Aerosol Forecasting and Reanalysis at GMAO

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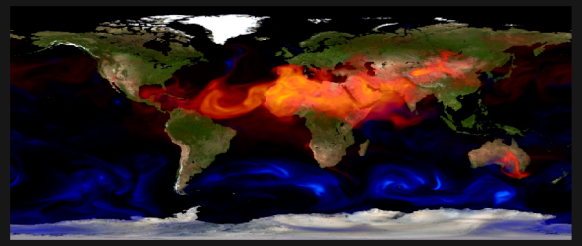
Outline

- Modeling and Data Assimilation at GMAO
- GMAO Products and Resources:
  - GEOS-5 Near Real Time Forecasts
  - MERRA-2 Reanalysis
  - Web Visualization and Resources
- Concluding Remarks

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
- Developing a comprehensive **aerosol data assimilation capability** for constraining and calibrating aerosol transport models, including the estimation of emissions needed for driving such models
- Developing an **aerosol forecasting capability** in support of NASA field campaigns.
- Developing an **aerosol observing system simulation capability** for aiding planning of future NASA observing missions.

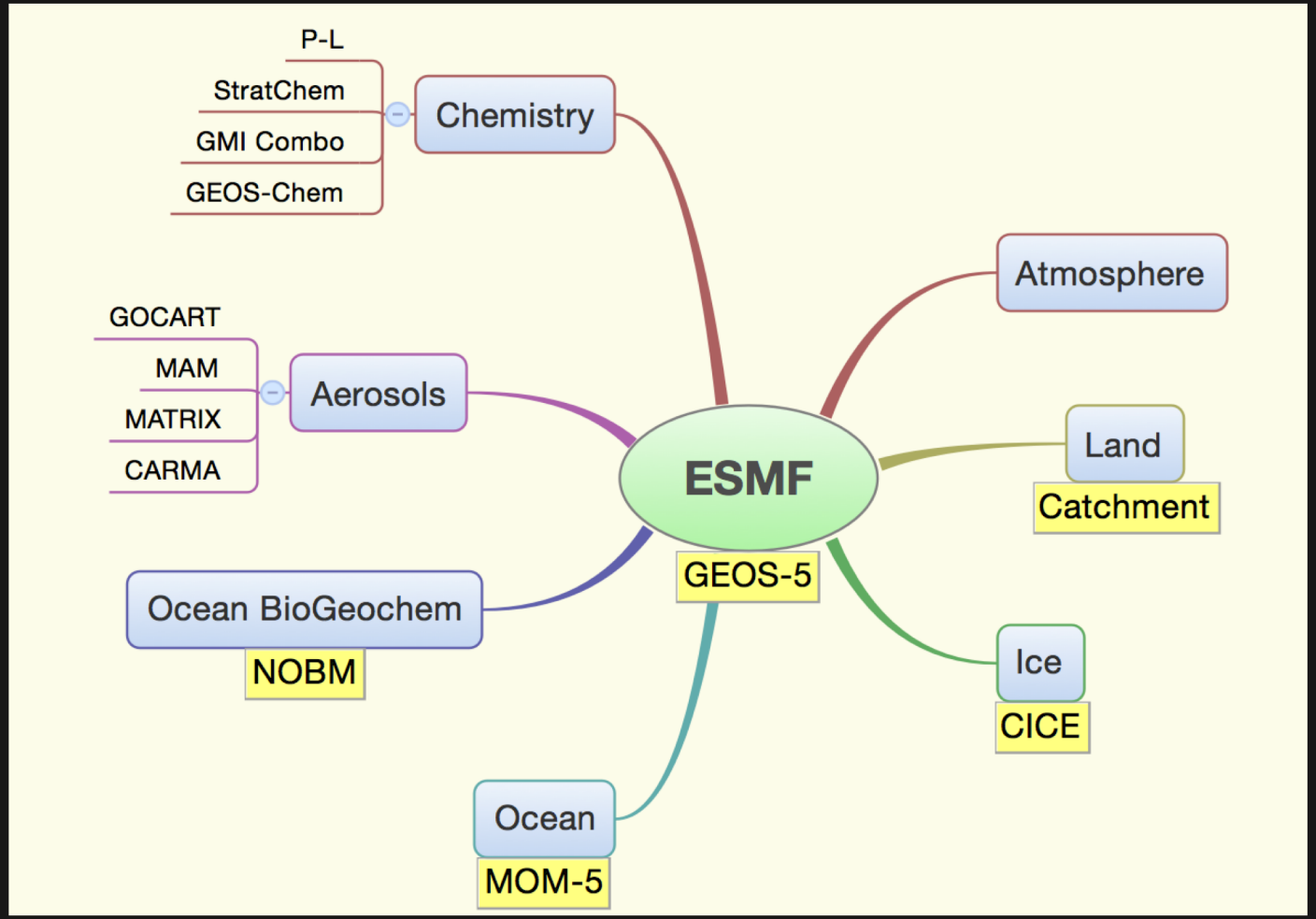
GEOS Earth System Model

Components coupling via the Earth System Model Framework (ESMF)

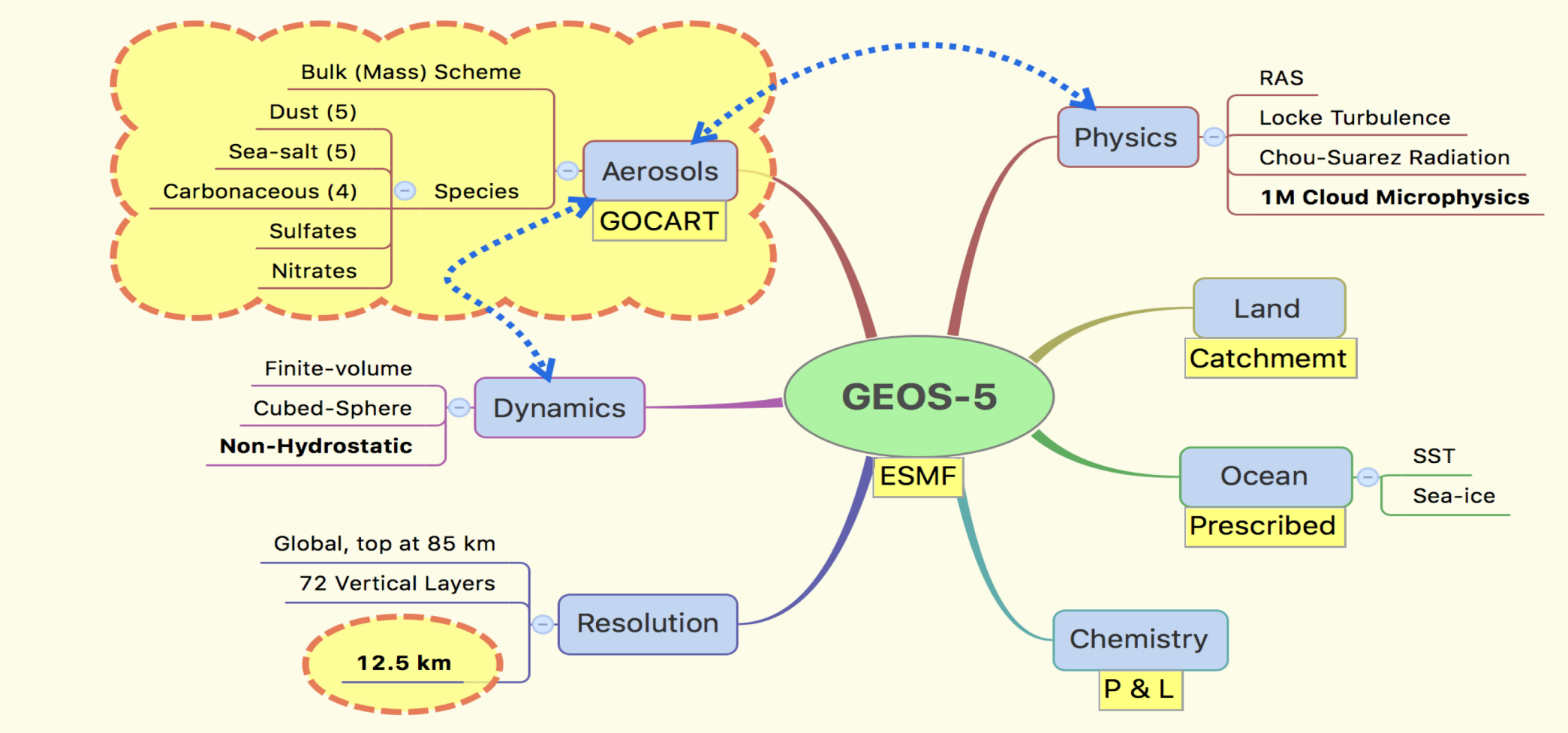
Aerosol and chemistry radiatively coupled to GCM

Applications:

- Weather and aerosol NRT forecasts
- Reanalysis
- Seasonal forecasts
- Observing System Simulation Experiments (OSSEs)

