Accounting for moisture sub-grid variability in AOD calculations

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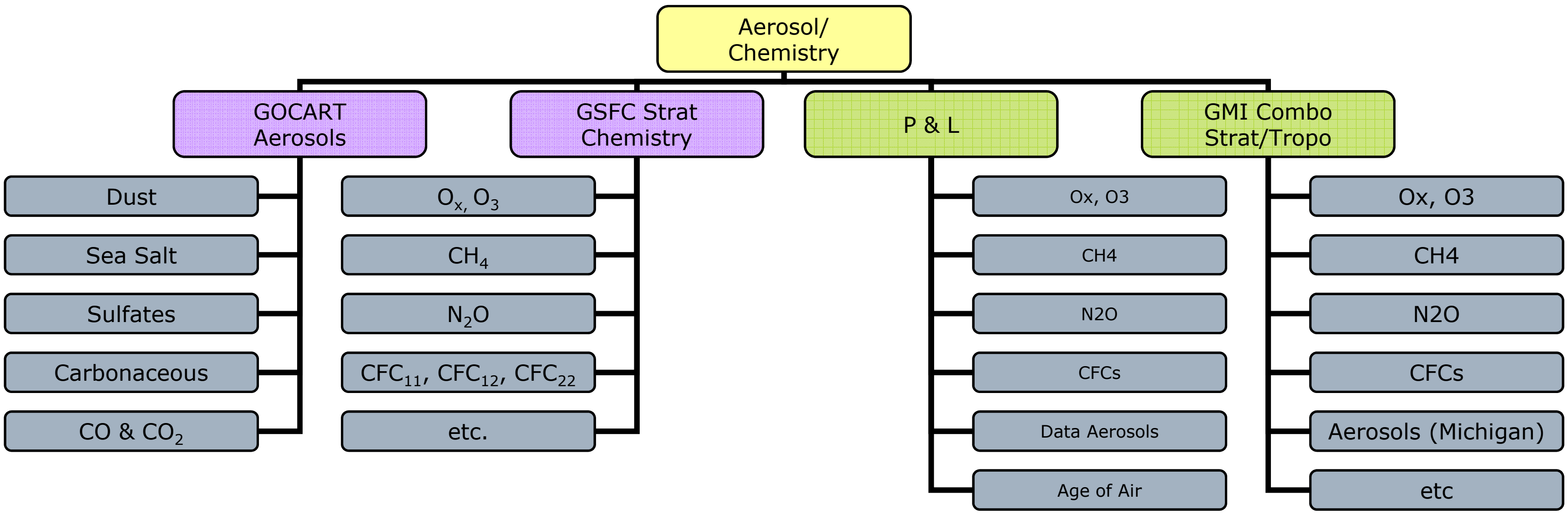
Outline

1. Background
   - The GEOS-5/GOCART system
     - The GEOS-5 global climate model
     - The GOCART component
   - Aerosol data assimilation
     - Optics/composition identifiability and bias correction
     - The satellite *Fair Weather Bias* for aerosols
2. Accounting for moisture subgrid variability
   - Extinction calculation in GEOS-5/GOCART
   - Cloud PDF schemes and the humidification factor
   - Case study: cloud resolving model as a test bed
3. Concluding Remarks

Origins…

- The current *on-line* GEOS-5 aerosol/ chemistry capabilities evolved from several *off-line* CTM efforts at NASA/GSFC:
  - GOCART aerosols, CO/CO_2 (Chin et al.)
  - CARMA aerosol microphysics (Toon et al., through Colarco)
  - StratChem (Douglas, Stolarski et al.)
  - GMI Tropospheric+Stratospheric (Combo) Chemistry
    - Which in turn derives from Harvard GEOS-Chem and StratChem

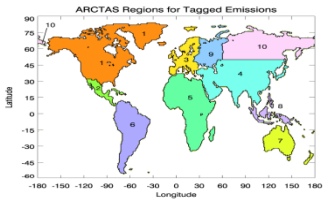
The AeroChem Component



At runtime one selects one or more packages to run, and in case of ambiguity,which package provides a specific input to radiation

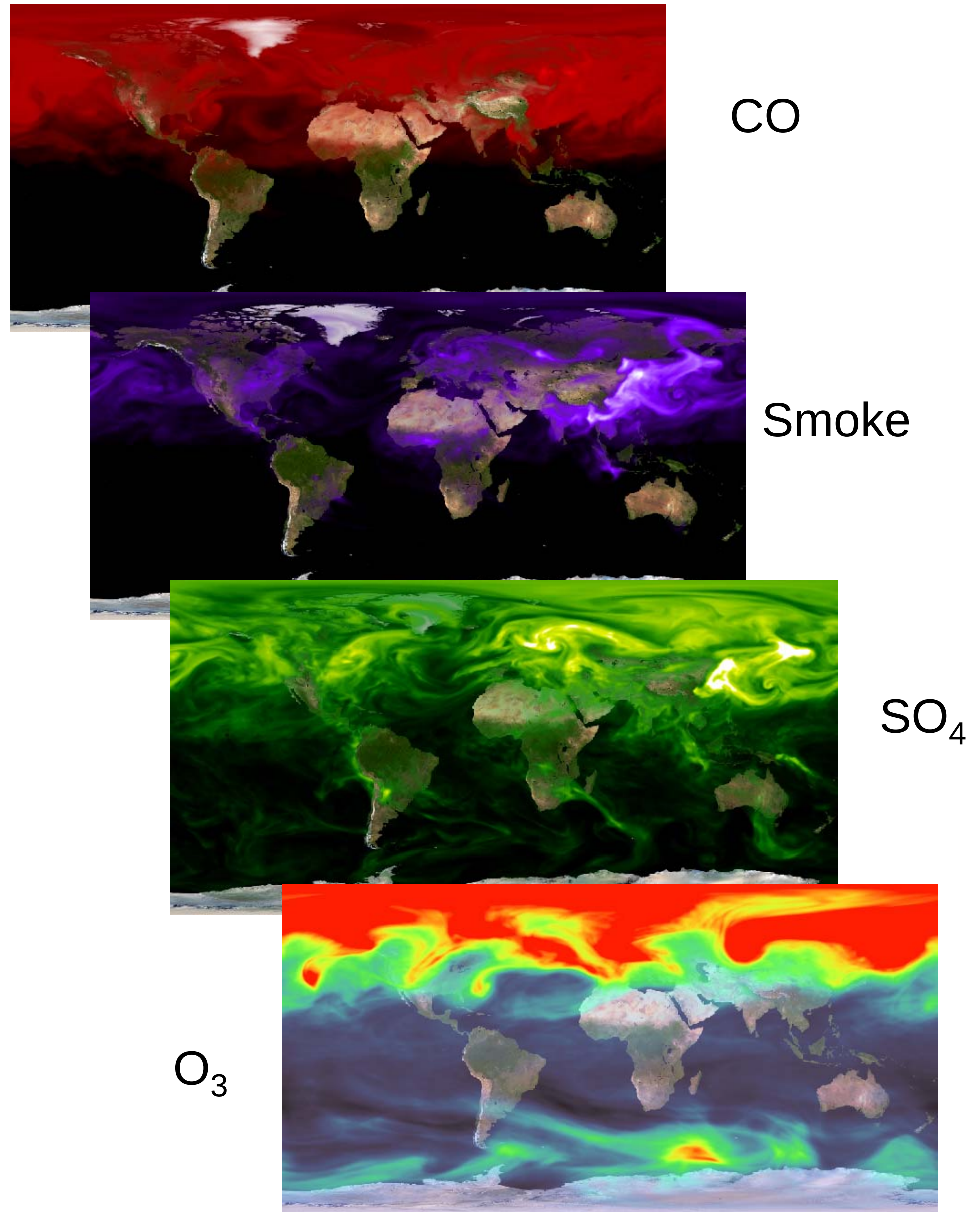
Aerosol Modeling at GSFC

- Aerosols transported on-line within GMAO’s GEOS-5 Climate/Forecasting models
  - In *climate* mode: no data assimilation
  - In *replay* mode, using assimilated meteorology
    - Aerosols transported on-line within the GCM, without need for time interpolation of winds/diagnostics
    - Can be used for aerosol data assimilation
  - In full *assimilation* mode, combined meteorological/aerosol assimilation
    - Effective way of dealing with contamination of TOVS/AIRS radiances by aerosols



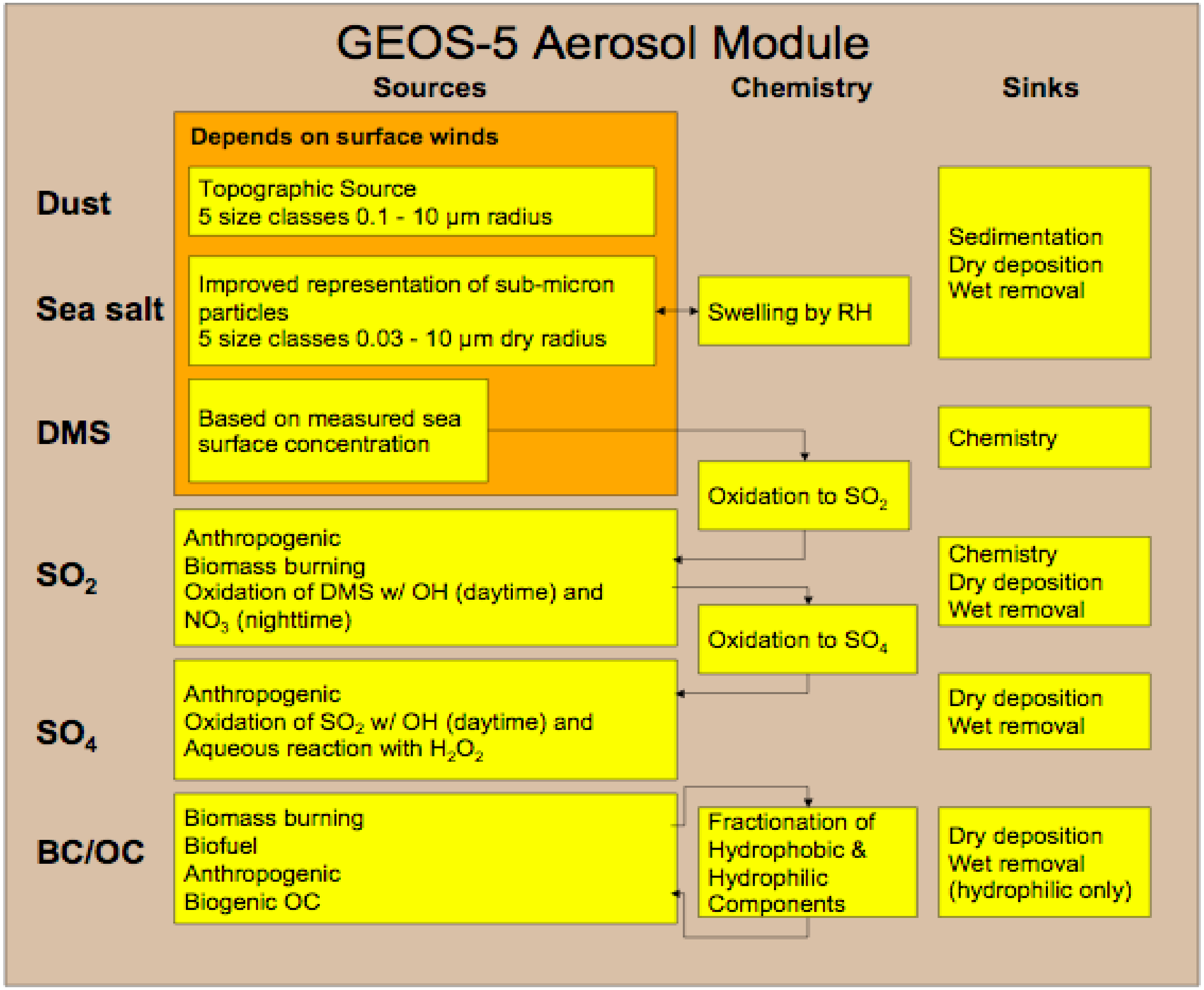
GEOS-5/GOCART Forecasts

- Global 5-day chemical forecasts customized for each campaign
  - O3, Aerosols, CO, CO_2,..
  - ½ degree globally, soon ¼ deg
- Driven by real-time biomass emissions from MODIS
- Pre-mission
  - System customization
- During-mission
  - Web visualization, data delivery
  - In-field forecasting support
  - Comparison to aircraft data
- Post-mission:
  - Gridded datasets available online for post mission analysis
  - In depth evaluation, model tuning
- A truly GSFC wide effort:
  - GMAO, ACDB, SIVO, NCCS



