
# Overview of the MERRA Aerosol Reanalysis:
## *Toward and Integrated Earth System Analysis*

Arlindo da Silva[1]
Arlindo.daSilva@nasa.gov

Peter Colarco[2] , Anton Darmenov[1,5], Virginie Buchard-Marchant[1,3], Cynthia Randles[2,3], Ravi Govindaradju[1,5]

*(1) Global Modeling and Assimilation Office, NASA/GSFC*
*(2) Atmospheric Chemistry and Dynamics Branch, NASA/GSFC*
*(3) GESTAR/Morgan State University*
*(4) GESTAR/USRA*
*(5) Science Systems and Applications, Inc.*

*4th WCRP International Conference on Reanalyses*
*7-11 May 2012, Silver Spring, Maryland USA*

# Outline

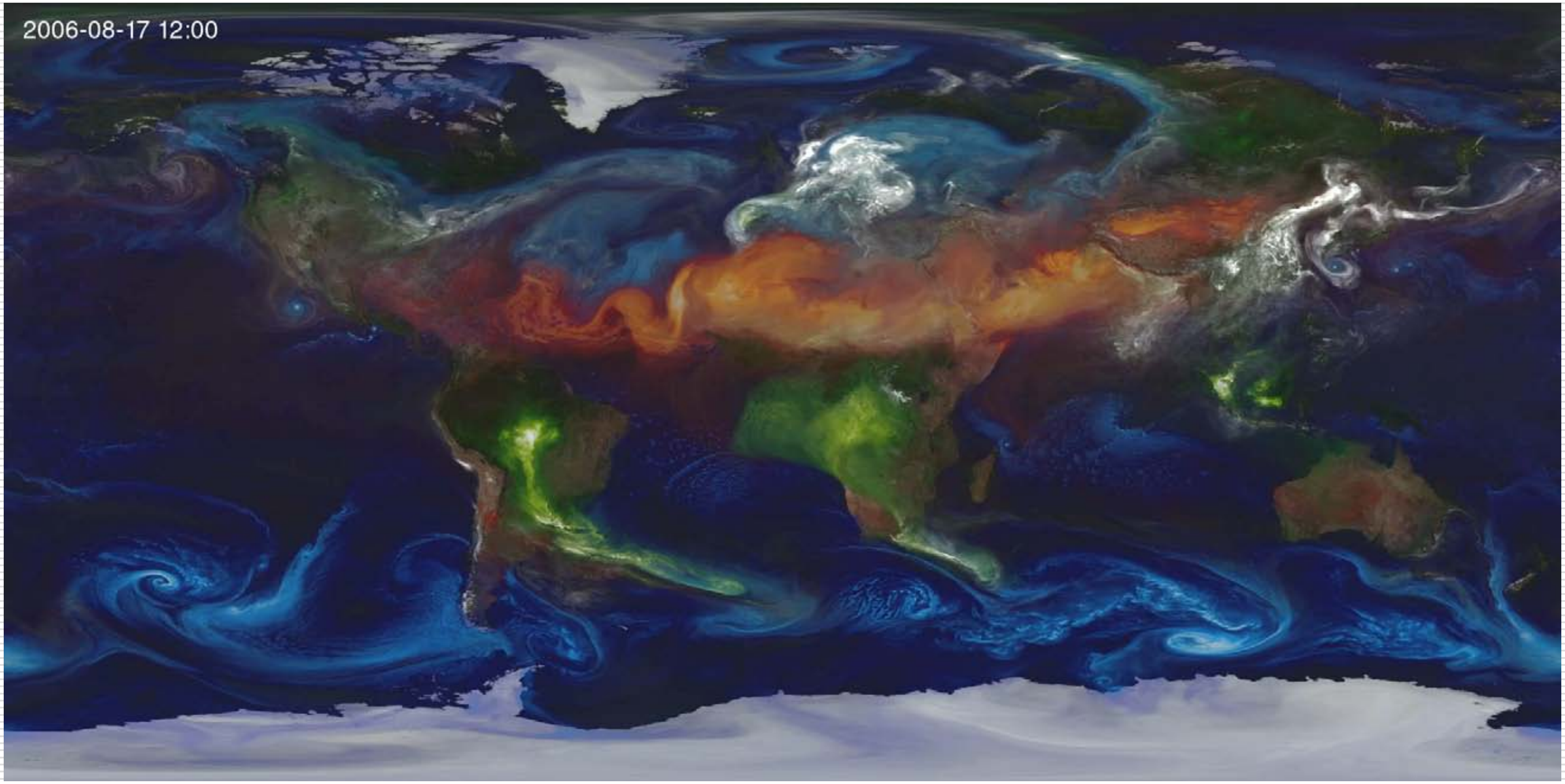
- Background: Toward an IESA
- System Overview
  - Model, emissions, assimilation
- MERRAero Validation
  - Comparison to AERONET & EOS sensors
- Aerosol Direct Radiative Forcing
- Global aerosol mass budget
- Concluding Remarks

# Atmospheric Aerosols

- Aerosols: particulates suspended in air
  - smoke
  - regional fine particles from pollution
  - desert dust and sea salt spray

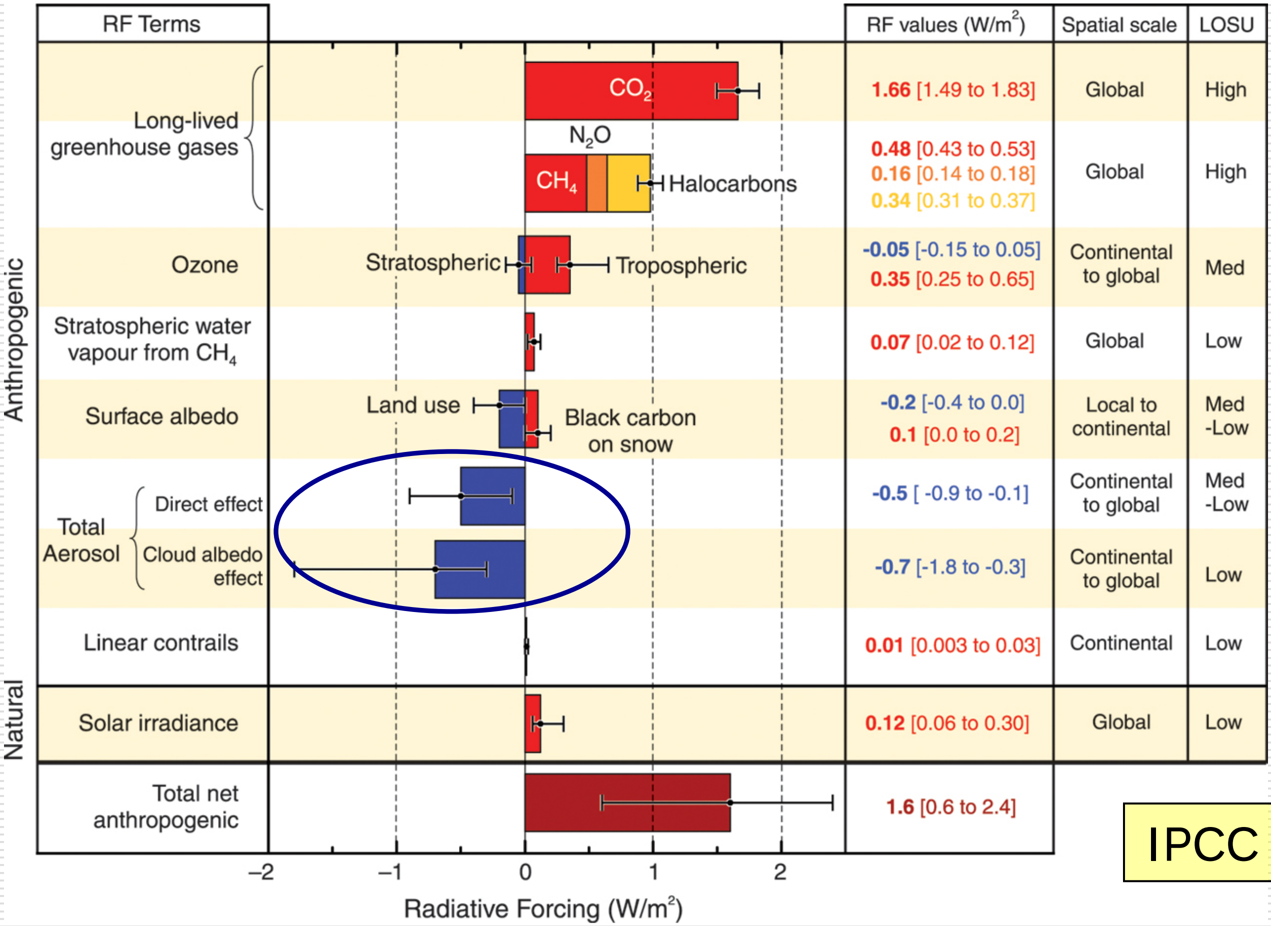
- Life time: only a few days
- Major environmental effects:
  - weather modification by affecting precipitation patterns and temperature profiles,
  - climate change by competing with regional effects of greenhouse warming,
  - health hazards from air pollution and more.

# Atmospheric Aerosols




GEOS-5 10km Global Mesoscale Simulation: SST, aerosol emissions

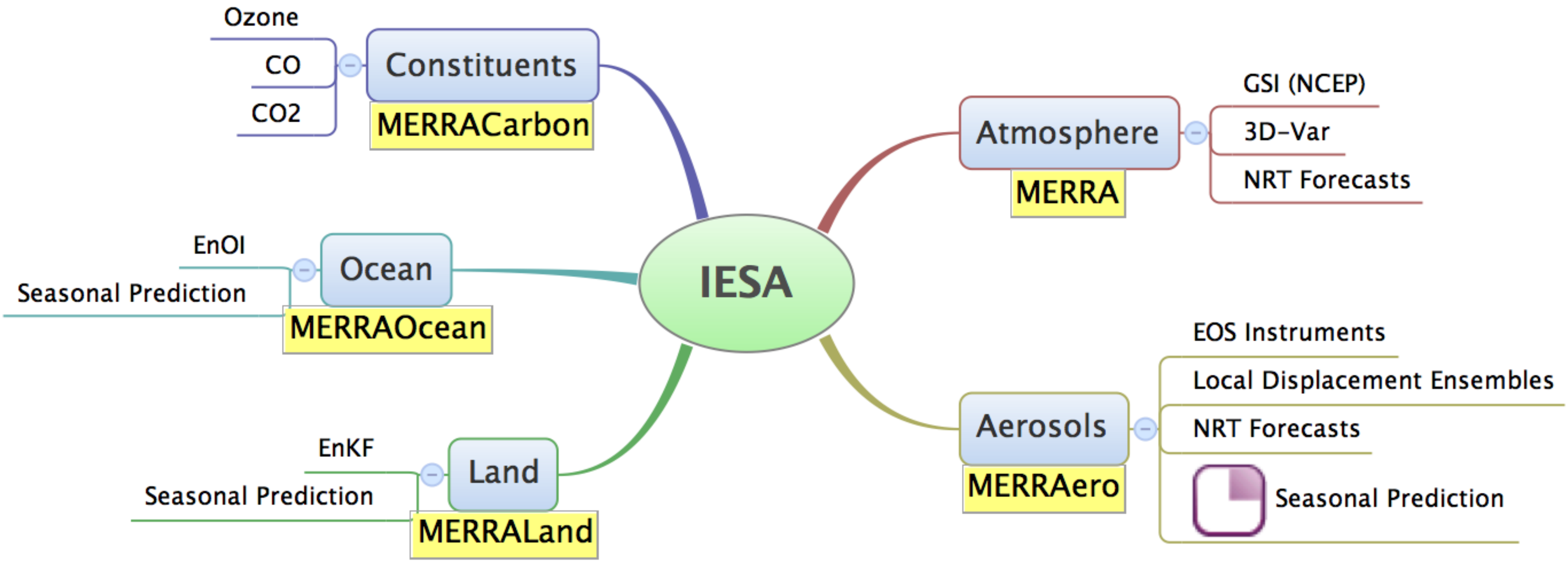
# Large Uncertainty in Aerosol Radiative Forcing




IPCC 2007

Global Mean Radiative Forcing

# Integrated Earth System Analysis




Preliminary IESA (PIESA): MERRA driven component reanalysis

# MERR*Aero* Overview

| Feature | Description |
|---|---|
| **Model** | GEOS-5 Earth Modeling System (w/ GOCART)<br>Constrained by MERRA Meteorology (Replay)<br>Land sees obs. precipitation (like MERRA*Land*)<br>Driven by QFED daily Biomass Emissions |
| **Aerosol Data Assimilation** | Local Displacement Ensembles (LDE)<br>MODIS reflectances<br>AERONET Calibrated AOD's (Neural Net)<br>Stringent cloud screening |
| **Period** | mid 2002-present (Aqua + Terra) |
| | 2000-mid 2002 (Terra only) |
| **Resolution** | Horizontal: nominally 50 km<br>Vertical: 72 layers, top ~85 km |
| **Aerosol Species** | Dust, sea-salt, sulfates, organic & black carbon |

