Developments and Applications of NOAA's Global Aerosol Forecast systems

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Section: Advances in regional and global scale aerosol modeling

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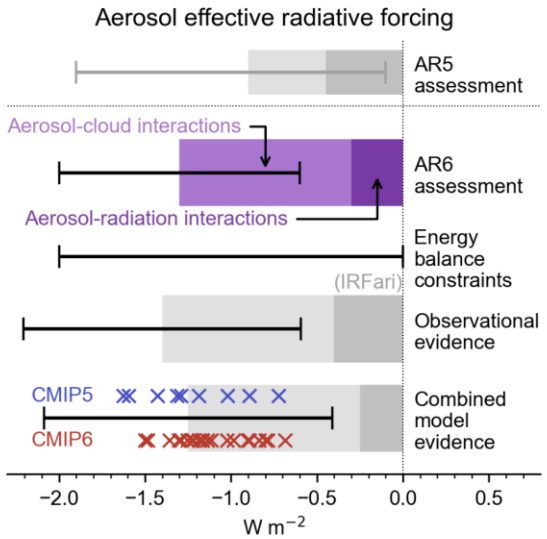
Motivation





The role of aerosols in the Earth's radiation balance has been investigated by the climate modeling communities since early 1990s.



Aerosols are assessed to have contributed an effective radiative forcing (ERF) of -1.1 Wm^{-2} over 1750-2019.

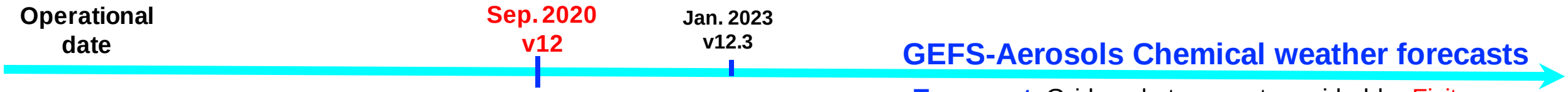
IPCC AR6 Chapter 7 2021

Raise concerns about the impacts of aerosols and more complex chemistry on weather forecast, subseasonal to seasonal (S2S) prediction and climate change

Most Numerical Weather Prediction (NWP) operational models are still using the average effect of aerosols on the radiative balance, which have not involved the importance of aerosols on S2S scale.

NOAA's operational air quality predictions in NWS contribute to protection of lives and health in the US, which requires sustainable development and improvement of global forecast system for operational aerosol and air quality predictions.

NOAA's Global Aerosol Forecast Systems



	NGACv2	GEFS-Aerosols GEFS v12 & v12.3
ATM model	NEMS GSM	FV3
Physics	GFS v2015	GFSv15
Horizontal Res.	~100km	~25km
Vertical Res.	64 layers	65 layers
Infrastructure	ESMF	NUOPC
Aerosol/Chem Components	1st NASA GOCART	GSL GOCART (based on WRF-Chem)

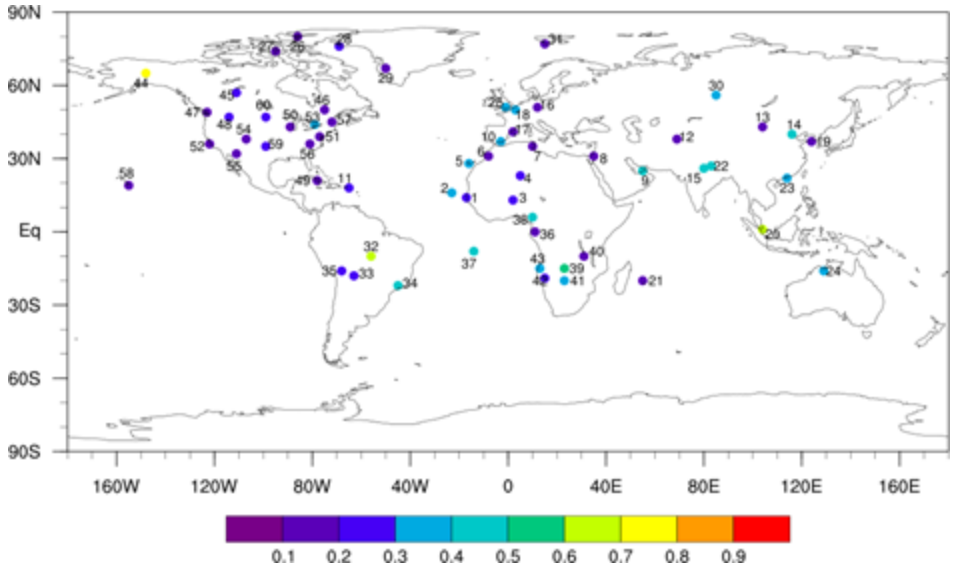
Atmospheric model only, direct radiative feedback is coming from climatological aerosol reanalysis data