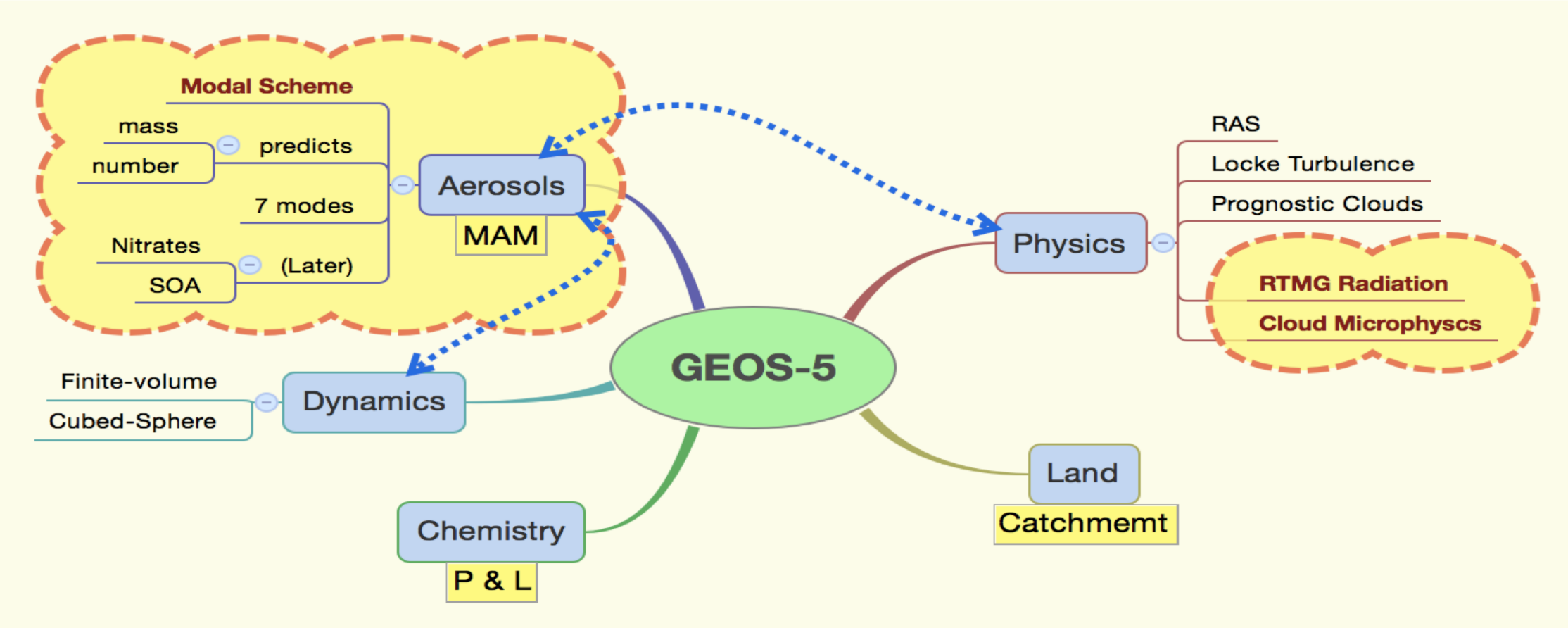


GEOS-5 Model Configuration for current Forward Processing System



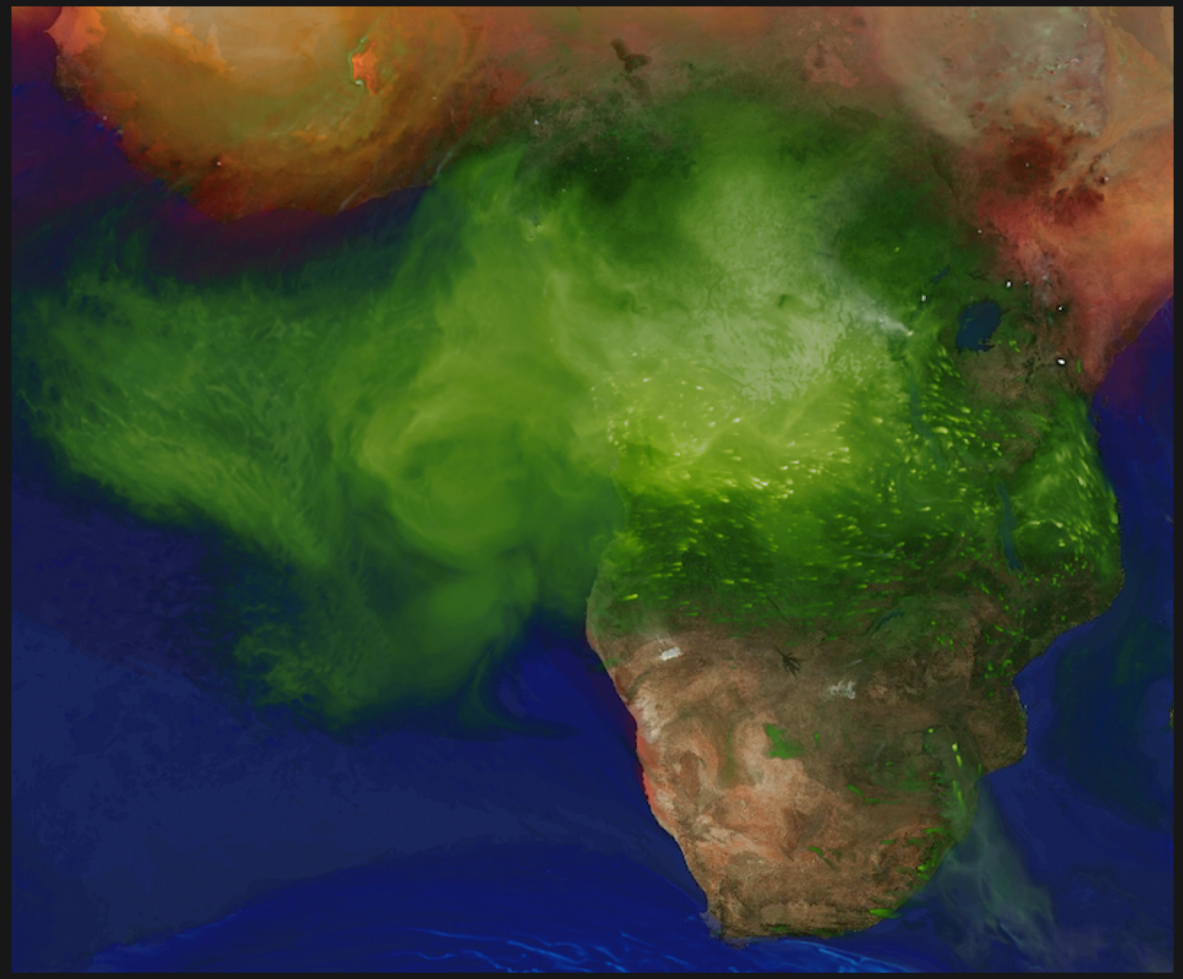
Global, 12.5 km, 72 Levels, top at 0.01 hPa

Current GEOS-5 Development: Aerosol & Clouds Microphysics



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

Biomass Burning Emissions



QFED: Quick Fire Emission Dataset

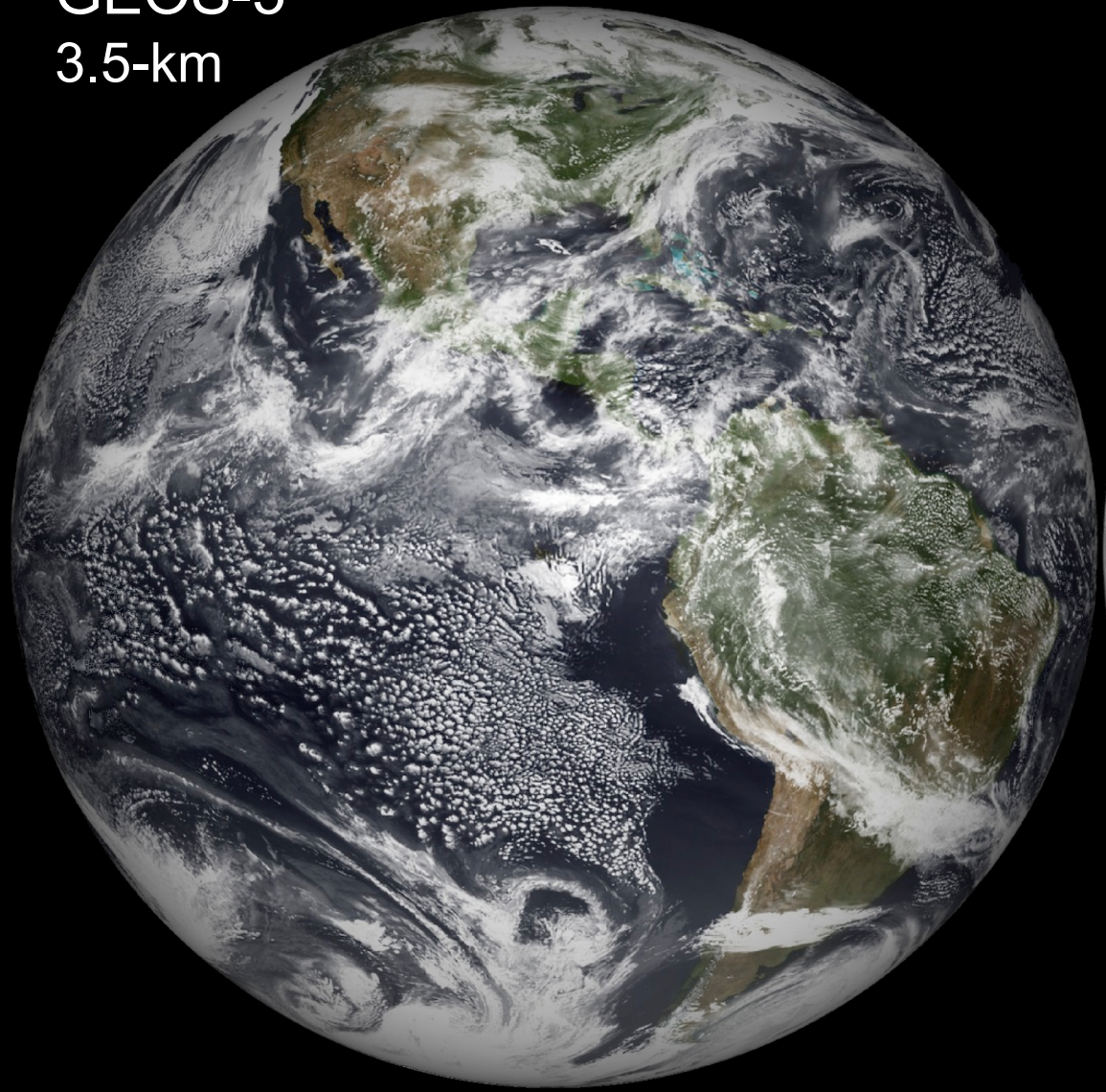
- Top-down algorithm based on MODIS Fire Radiative Power (AQUA/TERRA)
- FRP Emission factors tuned by means of inverse calculation based on MODIS AOD data.
- Daily mean emissions, NRT
- Prescribed diurnal cycle
- In GEOS-5 BB emissions are deposited in the PBL.

