Aerosol Data Assimilation at NASA/GSFC

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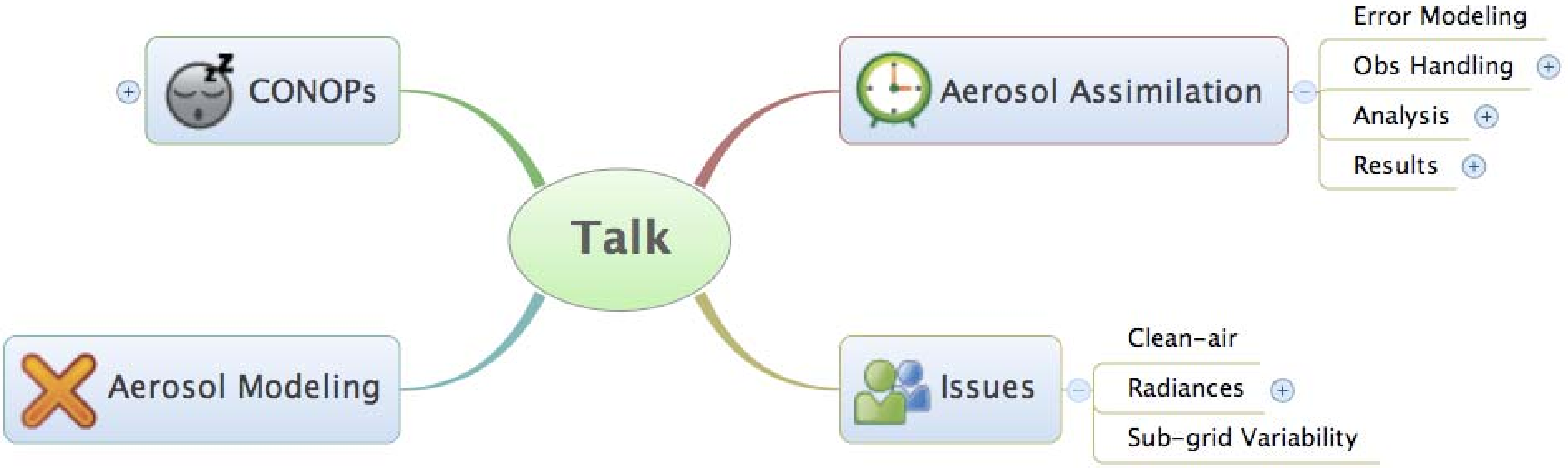
(3) GEST/UMBC

Aerosol Observability Workshop

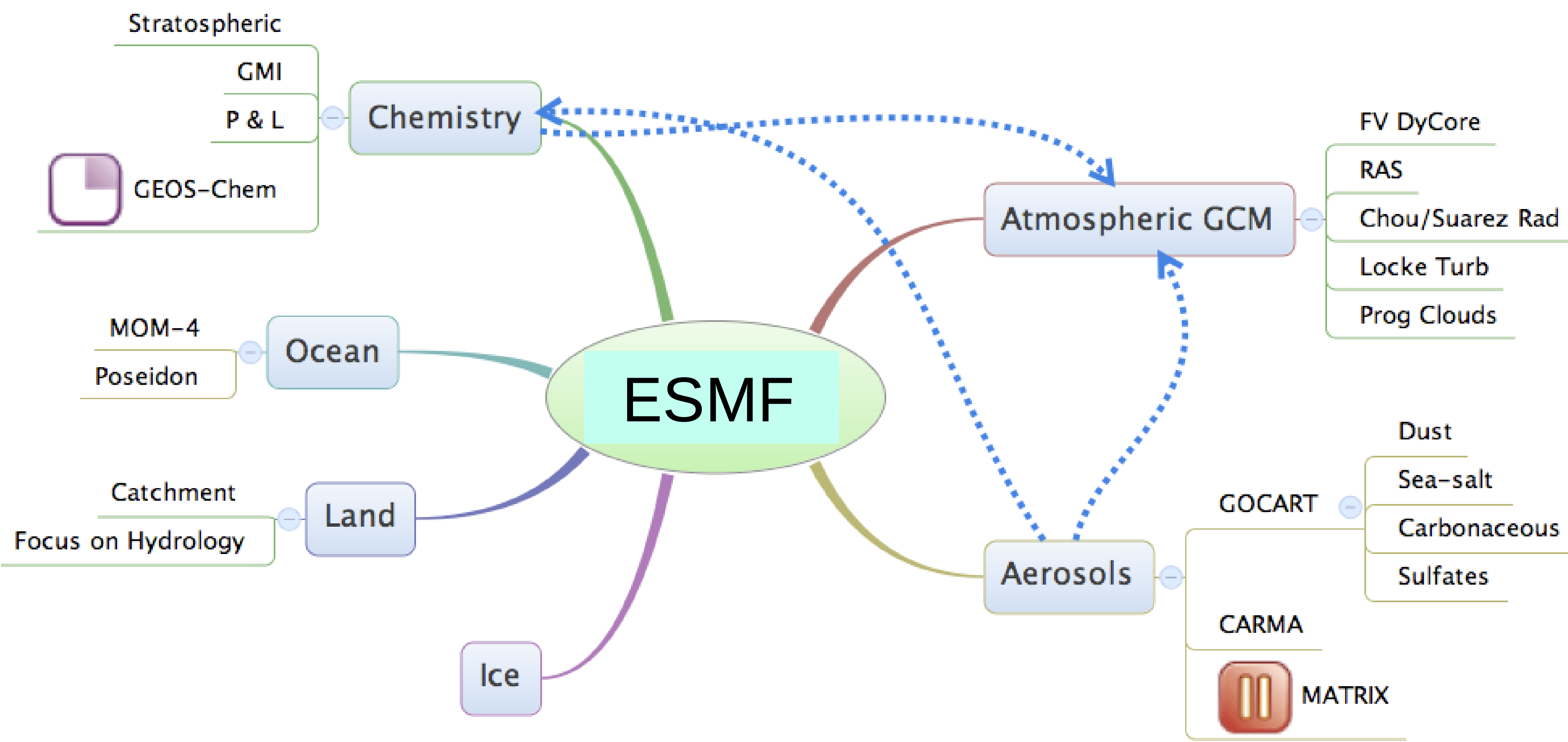
Casa Munras Hotel, Monterey, CA

27-29 April 2010

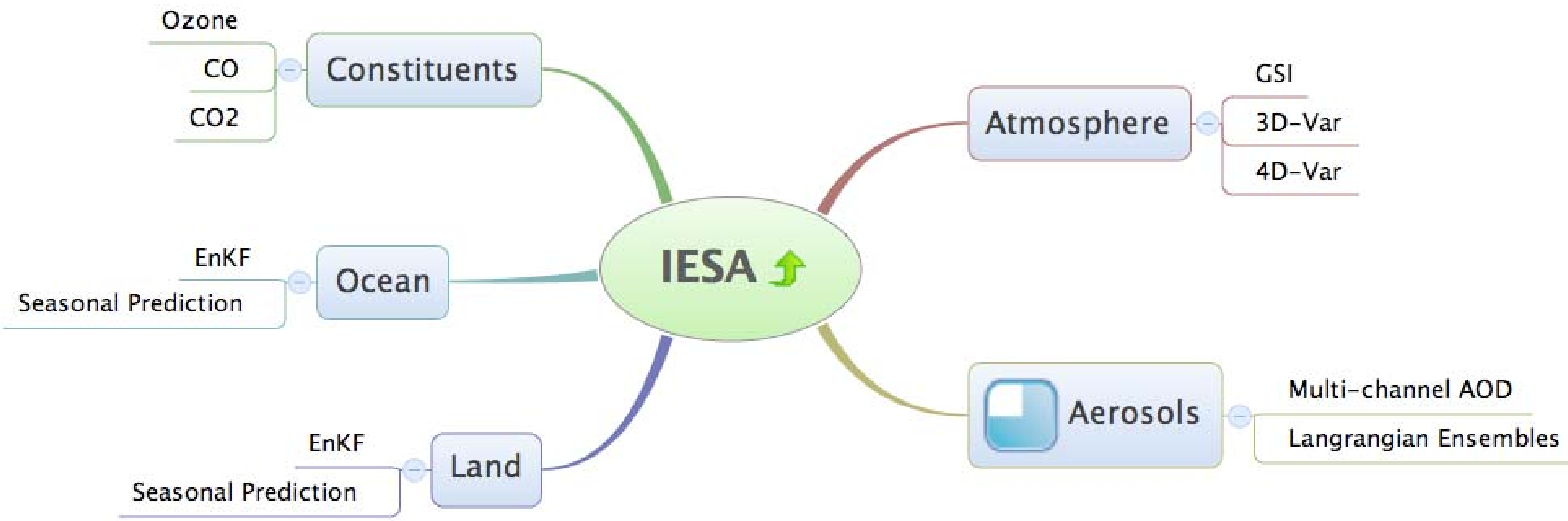

Talk
CONOPs
Aerosol Modeling
Aerosol Assimilation
Error Modeling
Obs Handling
Analysis
Results
Issues
Clean-air
Radiances
Sub-grid Variability

GMAO at a Glance...

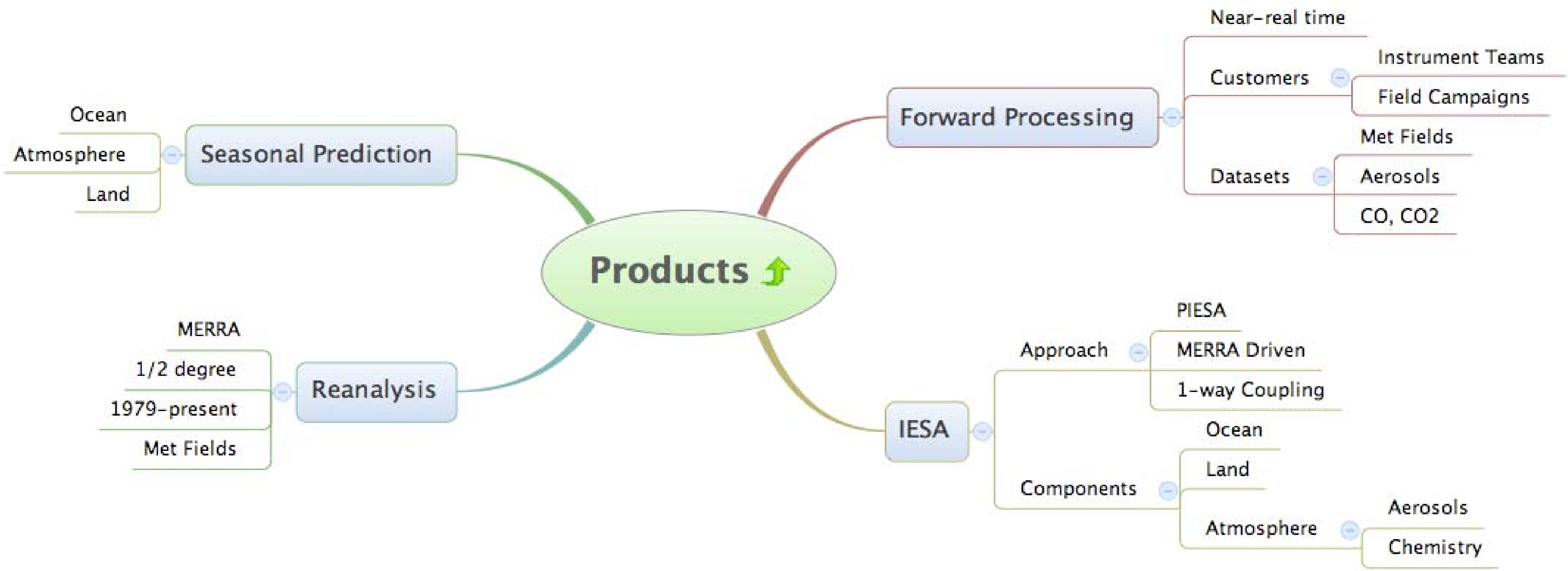
GEOS-5 Earth-System Model



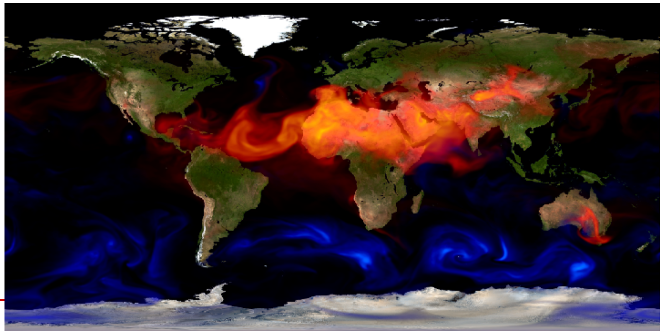
Integrated Earth System Analysis



Products


Products
Seasonal Prediction
Ocean
Atmosphere
Land
Reanalysis
MERRA
1/2 degree
1979-present
Met Fields
Forward Processing
Near-real time
Customers
Instrument Teams
Field Campaigns
Datasets
Met Fields
Aerosols
CO, CO2
IESA
Approach
PIESA
MERRA Driven
1-way Coupling
Components
Ocean
Land
Atmosphere
Aerosols
Chemistry

Aerosol activities at GMAO

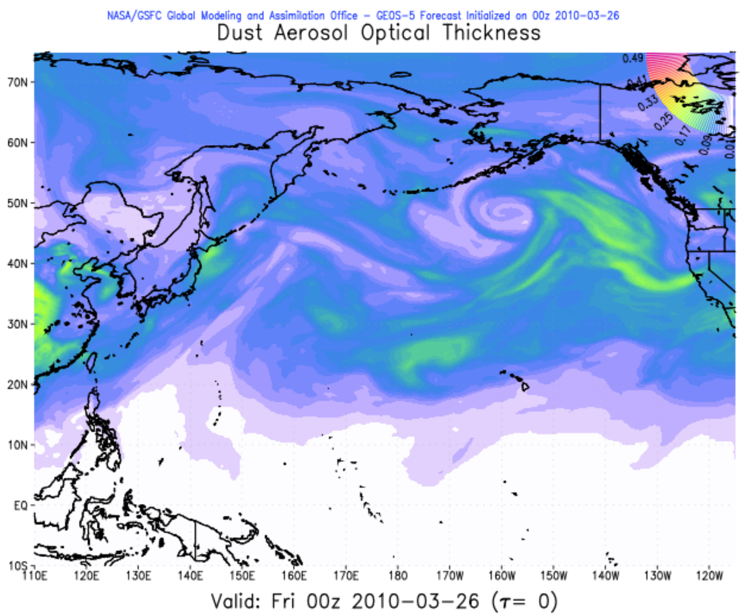


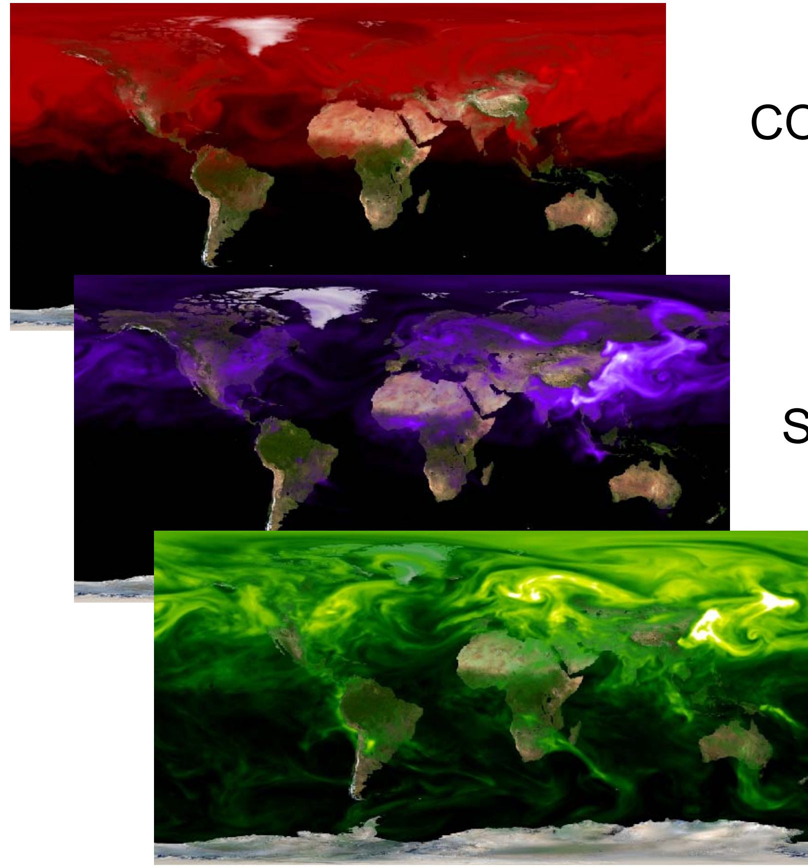
- Developing a **hierarchy of *global* models** capable of skillfully representing
  - the global aerosol distribution as depicted by available in-situ and remotely-sensed measurements
  - the microphysical processes needed for parameterizing cloud/precipitation-aerosol feedbacks
  - Aerosol interaction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

