Aerosol Forecasting, Reanalysis and Potential Connections to SPARTAN

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Third International SPARTAN Meeting:
Exploring and Developing Collaborations
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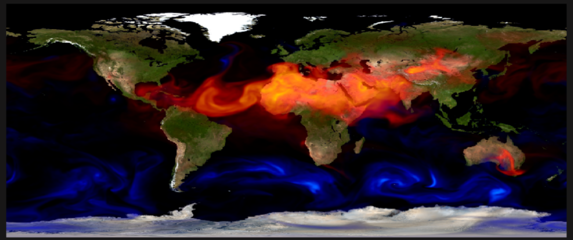
Outline

- Modeling and Data Assimilation at GMAO
- GMAO Products and Resources:
  - GEOS-5 Near Real Time Forecasts
  - MERRA-2 Reanalysis
  - Web Visualization and Resources
- Potential Connections to SPARTAN
- 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 reanalysis capability** for climate record keeping
- Developing an **aerosol observing system simulation capability** for aiding planning of future NASA observing missions.

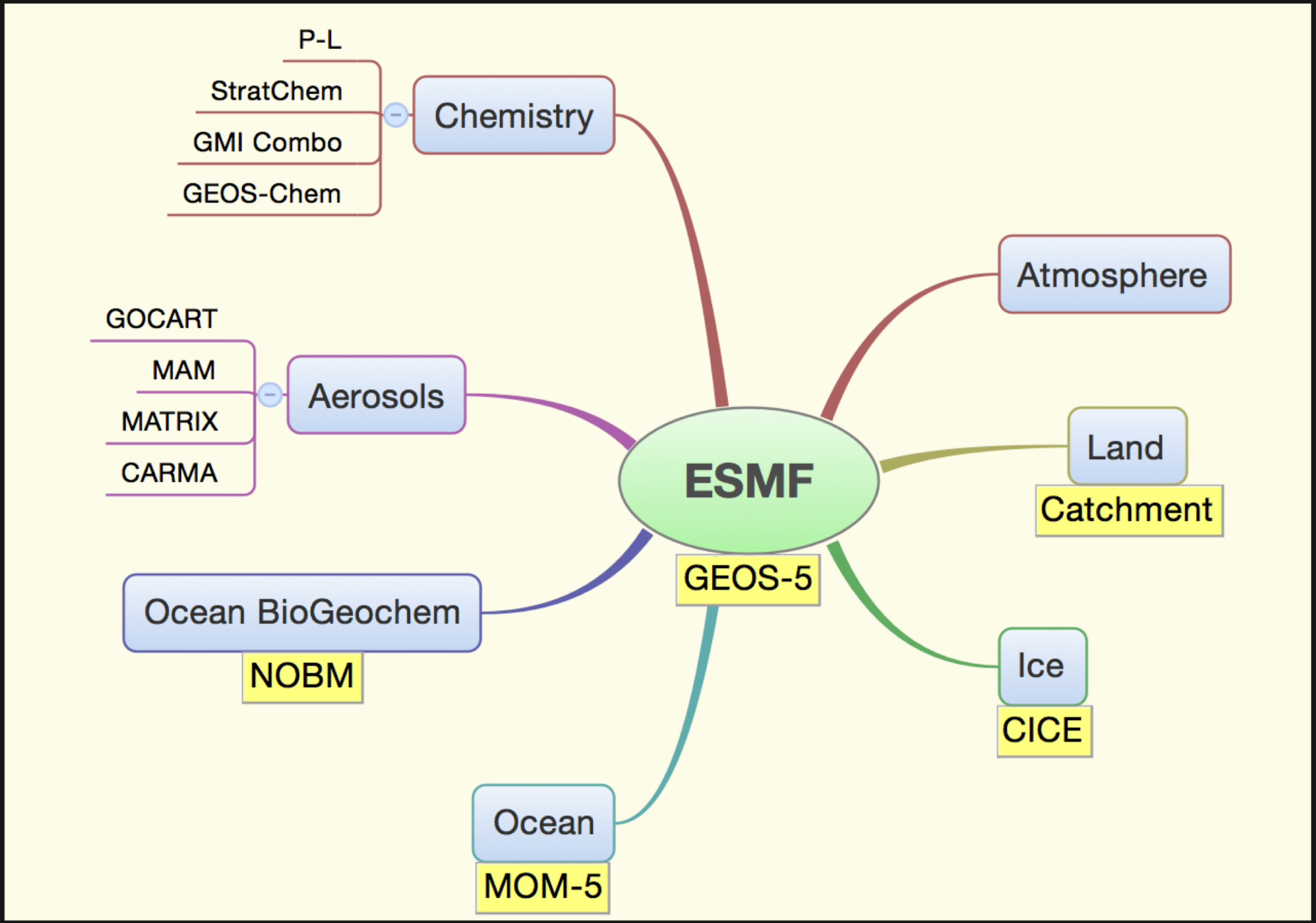
GEOS Earth System Model

Components coupling via the Earth System Model Framework (ESMF)

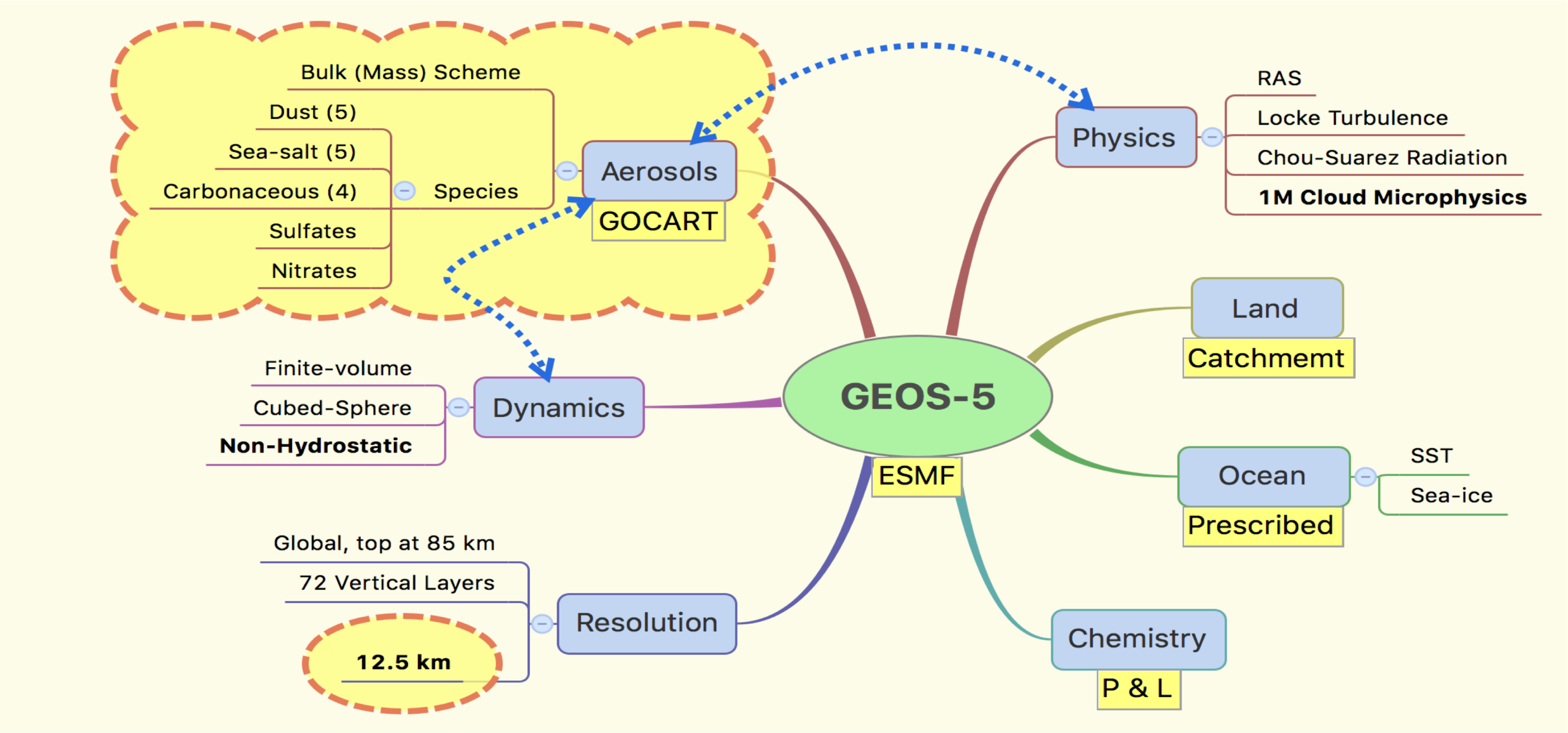
Aerosol and chemistry radiatively coupled to GCM

Applications:

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

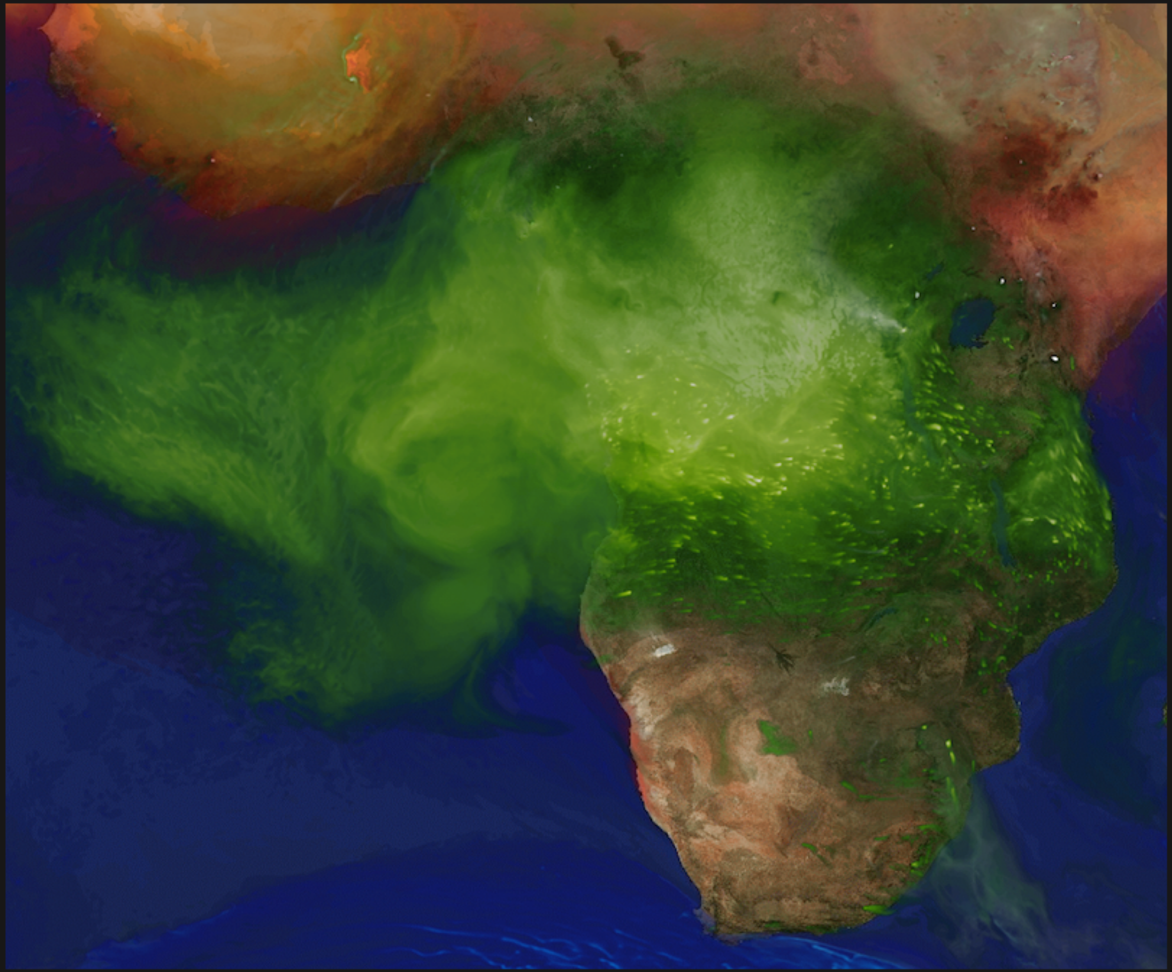


GEOS Model Configuration for current Forward Processing System



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

Biomass Burning Emissions



QFED: Quick Fire Emission Dataset

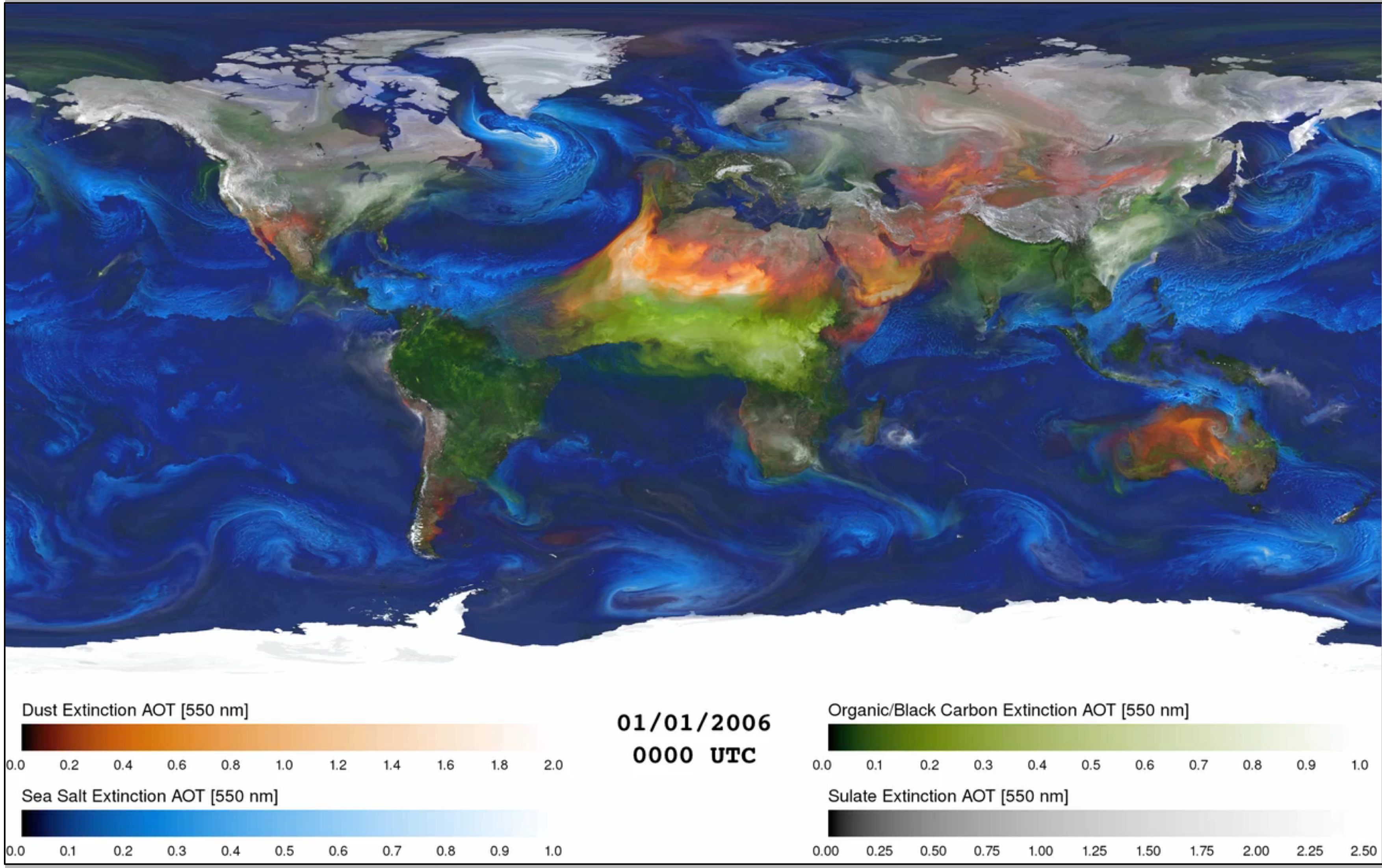
- Top-down algorithm based on MODIS Fire Radiative Power (AQUA/TERRA)
- FRP Emission factors tuned by means of inverse calculation based on MODIS AOD data.
- Daily mean emissions, NRT
- Prescribed diurnal cycle
- In GEOS-5 BB emissions are deposited in the PBL.

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.

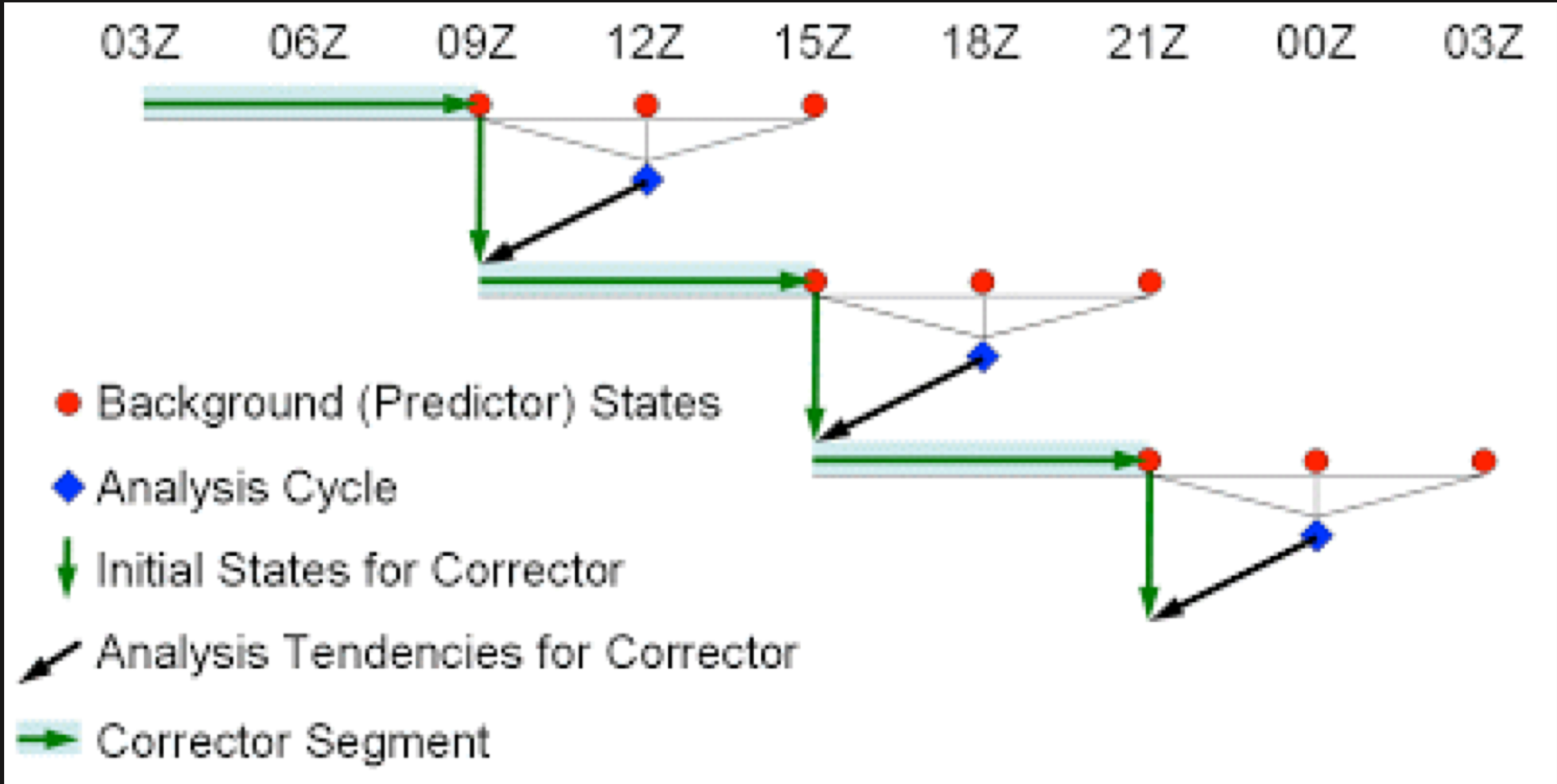


NASA Earth Science Satellites

Why Aerosol Data Assimilation?

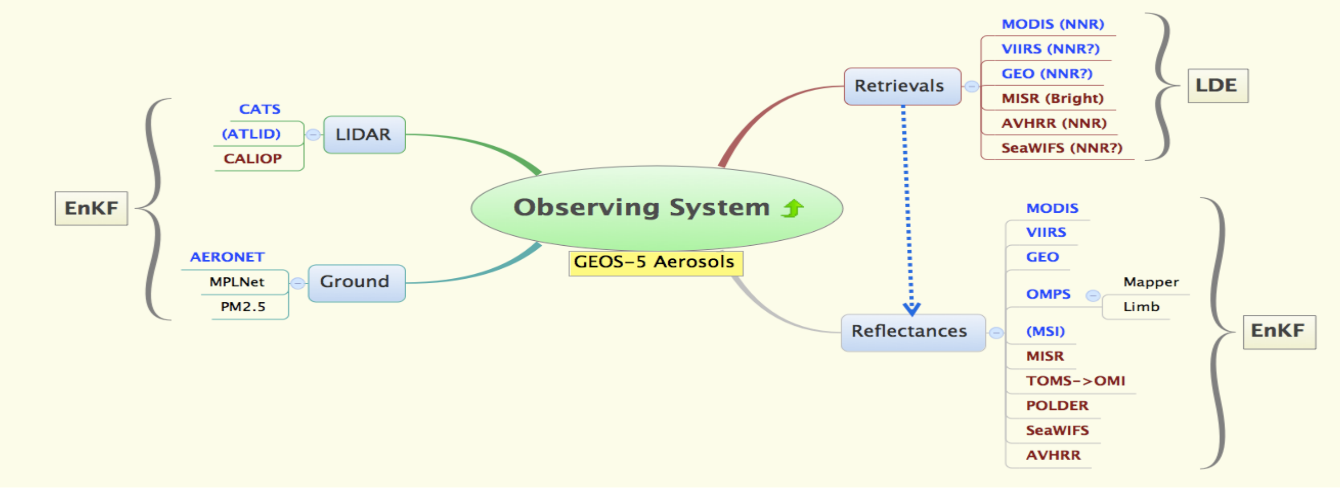
- Models are useful but difficulty in specifying emissions, microphysical processes and transport lead to large uncertainties
- While there are a large number of aerosol sensors, there are still large blind spots:
  - ✓ Measurements are usually vertically integrated
  - ✓ Diurnal cycle is not represented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

Typical Data Assimilation Cycle



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

Aerosol Data Assimilation

❑ State representation

- Multiple 3D concentrations
  - ✓ Mass
  - ✓ Number (modal schemes)
  - ✓ Bin sizes (sectional schemes)
- Number of tracers: tens to hundreds