Model resolution ≈ Satellite scales

~50-million pixels

GEOS-5

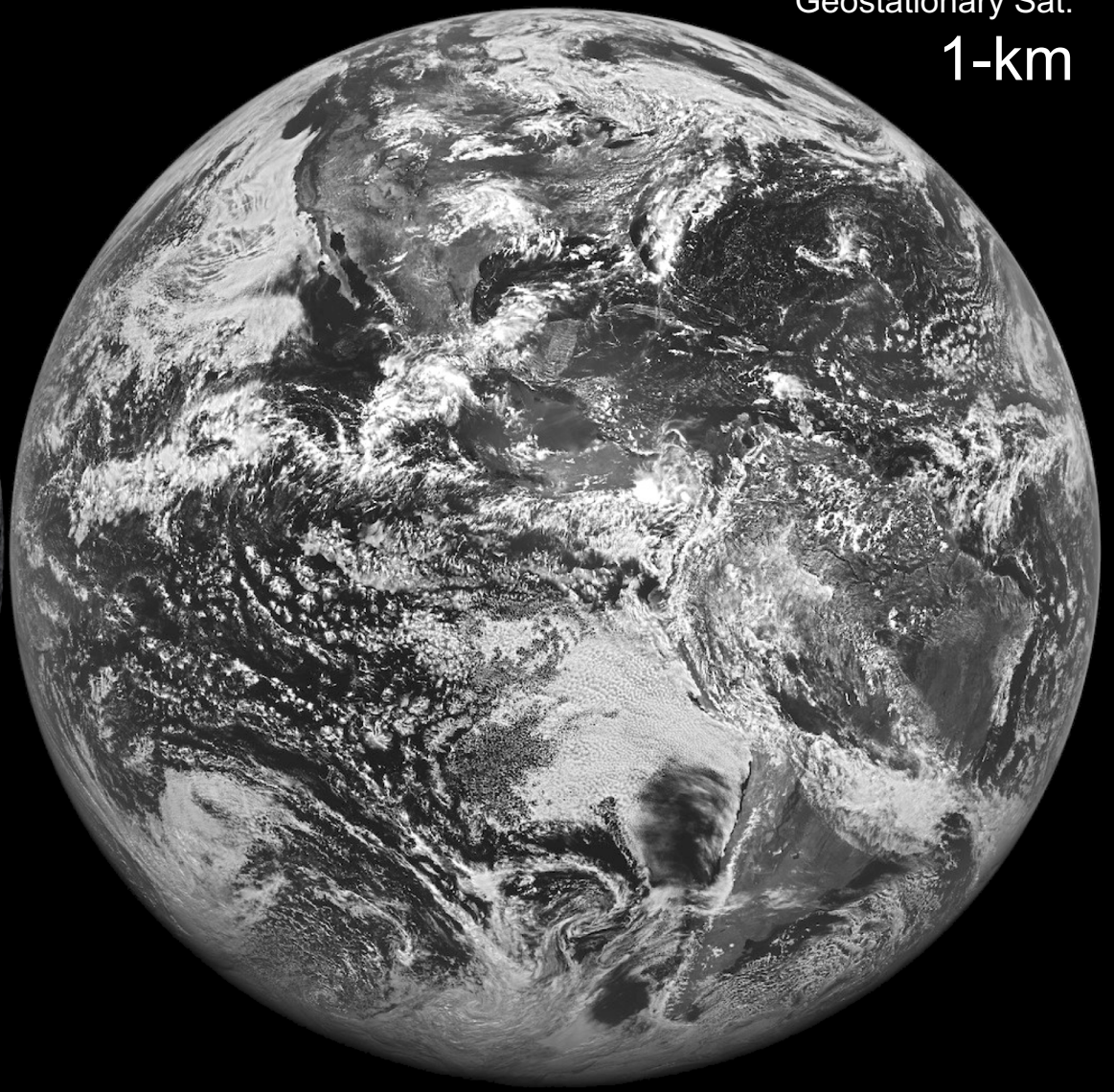
3.5-km



~200-million pixels

Geostationary Sat.

1-km

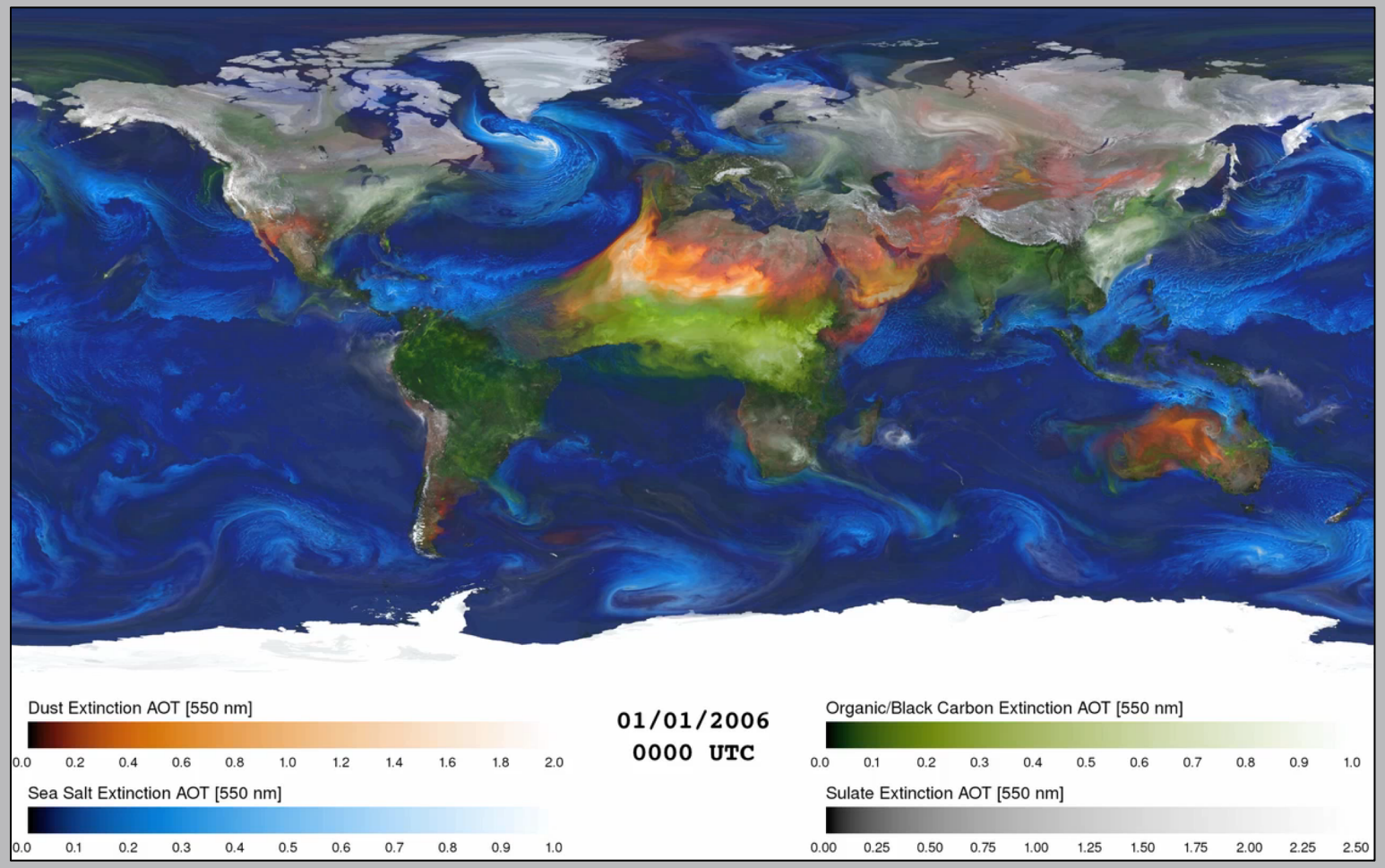


Global Aerosols

7 km GEOS-5 Nature Run
Global Mesoscale Simulation

Goddard SPACE FLIGHT CENTER

Aerosols play an important role in both weather and climate. They are transported around the globe far from their source regions, interacting with weather systems, scattering and absorbing solar and terrestrial radiation, and modifying cloud micro- and macro-physical properties. They are recognized as one of the most important forcing agents in the climate system.



Sulfur Dioxide
Sulfate Aerosols

7 km GEOS-5 Nature Run
Global Mesoscale Simulation

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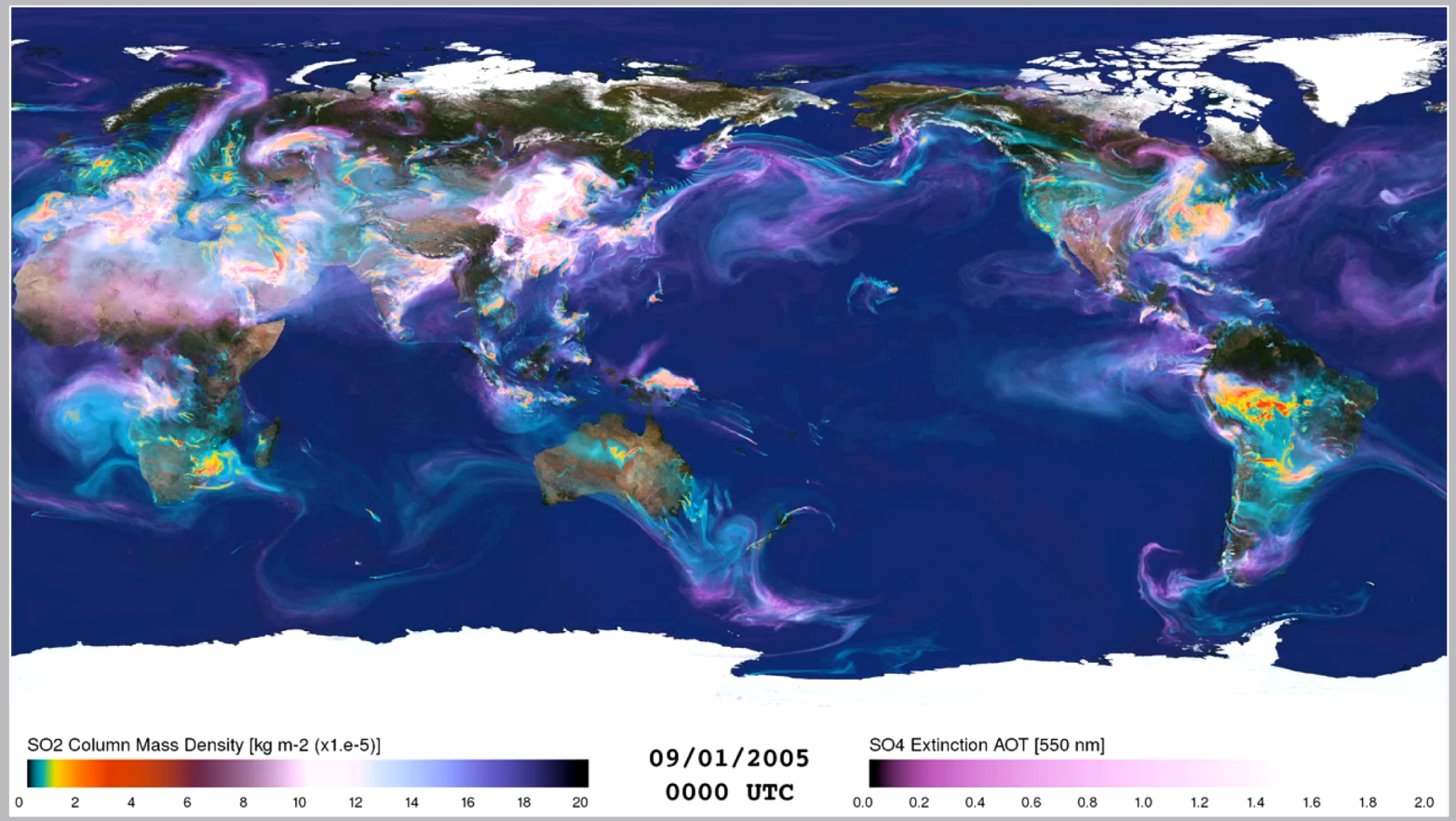
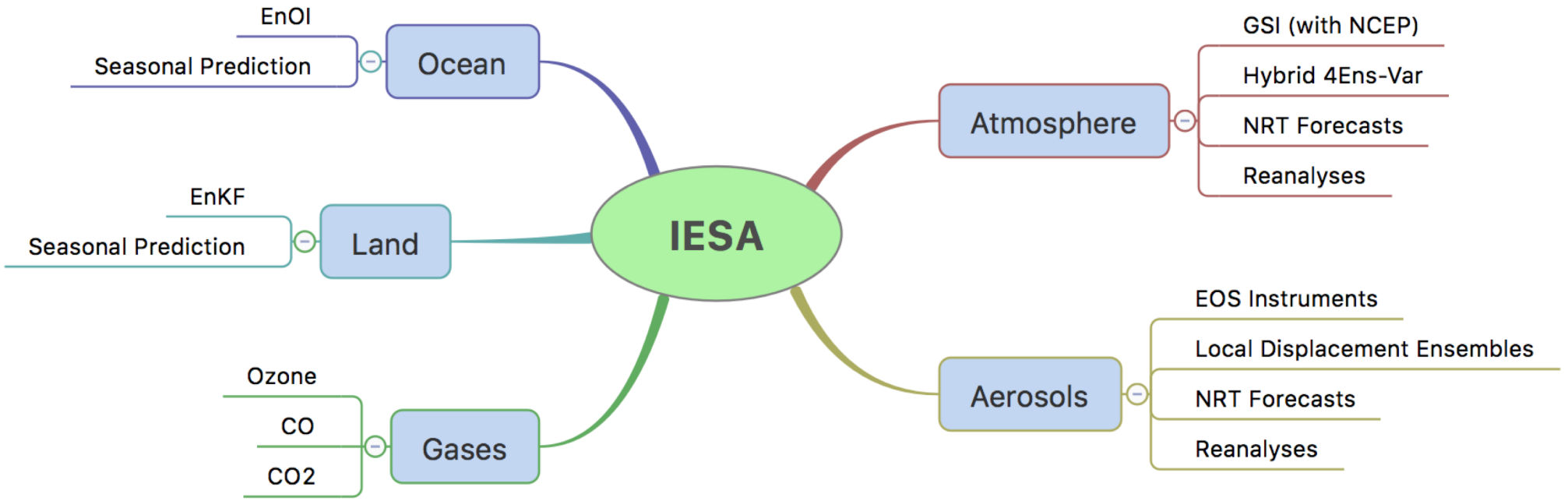
Sulfur dioxide (SO_2), produced during the burning of fossil fuels and from volcanic eruptions, is a short lived gas which can act as pollutant near the surface with detrimental health and acidifying effects. With a mean life time of just a couple of days in the troposphere, emitted SO_2 is quickly converted to sulfate aerosol (SO_4) through oxidation by OH or by reaction with H_2O_2 within clouds. The resulting SO_4 exerts a direct radiative effect on the atmosphere and it can also have an indirect radiative effect by inducing changes in cloud and precipitation microphysics.



