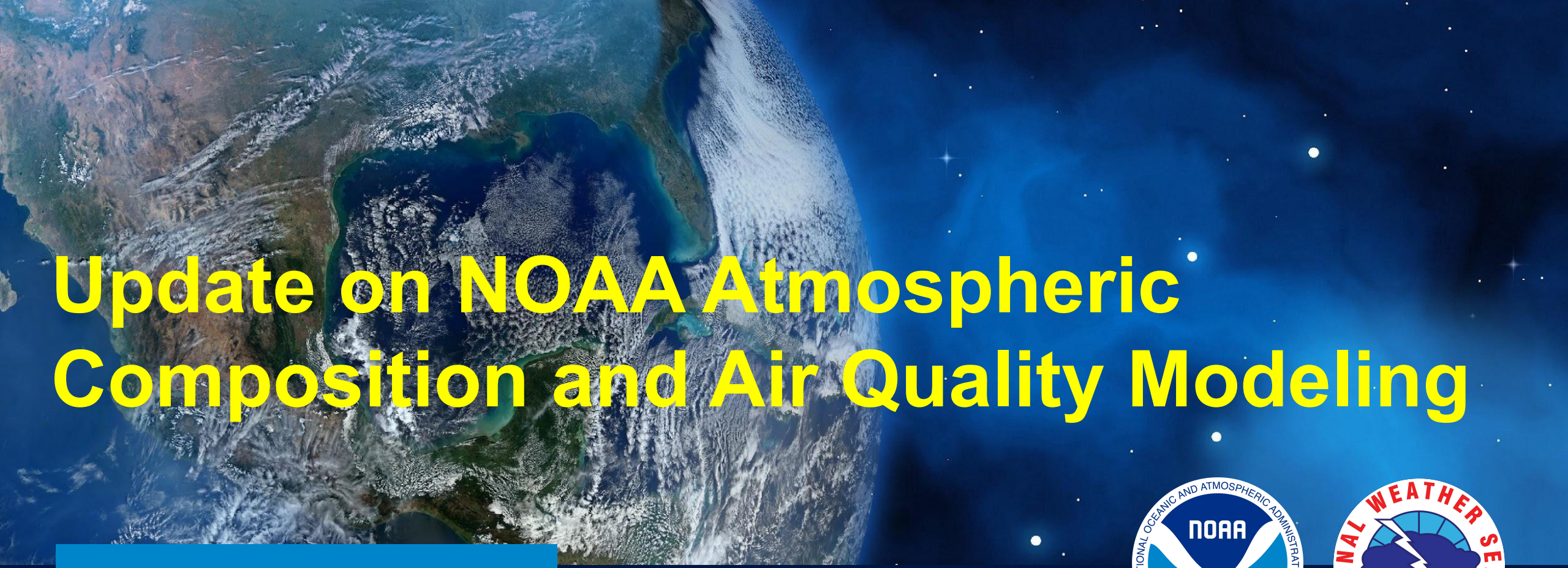


Update on NOAA Atmospheric Composition and Air Quality Modeling

Fanglin Yang

NOAA/NWS Office of Modeling and Development

ICAP 2026 Meeting, Online Presentation

U.S. Department of Commerce

National Oceanic and Atmospheric Administration

National Weather Service

Acknowledgements

NWS/OMD: Barry Baker, Kai Wang, Li Pan, Partha S Bhattacharjee, Binyu Wang, Raffaele Montuoro, Fanglin Yang, Ho-Chun Huang, Cory Martin, Andrew Tangborn, Yaping Wang
OAR/ARL: Patrick Campbell, Youhua Tang, Beiming Tang, Wei Li, Wei-Ting Hung, Irena Ivanova, Zach Moon, Sonny Zinn, Tianfeng Chai, Mark Cohen, Alice Crawford
OAR/GSL: Li (Kate) Zhang, Ravan Ahmadov, Ligia Bernardet, Shan Sun
OAR/CSL: Rebecca Schwantes, Jian He, Quazi Rasool, Brian McDonald
NESDIS/STAR: Xiaoyang Zhang, Ethan Hughes, Shobha Kondragunta

Funding Sources
Weather Program Office
Office of Science and Technology
UFS R2O
Bi-Partison Infrastructure Law Bil-Fire3
Disaster Relief Supplemental Appropriations (DSRA) Fire-2 and Fire-3

NOAA Offices and Labs: Contributing to Atmospheric Composition and Air Quality Modeling

- **NWS Office of Modeling and Development (OMD)**
  - Development and transition to operations AQ/AC models.
- **NESDIS STAR**
  - Satellite observations; Blended Global Biomass Burning Emissions Product (GBBEPx) and Regional ABI and VIIRS fire Emissions (RAVE) products OMD modeling uses.
- **OAR Chemical Sciences Lab (CSL)**:
  - Atmospheric chemistry science, emissions, chemical mechanisms, observations, field campaigns. Collaborate with OMD for global chemistry and aerosol modeling.
- **OAR Global Systems Lab (GSL)**:
  - Development of HRRR-smoke and RRFS-smoke-dust models; Collaborate with OMD for global aerosol modeling.
- **OAR Air Sources Lab (ARL)**:
  - Atmospheric transport and dispersion, boundary-layer processes, air quality applications. Collaborate with OMD for regional air quality and global aerosol and chemistry modeling.

OMD also collaborates with NASA/GSFC, EPA, and universities (George Mason Univ and Northeastern Univ etc) for AQ/AC modeling.

NOAA AQ/AC Modeling Systems

Current Operations

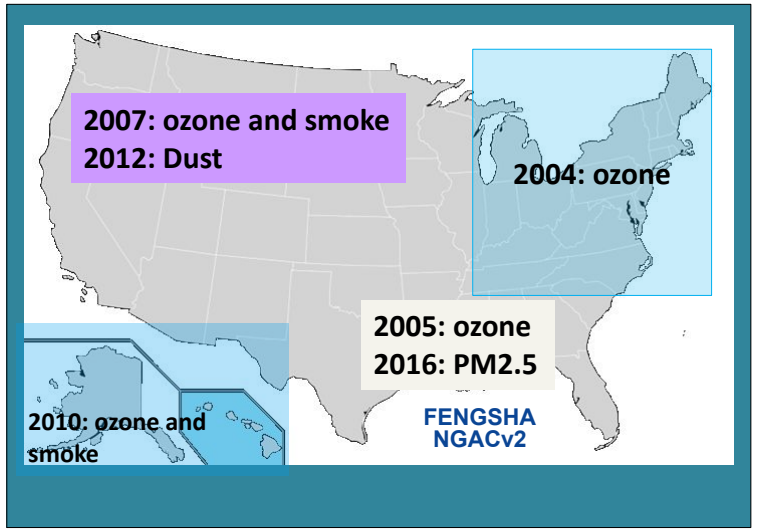
- AQMv7: regional air quality
- GEFS-Aerosol v12: global aerosols
- RAP/HRRR: smoke
- HYSPLIT v9: dispersions of smoke and other hazardous materials
- RRFSv1: smoke and dust
- GFS: stratospheric O3

