Update on GEOS Aerosol Modeling System

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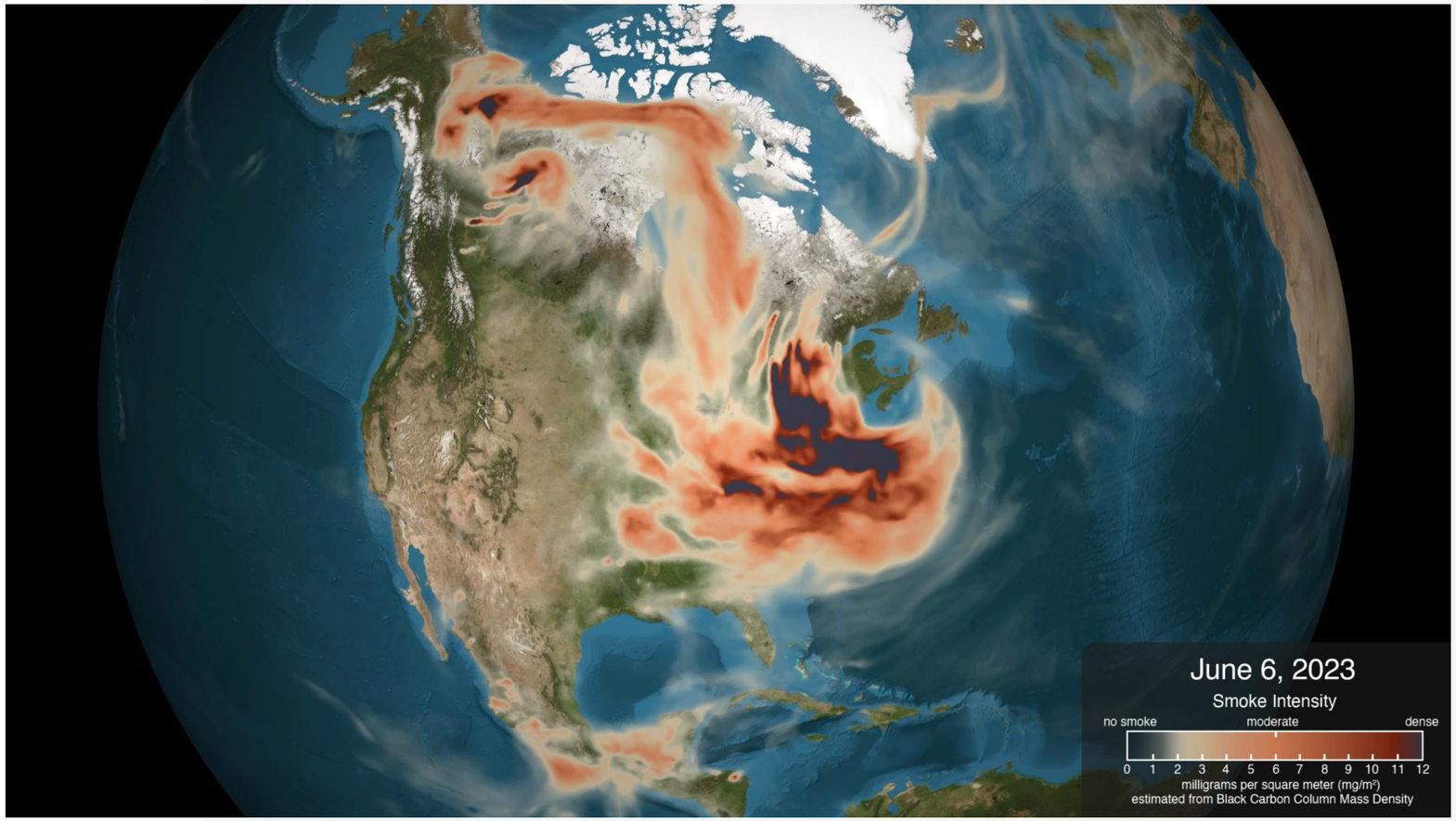
Outline

- GEOS Systems Updates
  - MERRA21C Preliminary Evaluation
- Aerosol Data Assimilation Updates
  - Transition to VIIRS
- QFED Updates
- Projects
  - Field Campaign Support
- Summary



GEOS Main Systems Status

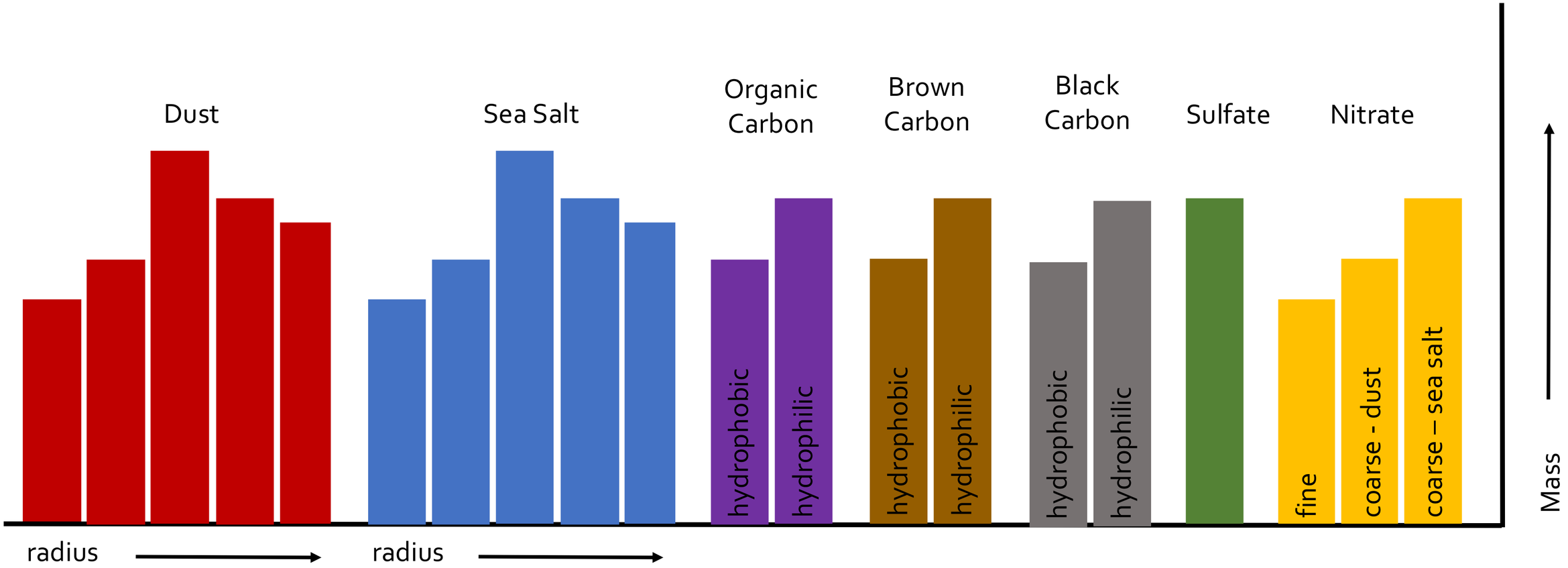
GEOS products	Purpose	Nominal Res	Aerosol DA	Details
Forecast Systems				
GEOS-FP	Weather/aerosols analyses and forecasts	12 km	X	• GOCART-2G • MODIS + AERONET • VIIRS has been tested, not implemented yet
GEOS-S2S-3	Coupled system for S2S predictions	50 km	X	• GOCART • MODIS + AERONET
GEOS-CF-2	Composition Forecast Full reactive gas chemistry	25 km	(X)	• GEOS-Chem v14 • Aerosol DA used to replay meteorology, prognostic aerosols are unconstrained
Reanalysis Systems				
MERRA-2	Gelaro et la, 2016, Randles et al., 2017	50 km	X	• GOCART • MODIS +AERONET
GEOS-IT	N.R.T analysis system for Instrument Teams	50 km	X	• GOCART • MODIS + AERONET
MERRA-21C	Current reanalysis in production	25 km	X	• GOCART-2G • MODIS+AERONET • Will transition to VIIRS soon

Aerosol DA Approach: PSAS Based

- **Solver:** PSAS 2D-Var
- **Control variable:** 2D single-λ AOD
- **Observations:** single-λ NNR AOD (550 nm)
- **Background Error:** Static B

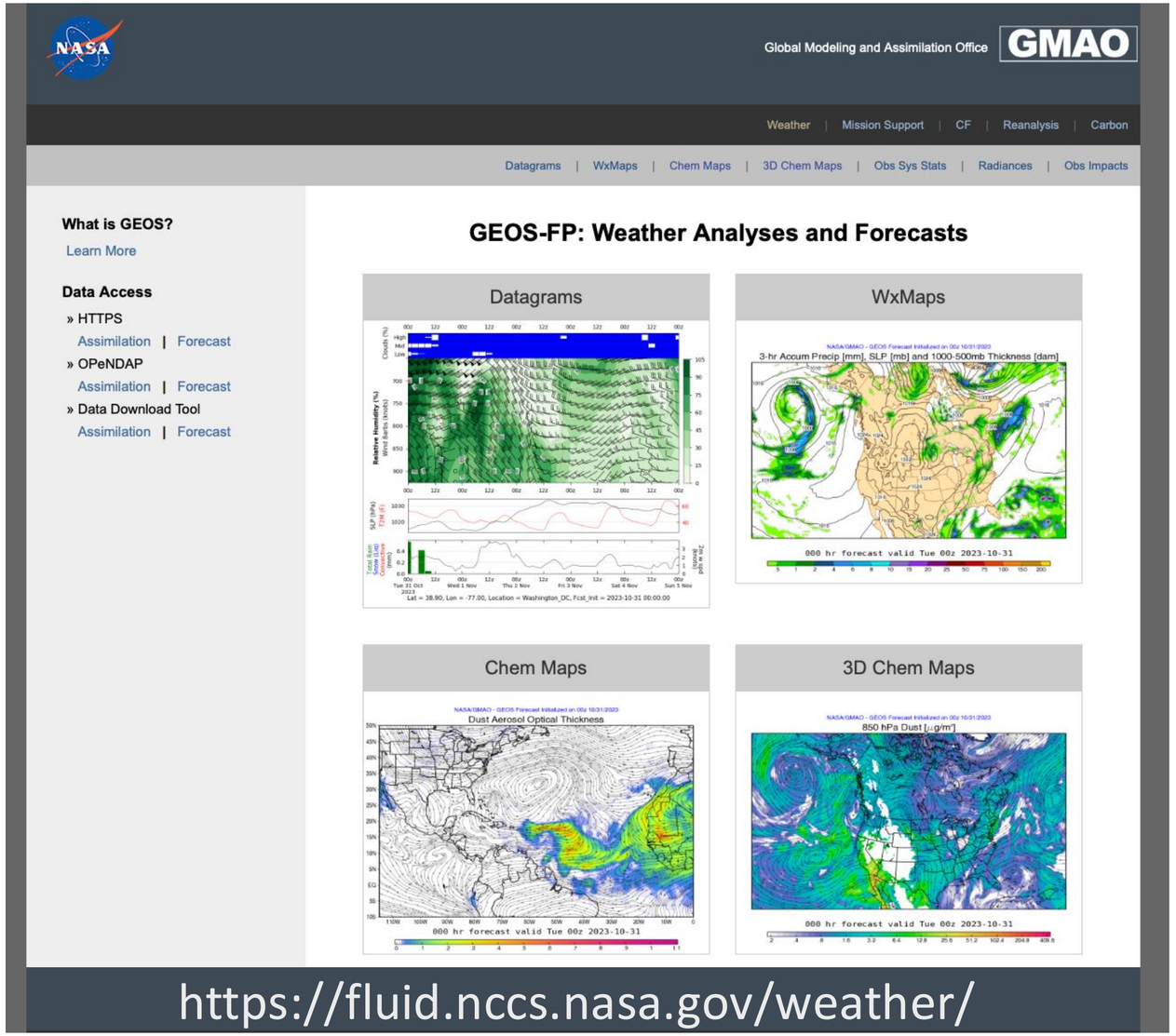
GOCART-2G Status

- Separation of organic aerosol into “white” (anthropogenic) and “brown” (biomass burning) components with distinct optical properties
- Increase OA:OC ratio in line with recent airborne measurements (e.g., ATom)
- Inclusion of an ACHEM-driven SOA scheme for anthropogenic and biomass burning sources
- Inclusion of a HEMCO/MEGAN-driven biogenic SOA scheme
- Introduction of “point wise” source emissions for pyroCb inputs (not used for MERRA21C)
- Update anthropogenic emissions to downscaled-CEDS emission inventory
- Input oxidant fields are MERRA-2 GMI (valid range of both is 1980 - 2019; padding outside years with endpoints)