Global 5-day chemical forecasts customized for each campaign

- O3, Aerosols, CO, CO_2,..
- 1/4 degree globally

Driven by real-time biomass emissions from MODIS



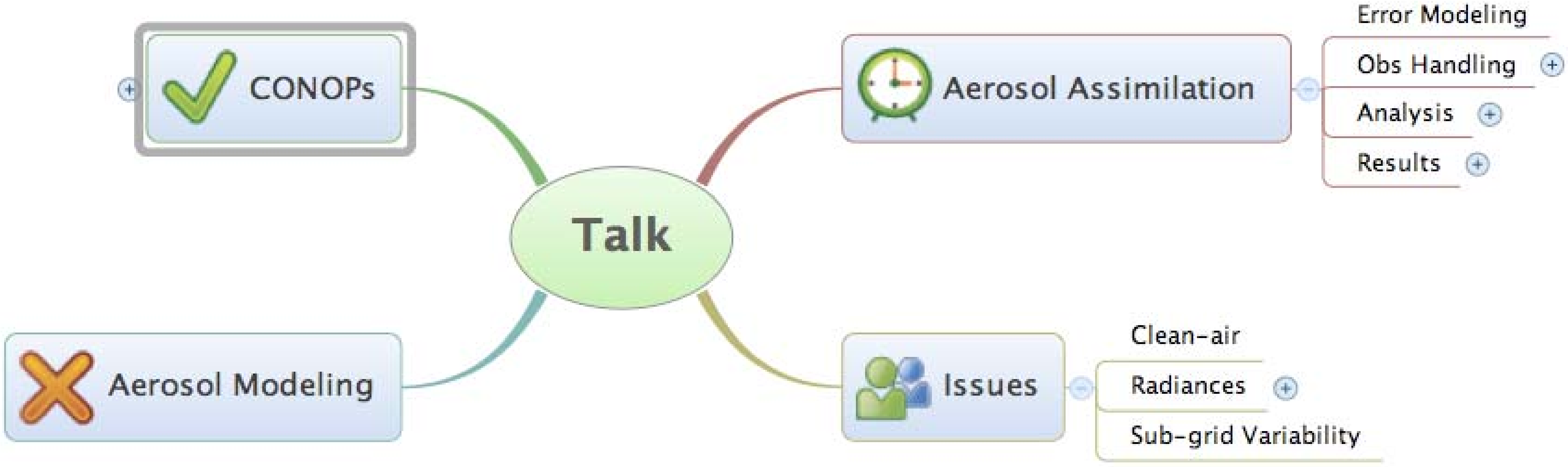


CO

Smoke

SO_4

http://gmao.gsfc.nasa.gov/projects/glopac/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Clean-air
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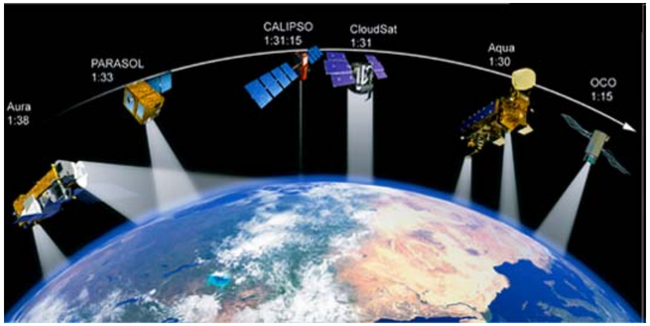
Aerosol Data Assimilation

- Focus on NASA EOS instruments



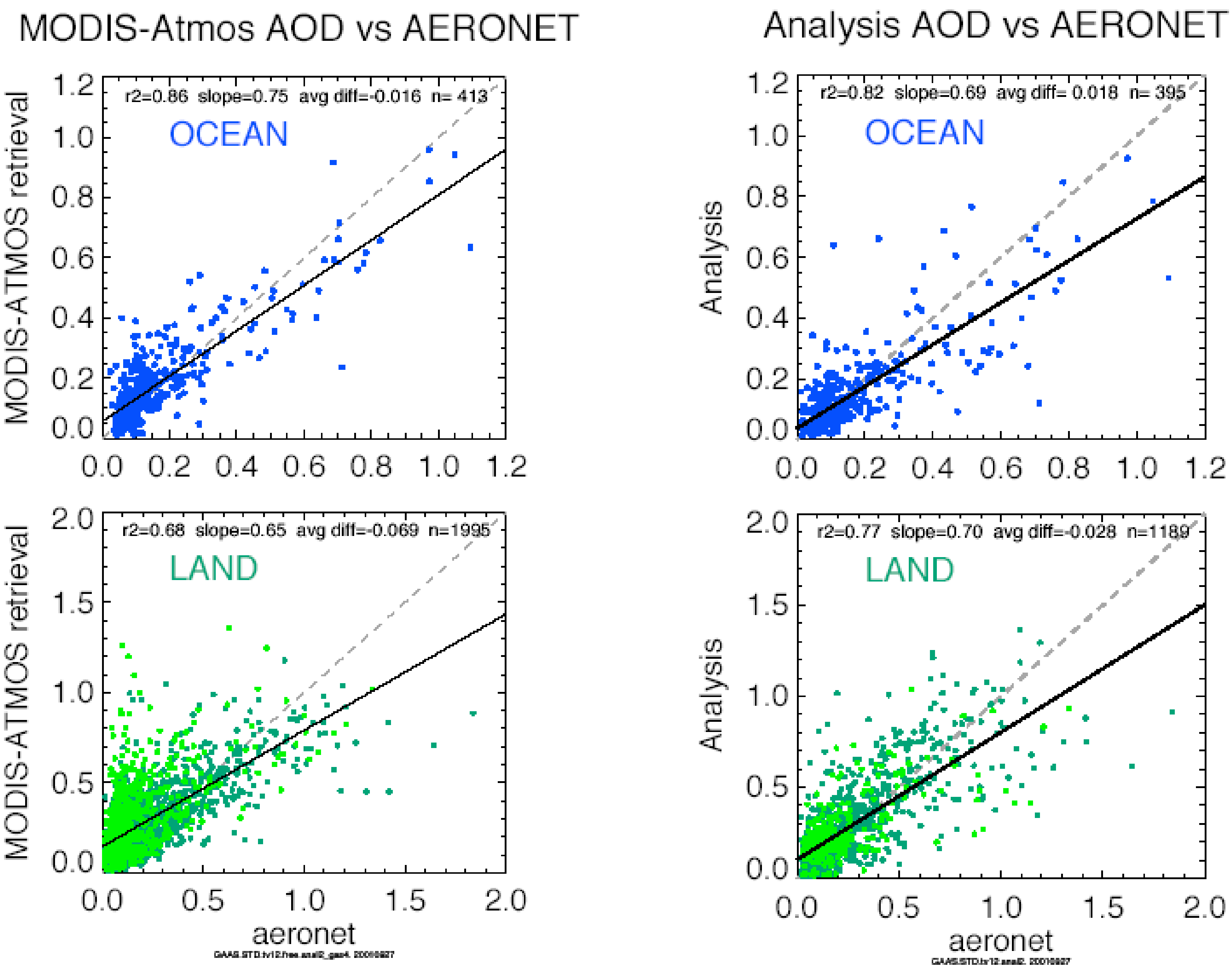
- Global, high resolution (1/4 deg) AOD analysis
- Multi-channel
- 3D increments by means of Lagrangian Displacement Ensembles

Radiances:

•Previously, 1D-Var scheme using GOCART aerosol fields as background (*Weaver et al 2005*)

•Currently developing OMI observation operators, towards 1D VAR

•Goal: Unified MODIS/OMI 1D-Var


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
aeronet
r2=0.77 slope=0.70 avg diff=-0.028 n=1189
LAND
Analysis
aeronet

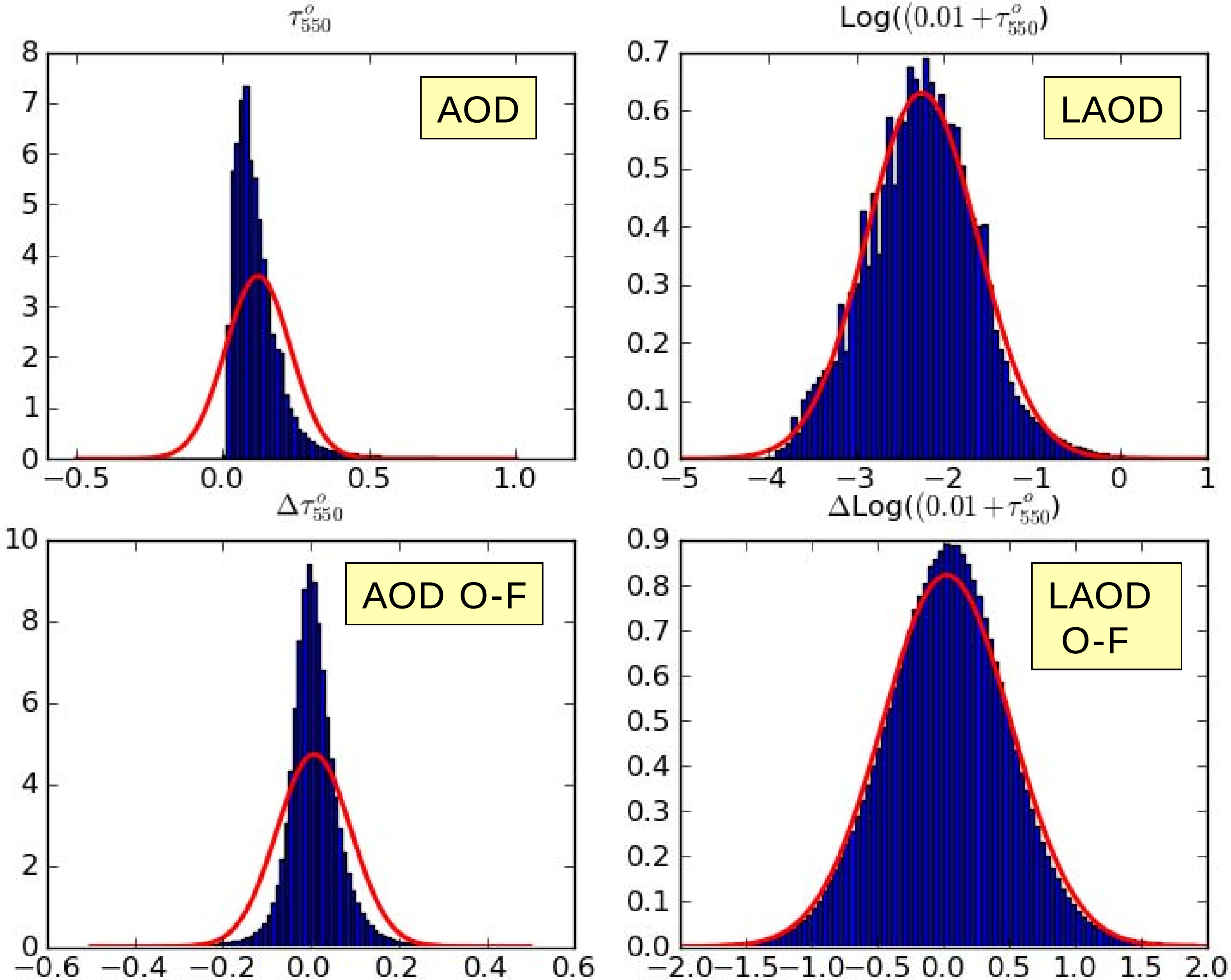
Data Type

- 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

MODIS/TERRA Ocean



Quality Control

- 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
- Data correction:
  - None currently
  - Considering NRL type of procedures

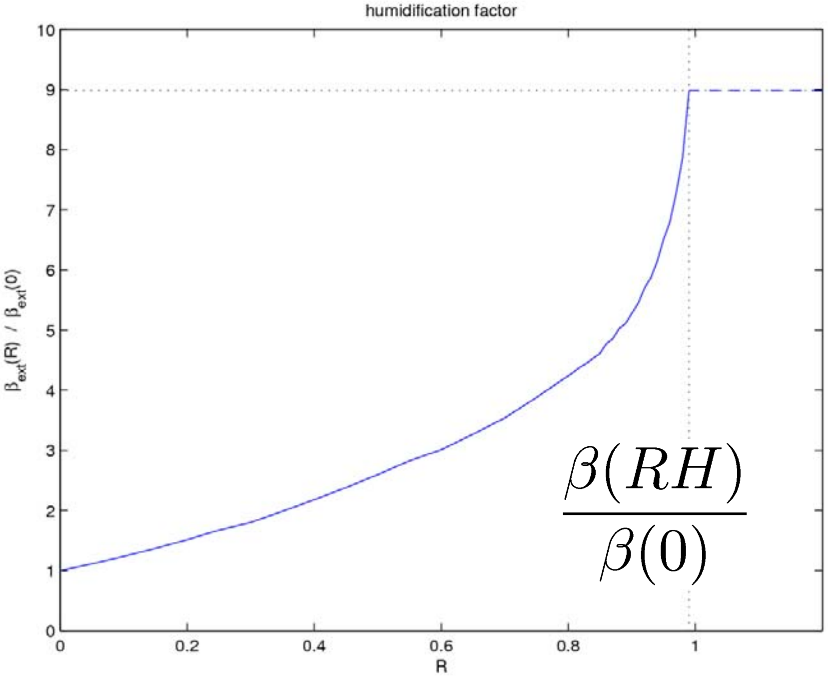
Hygroscopic Aerosols

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

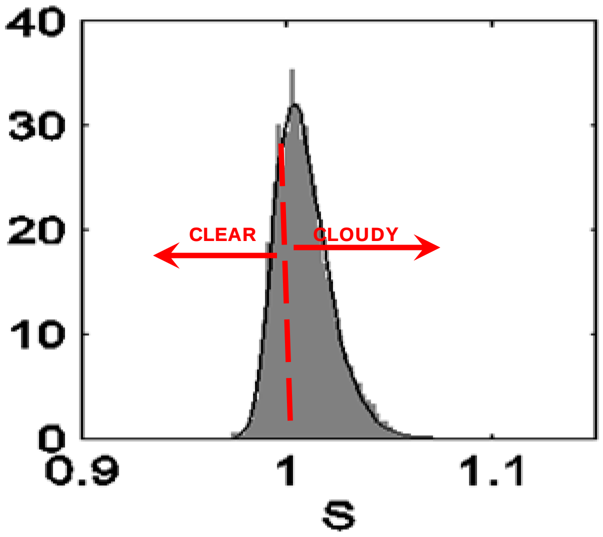
$$\hat{\beta} = \frac{\beta(RH)}{\beta(0)} \sim 1 - 10$$