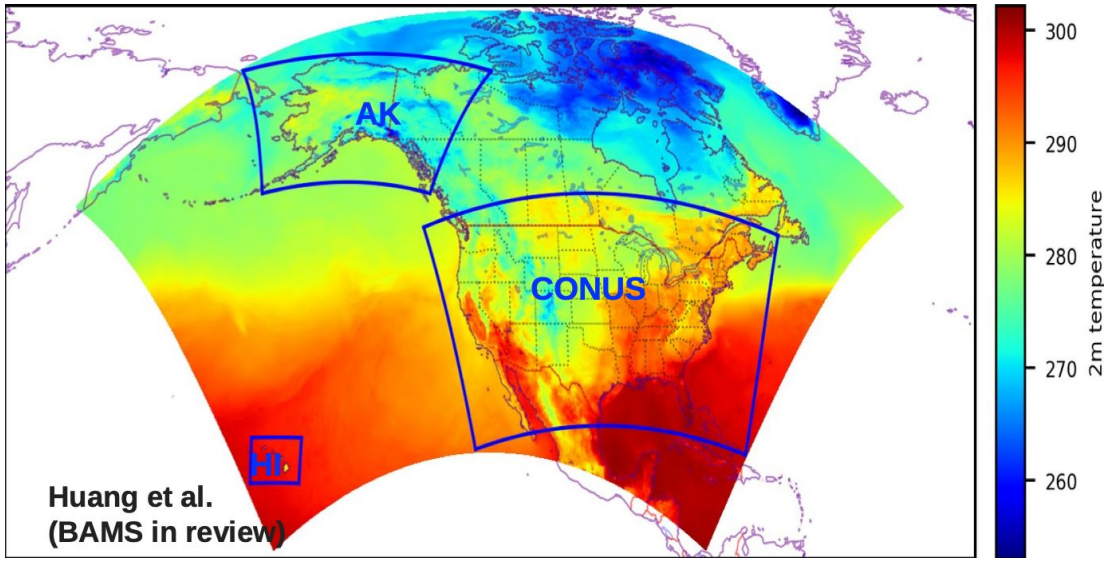
Upcoming Updates and Applications (FY28)

- Newly developed Global Chemistry and Aerosol Forecast (GCAFS)
- AQMv8

AQM - Regional Air Quality Forecast Modeling

- The AQM is the chemistry component within the UFS and is coupled to the UFS atmosphere component.
  - AQM uses the EPA CMAQ 5.2.1 as a single column model and coupled through the UFS infrastructure.
  - Produces its own Meteorology with boundary conditions provided by the NOAA/NCEP Global Forecast System
- The National Air Quality Forecasting Capability (NAQFC) is based on NOAA's Unified Forecast System (UFS) and integrated air quality model (UFS-AQM) → daily forecasts of surface ozone and $PM_{2.5}$ concentrations up to 72 hours in advance across North America.
- Initial implementation of online-coupled AQM version 7 (AQMv7) in April 2024 → major milestone in operational air quality forecasting → enhanced wildfire air quality impacts.
- Results can be seen: https://airquality.weather.gov/
- Data is available through the NOAA NOMADS and AWS
  - https://nomads.ncep.noaa.gov/
  - https://registry.opendata.aws/noaa-nws-naqfc-pds/



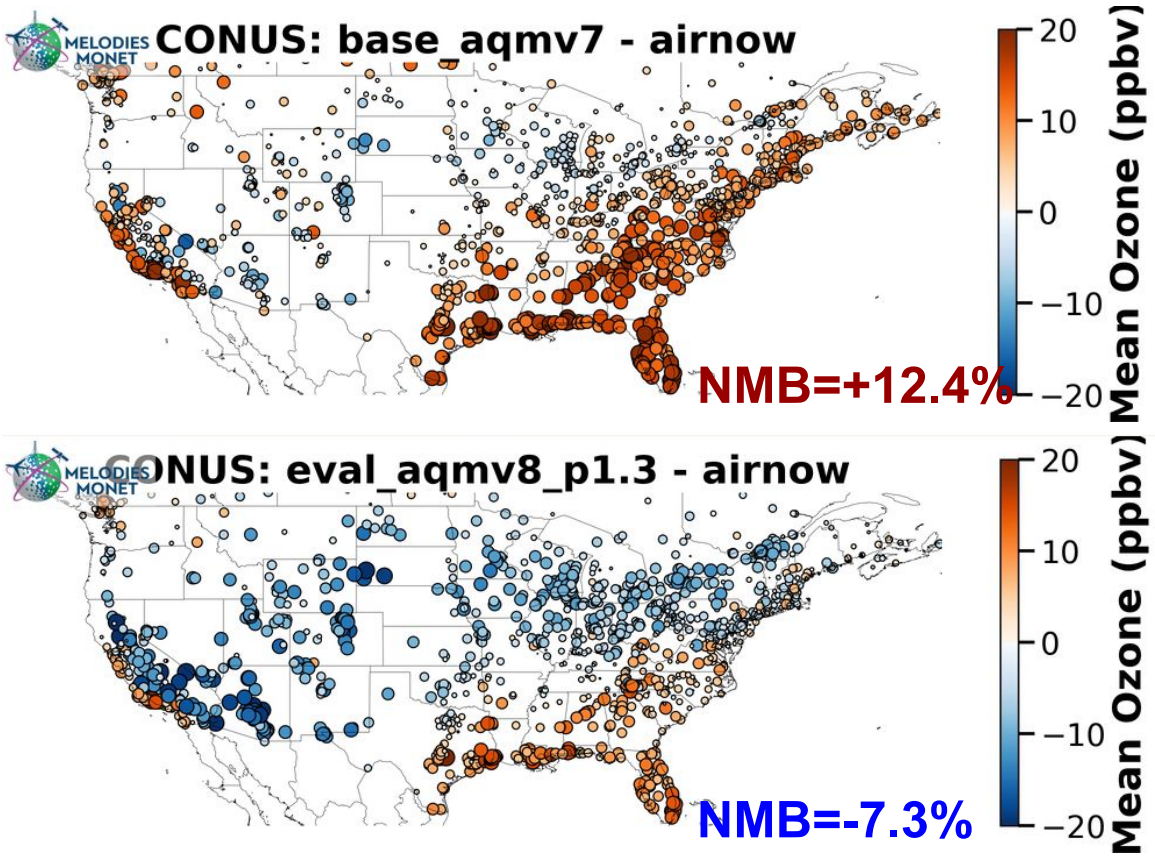


AQM v8 Implementation Plan

Implementation Date : DELAYED to FY28 due to HPC upgrade

Planned Updates:

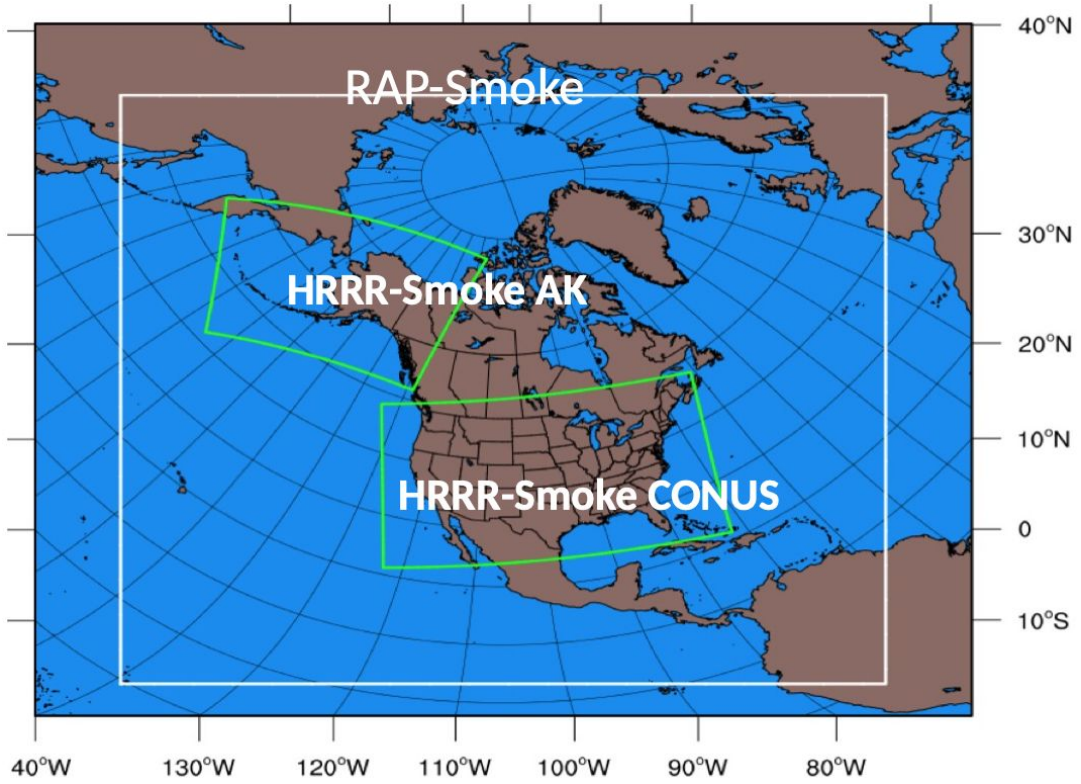
- Update CMAQ submodule **v5.2.1 -> v5.4**
- Update global and CONUS emissions
  - **CEDS** 2019 -> 2022
  - **NEI/NEMO** 2016 -> 2022
  - **SoilNOx** updates
  - Enhanced FENGSHA **windblown dust**
- Update from GFSv16 to v17 physics
  - Updated gravity wave drag
  - NOAH -> NOAH-MP Land surface model
  - GDFL-MP -> Thompson microphysics
  - K-EDMF -> TKE-EDMF
- In-Canopy effects in physics and chemistry
- Updated vertical gaussian plume distribution



RAP/HRRR -- Operational Regional Smoke/Dust

RAP/HRRR Operational Smoke Forecast Models

- A smoke tracer was integrated into the operational RAP/HRRR weather forecast models in late 2020.
- Near-Real-Time (NRT) fire emissions and heat fluxes are estimated using satellite fire radiative power (FRP) data from MODIS.
- RAP-Smoke (13km): Simulates smoke transport over Central and North America and provides lateral boundary conditions for HRRR-Smoke.
- HRRR-Smoke (3km): Captures mesoscale flows and smoke transport, particularly effective in complex terrain.
- The model incorporates smoke-related feedbacks on both radiation and visibility.

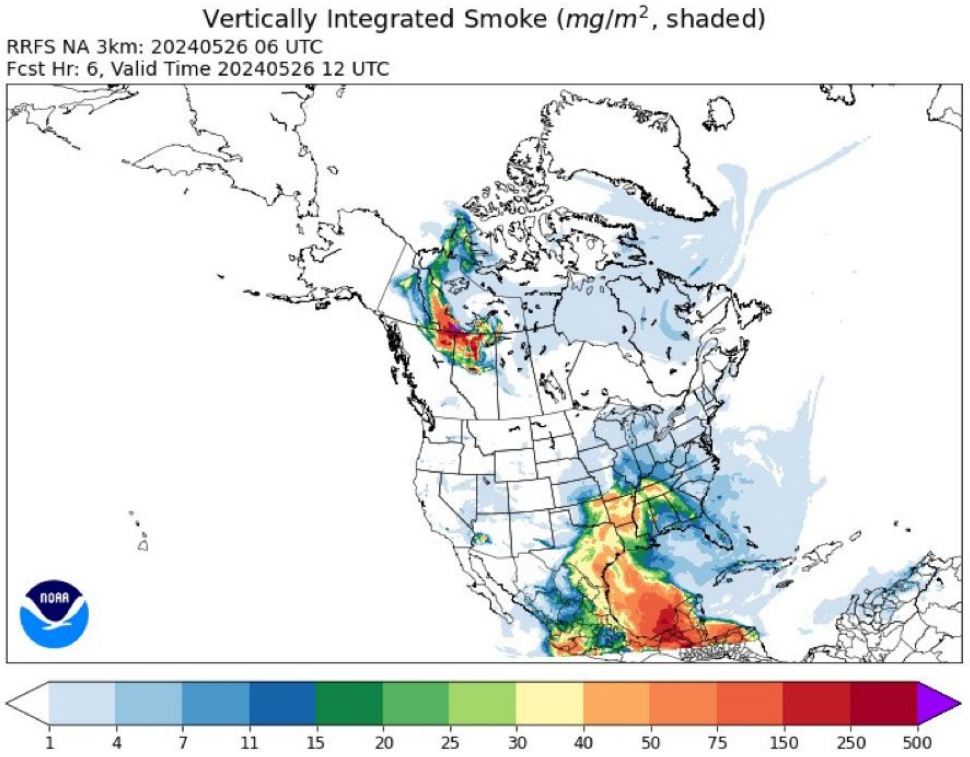


Transitioning to RRFS-SD

RRFS-SD: Next-Gen Smoke & Dust Forecasting

- **Comprehensive Aerosol Tracking:** Predicts **PM2.5 smoke** (via NESDIS RAVE) and **fine/coarse dust** (via FENGSHA model).
- **New** high resolution dust forecast for extreme events
- **Integrated Radiative Impacts:** Accounts for the effects of smoke and dust on **solar radiation and visibility**.
- **High-Frequency Updates:** * **4 cycles per day** (up to 60-hour forecasts).
  - **Hourly updates** for the first 18 hours.
- **Advanced Fire Intelligence:** Features the new **Hourly Wildfire Potential (HWP)** index.
- **Status:** Currently in real-time testing; operational implementation scheduled for **Q3 2026**.

