Assimilation of Cloud and Aerosol Observations in GEOS-5

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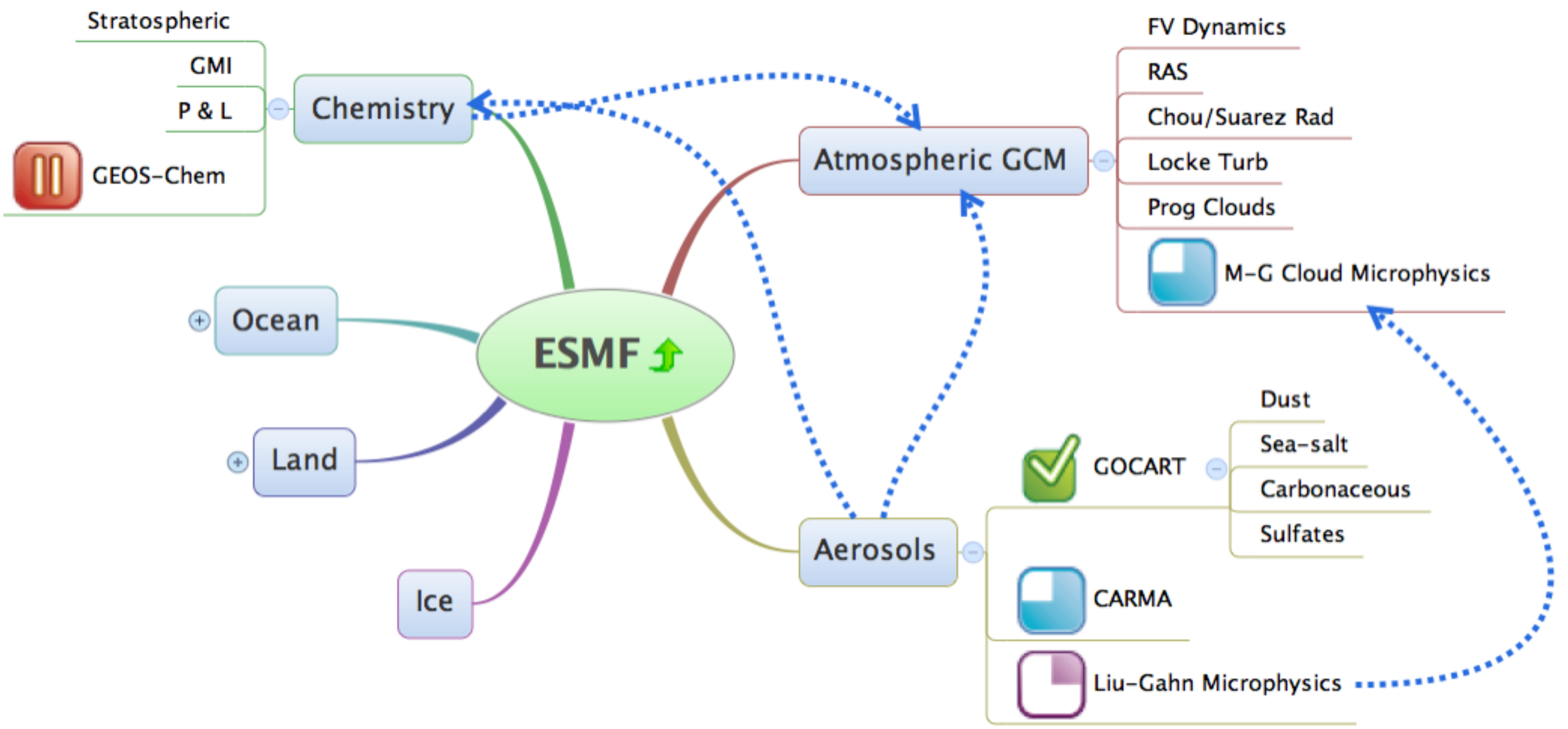
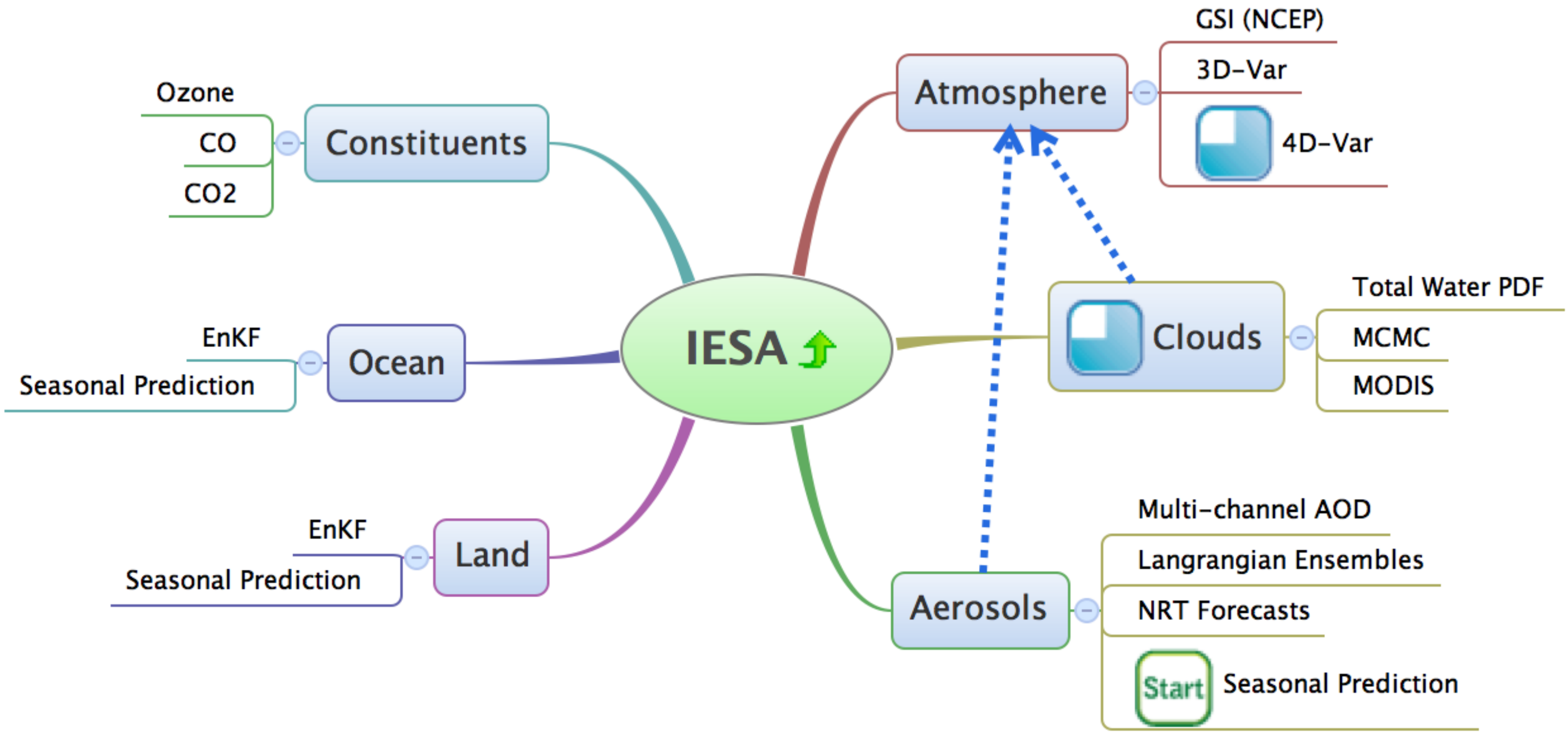
Workshop on Observations and Modeling of Aerosol and Clouds
Paris, September 12-14, 2011