# MERR*Aero* Status

| Version | Description |
|---|---|
| **1.0 (Pilot)** | • Period completed: 2003-2010<br>• Not publicly released |
| **1.1<br>(In Progress)** | • Revised removal processes<br>• Retuned seasalt emissions, optics<br>• Improved vertical distributions<br>• Land surface driven by observed precipitation<br>• Wet removal modulated by obs. precipitation<br>• Intended for public release<br>• Expected Availability: Summer 2012 |

# MERR*Aero* Sample Products

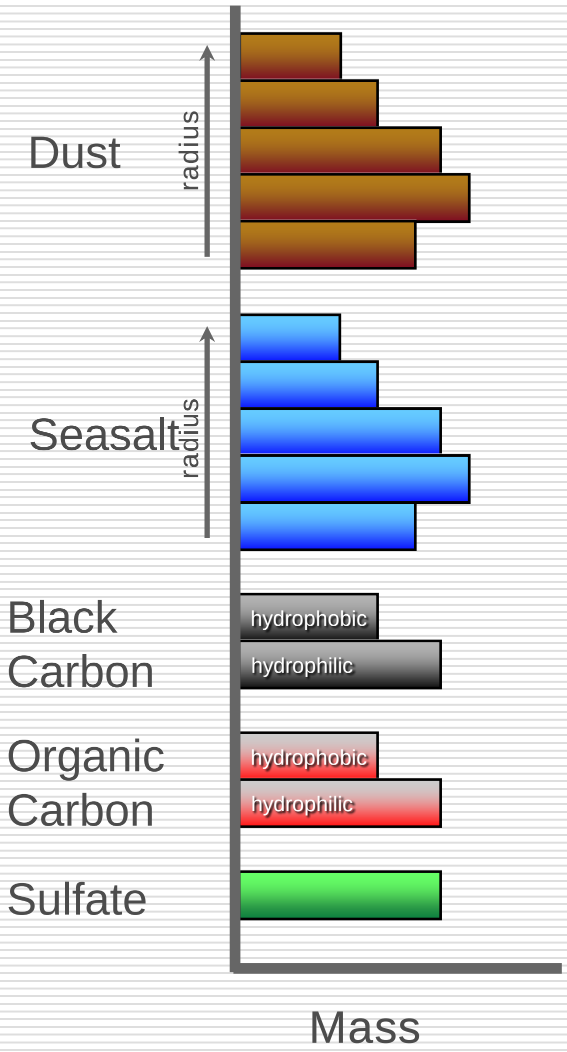
## 2D Datasets

- Hourly, 3-hourly
- Speciated
  - AOT, AAOT, PM2.5, PM10
    - 12 wavelengths
    - 340, 380, 440, 470, 500, 550, 670, 865, 1024, 1240, 1640, 2130
  - Surface & column mass
  - Sources & sinks
- Non-speciated
  - Aerosol radiative forcing
  - UV aerosol Index

## 3D Datasets

- 3-hourly
- Speciated:
  - Aerosol mixing ratio
- Non-speciated
  - 355nm, 532nm, 1024nm
  - Aerosol Extinction
  - Single Scattering Albedo
  - Asymmetry parameter
  - Backscatter
  - Attenuated Backscatter (TOA & SFC)

# GOCART Component



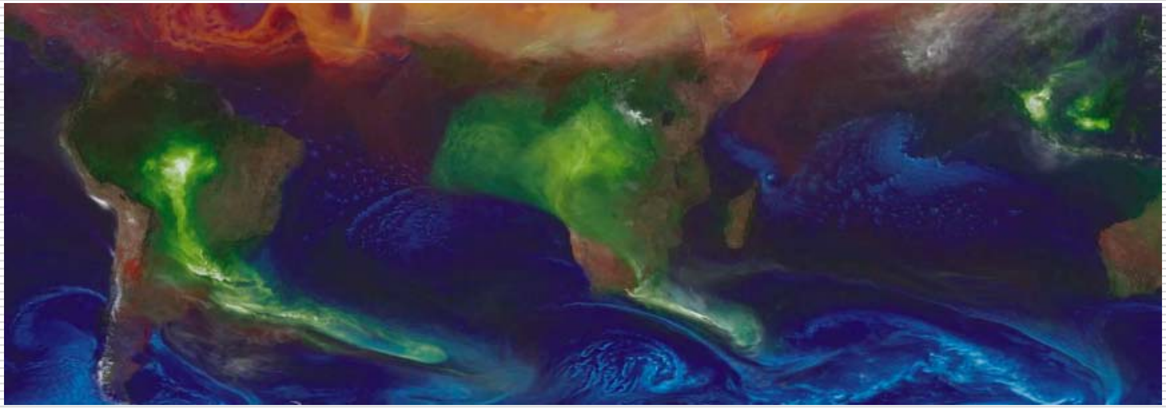

- Goddard Chemistry, Aerosol, Radiation, and Transport Model [Chin et al. 2002]
- Sources and sinks for 5 non-interactive species

| | |
|---|---|
| **dust** | wind and topographic source, 5 mass bins |
| **sea salt** | wind driven source, 5 mass bins |
| **black carbon** | anthropogenic and wildfire source, mass hydrophic and hydrophilic |
| **organic carbon** | anthropogenic, biogenic, and wildfire source, mass hydrophic and hydrophilic |
| **sulfate** | anthropogenic and wildfire source of SO2, oxidation to SO4 mass |

- Convective and large scale wet removal
- Dry deposition (and sedimentation for dust and sea salt)
- Optics based primarily on OPAC

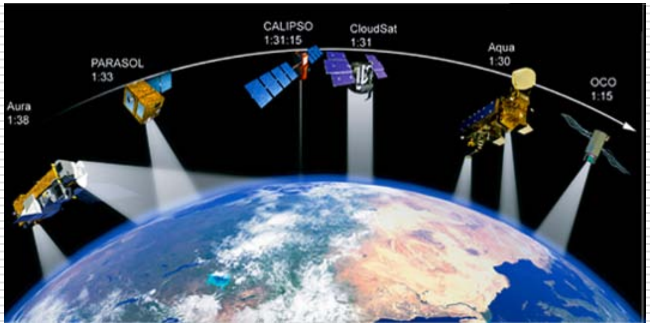
# QFED: Quick Fire Emission Dataset

- 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
- Prescribed diurnal cycle



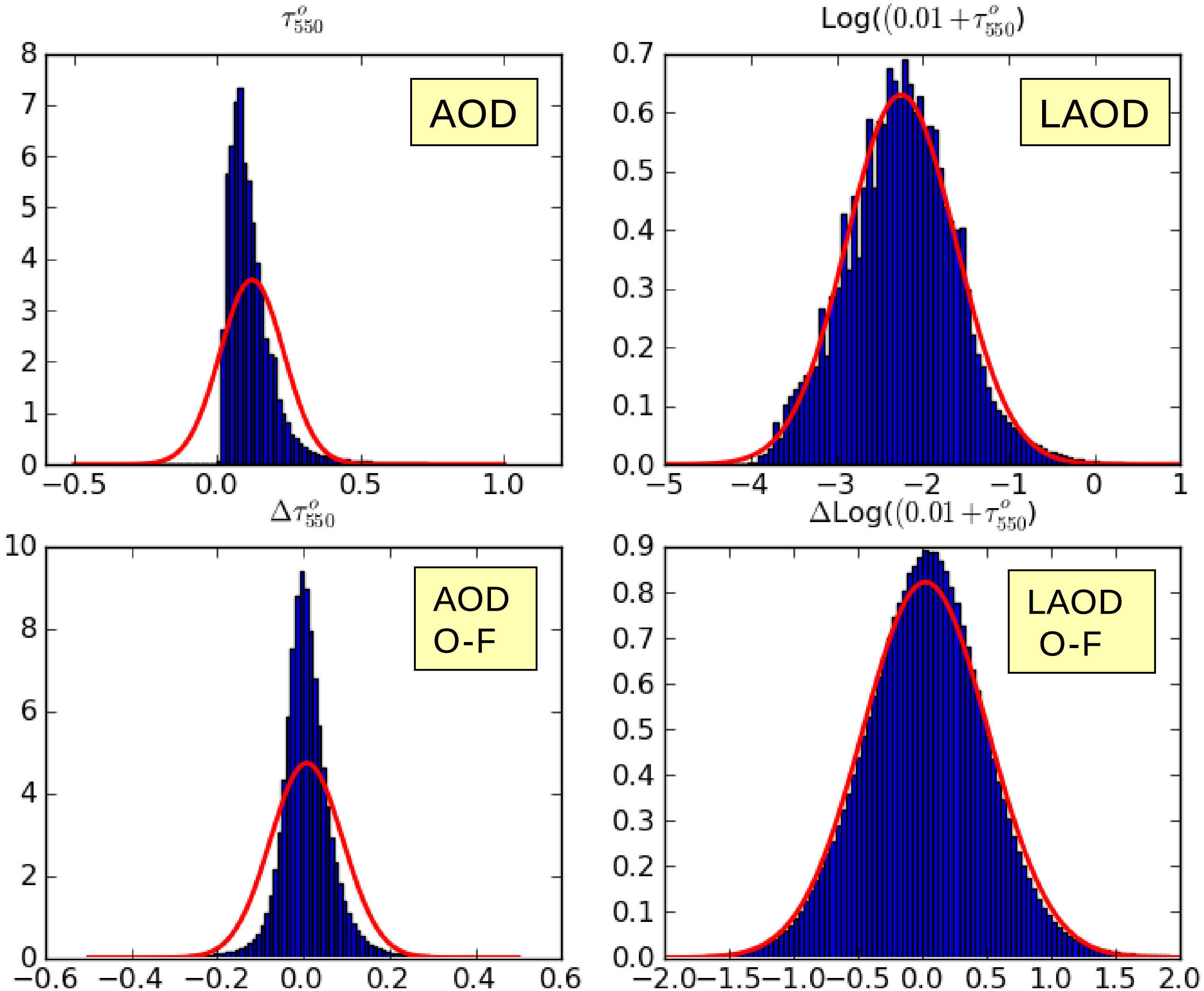
# Aerosol Data Assimilation

- Focus on NASA EOS instruments, MODIS for now



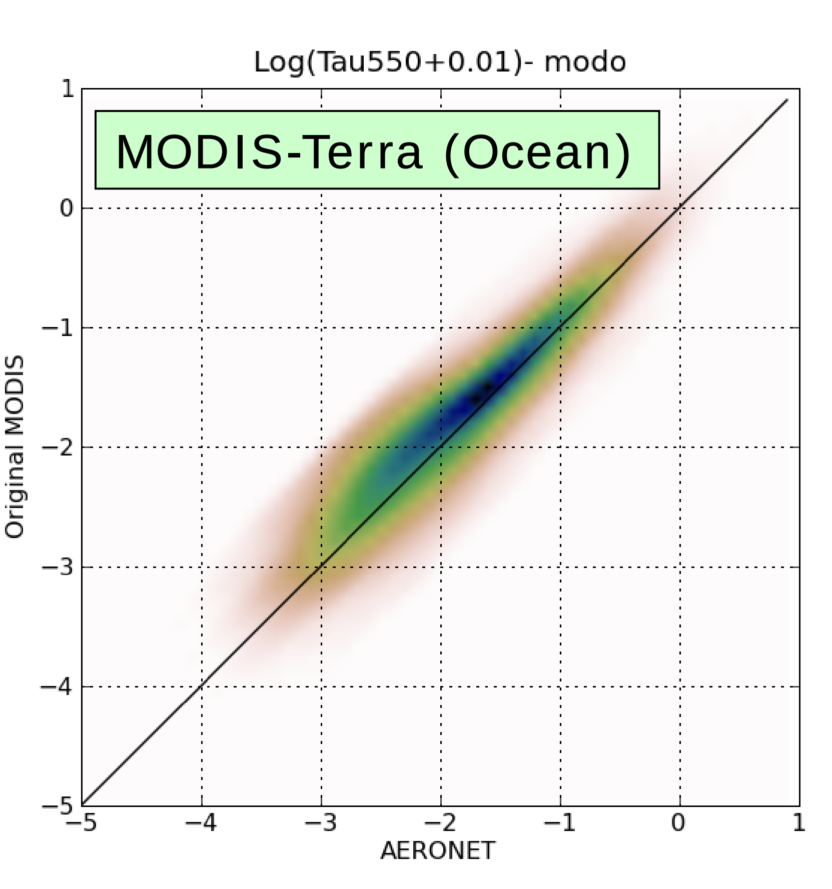

- Global, high resolution 2D AOD analysis
- 3D increments by means of Local Displacement Ensembles (LDE)
- Simultaneous estimates of background bias (*Dee and da Silva 1998*)
- Adaptive Statistical Quality Control (*Dee et al. 1999*):
  - State dependent (adapts to the error of the day)
  - Background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