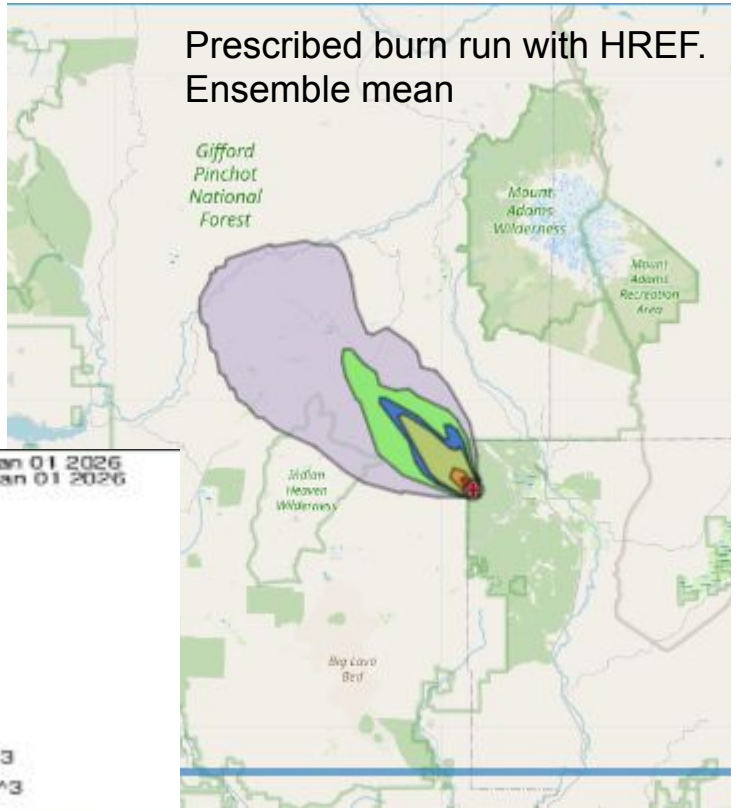
3 km RRFS limited area model domain



View Real-Time Fields: rapidrefresh.noaa.gov/RRFS-SD

HYSPLIT v9

- Implementation of the **Transfer Coefficient Matrix (TCM) for volcanic emissions and Regional Specialized Meteorological Center (RSMC) (radiological releases).**
  - computes source-receptor relationship based on time resolved, unit source emission runs.
  - can be used to quickly update dispersion forecasts when new emissions become available without having to re-run simulations
  - Important for ongoing events to incorporate improved emissions estimates
  - can be used for constructing ensembles representing uncertainty in emissions
  - can be used for estimating emissions using available observations.
- **HYSPLIT coupling with RRFS (deterministic and ensemble)**
  - NAM and HREF coupling will be retired. RRFS will provide the same or higher temporal and spatial resolution meteorological fields to HYSPLIT.
  - Domains include North America, CONUS, Alaska, Hawaii, Puerto Rico, fire weather.
- **Updated HYSPLIT coupling for GFS and GEFS**
  - increase number of vertical levels and forecast length.
- Update HYSPLIT to version 5.3



GFS Stratospheric Ozone

McCormack et al. (2006)
Parametrization for Ozone Forecast

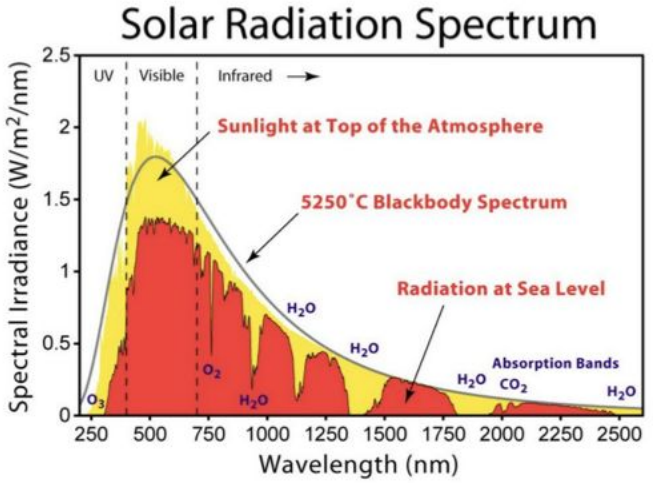
First-order Taylor series in three variables for the ozone rate of change

$$dr_{O3}/dt = P\text{-}L = (P\text{-}L)_0 + d(P\text{-}L)/dr_{O3}|_0 (r_{O3} - r_{O3,0}) + d(P\text{-}L)/dT|_0 (T - T_0) + d(P\text{-}L)/dS_{O3}|_0 (S_{O3} - S_{O3,0})$$

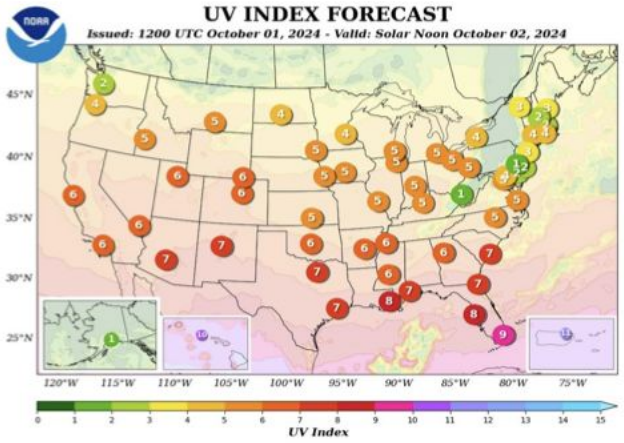
S is partial column ozone above that point

All terms calculated using 2-D chemistry model CHEM2D

For **O3 initialization**, GFS/GDAS assimilates retrievals from OMI on Aura and OMPS on NPP and NOAA-21 satellite observations. The OMPS products are both a profile and a total column.



Stratospheric Ozone contributes significantly to model radiation balance



NCEP/CPC uses GFS ozone forecast as input for predicting UV index

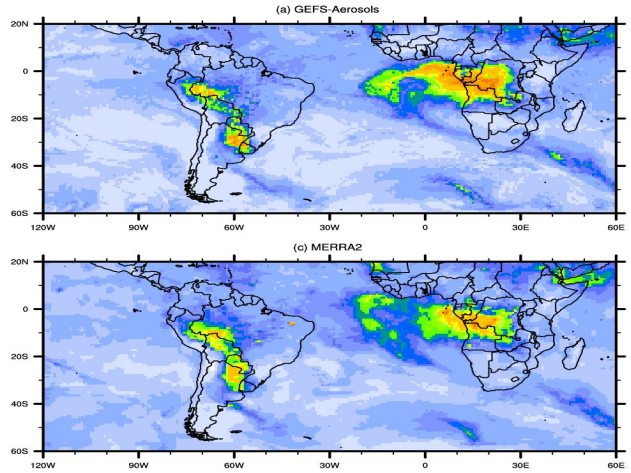
https://www.cpc.ncep.noaa.gov/

Current and Historical Aerosol Forecasting at NOAA

NGAC: The NCEP GFS Aerosol Component (NGAC), implemented into operation in **2012**, was the first global system to allow for interactive aerosol forecasting at NCEP. It was developed by EMC and GSFC using the NASA GOCART aerosol model.

GEFSv12 - Aerosol

- Aerosol component module was developed through collaboration between EMC and OAR labs (GSL, CSL, and ARL) and was integrated online with FV3-based GFS within the NEMS/NUOPC framework.
- It was based on **WRF-Chem** and incorporated several key elements: the bulk modulus from GOCART, the biomass burning plume rise module from HRRR-Smoke, the FENGSHA dust scheme developed by ARL, GBBEPx.v3 for biomass burning emissions, and the CDES global anthropogenic emission inventory.
- Sub-grid-scale transport, wet scavenging and deposition were handled inside the atmospheric physics routines. with updates to AOD and wet scavenging computations
- It was implemented into NCEP operations as part of the GEFS ensemble in **September 2020**, utilizing a 25-km resolution, 4 cycles per day, and forecast up to 5 days.
- Primary products are PM2.5 and PM10



Total AOD, August 25, 2019
(Zhang et al., GMD, 2022)