GEOS-5 Earth-System Model

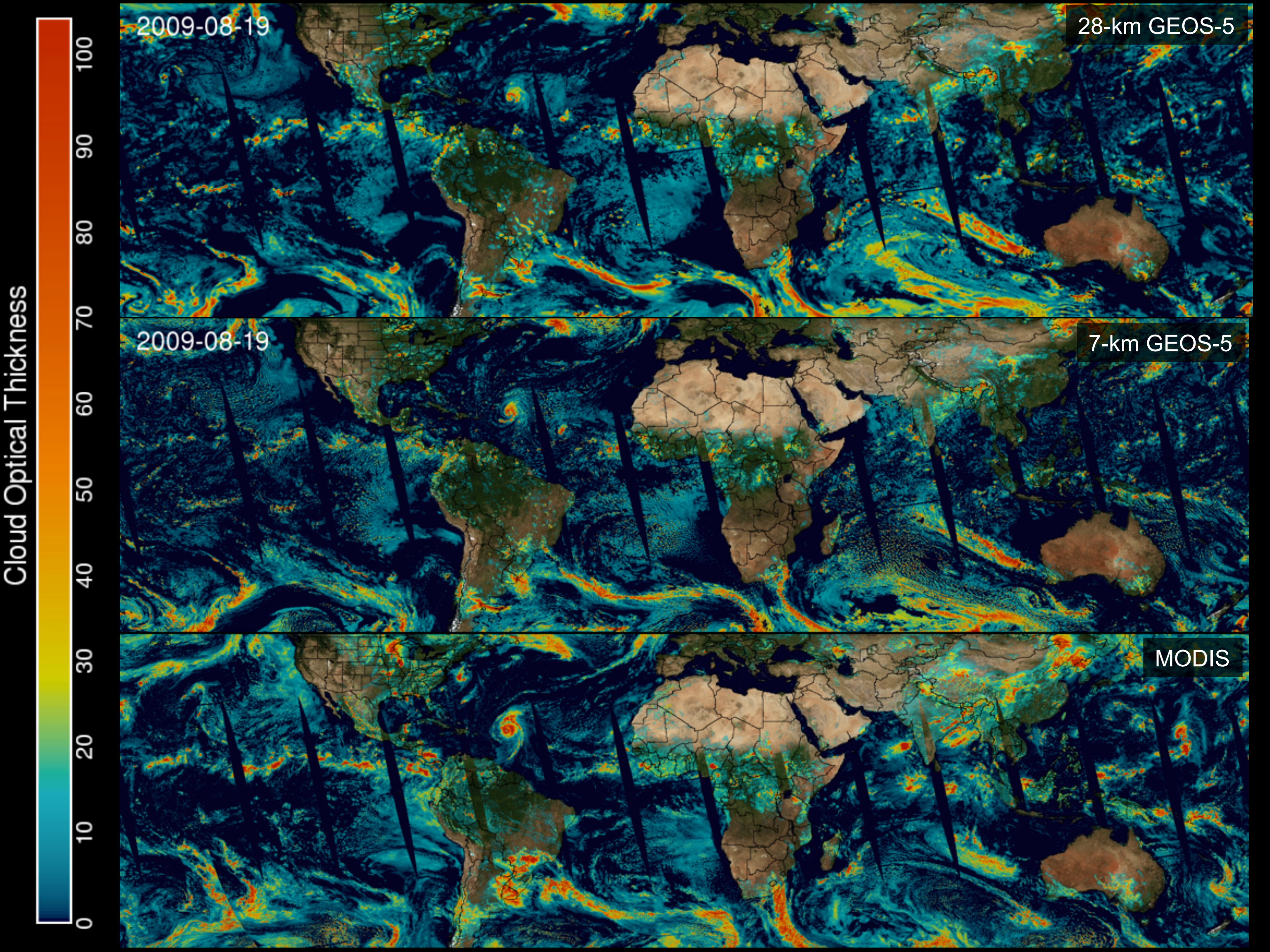


From weather to seasonal to decadal time scales

Integrated Earth System Analysis



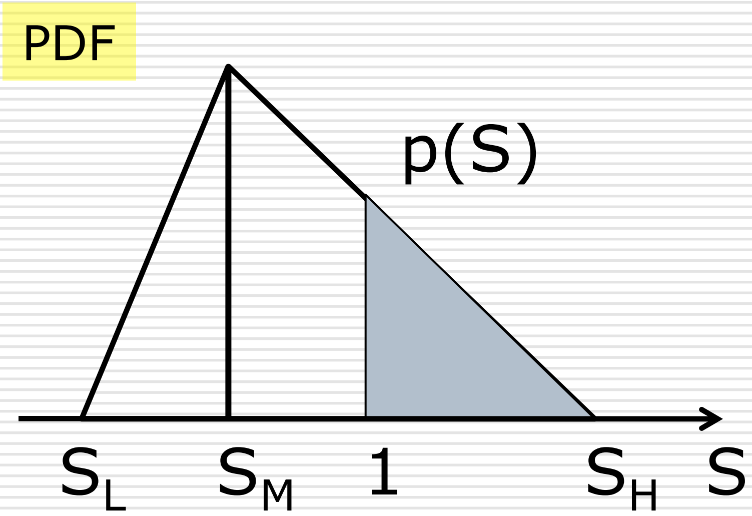
Preliminary IESA (PIESA): MERRA driven component reanalysis


Cloud Optical Thickness
0
10
20
30
40
50
60
70
80
90
100
2009-08-19
28-km GEOS-5
2009-08-19
7-km GEOS-5
MODIS

Cloud Data Assimilation

- We cannot simply insert clouds in the model
  - We need to convince the model to make clouds
- Recent GCM cloud parameterizations are based on a PDF of total water (vapor+condensate)
  - much higher resolution satellite data can be used to constrain total water PDF
  - “Cloud relocator”
- Improved cloud distribution essential for effective assimilation of cloudy radiances in 3D/4D Var:
  - Microwave data used to constrain cloud liquid water
- Data retention requires high degree of consistency across GCM and assimilation algorithms.
- Validation: CloudSat, CERES, SRB

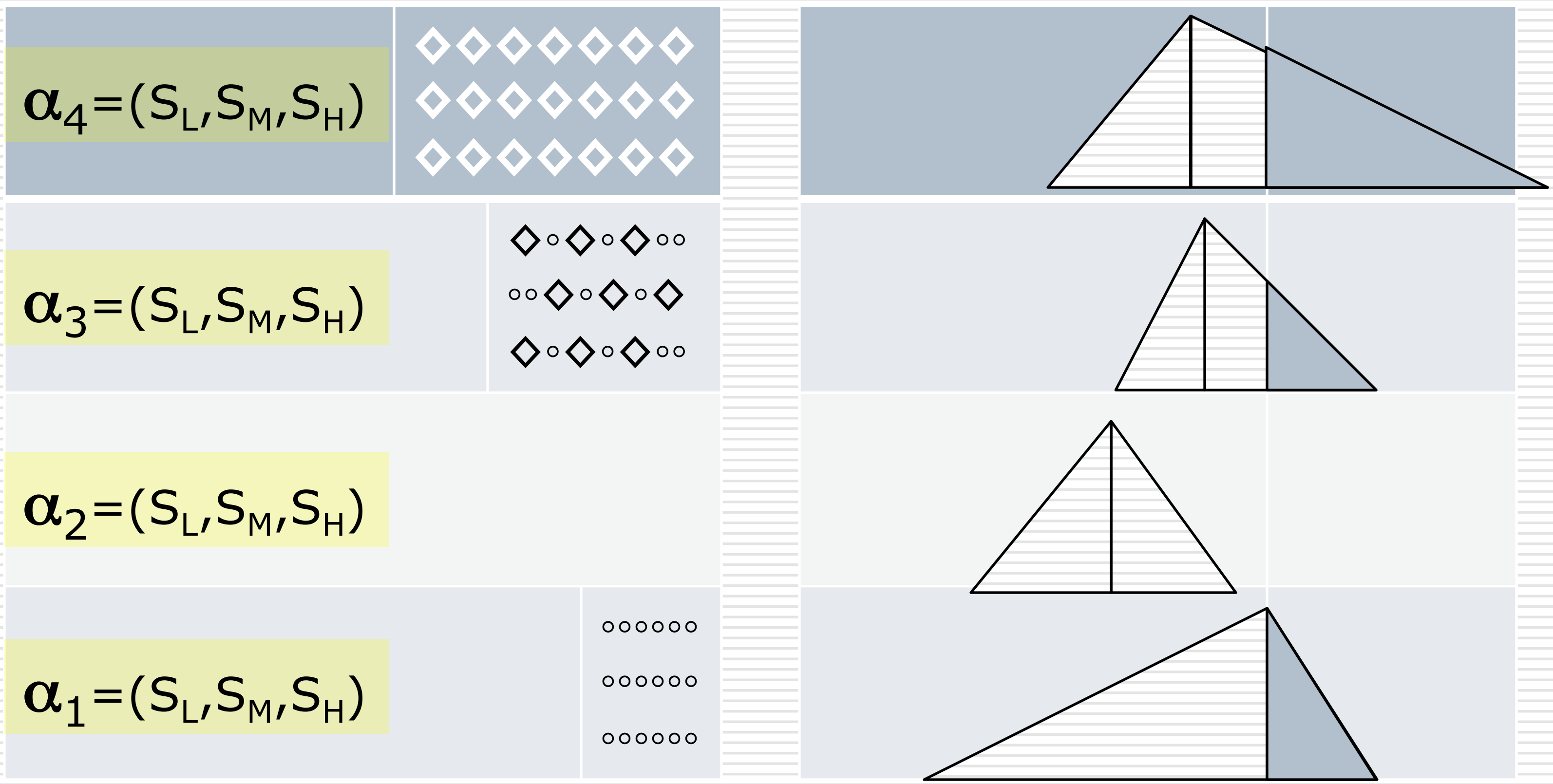
Total Water Triangular PDF Single Gridbox



$S = (q_v + q_L + q_I) / q_S(T)$

- Given (S_L,S_M,S_H) we can compute
  - c_F, cloud fraction
  - q_V, vapor
  - $q_C = q_L + q_I$
- Conversely, given (c_F,q_V,q_C) we can reconstruct the PDF