❑ Emissions:

- ✓ Dynamic: dust, marine, biogenic aerosols
- ✓ Remotely sensed: biomass burning
- ✓ Inventories: anthropogenic

❑ Observation operators

- Intrinsic aerosol optical properties needed for remotely sensed data:
  - ✓ Mass extinction coefficient, single scattering albedo, phase matrix
  - ✓ These are often poorly known but assumed to be known due to identifiability issues:

$$\tau = \beta \bullet \mathbf{M}$$

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:

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

GOING TO 3D CONCENTRATIONS

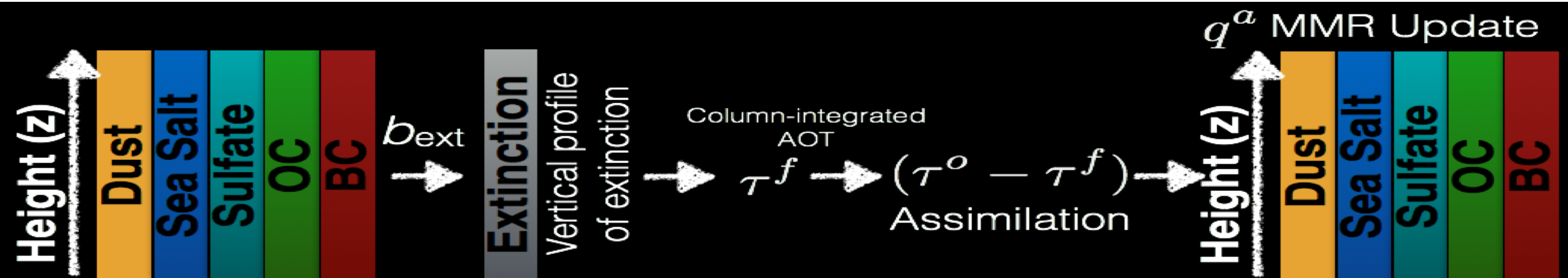
- Based on error covariances:

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

- Using ensemble perturbations,

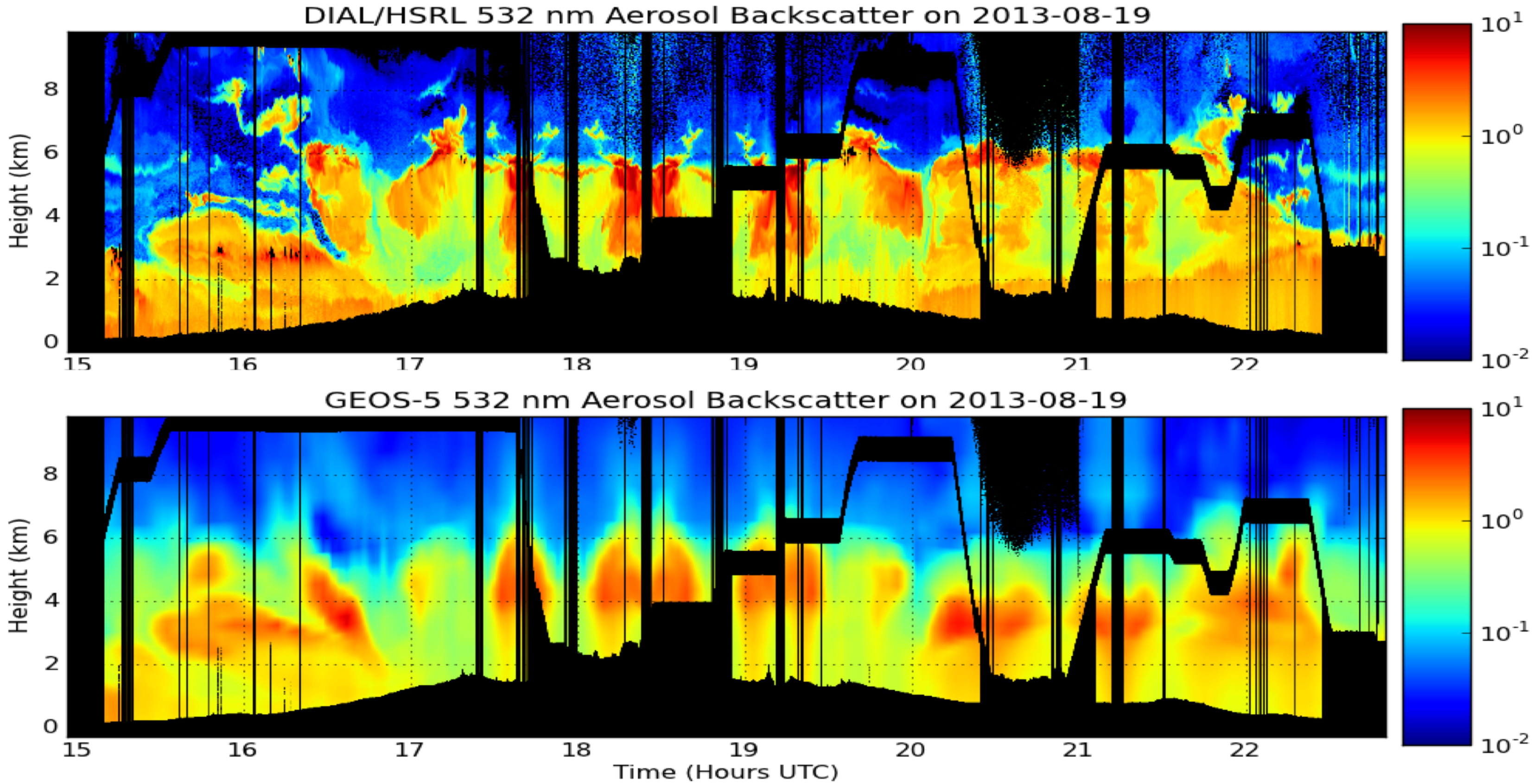
$$\delta q^a = XY^T\left(YY^T\right)^{-1}\delta\tau^a$$

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



Field Campaign Support

- Global 5-day chemical forecasts
  - ✓ O3, aerosols, CO, CO2, SO2
  - ✓ 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, HS3 ,SEAC4RS, ATom, ORACLES, etc.

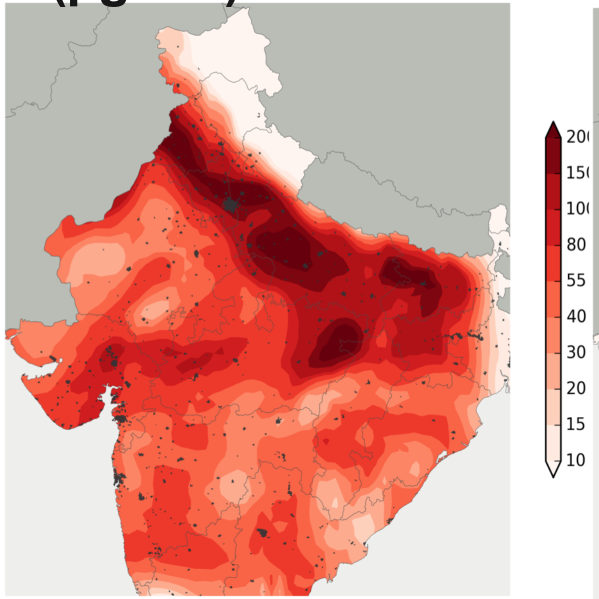


Comparison of observed (top) and simulated (bottom) aerosol backscatter for a slight during the 2013 SEAC4RS campaign.