Aerosol Processes by GEOS-5

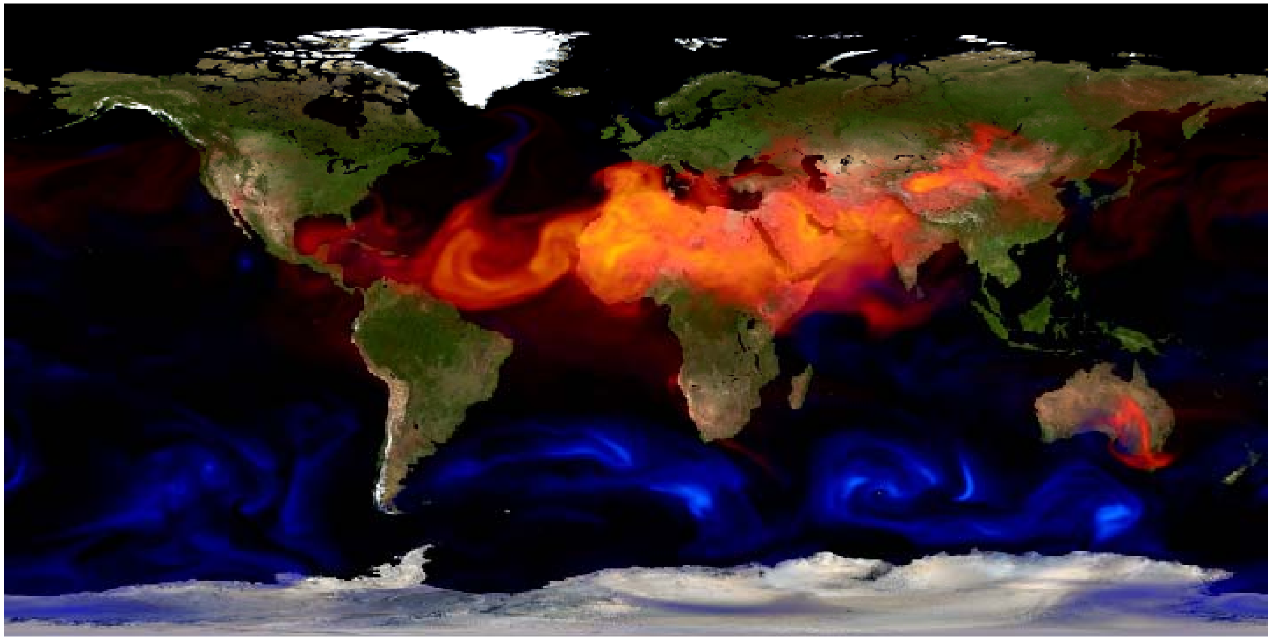
- Advection:
  - Same Lin-Rood used my many off-line CTMs
- Diffusion:
  - GEOS-5 has Lock type PBL parameterization
- Convective transport:
  - Relaxed Arakawa-Schubert (RAS) parameterization
  - RAS provides convective transport as well as scavenging
- Aerosol direct effects:
  - Chou et al. radiation package
  - Model transports *dry* aerosol mass; RH hygroscopic growth included during Mie calculation
- Indirect effects (not yet integrated):
  - Nenes and Seinfeld parameterization for water clouds; additional ice clouds paramerization(Y.Sud)