Grid Column



- Copulas implements multi-layer PDF

Bayesian Parameter Estimation

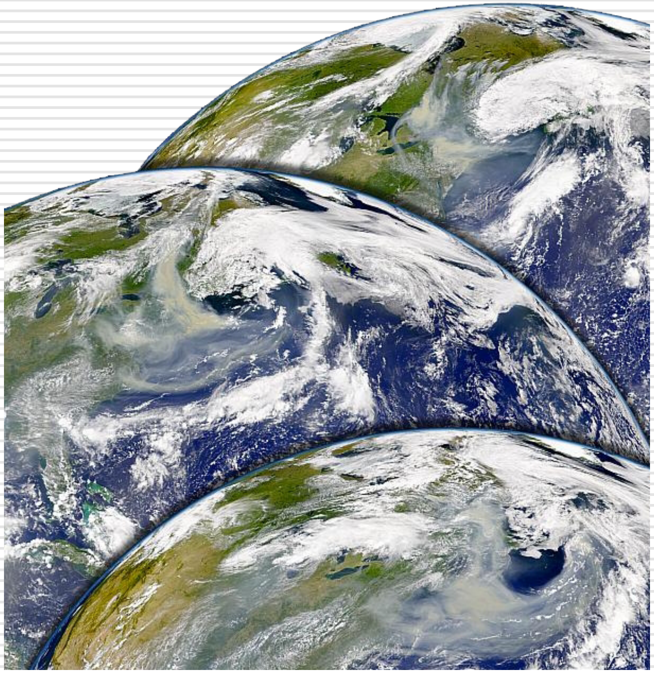
- Within a grid column, consider a set of measurements

$$\boldsymbol{y} = (y_1, \dots, y_P)$$

  say MODIS cloud top pressure, cloud optical depth
- Goal:
  - estimate PDF parameters α_k
  - Given the observations $\boldsymbol{y}$
- Bayes theorem:

$$p(\alpha|\boldsymbol{y}) \sim p(\boldsymbol{y}|\alpha)\, p(\alpha)$$

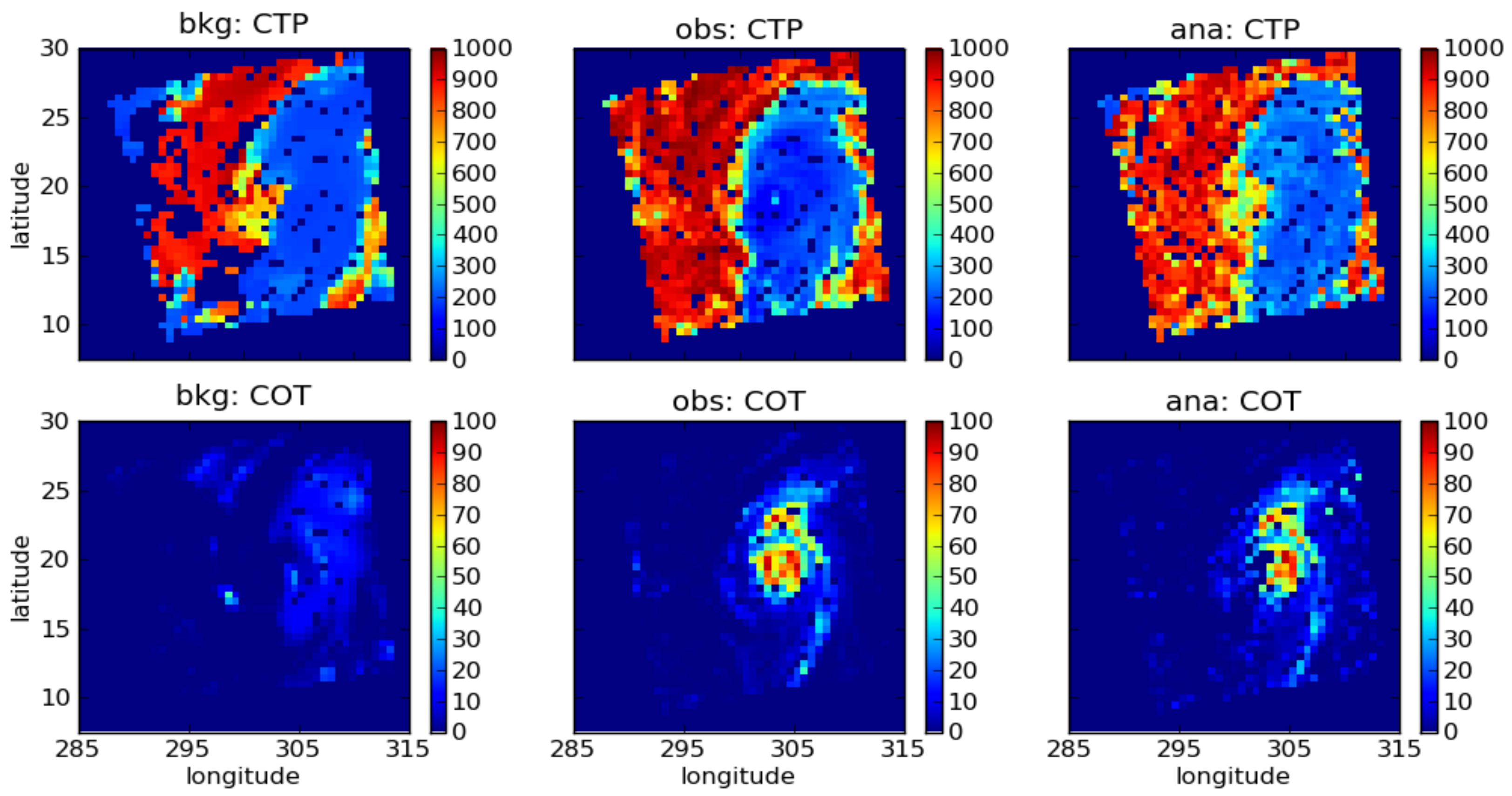
- Maximum-likelihood estimation
  - Find α that maximizes $p(\alpha|\boldsymbol{y})$



Parameter Estimation

- Evaluating $p(\mathbf{y}|\alpha)$
  - Given α, generate sub-columns by sampling the multidimensional PDF
  - Simulate observables for each sub-column
  - Use these sub-columns to obtain a *Kernel Density Estimate* (KDE) of p at the observational points $\mathbf{y}$
- Optimization
  - Markov Chain Monte Carlo method
    - Modified Metropolis-Hastings algorithm

Example: Hurricane Bill



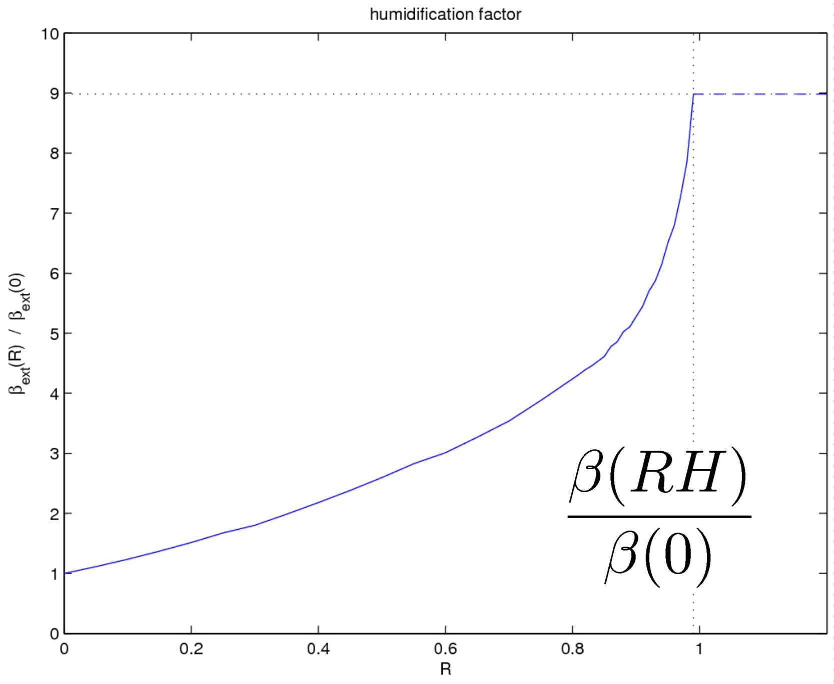
Hygroscopic Aerosols

GOCART prognosticate aerosol dry mass mixing ratio $q_{\rm dry}$, with humidification effects being included diagnostically prior to computing optical depth