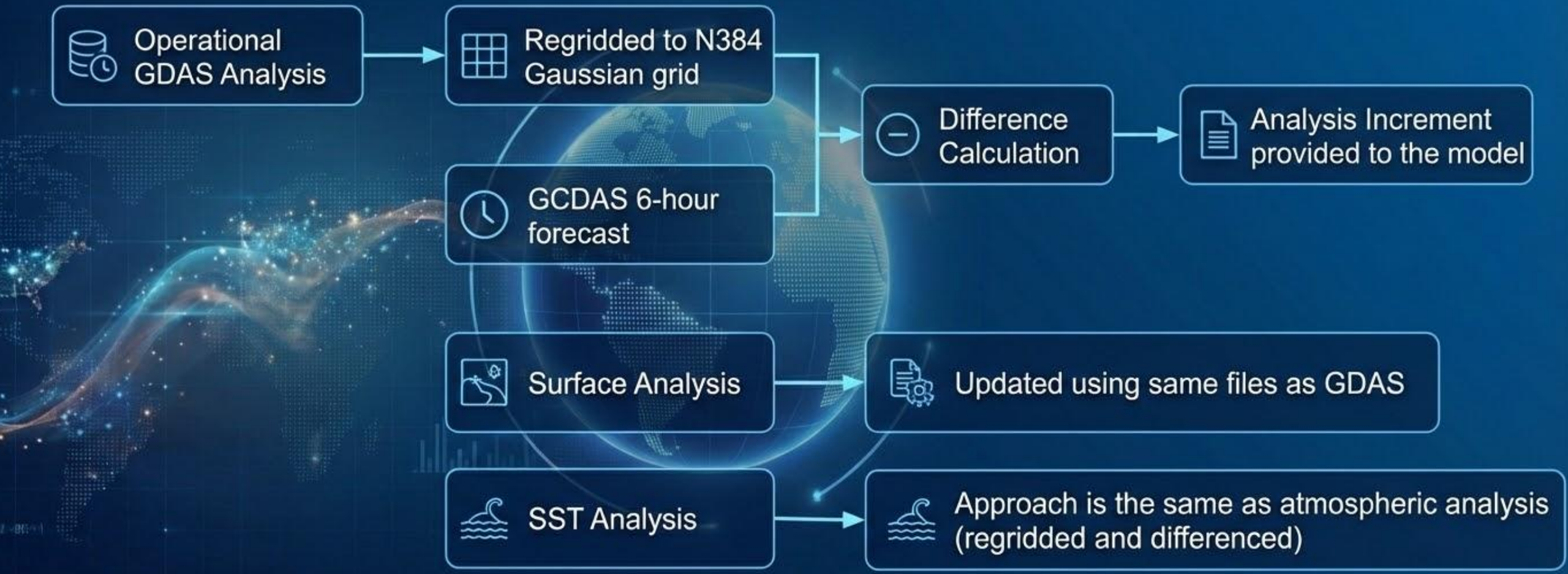
GCAFS - Global Chemistry and Aerosol Forecast System

- The NOAA Global Chemistry and Aerosol Forecast System (GCAFS) was expected to begin operations in 2026.
  - **DELAYED** due to operational HPC change
- GCAFS aerosol modules incorporate NASA's GOCART model.
- 15 aerosol species: dust, sea salt, black carbon, organic carbon and sulfate.
- **GCAFS include a Global Chemistry and Aerosol Data Assimilation System (GCDAS) for the first time and will use the Joint Effort for Data assimilation Integration (JEDI).**

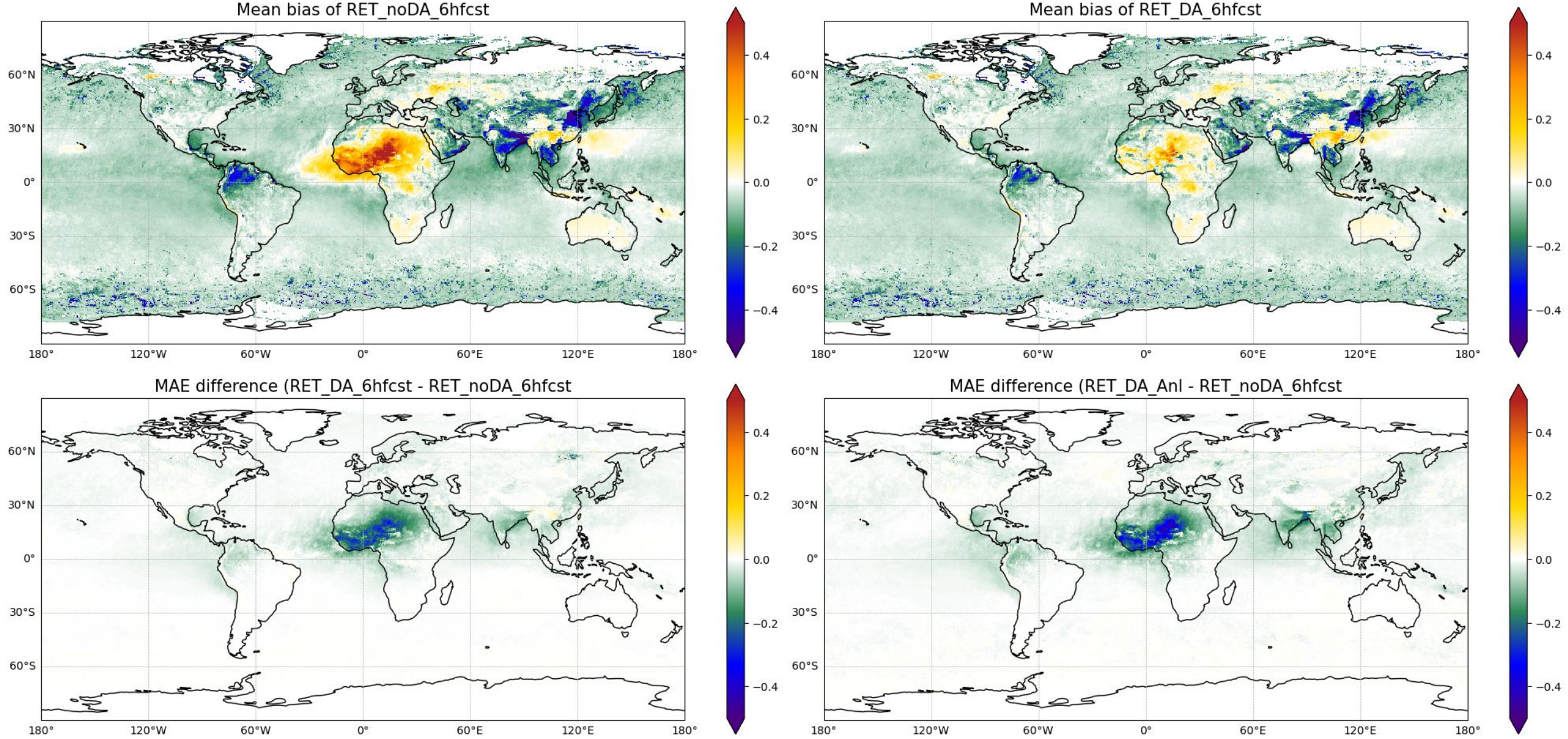
Scope of Changes

- Doubling of the model vertical resolution from 64 layers to 127 layers to match the vertical resolution of the Global Forecast System (GFS), which provides medium-range weather forecasts
- Update the physics to the GFSv17 physics
- Updates to the fengsha dust emissions scheme, large scale wet scavenging, and settling velocity
- Updated chemical mechanism to the GOCART2G aerosol model
- Upgrades to the biogenic and anthropogenic emissions datasets and processing to the Community Emissions Data System (CEDS) 2022 base version
- Introduction of GCDAS - the Global Chemistry Data Assimilation System
    - Assimilation of Visible Infrared Imaging Radiometer Suite (VIIRS) Aerosol Optical Depth (AOD) retrievals provided by NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) in a 3D-Variational analysis four times per day using JEDI