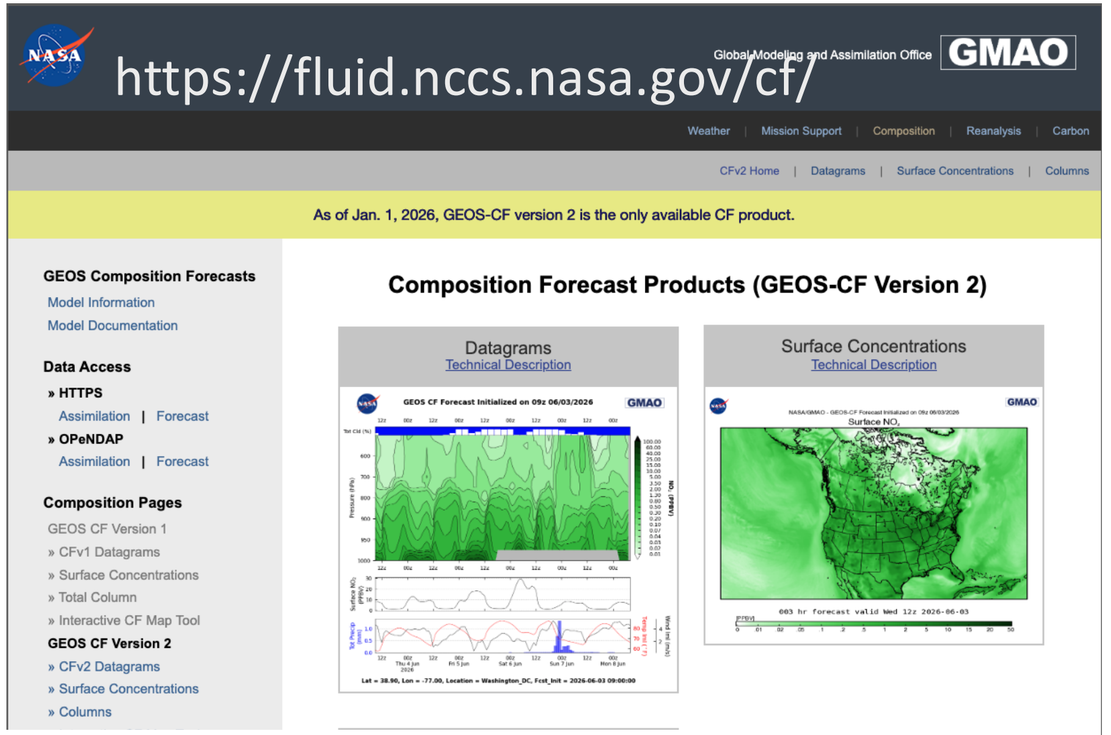
GEOS-FP

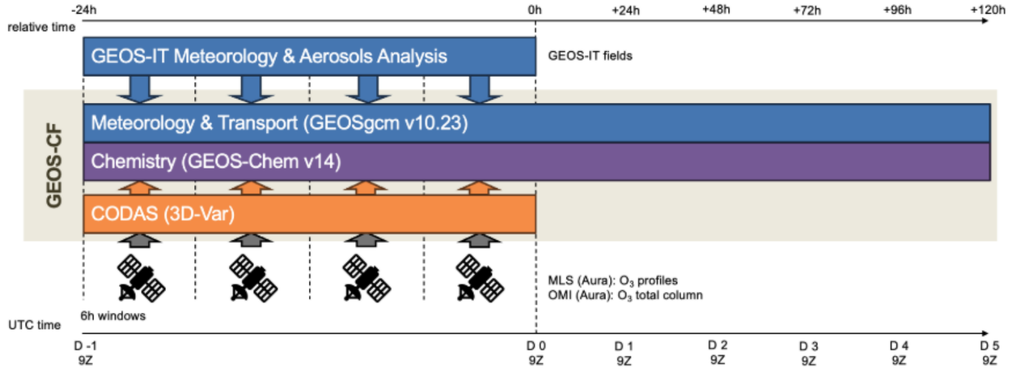
- GEOS near-real time system
- Currently: Version 5.43.0 (updated on Feb 26, 2026)
- ~12 km horizontal, 72 levels to ~80 km
- GOCART-2G – adds brown carbon
- Aerosols are inline and radiatively interactive with meteorology
- Assimilation of MODIS NNR and AERONET AOD at 550 nm
- 4x daily forecasts
- This is input to ICAP MME
  - OC → OC + BRC



GEOS-CF2

- GEOS near-real time composition forecast system
- Currently: Version 2 (updated on Aug 2025)
- ~25 km horizontal, 72 levels to ~80 km
- GEOS-CHEM v14
- Assimilation of MODIS NNR and AERONET AOD at 550 nm to replay radiatively coupled meteorology
- Aerosols are free-running within GEOS-CHEM
- 1x daily 5-day forecasts



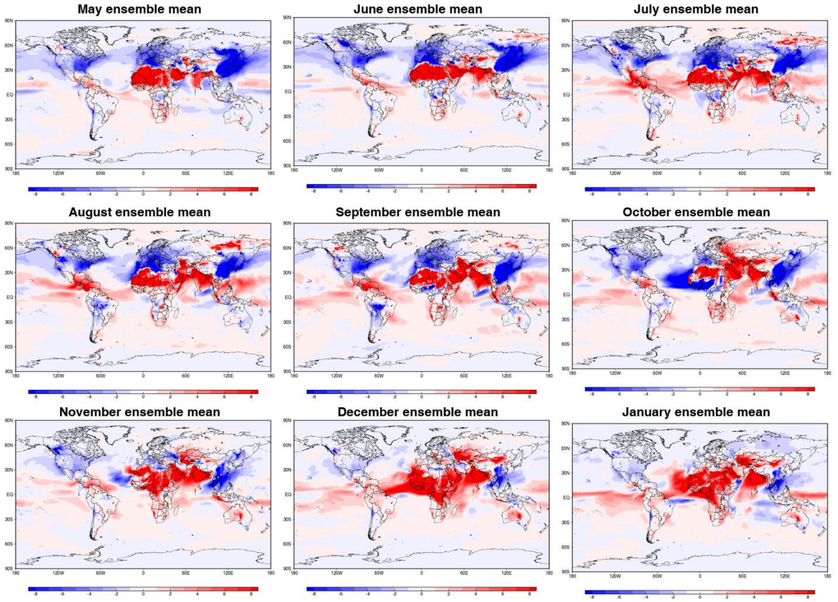


GEOS S2S-3

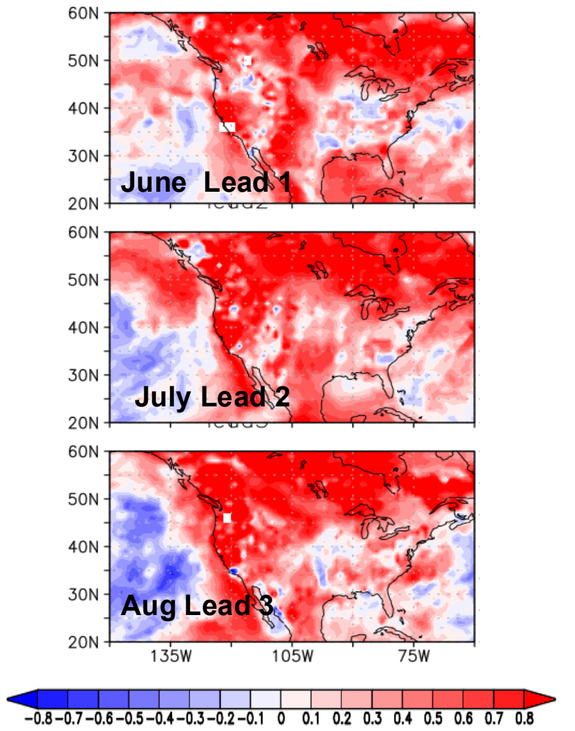
- Sub-seasonal/Seasonal ensemble forecasts
- Currently: Version 3 (updated in May 2026)
  - 40 ensemble members for first 3 months
  - 10 members for the remaining 6 months
- Atmosphere: GEOS-IT replay
  - ~50 km horizontal, 72 levels to ~80 km
  - GOCART Aerosols are inline and radiatively interactive with meteorology
  - Assimilation of MODIS NNR and AERONET AOD at 550 nm
  - 2-moment cloud microphysics
- Coupled ocean (MOM5)
  - ~25 km resolution, 50 vertical levels
  - Weakly coupled DA
  - Using analysis for forecast initialization
- This is input to National MME

https://gmao.gsfc.nasa.gov/gmao-products/geos-s2s-3/forecast-data_geos-s2s-3/aerosol/

S2S_3 May release: PM2.5 Anomaly (μg m⁻³)

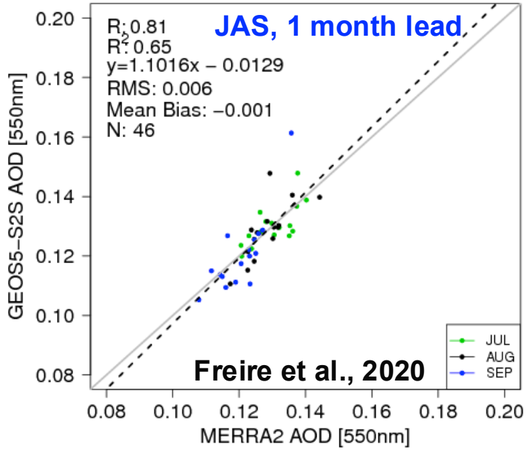


PM2.5 Anomaly Correlation



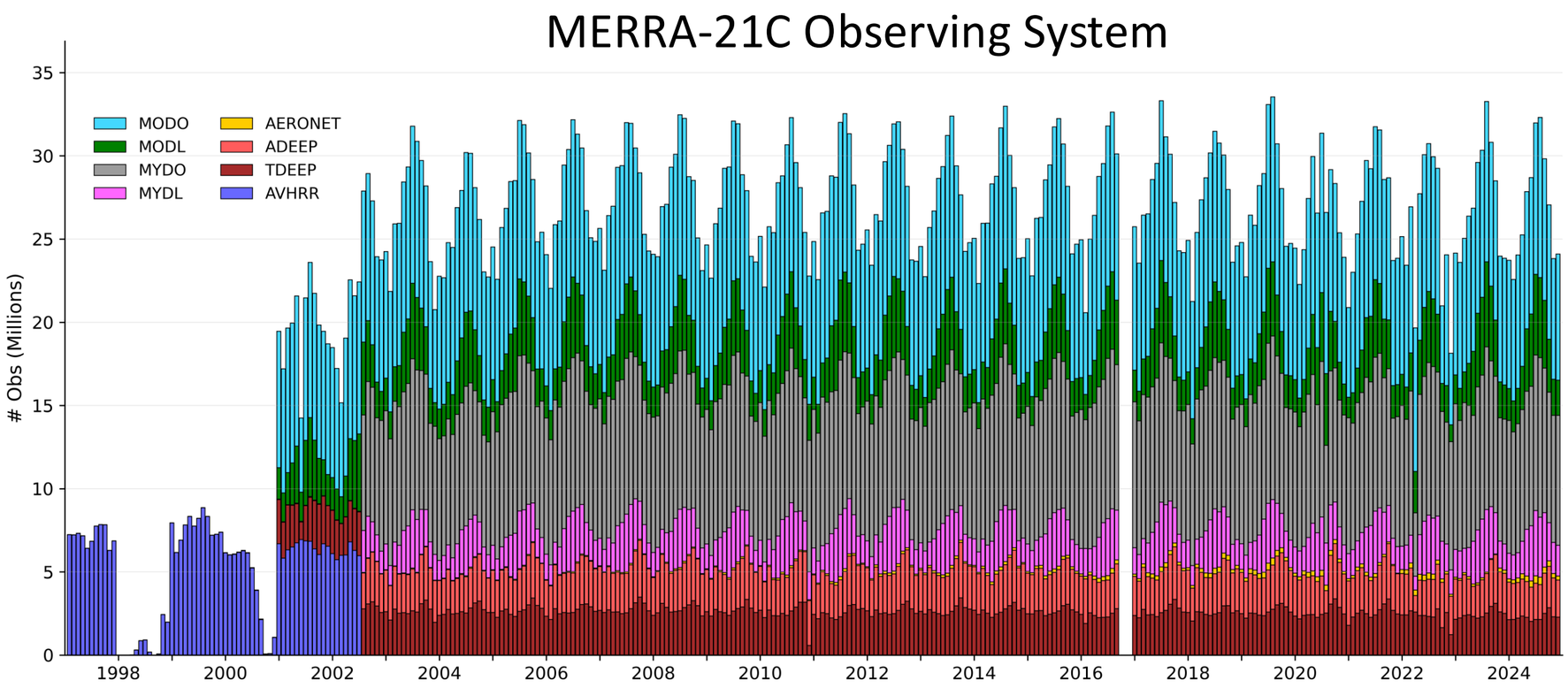
Analysis of Zhao Li

Global Mean Aerosol Optical Depth (2000-2015)