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

PDF-based cloud scheme

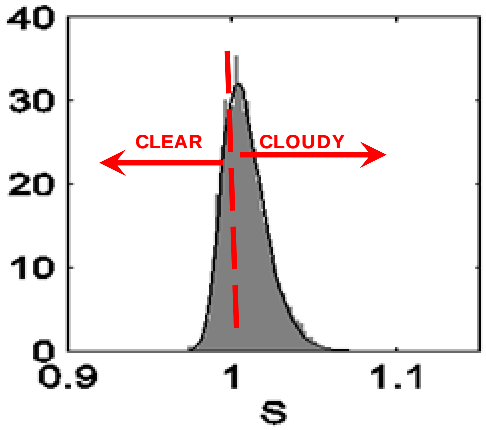
- For a given grid-box, the sub-grid variability of q_t is modeled by a (non-gaussian) PDF.
- PDF parameters such as skewness are modeled from large scale factors such as wind shear and static stability.
- Large-cale cloud fraction is simply the area to the right of $S = 1$



PDF-based Humidification

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

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

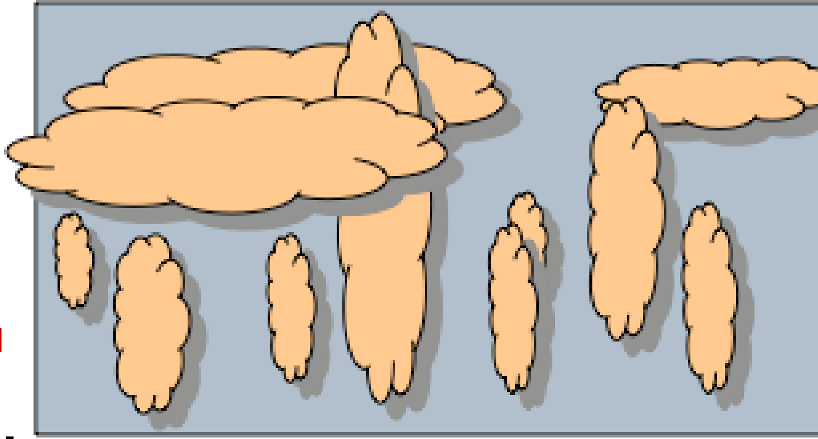


where the *cloud fraction* f is given by

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

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

AOD from Satellites

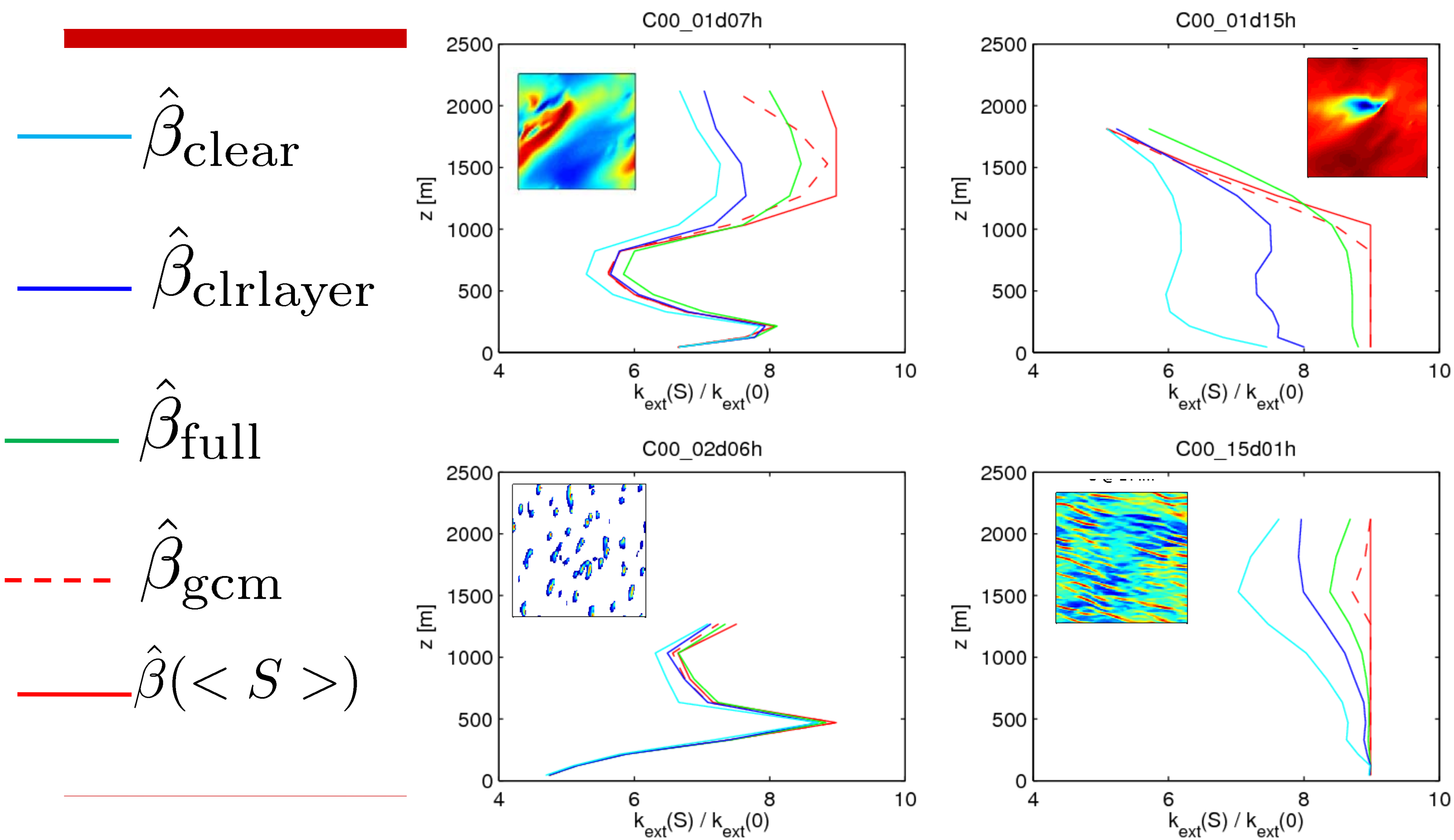


- Most satellites (AVHHR, MODIS, MISR, PARASOL, etc.) can only produce AOD retrieval in cloud clear conditions
- Therefore, the consistent model diagnostic to be validaded is

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

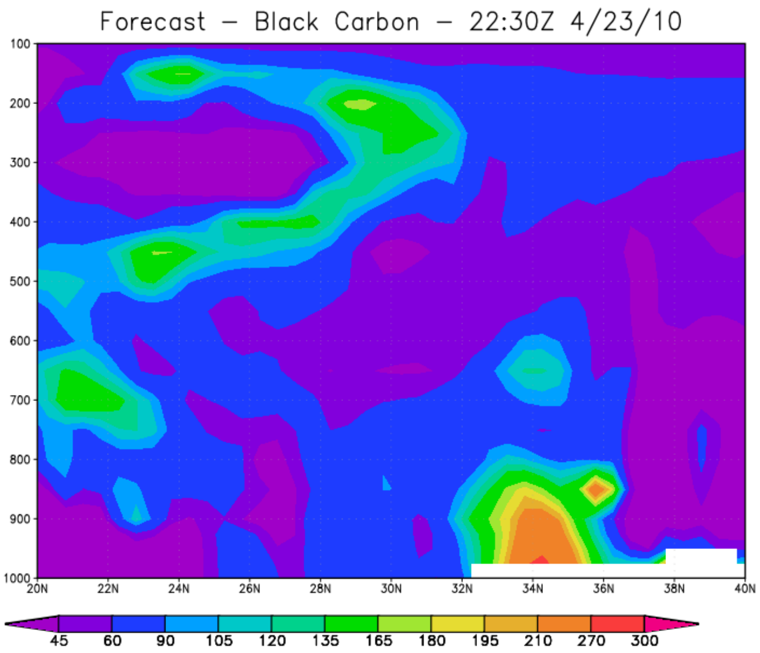
- Moreoer, the whole coulumn must be clear.

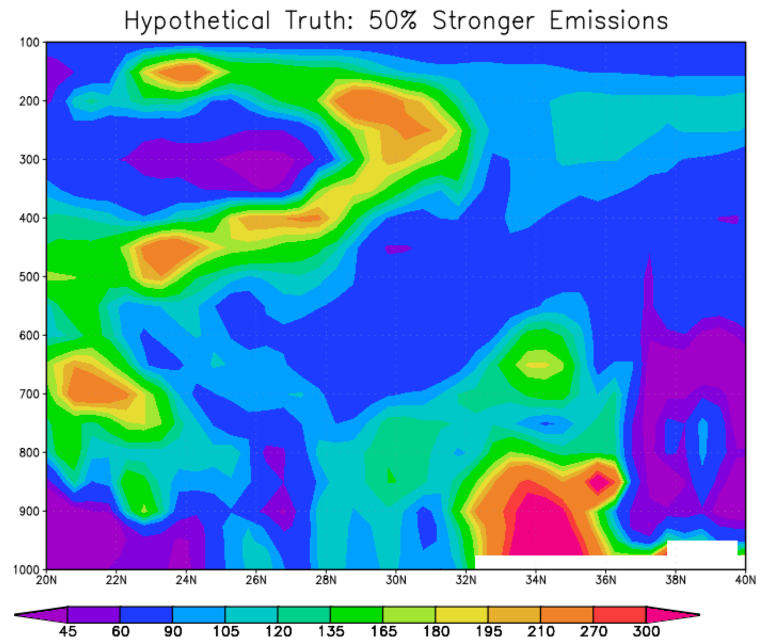
Humidification Factor: Sulfates

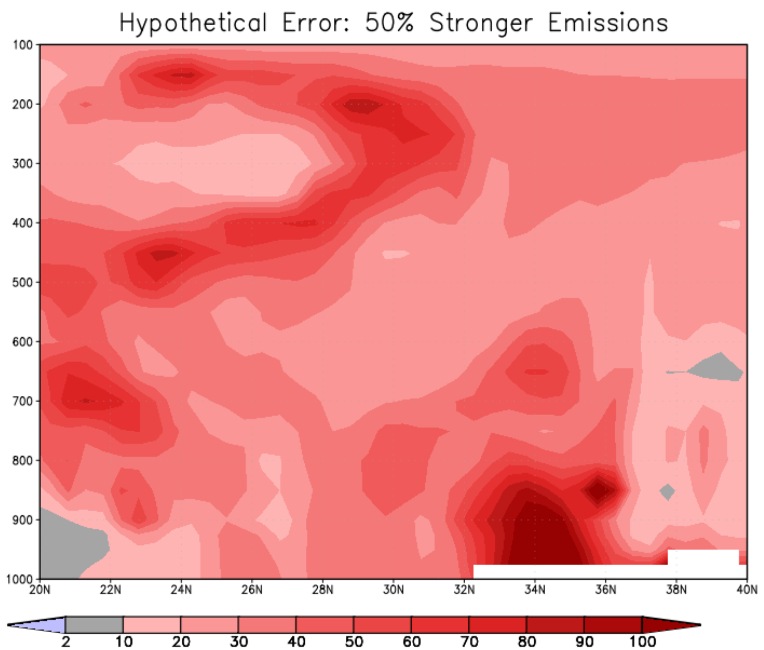


Forecast Error Characterization

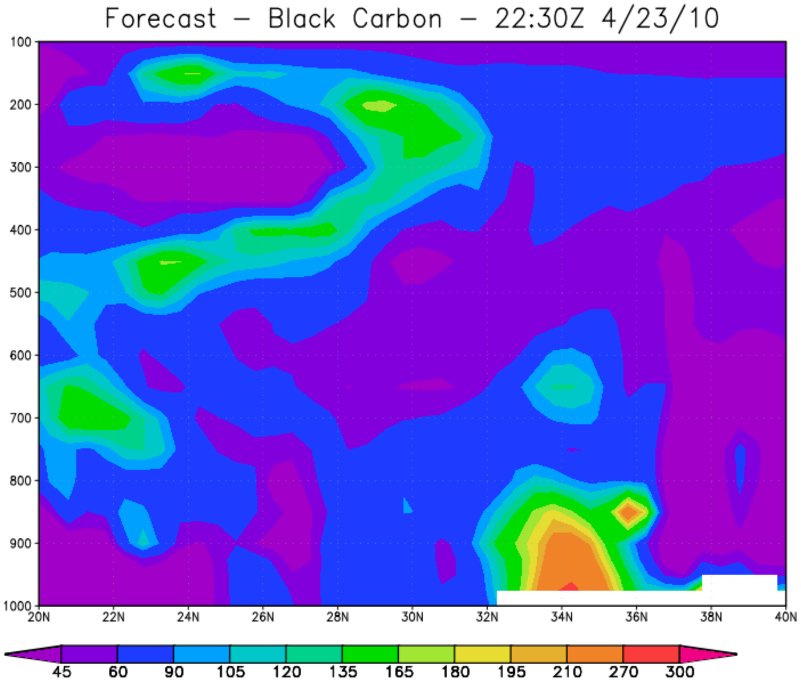
- Broadly speaking, the *background* error in aerosol concentration arises from
  - Deficiencies in emissions
  - Erroneous transport
  - Faulty parameterization of aerosol processes
  - Inaccurate initial conditions (e.g., wrong vertical distribution)
- While these errors are practically *unknowable*, physically-based modeling of these errors remain the only feasible alternative.

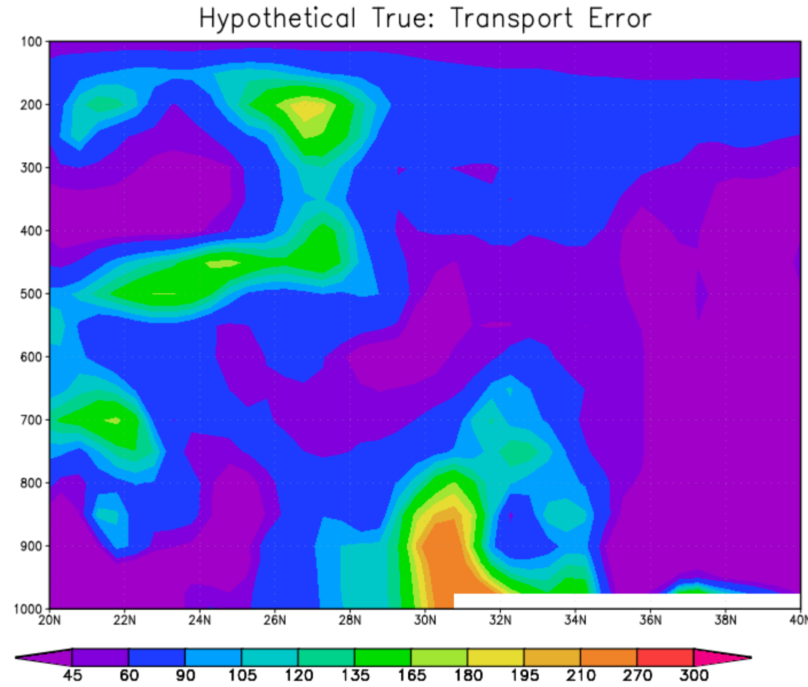


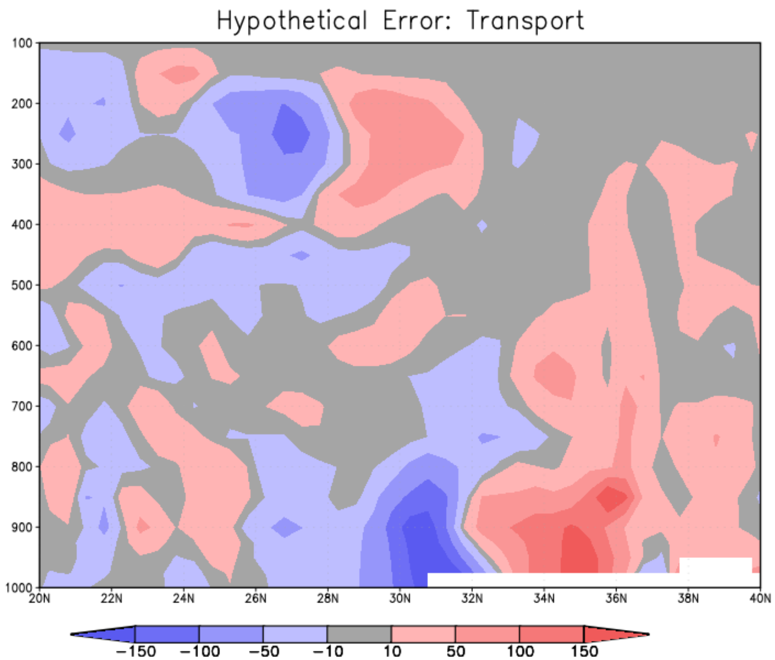




Uniform emission errors tend to have same vertical structure of *background.*







Transport errors tend not to have same vertical structure of *background.*

Clean-air measurements are critical.