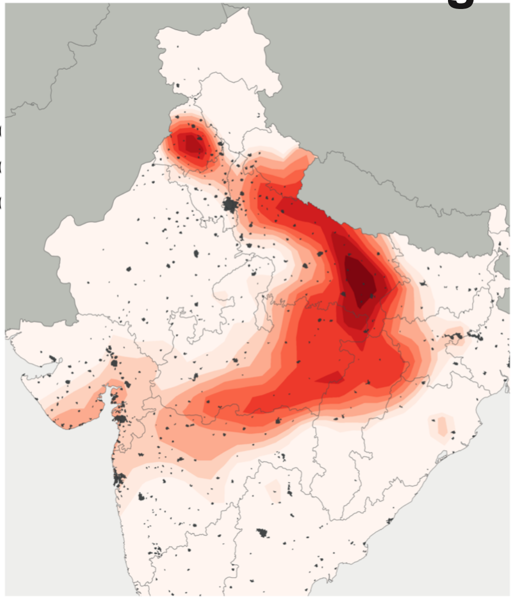
Understanding extreme AQ events

Analysis of the drivers of 2016 Indian Air Quality Episode

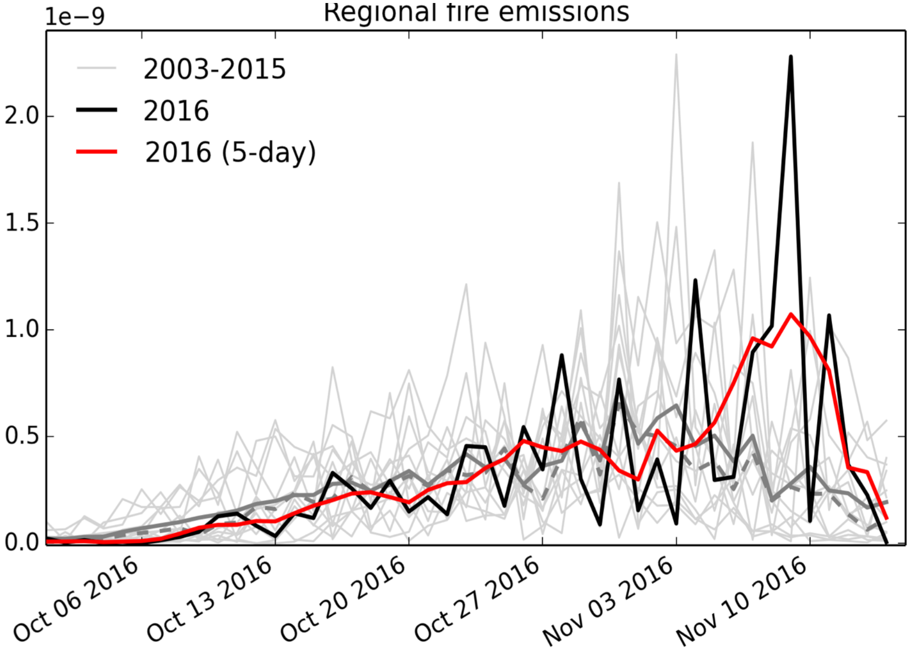
GEOS PM2.5 (µg m^{-3}) 20161106



PM2.5 due to biomass burning

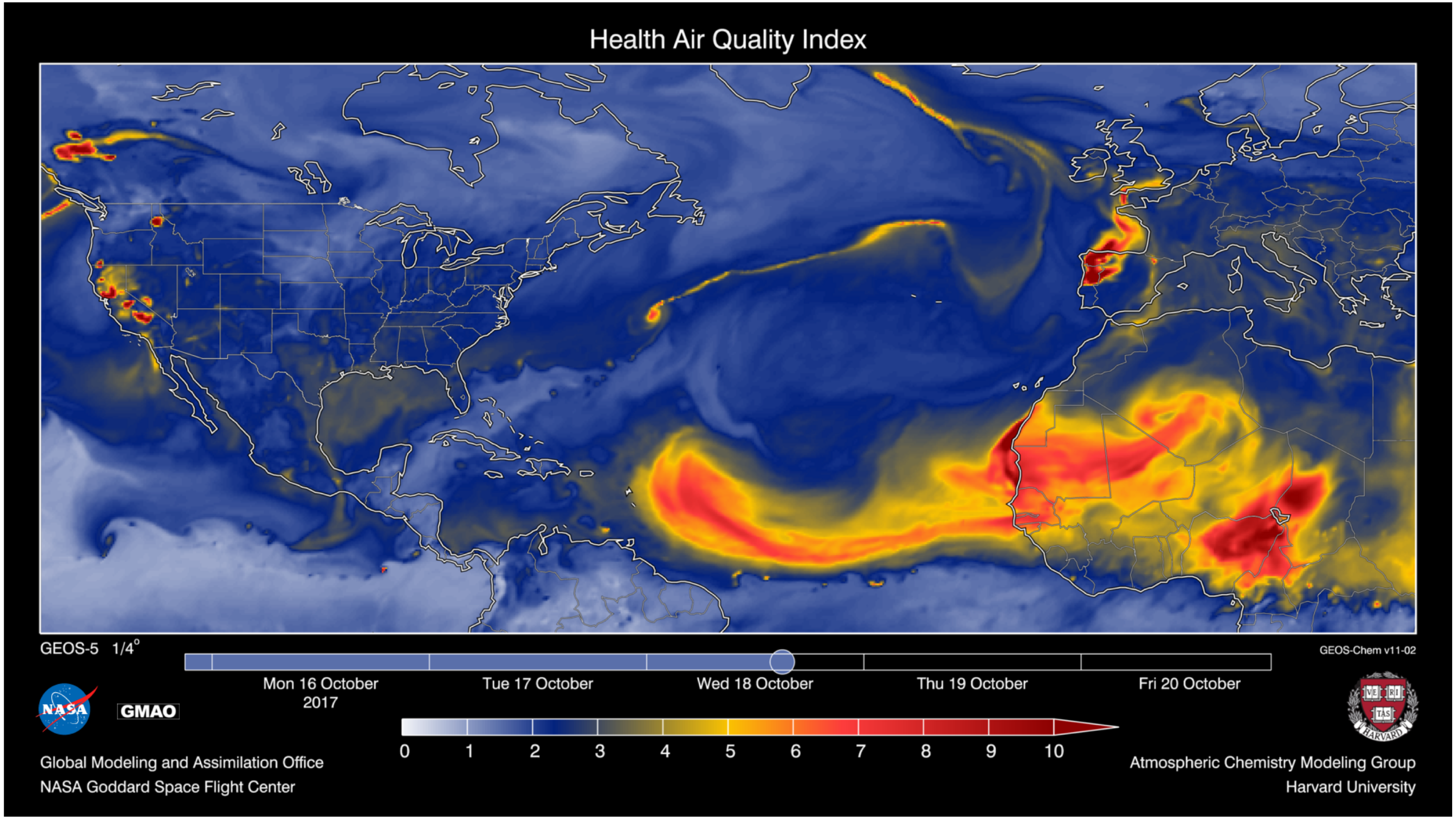


QFED CO Emissions (kg m^{-2} s^{-1})



- NRT diagnosis of fire emissions leads to improved ability to understand extreme events as they happen. In this example, later and more intense burning of crop residue contributed to extremely high $PM_{2.5}$ for millions of people.

High-resolution 5-day forecasts of atmospheric composition



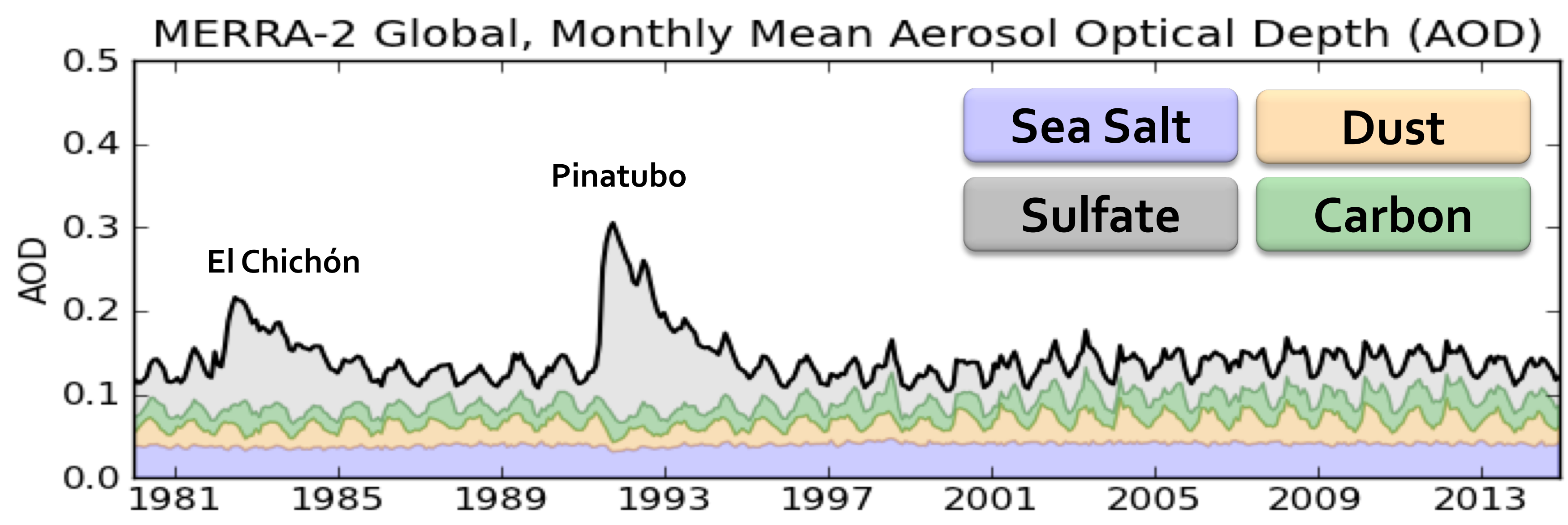
Web Resources

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

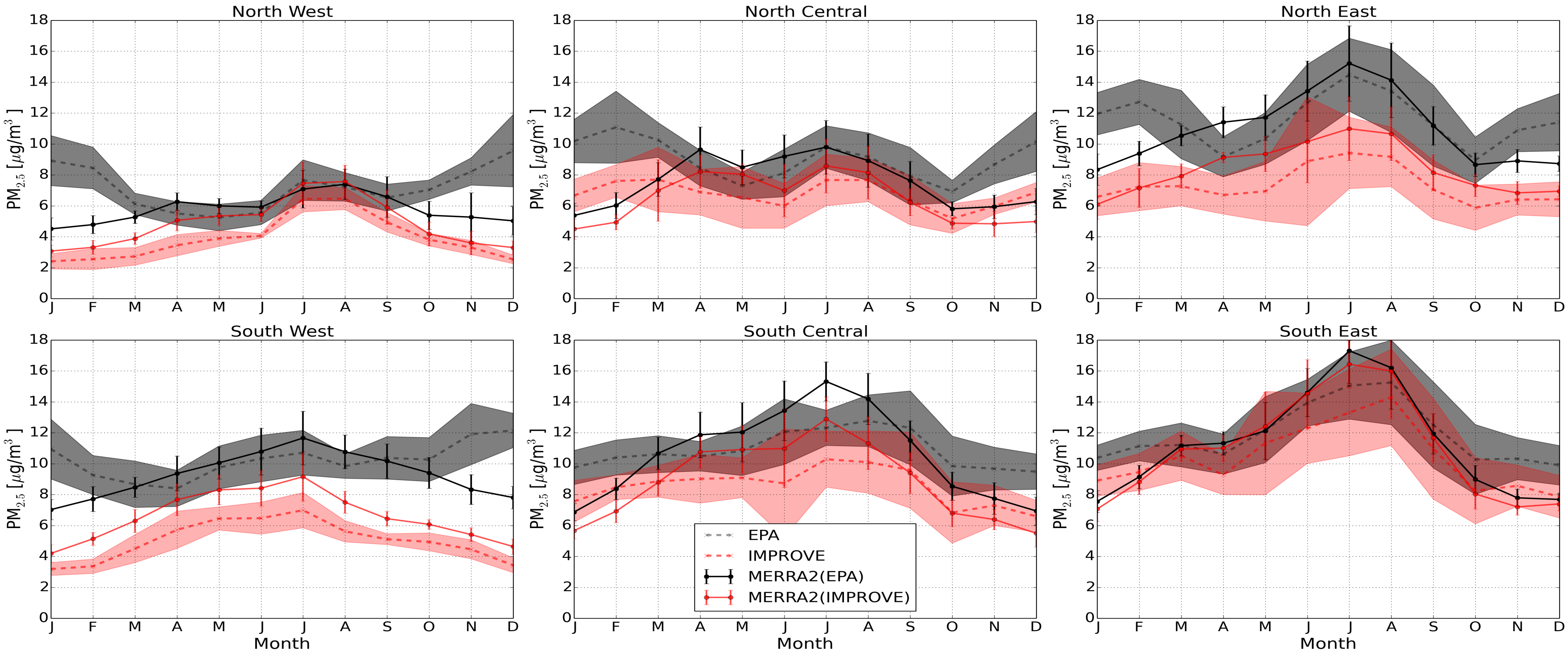
Aerogram Example

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).



