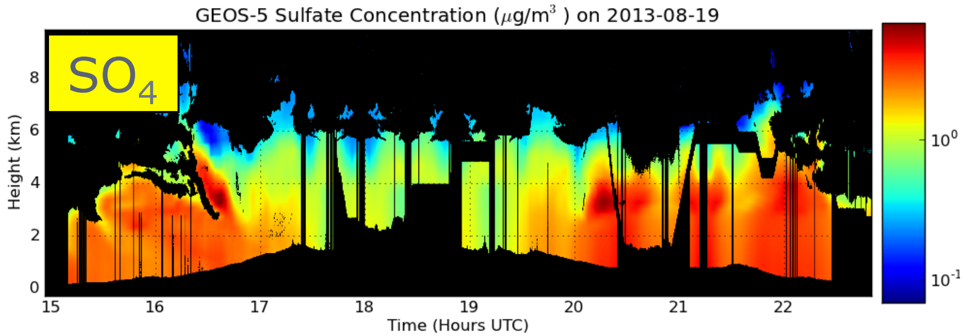
GEOS-5 532 nm Aerosol Backscatter on 2013-08-19

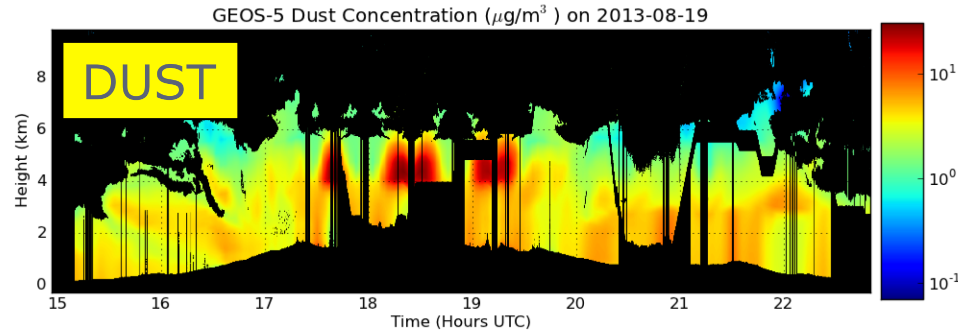


GEOS-5 Species: Background









Except for Dust, all particles assumed spherical

DIAL HSRL: 1-D Var

- Observables:
  - Backscatter: 532 nm and 1064 nm
  - Extinction: 532 nm
- Control variables:
  - GOCART species (dust, sea-salt, BC, OC, SO_4)
- Observation operators:
  - Rely on *prescribed* Aerosol Optical Properties (AOP)
  - In principle AOP's should be jointly estimated

Identifiability Issues

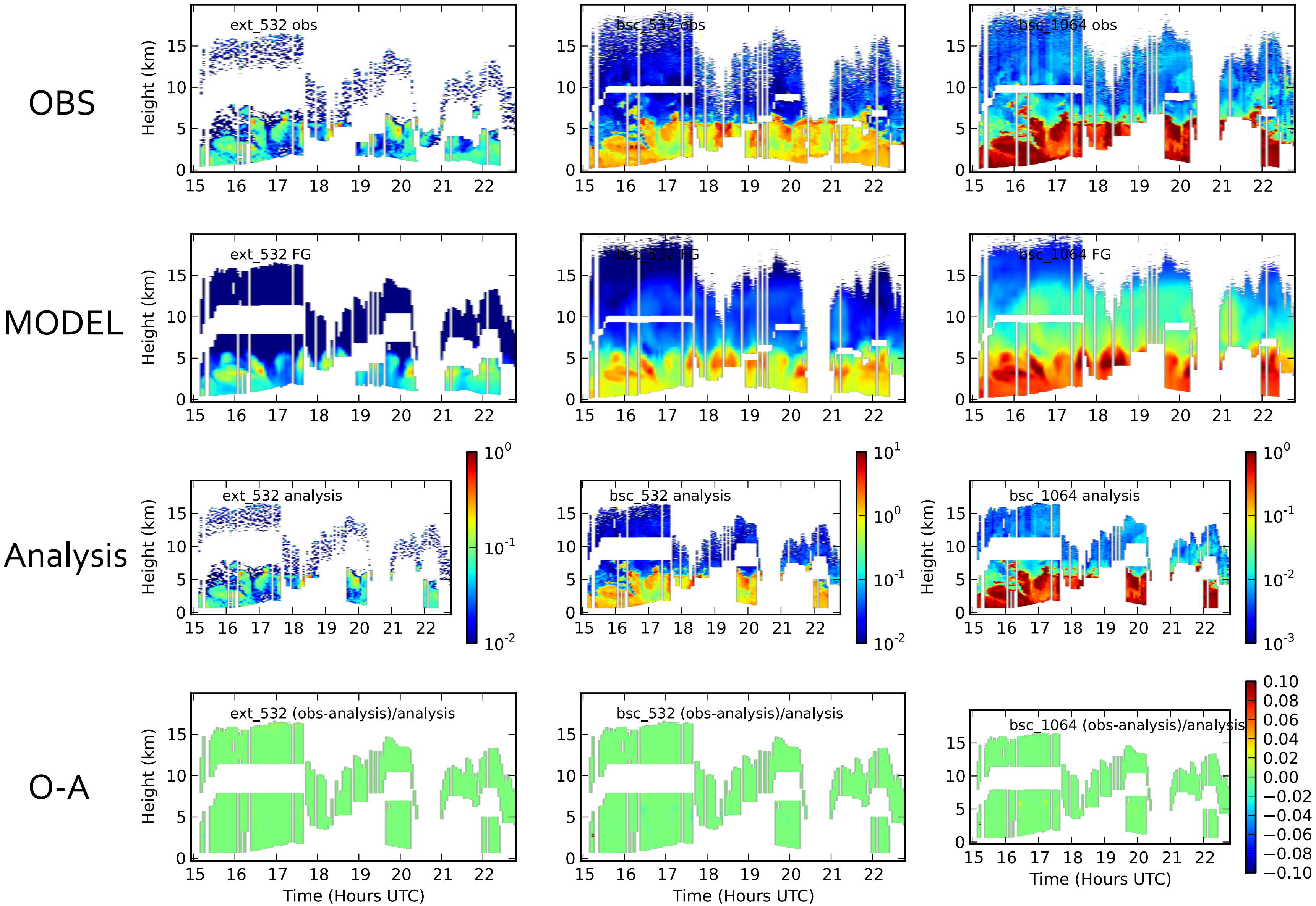
- Example: aerosol extinction coefficient