Atmosphere Initialization

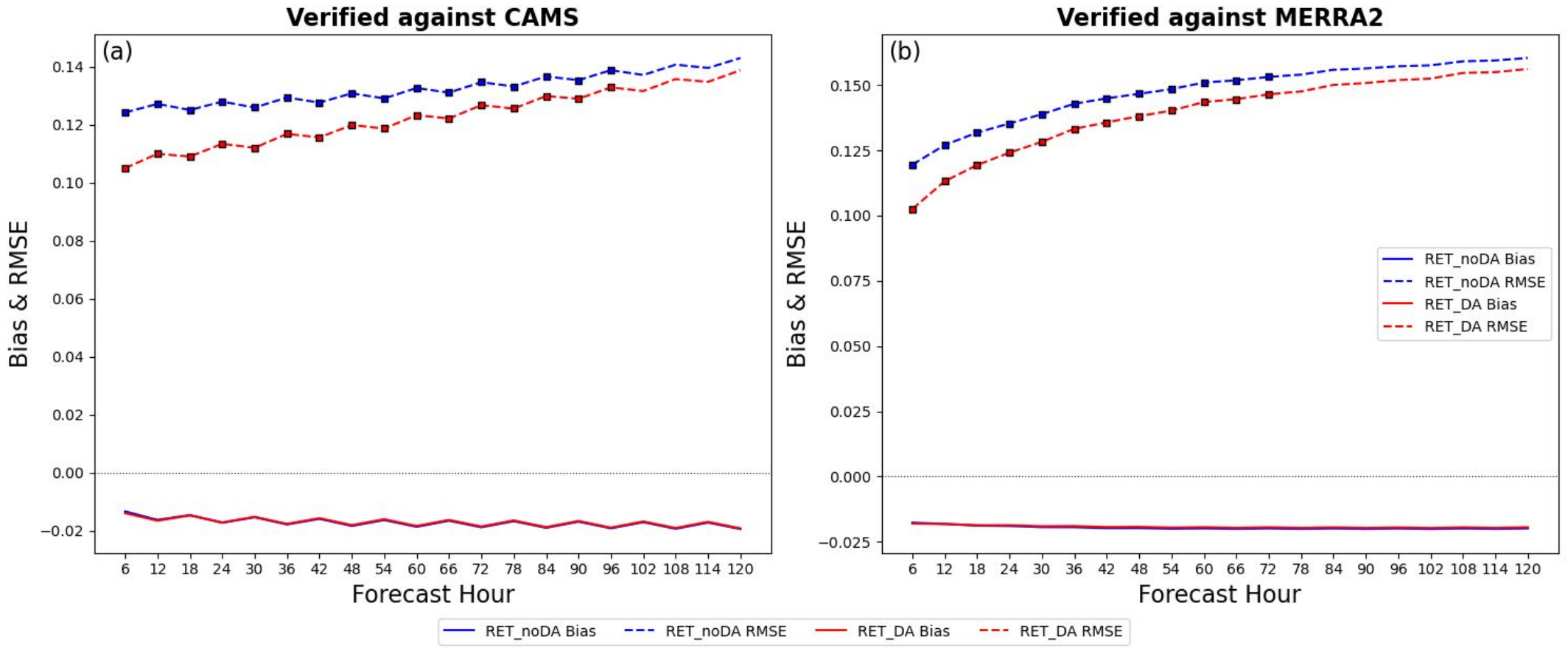


2024-01-09 to 2024-05-18



Bias and the difference of mean absolute error (MAE) of total AOD between DA and noDA against MODIS

Impact of DA on long forecast

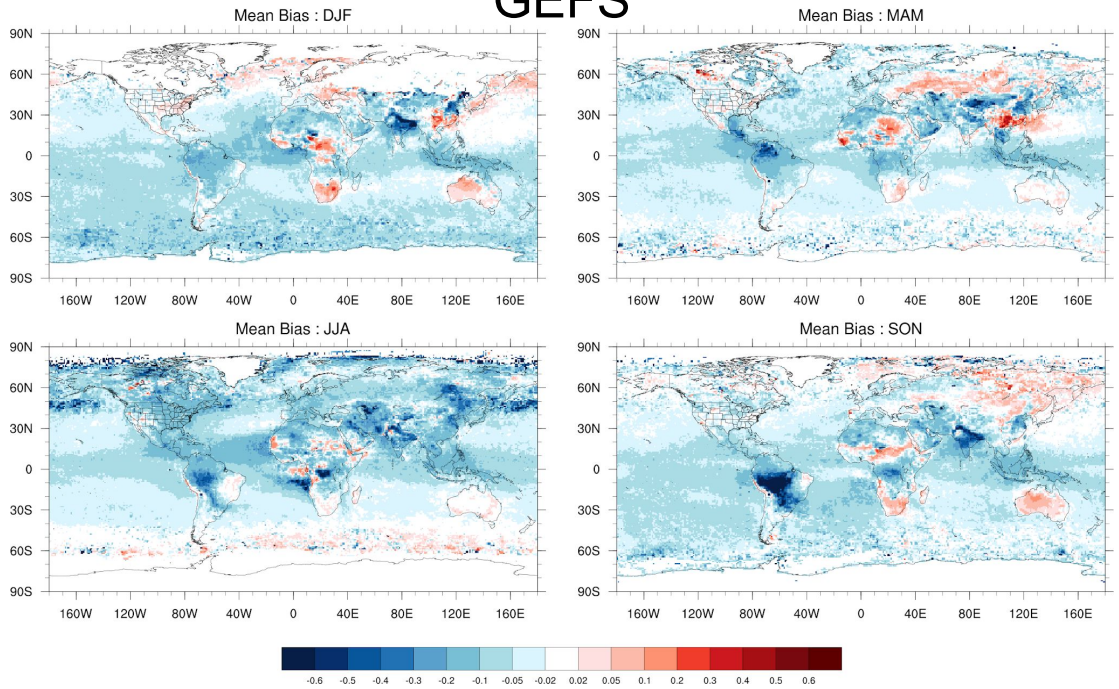


Accumulated bias and RMSE of total AOD against CAMS and MERRA2 from 255 5-day forecasts initialized every 12 hours from 9 Jan to 15 May 2024. The dots denoting the difference between RET_DA and RET_noDA are statistically significant.