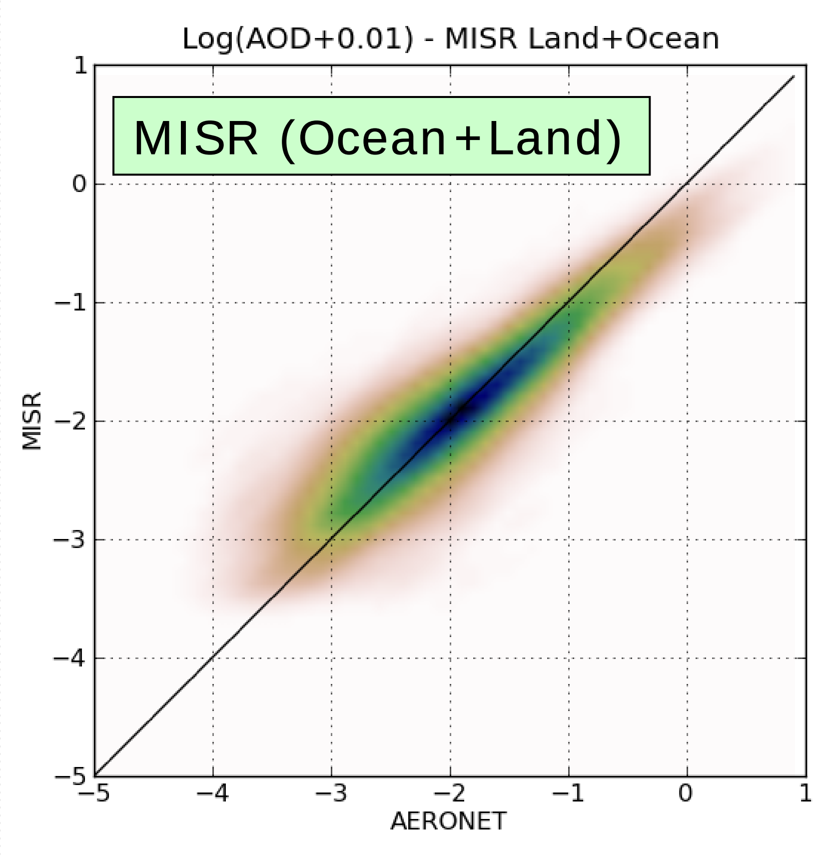
# Analysis Variable: $\eta = \log(\tau + 0.01)$




MODIS/TERRA Ocean

# AERONET-MODIS/MISR Joint PDF




Observation bias correction is necessary.

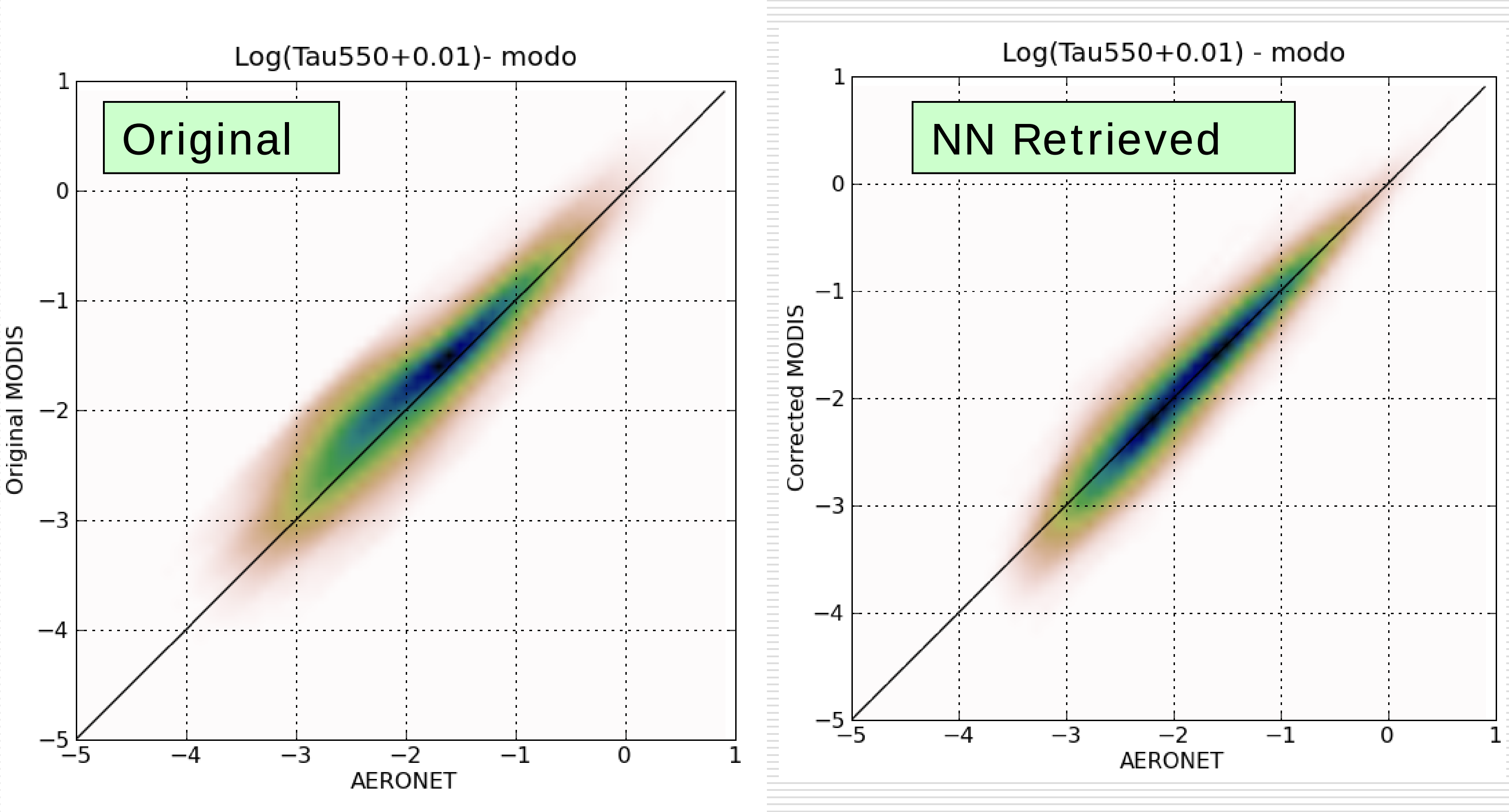
# Neural Net for AOD Empirical Retrievals

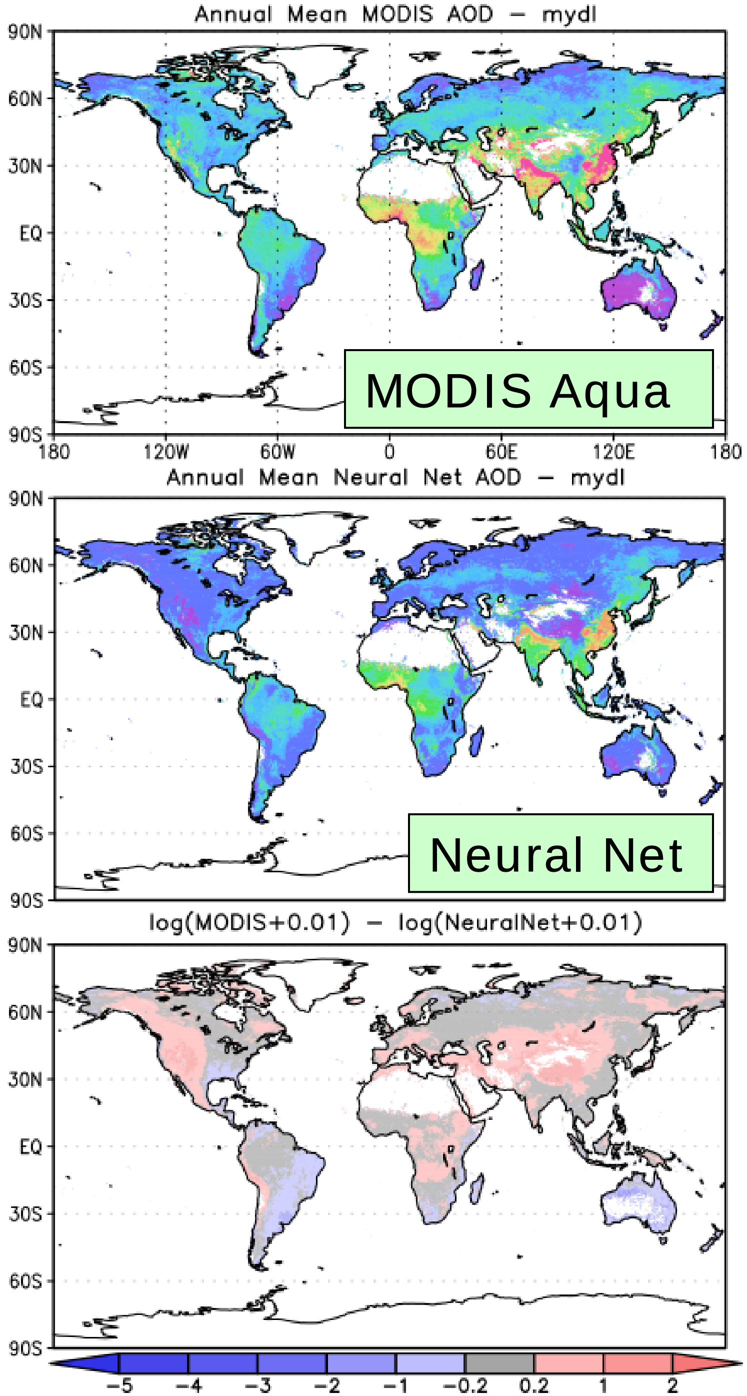
- Ocean Predictors
  - Multi-channel
    - TOA Reflectances
    - ~~Retrieved AOD~~
  - Angles
    - Glint
    - Solar
    - Sensor
  - Cloud fraction (<85%)
  - Wind speed
- Target: AERONET
  - Log(AOD+0.01)