NASA Earth Science Satellites

Integrated Earth System Analysis (IESA)
Data Assimilation for the Earth System



GEOS-5 has *Data Assimilation* efforts associated with each major component

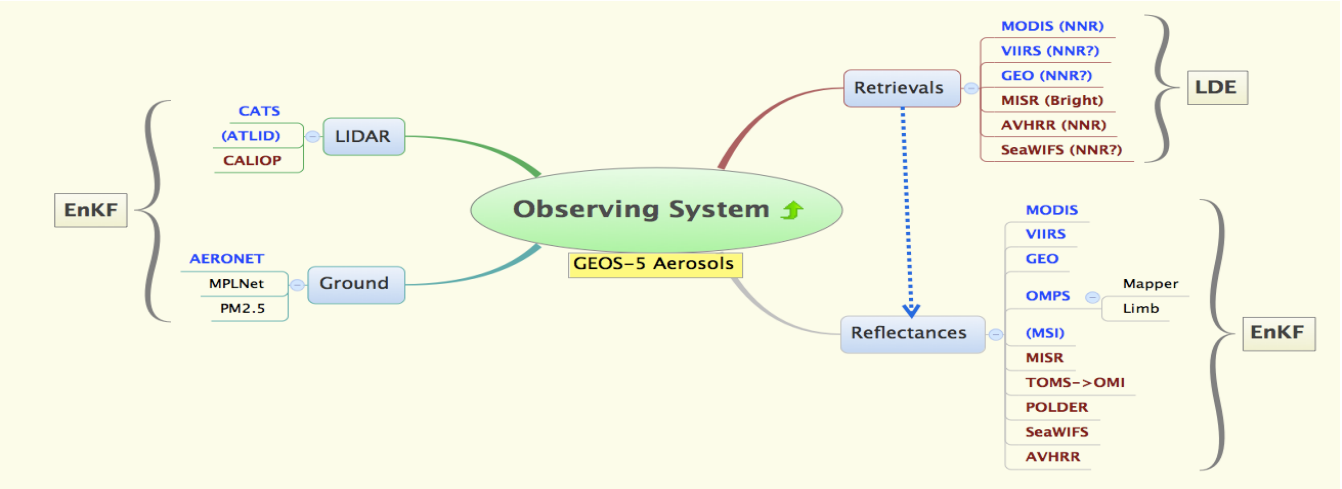
- ❑ Concurrent atmospheric and aerosol data assimilation for Wx time scales
- ❑ Concurrent ocean and land-surface assimilation for seasonal prediction
- ❑ Evolving into to a fully *integrated* (if not *coupled*) IESA

Why Aerosol Data Assimilation?

- **Models are useful but difficulty in specifying emissions, microphysical processes and transport lead to large uncertainties**
- **While there are a large number of aerosol sensors, there are still large blind spots:**
  - Measurements are usually vertically integrated
  - Diurnal cycle is not represented by polar orbiters
- **Data assimilation can act as an integrator of model/obs information and as a conveyor of past observations**

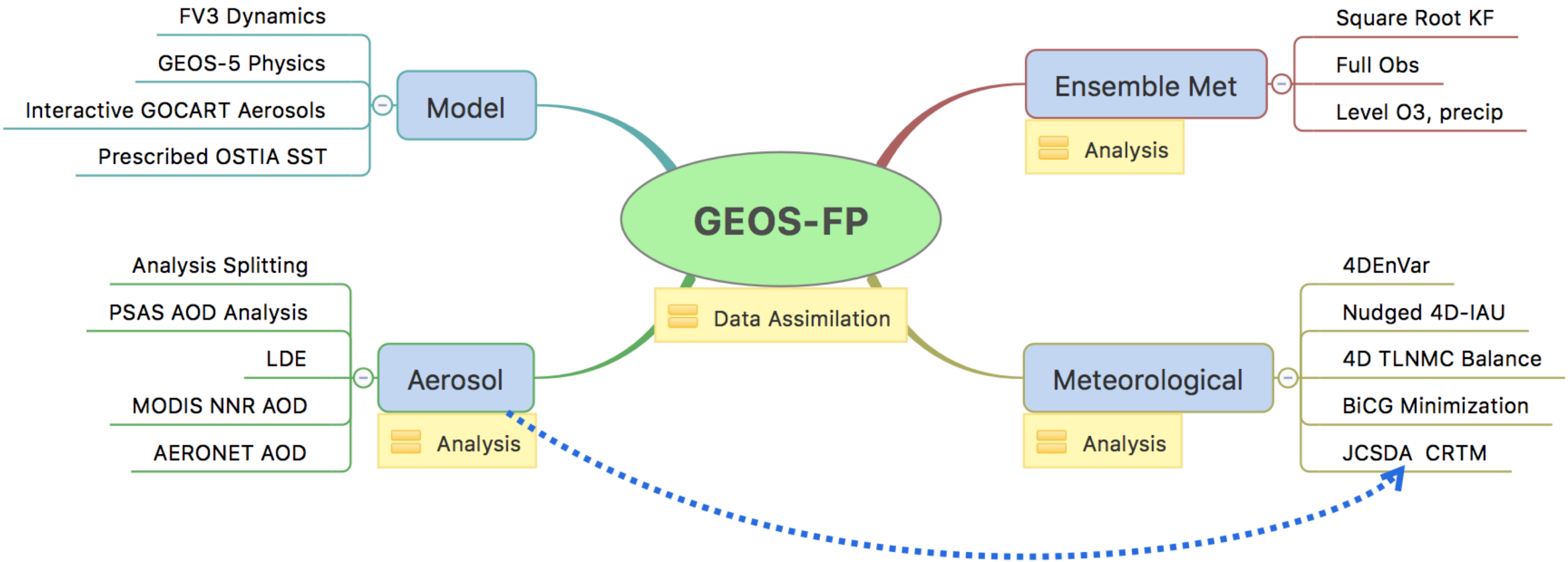
Aerosol Observing System

- **Aerosol Optical Depth (AOD) is the most commonly available observable**
  - Vertically integrated mass weighted by extinction coefficient, summed over multiple species: *low observability*
  - Available multi-spectral AOD measurements are not really measured
- **Radiance assimilation:**
  - Vector scattering calculations needed for UV-VIS measurements are not cheap
  - Surface BRDF characterization is a challenge
- **Surface PM 2.5**
  - Single level
  - Often plagued by representativeness



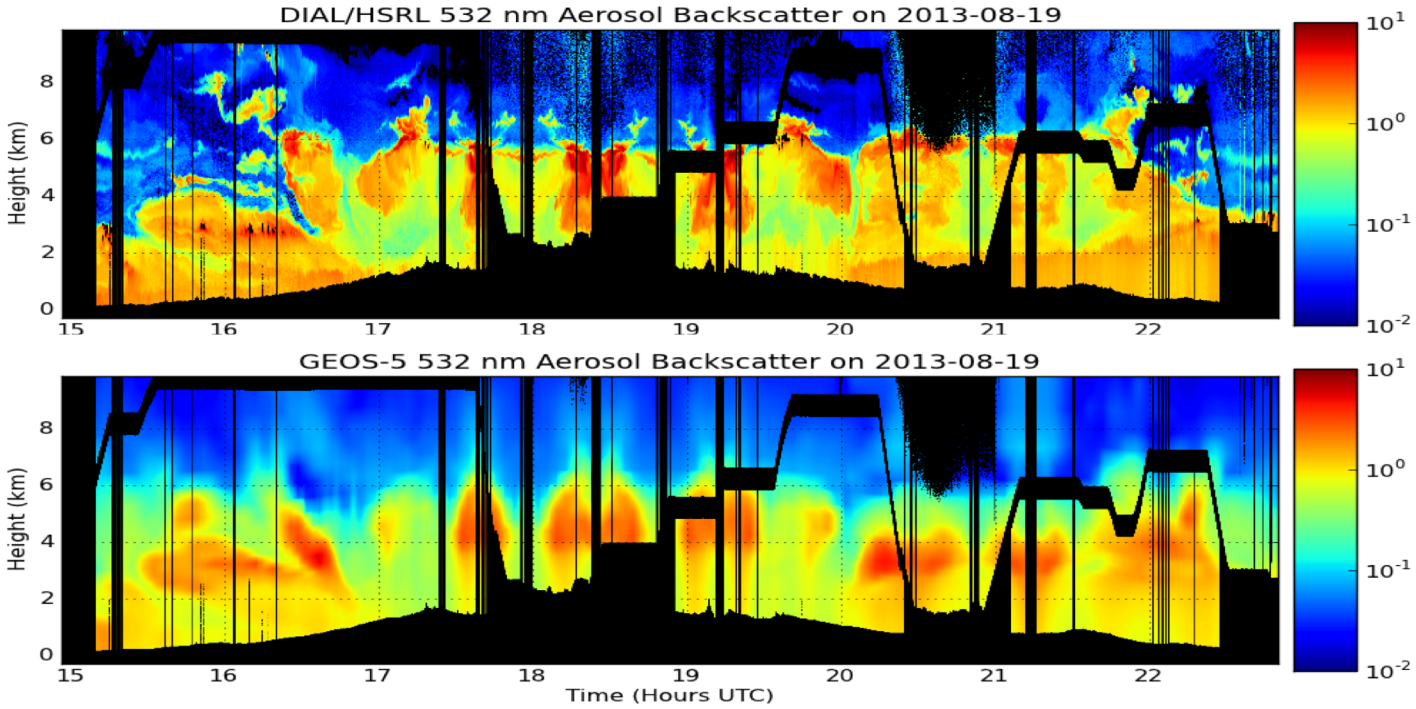
- **Lidar measurements provide vertical info**
  - Spatially coverage is poor (pencil thin)
  - Attenuated backscatter again requires optical assumptions which are not directly measured
    - New HSRL concept is promising

GEOS-FP: Meteorological & Aerosol DA



Field Campaign Support

- Global 5-day chemical forecasts
  - O_3, aerosols, CO, CO_2, SO_2
  - Nominally 12.5 km
- Driven by real-time biomass emissions from MODIS FRP (QFED)
- Constituents transported on-line, interactively
- Since 2007 supported several field missions including TC4, ARCTAS , GloPac, ATTREX, DISCOVER-AQ, HS_3 ,SEAC4RS, etc.