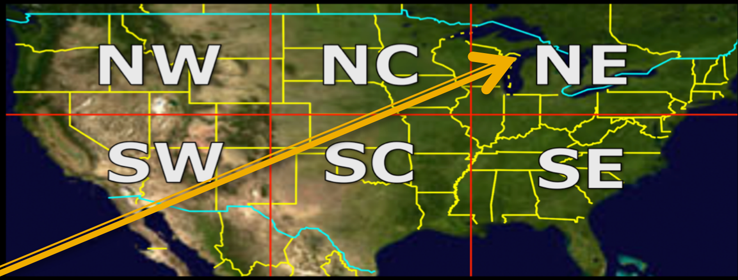
$PM_{2.5}$ (Total) Regional Climatology



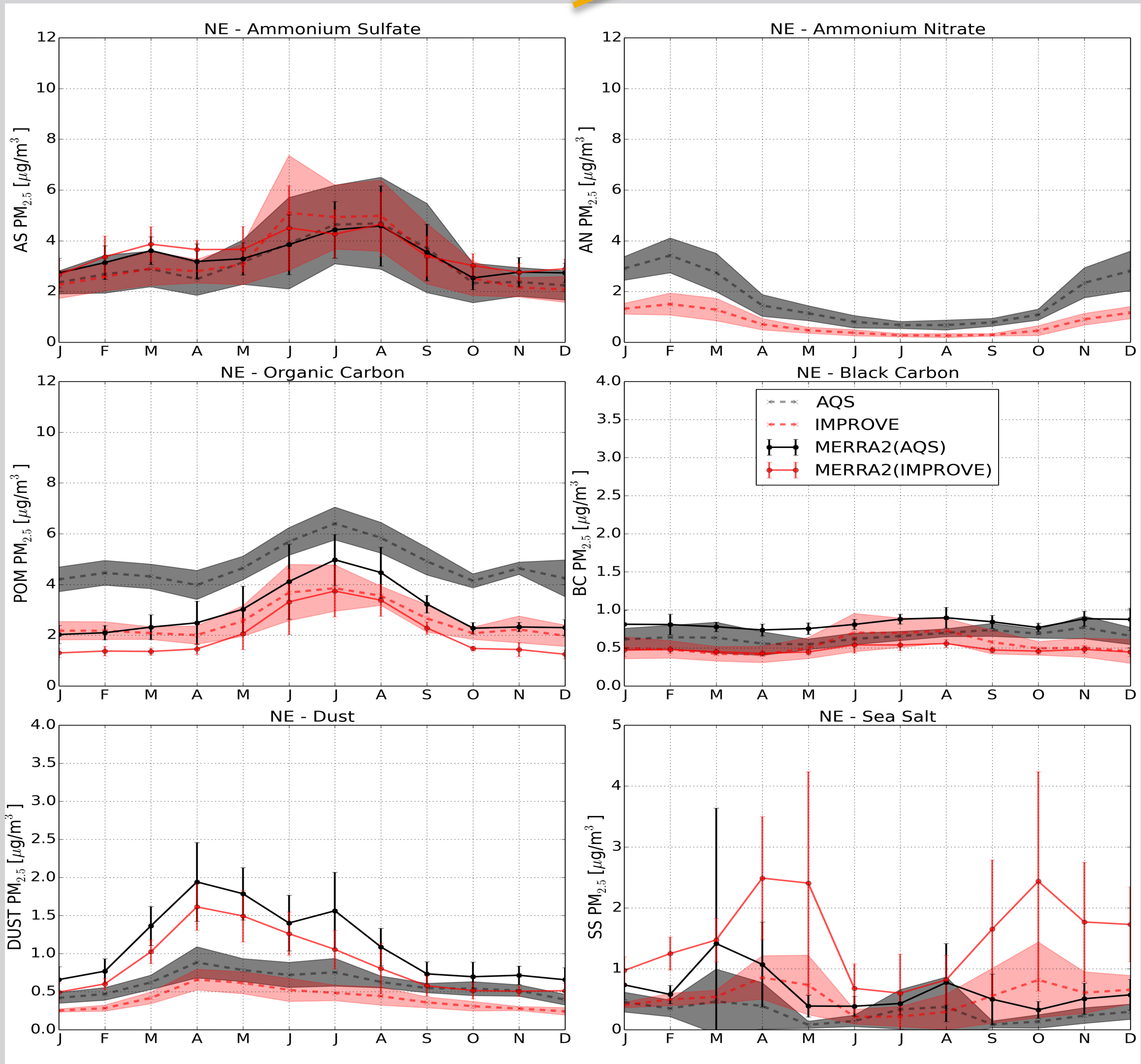
Comparison with in-situ measurements after *Buddy Check*

MERRA-2
Evaluation Highlights

PM2.5 by Species At Northeast



- Relatively good agreement for **Sulfates**
- MERRA-2 lacks **Nitrates** altogether
- Underestimation of **Carbonaceous** near urban areas
- Too much **dust**
- Too much **sea-salt** at coastal stations



MERRAero Evaluation Highlights

- Relatively good agreement for **Sulfates**
- Underestimation of **Carbonaceous** near urban areas
- Too much **dust**
- Too much **sea-salt** at coastal stations

PM2 by Species over Europe

S. Provençal et al. / Atmospheric Pollution Research 8 (2017) 374–382

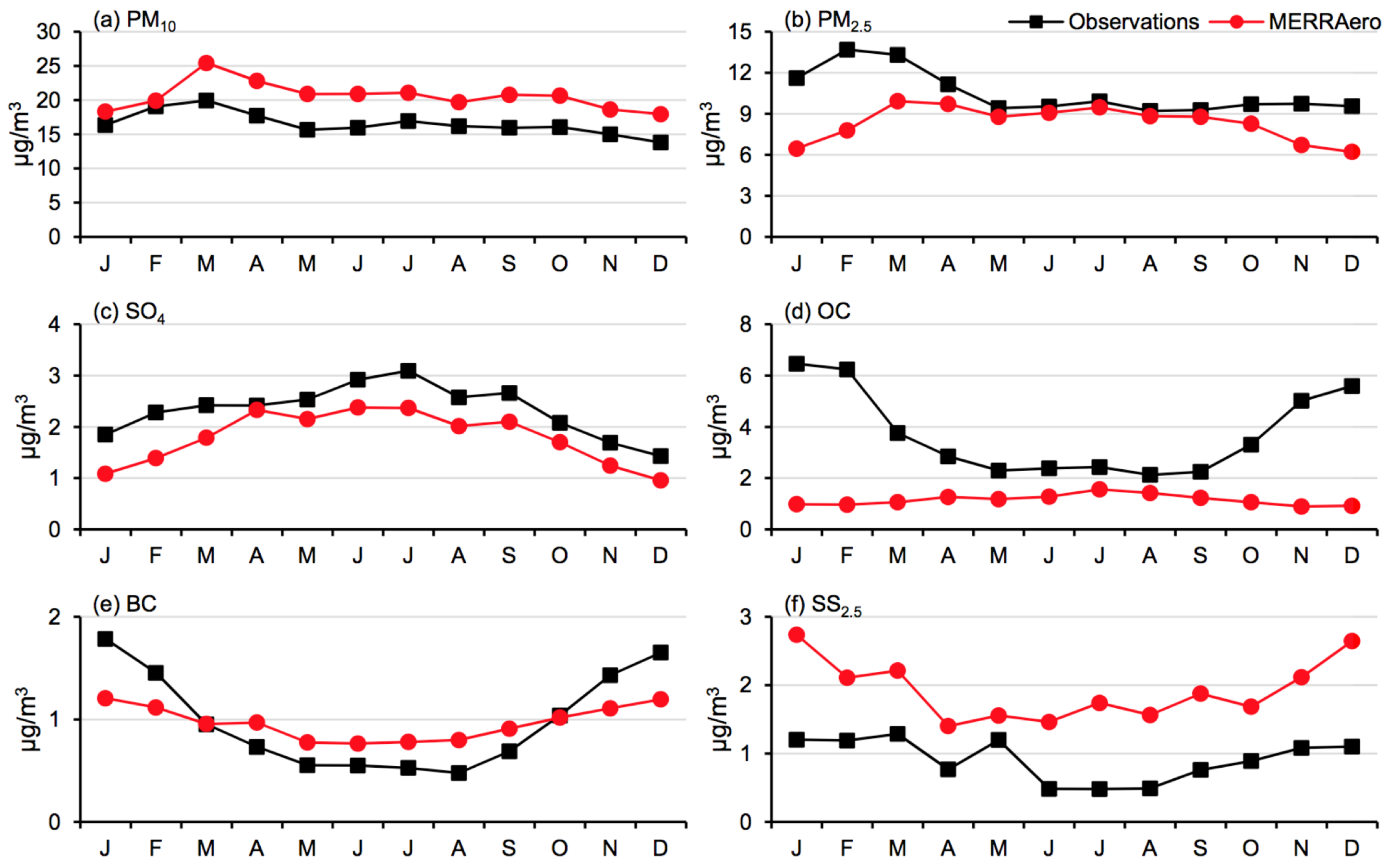


Fig. 4. Monthly averages of PM concentration and species observations and simulations over the ensemble of European locations.

MERRAero
Evaluation Highlights

PM2.5 Israel

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Provençal et al., Aerosol and Air Quality Research, 17: 253–261, 2017 257

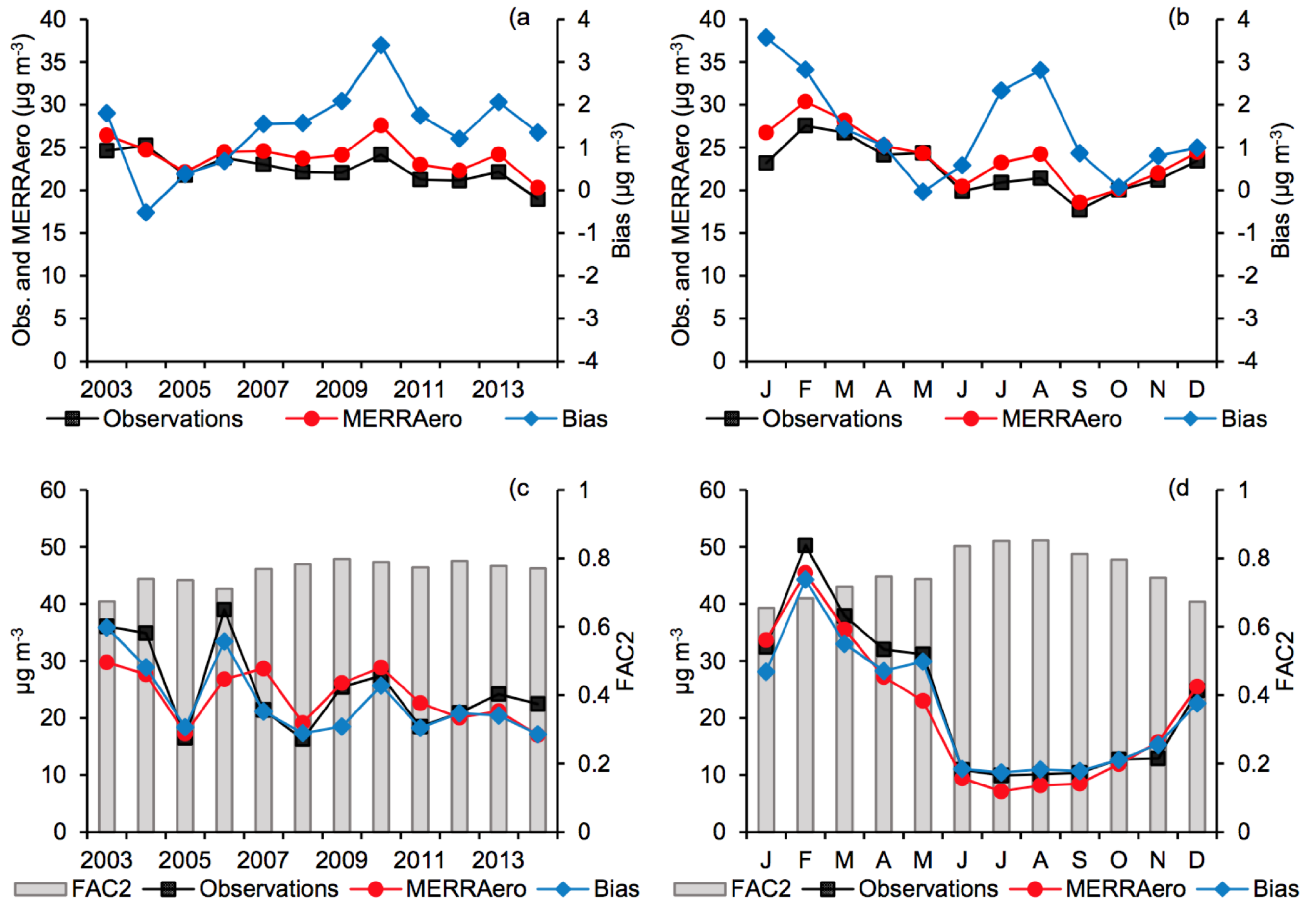

Fig. 3. (a) Yearly and (b) monthly average of [$PM_{2.5}$] observation, simulation and bias, and (c–d) similarly for the SD and FAC2, for the ensemble of locations in Israel.