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

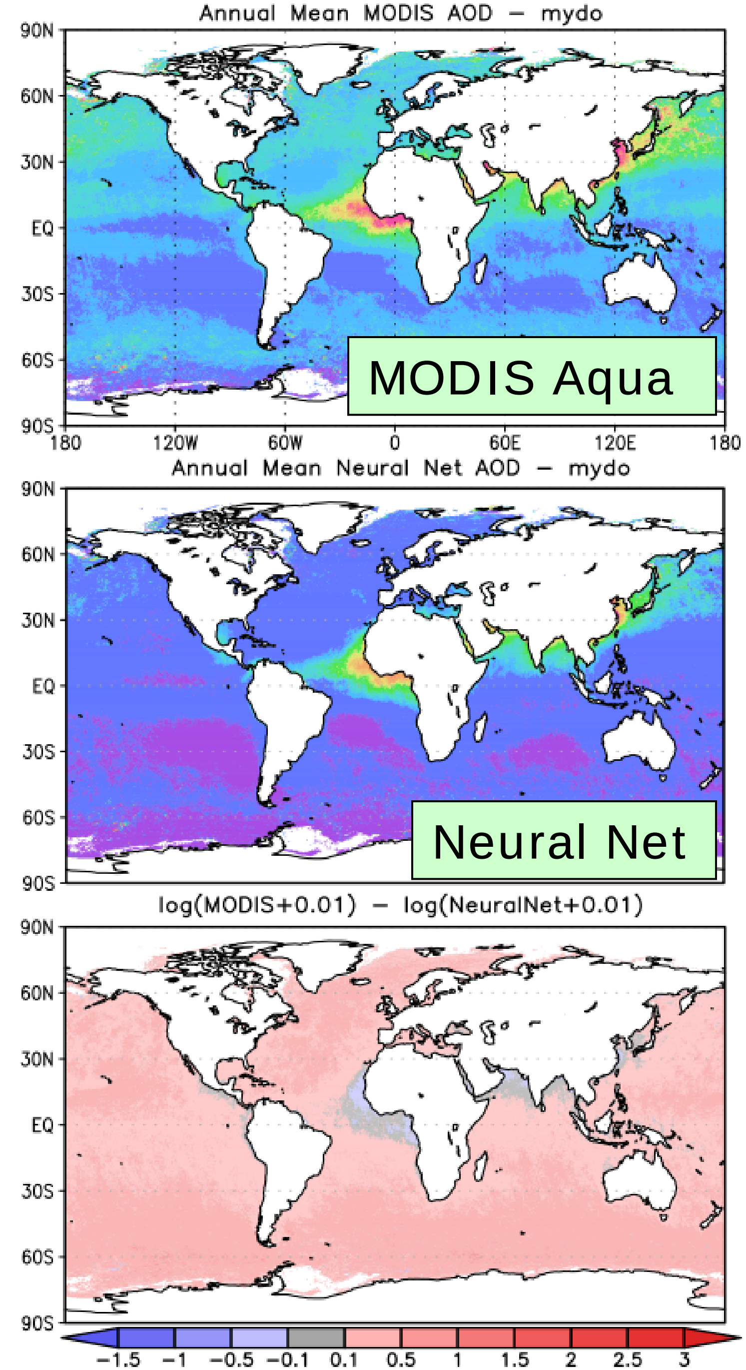
# MODIS AOD over Ocean

# Neural Net Retrievals (Terra)

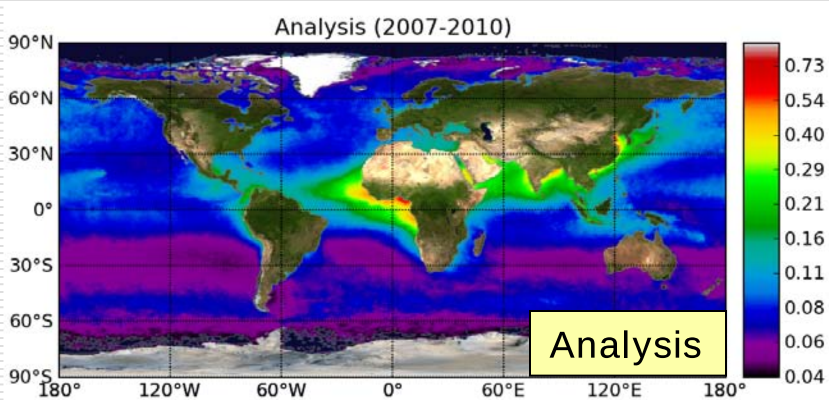


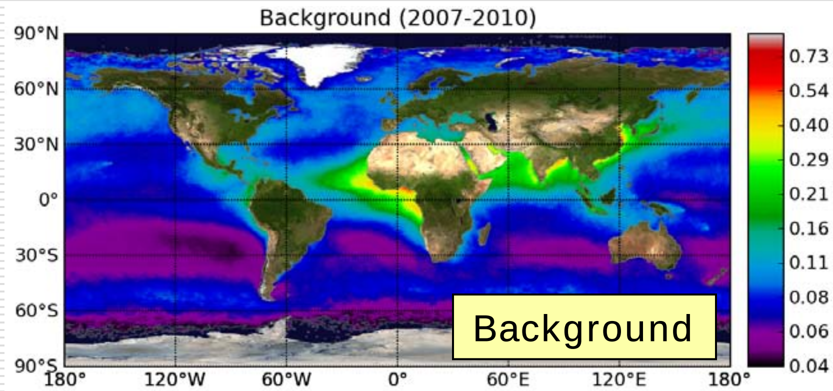


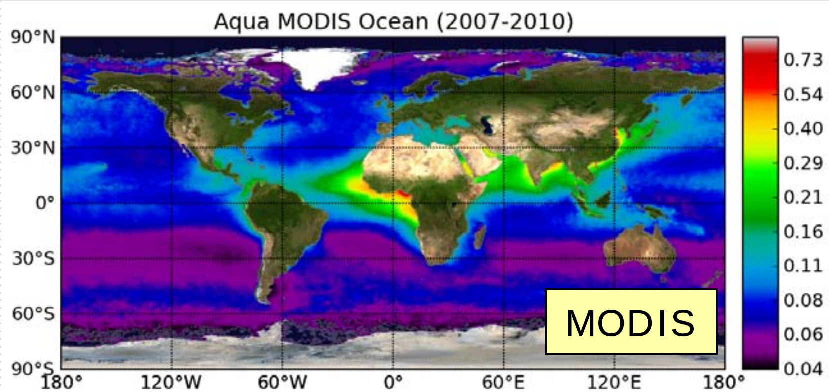

Annual Mean 2008

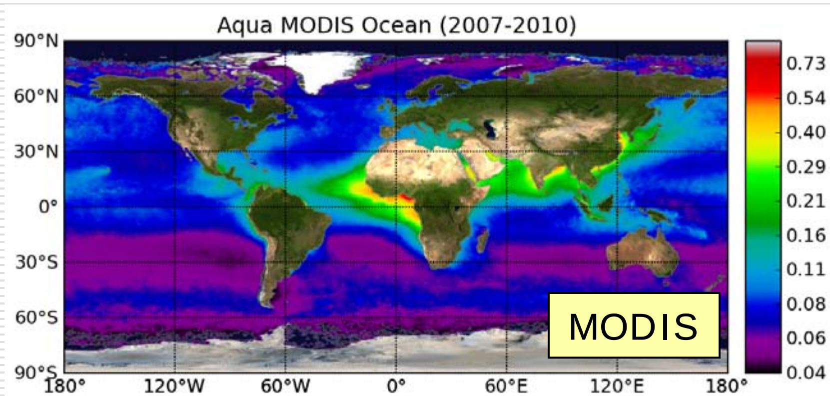


# MERR*Aero* sampled as Aqua MODIS (Ocean)



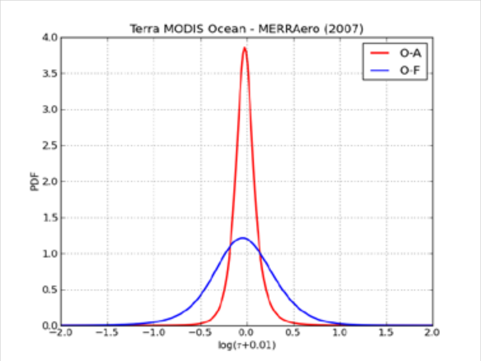
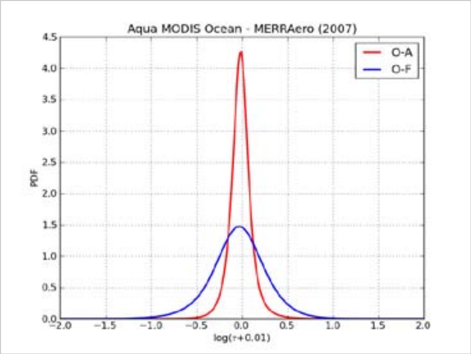
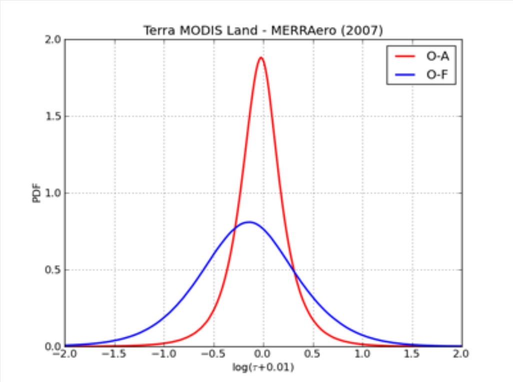
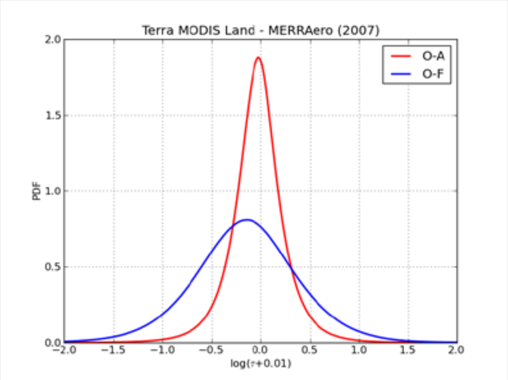




Analysis has a very small annual mean bias

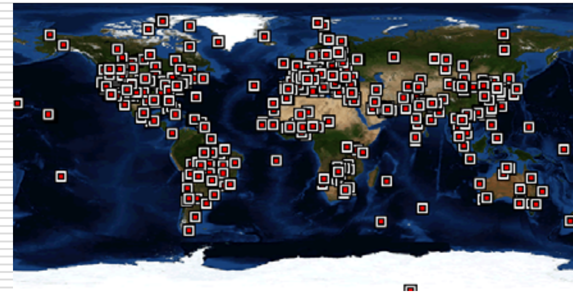
# Fit to observations

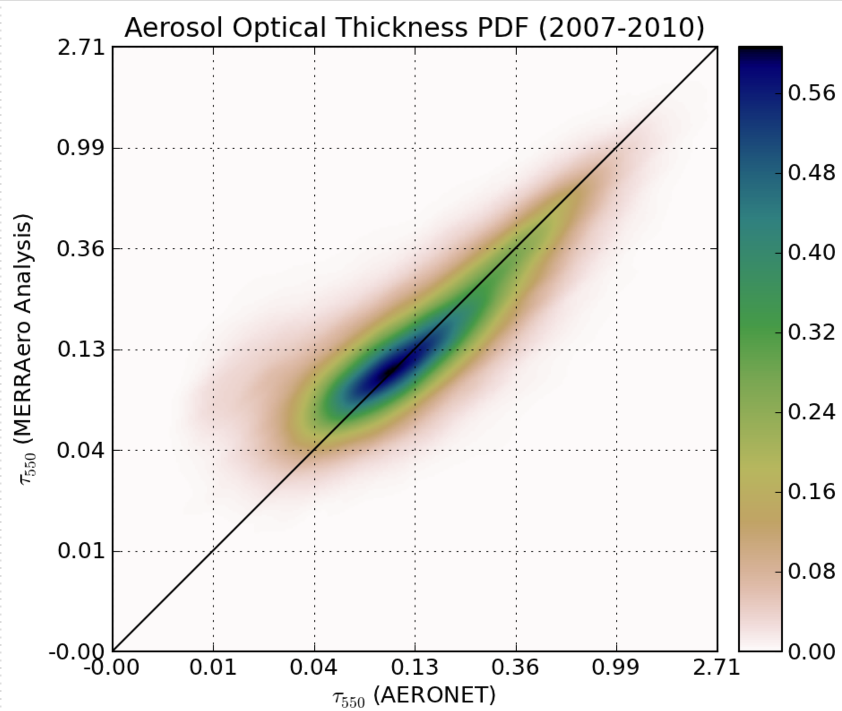
| | Terra | Aqua |
|---|---|---|
| OCEAN |   |   |
| LAND |   |   |