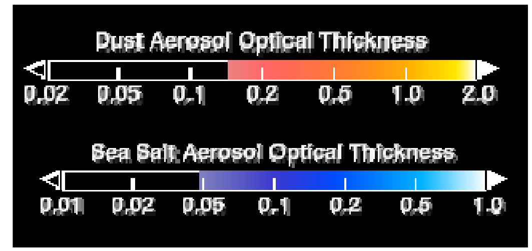


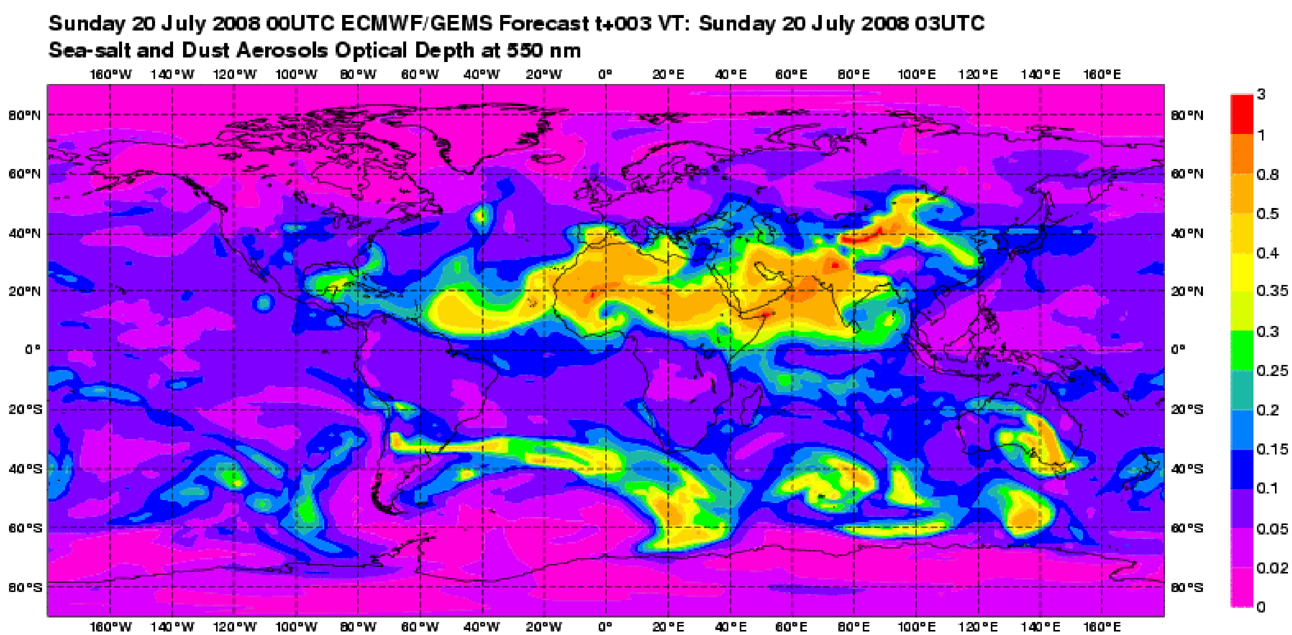
Collaborator: Mian Chin, Code 613.3

Dust + Sea Salt

GEOS-5/GOCART

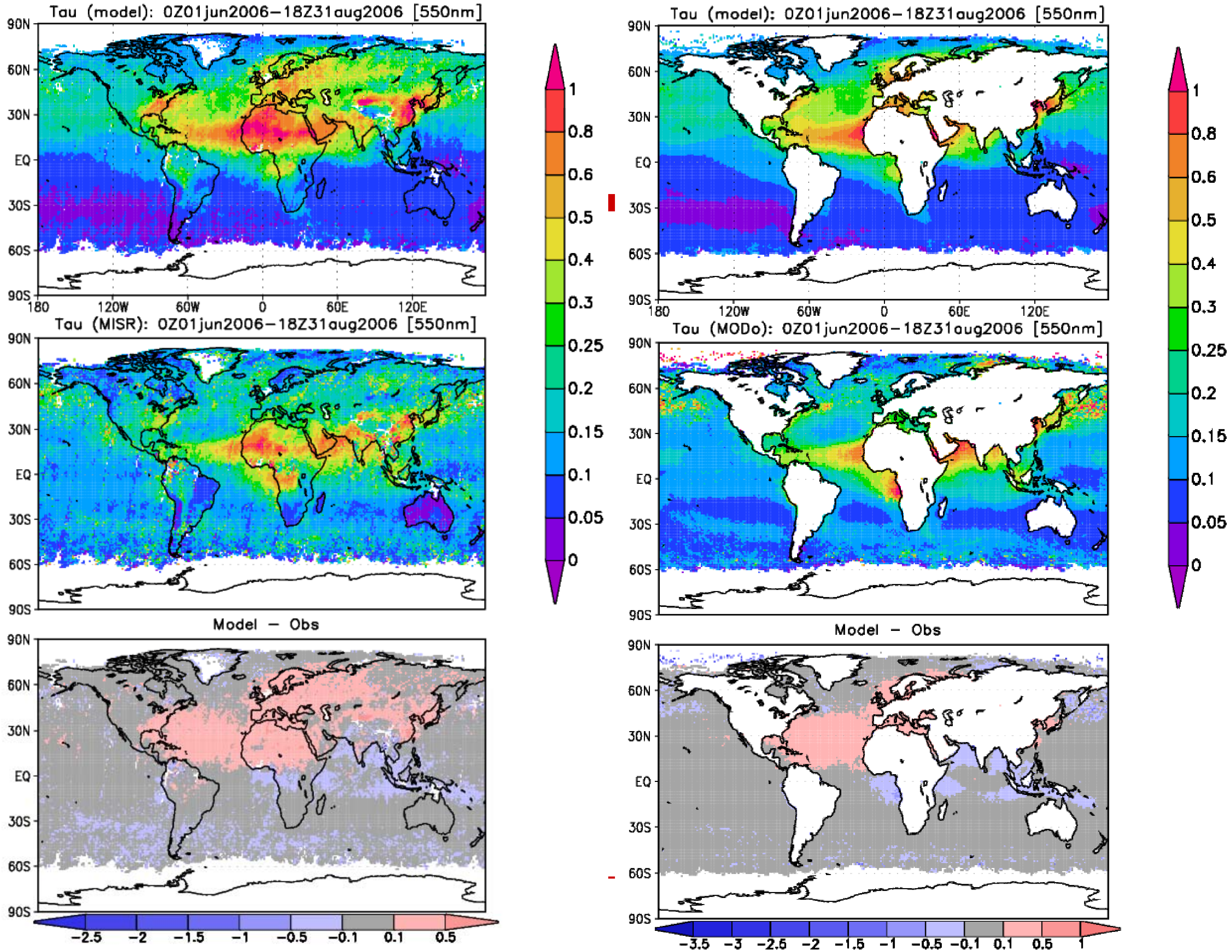




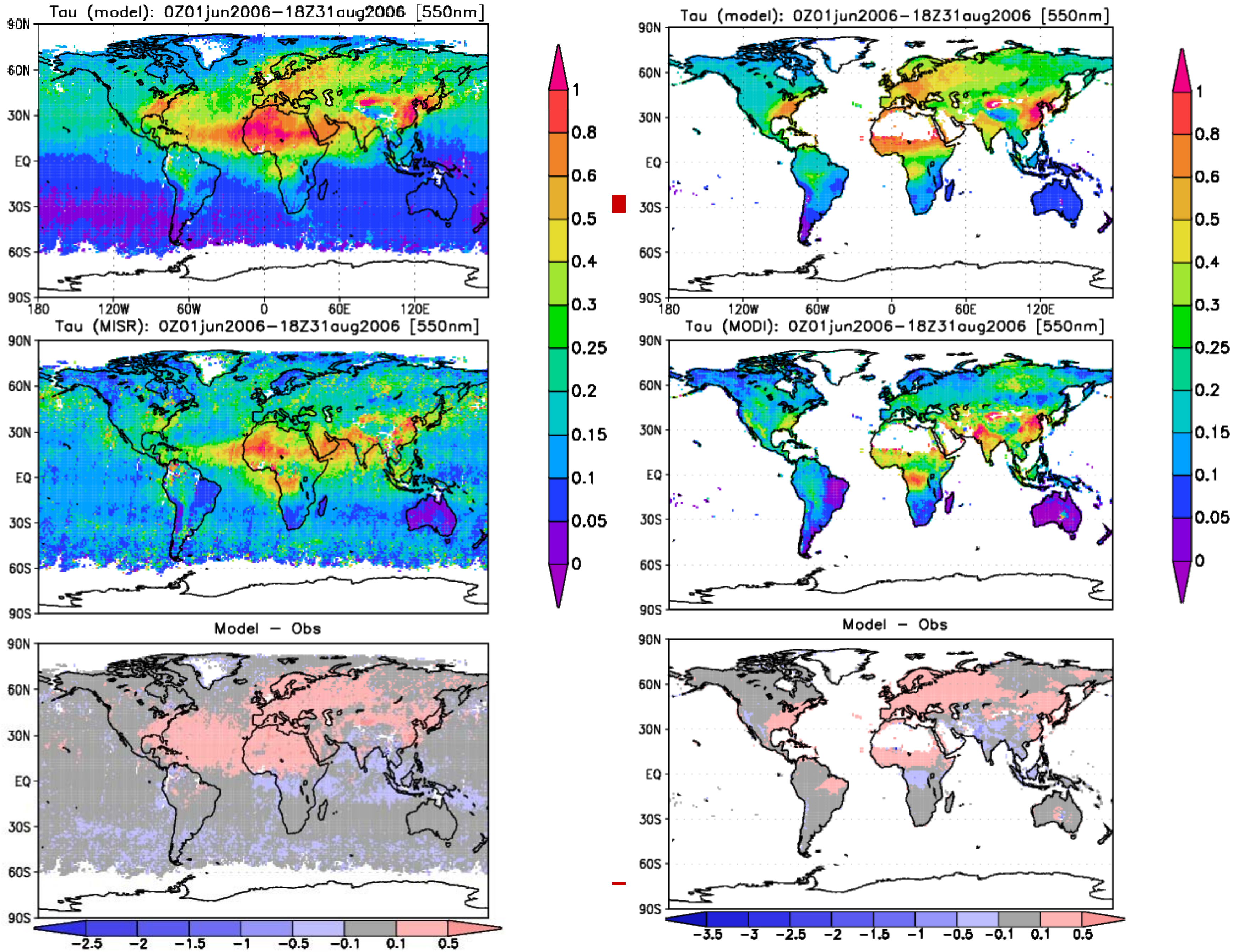


Forecast Valid at
3Z 20 July 2008

ECMWF



Tau (model): 0Z01jun2006-18Z31aug2006 [550nm]
Tau (MISR): 0Z01jun2006-18Z31aug2006 [550nm]
Model – Obs
Tau (model): 0Z01jun2006-18Z31aug2006 [550nm]
Tau (MODo): 0Z01jun2006-18Z31aug2006 [550nm]
Model – Obs
90N 60N 30N EQ 30S 60S 90S
180 120W 60W 0 60E 120E
1 0.8 0.6 0.5 0.4 0.3 0.25 0.2 0.15 0.1 0.05 0
-2.5 -2 -1.5 -1 -0.5 -0.1 0.1 0.5
-3.5 -3 -2.5 -2 -1.5 -1 -0.5 -0.1 0.1 0.5 1



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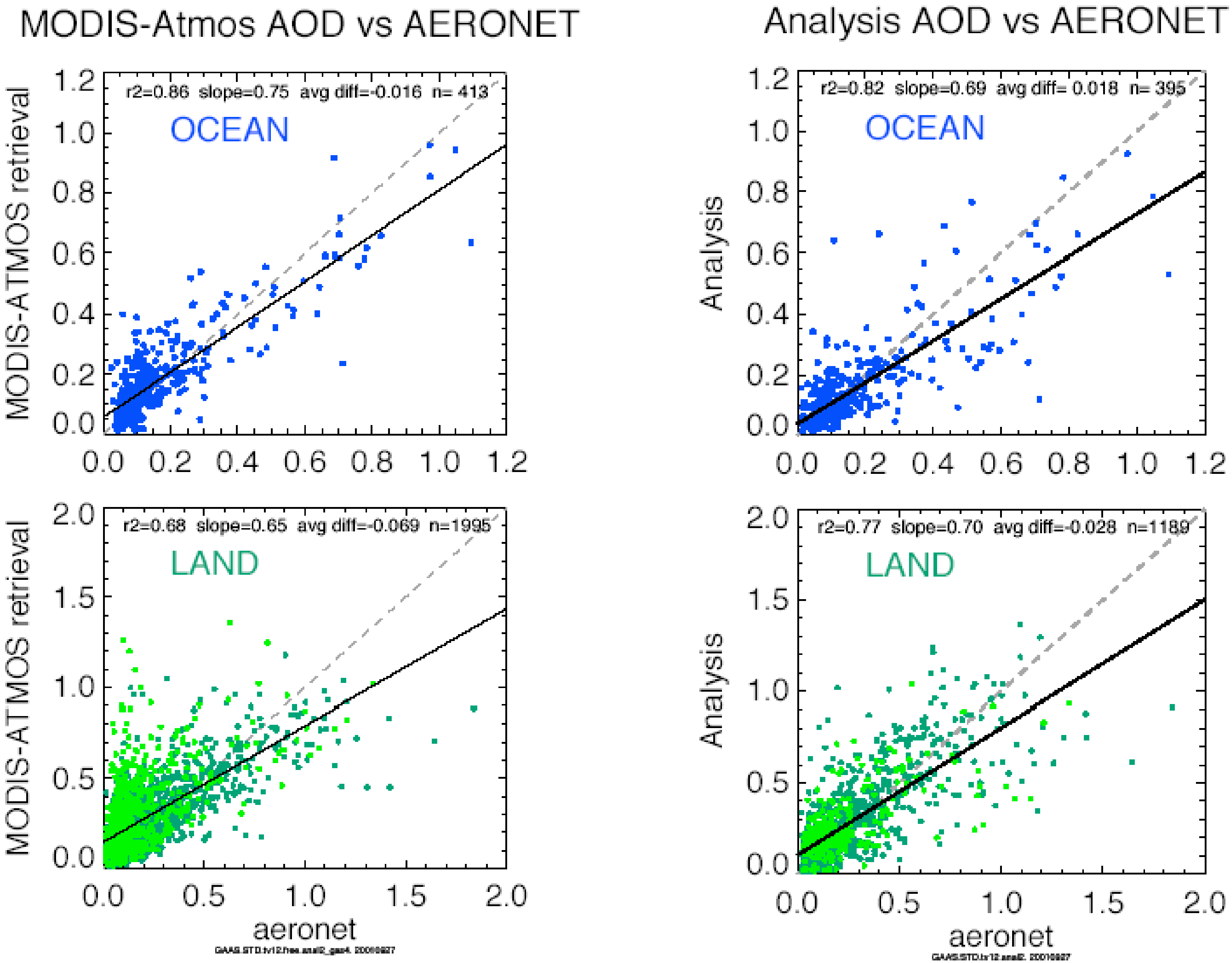
–3.5 –3 –2.5 –2 –1.5 –1 –0.5 –0.1 0.1 0.5

Aerosol Data Assimilation at GMAO

- Emphasis on estimation of
  - Global, 3D aerosol concentrations
  - Aerosol sources and model parameters
  - Observing System Simulation Experiments (OSSE)
  - Aerosol effects on climate, focus on hydrologic cycle
  - Aerosol forecasting capability in support of field campaigns

MODIS Radiances

- 1D-Var scheme using GOCART aerosol fields as background (Weaver et al 2005)
  - Ocean: draws to all 7 MODIS channels, drawing the tighest to 870nm
  - Land: draws only to 466 nm
- Algorithm not integrated into GMAO's realtime aerosol forecasting system


MODIS-Atmos AOD vs AERONET
Analysis AOD vs AERONET
r2=0.86 slope=0.75 avg diff=-0.016 n= 413
OCEAN
MODIS-ATMOS retrieval
r2=0.82 slope=0.69 avg diff= 0.018 n= 395
OCEAN
Analysis
r2=0.68 slope=0.65 avg diff=-0.069 n=1995
LAND
MODIS-ATMOS retrieval
r2=0.77 slope=0.70 avg diff=-0.028 n=1189
LAND
Analysis
aeronet
aeronet

Issues in aerosol assimilation

I. Microphysical parameters/
composition identifiability

The measurement equation

The starting point of any data assimilation is the so-called *measurement equation*

$$y^o = h(x^t) + \epsilon^o$$

h is a function that maps model variables x into observatbles y

x^t is the reference *truth* at the scales represented by the model

ϵ^o is the observation error which includes

1. *detector noise*
2. errors in the forward model h
3. representativeness errors (scales seen by the observating system but not represented by the model).