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

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

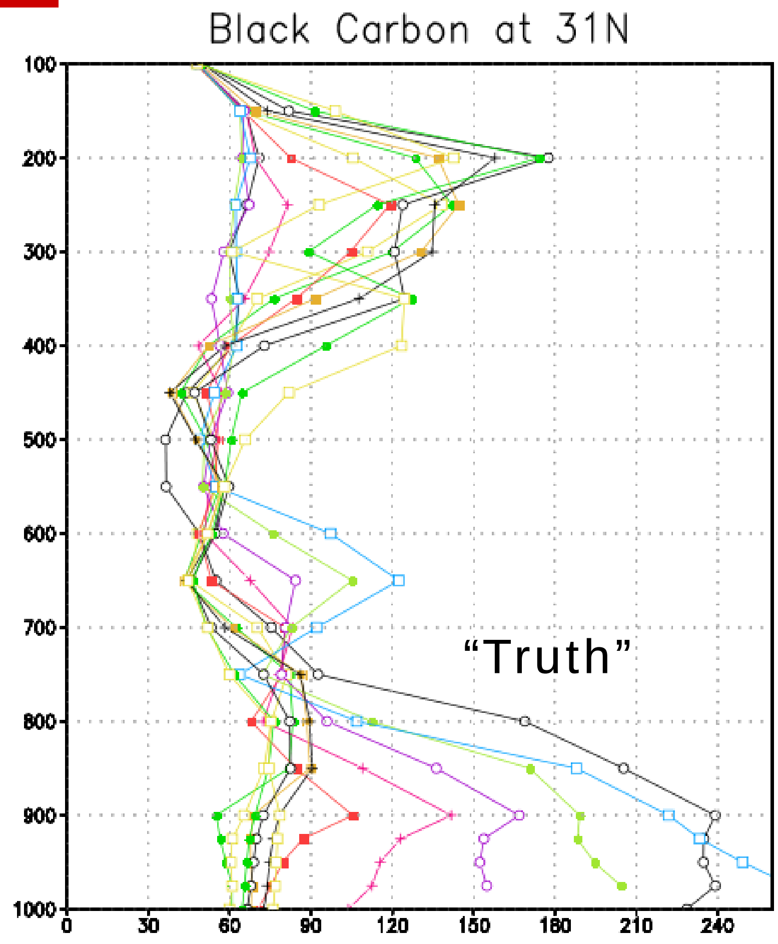
it follows that

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

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

Lagrangian 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



Sequential Bias Estimation

Dee and da Silva (1998) showed how to produce unbiased analysis when the forecast is biased.

The idea is to provide a running estimate of the bias to correct the forecast accordingly. The modified two-step algorithm is:

1. Forecast bias estimation:

$$b^f = b^f - L\left[w^o - (w^f - b^f)\right]$$

2. Unbiased analysis equation:

$$w^a = (w^f - b^f) + K\left[w^o - (w^f - b^f)\right]$$

AOD Background Error Specification

- Adaptive ML tuning for non-homogenous observing systems (Dee and da Silva 1999)
- Parameters:
  - Correlation length
  - Scalar gain: $\kappa = \sigma_f^2 / (\sigma_f^2 + \sigma_o^2)$
  - Innovation variance derived from sample statistics

In a nutshell...

- *Sequential Bias Estimation* is aimed at addressing systematic errors as those arising from faulty emissions/optical assumptions.

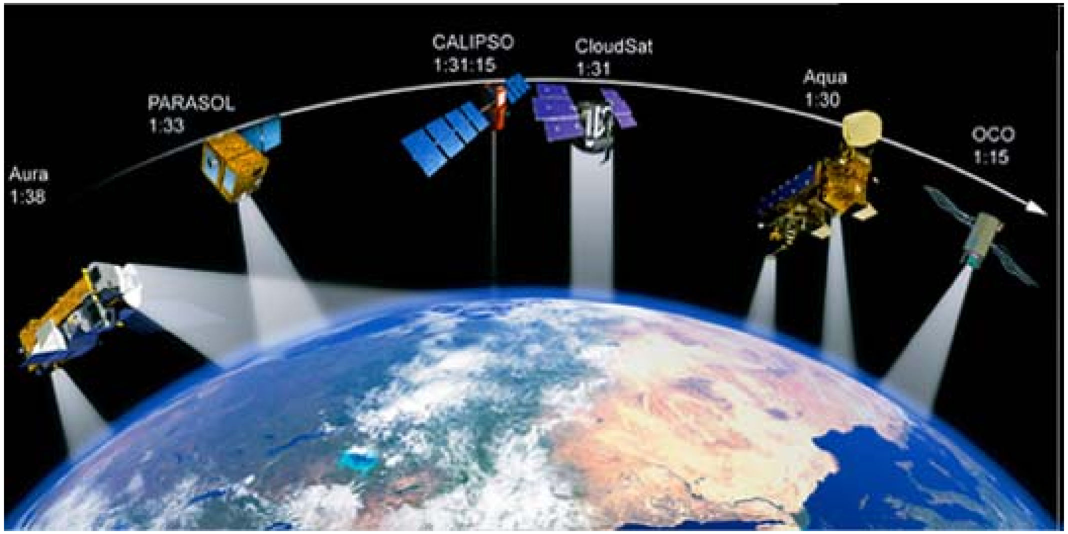
- AOD minimum variance analysis is aimed at taking care of the plume relocation problem.

Preliminary Results

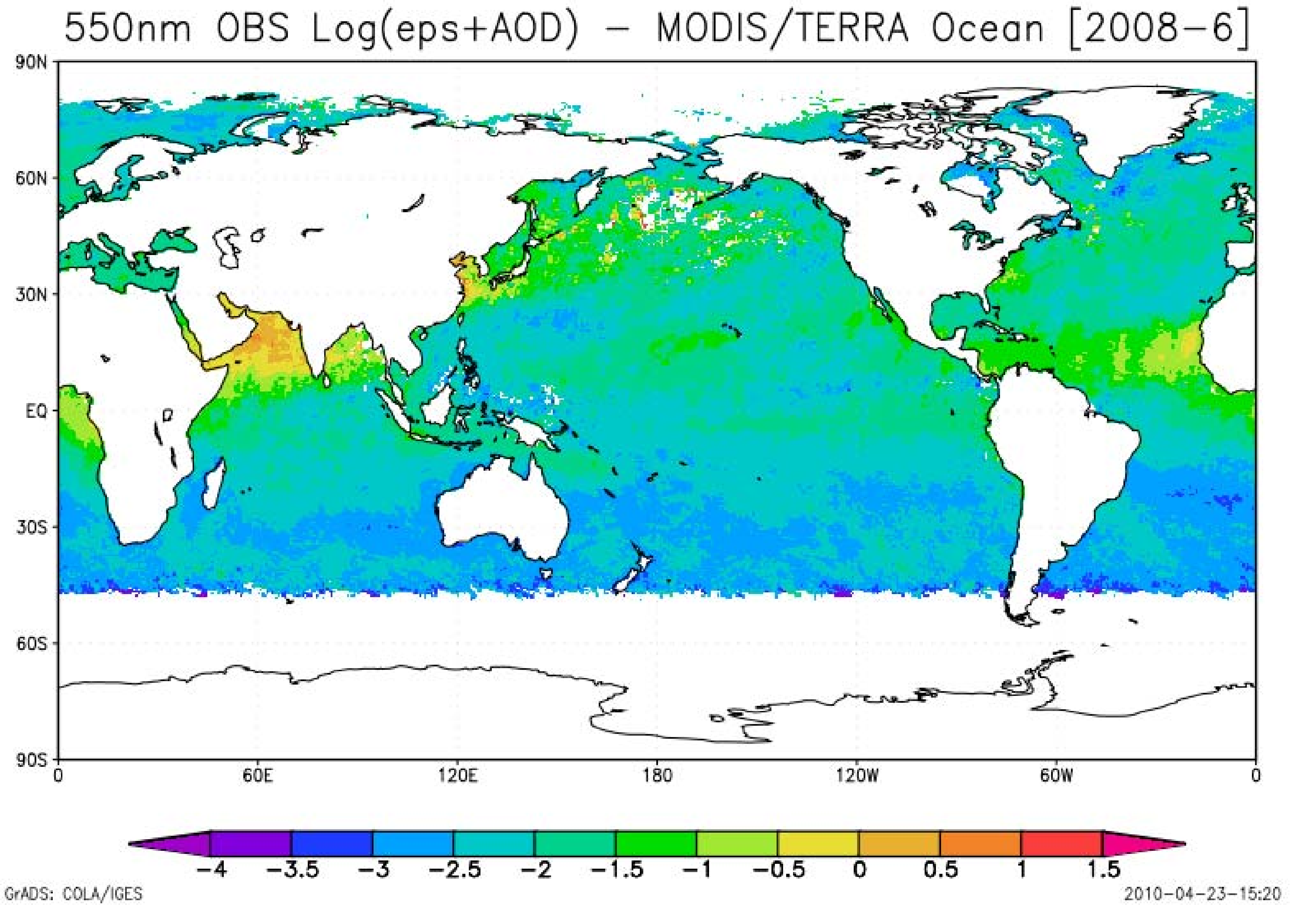
- Static AOD analysis for the ARCTAS period
  - March through August 2008
- Multi-channel:
  - 470nm, 550nm, 660nm, 870nm
- Main objectives:
  - Tune assimilation system without feedback issues
  - Diagnose homogeneity of observing system
  - Evaluate adaptive error covariance estimates
  - Examine effectiveness of LDE approach for generating 3D increments
  - Provide baseline for fully cycling system

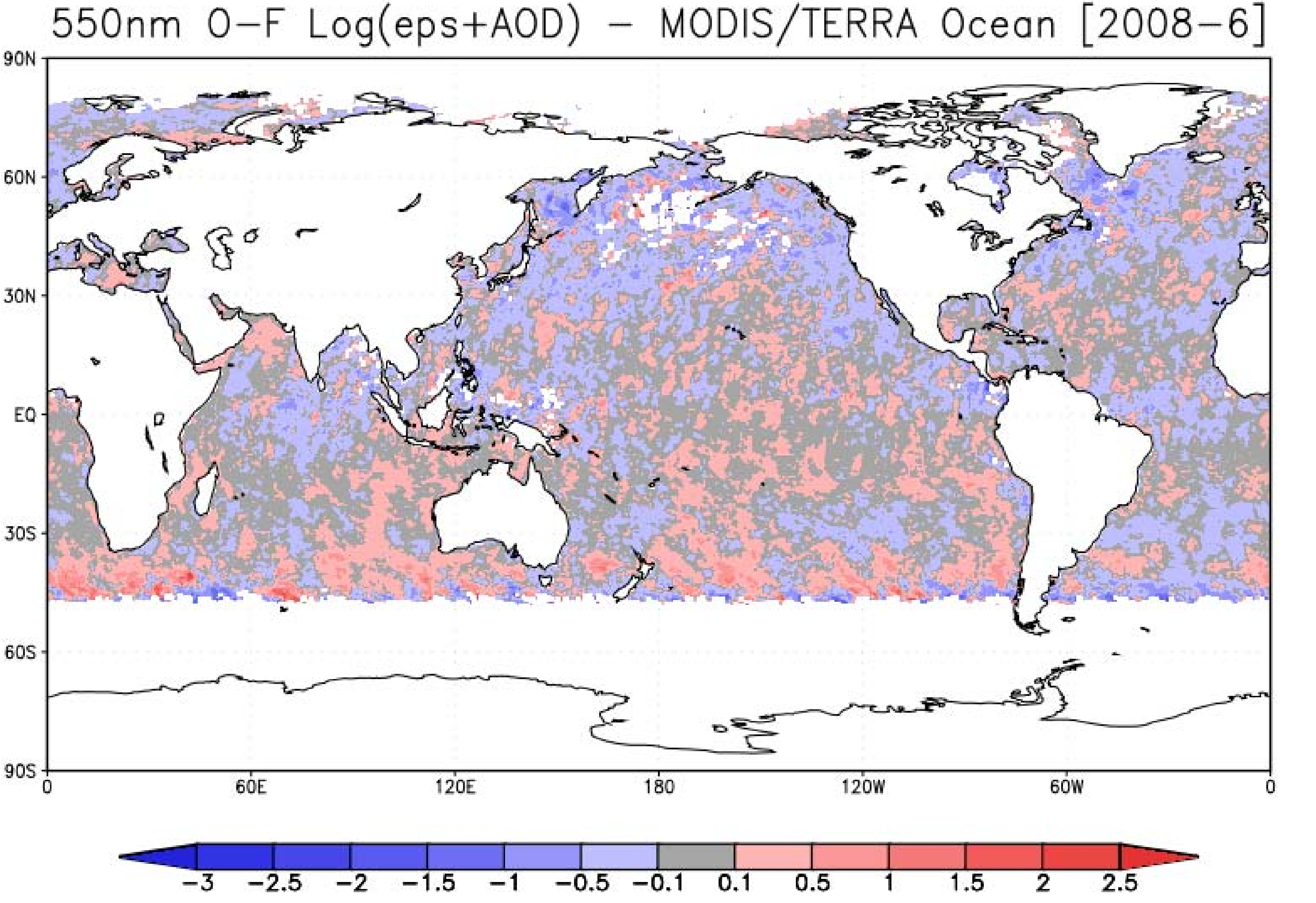
Data Sources

- AOD retrievals from:
  - MODIS
    - AQUA
    - TERRA
    - Land
    - Ocean
    - Deep-Blue
  - MISR
  - OMI
  - PARASOL
- Validation:
  - AERONET
  - PM 2.5
  - CALIPSO