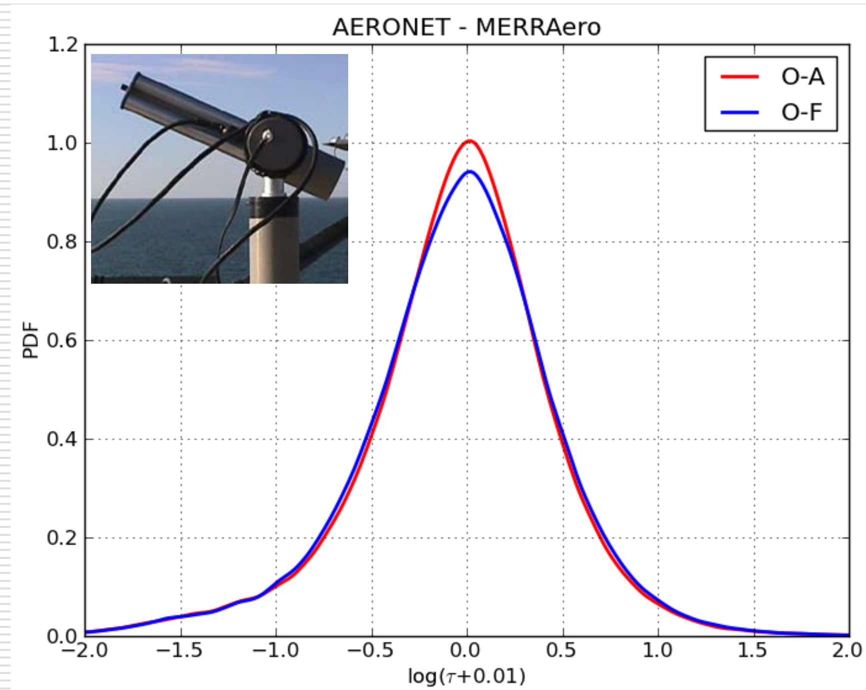
O-A
O-F

$$\eta = \log(\tau + 0.01)$$

# AERONET Validation

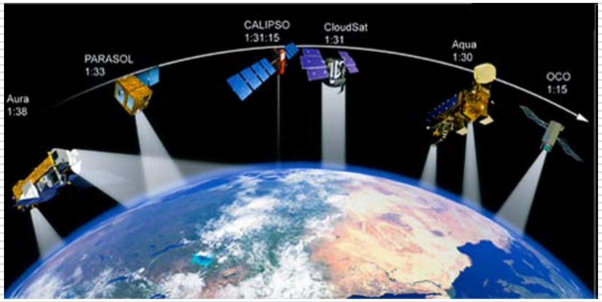


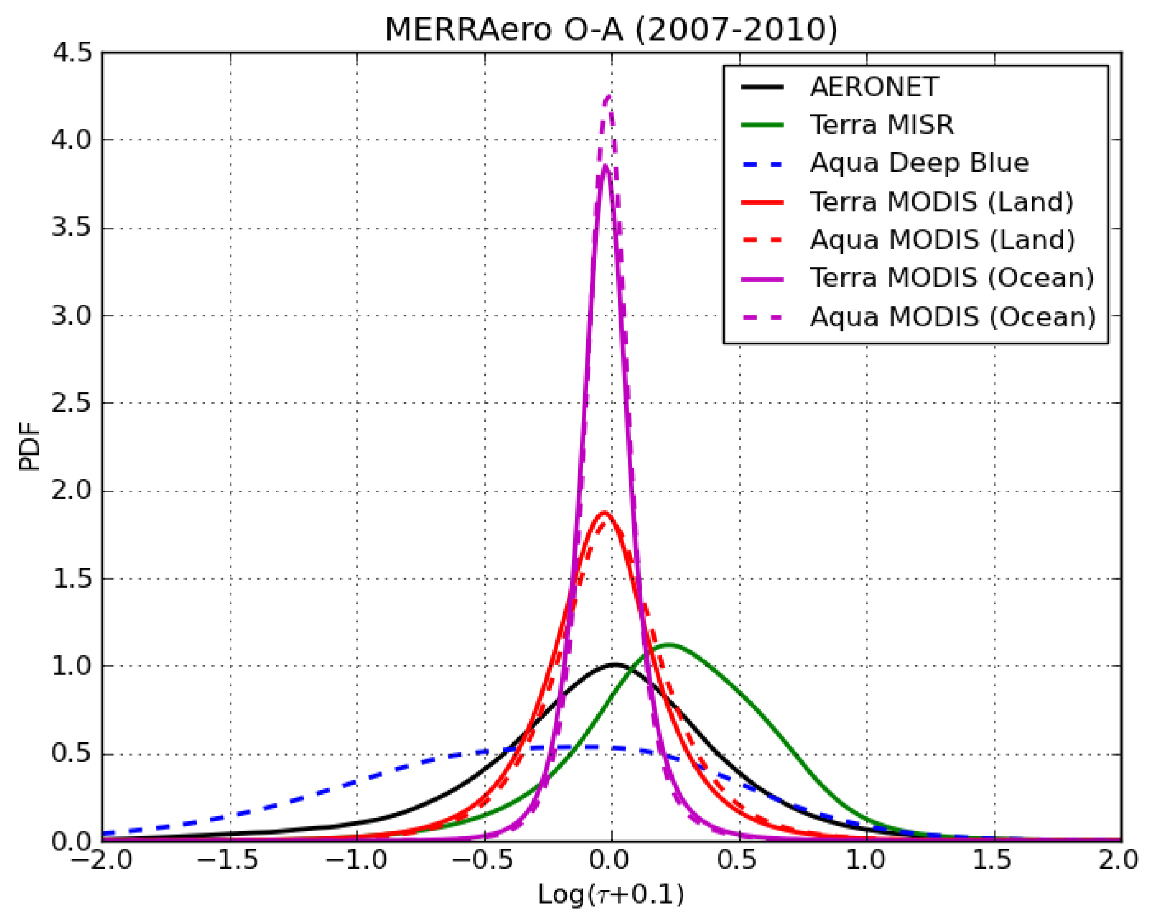



$$\eta = \log(\tau + 0.01)$$

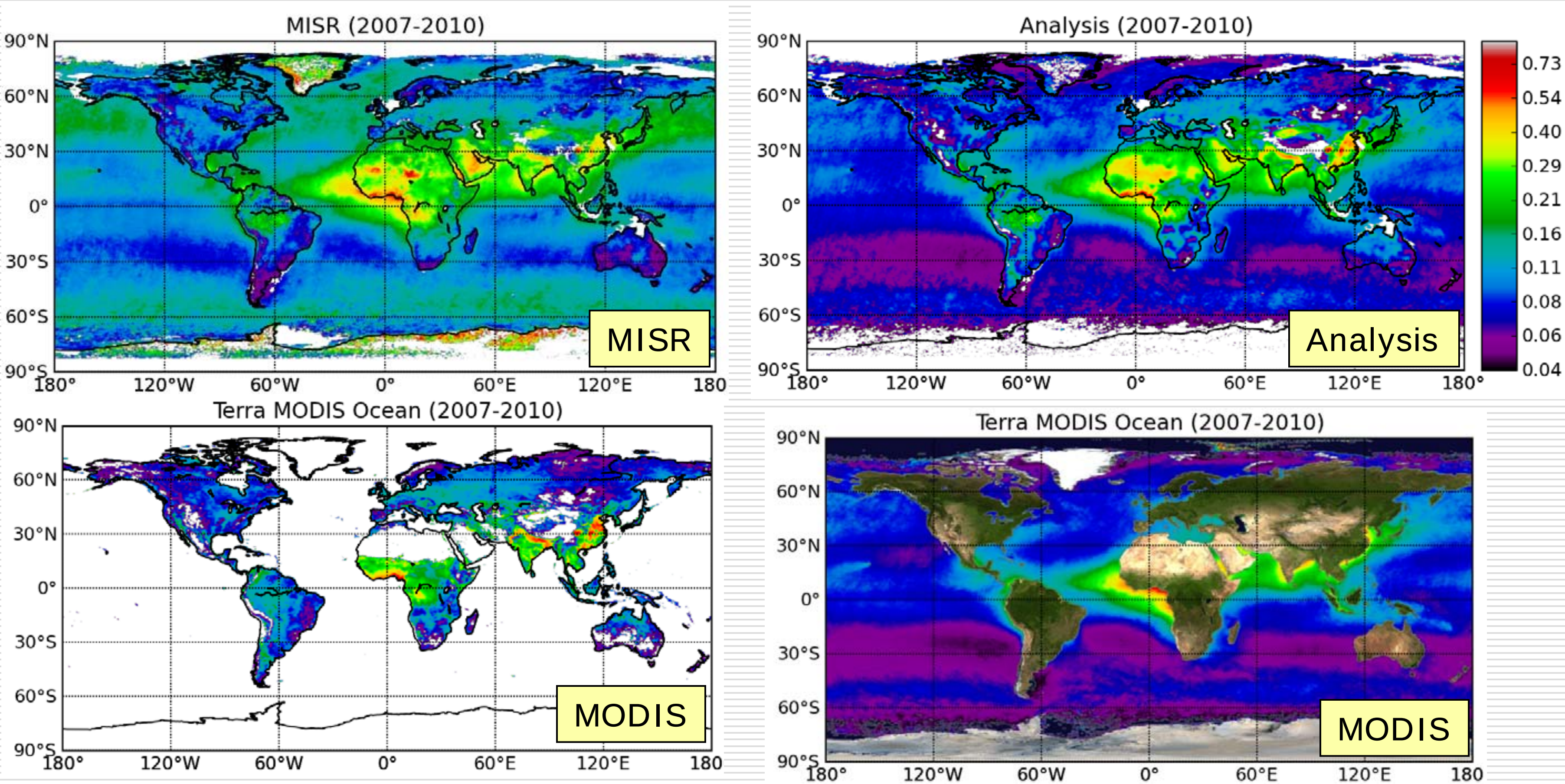
# Multi-sensor Intercomparison



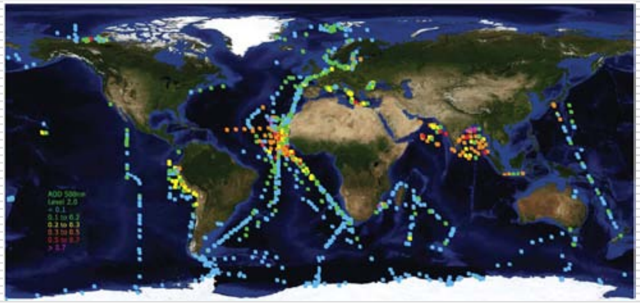

$$\eta = \log(\tau + 0.01)$$

# MISR/MODIS Intercomparison

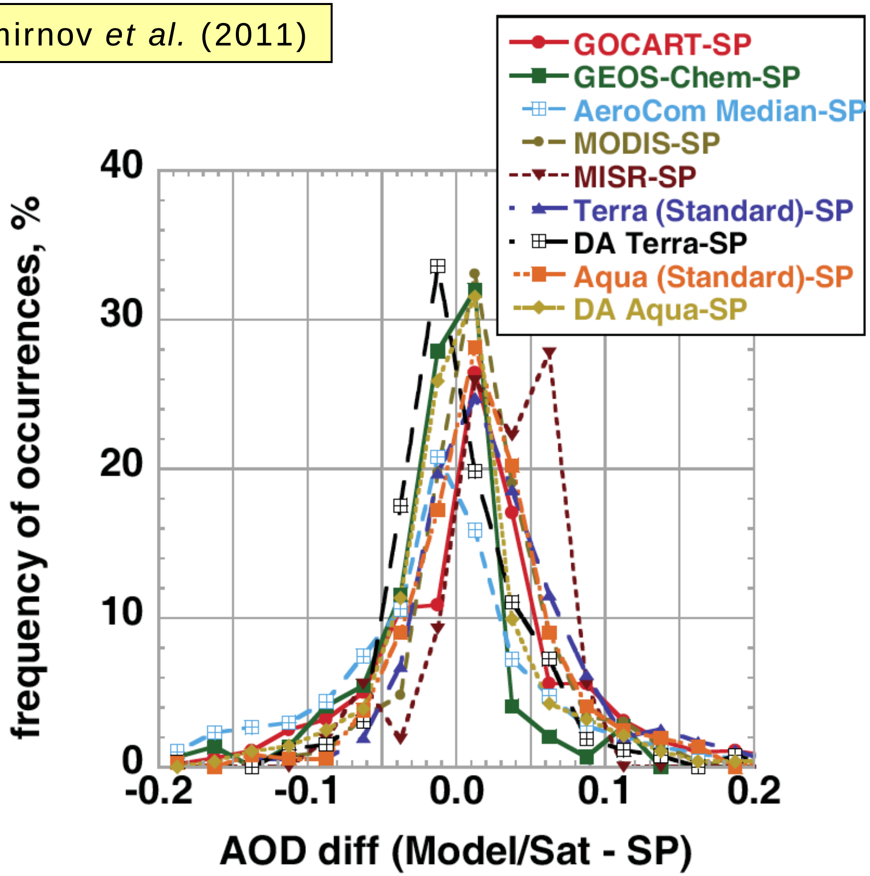


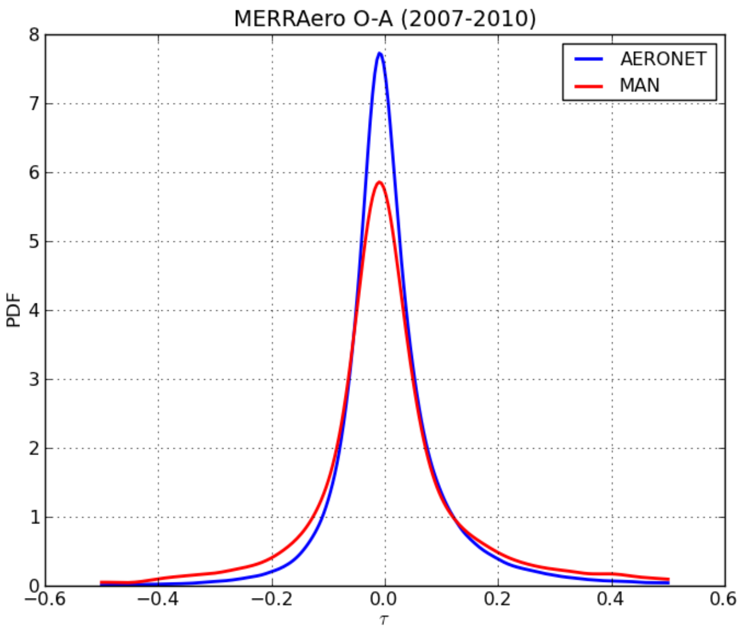

Cloud screening explains our reduced AOD over oceans

# Maritime Aerosol Network

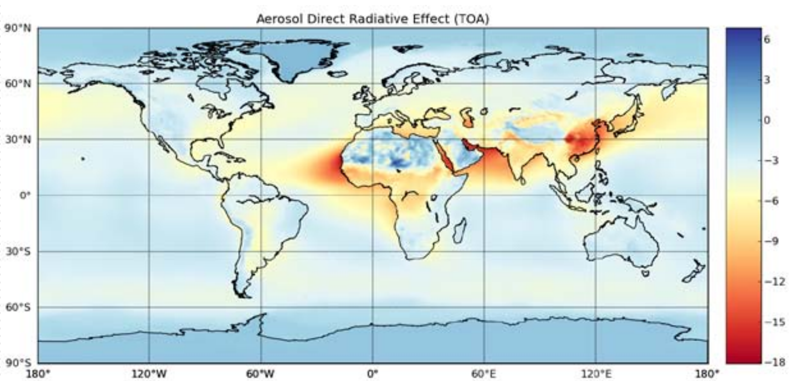


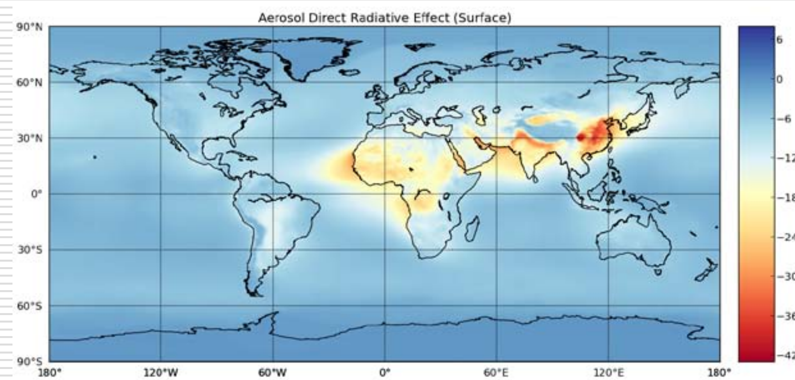
Smirnov *et al.* (2011)