Observation operator for AOD

- Global aeorosol transport models typically provide *dry* mass mixing ratio for each species
- To match radiances or retrieved AOD, RH and microphysical parameters *p* need to be specified, e.g.,

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

Need for Bias correction

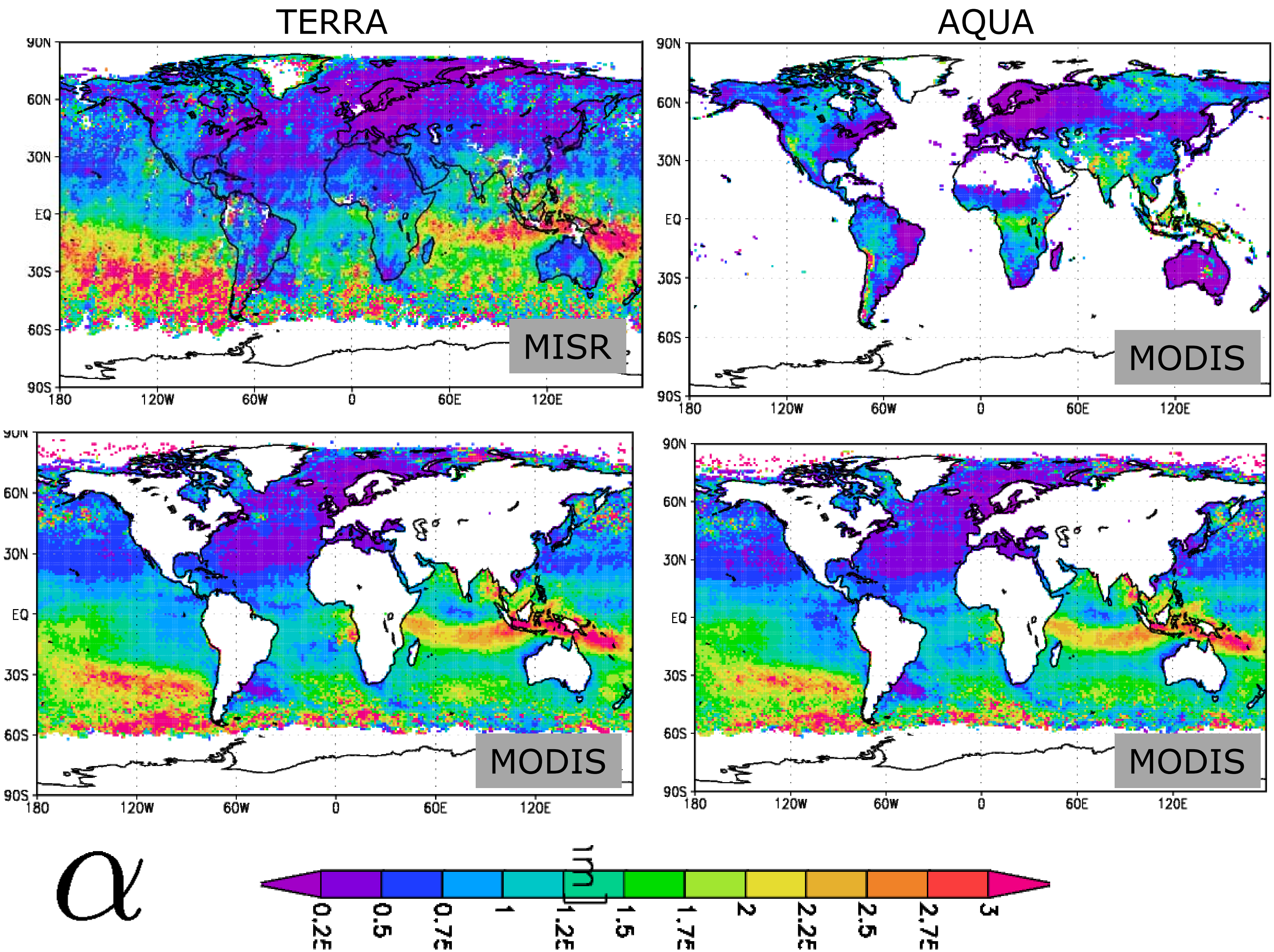
- Discrepancies between modeled and observed AOD are due to
  - Model deficiencies (transport, emissions, resolution)
  - Wrong (or inconsistent) optical parameters
- Ignoring uncertainties in microphysical parameters causes the model to take the blame
  - Often, information from data cannot be retained
  - Inconsistencies between instruments introduce artificial time variability

A very simple scheme

- For each instrument, estimate a simple linear correction term

$$\tau^{\mathrm{o}} = \alpha \cdot \tau^{\mathrm{model}}$$

- Parameter α is estimated by simple least-squares
- This amounts to an *observation* (forward model, rather) bias correction
- Reduces observing system discontinuities, data retention by the model

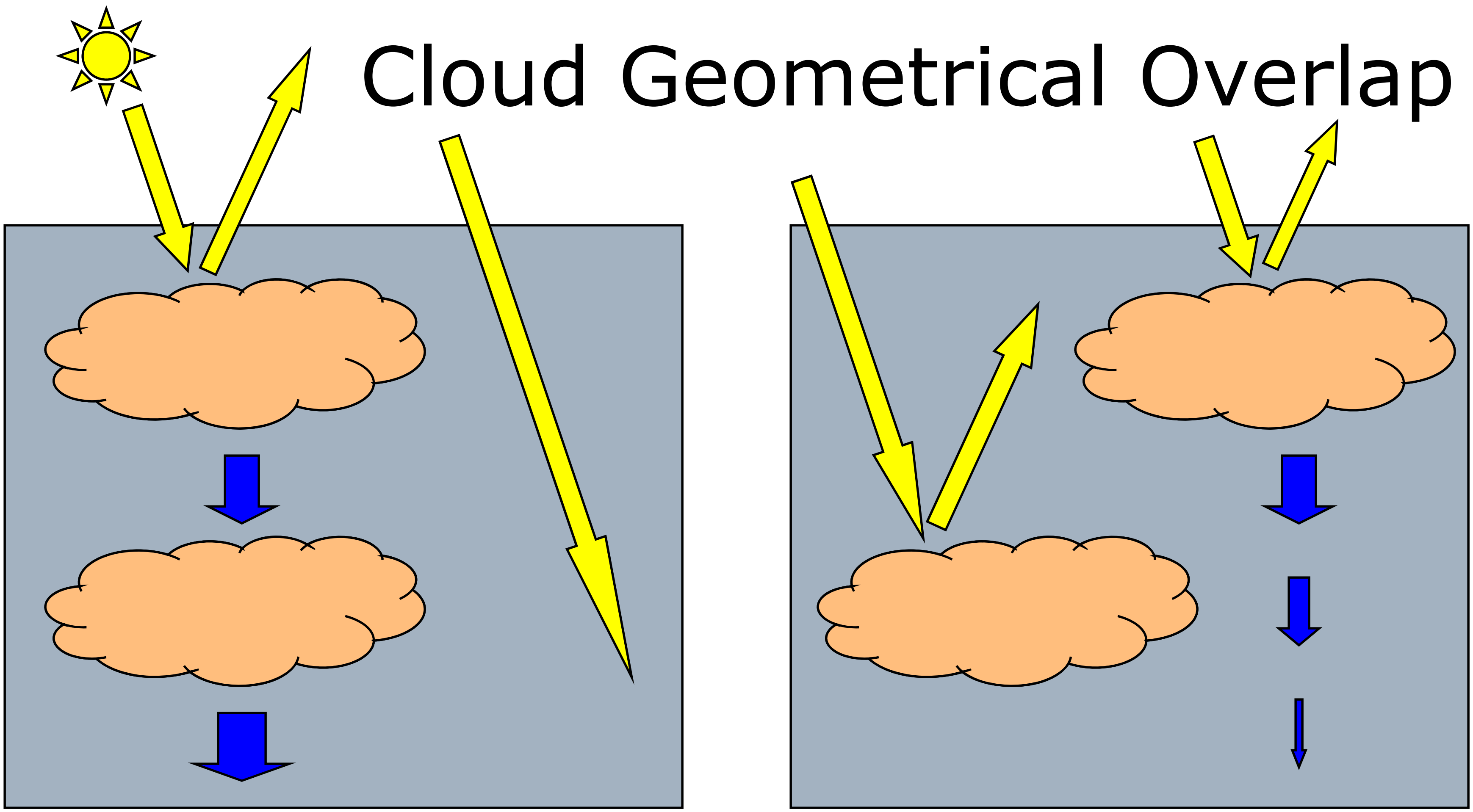


TERRA
AQUA
MISR
MODIS
MODIS
MODIS
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
α
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3

Issues in aerosol assimilation

II. Accounting for moisture sub-grid variability under partially-cloudy conditions

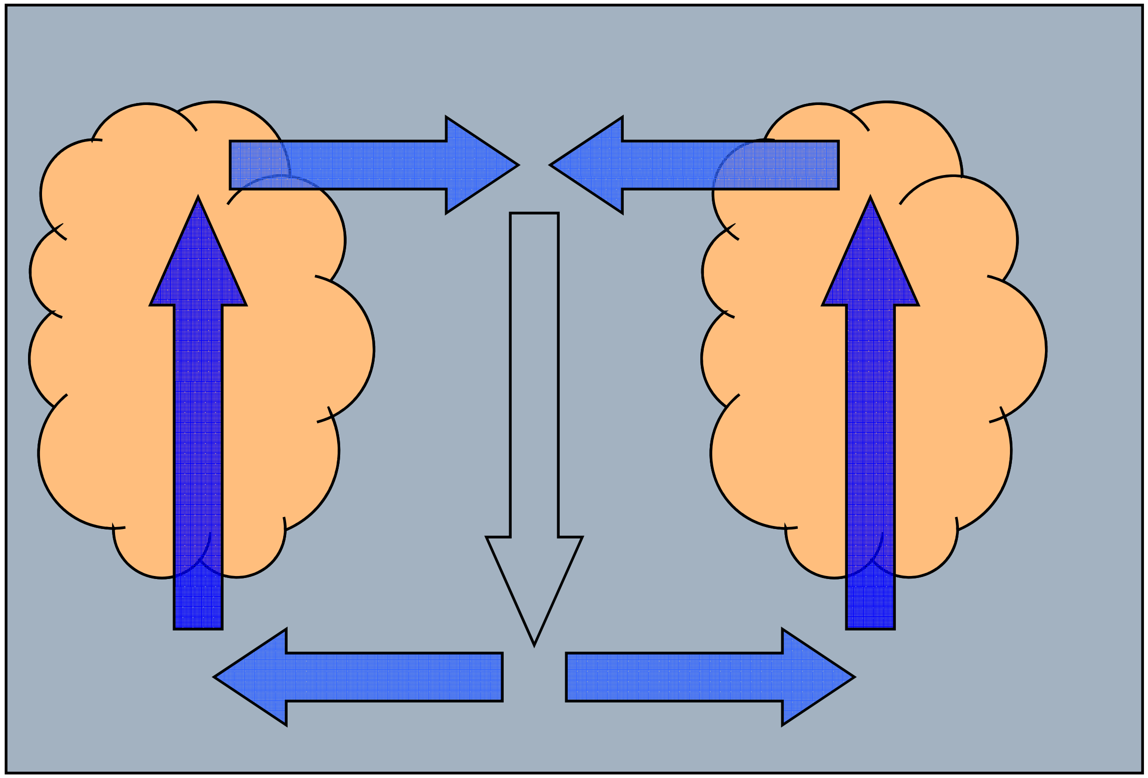
Cloud Geometrical Overlap



Both cases have two cloud layers with the same cloud fraction in each, but the column cloud fraction (and radiative fluxes) are very different.

Aerosols can be detected from space on the left, but not on the right.