- **Transport:** Grid-scale transport provided by Finite-Volume (FV3) dynamical core. Sub-grid transport by PBL and convection in GFS physics. Tracer convective transport and wet scavenging are included in Simplified Arakawa-Schubert (SAS) scheme.
- **GEFS-Aerosols Chemistry:** simplified parameterization of sulfur/sulfate chemistry, hydrophobic and hydrophilic black and organic carbon (BC and OC), 5-bin sea salt, 5-bin dust,
- **Emission:** Global CEDS (2014 or 2019) anthropogenic emission. NESDIS Global Biomass Burning Emission Product (GBBEPx) with FRP used for fire size and location. 1D cloud model is used to calculate injection heights and plume rise emission rates online.
- **Sea-salt and Marine Dimethyl Sulfide:** NASA GEOS-5 GOCART sea salt scheme. GOCART monthly values of marine dimethyl sulfide as in Lana et al. (2011)
- **FENGSHA dust scheme:** Empirical model based solely on soil type for saltation and used in current NAQFC (Tong et al; Baker et al.)

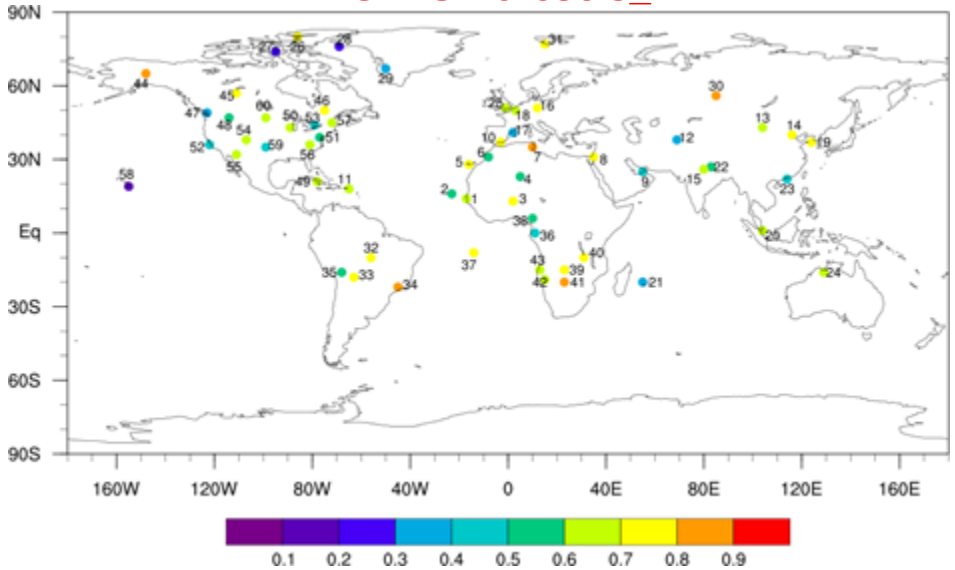
Performances of GEFS-Aerosols AOD Predictions

Daily AOD Correlation Coefficients (201907-201911)