$$\epsilon = \sum_{species} f(n_s, r_s, \lambda)\rho_s$$

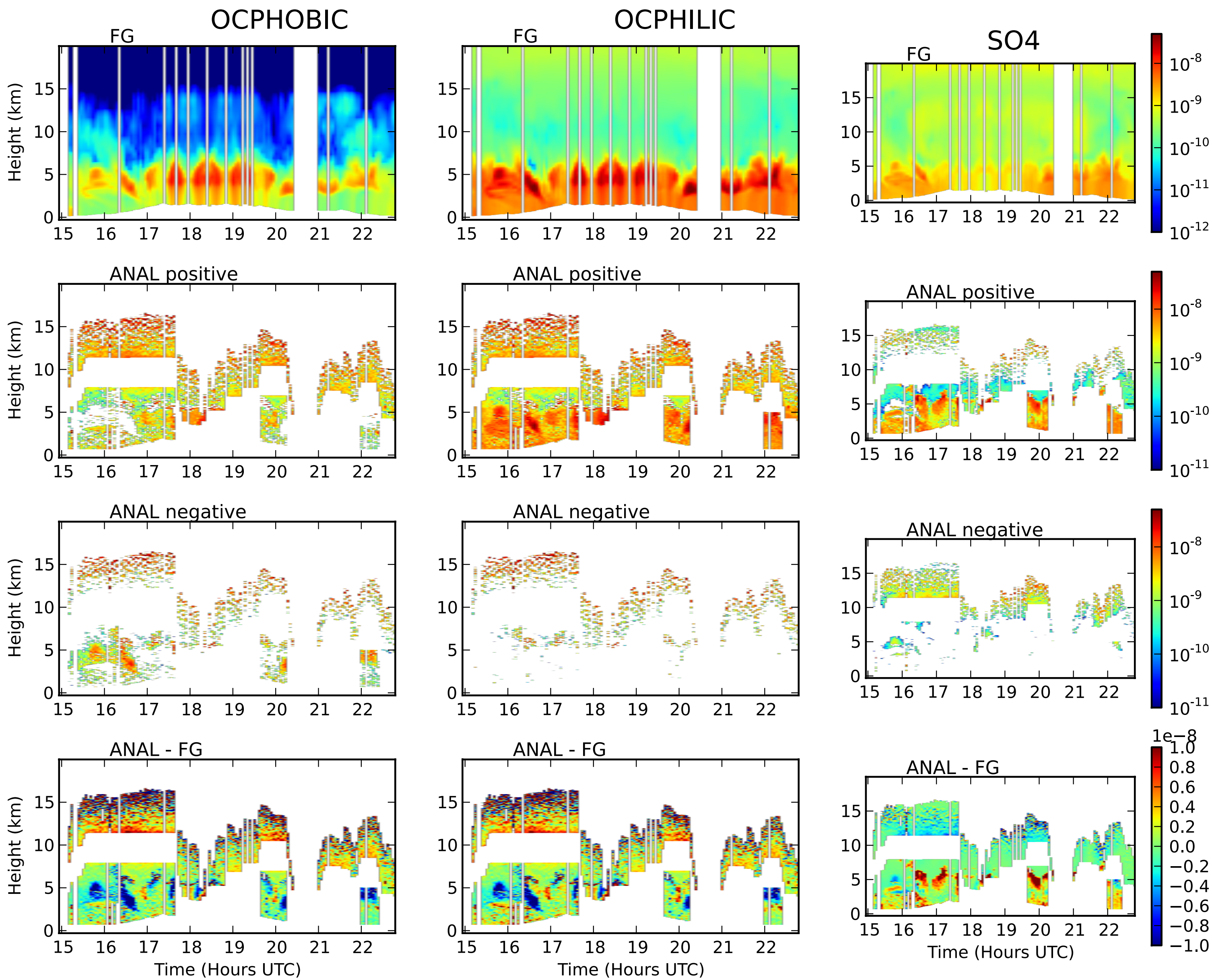
Tracer Concentration

- Typically AOP f is prescribed and ρ_s is the control variable
- Satisfying backscatter and extinction observational constraints is not so trivial if AOPs are not adequate

Limit Case: Small Obs Error



at the expense of negative mass …



Work in progress …

- Joint estimation of concentrations and optical properties
- Not yet clear whether simplified optical models in GOCART will be sufficient
- Additional number concentration control variable in new aerosol microphysical module may prove essential.
- Similar challenges are likely present in assimilation of multi-spectral AOD/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

MAN Validation