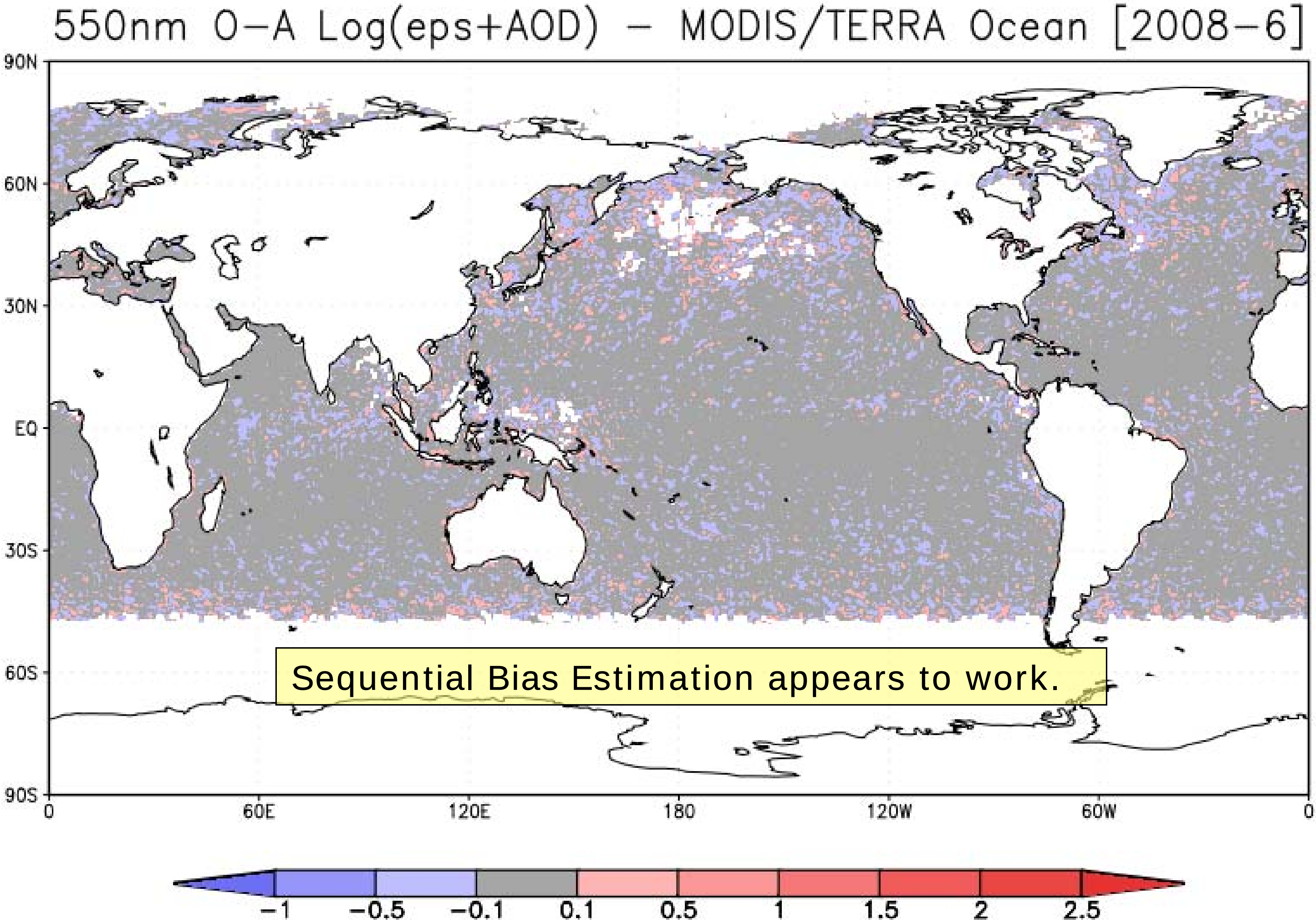


Passive data in BLUE

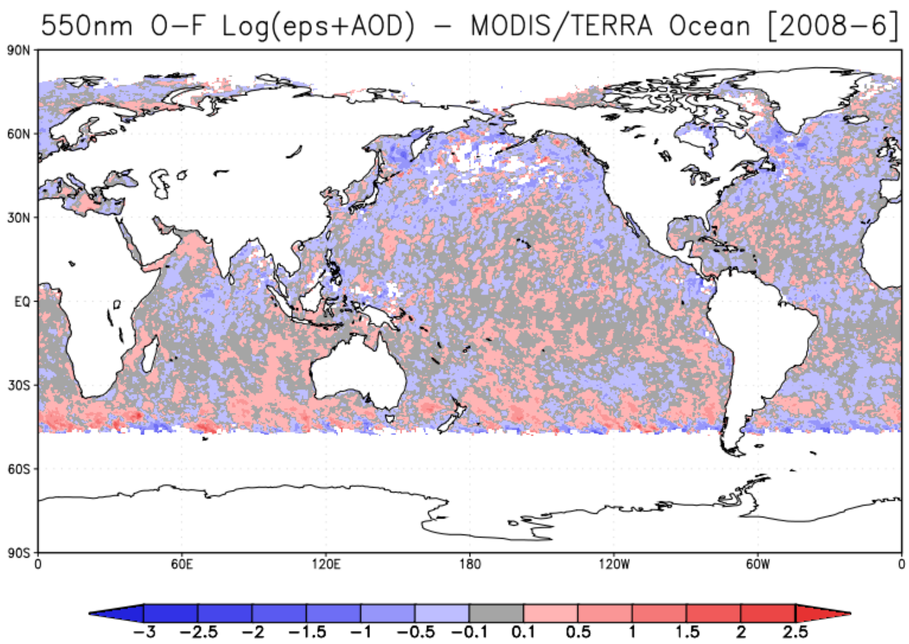

550nm OBS Log(eps+AOD) - MODIS/TERRA Ocean [2008-6]
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
GrADS: COLA/IGES
2010-04-23-15:20

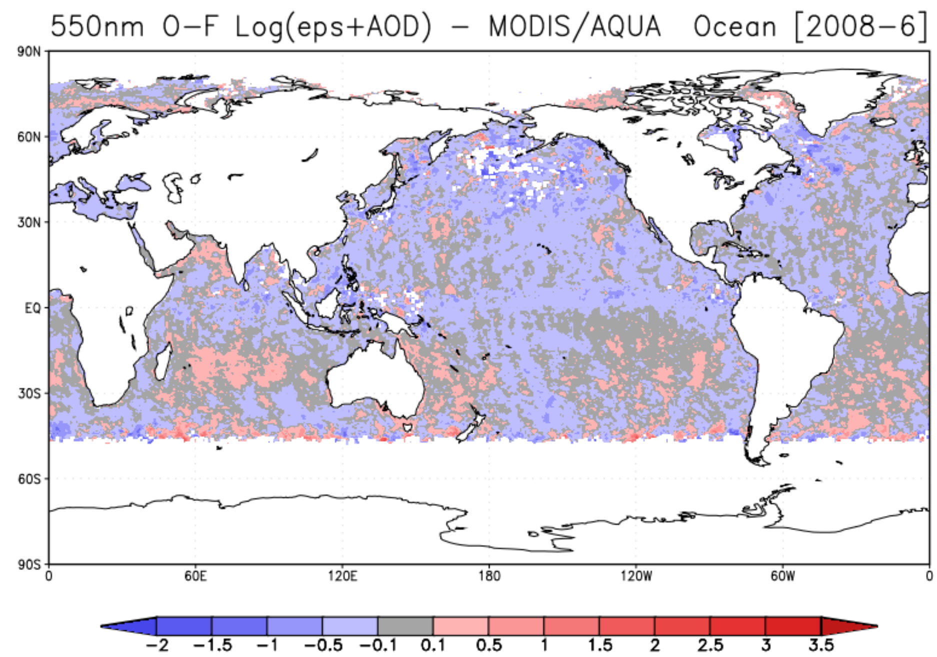


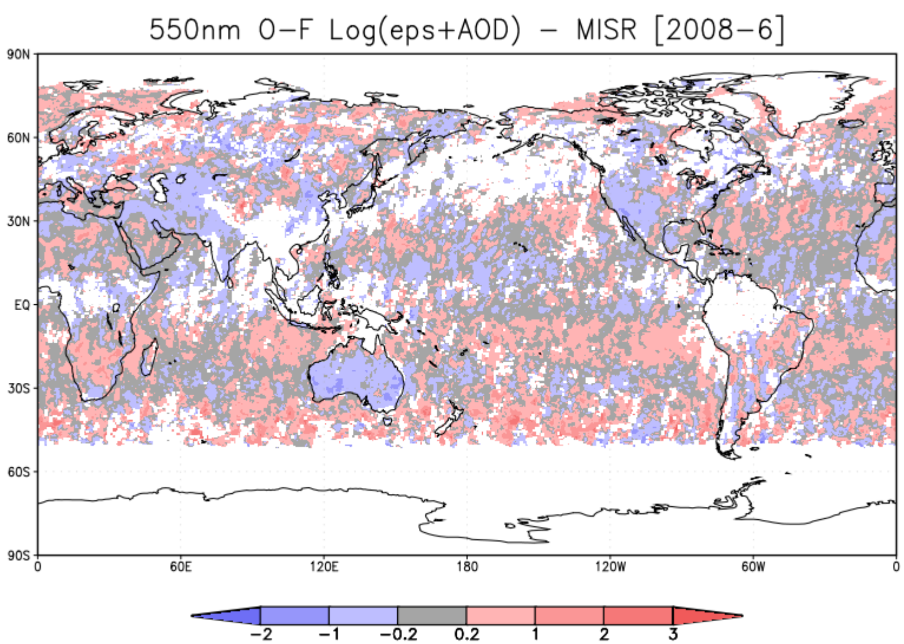
550nm O-F Log(eps+AOD) - MODIS/TERRA Ocean [2008-6]
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
-3
-2.5
-2
-1.5
-1
-0.5
-0.1
0.1
0.5
1
1.5
2
2.5



Sequential Bias Estimation appears to work.