Dynamical predictions of AOD and PM2.5 on sub/seasonal scale can be skillful

MERRA-21C Status



- MERRA-21C is a stepping stone toward an eventual MERRA-3
- 3 parallel streams
  - 3rd stream is nearly up to present day
- Notable for first system running GOCART2G and updated emissions
  - Adds Nitrate and Brown Carbon

MERRA-21C

A Twenty First Century Retrospective Analysis to bridge EOS and prepare MERRA-3

Fundamental Characteristics

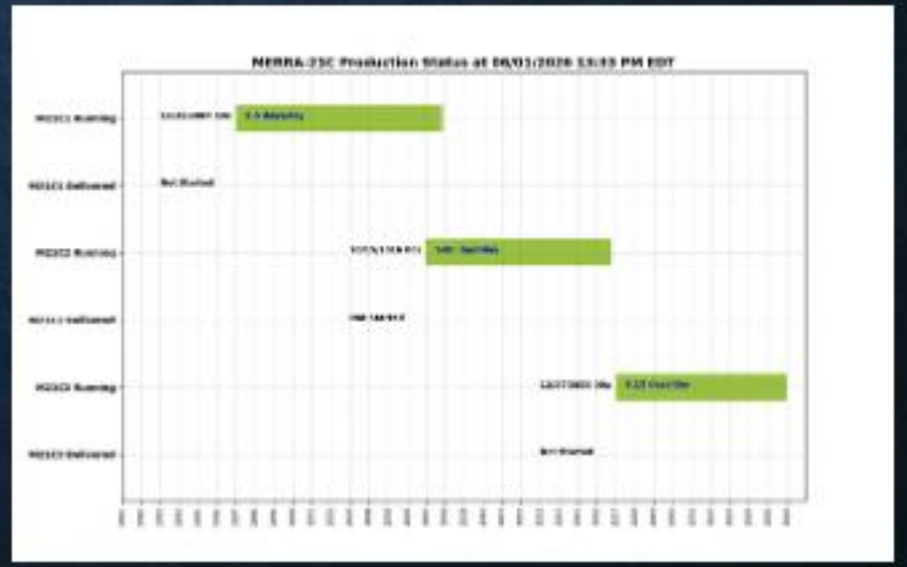
- **Period:** Covers 1998 to present, bridging EOS observations (hourly – monthly freq.).
- **Domain:** Global, 25 km horizontal grid with 72 vertical levels.
- **Physics:** Updates to Radiation and Aerosols (GOCART 2G).
- **Assimilation:** Hybrid 4DEnVar / All-sky microwave assimilation / commercial data.

Significant Features

- **PBL:** New constant height collection 100m intervals up to 4km
- **Aerosols**: Assimilated and interactive
- **Ensemble Spread**: Forecast variance in several fields
- **Cryosphere**: Expanded diagnostics
- **Fire Weather**: Consolidated quantity collection with a Fire Weather Index

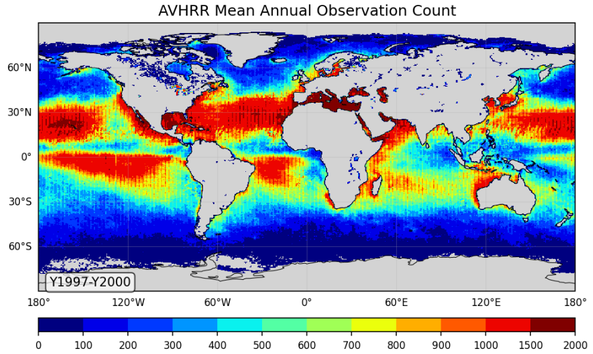
Sector Relevance

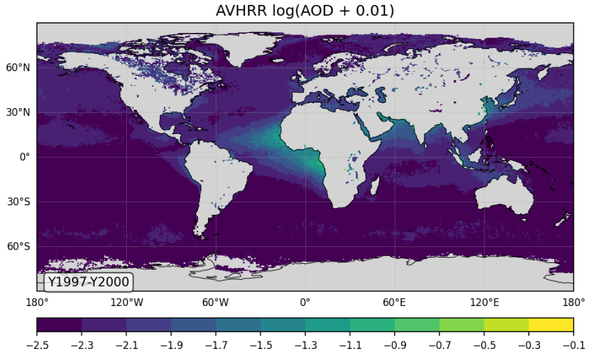
- **Energy:** Wind turbine hub-height analysis and solar UV index
- **Finance:** Climate-economic studies for economic risk.
- **Health:** Air quality tracking (PM2.5/PM10) and heat exposure.
- **Ecology:** Avian migration paths and Fire Weather Index.

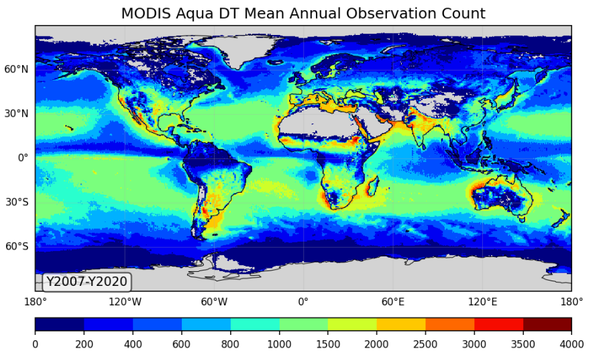


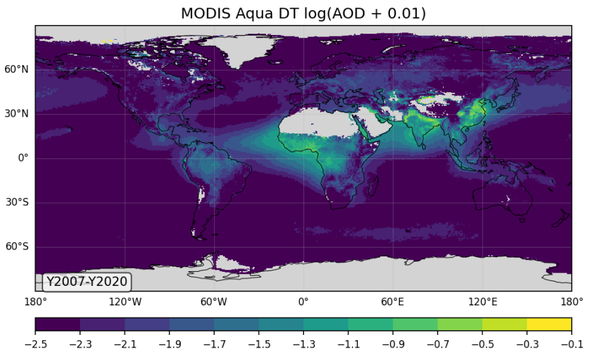
Content derived from Mike Bosilovich and Amal El Akkraoui

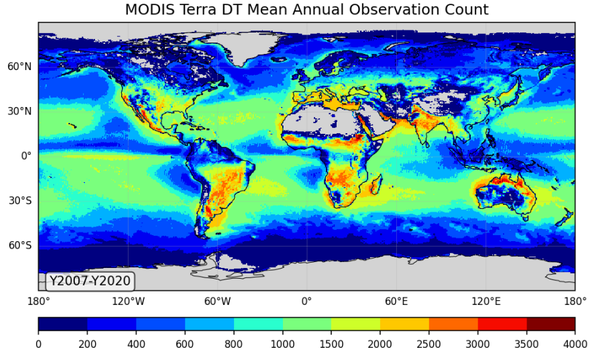
MERRA-21C – Annual observation count and AOD