Vertical Correlations in Moisture



I. Low shear convection

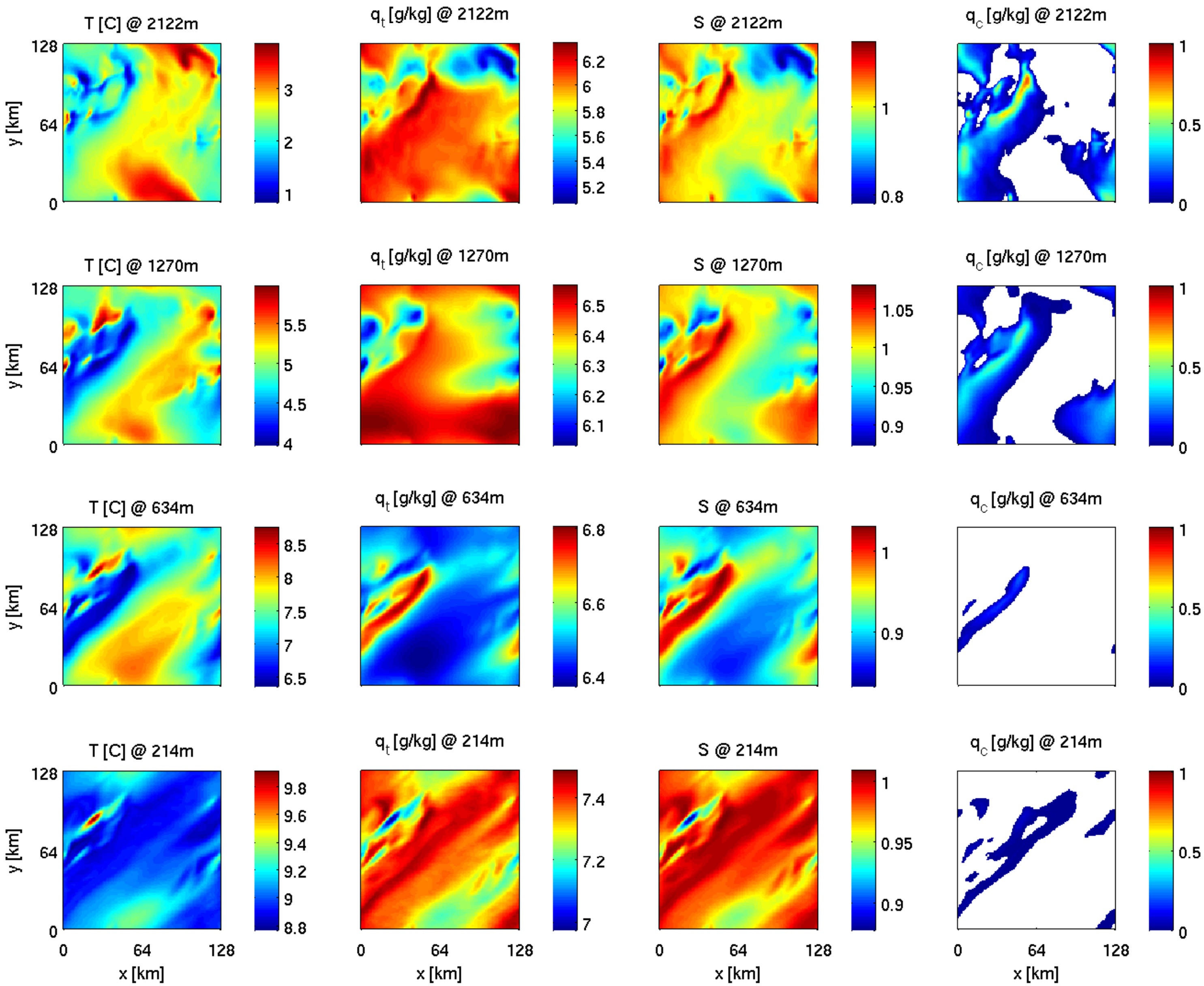
Strong vertical correlations in moist and dry air

Satellites can detected aerosols only in the dry air portion.

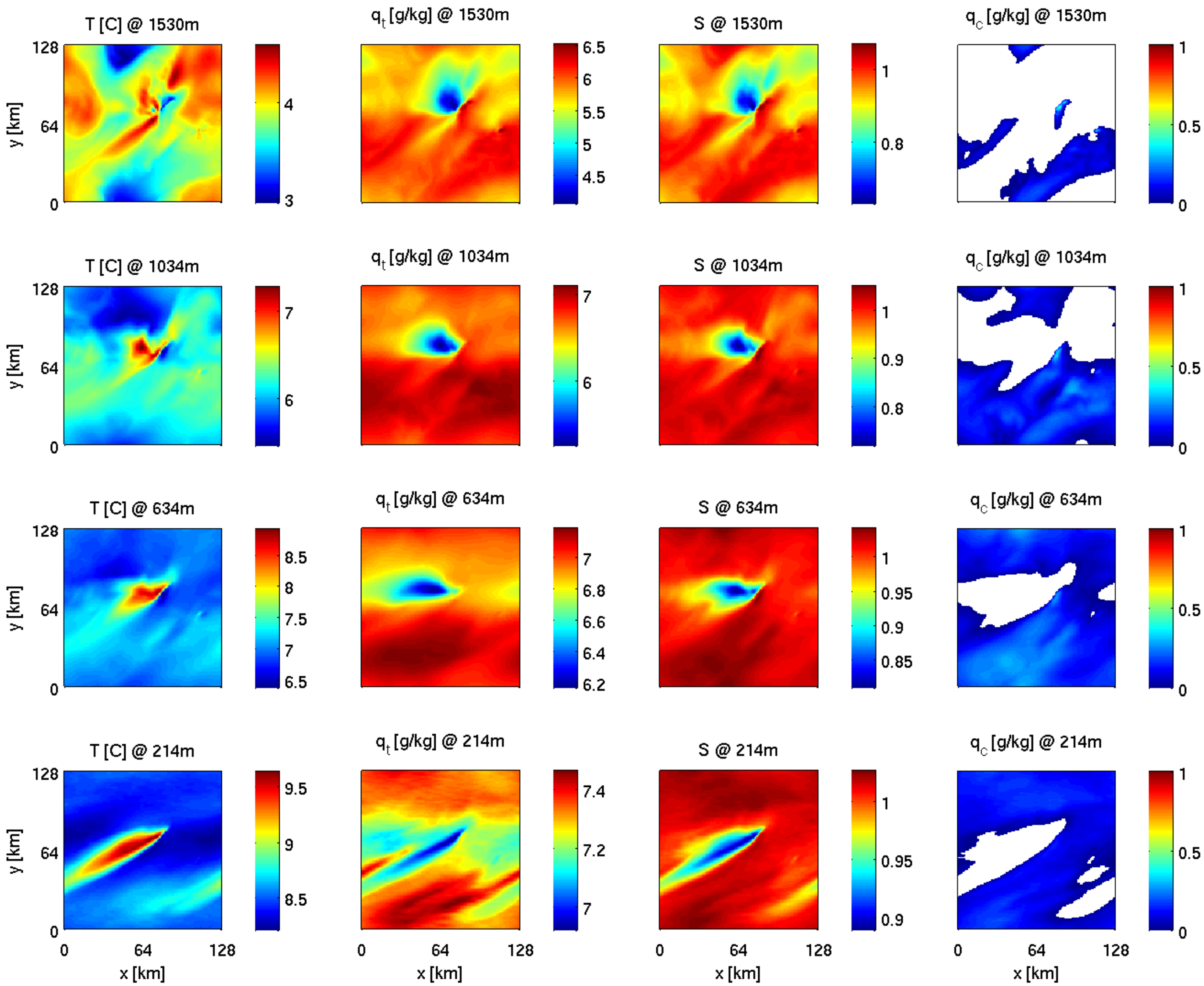
Cloud Resolving Model as Testbed

- Goddard Cumulus Ensemble Model (GCE)
- Snapshot from a simulation from an ARM IOP over the Southern Great Plains site
  - *Forced by observed fluxes and land-assimilation system*
  - *Hourly output for March 2000*
  - *Zeng et al (2007)*
- Resolution: is 1 $km^{2,}$ 41 layers
- Domain: 128km x 128km
- Lowest 12 layers (z <≈ 2200 m)
  - above freezing and ice-free

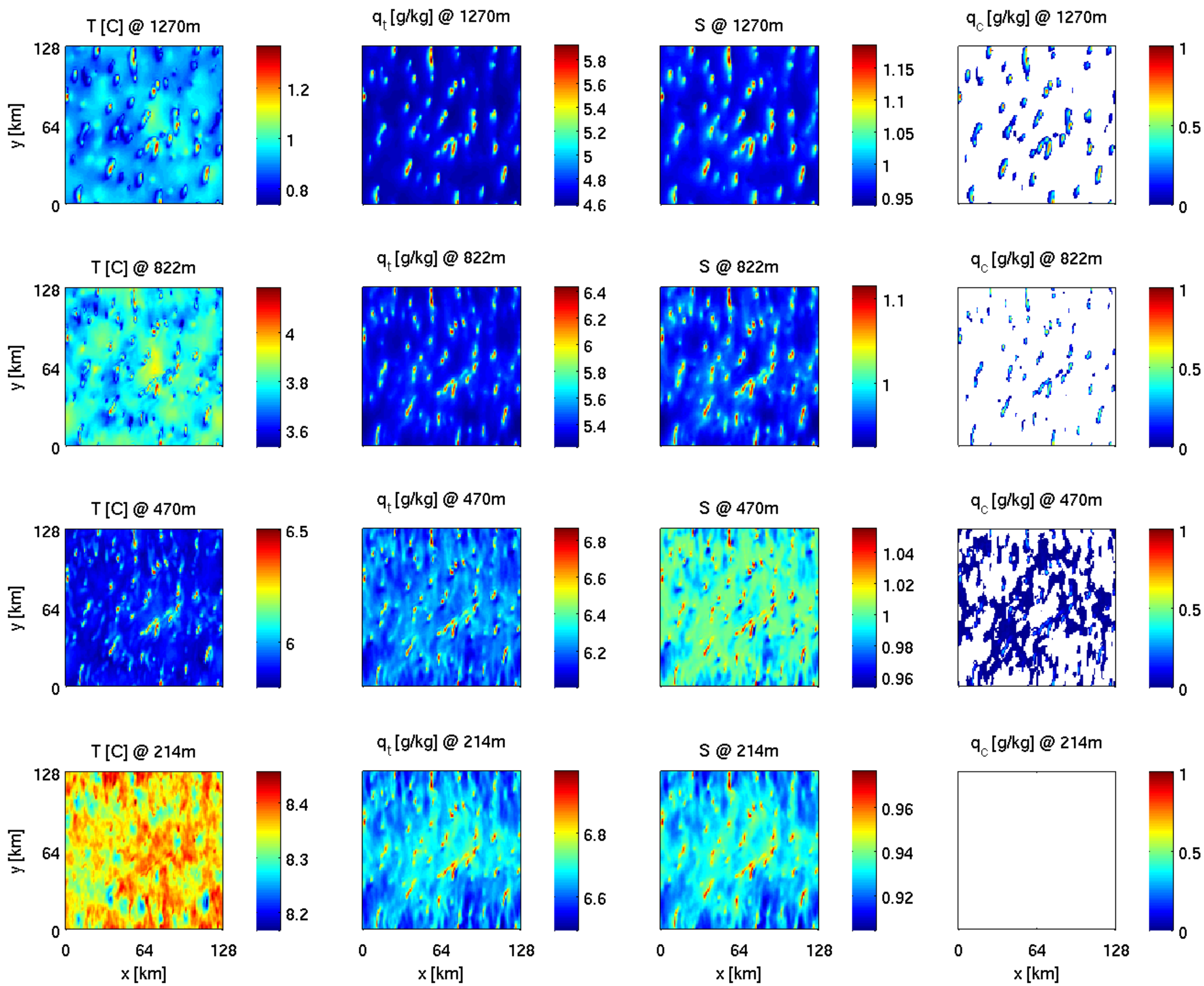
Case 1: one day after passage of a cold front