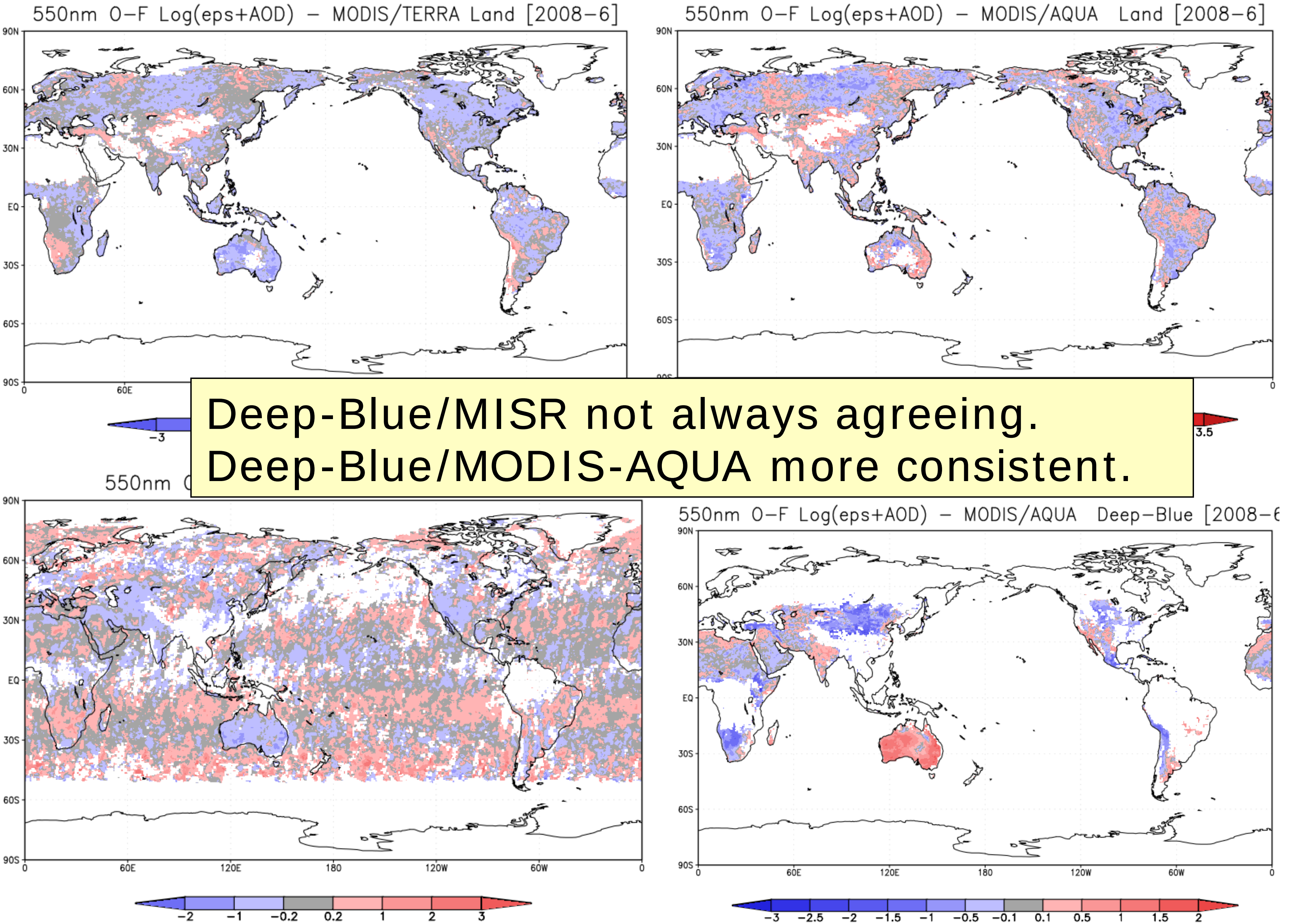


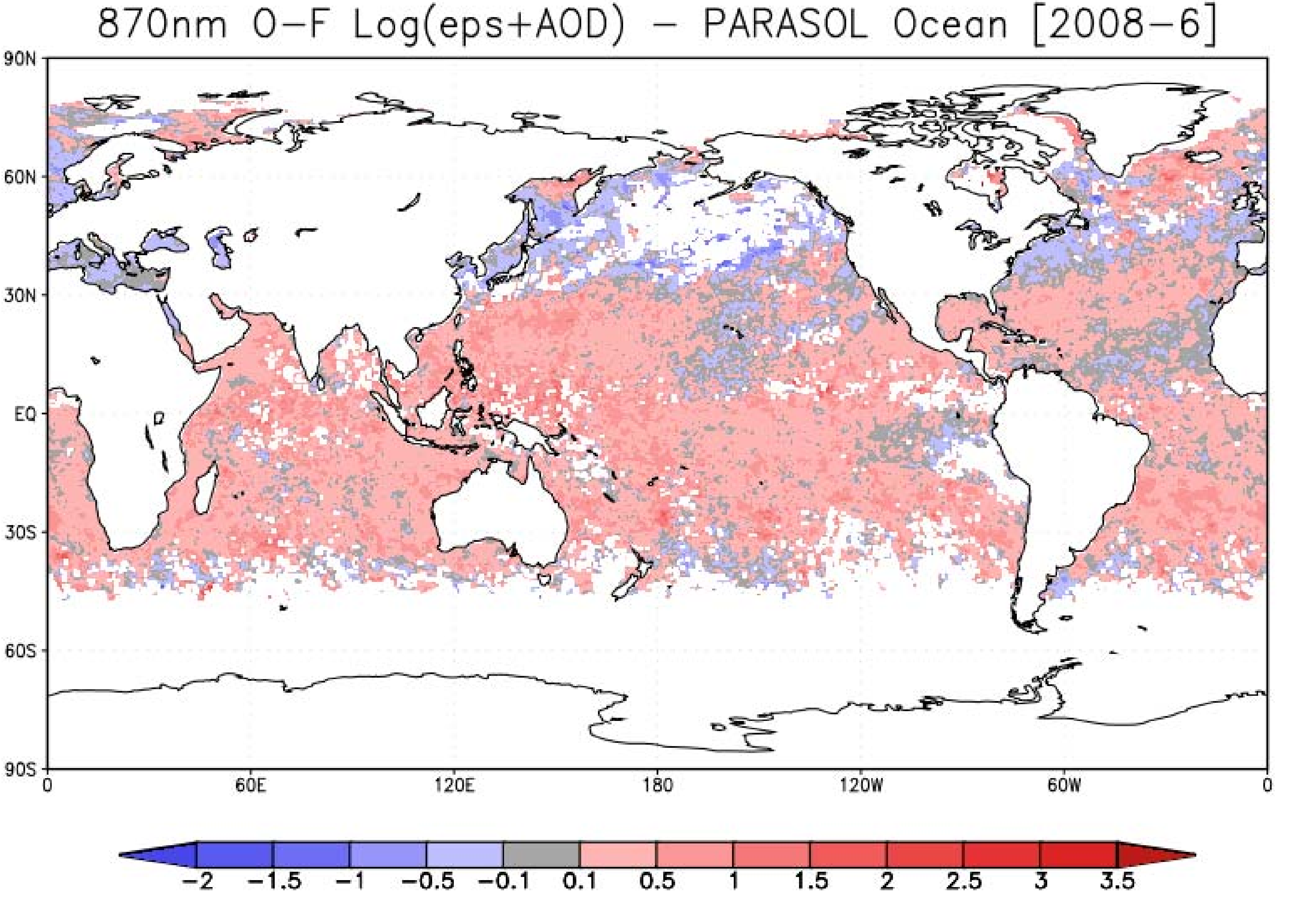




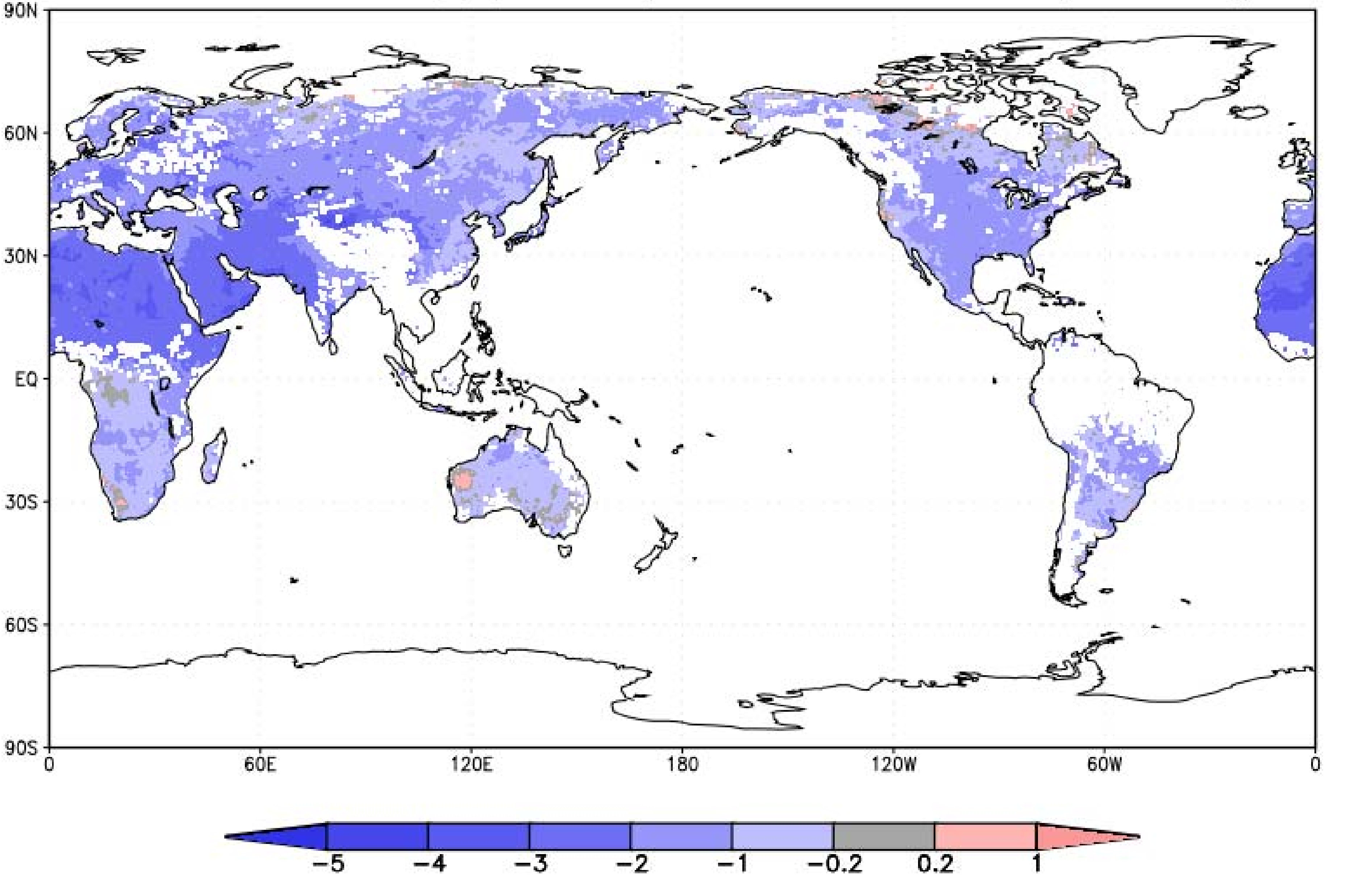
Better consistency between TERRA instruments.

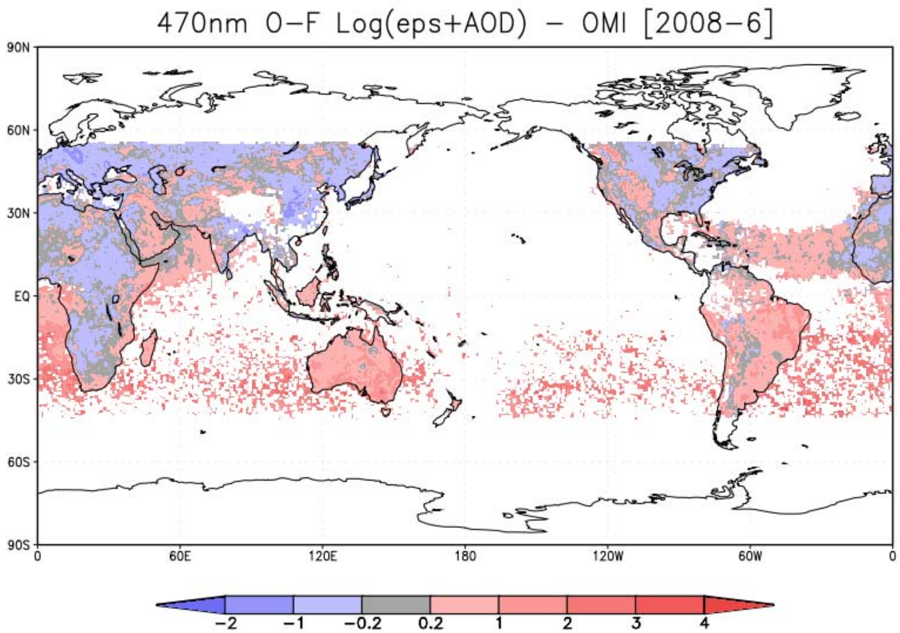
Deep-Blue/MISR not always agreeing.
Deep-Blue/MODIS-AQUA more consistent.

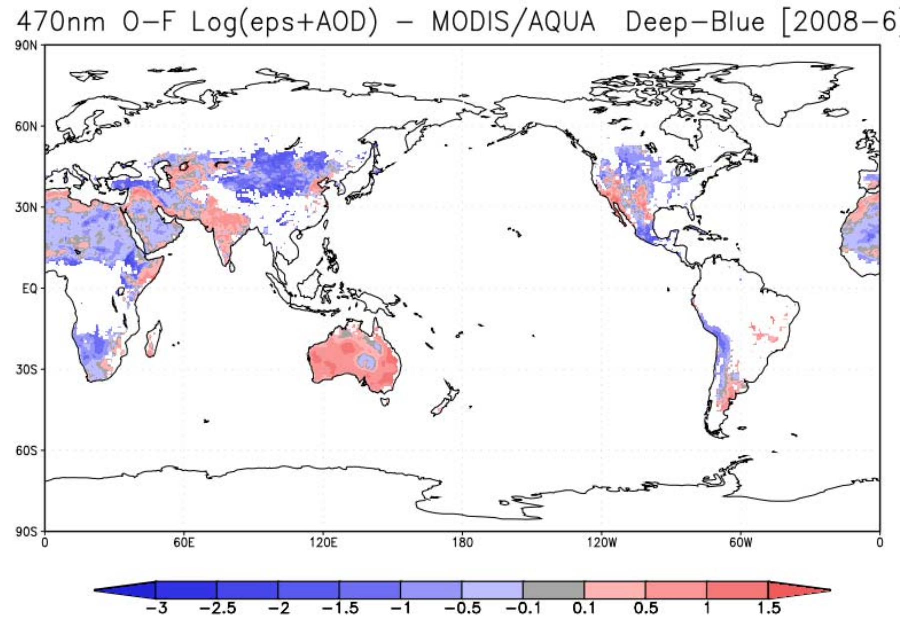


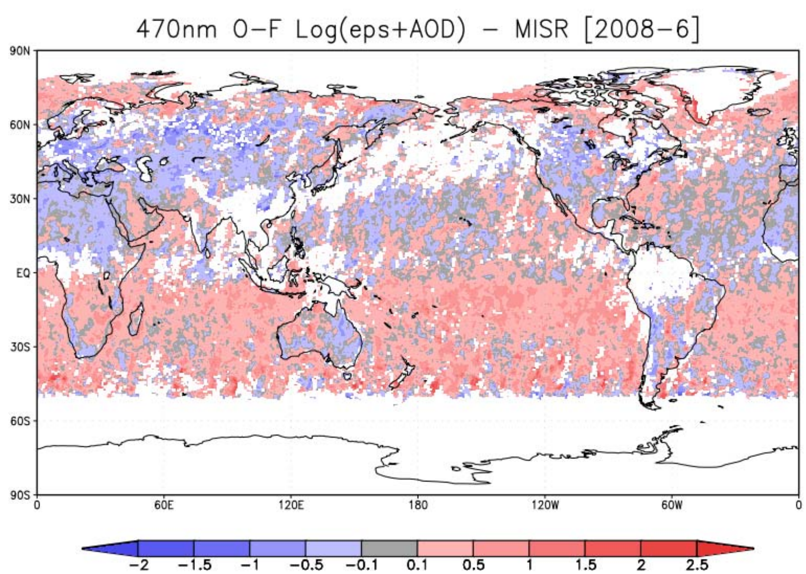

870nm O-F Log(eps+AOD) - PARASOL Ocean [2008-6]
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
-2
-1.5
-1
-0.5
-0.1
0.1
0.5
1
1.5
2
2.5
3
3.5

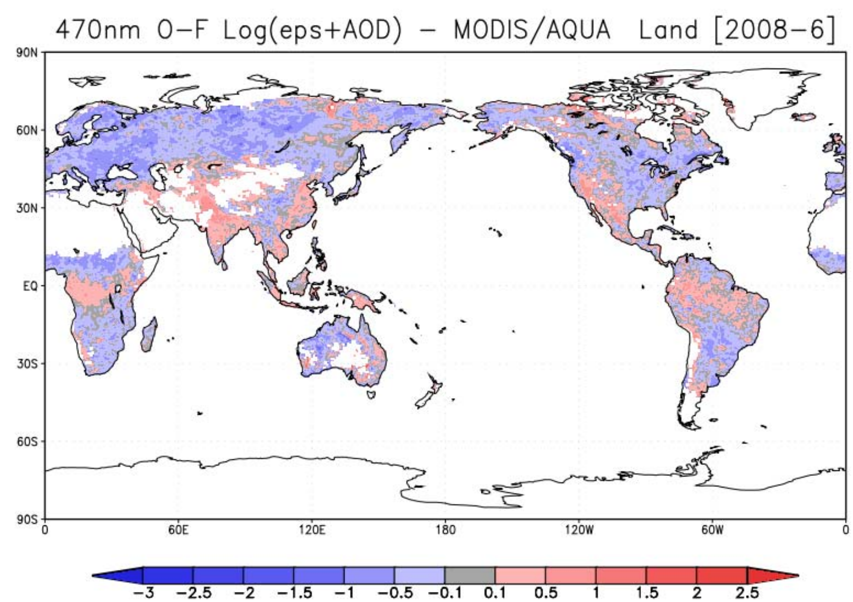
870nm O-F Log(eps+AOD) - PARASOL Land [2008-6]



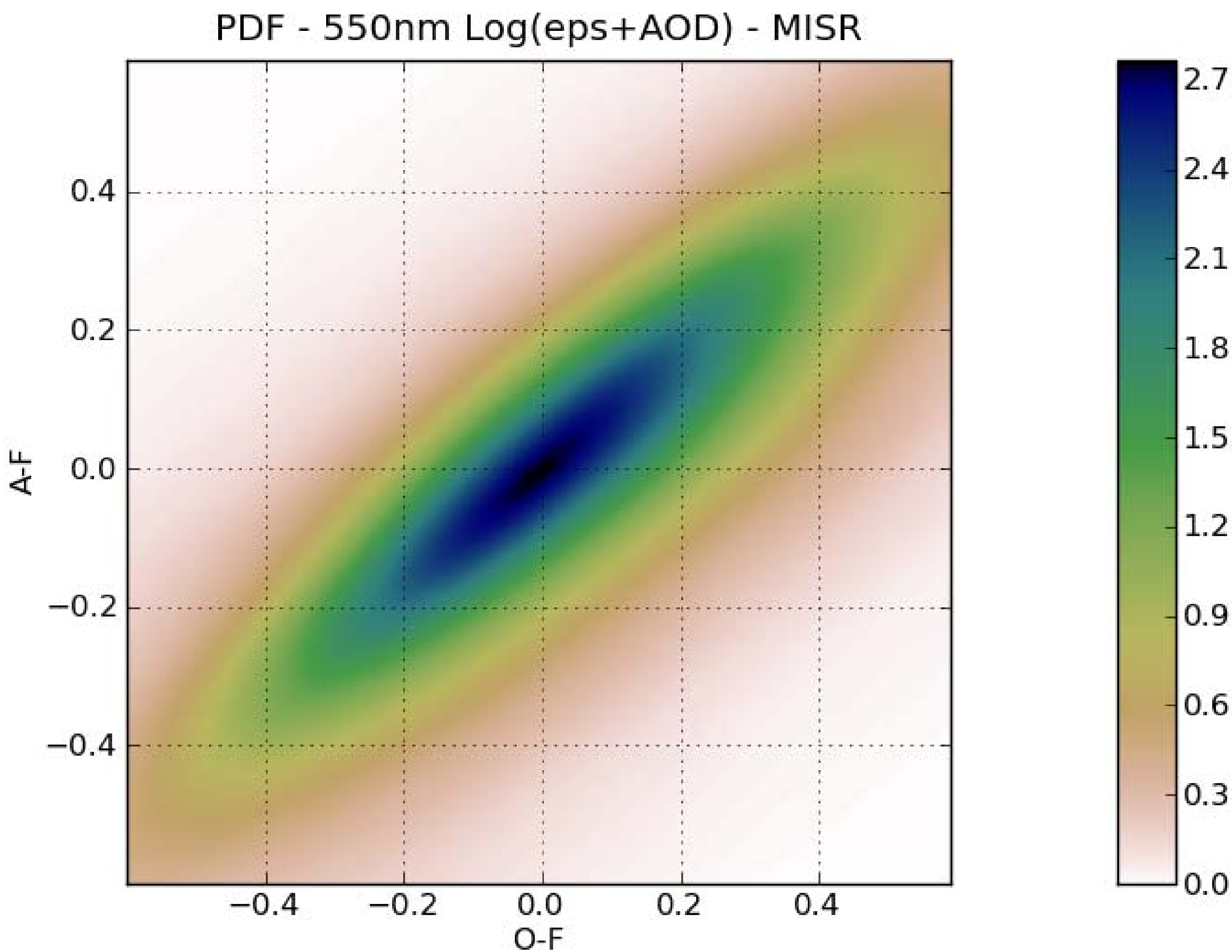

470nm O-F Log(eps+AOD) - OMI [2008-6]
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
-2
-1
-0.2
0.2
1
2
3
4


470nm O-F Log(eps+AOD) - MODIS/AQUA Deep-Blue [2008-6]
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
-3
-2.5
-2
-1.5
-1
-0.5
-0.1
0.1
0.5
1
1.5