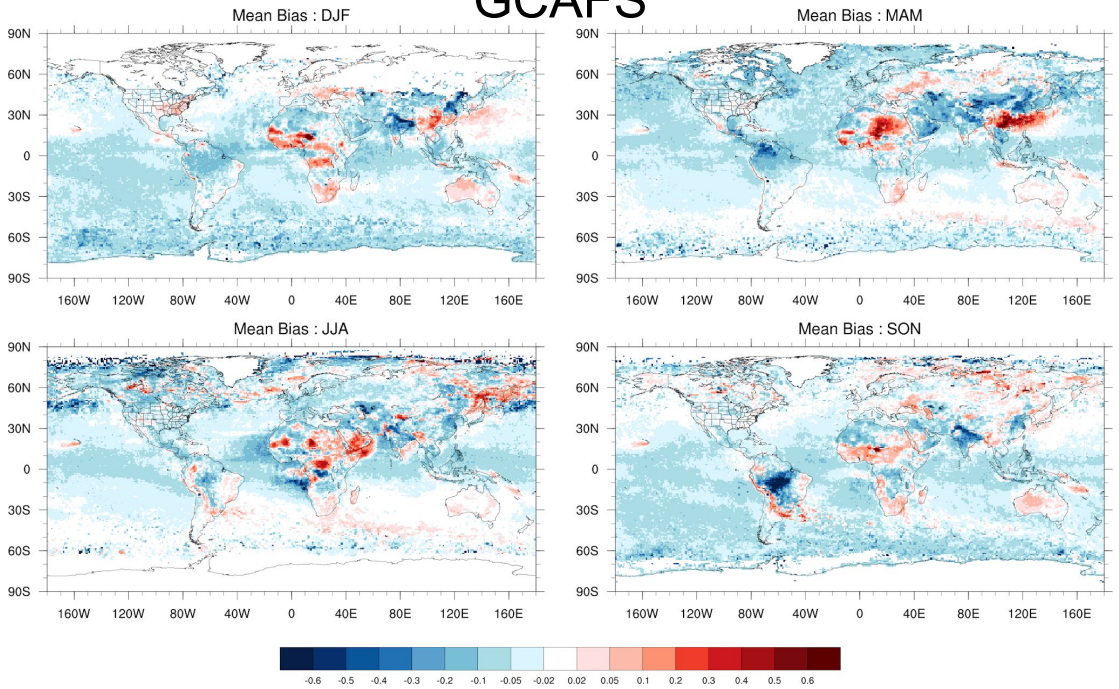
GCAFS vs MODIS

The Benchmark: Mean Bias evaluated against MODIS satellite observations across four seasons. Blue = Under-prediction; Red = Over-prediction.

GEFS



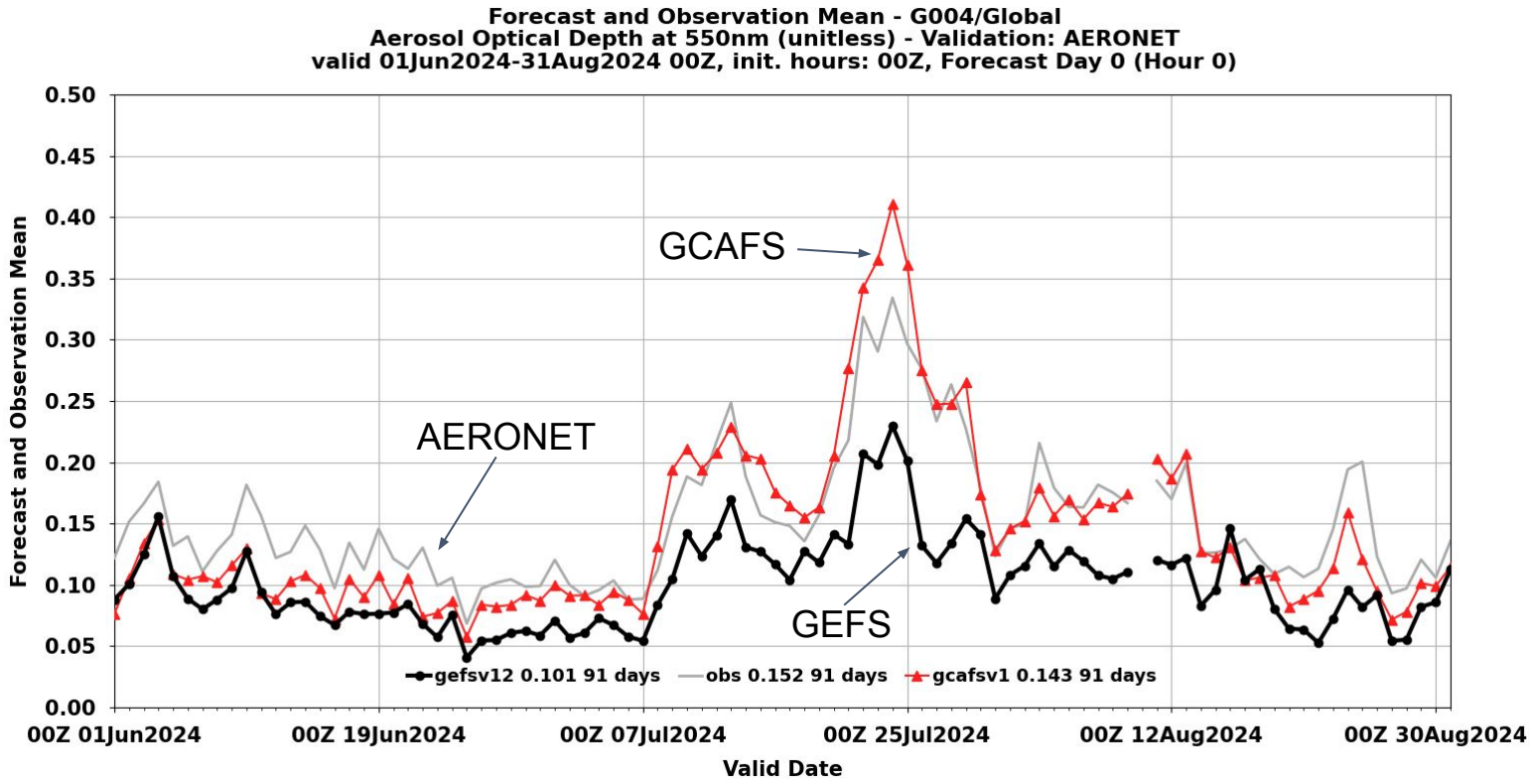
GCAFS



- **The Old Baseline (GEFS-Aerosol): Severe Missing Mass.** The old model suffered from massive under-predictions (dark blue), entirely missing major seasonal aerosol events like the Amazon biomass burning season (SON) and Northern Hemisphere boreal summer fires (JJA across Canada/Russia).
- **The GCAFS Improvement: Recovering the Signal.** GCAFS drastically reduces these severe negative biases. Notice the major visual improvement in **JJA** (the dark blue band across the top is largely gone) and **SON** (the deep blue hole over South America is significantly filled in).
- **The Takeaway:** GCAFS successfully fixes the old model's tendency to grossly under-predict major seasonal smoke and fire events. While some regional over-predictions remain (e.g., Saharan dust in MAM), the global distribution is vastly more balanced and realistic.