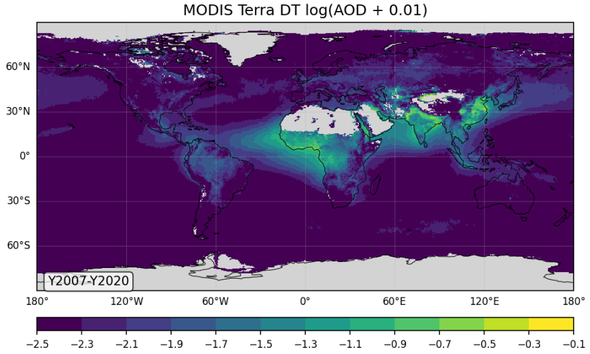


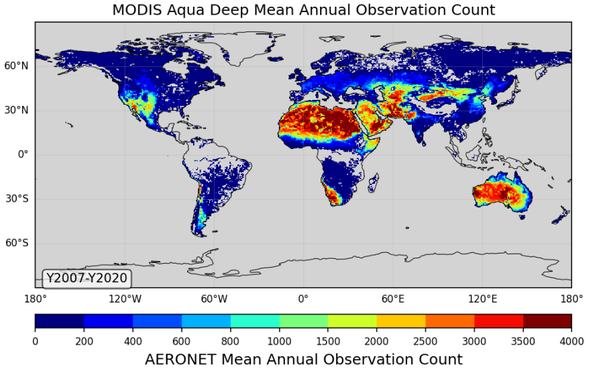


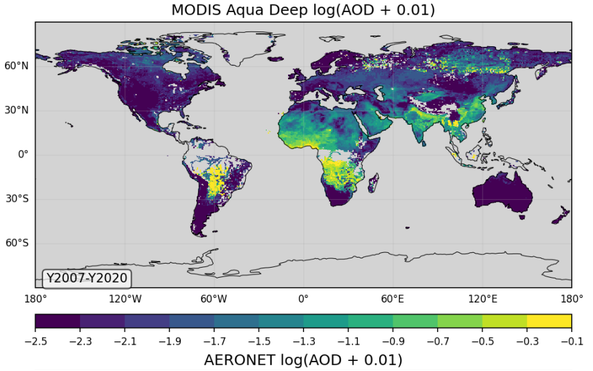


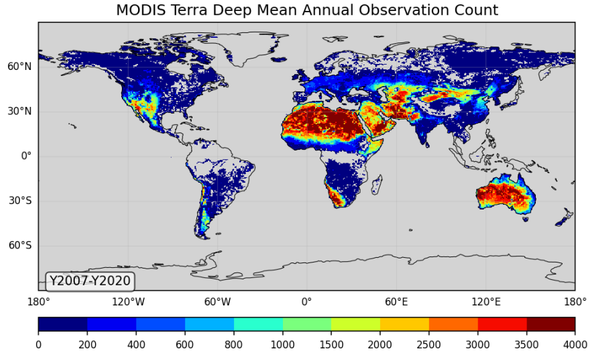


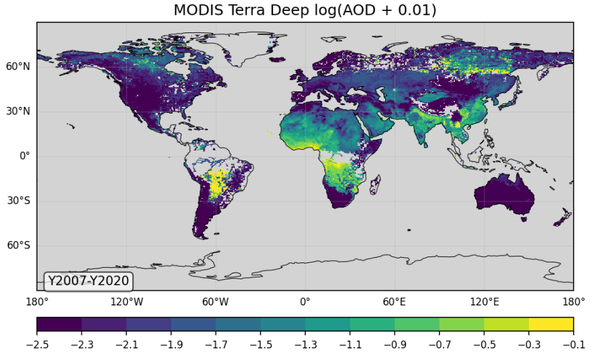


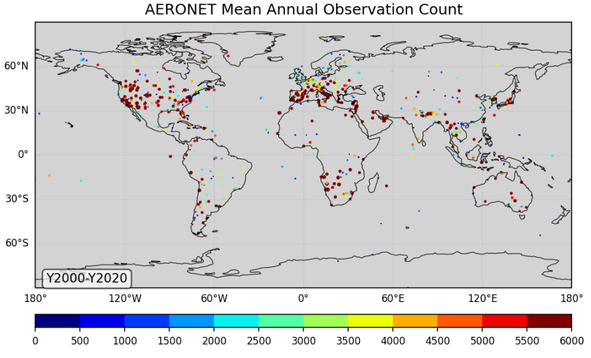


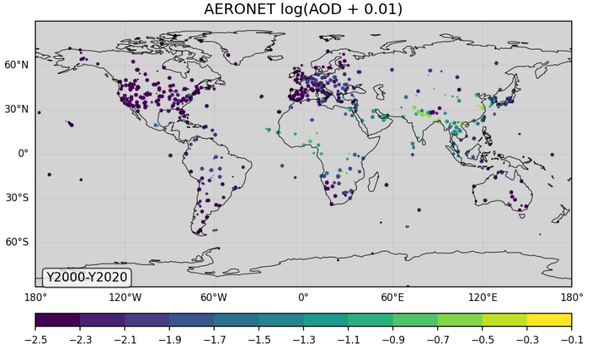












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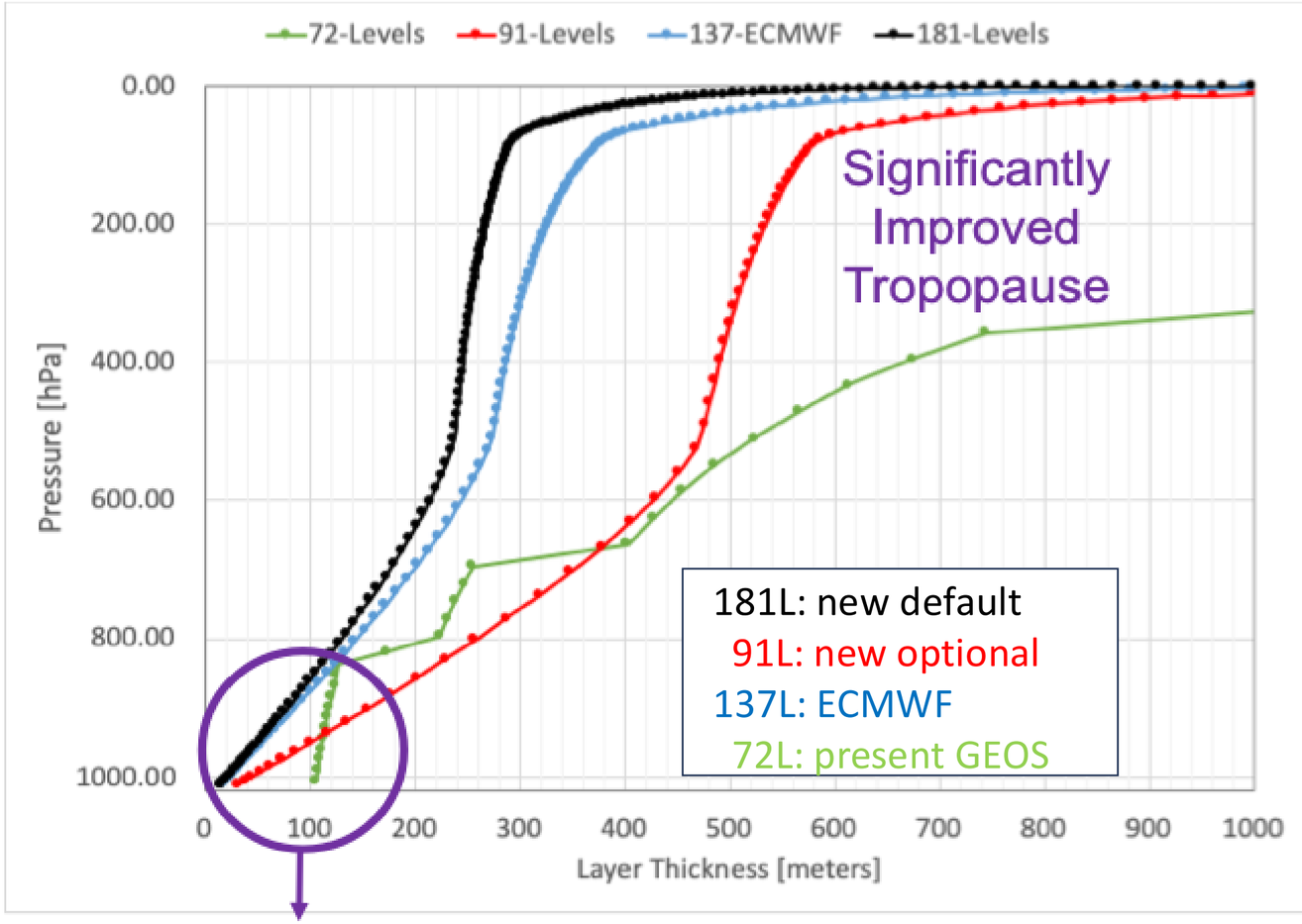
GEOS v12

- Increased vertical resolution, from 72 to 181 levels, improves PBL and stratosphere resolution
- Transition to GFDL 1-moment microphysics adds prognostic rain, snow, and graupel.
- Updates to Grell-Freitas deep convection improves transport, optional cold pools.
- UW shallow convection: revised momentum transport
- NCAR gravity wave drag scheme improves Quasi-Biennial Oscillation
- FV3 dynamics non-hydrostatic for C360+ (dx<25 km)

Vertical grid spacing

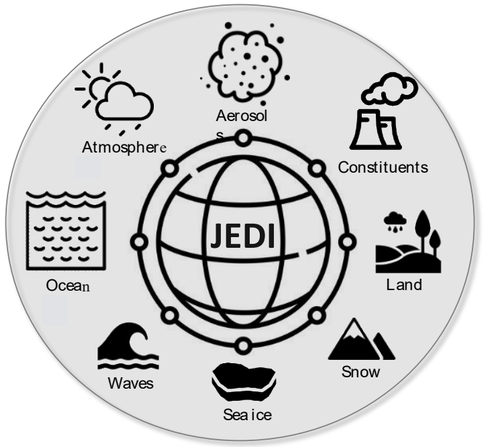


Aerosol Data Assimilation Updates

GEOS JEDI Aerosol Data Assimilation: Transition & Status

Strategic Vision:

- **Unifying DA:** Replacing legacy, purpose-built systems (like PSAS) with a unified, coupled DA system based on GEOS and JEDI.
- **Multi-Agency R2O:** Capitalizing on JEDI to exploit diverse Earth-system observations and accelerate research-to-operations.

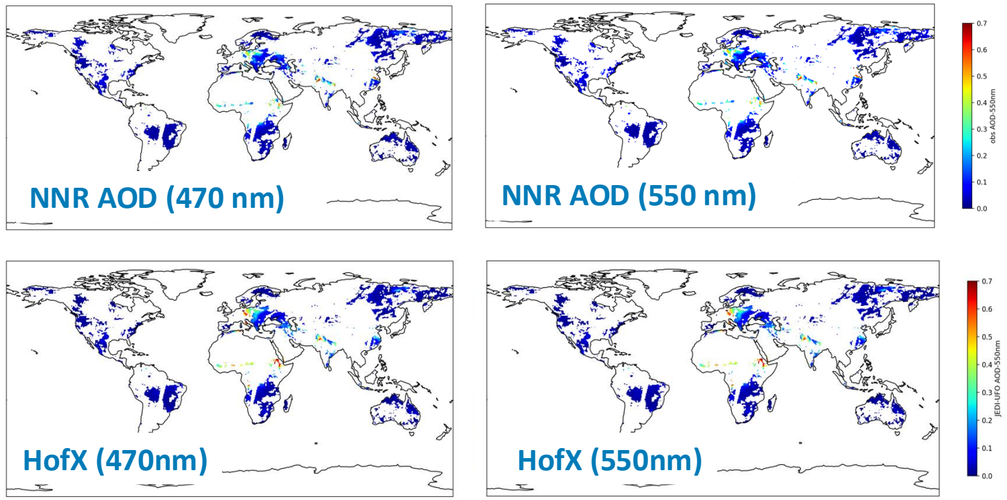


Scientific Advancements (PSAS → JEDI)

- **Solver:** Moving from PSAS 2D to **JEDI 3D-EnVar**.
- **Variables:** Upgrading from 2D single-λ AOD to **3D multi-λ extinction profiles**.
- **Background Error:** Transitioning to flow-dependent errors using meteorological ensembles.

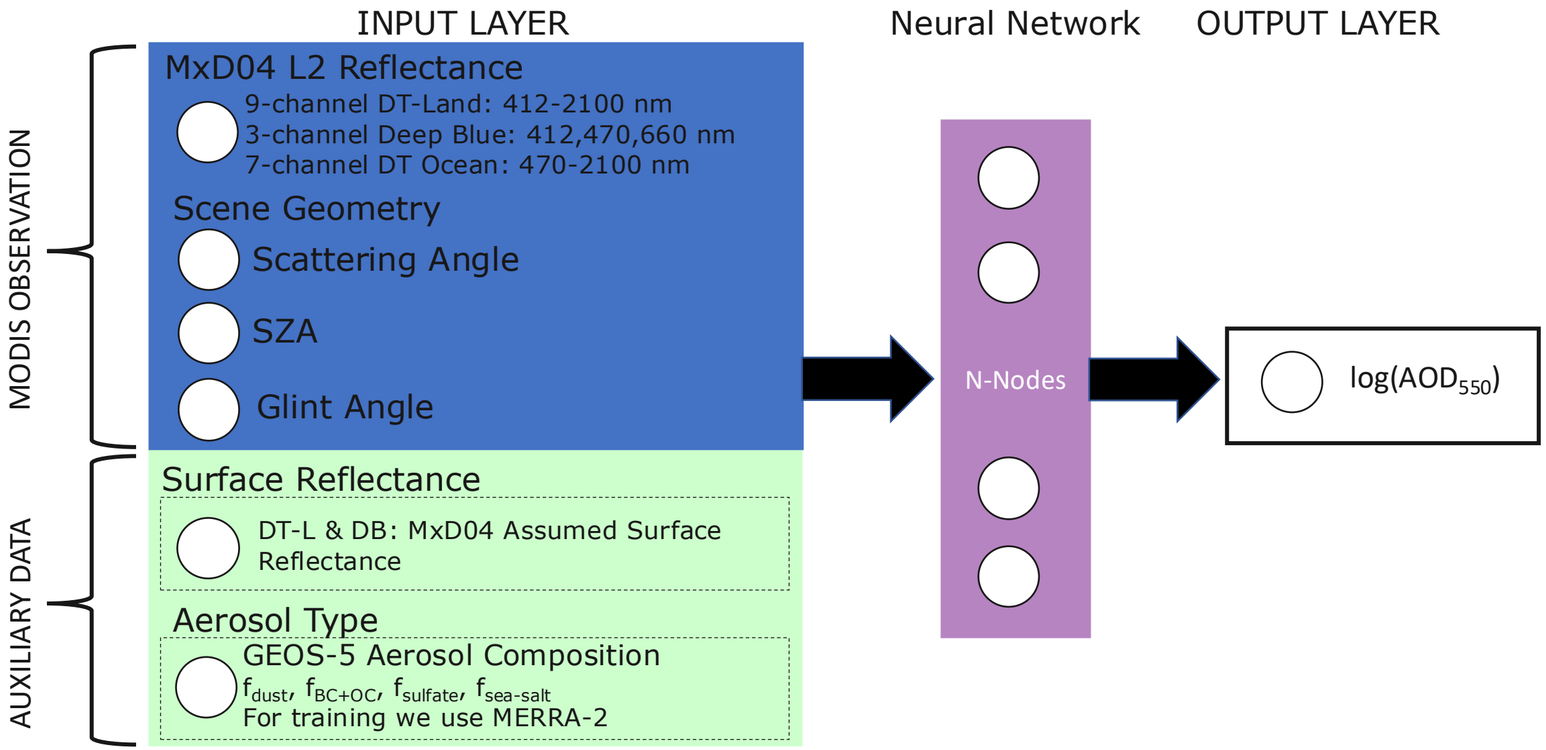
Current Status & Results

- **Multi-wavelength AOD observation operator** successfully merged into JEDI/UFO. JEDI computing accurate HoFX multi-λ AOD (see figure).
- **IODA & QC:** NNR AOD conversion to JEDI/IODA format; Fortran/Python-based external quality control (background/ iterative buddy checks) are both completed.
- **Next Steps:** Background error under testing and updating GAAS modules to transform extinction increments into mass mixing ratios for the GEOS model.