Comparison of observed (top) and simulated (bottom) aerosol backscatter for a slight during the 2013 SEAC4RS campaign.

Why we make a reanalysis?

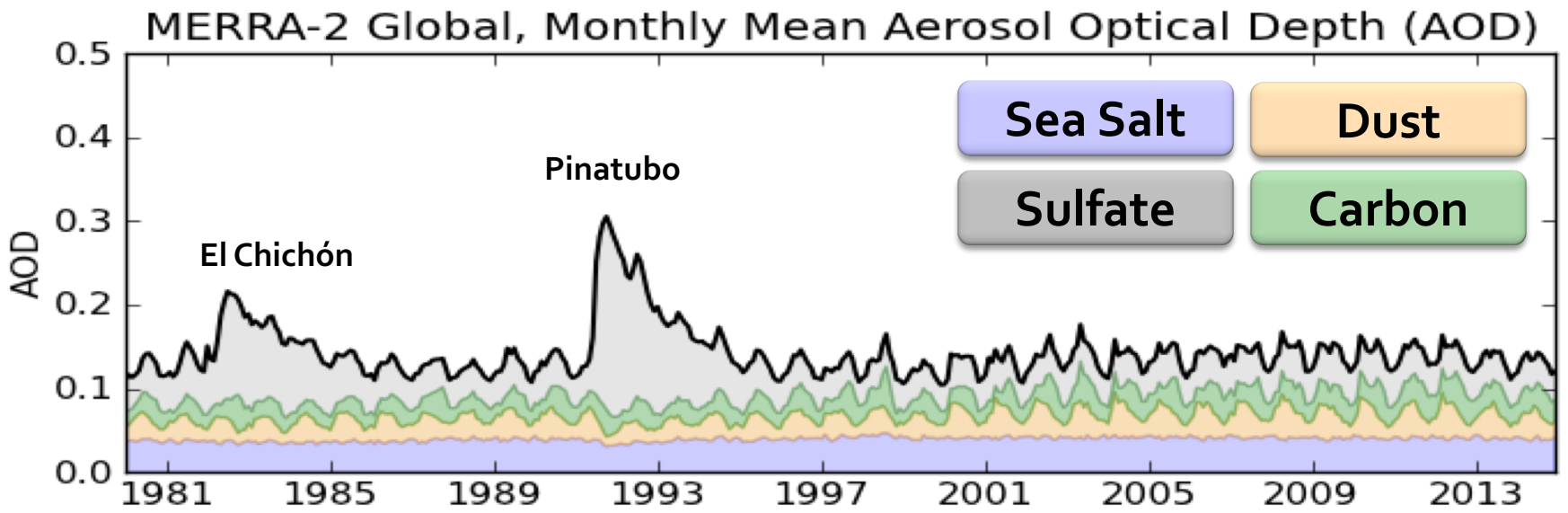
A consistent reprocessing of Earth system observations using a modern, unchanging data assimilation system

- Relies on models to interpret, relate and combine many different observations from multiple sources
- Produces multi-decadal gridded data sets that estimate a large variety of Earth system variables, including ones that are not directly observed
- Has become fundamental to research and education in the Earth Sciences

A successful reanalysis ***requires*** a good forecast model combined with bias-corrected/quality controlled observations

MERRA-2 Global Mean AOD Analysis: 1980 - Onward

- Unique amongst its peers, the MERRA-2 reanalysis now includes an aerosol reanalysis for the modern satellite era (1980 – onward).
- Aerosols are ***coupled*** to the meteorological reanalysis (both radiatively and through emissions/loss processes).



MERRA-2
Evaluation Highlights

Aerosol Absorption

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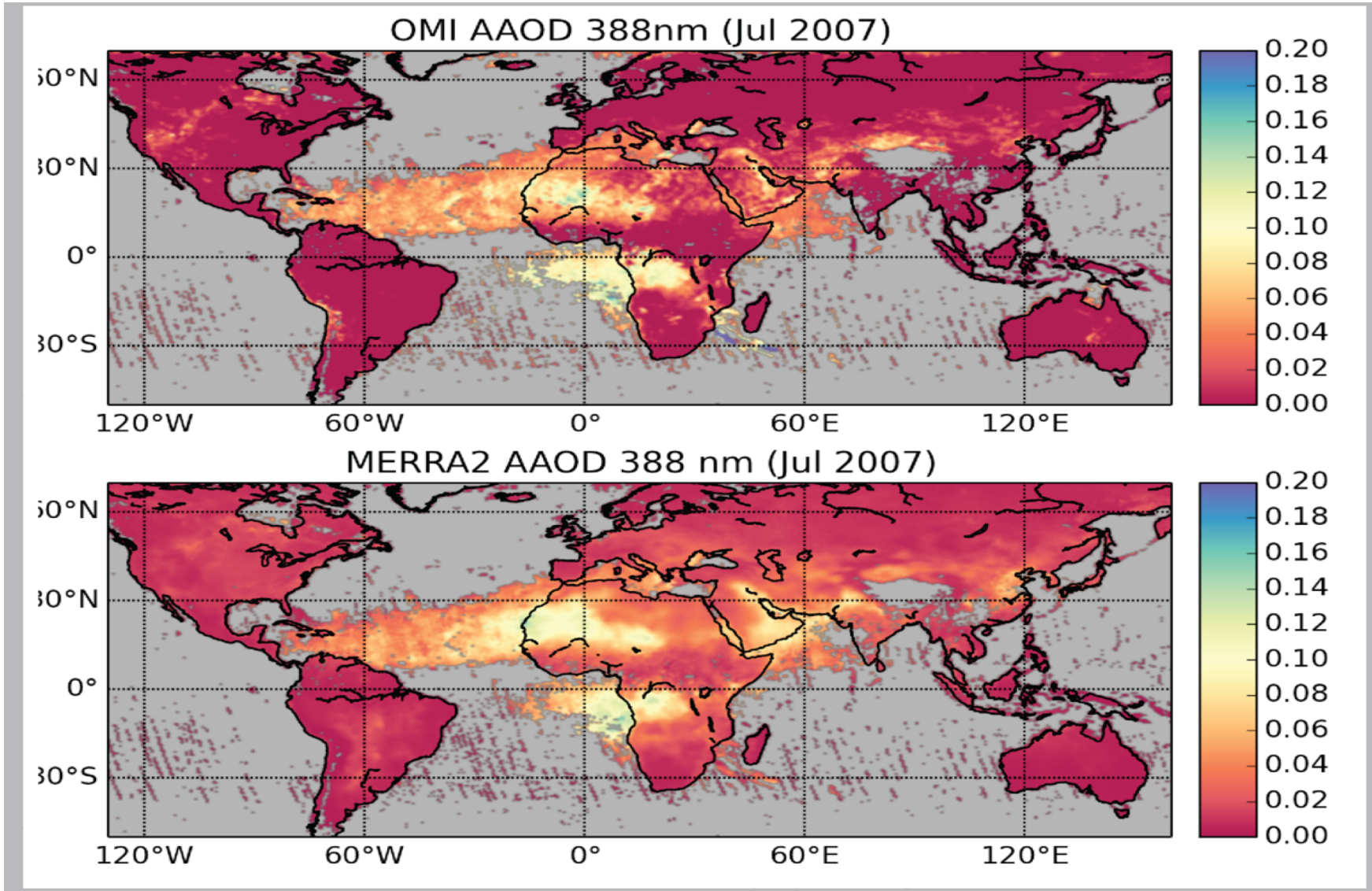
- Comparison of MERRA-2 Absorption Optical Depth (AAOD) with OMI retrievals
- Good agreement for African dust and smoke
- North American biomass burning underestimated according to OMI



Web Resources

https://gmao.gsfc.nasa.gov/

Relevant URLs

Site	URL
GMAO Home Page	https://gmao.gsfc.nasa.gov/
Weather Analysis & Prediction	https://gmao.gsfc.nasa.gov/weather_prediction/
GEOS NRT Product Information	https://gmao.gsfc.nasa.gov/GMAO_products/NRT_products.php
GEOS-FP File Specification	https://gmao.gsfc.nasa.gov/products/documents/GEOS_5_FP_File_Specification_ON4v1_1.pdf
GMAO Publications	https://gmao.gsfc.nasa.gov/pubs/
MERRA-2 Project Page	https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/
Forecast Web Visualizations	https://fluid.nccs.nasa.gov/weather/
NRT Data Access: data files - Assimilation - Forecasts	 - https://portal.nccs.nasa.gov/datashare/gmao_ops/pub/fp/das/ - https://portal.nccs.nasa.gov/datashare/gmao_ops/pub/fp/forecast/
NRT Data Access: OPeNDAP - Assimilation - Forecasts	 - https://opendap.nccs.nasa.gov/dods/GEOS-5/fp/0.25_deg/assim - https://opendap.nccs.nasa.gov/dods/GEOS-5/fp/0.25_deg/fcast

Relevant Aerosol Data Products

Collection	Variables
inst3_3d_aer_Nv 3D Instantaneous Aerosol Concentrations	Dust (5 bins) , sea-salt, (5 bins), organic and black carbon, sulfates, nitrates
tavg3_2d_aer_Nx 2D Time-averaged Primary Aerosol Diagnostics	Aerosol optical depth, surface concentration and column amounts, angstrom exponent, vertically integrated mass flux
tavg3_2d_adg_Nx 2D Time averaged Secondary Aerosol Diagnostics	Emissions, deposition, chemical production

Concluding Remarks

- Aerosols are an integral part of the GEOS-5 N.R.T. and re-analysis systems
- Constrained by assimilation of satellite data, GEOS aerosol analyses and forecasts provide estimates of
  - ✓ Speciated aerosol optical depth
  - ✓ Speciated surface deposition
  - ✓ Oportunities for development of *Model Output Statistics (MOS)* for sites of interest to the solar industry.
- MERRA-2 provides the first integrated aerosol-meteorology reanalysis for the satellite era (1980-present, better constrained for 2000-present)
- Current GEOS-5 developments incorporate cloud and aerosol microphysics
  - ✓ Aerosol-cloud interactions, missing species
  - ✓ There is great need for in-situ and remotely sensed data to evaluate/validate new parameterizations