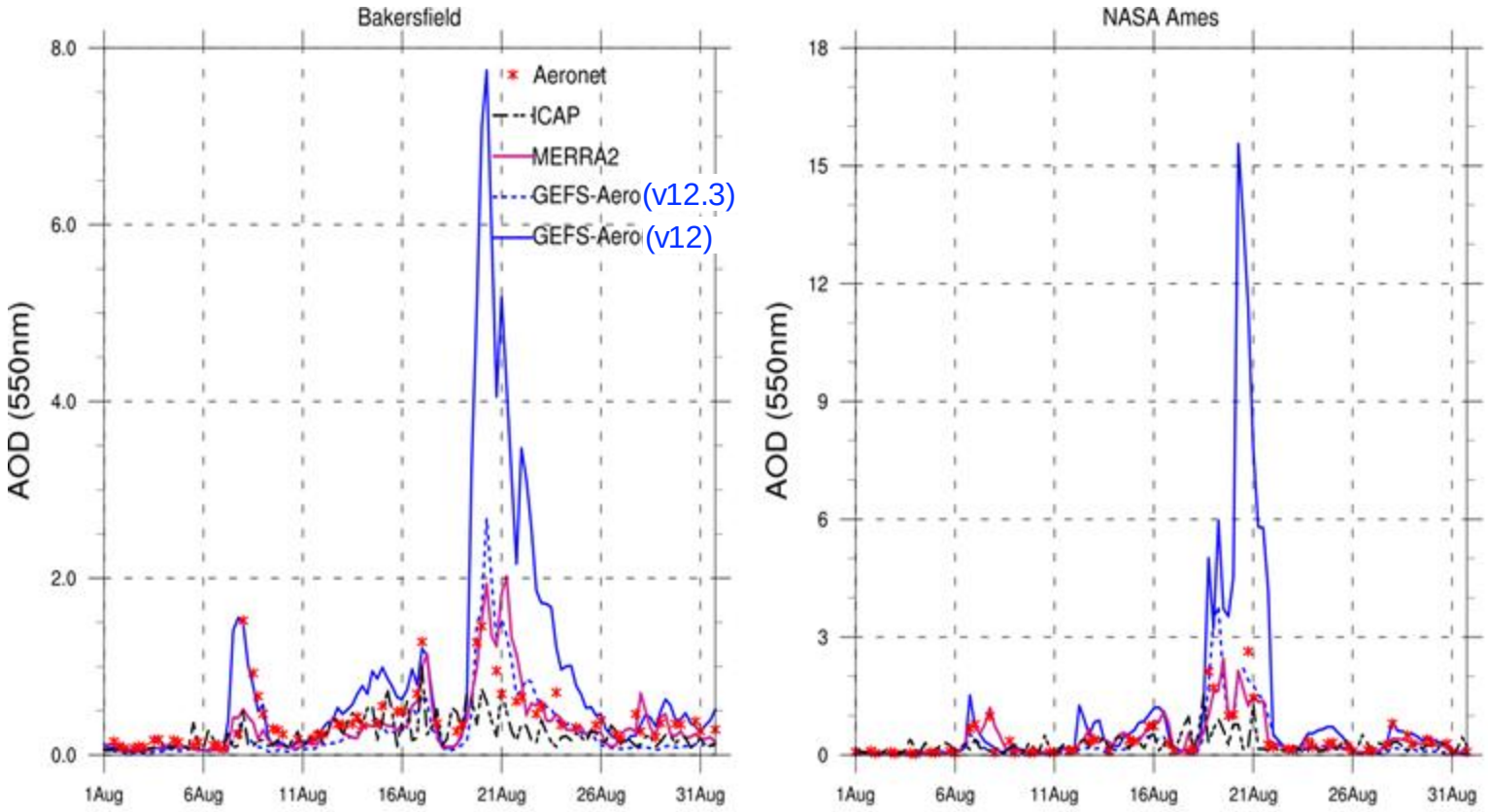
NGACv2



GEFS-Aerosols_v12



Day 1 AOD forecast August 2021



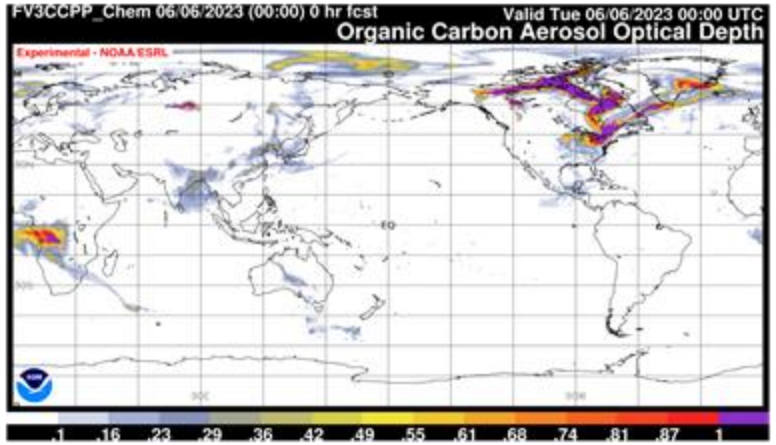
The significantly overpredicted peaks in GEFS-Aerosols v12 have been improved in v12.3, which are close to the MERRA-2 reanalysis and AERONET observation.