Transition to VIIRS AOD Assimilation

GEOS NNR for AOD

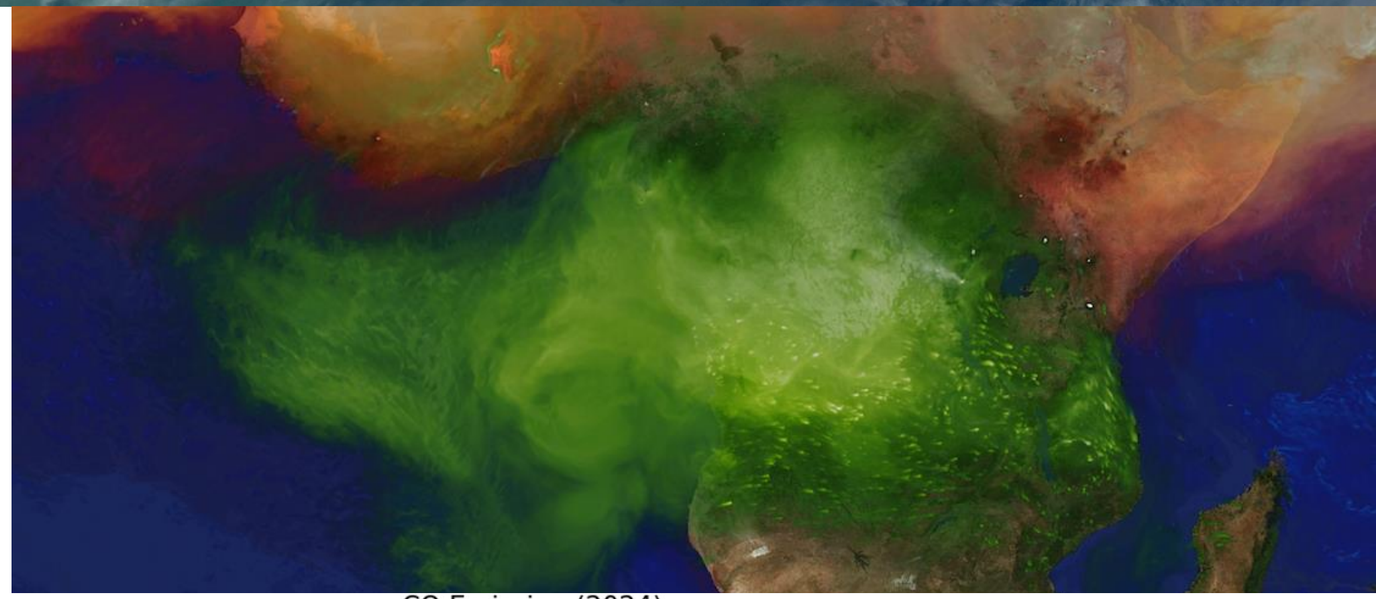


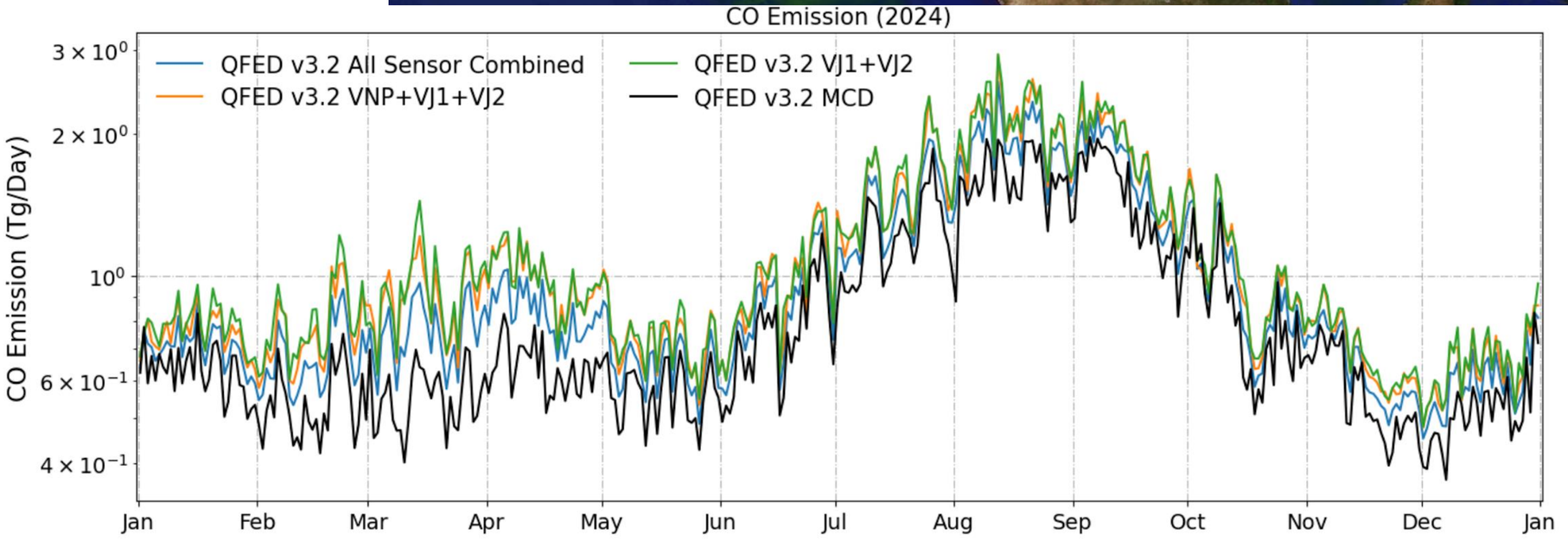
- MODIS Deep Blue, Dark Target Ocean and Dark Target Land AOD are predicted by independent neural networks
- VIIRS is treated similarly
  - Only the bright land surface AERDB retrievals are utilized (when 412 nm reflectance is reported)
  - The AERDT reported cloud fraction is used to QC-filter AERDB (CF<0.1)
- Where both DT and DB observe, preference for DT

QFED Updates

QFED: Quick Fire Emission Dataset

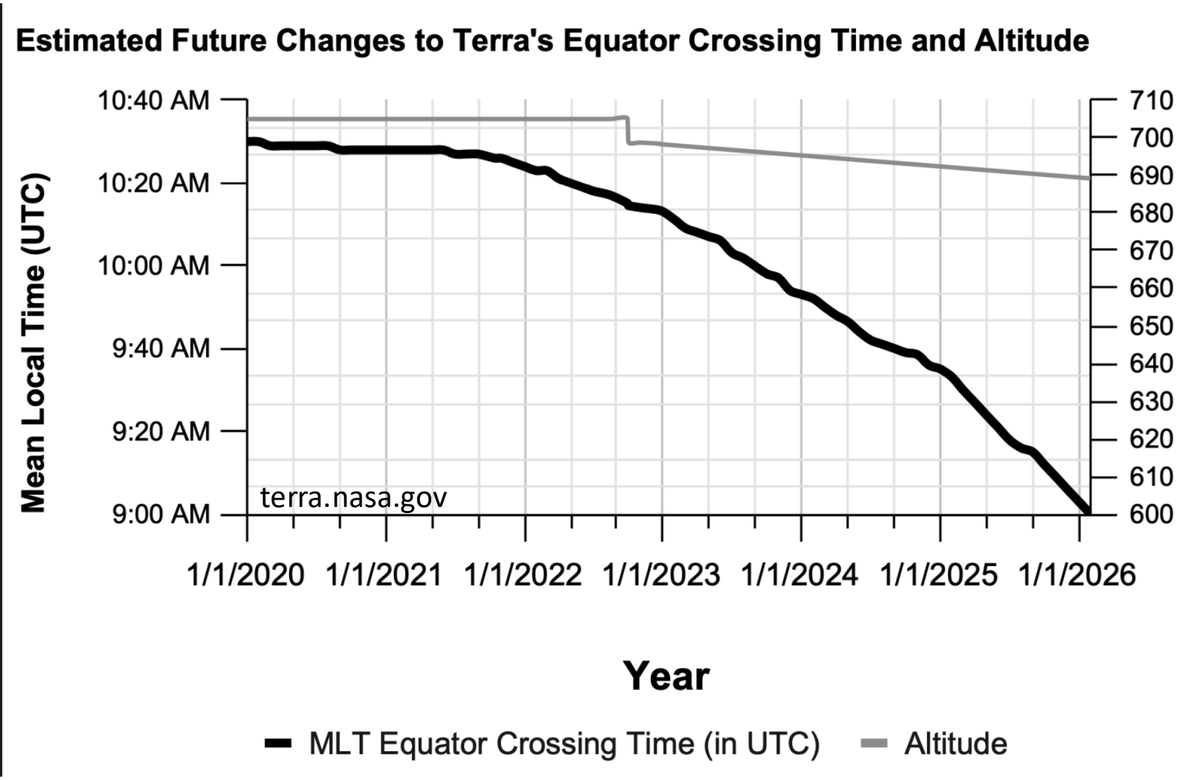
- GMAO's FRP based biomass burning emissions for GEOS systems
  - Global aerosol and trace gas emissions with biome and species level control
- Current Operational version: v2.6r1
- Latest Release: v3.2
  - NOAA-20 & NOAA-21
  - Designed for continuity in reanalysis
  - Will be released on GES DISC



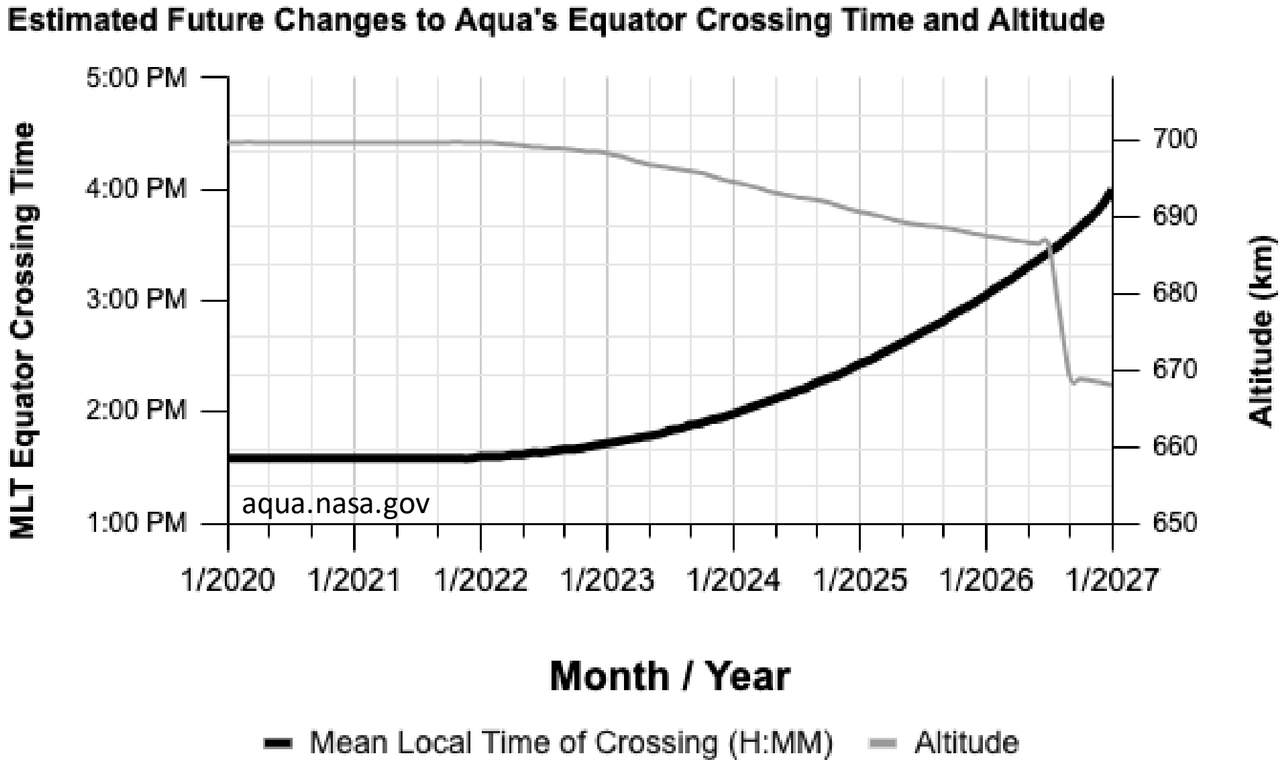


Terra and Aqua Drift

- Terra's observation time is getting earlier

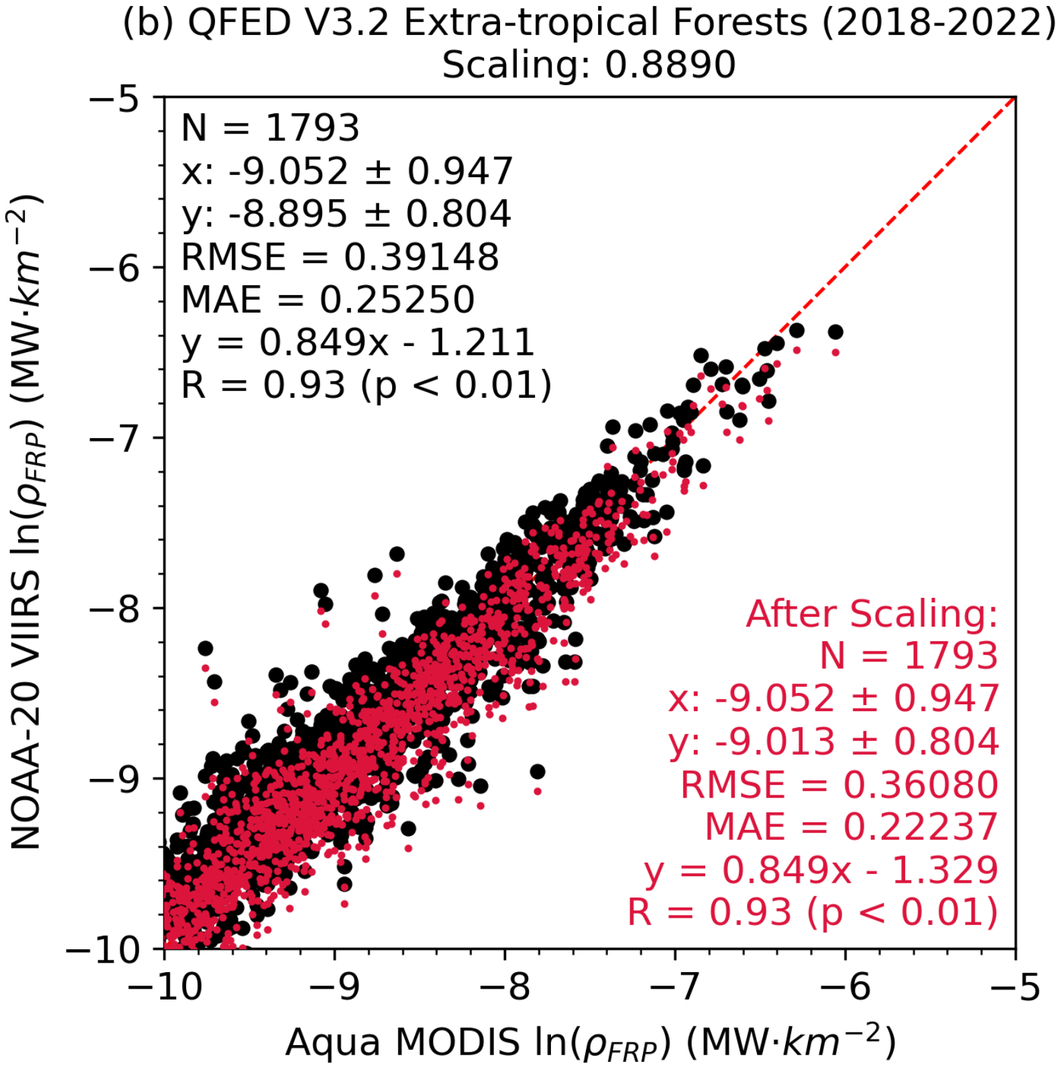


- Aqua's observation time is getting later



- These orbital changes impact fire detection
- On average, wildfires peak in the afternoon -> Terra is increasingly underestimating fire activity
- To maintain continuity in reanalysis, we make NOAA-20 & 21 look like today's MODIS