Extra Slides

Aerosol Analysis: Splitting

2D AOD ANALYSIS

- Observable 550 nm AOD is 2D
  - Constrains column averaged optics
  - Cannot constrain speciation or vertical distribution
- Analysis in observation space:

$$\tau^a \equiv Hq^a = H\left(q^b + \delta q^a\right) = \tau^b + \delta\tau^a$$

GOING TO 3D CONCENTRATIONS

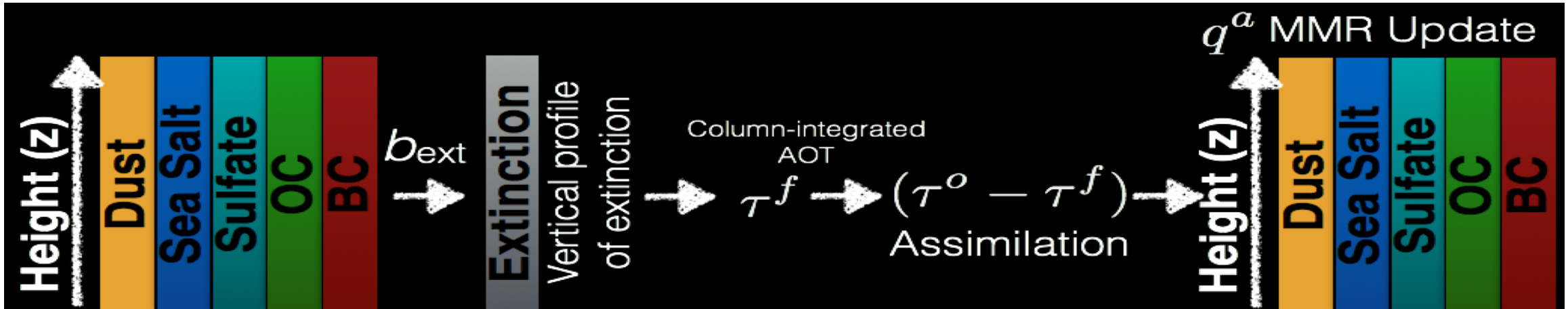
- Based on error covariances:

$$\delta q^a = BH^T\left(HBH^T\right)^{-1}\delta\tau^a$$

- Using ensemble perturbations,

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

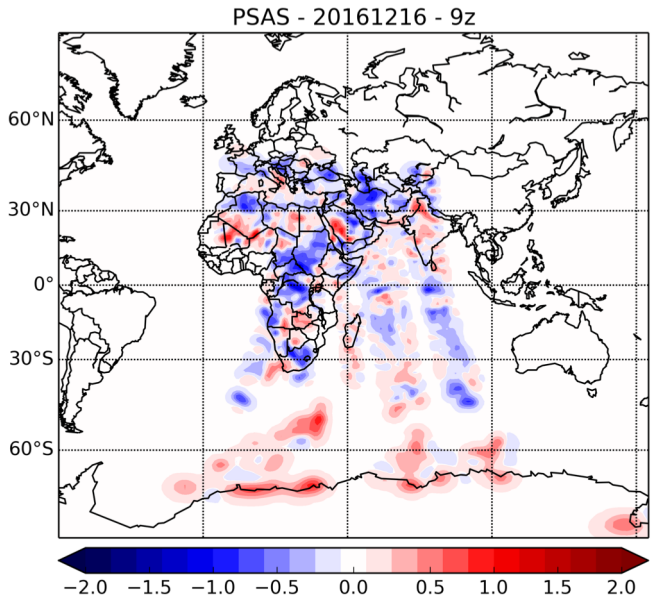
- NRT GEOS-5 uses Local Displacement Ensembles (LDE), in 1D
- Developing EnKF for Aerosols



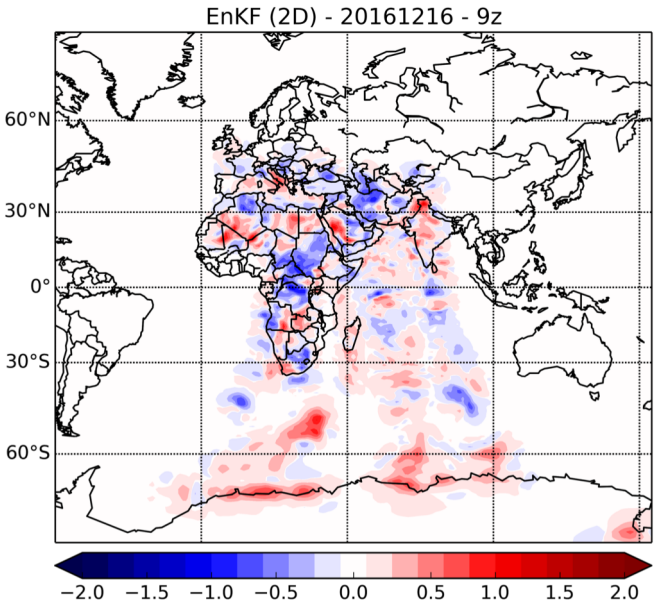
In Development: Aerosol EnKF

- **As part of GMAO's hybrid system, aerosol ensemble members are produced as a matter of routine**
- **The same Whitaker-Hamill EnKF used the hybrid Meteorological assimilation has been adapted for aerosols**
- **Target observation systems**
  - Multi-spectral AOD: 470, 550 and 870 nm
  - Lidar attenuated backscatter
  - Sensors: MODIS, VIIRS, GEO, CATS/CALIOP, TropOMI

PSAS AOD inc (current method)

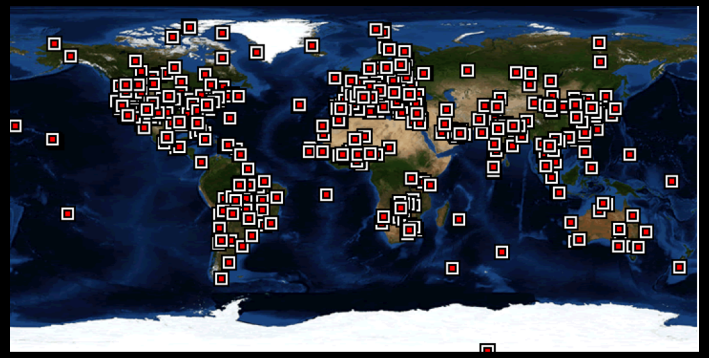


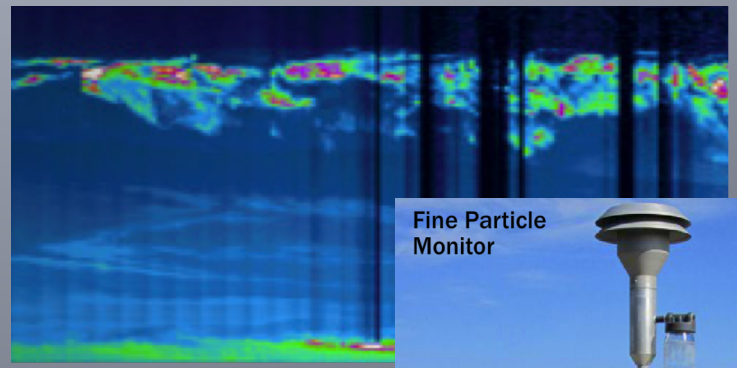
EnKF AOD inc Ensmean



MERRA-2 Aerosols Evaluation Highlights

Using Independent Observations





MERRA-2
Evaluation Highlights

Historical Cruises

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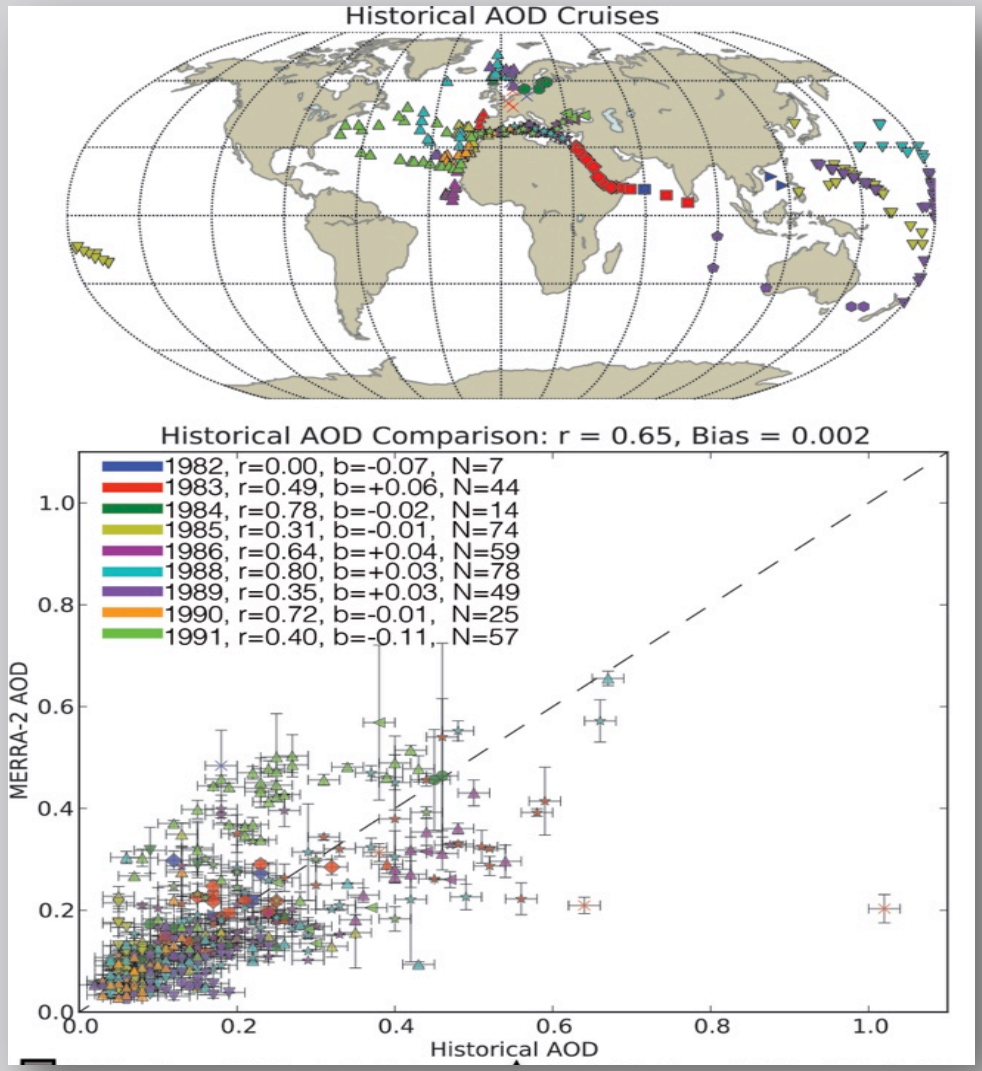
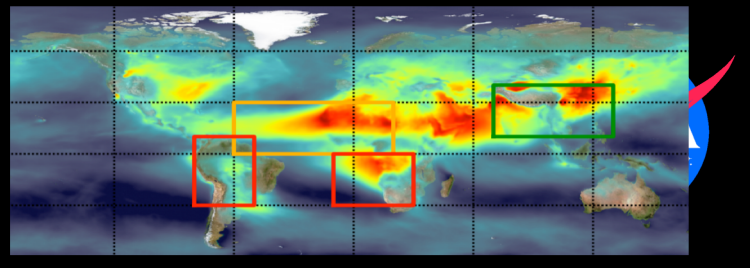
Independent AOD data is scant before the EOS Period.