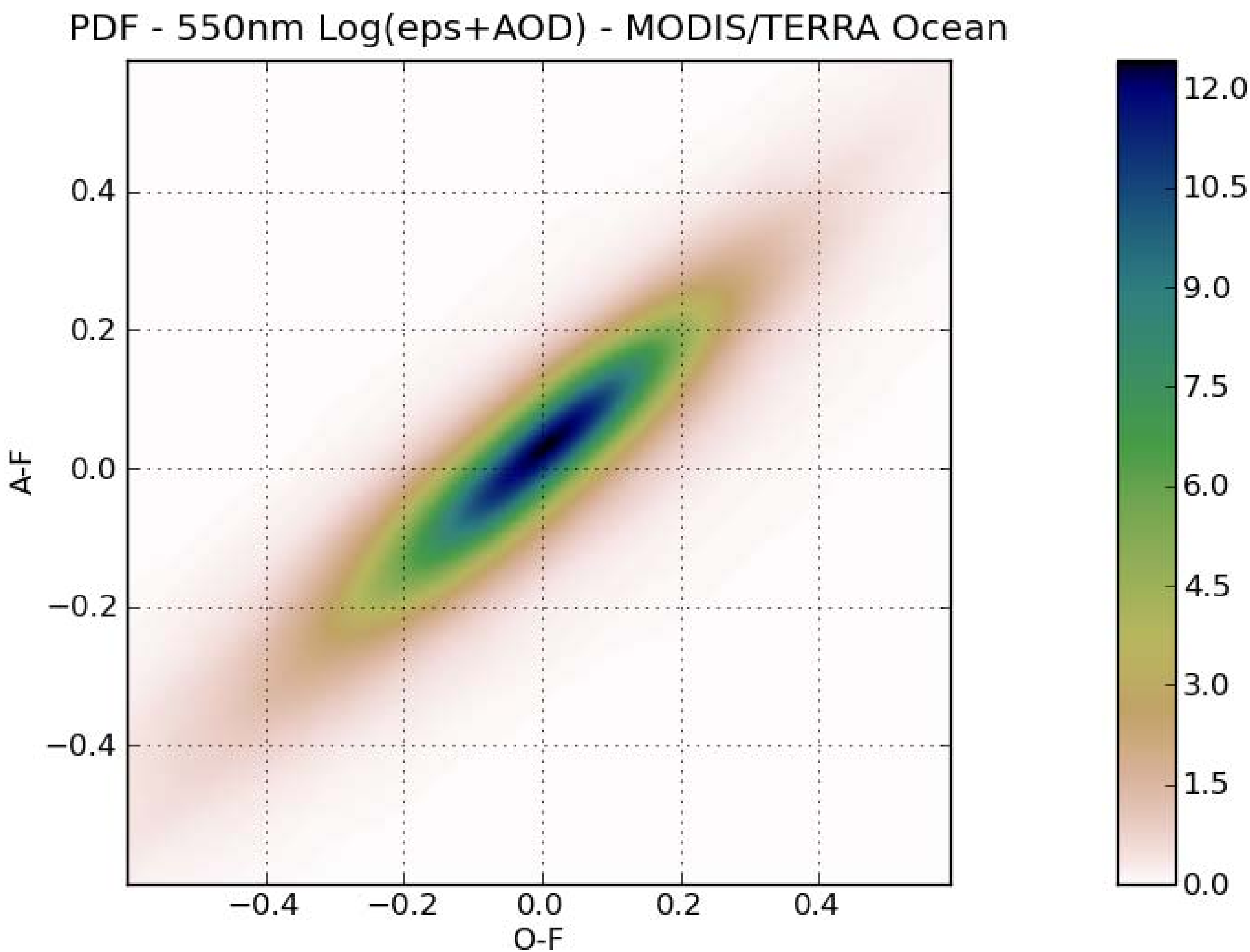

470nm O-F Log(eps+AOD) - MISR [2008-6]
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
-2
-1.5
-1
-0.5
-0.1
0.1
0.5
1
1.5
2
2.5

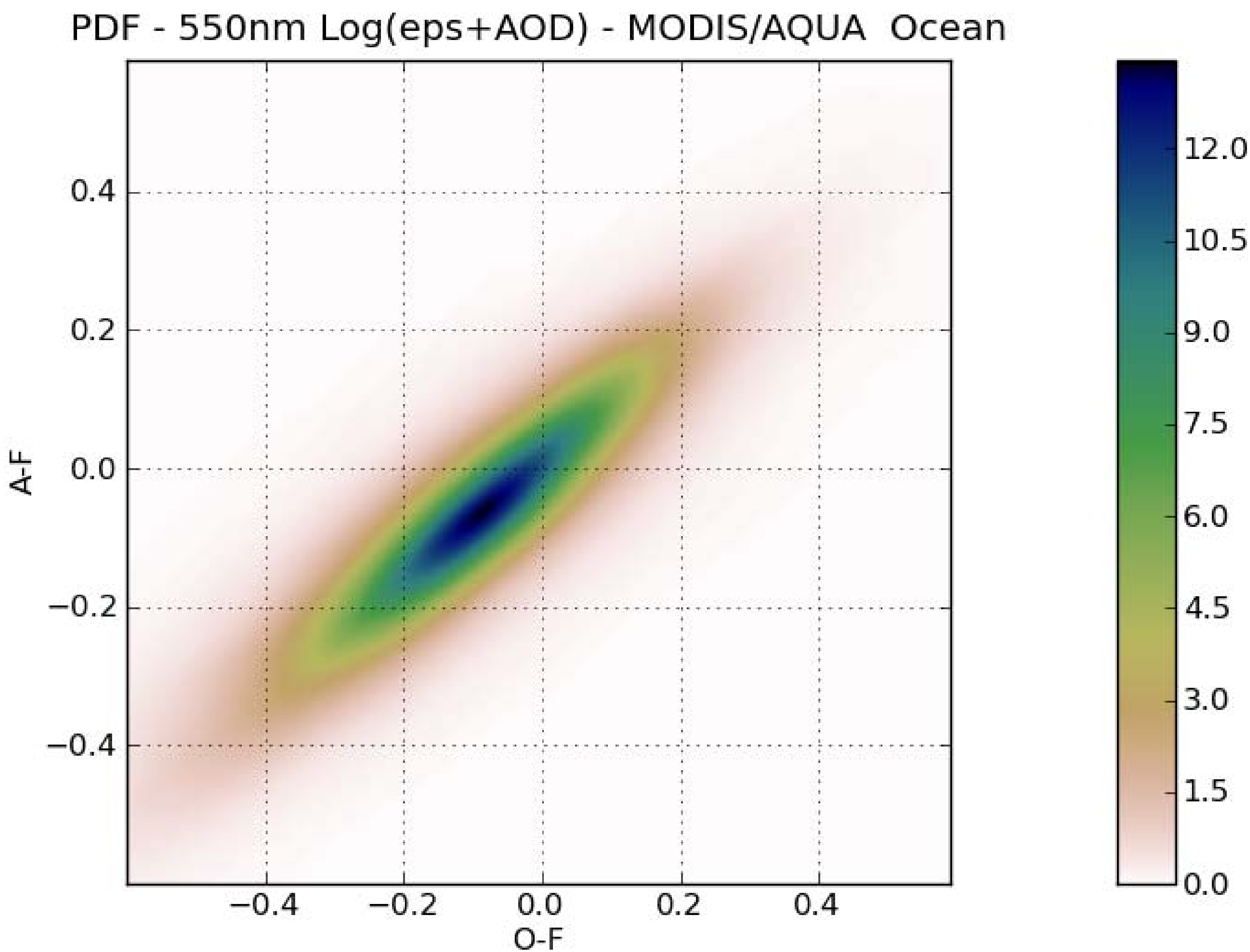

470nm O-F Log(eps+AOD) - MODIS/AQUA Land [2008-6]
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
-3
-2.5
-2
-1.5
-1
-0.5
-0.1
0.1
0.5
1
1.5
2
2.5