$$\tau = \beta(RH; p) \cdot q_{\rm dry} \cdot \rho_a \delta z$$

The normalized mass extinction efficiency

$$\hat{\beta} = \frac{\beta(RH)}{\beta(0)} \sim 1 - 10$$



$\hat{\beta}$ saturates at 99%

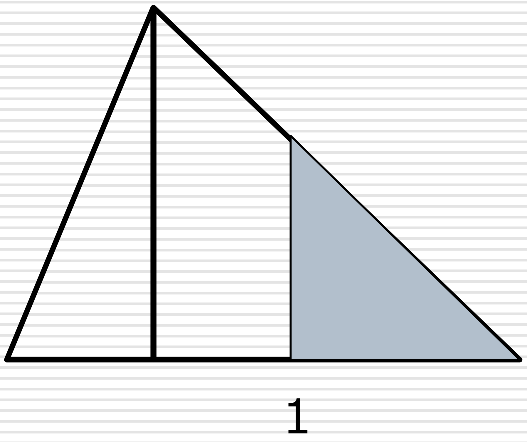
PDF-based Humidification

PDF-based cloud schemes as in GEOS-5 can be used to estimate the mean humidification effect on a GCM gridbox

$$\begin{aligned} <\hat{\beta}> &= \int_0^\infty p(S)\hat{\beta}(S)dS \\ &= \int_0^1 p(S)\hat{\beta}(S)dS + \int_1^\infty p(S)\hat{\beta}(S)dS \\ &= (1-f)\cdot <\hat{\beta}>_{\rm clear} + f\cdot <\hat{\beta}>_{\rm cloudy} \end{aligned}$$

where the *cloud fraction* f is given by

$$f = \int_1^\infty p(S)ds$$



A PDF of water vapor + condensate is provided in each gridbox

Satellite retrievals: $\tau_{\rm clear} = \beta_{\rm clear}(RH)\cdot q_{\rm dry}\cdot \rho_a \delta z$