# Clear-Sky Aerosol Direct Radiative Effect

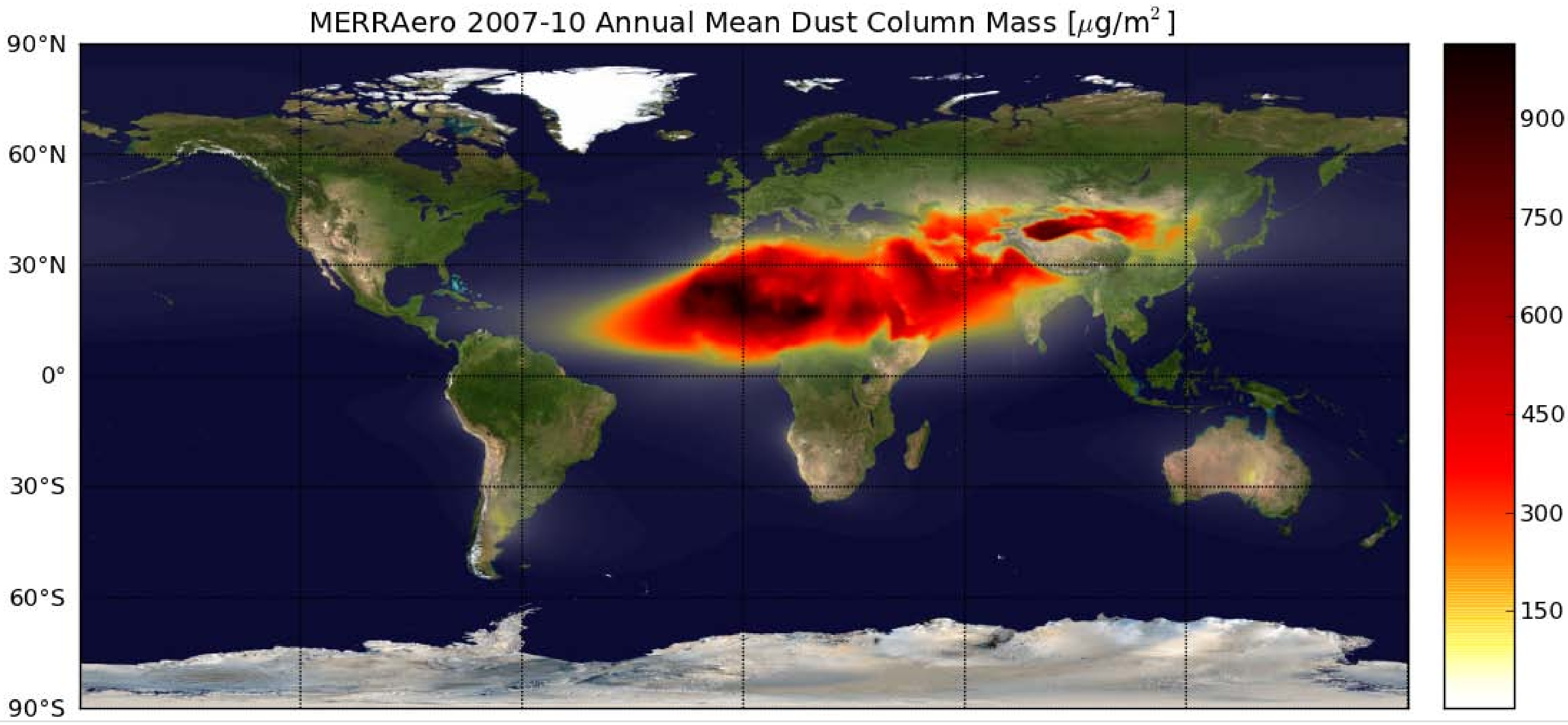


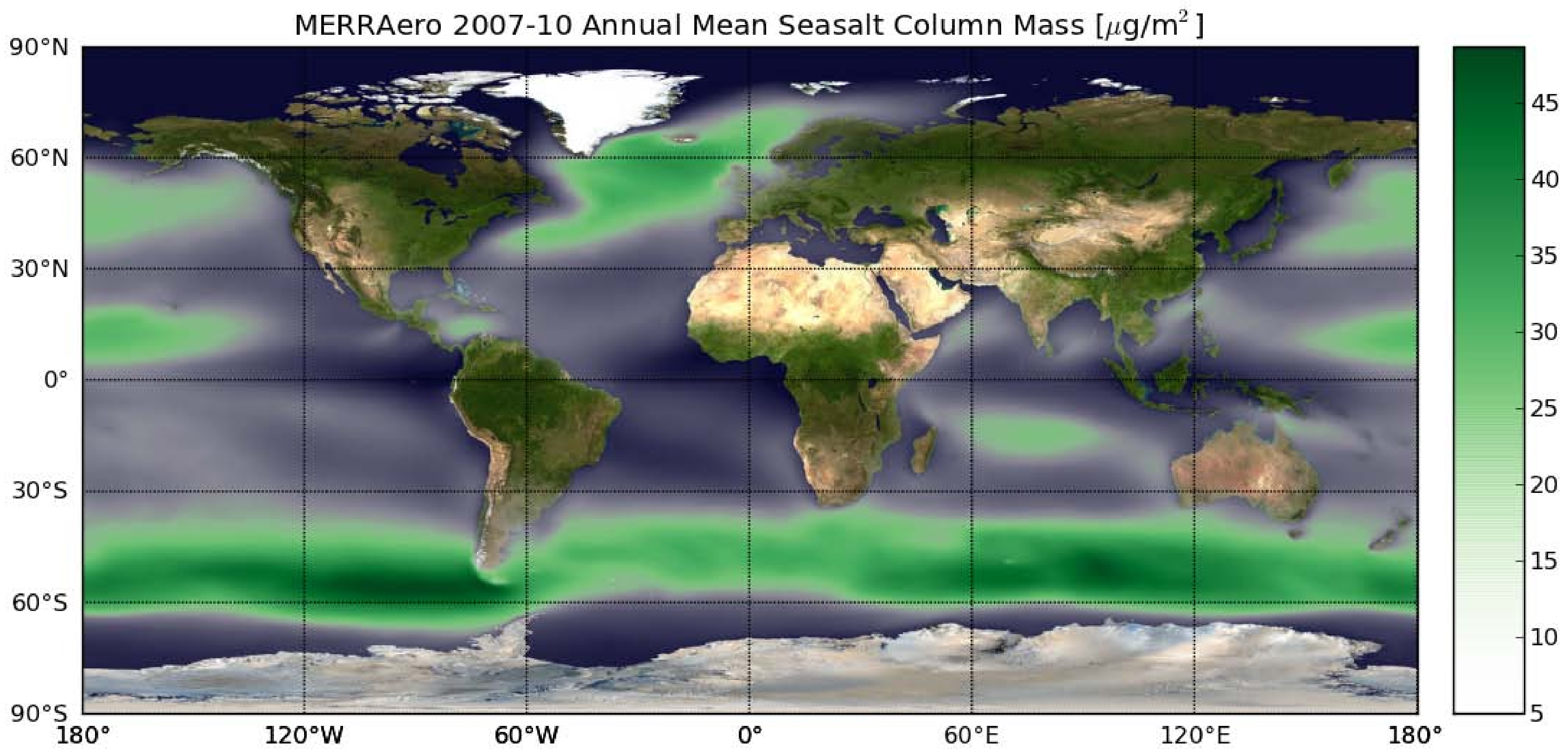

| Source | TOA SW DRE Ocean (Land) | Atmos. Ocean (Land) | Surface SW DRE Ocean (Land) |
|---|---|---|---|
| **MERRAero** | -3.8 (-4.3) | 2.8 (6.8) | -6.6 (-11.1) |
| Other Observational<br>Yu *et al.* (2006) | -5.5 ± 0.2 (-4.9 ± 0.7) | 3.3 (6.8) | -8.8 ± 0.7 (-11.8±1.9) |
| Multi-model Ensemble<br>Yu *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) |