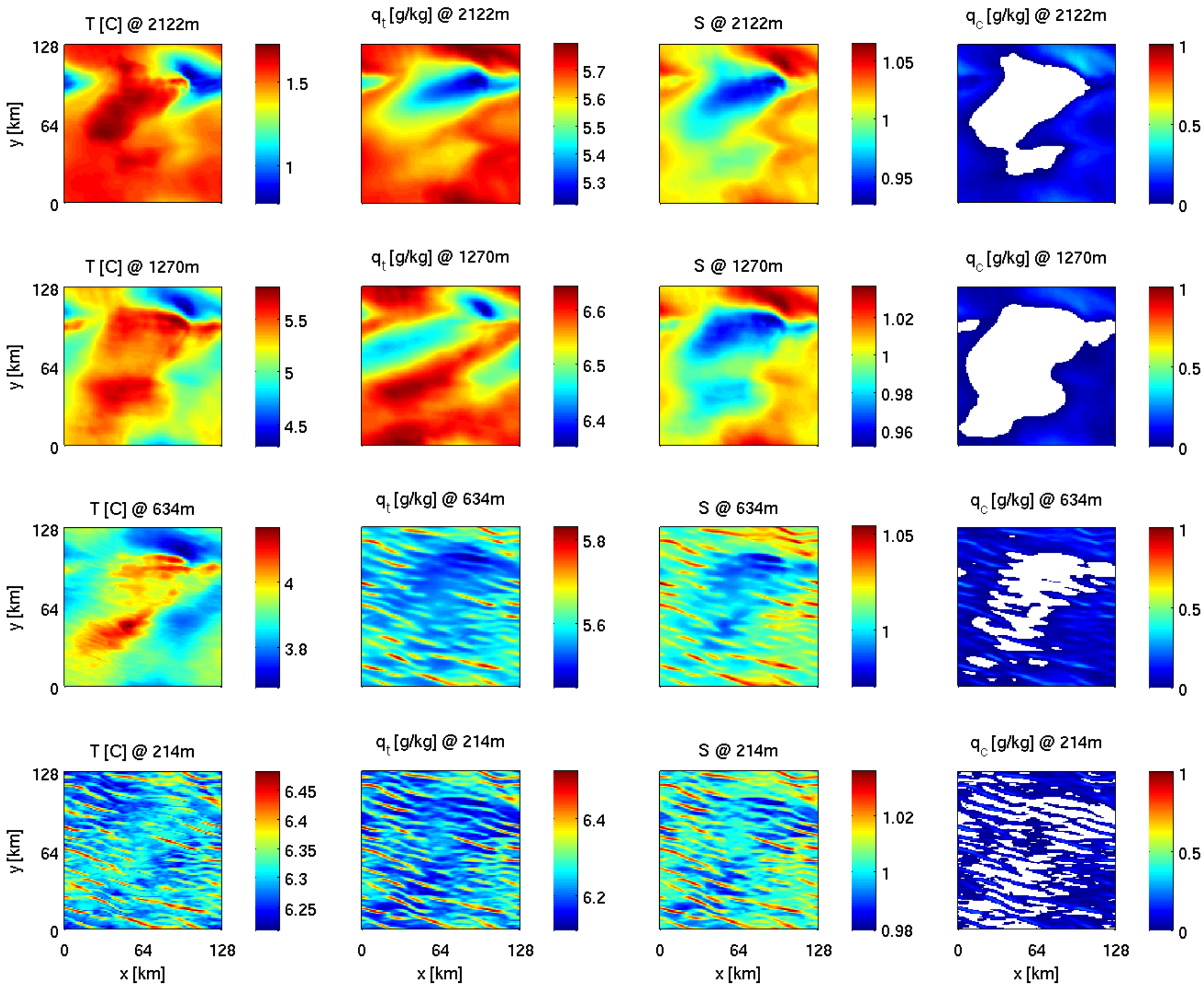
Case 2: dry/warm core



Case 3: Popcorn cumulus



Case 4: Layered Clouds



Moisture Sub-grid variability

Consider the total water (vapor + condensate)

$$q_t = q_{\text{Vapor}} + q_{\text{Liquid}} + q_{\text{Ice}} \equiv q_{\text{v}} + q_\ell + q_{\text{i}}$$

and define

$$S = \frac{q_t}{q_s(T)}$$

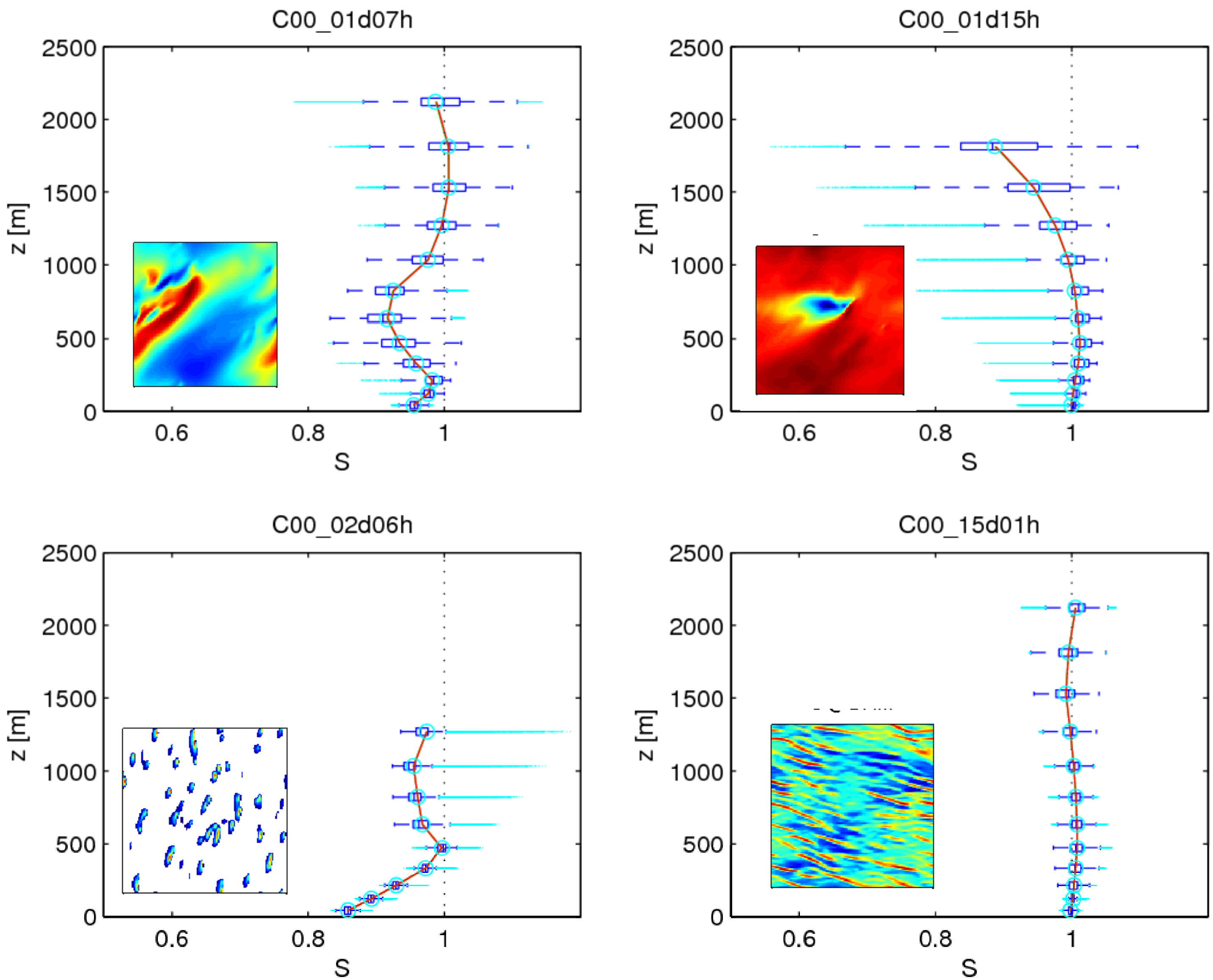
Let $< \cdot >$ denote horizontal mean (proxy for GCM gridbox mean)

$$q_t =< q_t > + q_t'$$

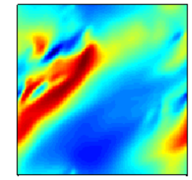
It follows that

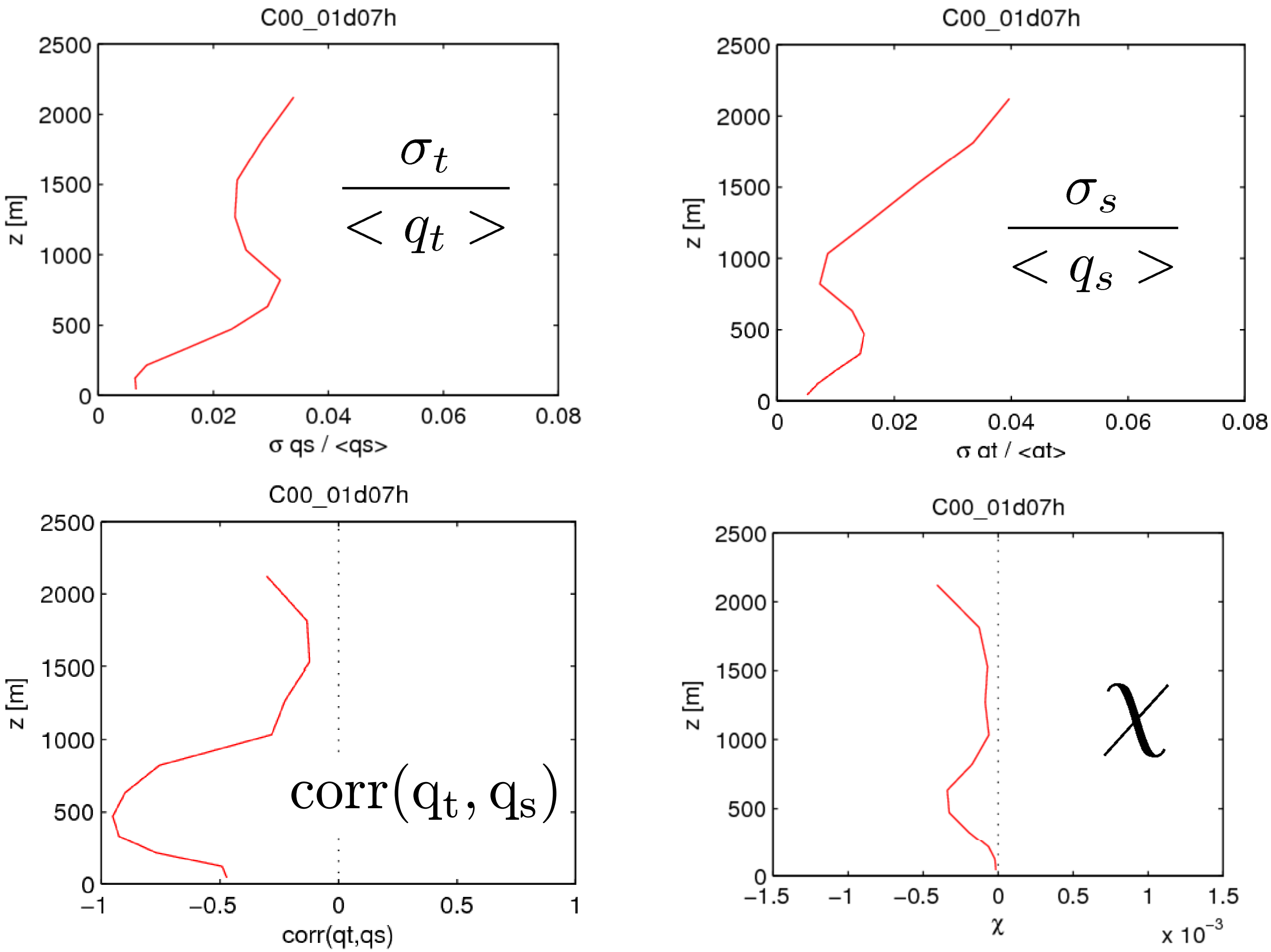
$$< S > \approx \frac{< q_t >}{< q_s >}\left(1 - \frac{< q_t' q_s' >}{< q >< q_s >}\right) \approx \frac{< q_t >}{< q_s >} \approx \frac{< q_t >}{q_s(< T >)}$$