Humidification Factor: Sulfates

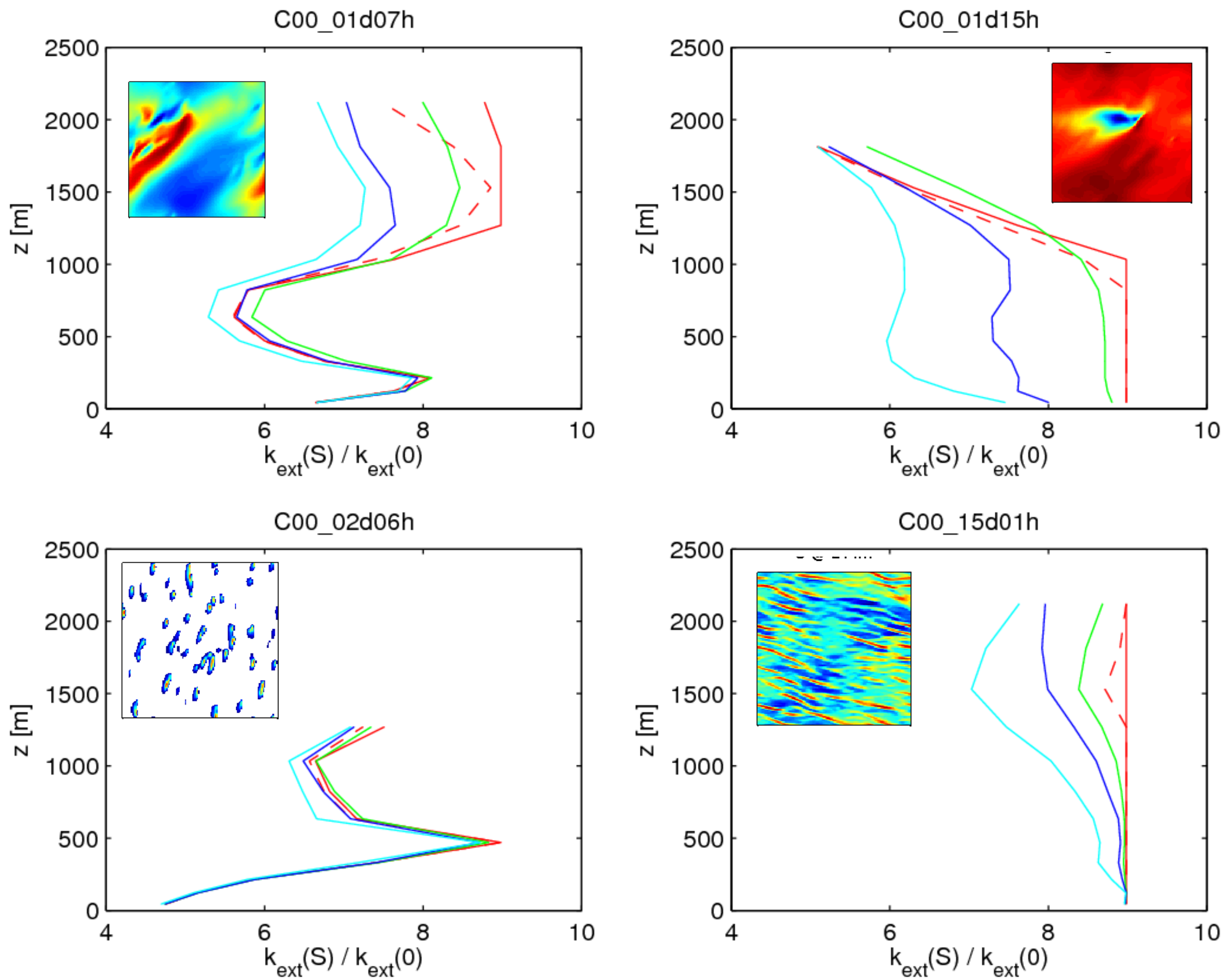
$\hat{\beta}_{\mathrm{clear}}$

$\hat{\beta}_{\mathrm{clrlayer}}$

$\hat{\beta}_{\mathrm{full}}$

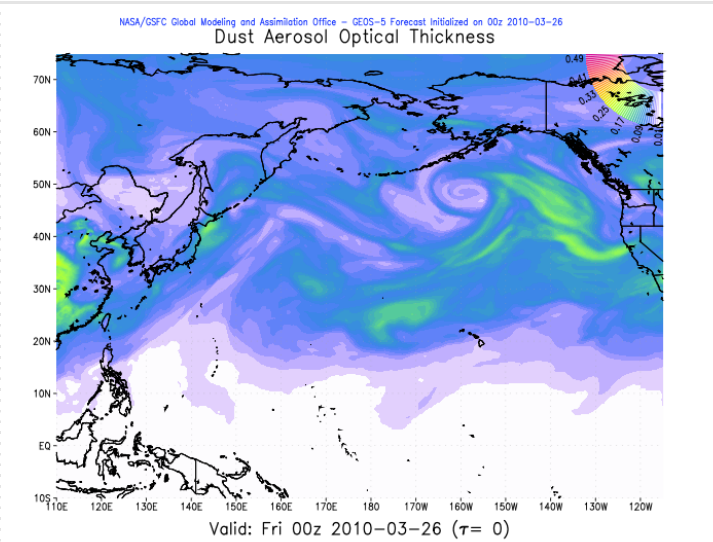
$\hat{\beta}_{\mathrm{gcm}}$

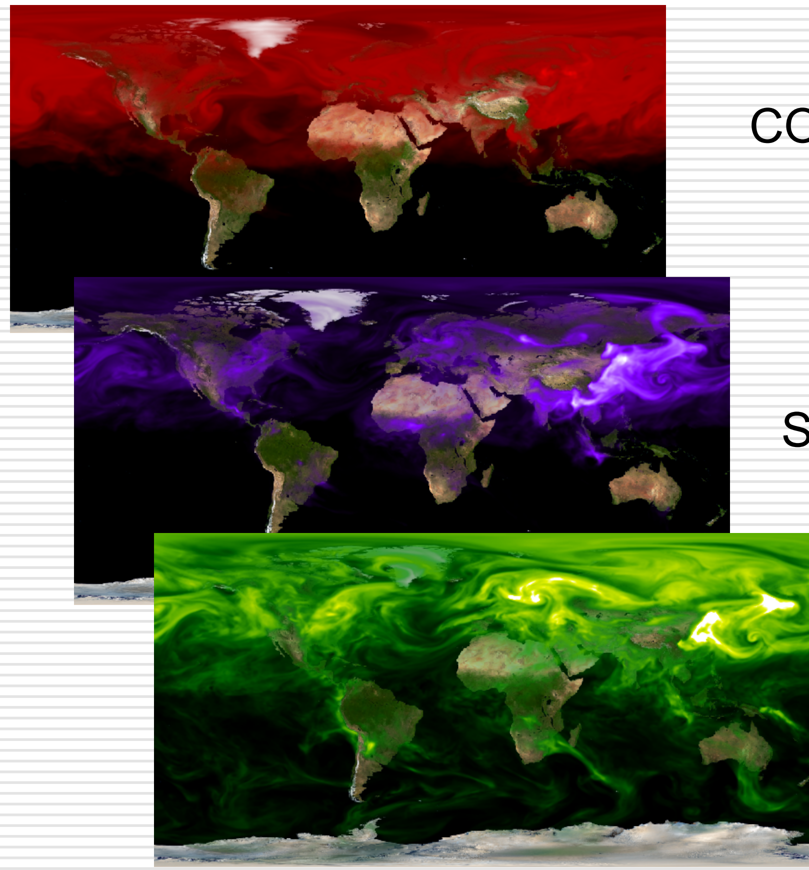
$\hat{\beta}(< S >)$



GEOS-5 Forecasting Support
DISCOVER-AQ

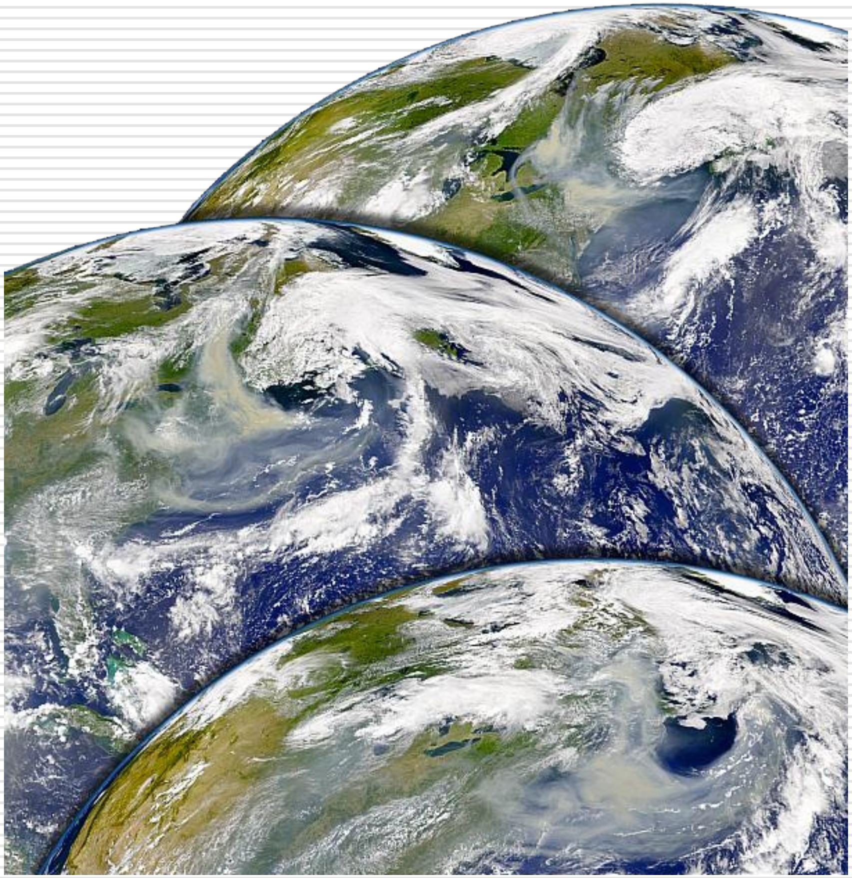
- Global 5-day chemical forecasts customized for each campaign
  - O3, aerosols, CO, CO_2, SO_2
  - Resolution: Nomally 25 km
- Driven by real-time biomass emissions from MODIS (QFED)
- MODIS aerosol assimilation





http://gmao.gsfc.nasa.gov/projects/DISCOVER-AQ/

International Cooperative for Aerosol Prediction (ICAP)

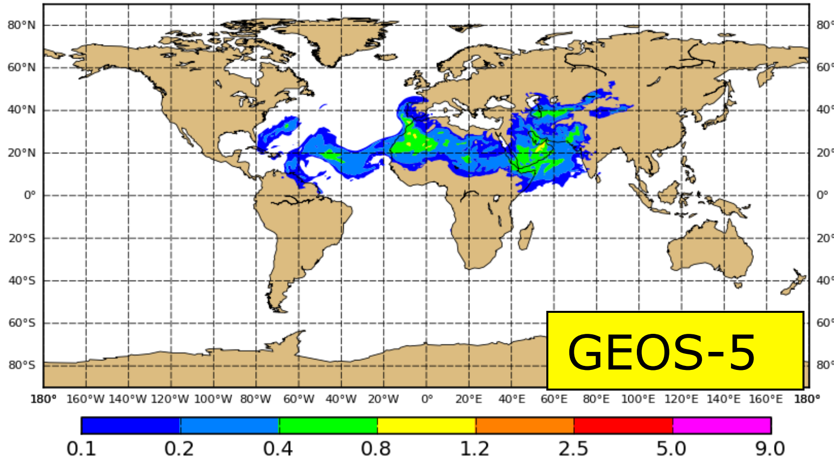


- ICAP is an emerging collaboration of "operational" aerosol forecasters and data providers to coordinate and improve aerosol prediction
- ICAP workshops
  - Observability, Monterey, CA, April 2010
  - Verification, Oxford, UK, Sept. 2010
  - Ensembles, Boulder, CO, May 2011
- Participants from all major operational centers: NRL, NCEP, NASA, ECMWF, JMA, UKMO
- Participants from major NRT data providers: ESA, EUMETSAT, JAXA, NASA, NESDIS

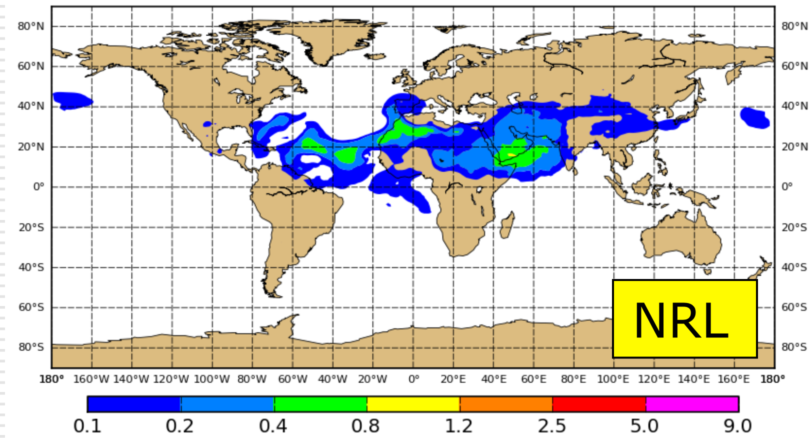
ICAP Multi-model Ensemble

Dust AOD

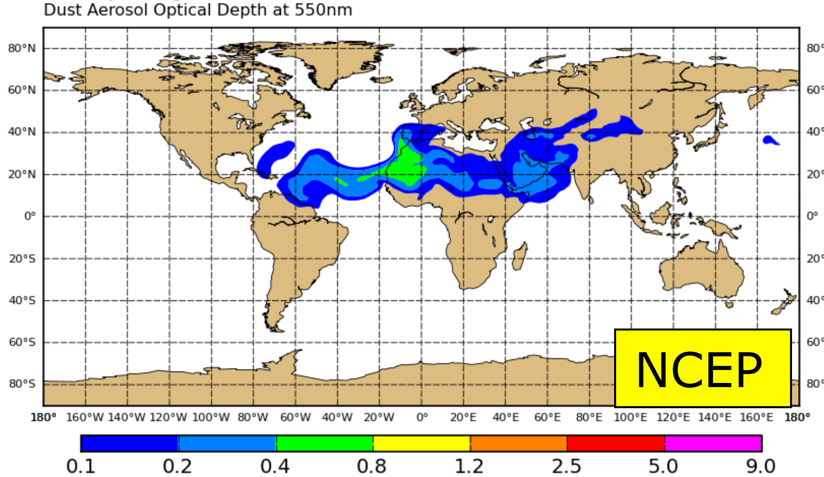
Saturday 20 August 2011 00UTC GEOS-5 Forecast t+006
Saturday 20 August 2011 06UTC Valid Time
Dust Aerosol Optical Depth at 550nm



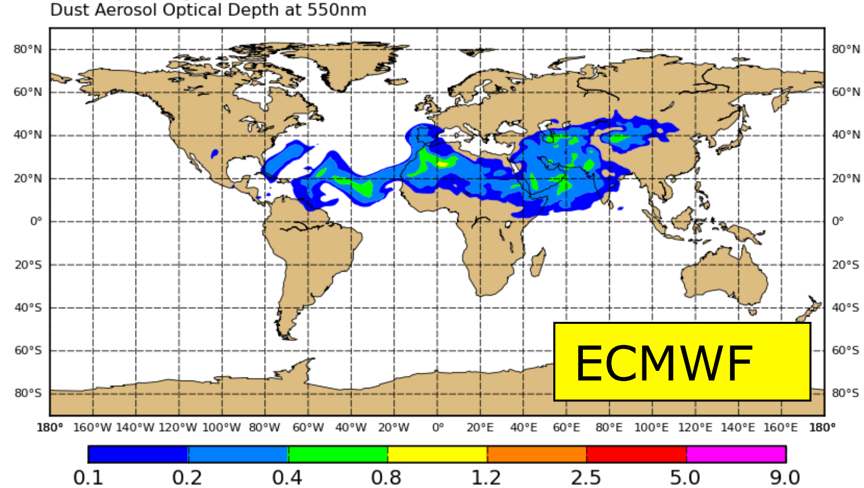
Saturday 20 August 2011 00UTC NAAPS Forecast t+006
Saturday 20 August 2011 06UTC Valid Time
Dust Aerosol Optical Depth at 550nm