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

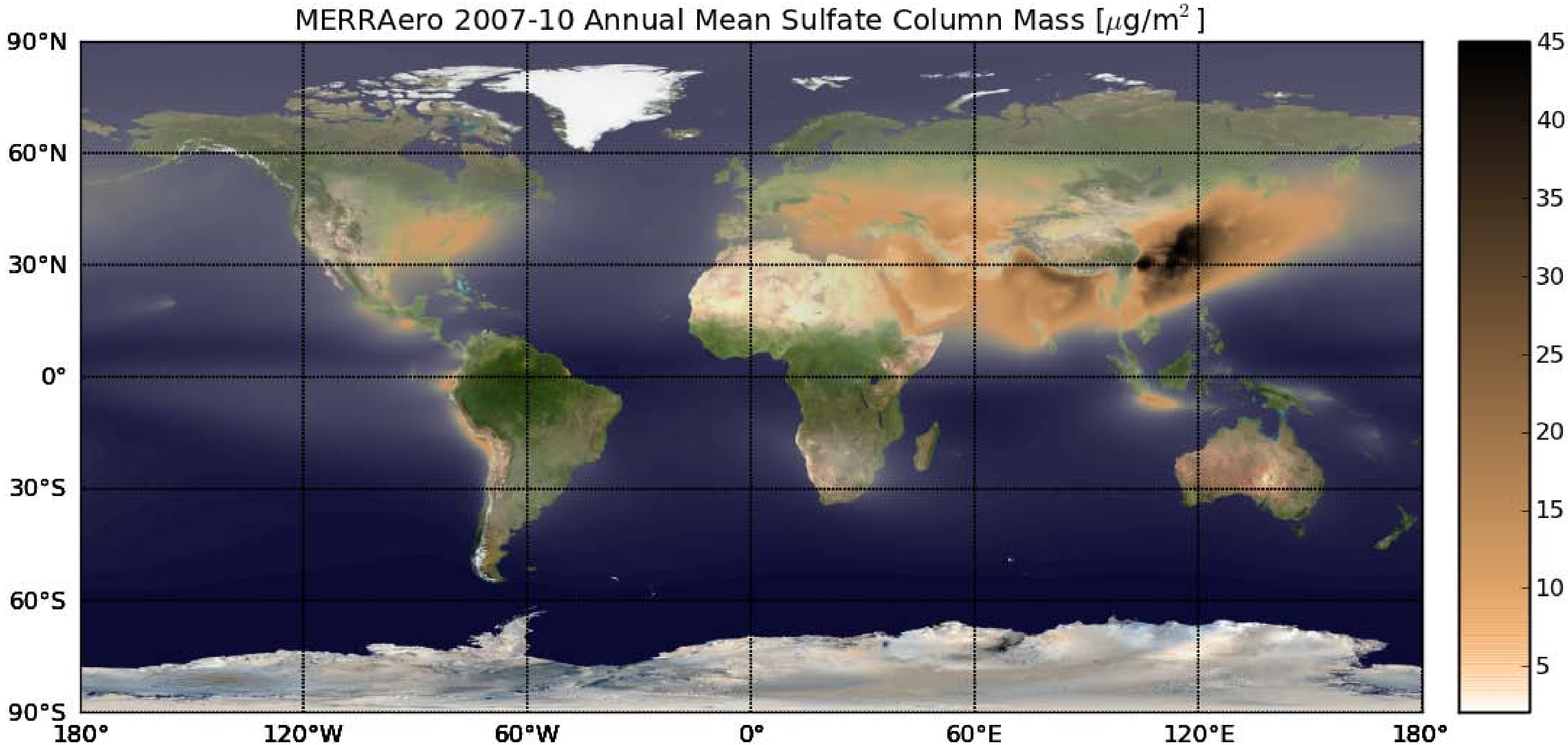
# Dust Annual Mean Mass



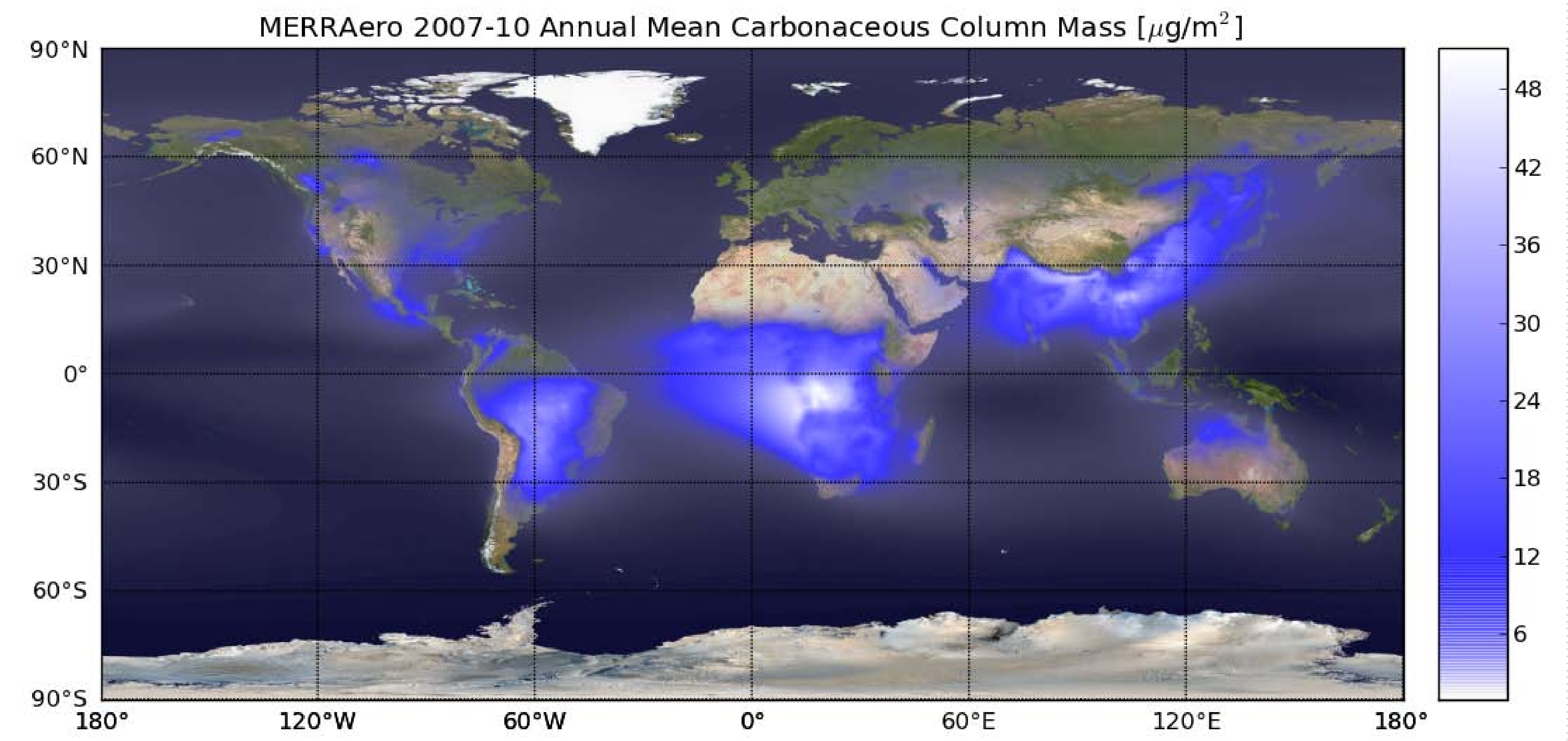
# Seasalt Annual Mean Mass



# Sulfate Annual Mean Mass



# Carbonaceous Annual Mass



# 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 |
| $\Delta q^a$ | Anaysis increments |
| $\tau$ | Analysis interval (3 hours) |
| $\langle \cdot \rangle$ | Mass weighted vertical integral |
| $\overline{(\cdot)}$ | Time average |

# Decomposing the Mass Flux

The vertically integrated mass flux can be decomposed in mean flow and eddy components

$$\mathbf{F} = \overline{\langle \mathbf{u} q \rangle} = \langle \overline{\mathbf{u}} \cdot \overline{q} \rangle + \overline{\langle \mathbf{u}' q' \rangle}$$

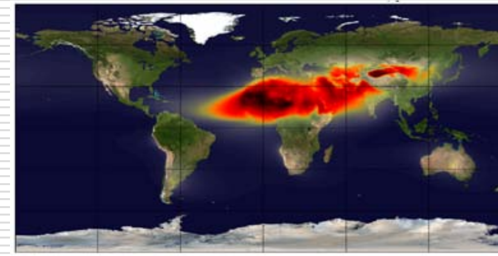
and rotational and divergent components

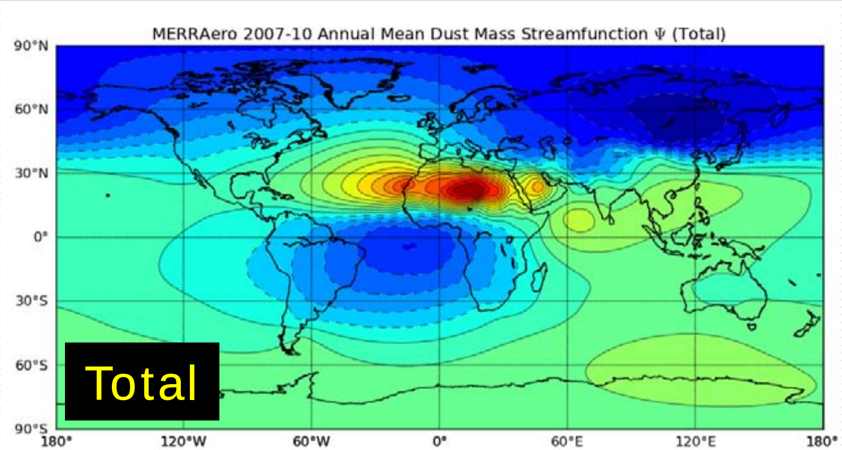
$$\begin{aligned} \mathbf{F} &= \mathbf{F}_\psi + \mathbf{F}_\chi \\ \mathbf{F} &= \mathbf{k} \cdot \nabla \times \mathbf{\Psi} + \nabla \chi \end{aligned}$$

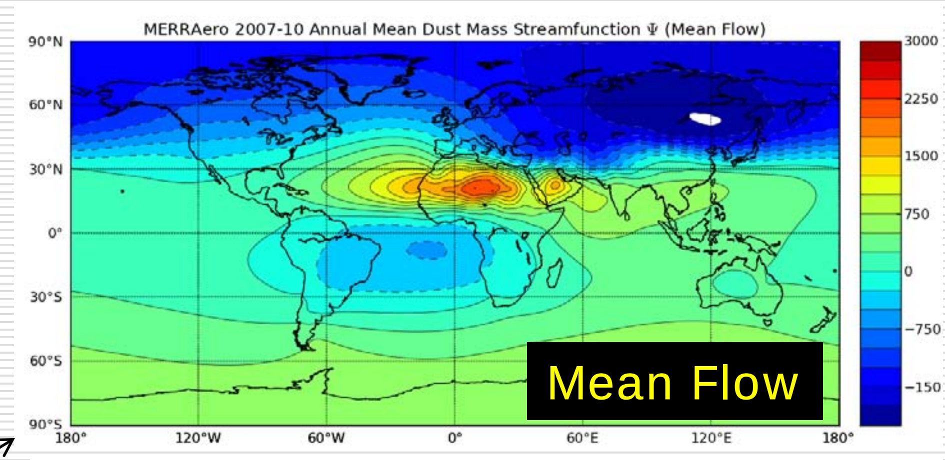
where the mass flux streamfunction $\mathbf{\Psi} = (0, 0, \psi)$ and potential $\chi$ satisfy:

$$\nabla^2 \psi = \mathbf{k} \cdot \nabla \times \mathbf{F} \qquad \text{and} \qquad \nabla^2 \chi = \nabla \cdot \mathbf{F}$$