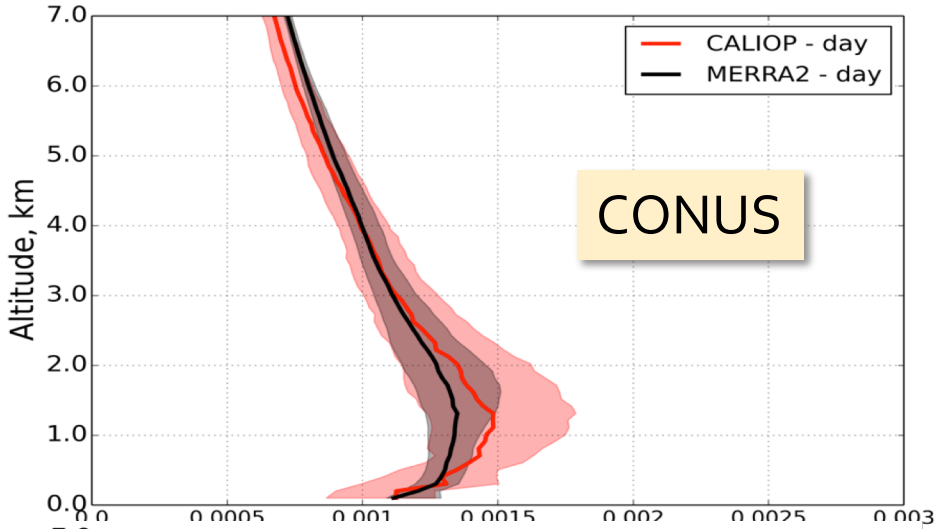
These historical ship cruises provides an unique opportunity to evaluate the assimilation of AVHRR data for the pre-EOS era.

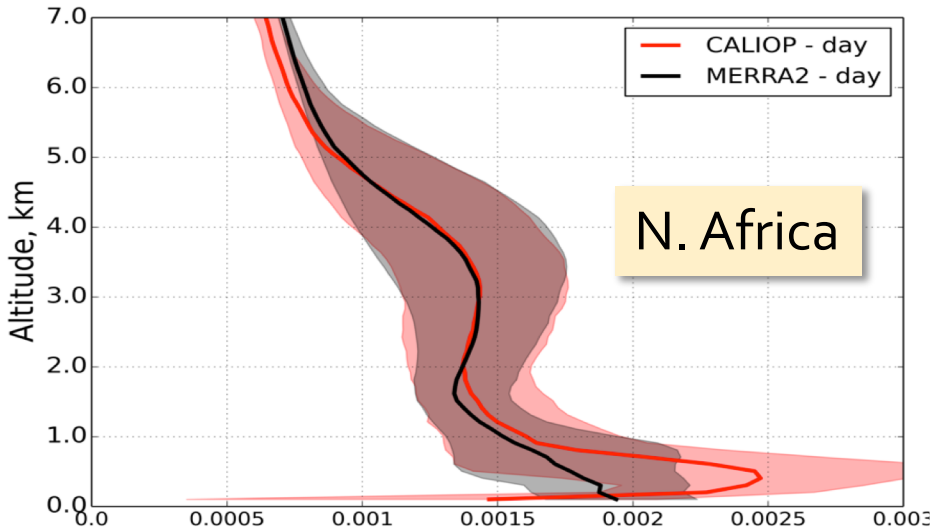


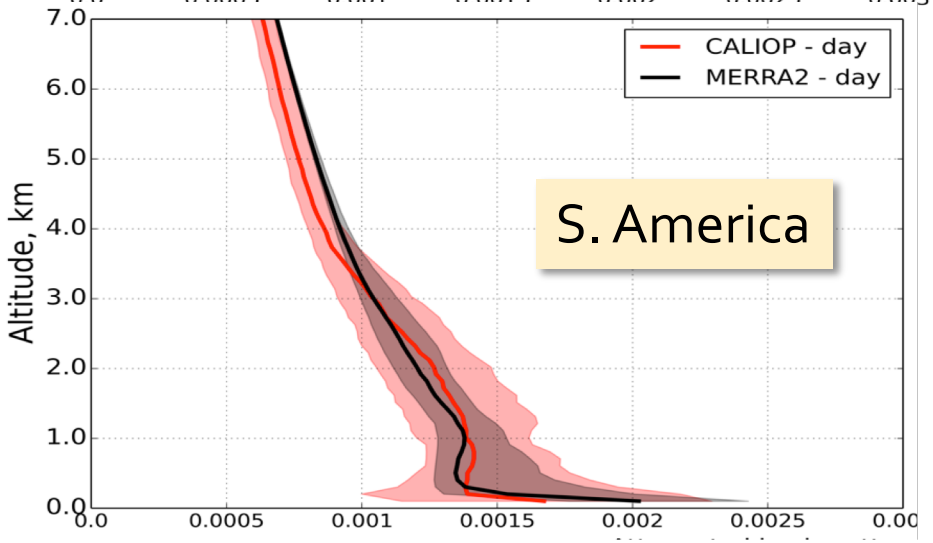
Vertical Structure: Comparison to CALIOP

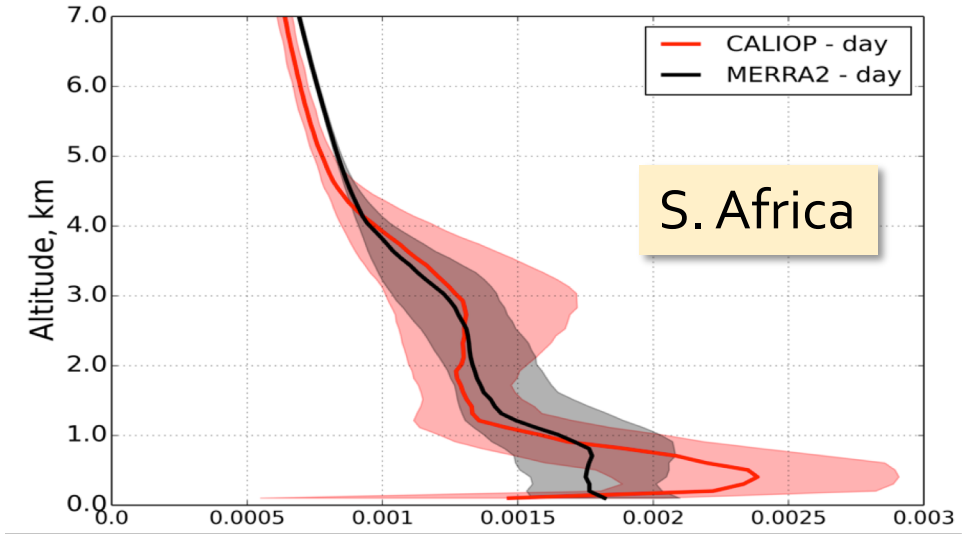


Attenuated Backscatter $km^{-1} sr^{-1}$









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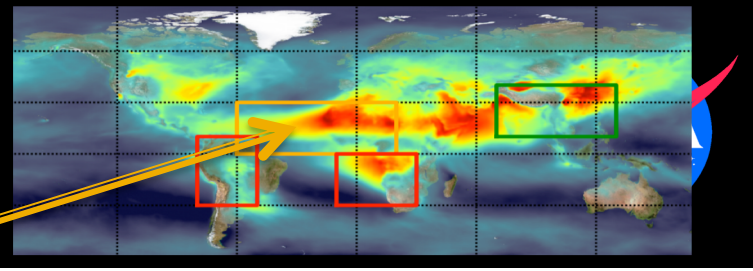
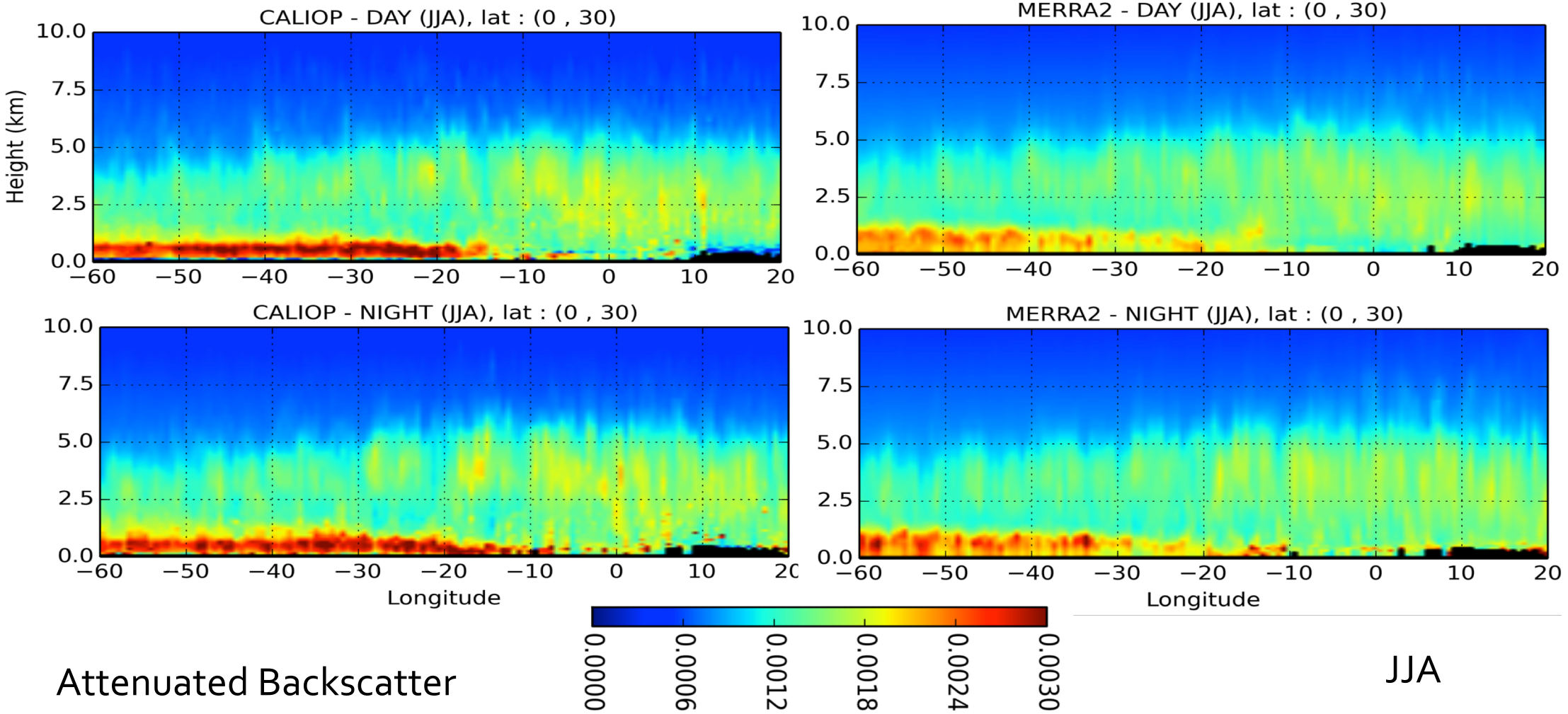