Saturday 20 August 2011 00UTC GOCART Forecast t+006
Saturday 20 August 2011 06UTC Valid Time
Dust Aerosol Optical Depth at 550nm



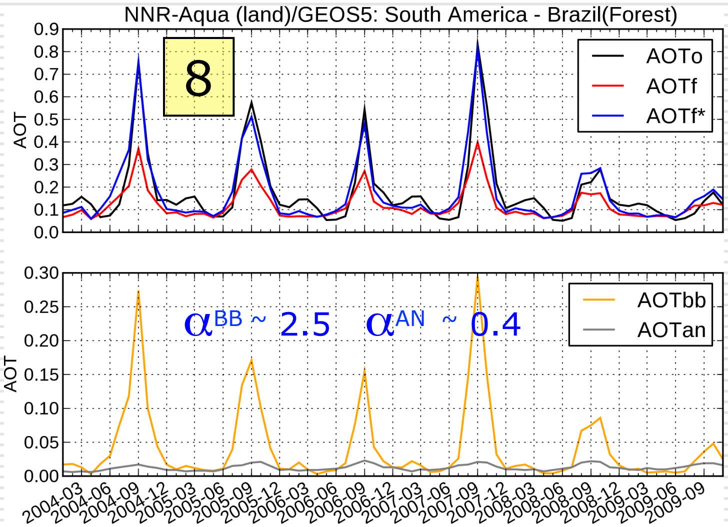
Saturday 20 August 2011 00UTC MACC Forecast t+006
Saturday 20 August 2011 06UTC Valid Time
Dust Aerosol Optical Depth at 550nm

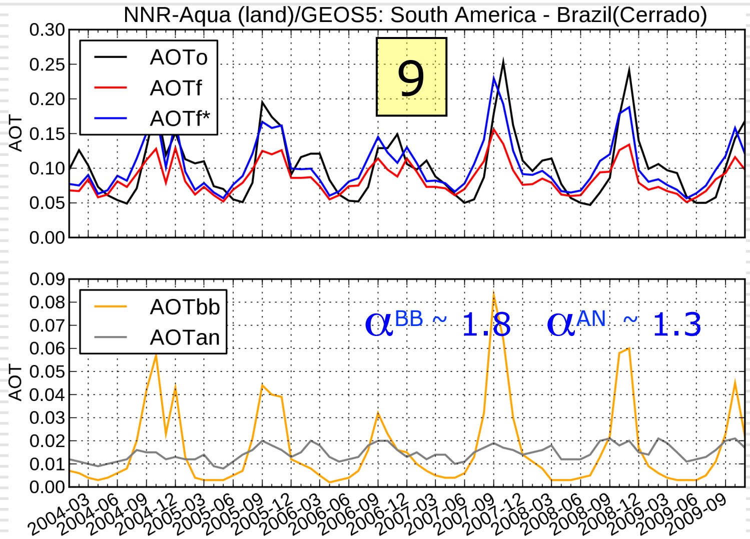


QFED: Quick Fire Emission Dataset

- Near real time estimates based on MODIS Fire products (AQUA/TERRA)
- Started as an attempt to use diurnal fire counts to better distribute in time the monthly GFED emissions
- Current focus on MODIS to be followed by
  - Geostationary
  - VIIRS
- Plume Rise model (Freitas *et al.*)
  - Driven by GEOS-5 meteorology
  - Under tuning/validation