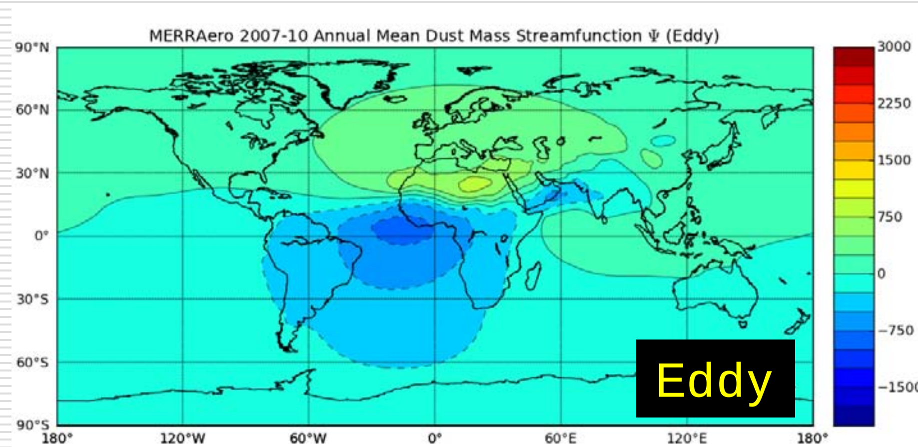
# Annual Dust Streamfunction





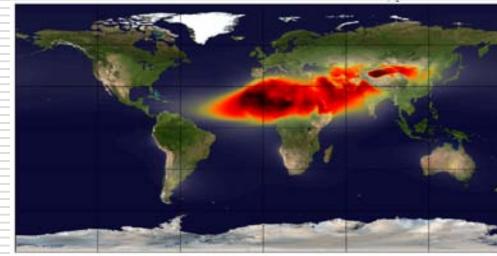



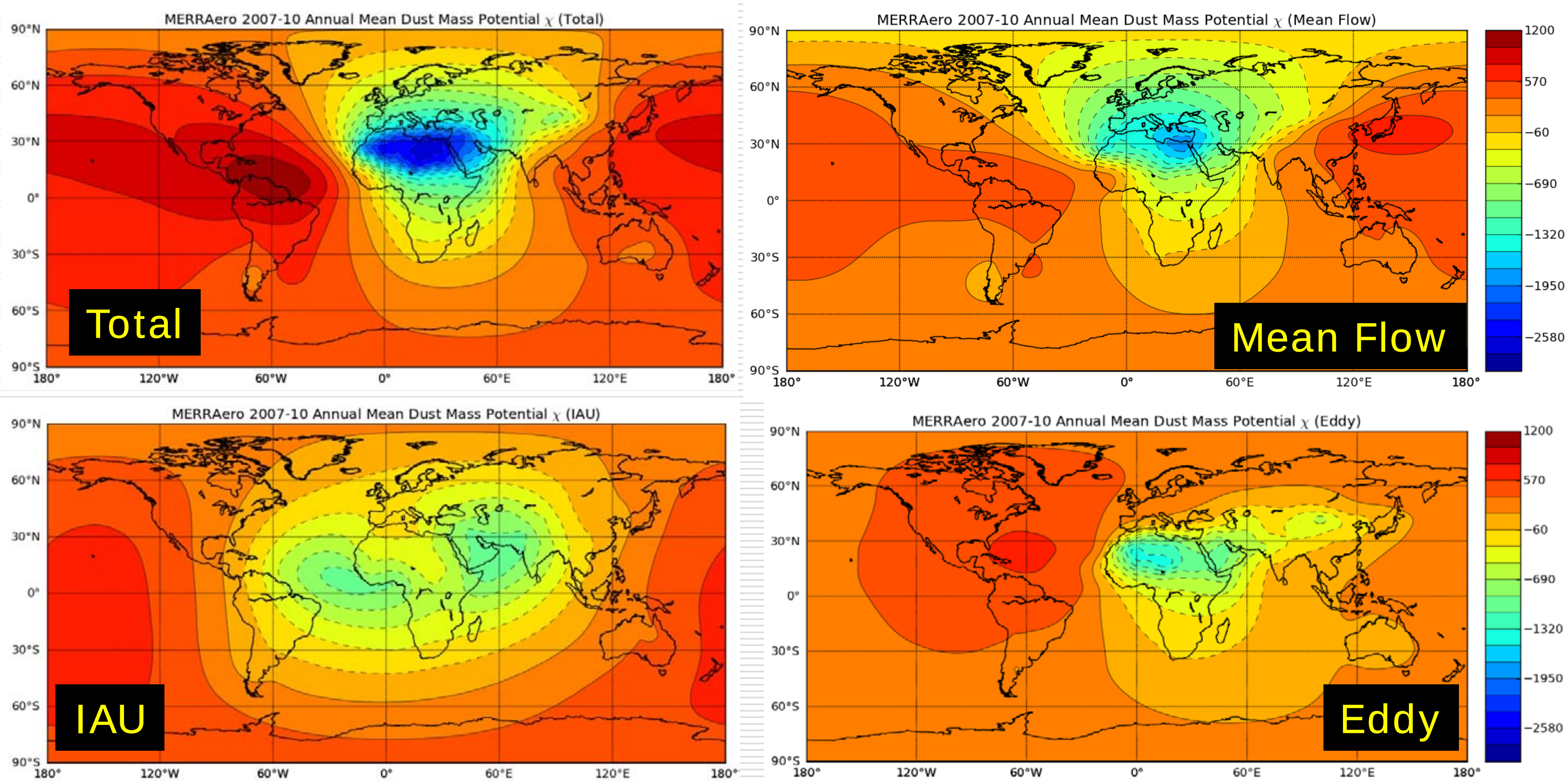

$$\mathbf{F} = \overline{\langle \mathbf{u} q \rangle} = \langle \overline{\mathbf{u}} \cdot \overline{q} \rangle + \overline{\langle \mathbf{u}' q' \rangle}$$




$$\nabla^2 \psi = \mathbf{k} \cdot \nabla \times \mathbf{F}$$

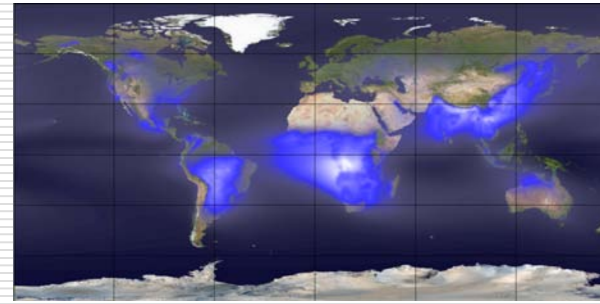
# Annual Dust Flux Potential

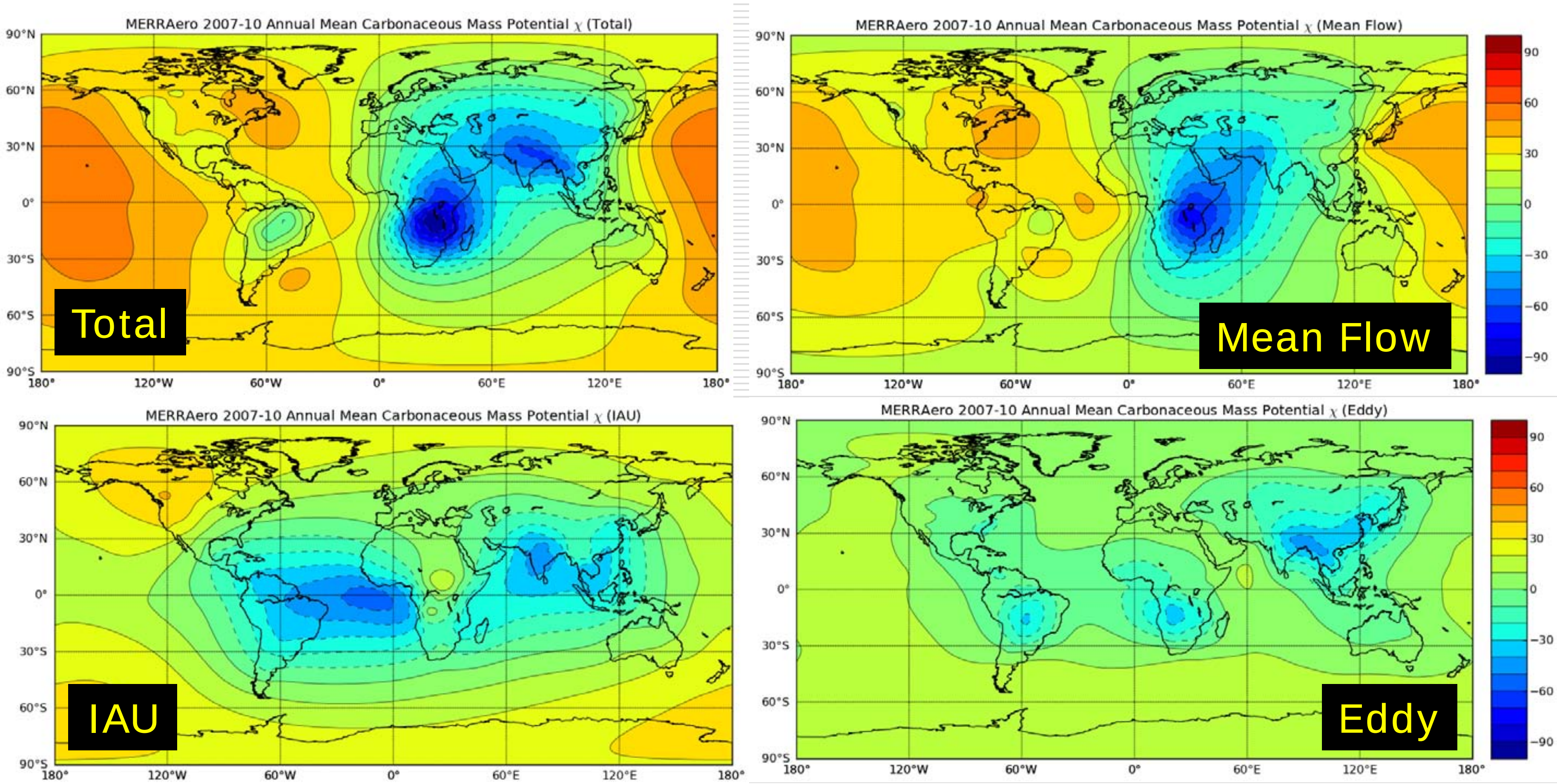





$$\chi = \nabla^{-2}\left[\left(\overline{E} + \overline{P} - \overline{L} + \overline{\frac{\langle \Delta q^a \rangle}{\tau}}\right]\right.$$

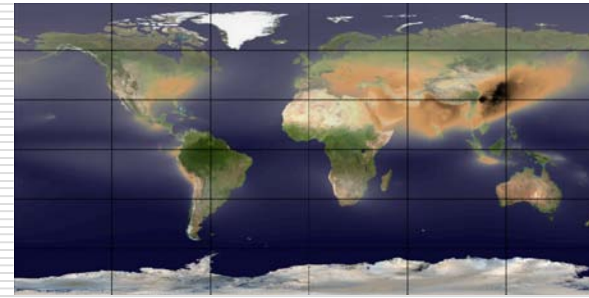
# Annual Carbonaceous Flux Potential

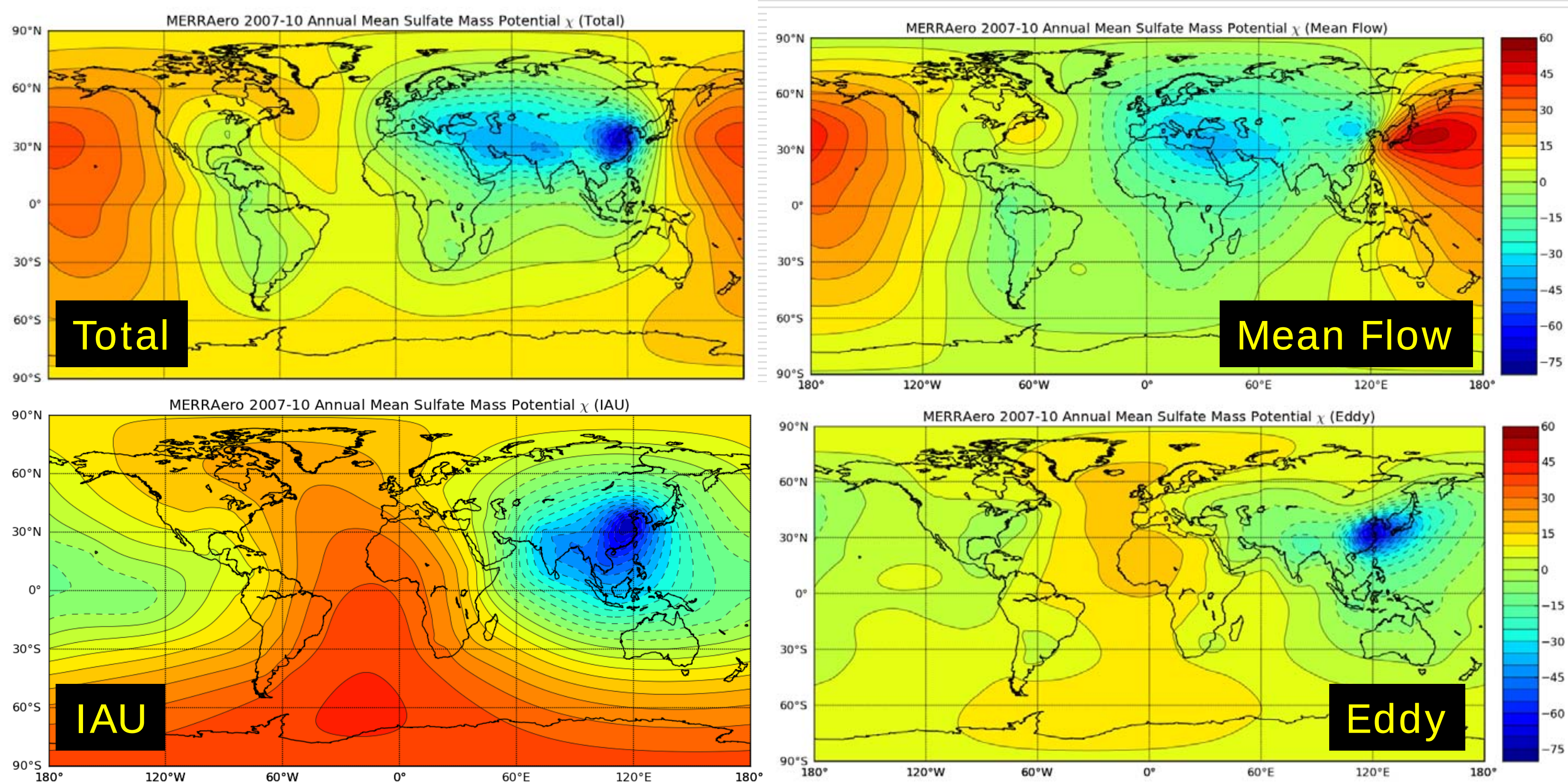





$$\chi = \nabla^{-2}\left[(\overline{E}+\overline{P}-\overline{L}+\frac{\overline{\langle\Delta q^{a}\rangle}}{\tau}\right]$$

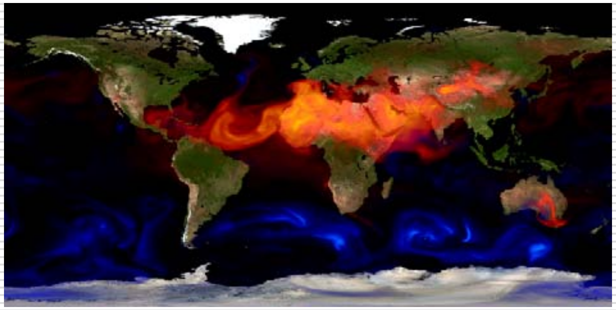
# Annual Sulfate Flux Potential






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

# Concluding Remarks



- MERR*Aero* provides timeseries of gridded aerosol products that are consistent with MODIS and in-situ AOD measurements
  - Step toward IESA
- Analysis increments useful to diagnose errors in emission/removal processes
- Inclusion of additional EOS aerosol sensors require systematic homogenization of observing system
  - MISR, MODIS/Deep Blue, OMI

# Going Further

- Multi-channel 1D-Var for EOS instruments
  - MODIS, MISR, OMI, VIIRS
- Assimilation of CALIPSO attenuated backscatter in hybrid GSI