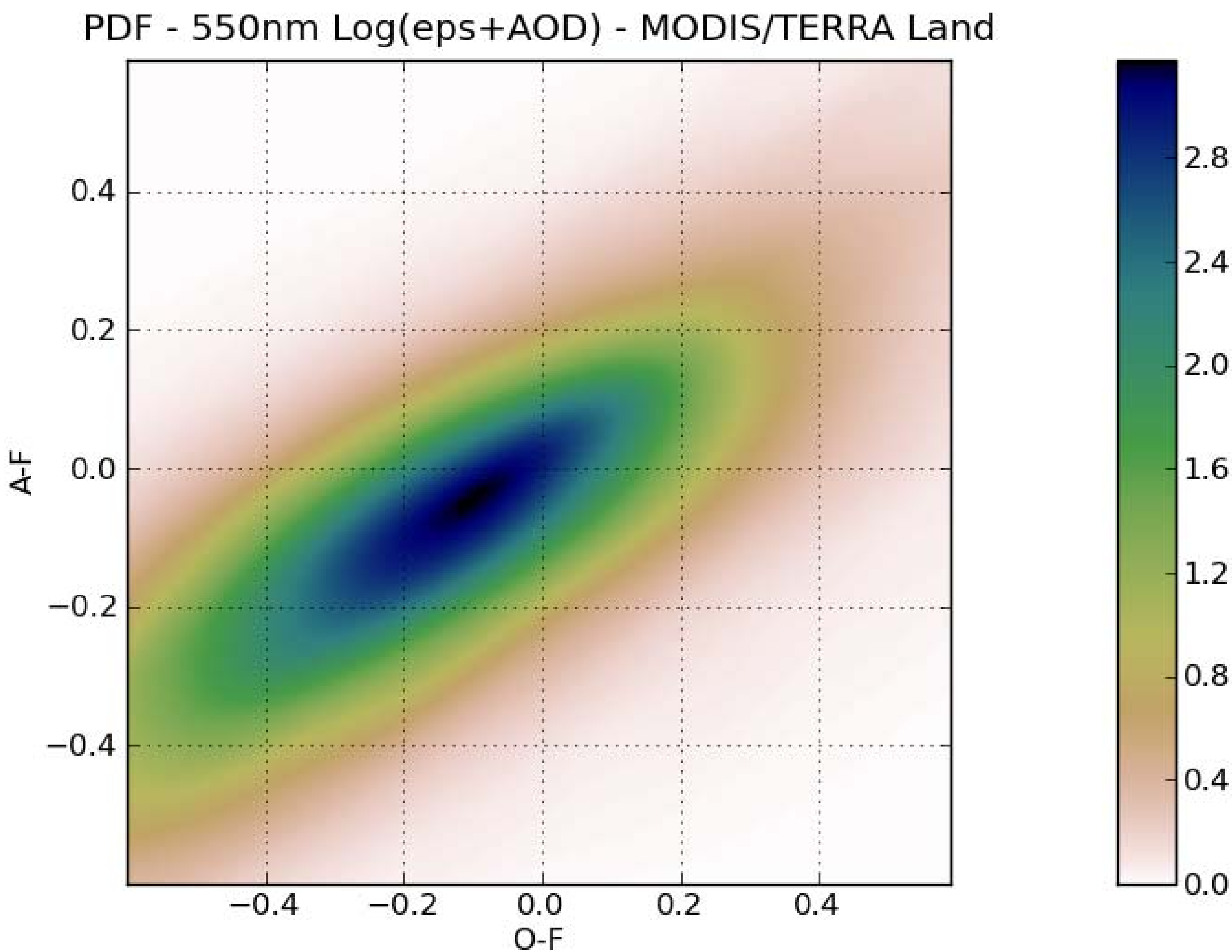
Contextual Bias

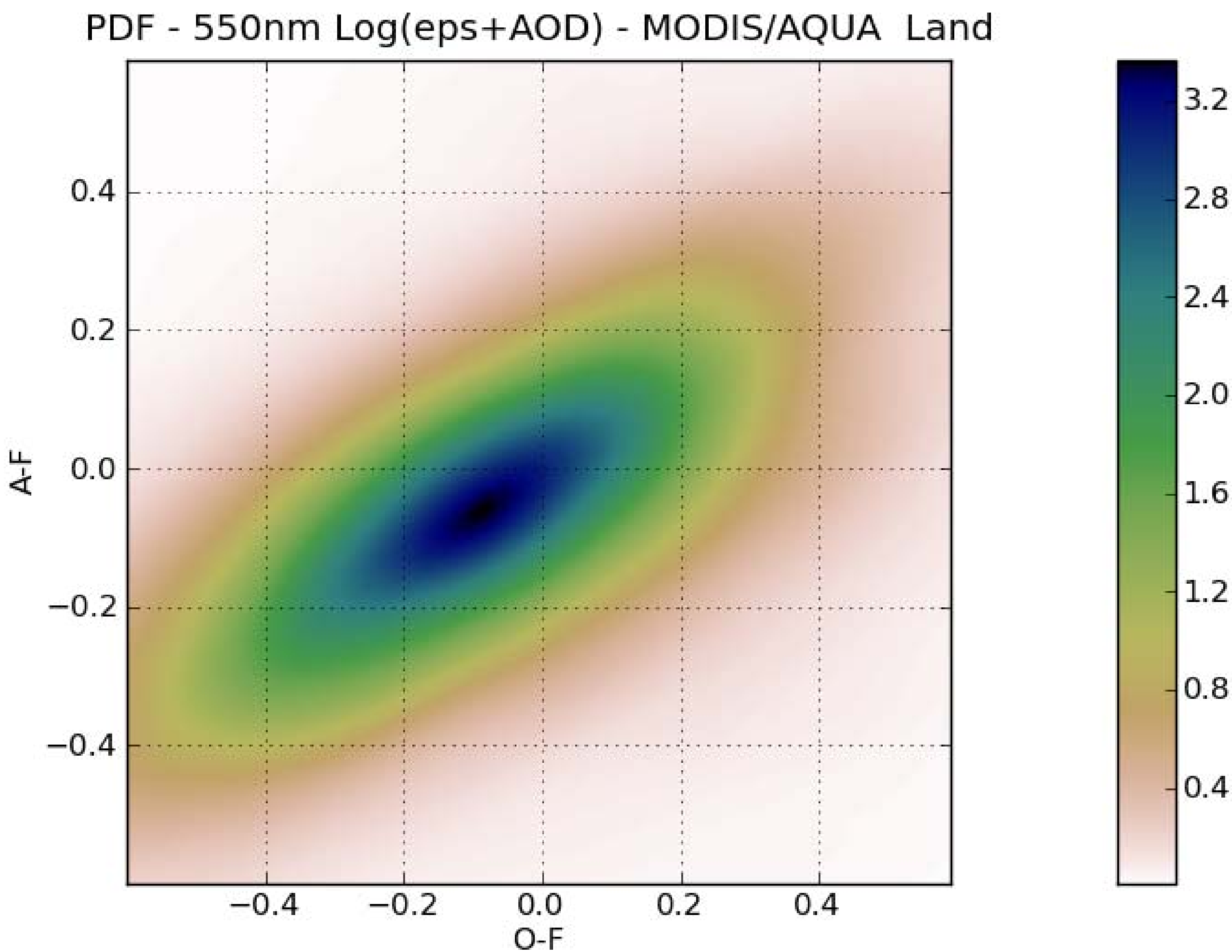


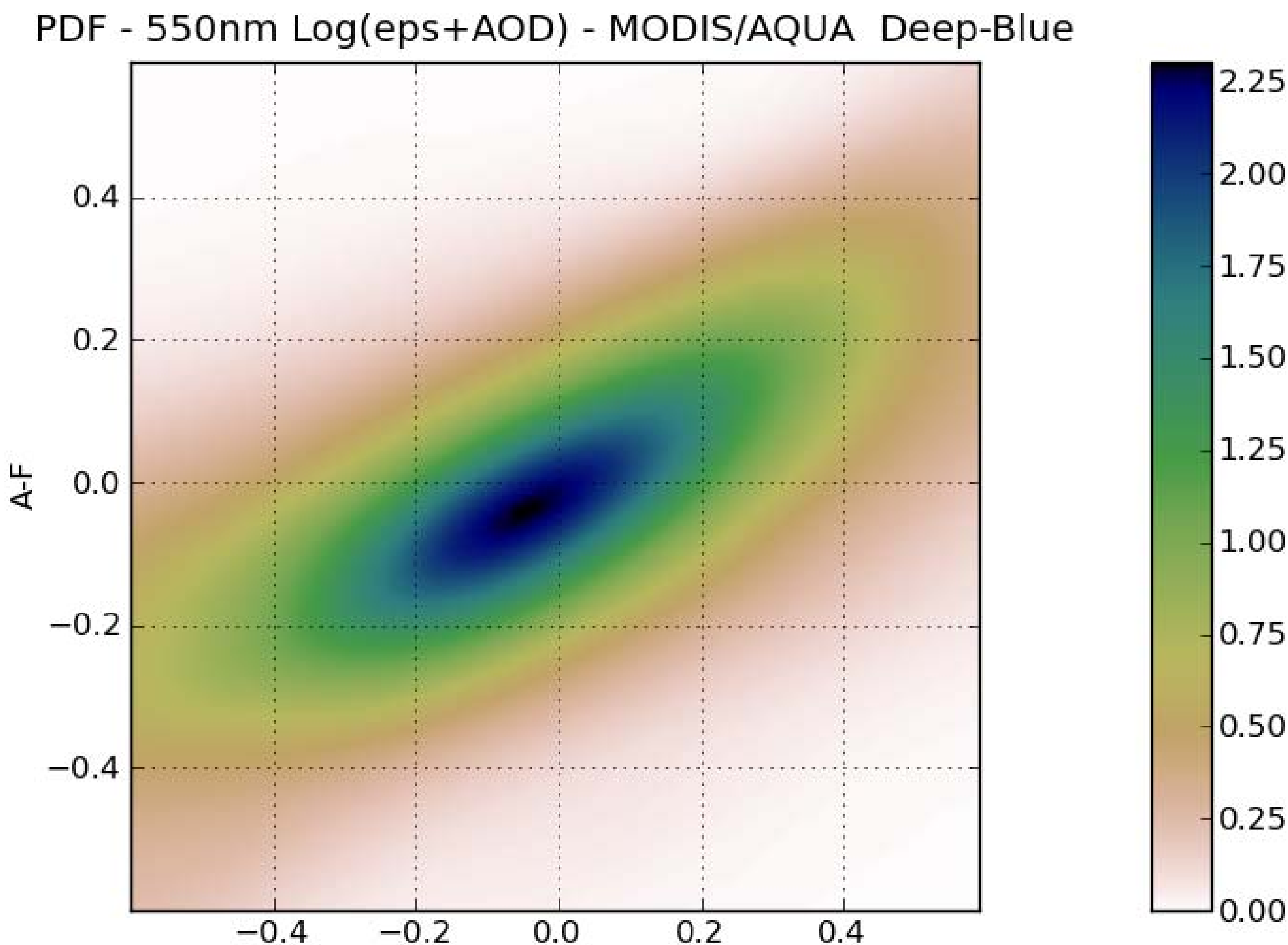
PDF - 550nm Log(eps+AOD) - MISR
A-F
O-F
0.4
0.2
0.0
−0.2
−0.4
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0


PDF - 550nm Log(eps+AOD) - MODIS/TERRA Ocean
A-F
O-F
0.4
0.2
0.0
−0.2
−0.4
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0

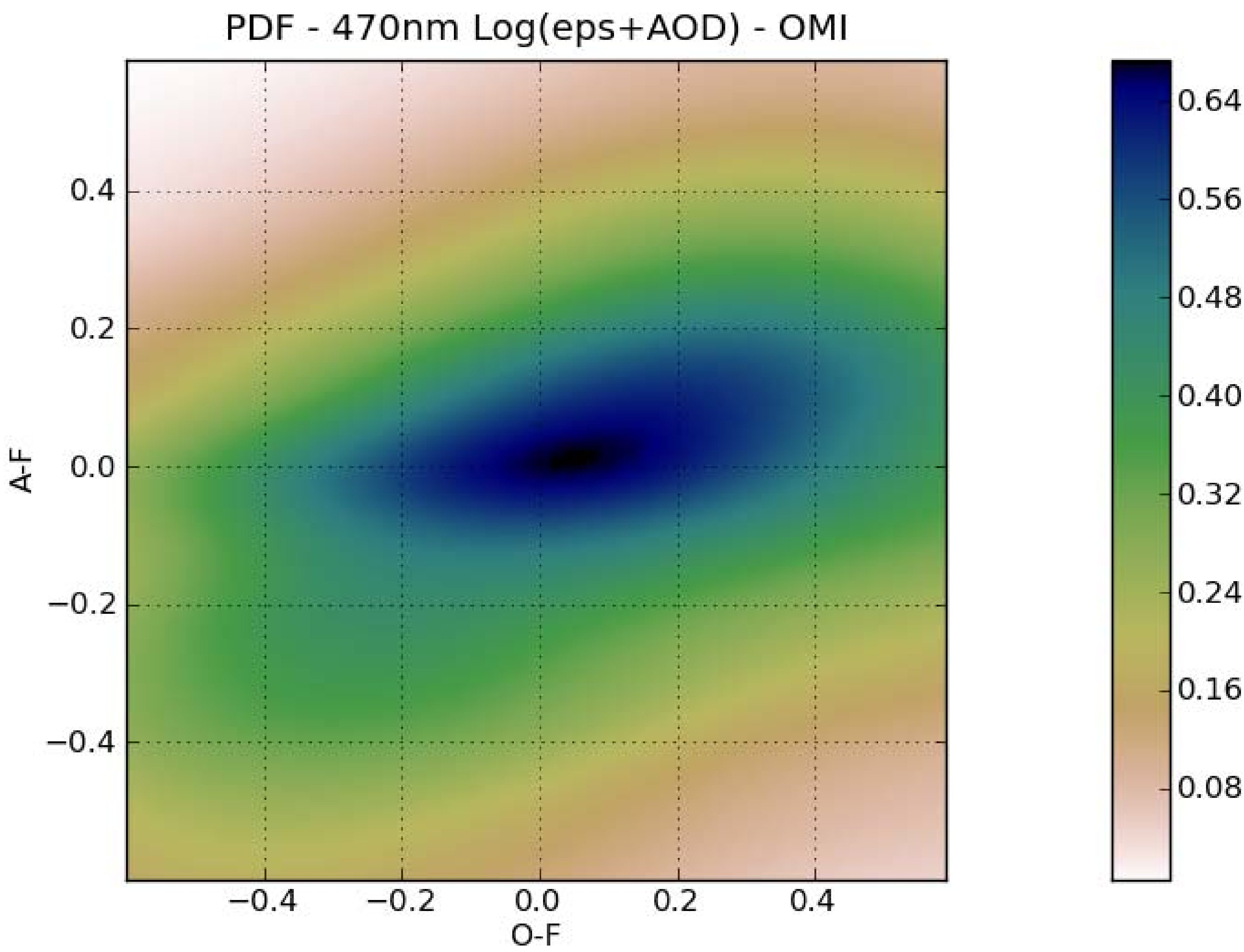

PDF - 550nm Log(eps+AOD) - MODIS/AQUA Ocean
A-F
O-F
0.4
0.2
0.0
−0.2
−0.4
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0

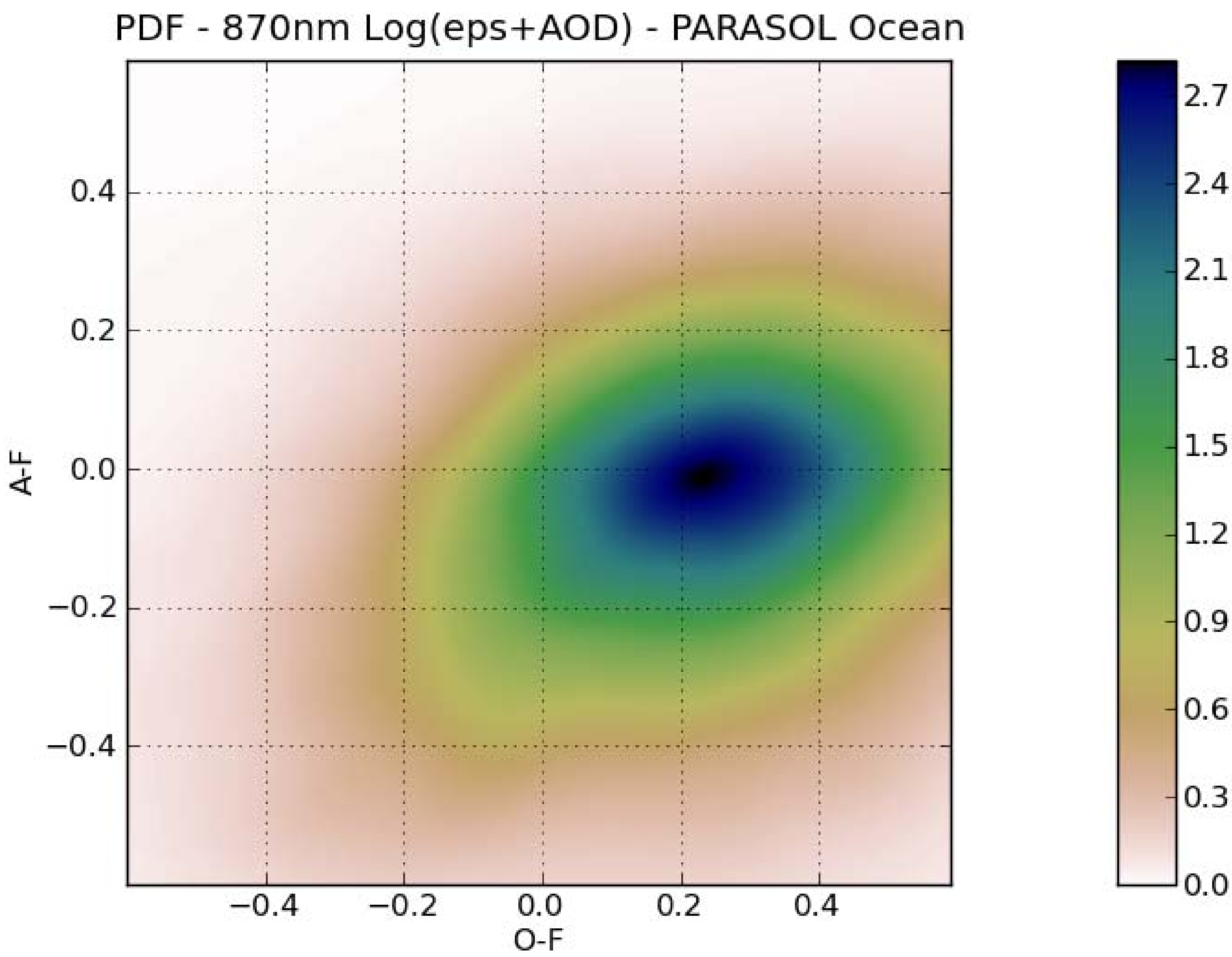

PDF - 550nm Log(eps+AOD) - MODIS/TERRA Land
A-F
O-F
0.4
0.2
0.0
−0.2
−0.4
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0

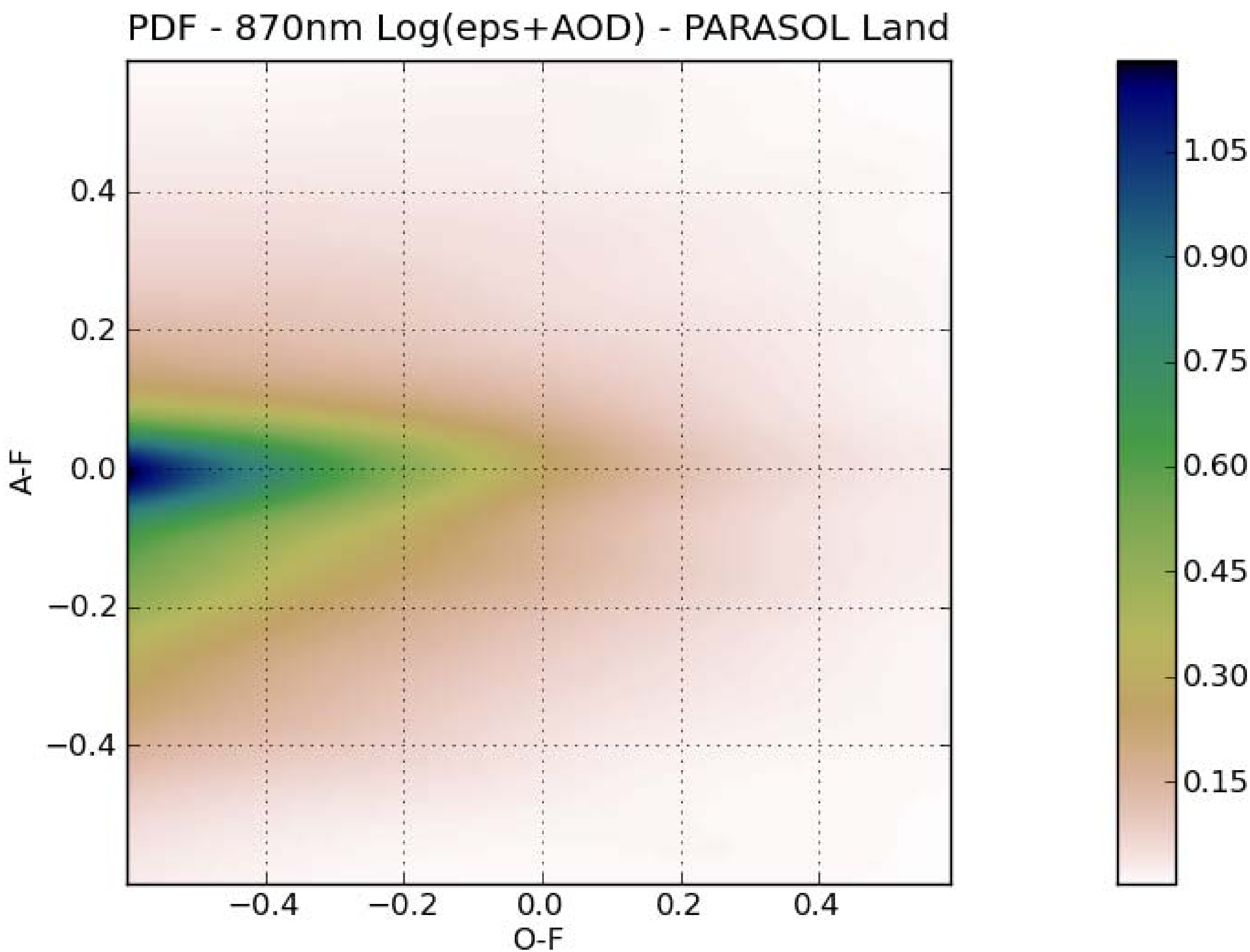

PDF - 550nm Log(eps+AOD) - MODIS/AQUA Land
0.4
0.2
0.0
−0.2
−0.4
A-F
−0.4
−0.2
0.0
0.2
0.4
O-F
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4



PDF - 550nm Log(eps+AOD) - MODIS/AQUA Deep-Blue
A-F
O-F
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00


PDF - 470nm Log(eps+AOD) - OMI
A-F
O-F
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
0.64
0.56
0.48
0.40
0.32
0.24
0.16
0.08


PDF - 870nm Log(eps+AOD) - PARASOL Ocean
A-F
O-F
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0


PDF - 870nm Log(eps+AOD) - PARASOL Land
A-F
O-F
0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
1.05
0.90
0.75
0.60
0.45
0.30
0.15

Observing System Summary

- Even without empirical corrections, MODIS and MISR show a good degree of consistency
  - More agreement between AM, PM satellites
  - Deep-blue not always agreeing with others, specially over Australia
- Despite cloud contamination, OMI AOD retrievals have improved
  - Absorption AOD is a more unique feature
- PARASOL not quite ready for prime time

Issues for Discussion

- For data assimilation, *clean air* observations is just as important as cases of high aerosol loading.
- Satellite aerosol observations suffer from *Fair Weather Bias*
  - Sub-grid variability needed for observation operator
- Radiance assimilation has the potential for
  - Ensuring consistency of optical properties
  - Ensuring spatial/temporal consistency of aerosol optical models
  - Easier observation error modeling