*Q*FED 2.2: MODIS AOD Calibration

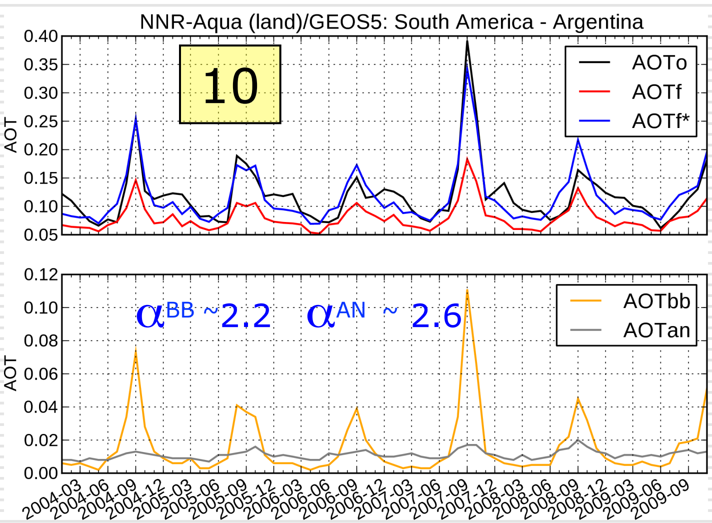


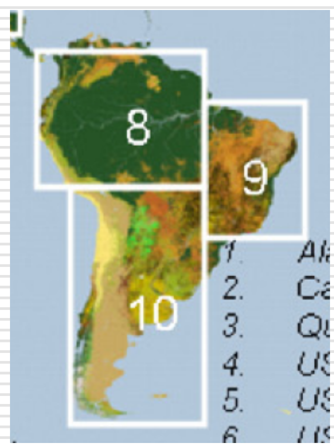


MODIS AOD

G5 QFED 2.2

G5 QFED 2.1



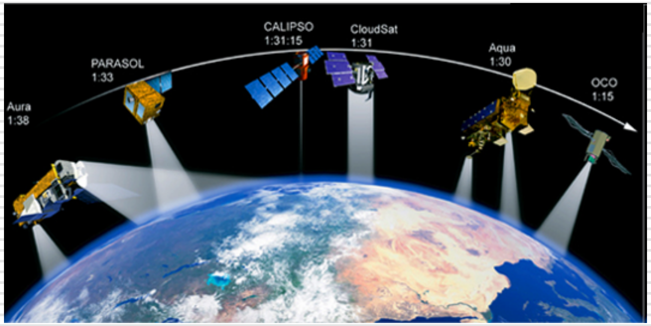


Biome	C
Tropical Forest	2.5
xTropical Forest	4.5
Savanna	1.8
Grassland	1.8

Tuning relative to QFED 2.1

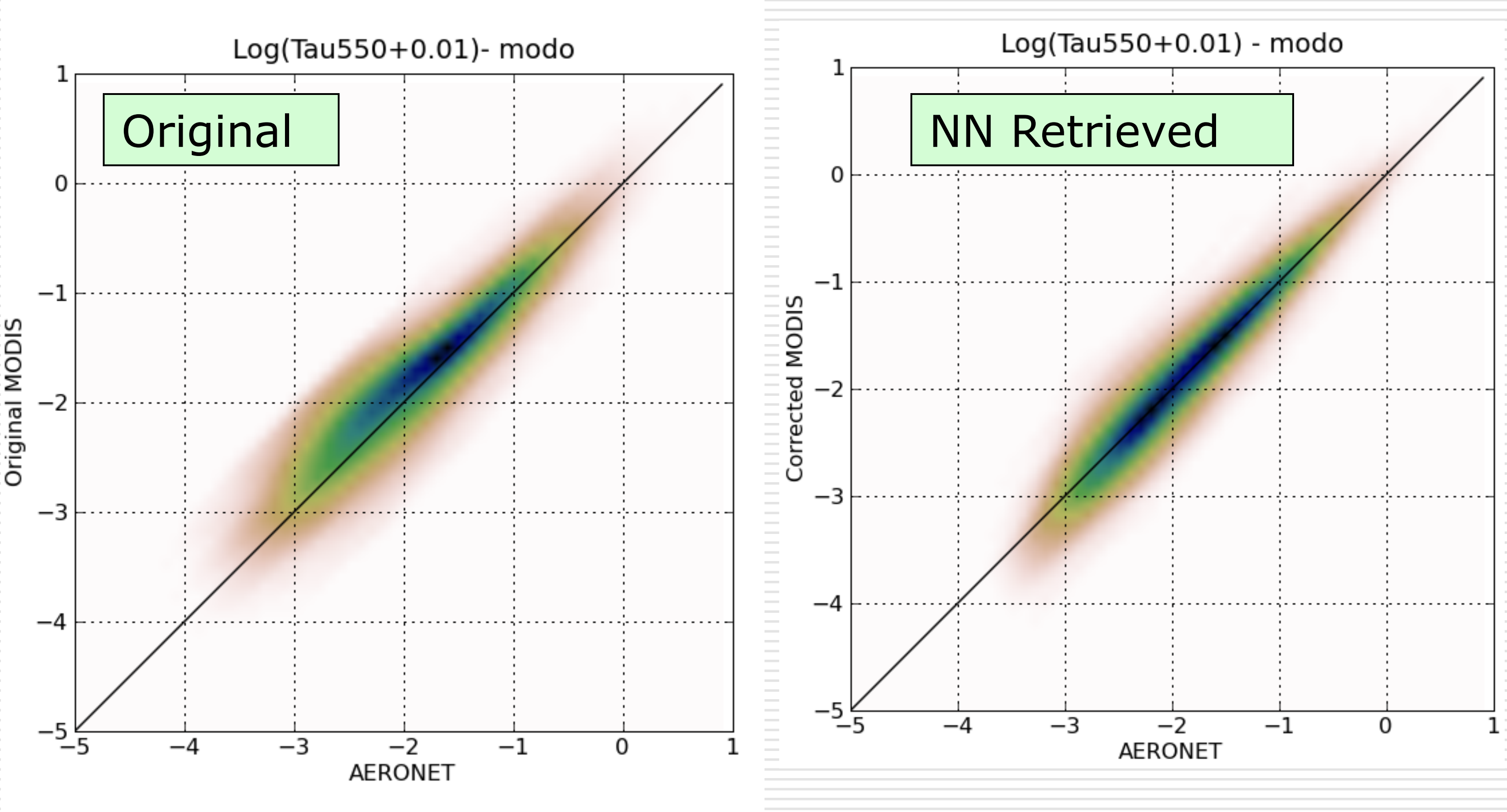
Aerosol Data Assimilation

- Focus on NASA EOS instruments

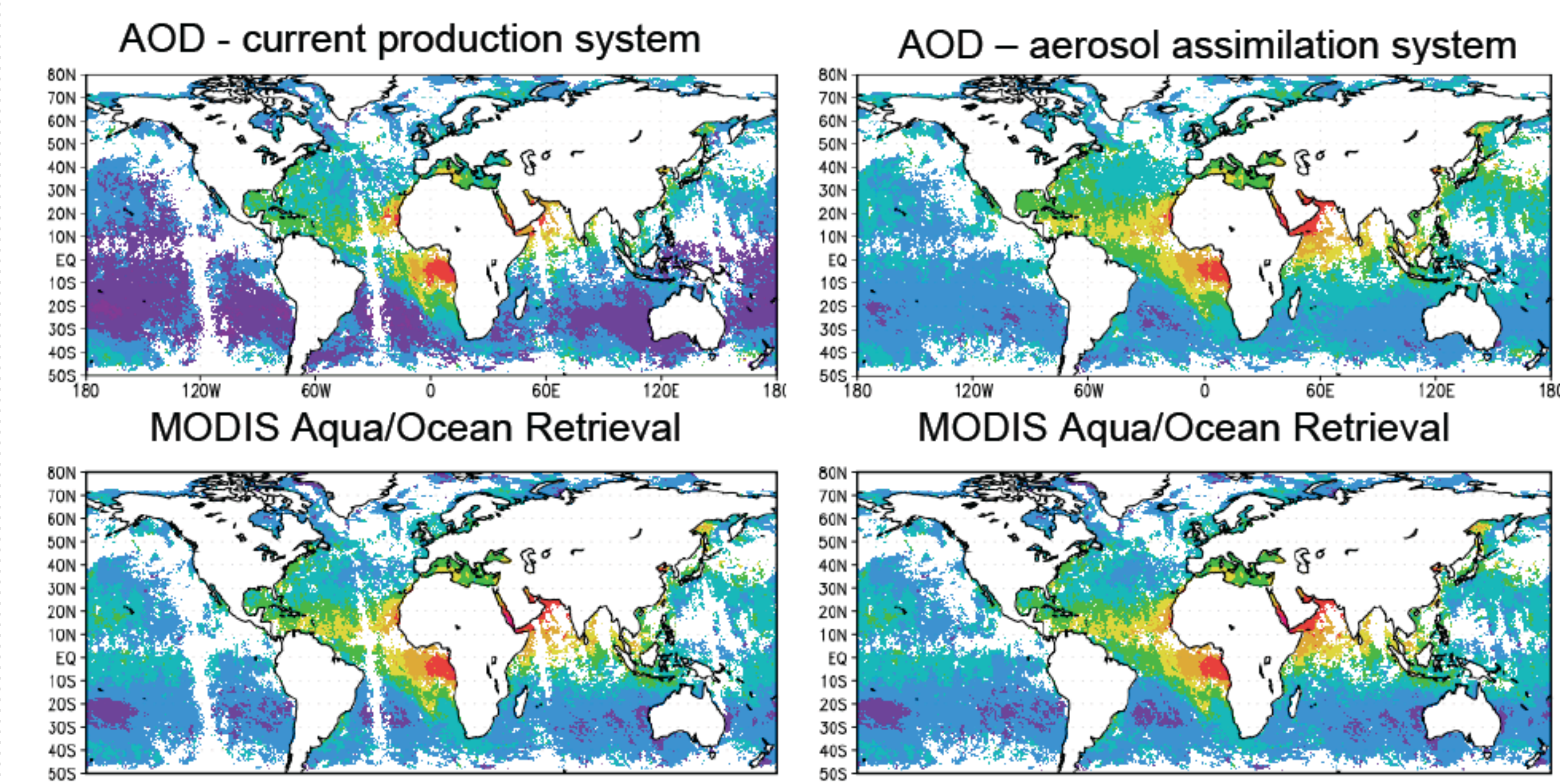


- Global, high resolution (1/4 deg) AOD analysis
- 3D increments by means of Lagrangian Displacement Ensembles (LDE)
- Simultaneous estimates of background bias (*Dee and da Silva 1998*)
- Adaptive Statistical Quality Control (*Dee et al. 1999*):
  - State dependent (adapts to the error of the day)
  - Background and Buddy checks based on log-transformed AOD *innovation*
- Error covariance models (*Dee and da Silva 1999*):
  - Innovation based
  - Maximum likelihood

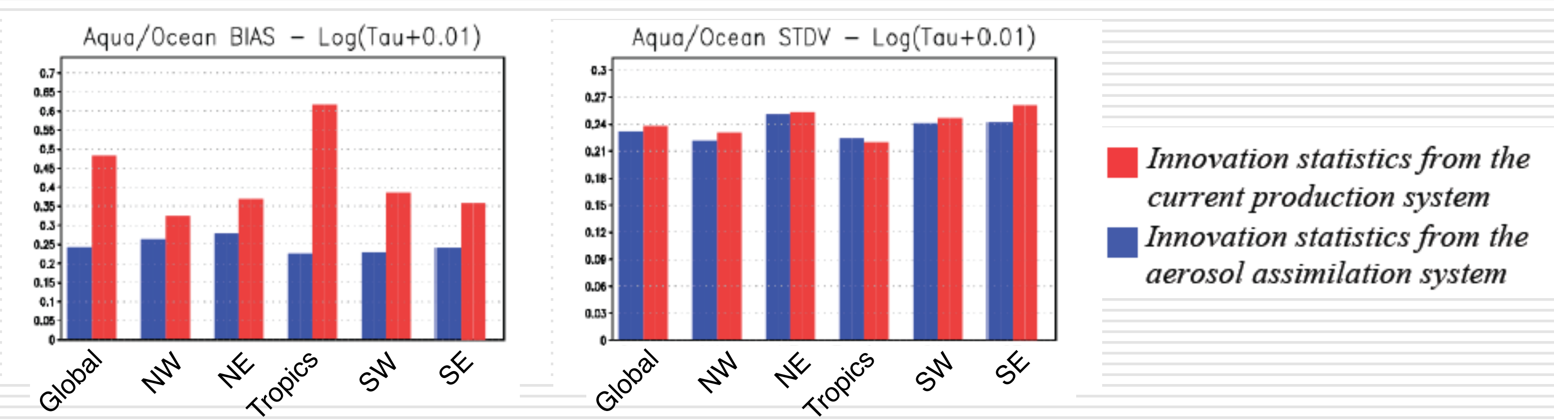
MODIS AOD over Ocean
Neural Net Retrievals (Terra)