Continuity from MODIS to VIIRS FRP



- Scaling factors were determined using a linear regression of global mean log FRP density against Aqua MODIS
- Only showing extratropical forests for simplicity but this was done independently for each biome and satellite
- We assessed scaling factors for a 5-year chunk (shown here) but ultimately selected 2024 to take advantage of the launch of NOAA-21 and minimize a jump in the historical record due to Terra's and Aqua's drifting orbits

Regional Scaling Factors to Fine Tune Emissions Continuity with QFED 2.6r1

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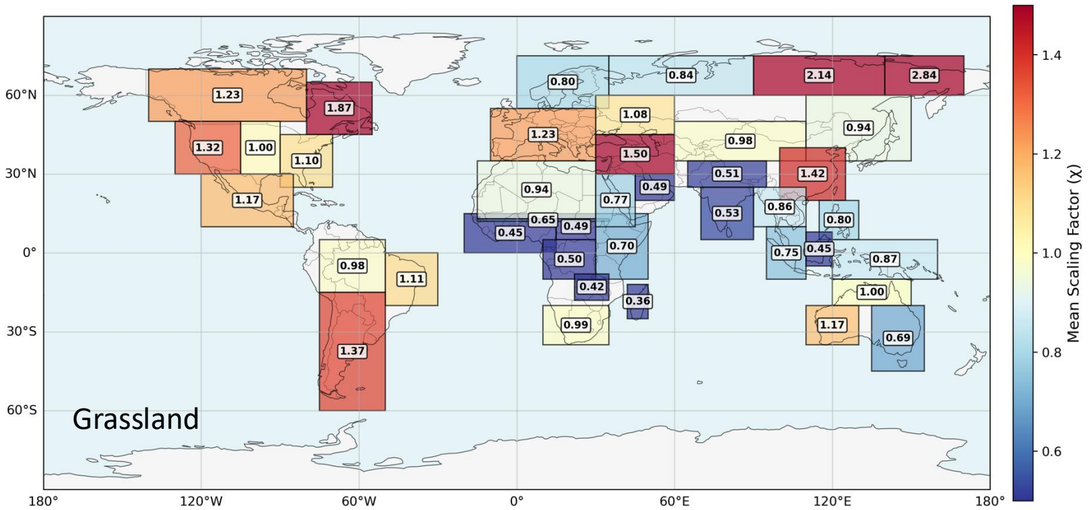
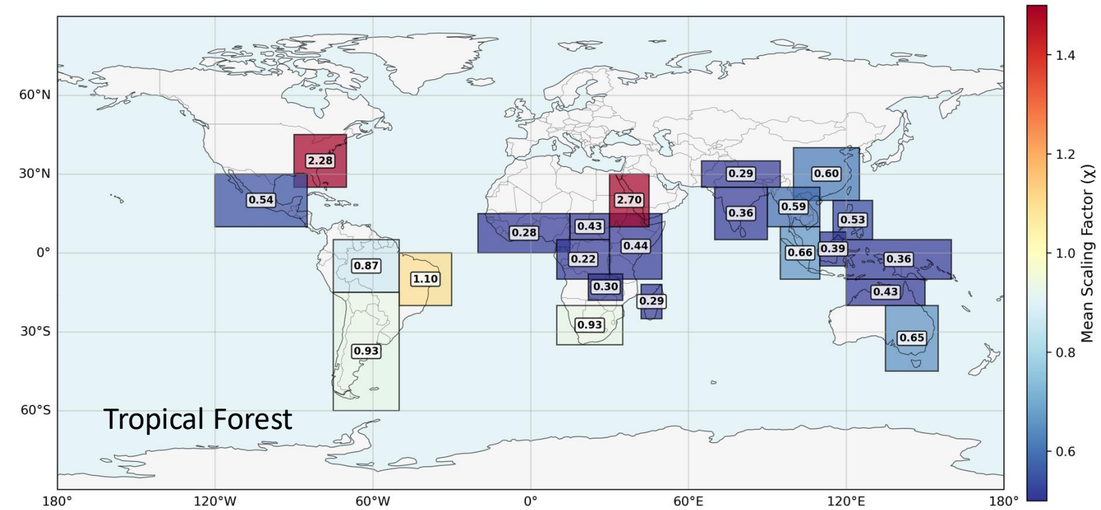
NASA

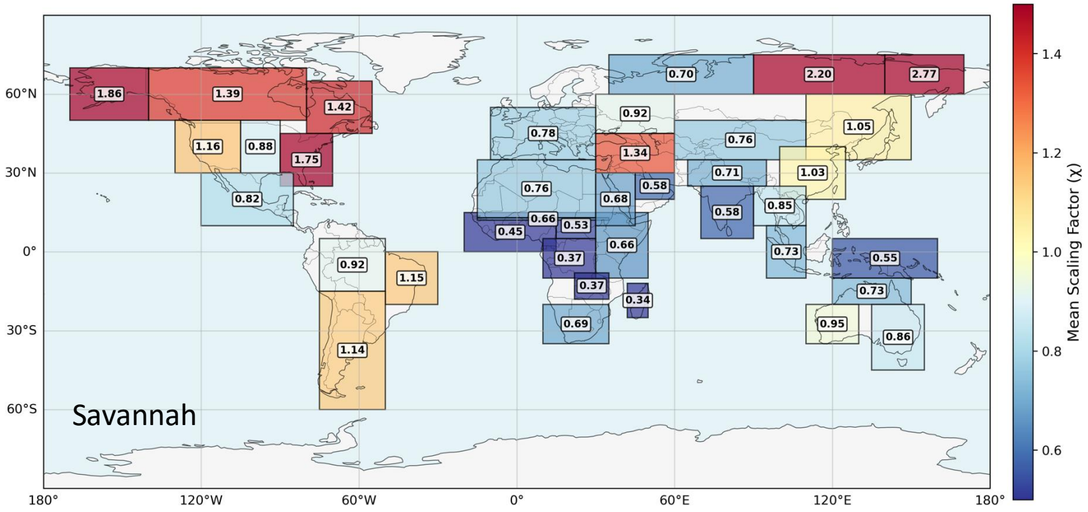
Regional Scaling Factors: QFED3 to QFED2 (gl - biomass_gl)
χ = exp(mean(log(QFED2)) - mean(log(QFED3)))



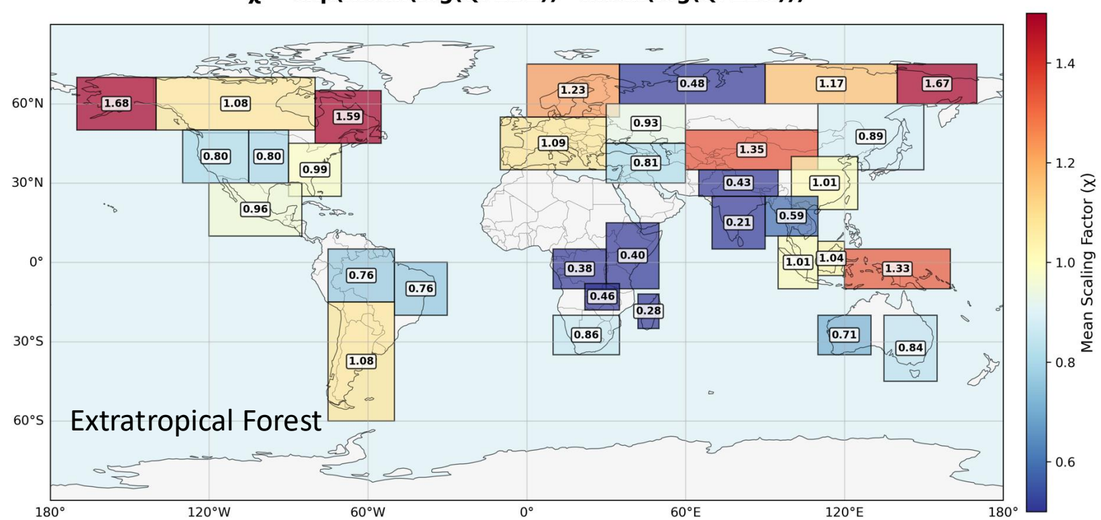
Regional Scaling Factors: QFED3 to QFED2 (tf - biomass_tf)
χ = exp(mean(log(QFED2)) - mean(log(QFED3)))



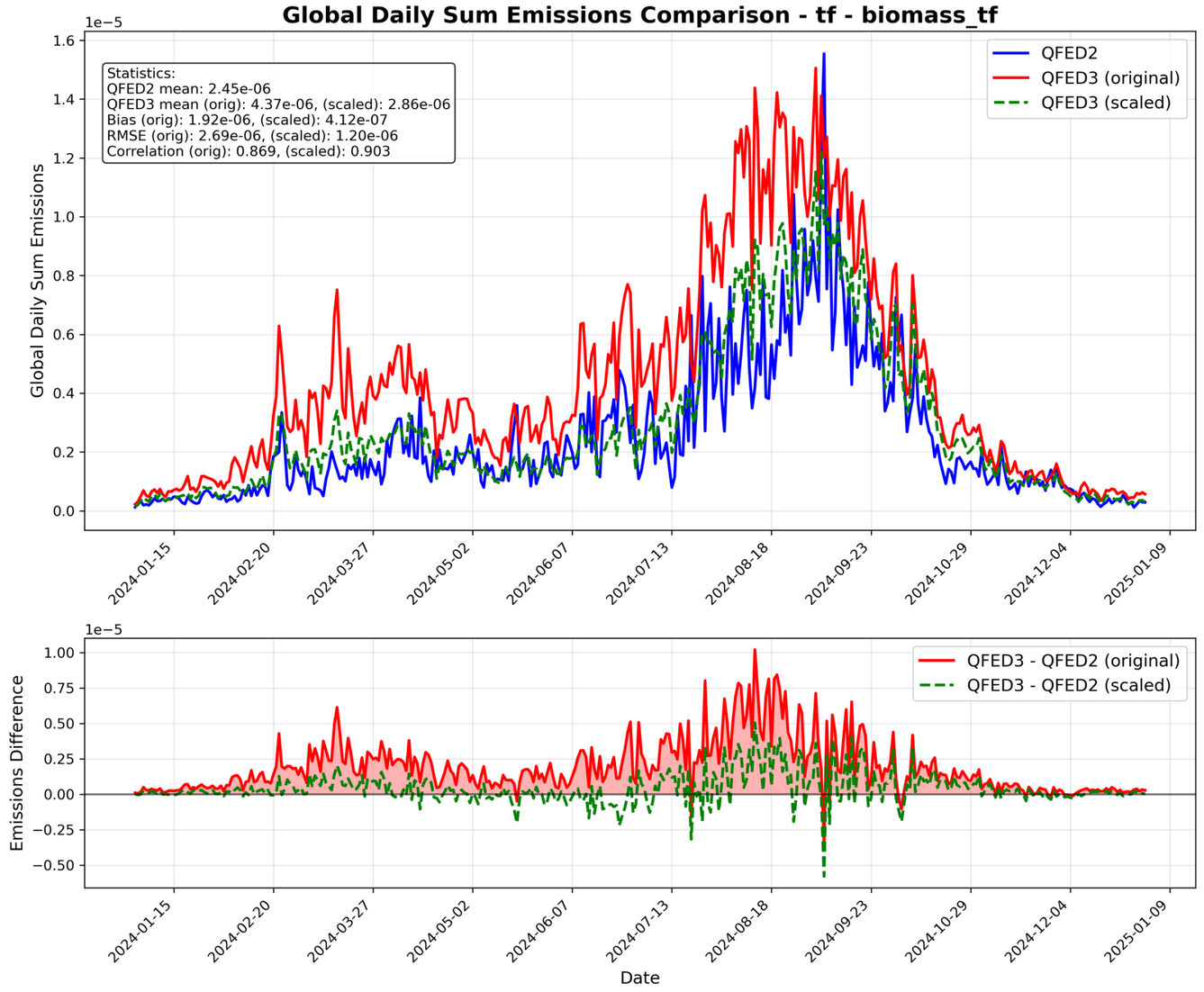
Regional Scaling Factors: QFED3 to QFED2 (sv - biomass_sv)
χ = exp(mean(log(QFED2)) - mean(log(QFED3)))