MERRAero
Evaluation Highlights

PM2.5 Taiwan

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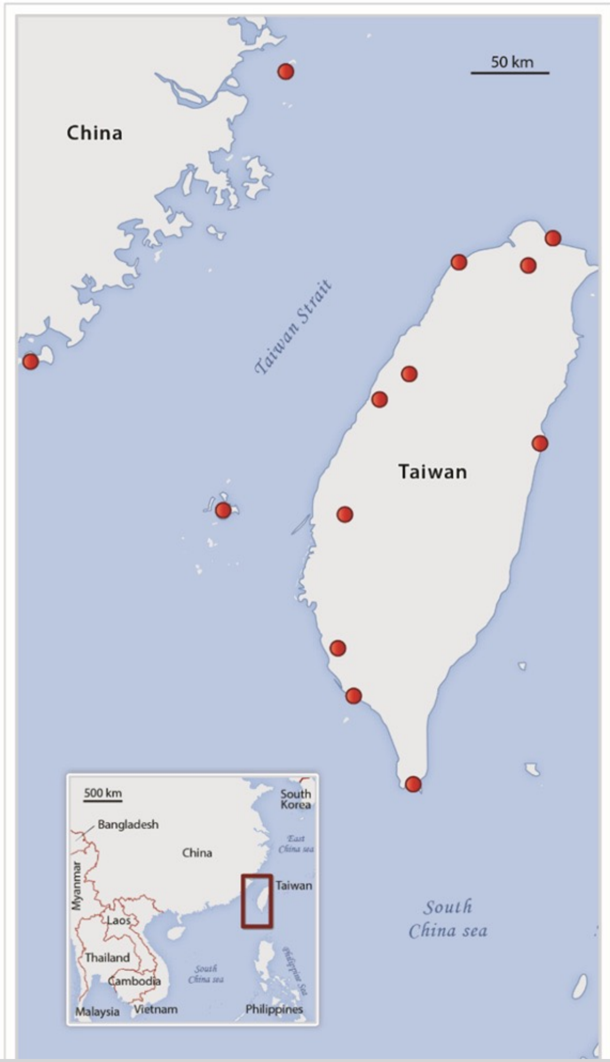


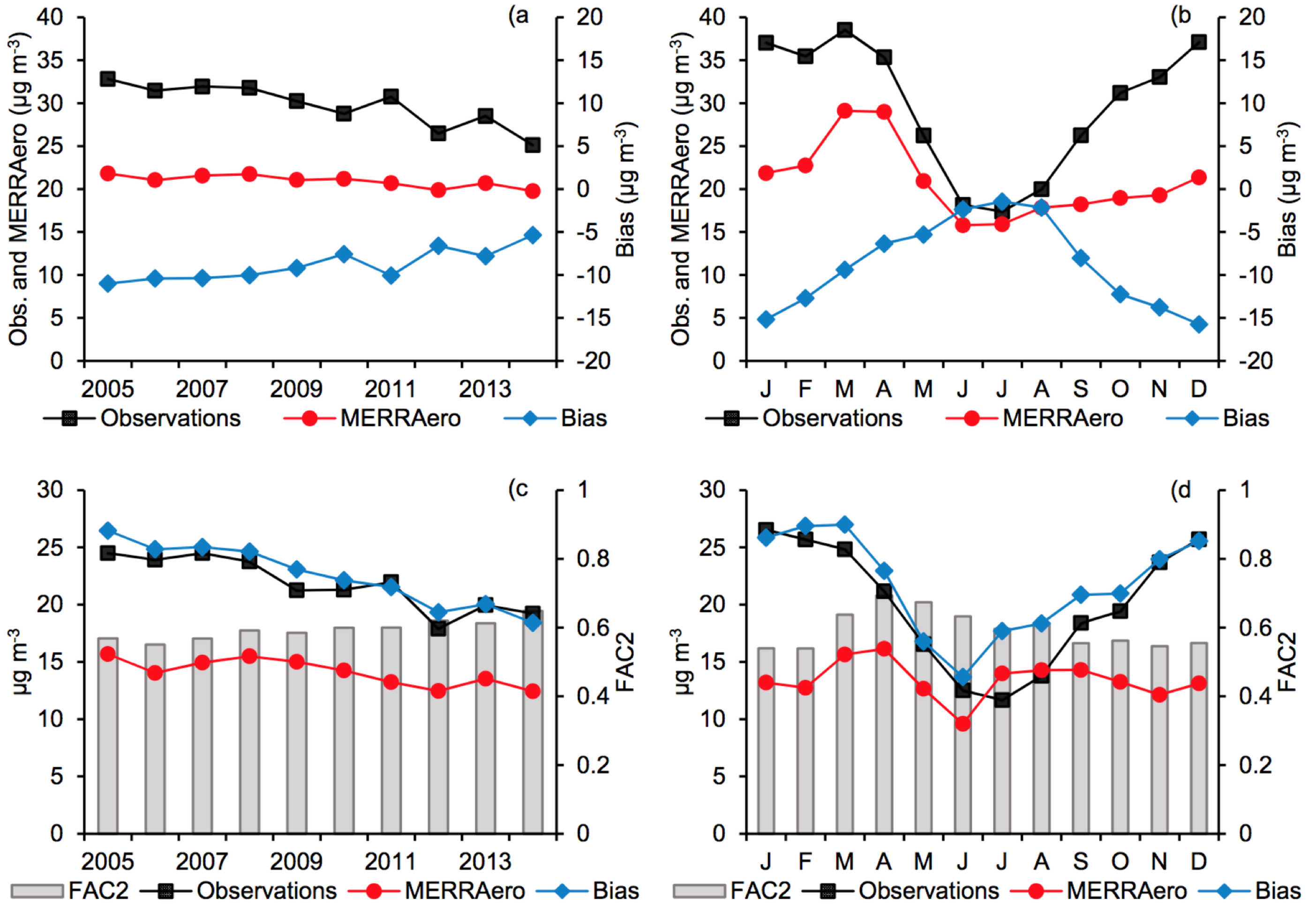
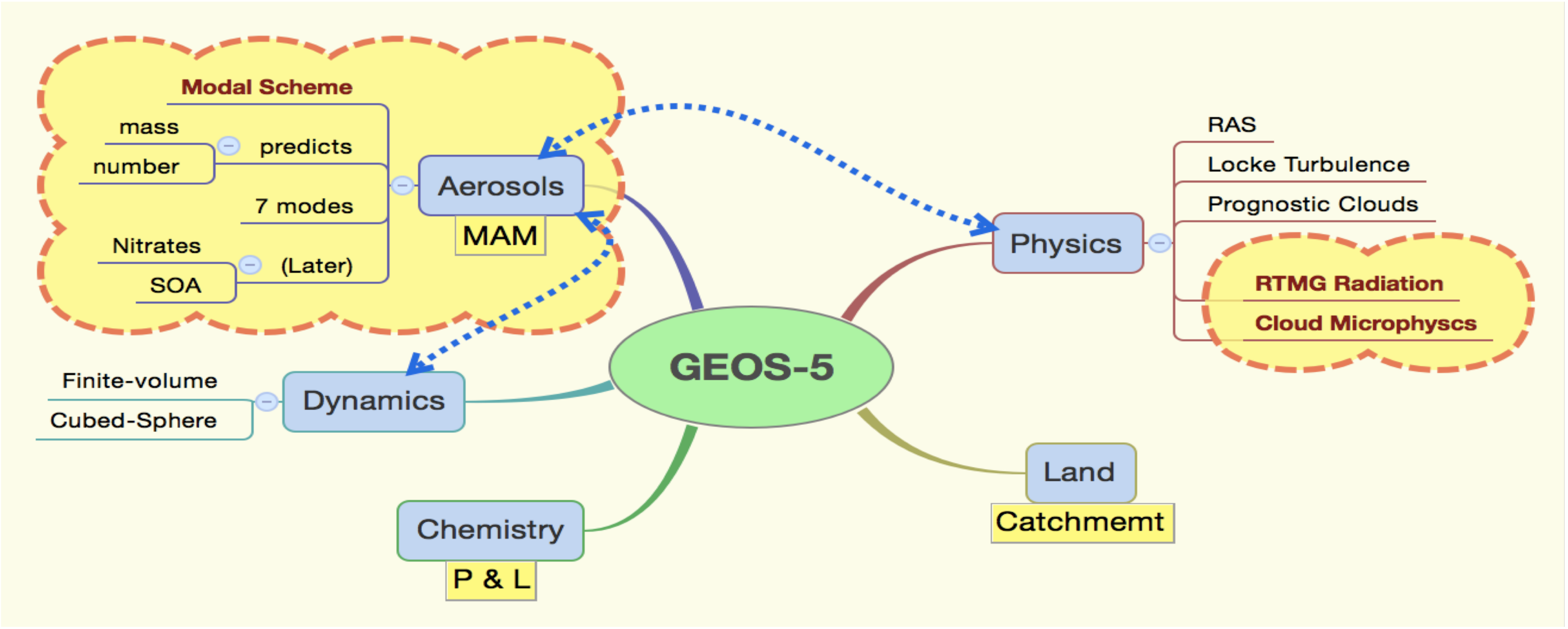


Fig. 5. (a) Yearly and (b) monthly average of [$PM_{2.5}$] observation, simulation and bias, and (c–d) similarly for the SD and FAC2, for the ensemble of locations in Taiwan.

Develop, Run, Rest (Analyze), Repeat

Current GEOS Development: Aerosol & Clouds Microphysics

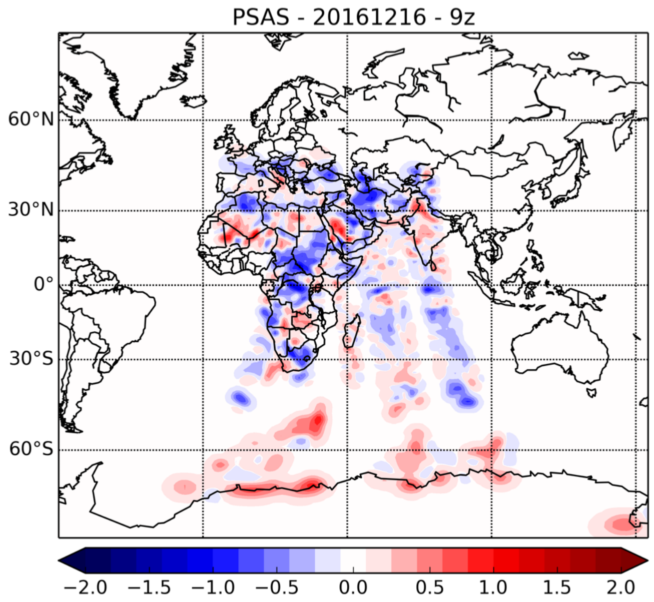


Global, **12.5 km**, **72** Levels, top at 0.01 hPa

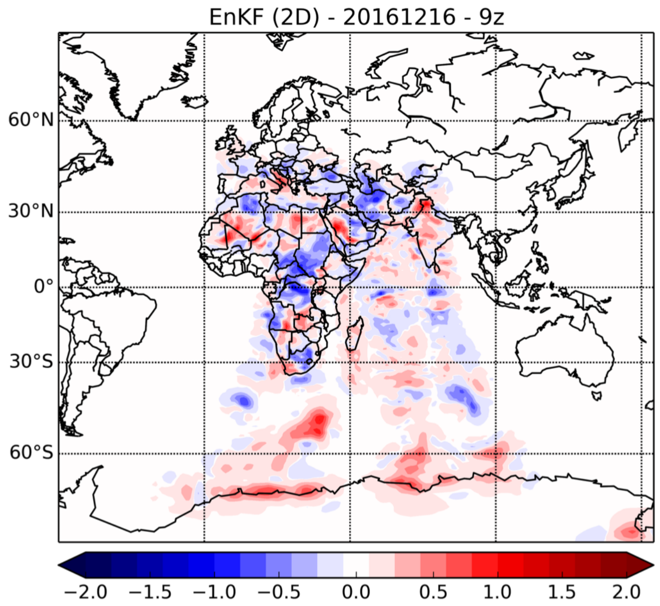
In Development: Aerosol EnKF

- **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



Potential Connections to SPARTAN

- While the explicit estimation of the ratio **η = PM2.5 /AOD** is not a central to the D.A. approach, the SPARTAN "super-sites" provide a **critical validation resource.**
- GEOS high-resolution aerosol analysis and forecasts, coupled to ***Model Output Statistics (MOS)*** for SPARTAN stations, can provide a valuable tool for
  - local AQ forecast (especially when no other source is available)
  - monitoring of instrument drifts
  - climatological characterization
- GEOS aerosol datasets, integrating global satellite and ground based measurements, may offer additional input to SPARTAN health impact studies.