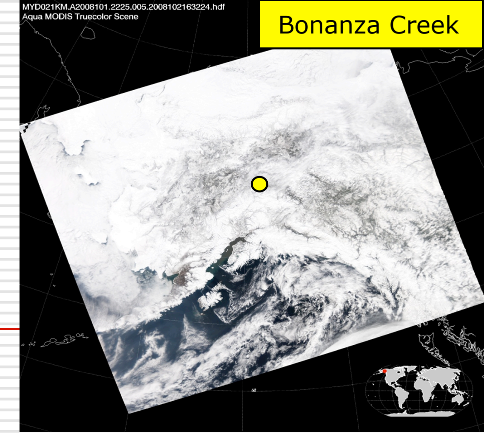
AOD Assimilation in Production System



3 hr Forecast

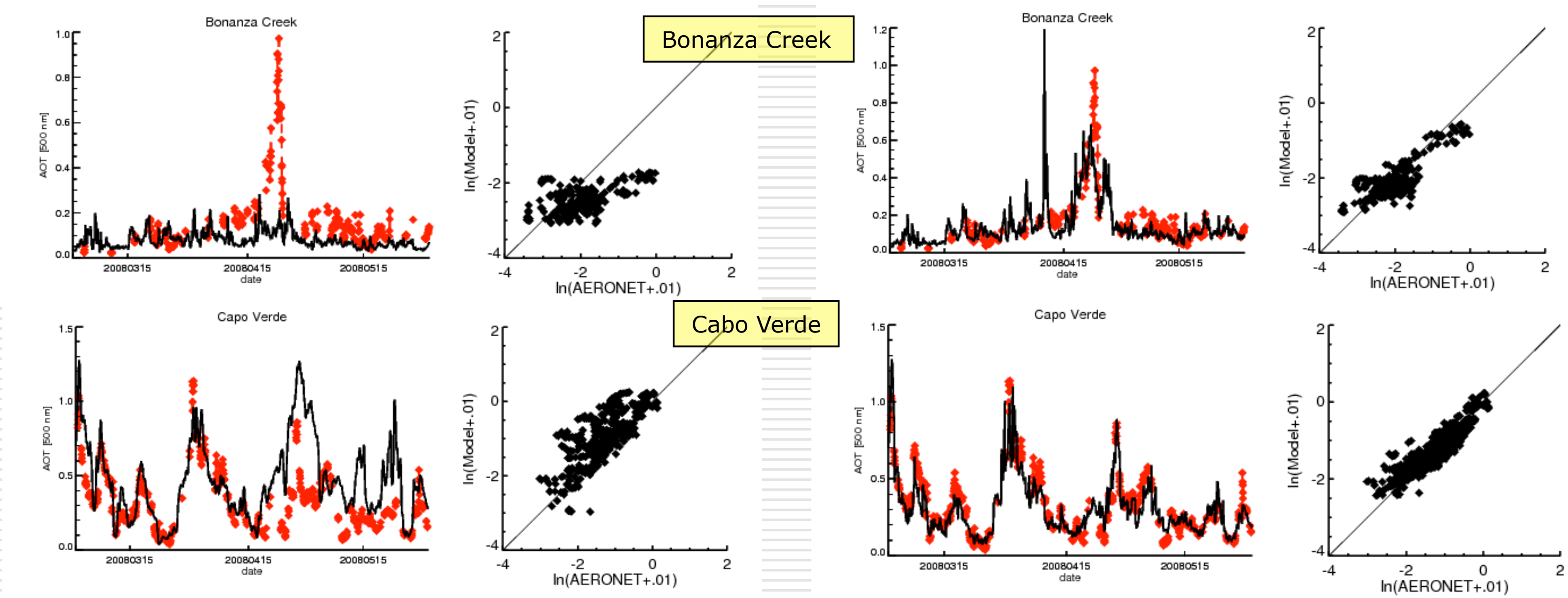


MERRA/Aerosol Mini-Reanalysis: 2003-11



GEOS-5 AOD
Without MODIS Assimilation

GEOS-5 AOD
With MODIS Assimilation

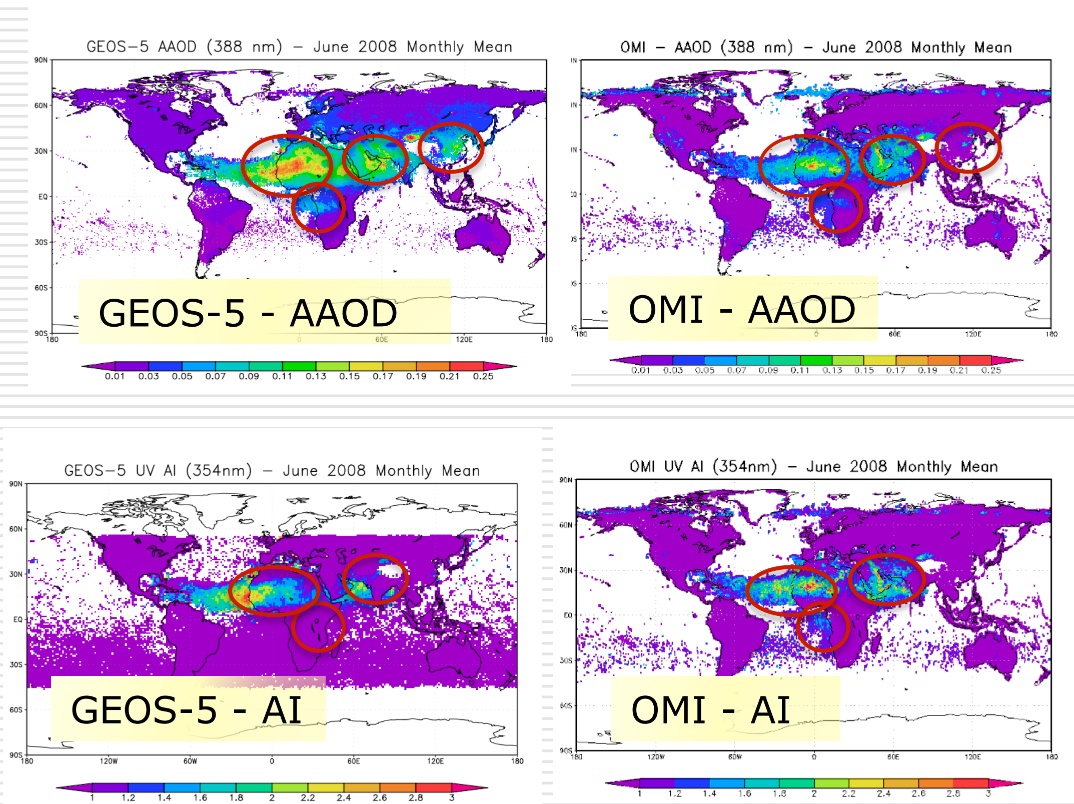


Comparison against independent AERONET ground stations.

Concluding Remarks

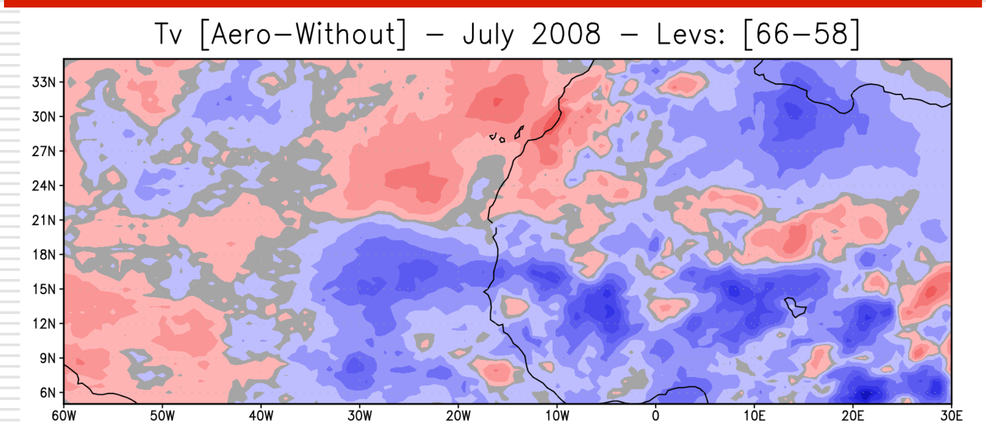
- As in GEOS-4, assimilation of MODIS clouds expected to improve model’s cloud radiative forcing
  - More reliable representation of RH sub-grid variability for assimilation of clear sky data
- Aerosol assimilation currently based on (bias-corrected) AOD retrievals
- Next step: 1D-Var physical retrievals using model state as prior.

OMI and AAOD

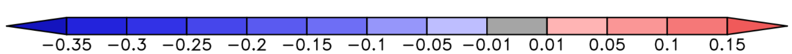


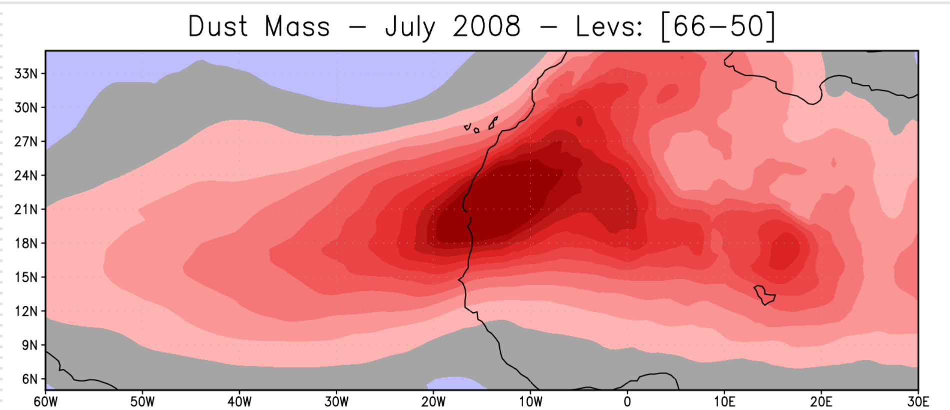
- Simulation of Radiances for direct comparison to satellite measurements
- Very useful to diagnose model/ retrieval discrepancies

Impact of Aerosols on GSI Temperature Analysis



$$\Delta T = T_{aero} - T_{control}$$





Aerosols included in observation operators for AIRS, HIRS, IASI