Regional Scaling Factors: QFED3 to QFED2 (xf - biomass_xf)
χ = exp(mean(log(QFED2)) - mean(log(QFED3)))

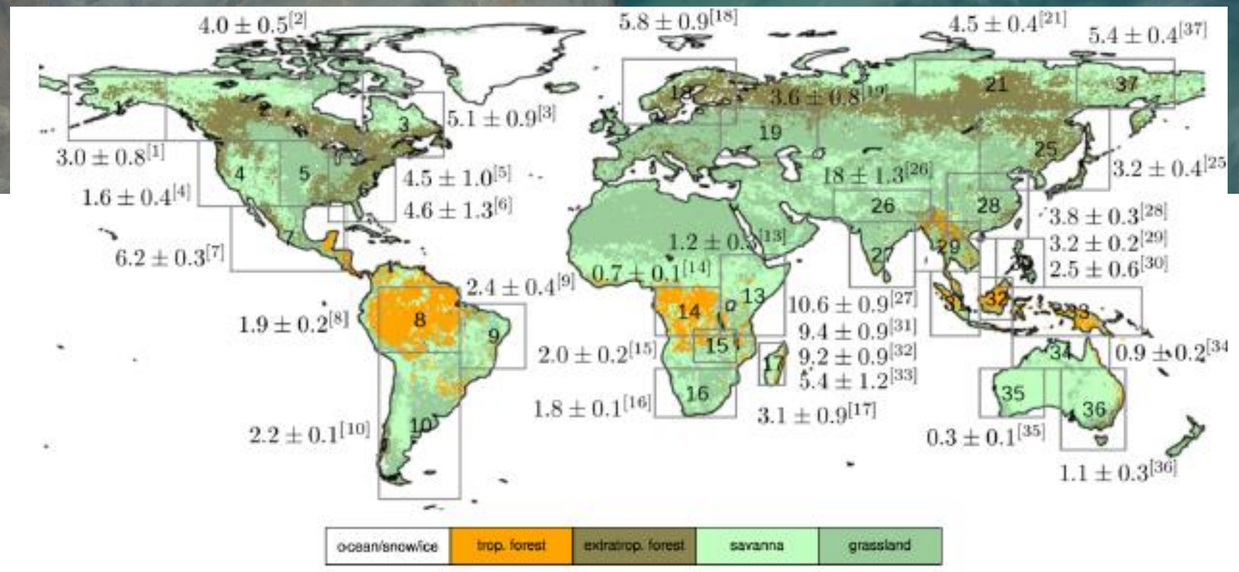


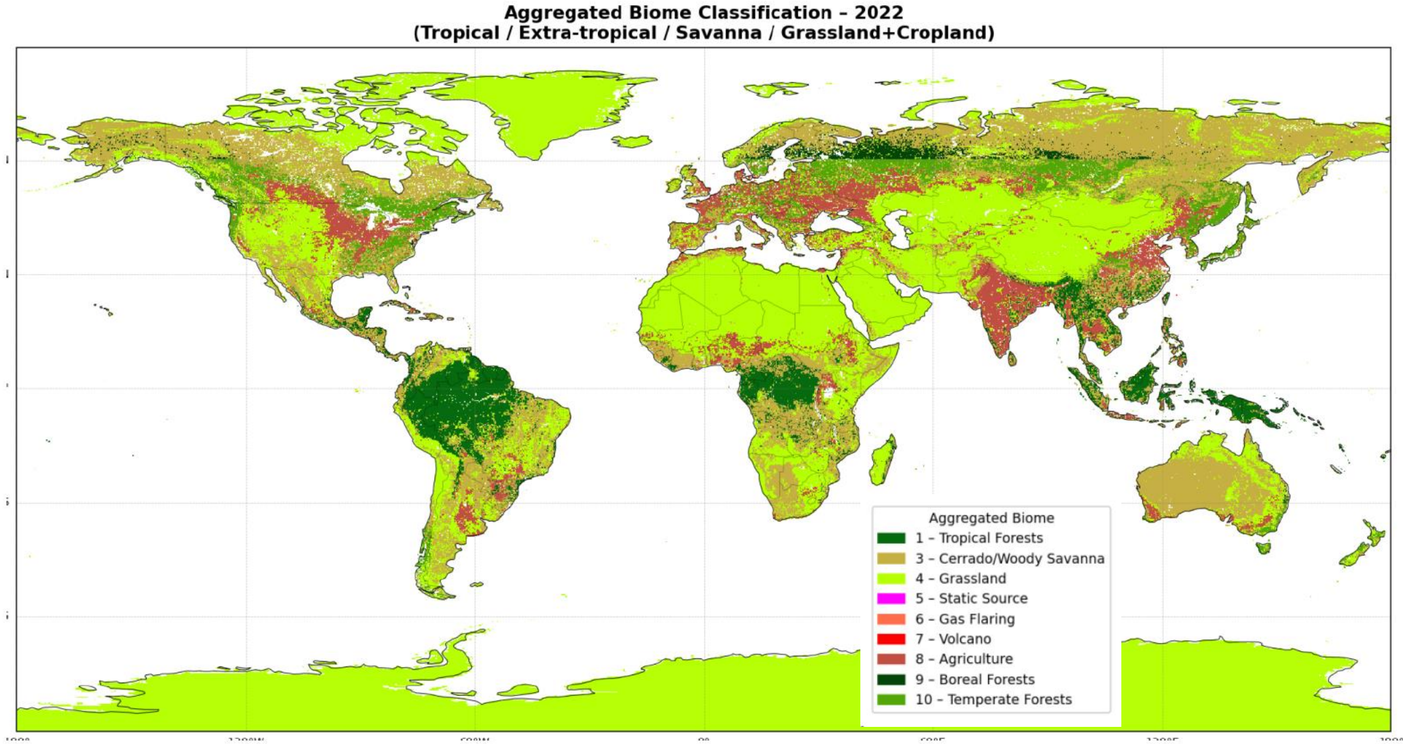
v3.2 Scaling on Global Organic Carbon Emissions: Tropical Forest



- Only showing tropical forest in the interest of time - biome with the largest impact from scaling
- We want the dashed green line to be closer the the blue in the top panel and hovering around zero in the bottom panel
- The positive bias is greatly reduced and the correlation is improved
- Scaling is applied to all species and works well for years other than 2024 (not shown by figure)

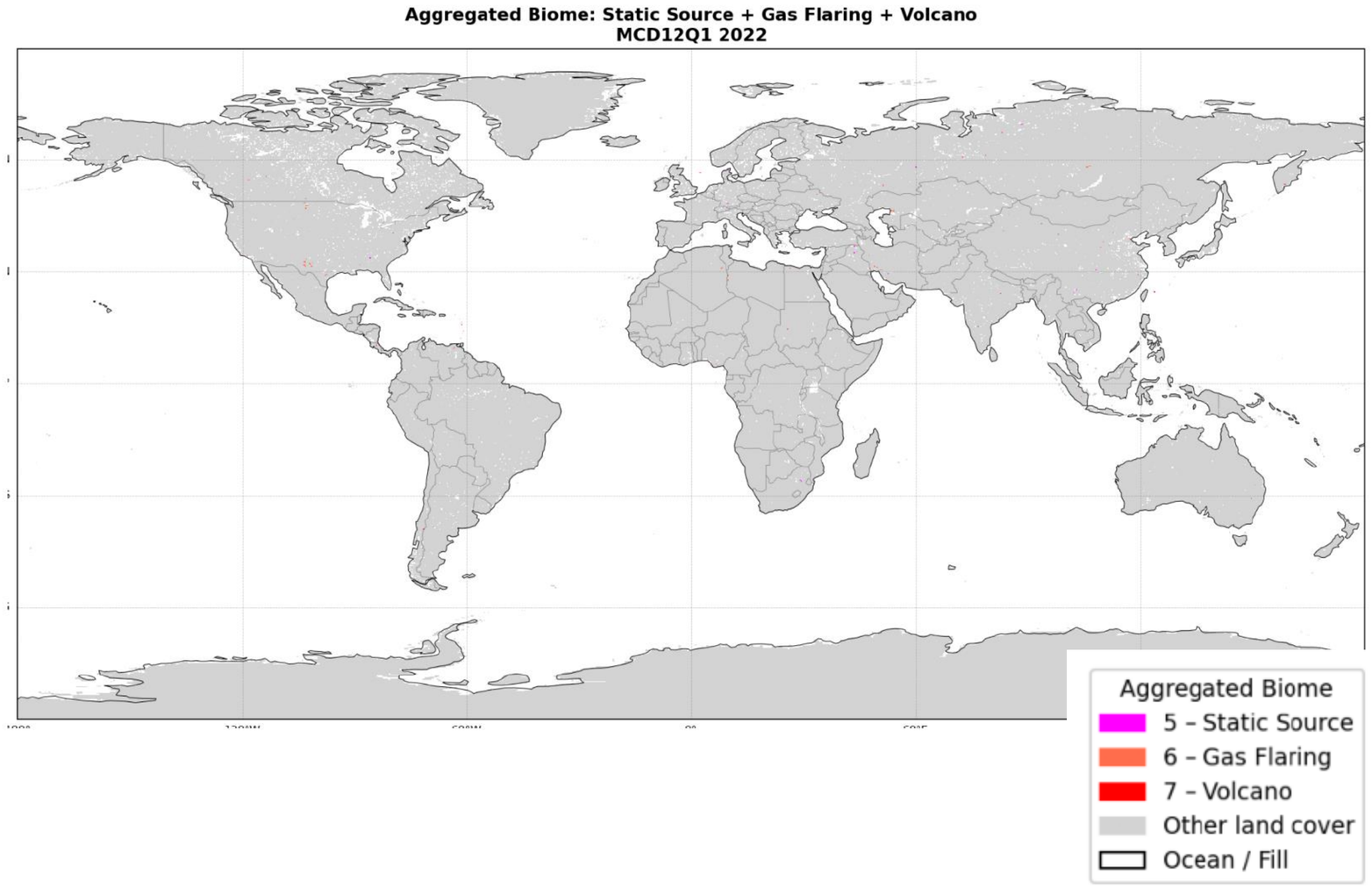
In Progress QFED v3.3



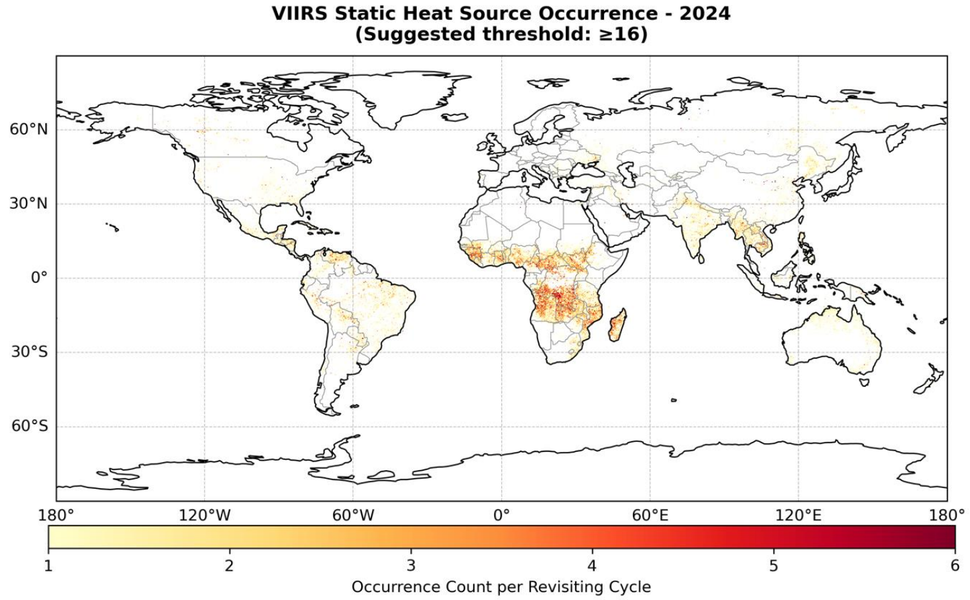


- v3.3 will be anchored to NOAA-20
  - Will scale MODIS FRP up to VIIRS
- Emission coefficients will be based on GFED5
- Implement annual vegetation maps
  - QFED has until now used a static biome map
  - New biome maps will include boreal forest and agriculture to align with Andrea (2019) emission factors