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
- 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

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

Useful References

Randles, C. A., DA SILVA, A. M., & Buchard, V. (2017). The MERRA-2 Aerosol Reanalysis, 1980–onward, Part I: System Description and Data Assimilation Evaluation. *Journal of Climate*. http://doi.org/10.1175/JCLI-D-16-0609.s1

Buchard, V., Randles, C. A., DA SILVA, A. M., Darmenov, A., Colarco, P. R., Govindaraju, R., et al. (2017). The MERRA-2 Aerosol Reanalysis, 1980 Onward. Part II: Evaluation and Case Studies. *Journal of Climate*, *30*(17), 6851–6872. http://doi.org/10.1175/JCLI-D-16-0613.1

Provençal, S., Buchard, V., DA SILVA, A. M., & Leduc, R. (2017). Evaluation of PM2. 5 Surface Concentrations Simulated by Version 1 of NASA's MERRA Aerosol Reanalysis over Israel and Taiwan. *Aerosol and Air Quality*, 17: 253–261, 2017

Buchard, V., DA SILVA, A. M., Randles, C. A., Colarco, P., Ferrare, R., Hair, J., et al. (2016). Evaluation of the surface PM2.5 in Version 1 of the NASA MERRA Aerosol Reanalysis over the United States. *Atmospheric Environment*, *125*, 100–111. http://doi.org/10.1016/j.atmosenv.2015.11.004

Buchard, V., Silva, A. M. D., Colarco, P. R., Darmenov, A., Randles, C. A., Govindaraju, R., et al. (2015). Using the OMI aerosol index and absorption aerosol optical depth to evaluate the NASA MERRA Aerosol Reanalysis. *Atmospheric Chemistry and Physics*, *15*(10), 5743–5760. http://doi.org/10.5194/acp-15-5743-2015

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Provençal, S., Kishcha, P., da Silva, A. M., Elhacham, E., & Alpert, P. (2017). AOD distributions and trends of major aerosol species over a selection of the world"s most populated cities based on the 1st version of NASA"s MERRA Aerosol Reanalysis. *Urban Climate*, 1–24. http://doi.org/10.1016/j.uclim.2017.04.001

MERRA-2
Evaluation Highlights

Aerosol Absorption

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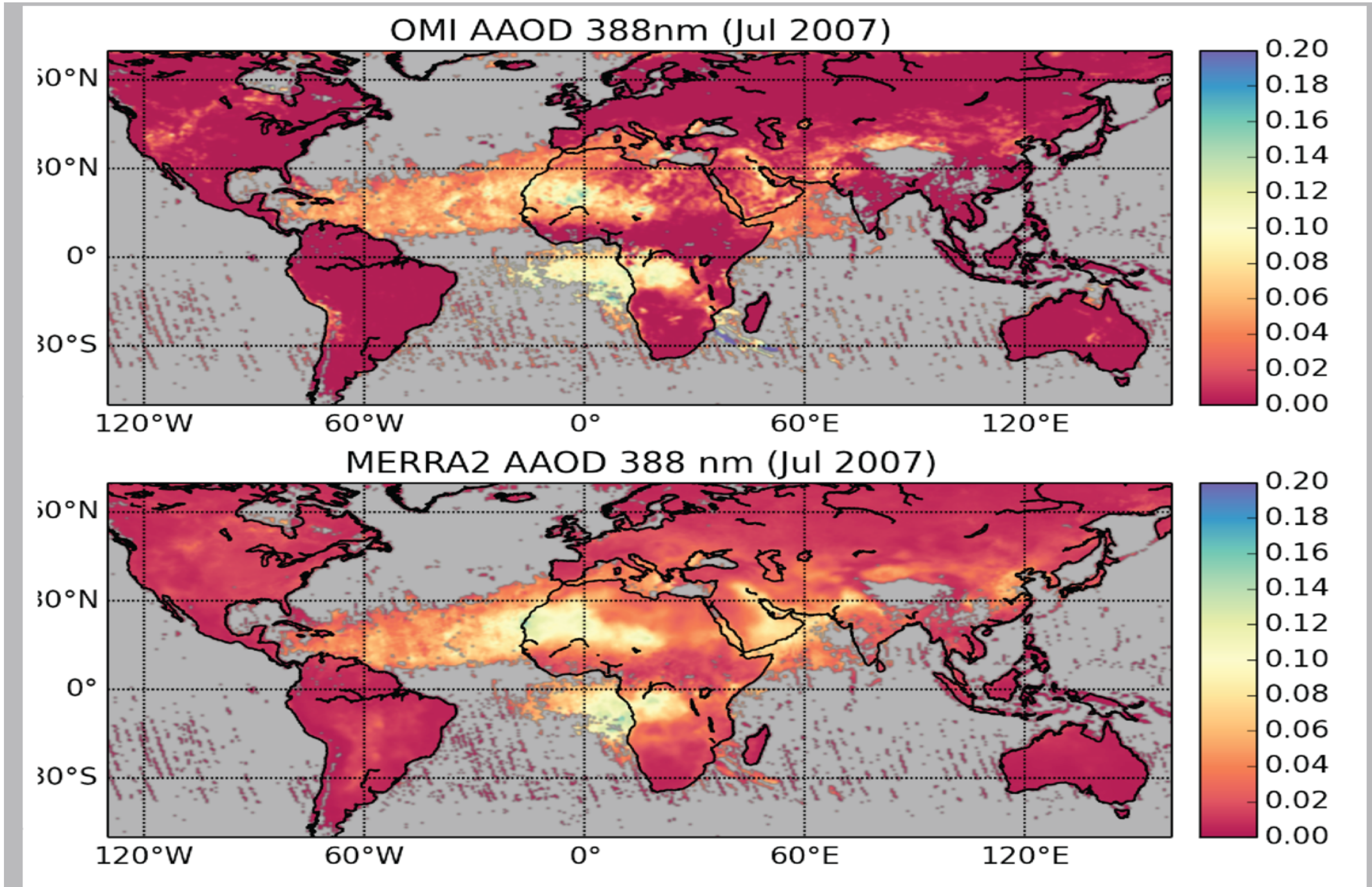
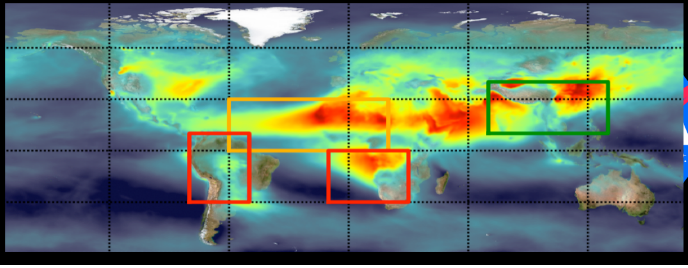
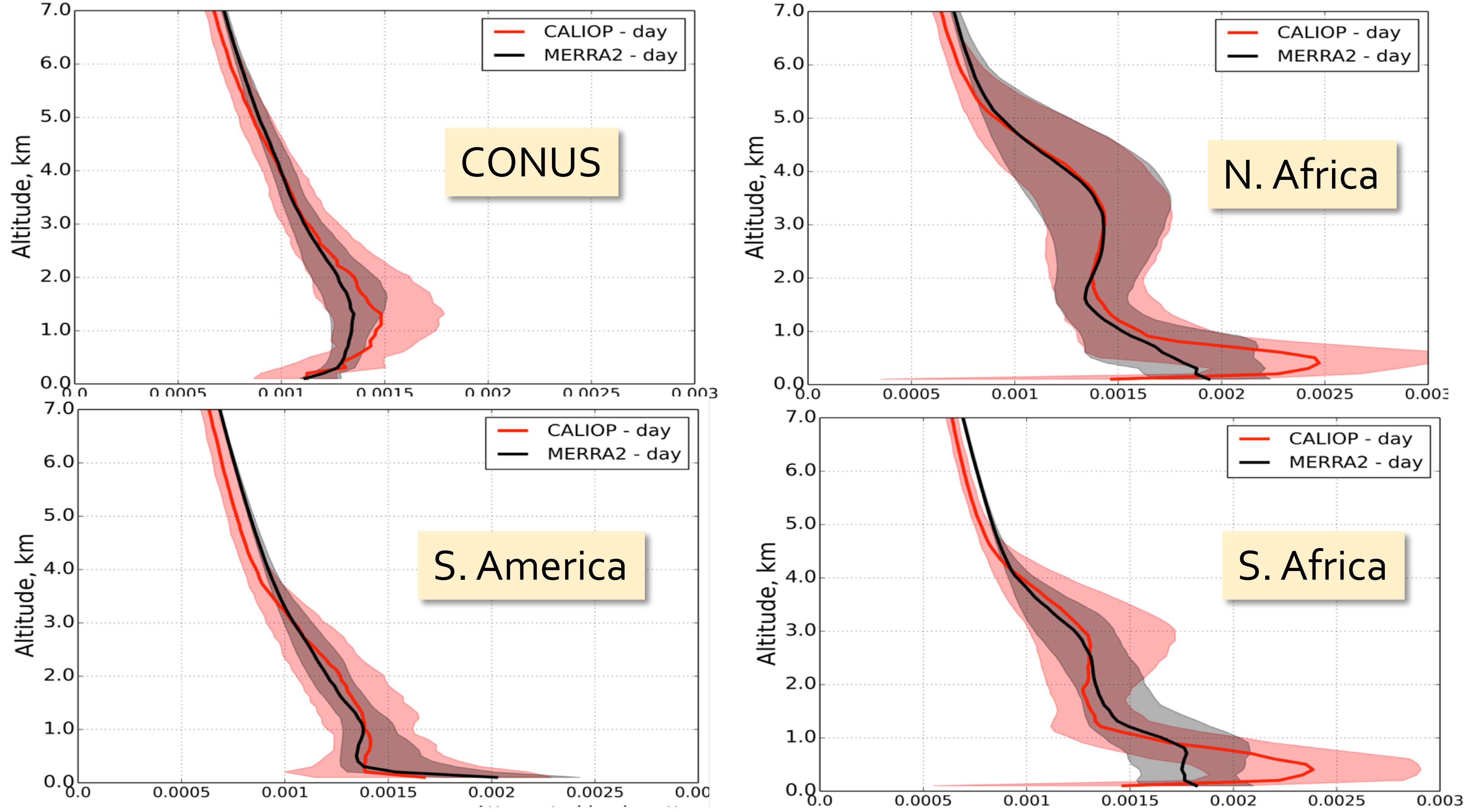
- Comparison of MERRA-2 Absorption Optical Depth (AAOD) with OMI retrievals
- Good agreement for African dust and smoke
- North American biomass burning underestimated according to OMI