S is by no means uniform



$$\chi \equiv \frac{< q_t' q_s' >}{< q_t >< q_s >} = \frac{\sigma_t}{< q_t >} \frac{\sigma_s}{< q_s >} \mathrm{corr}(\mathrm{q_t}, \mathrm{q_s})$$





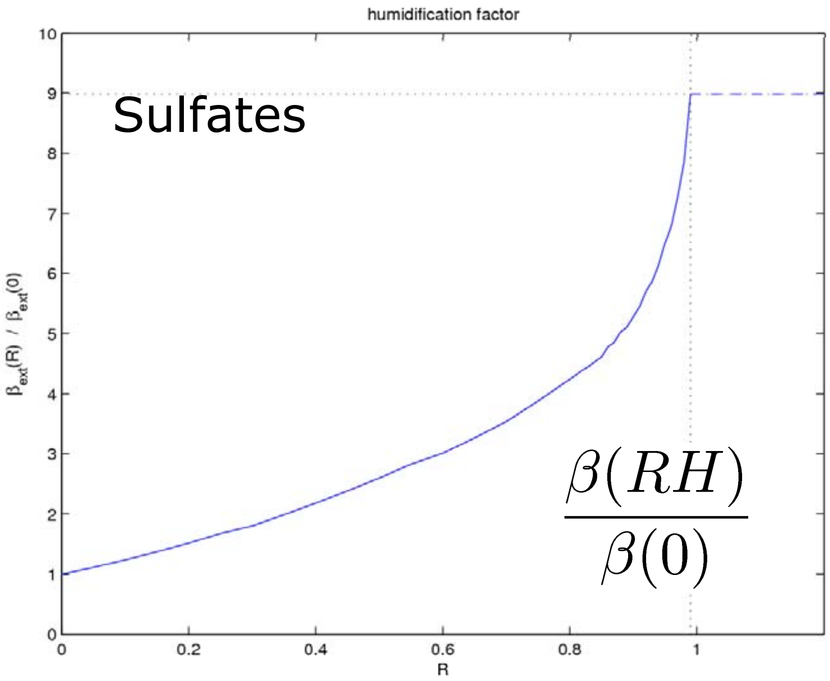
Hygroscopic Aerosols

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

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

The normalized mass extinction efficiency

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



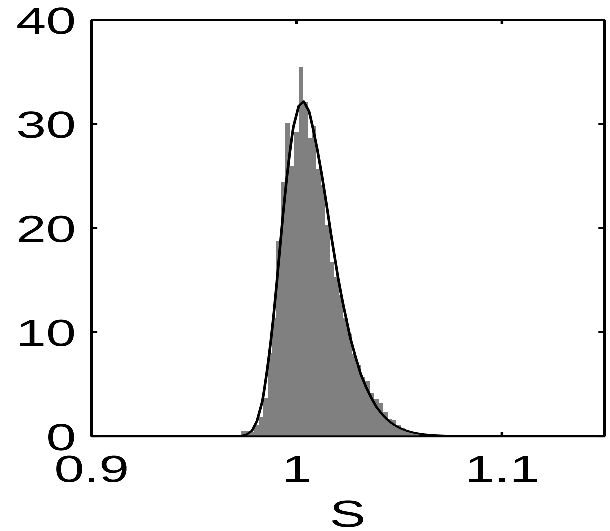
$\hat{\beta}$ saturates at 99%

PDF-based cloud scheme

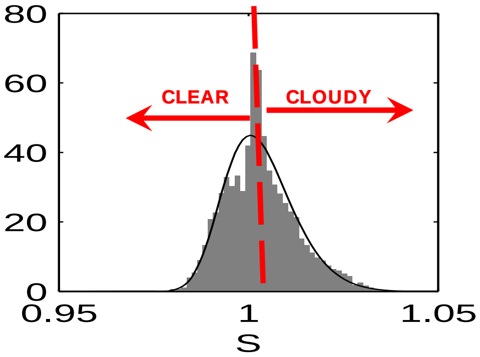
- For a given grid-box, the sub-grid variabiality of q_t is modeled by a (non-gaussian) PDF.

- PDF parameters such as skewness are modeled from large scale factors such as wind shear and static stability.

- Large-cale cloud fraction is simply the area to the right of $S = 1$



PDF-based Humidification



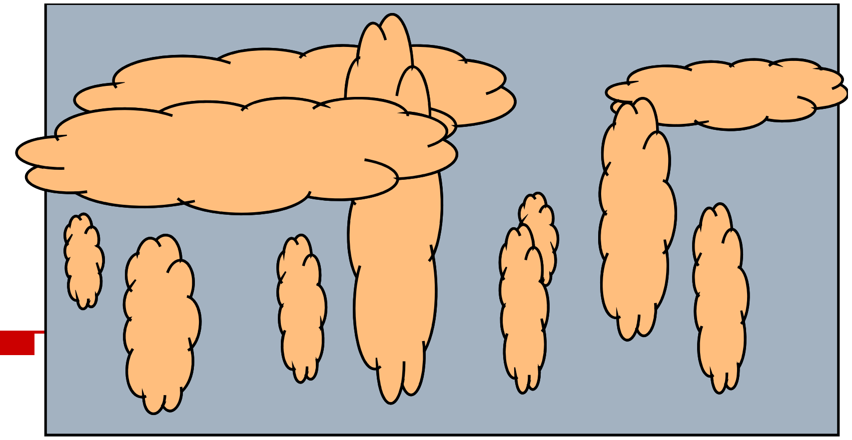
This PDF can be used to estimate the mean humidification effect on a GCM gridbox

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

where the *cloud fraction* f is given by

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

AOD from Satellites



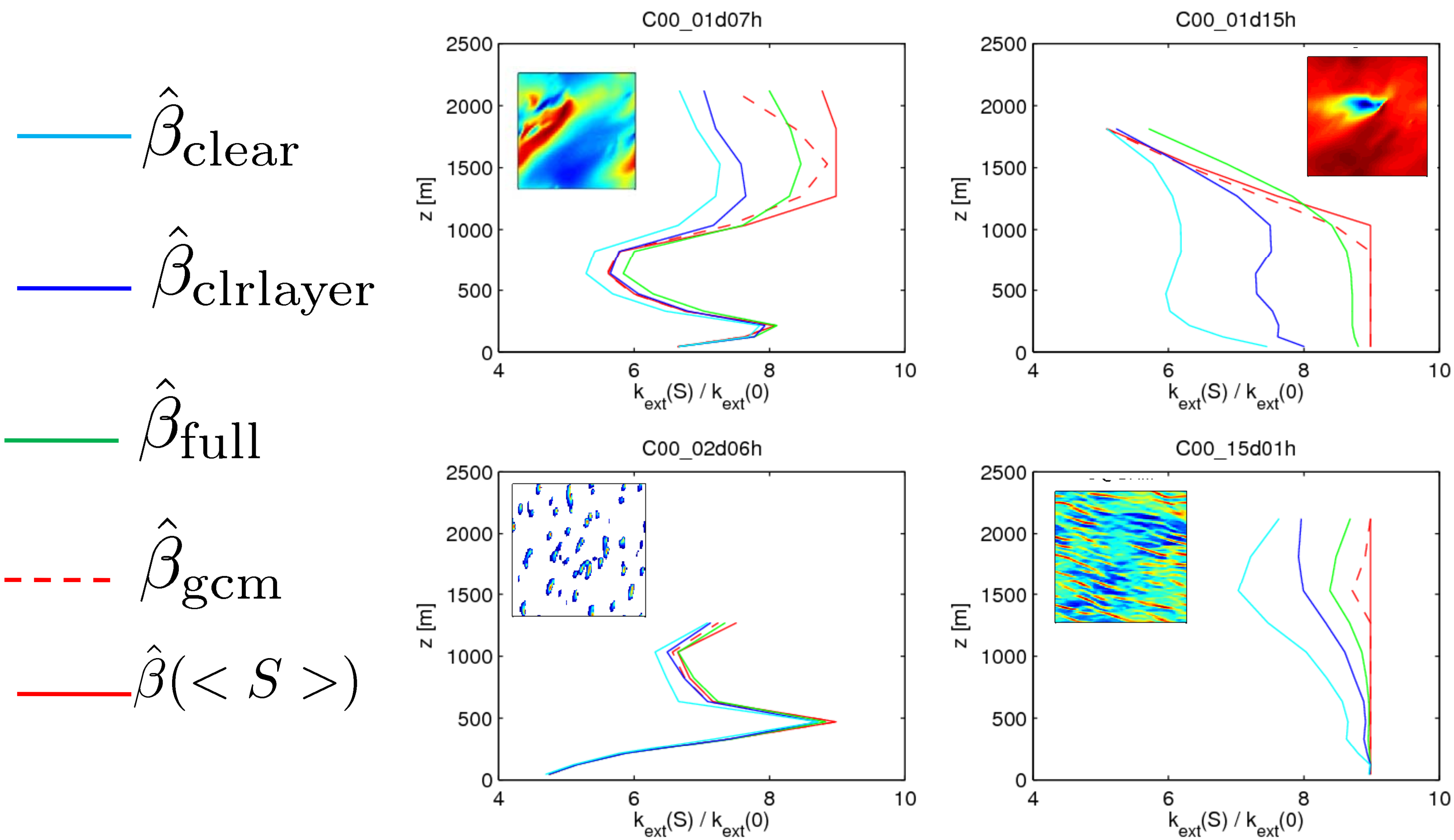
- Most satellites (AVHHR, MODIS, MISR, parasol, etc.) can only produce AOD retrieval in cloud clear conditions
- Therefore, the consistent model diagnostic to be validaded is

$$\tau_{\mathrm{clear}} = \beta_{\mathrm{clear}}(RH) \cdot q_{\mathrm{dry}} \cdot \rho_a \delta z$$