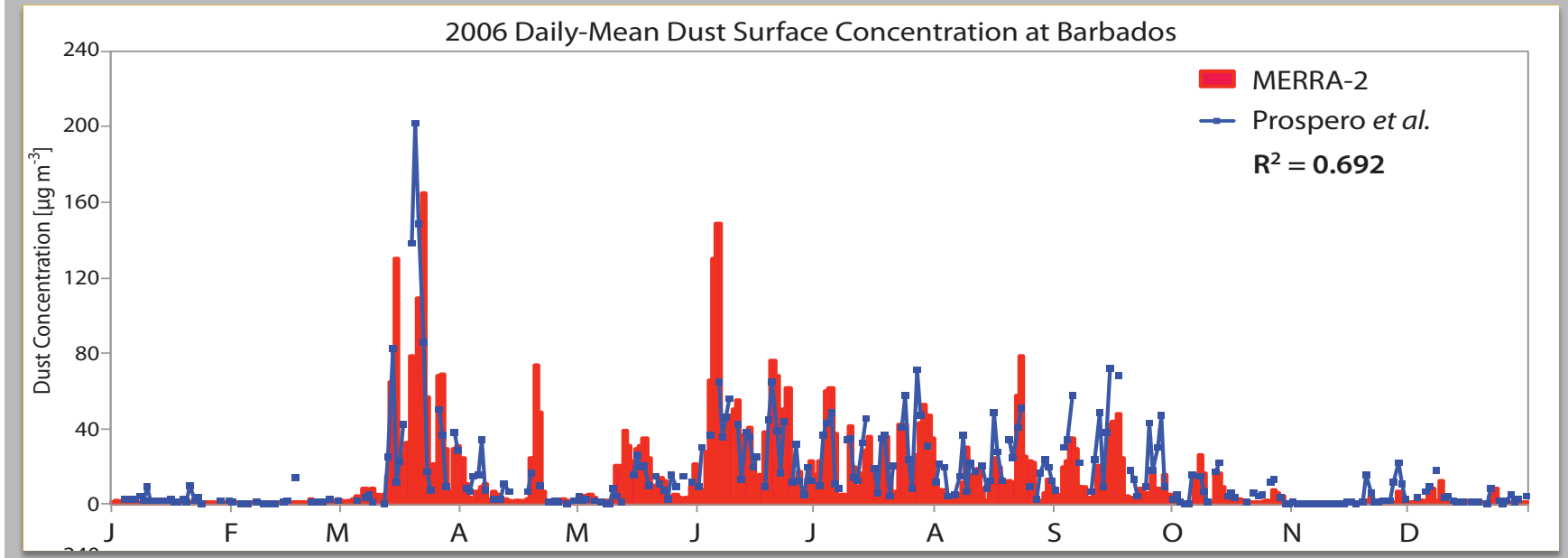
Attenuated Backscatter

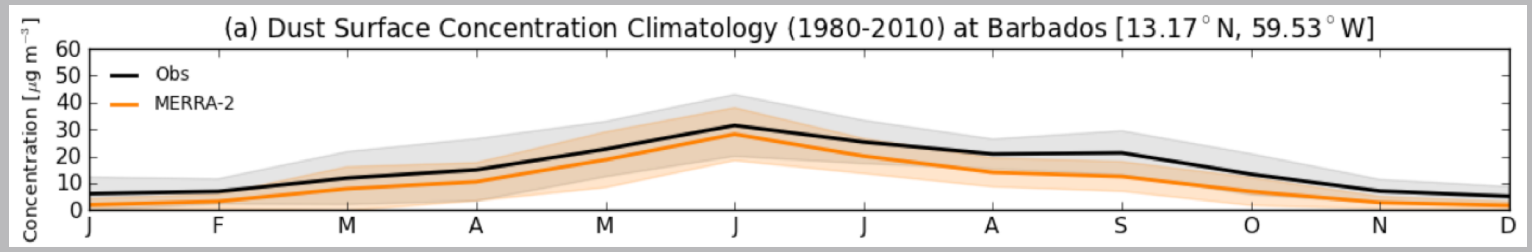
JJA

MERRA-2
Evaluation Highlights

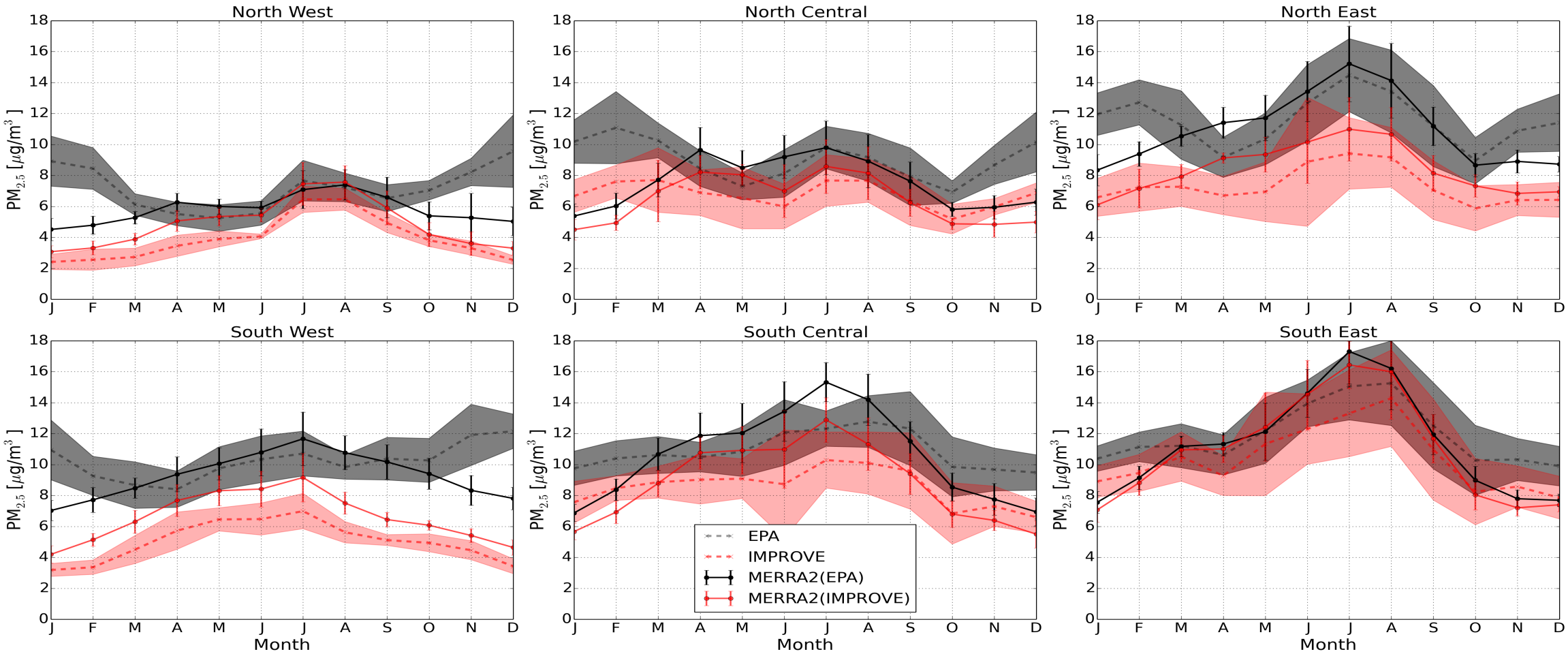
Dust Transport: Barbados

- High correlation with in-situ dust concentration measurements in Barbados
- Dust concentration seasonal cycle well captured in Barbados



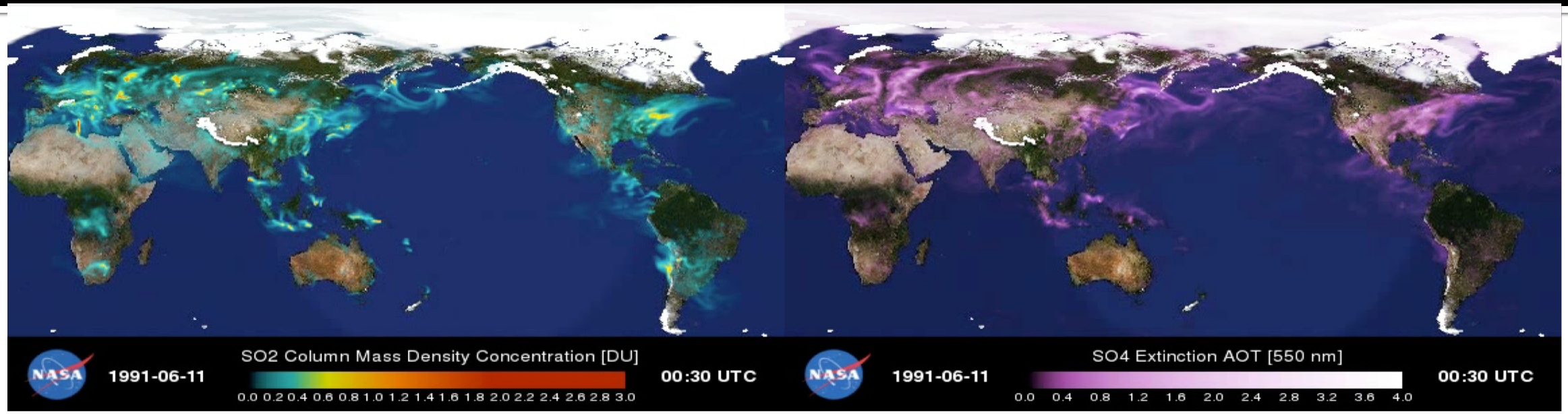


$PM_{2.5}$ (Total) Regional Climatology



Comparison with in-situ measurements after *Buddy Check*

MERRA-2: Pinatubo Eruption



- First aerosol assimilation to include major historic volcanic events like El Chichón (1982) and Pinatubo (June, 1991).
- Movie shows the co-evolution of gaseous SO_2 emissions from Pinatubo (left) and formation of the the sulfate aerosol plume (right) as SO_2 is converted into particles.
- SO_2 (g) is from emissions inventories and unconstrained by assimilation. Sulfate aerosol AOD (right), however, is impacted by the assimilation of total aerosol AOD.