Vertical Structure: Comparison to CALIOP

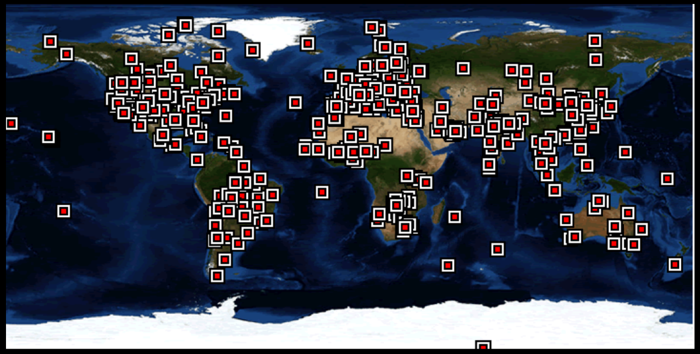


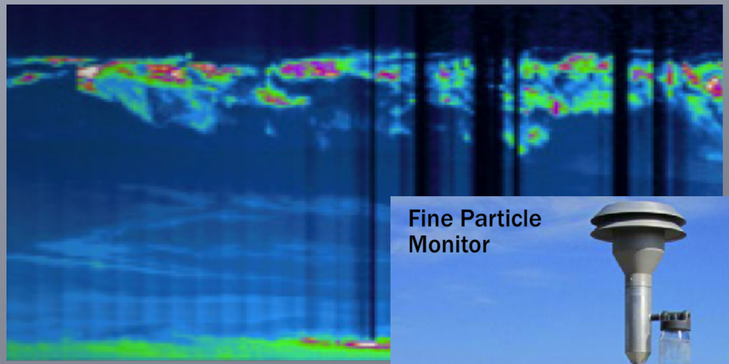
Attenuated Backscatter $km^{-1} sr^{-1}$



MERRA-2 Aerosols Evaluation Highlights

Using Independent Observations





MERRA-2
Evaluation Highlights

Historical Cruises

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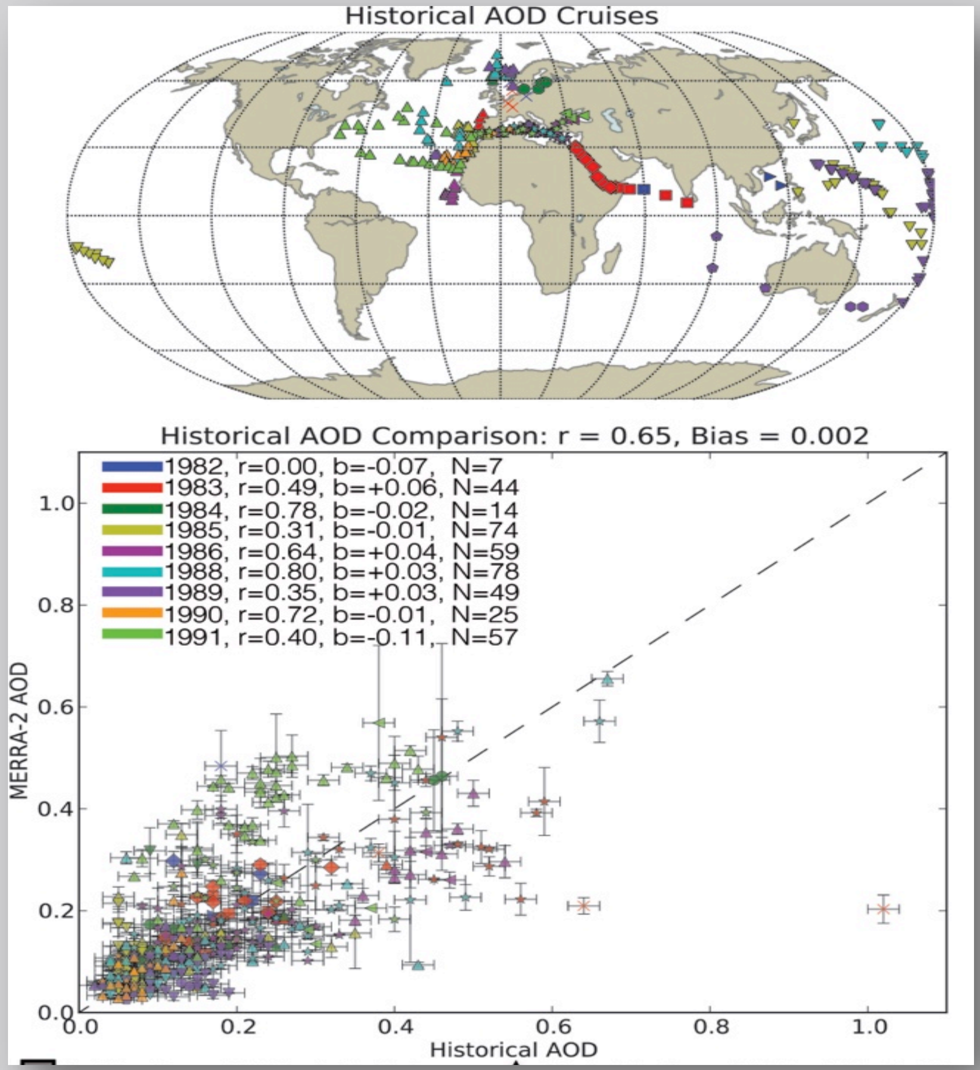
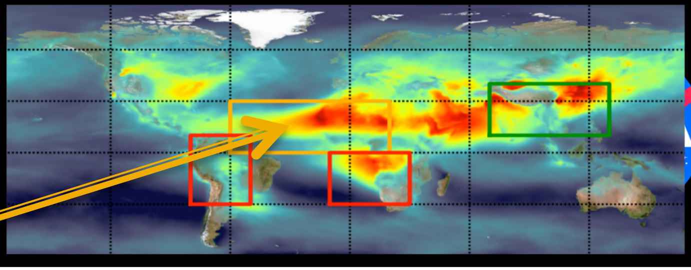
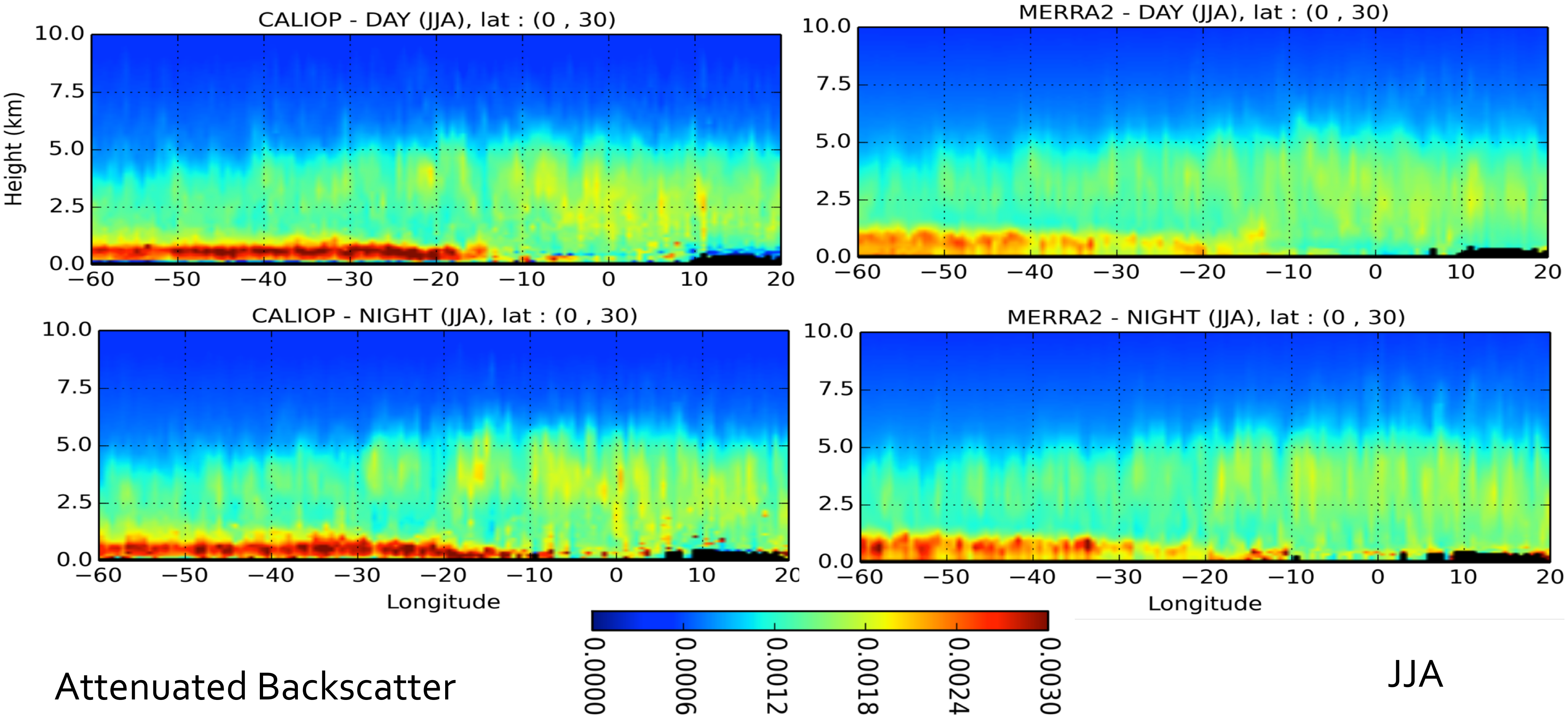
Independent AOD data is scant before the EOS Period.

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

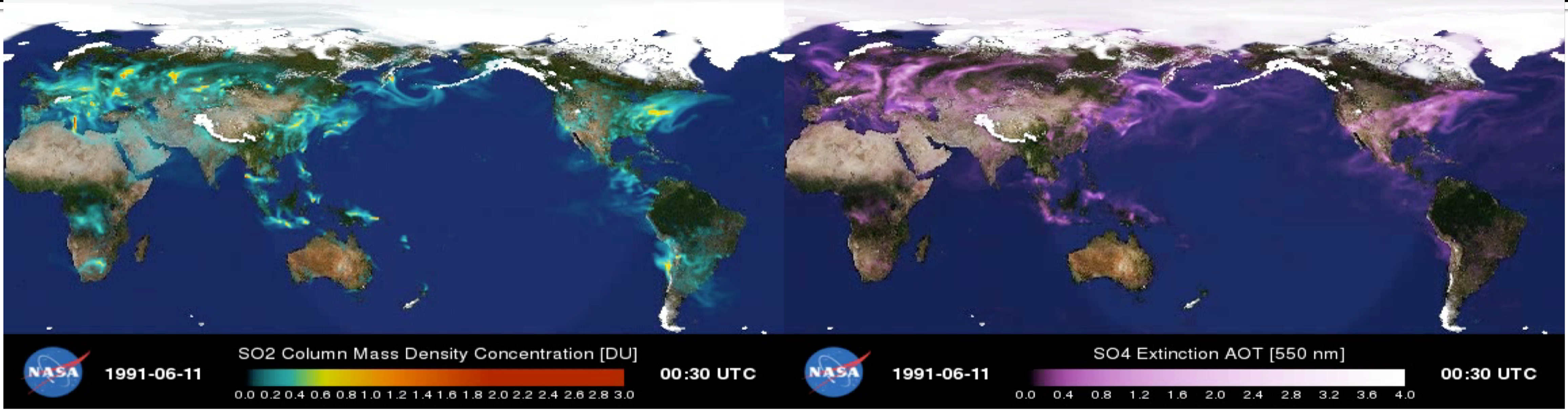




Attenuated Backscatter

JJA

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.