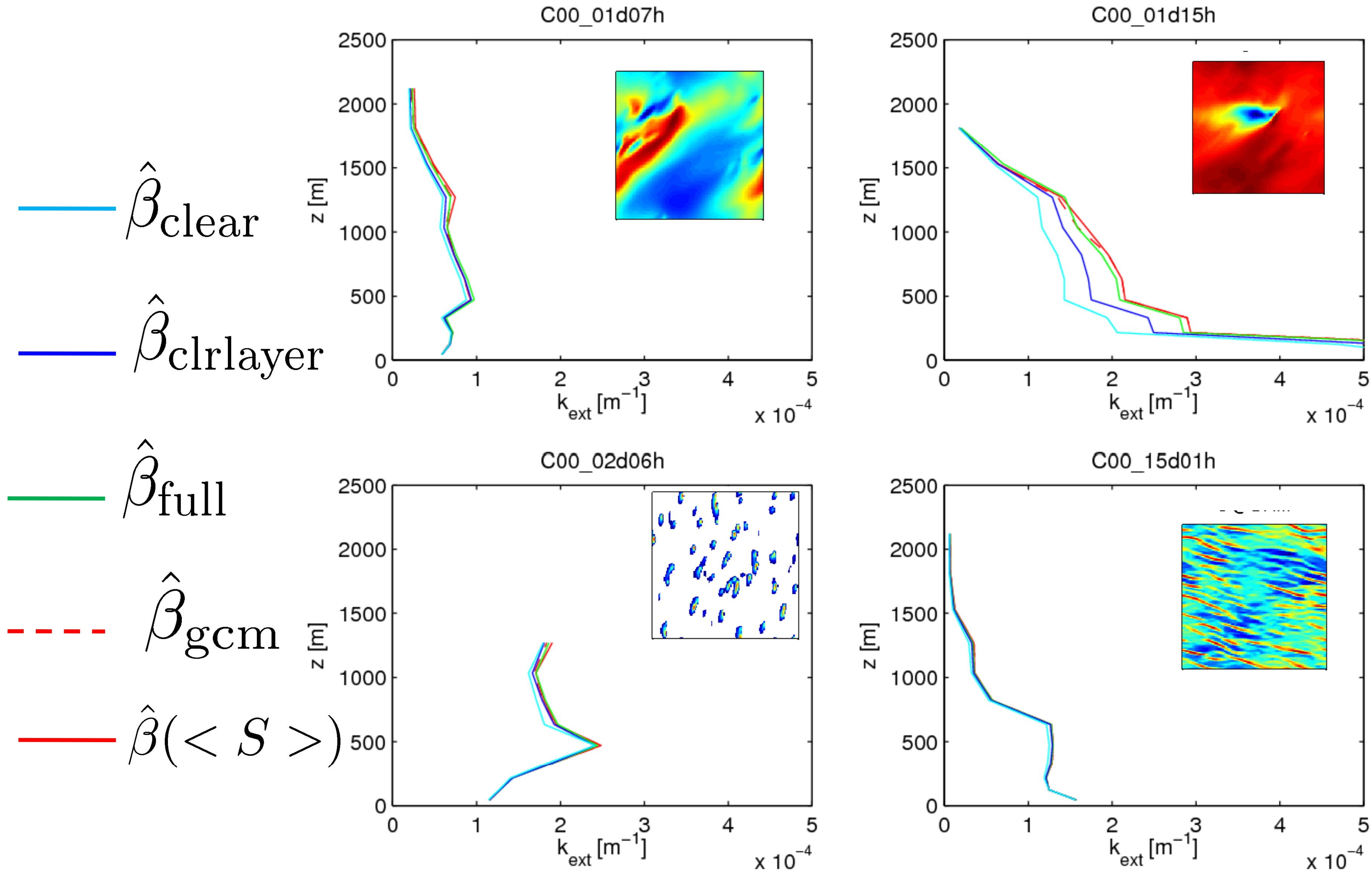
- Moreover, the whole column must be clear
- Recall that currently we compute

$$\tau_{\mathrm{gcm}} = \beta(< RH >) \cdot q_{\mathrm{dry}} \cdot \rho_a \delta z$$

Humidification Factor: Sulfates



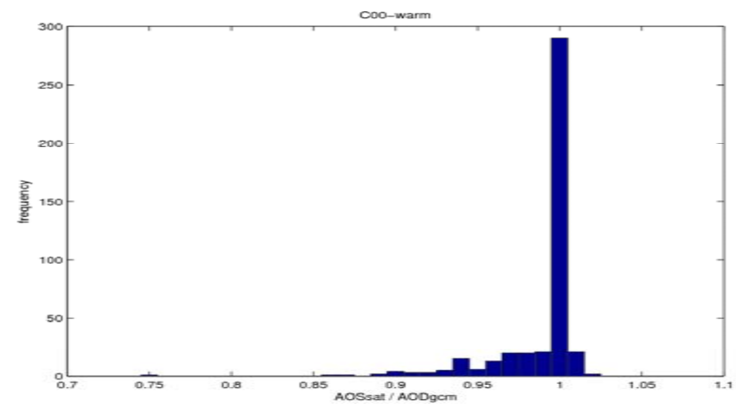
Aerosol Extinction: Sulfates

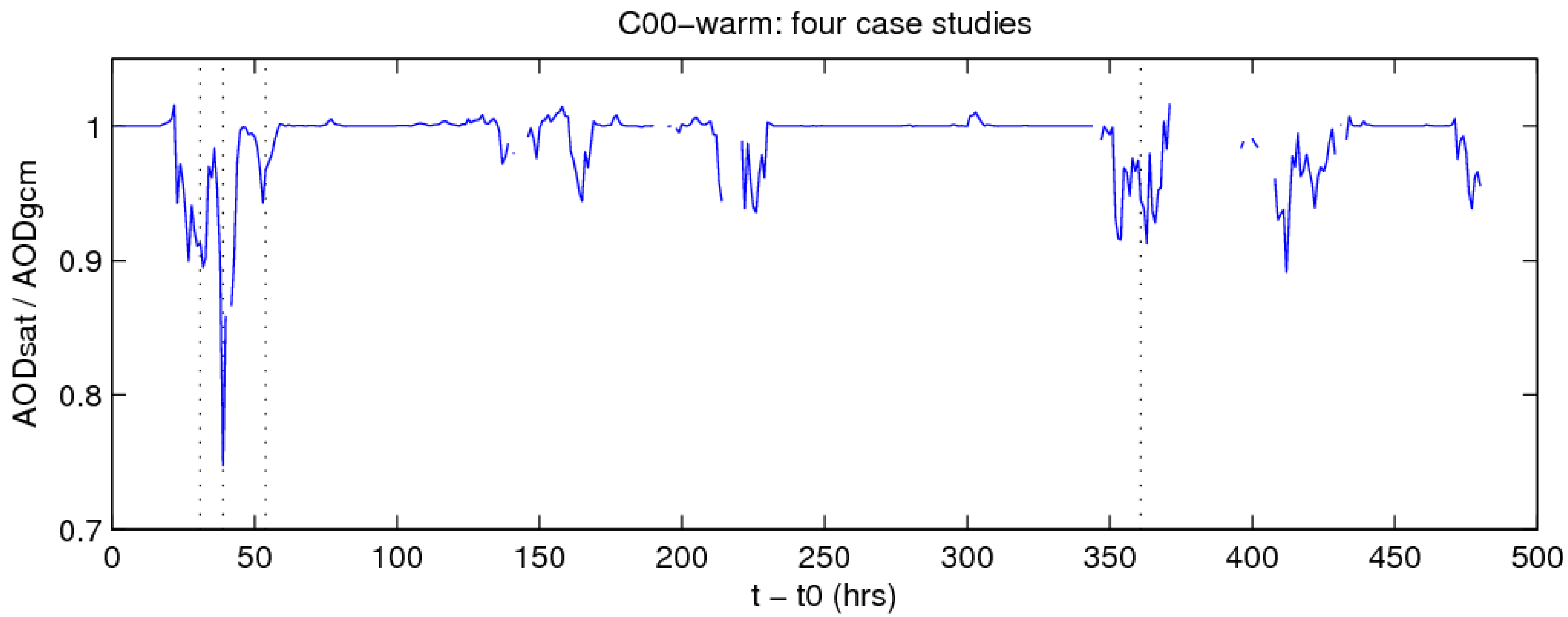


Aerosol Optical Depth: Sulfates

Aerosol Fair Weather Bias

Sub-grid scale effect on total column AOD are usually in the direction of reducing the optical depth.





Clouds in GEOS-5

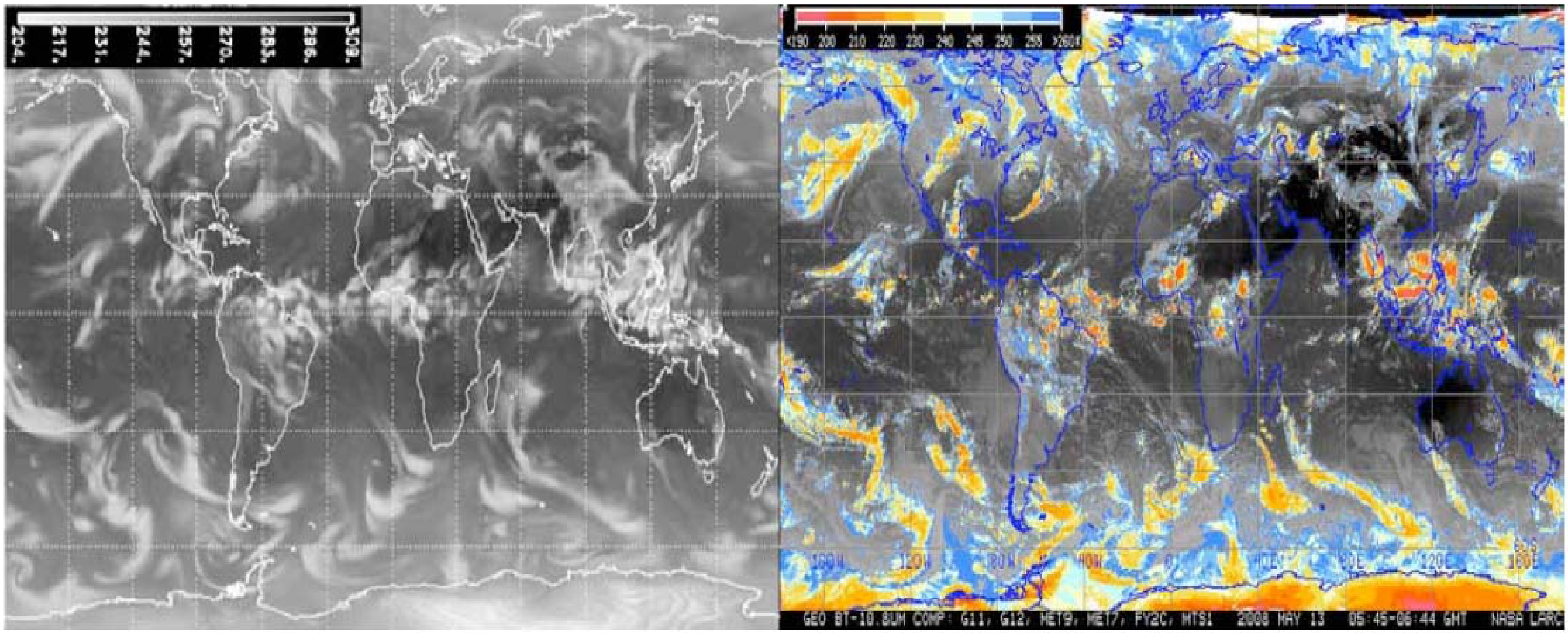


Fig. 8. GEOS-5 simulated brightness temperature GOES IR (left) compared to GEOsat IR observations, 6 UTC, 13 May 13 2008. Note the temperature scale differences.

Concluding Remarks

- A simple state dependent bias correction scheme has been applied to the AOD forward model for MISR, T/A MODIS and OMI
  - Overall reduction of error mean and stdv
  - Being extended to include multiple wavenumbers
- Moisture sub-grid variability can be used to diagnosed AOD as inferred from Satellites (clear column)
  - Fair weather bias: reduce AOD
- These developments provide the foundation for assimilating aerosols in GEOS-5.