Updates for QFED v3.3



- We have developed a dataset of known hot spots like solar farms, gas flaring, and volcanic eruptions
- These can be removed prior to emission calculation
- Gas flaring is currently double counted in GEOS by anthropogenic emissions

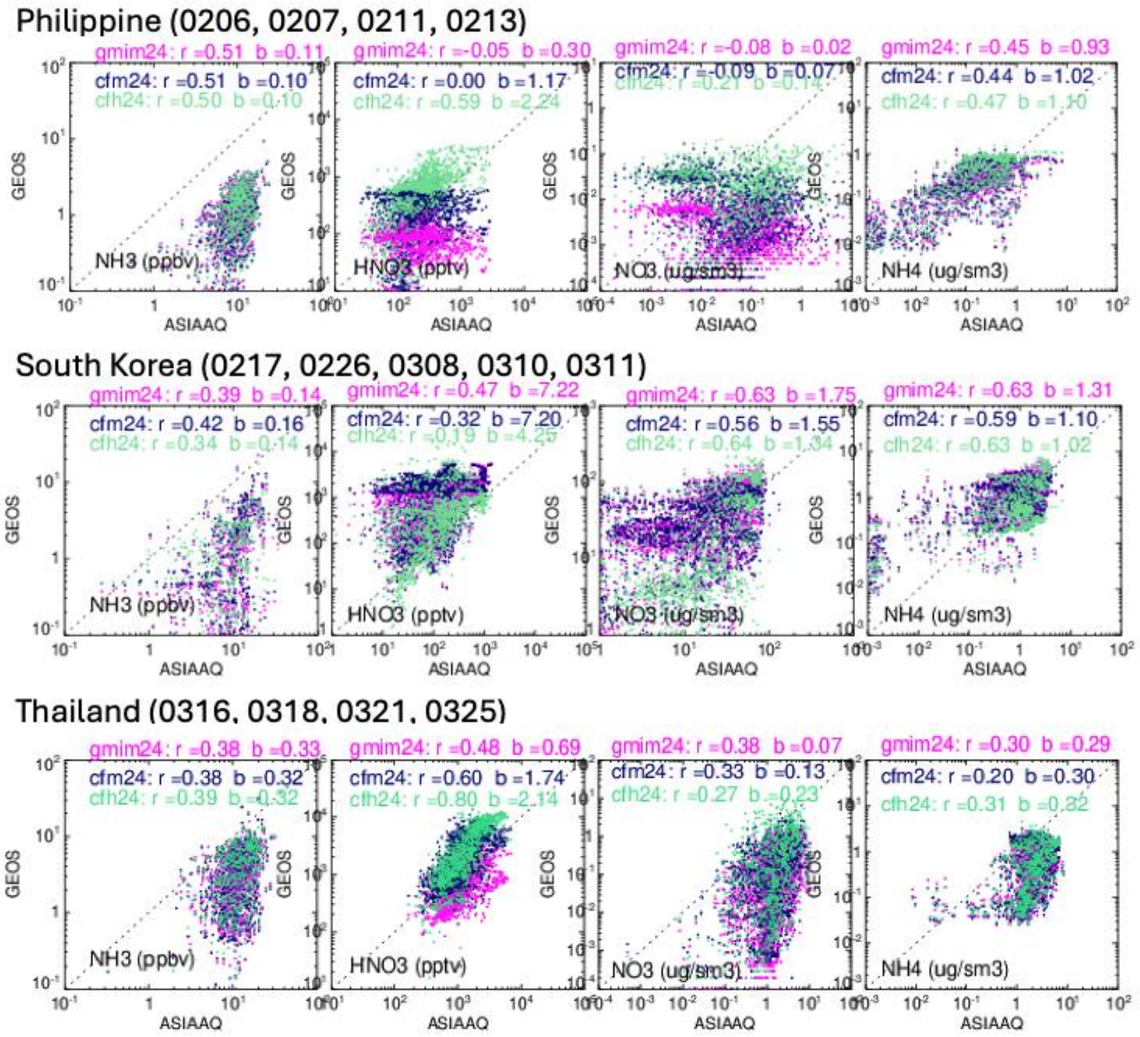


Projects

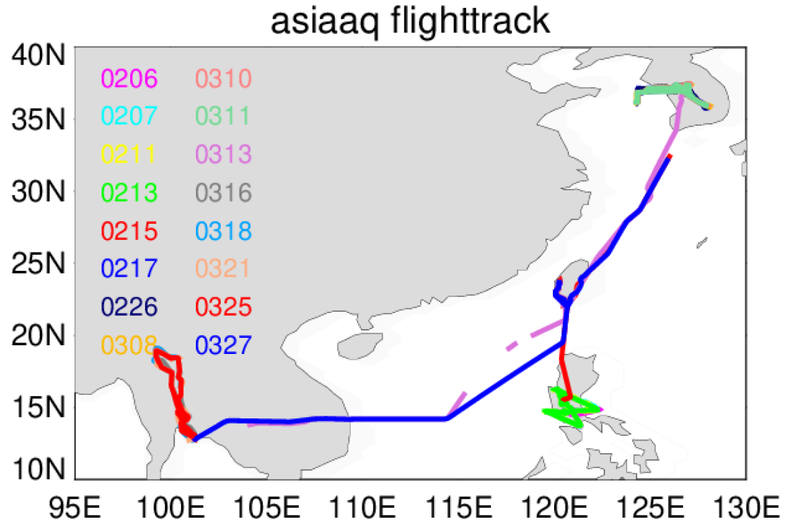
Field Campaign Support

ASIA-AQ Field Campaign

Assessing the Fidelity of Full Chemistry Simulations and MERRA2-GMI Climatology

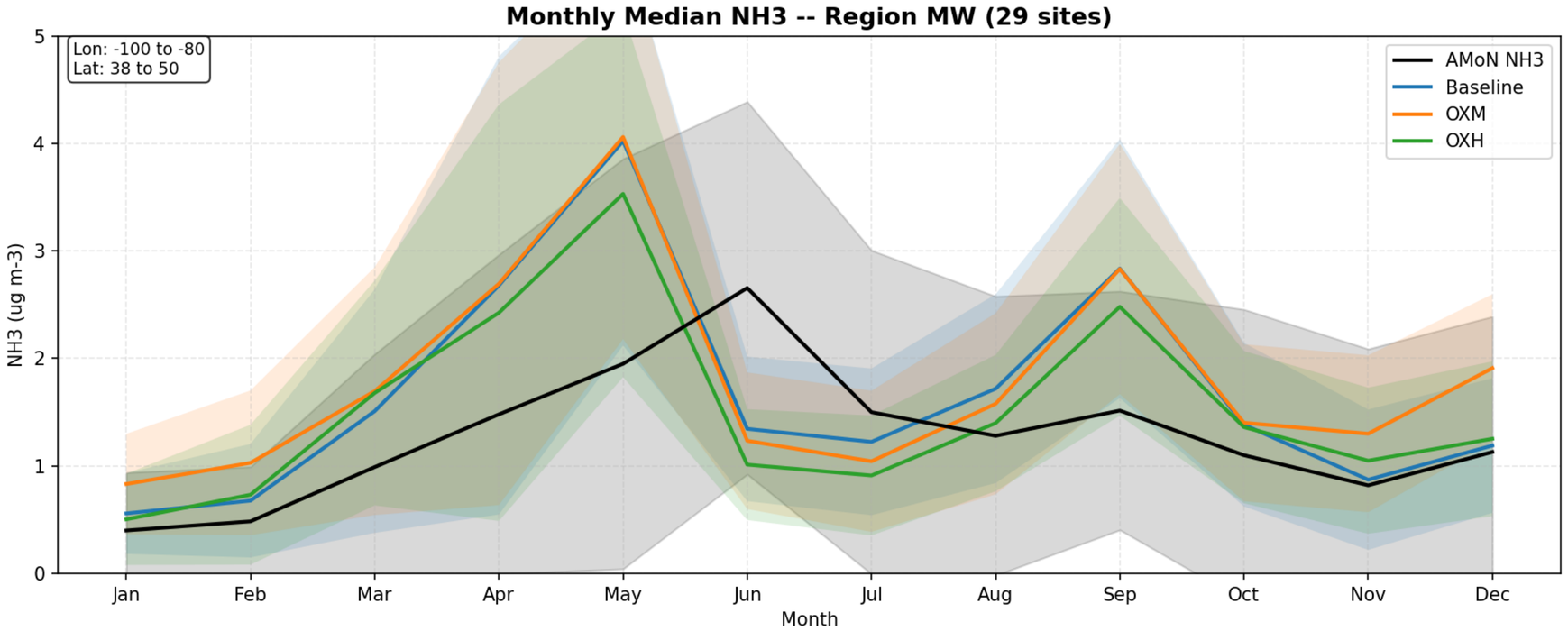


Flights over Korea, Phillipines, Taiwan, and Thailand Feb-Mar 2024



FarmFlux Field Campaign

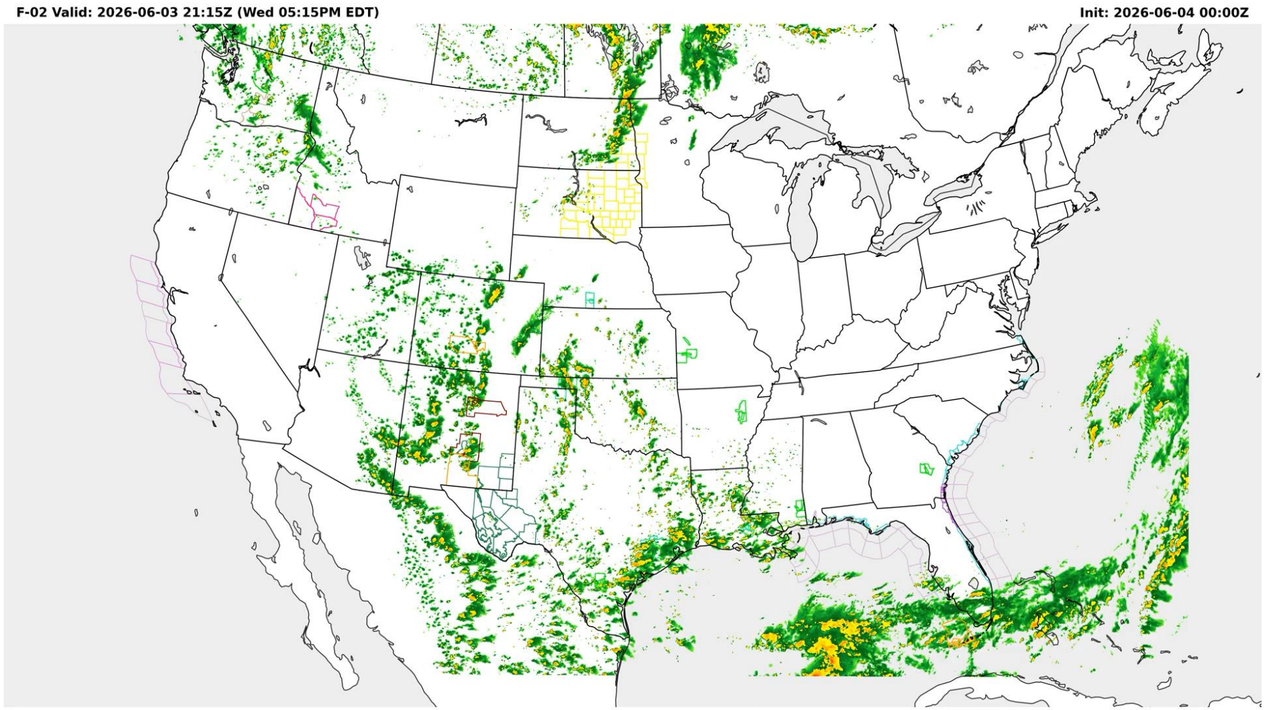
- Airborne mission to study the cycling of nitrogen between agricultural systems and the atmosphere
- GEOS will support flight planning and mission ops
- Objectives are to implement bidirectional NH3 exchange and improve emissions



Summary & Outlook

- Aerosol DA transition to VIIRS:
  - VIIRS AOD assimilation has comparable skill to MODIS
  - Further refinement of the observing system homogenization may be needed for future reanalysis applications
- QFED v3.2 Emissions finalized
  - Provides continuity with MODIS-based emissions at the regional scale
  - v3.3 is in development - focused on improved biome representation and speciation
- Next major GEOS release is v12
  - 181 Levels – better resolution in the lower atmosphere
  - Improved convection schemes
- Stretch grid implementation
  - 2 km resolution over CONUS

GEOS Stretch Grid Forecast



Backup