GCAFS vs MERRA2

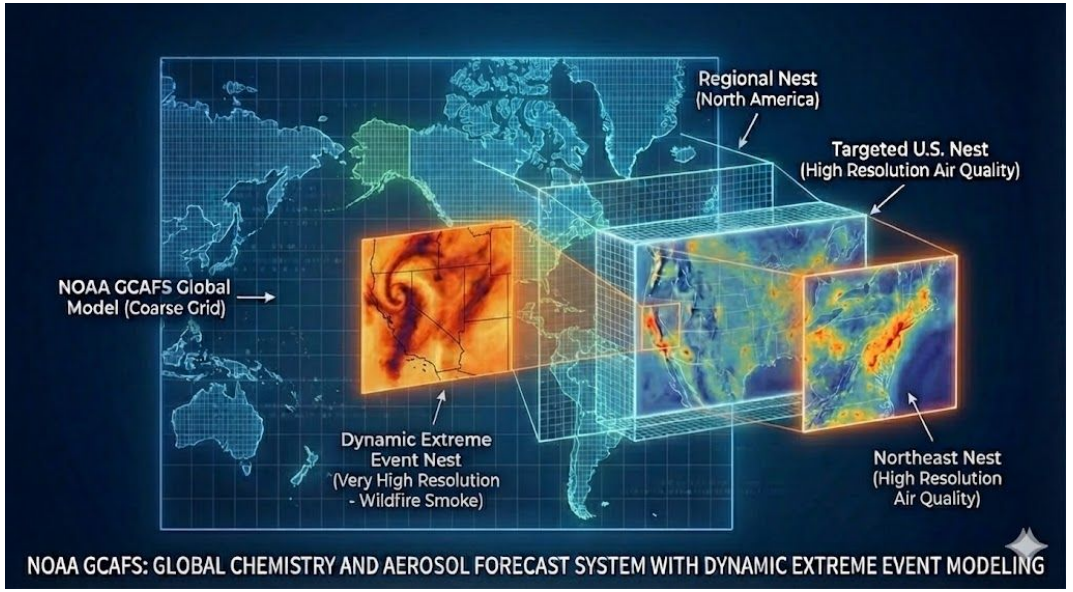
- **The Benchmark:** Global daily mean AOD validated against **AERONET** ground observations from June to August 2024 (JJA). *(Note: AERONET is a highly reliable ground-truth network of sun photometers).*
- **The Old Baseline (GEFSv12 - Black Line): Chronic Low Bias.** The old model consistently and severely under-predicted global aerosols throughout the summer. It completely failed to capture the massive mid-July AOD spike, resulting in a low overall average (0.101 vs the observed 0.152).
- **The GCAFS Improvement (Red Line): Tracking Reality.** The new GCAFS model hugs the observation curve (grey) beautifully. It successfully captures both the timing and the actual magnitude of the massive July aerosol events, bringing the summer mean up to 0.143—nearly a perfect match with observations.
- **The Takeaway:** GCAFS effectively cures the "missing mass" problem of the old system. It proves highly capable of forecasting sudden, large-scale summer aerosol events with exceptional daily accuracy.

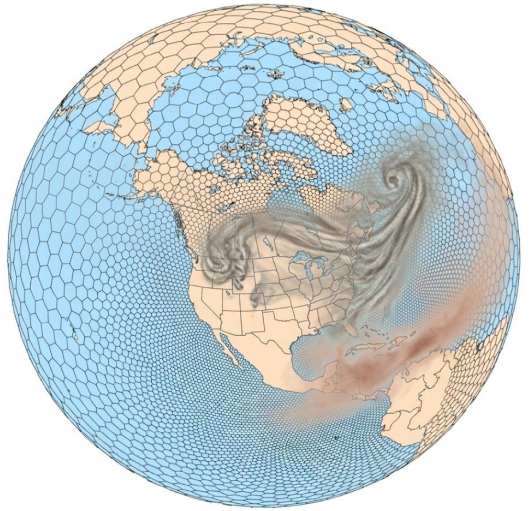


Future Plan

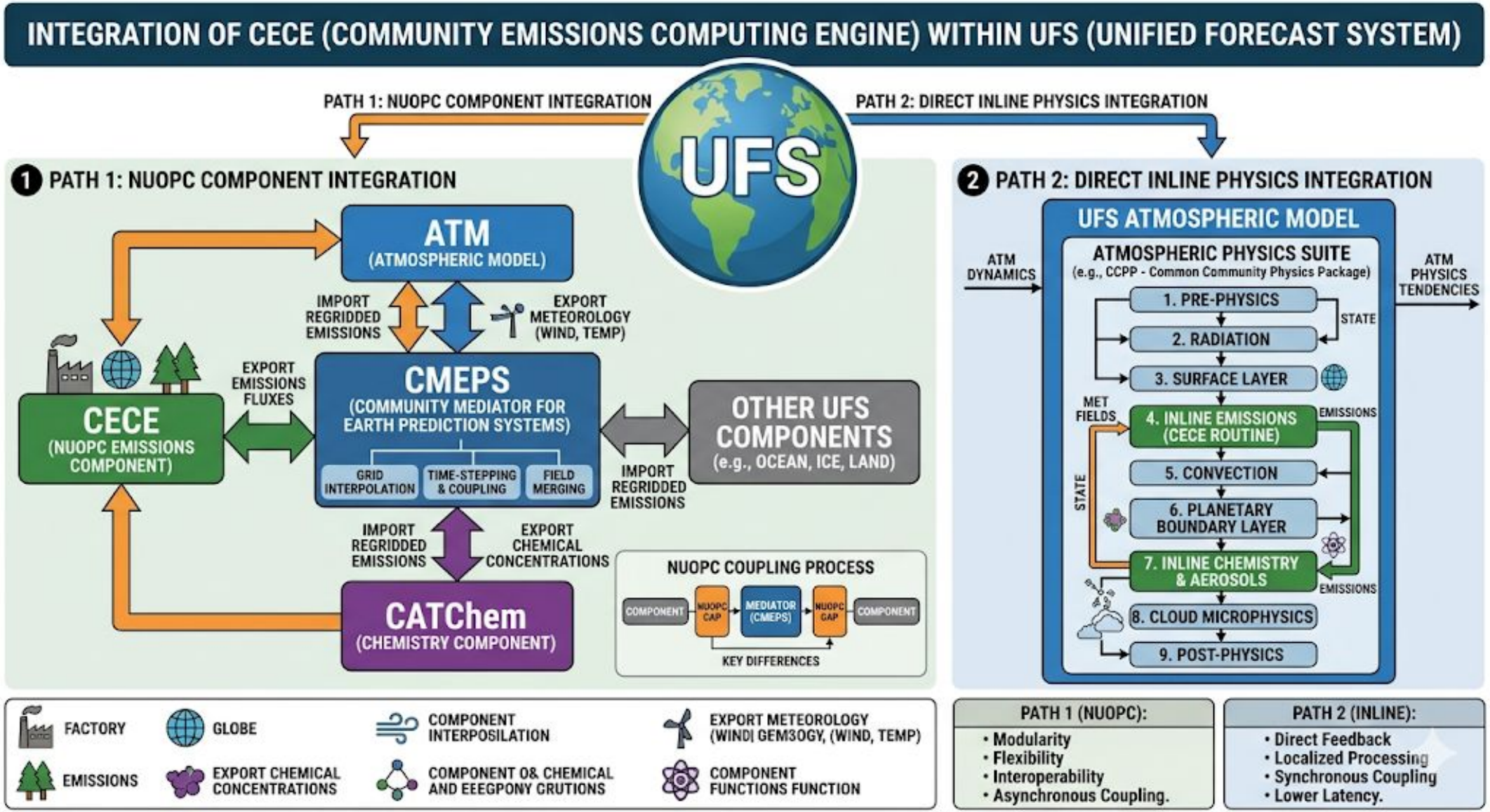
GCAFSv2 Goals and Priorities

- GCAFSv2:
  - Include gas-phase chemistry
  - Consolidate various global and regional AQ/AC modeling systems i.e. global and regional applications
  - Run higher resolution over target areas to predict atmospheric composition events either through regional refinement or nesting.
  - Full process level configurability, satisfying the need for a single component able to be used across applications





Composition Modeling within the UFS




Questions?
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