Applications of Global Aerosol Forecast Systems

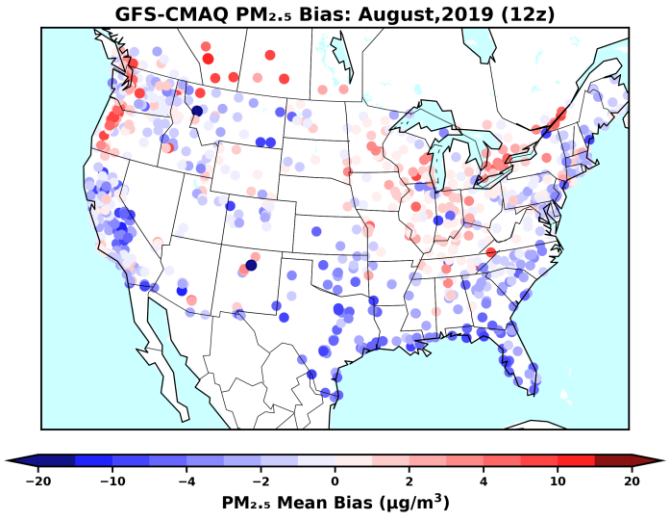
- **Chemical weather forecasts (daily to medium range of 5-7 days):** 3D aerosol concentrations (e.g. surface PM2.5), aerosol optical depth (AOD), aerosol column burden etc.
- **Subseasonal to seasonal predictions (~35-45 days):** Impact of aerosol direct feedback on S2S prediction, especially large pollution events of dust storm and wildfires

GEFS-Aerosols v12&v12.3 in global aerosol forecasts

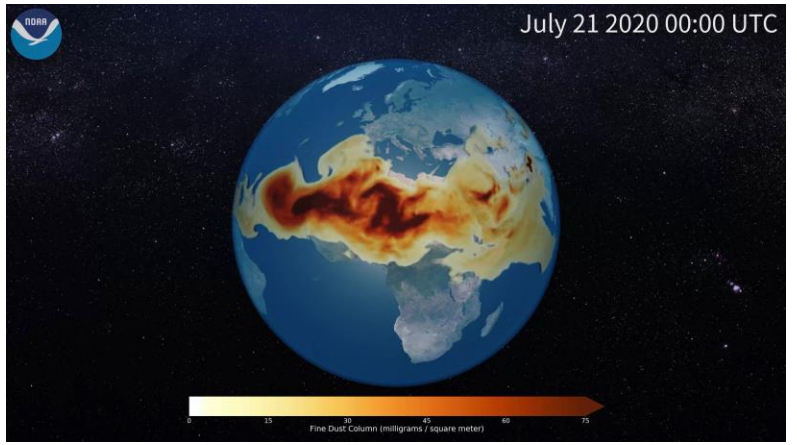
Fire OC AOD



Provide boundary condition to operational CMAQ at NCEP

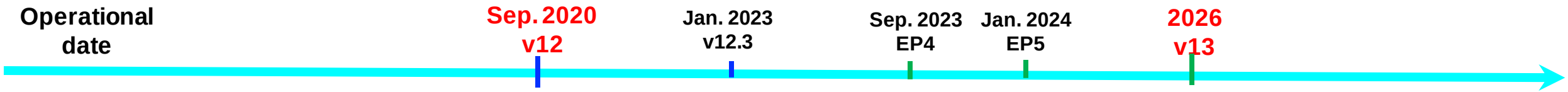


Dust



PM10 column burden, Tonga volcano

NOAA's Global Aerosol Forecast Systems



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- **UFS-Aerosols Chemistry:** simplified parameterization of sulfur/sulfate, nitrate and ammonium chemistry, hydrophobic and hydrophilic black and organic carbon, 5-bin sea salt, 5-bin dust.
- Different large scale wet deposition and settling schemes for aerosols compared to GEFS-Aerosols.
- Updated FENGSHA dust scheme

Atmospheric model only, direct radiative feedback is coming from climatological aerosol reanalysis data

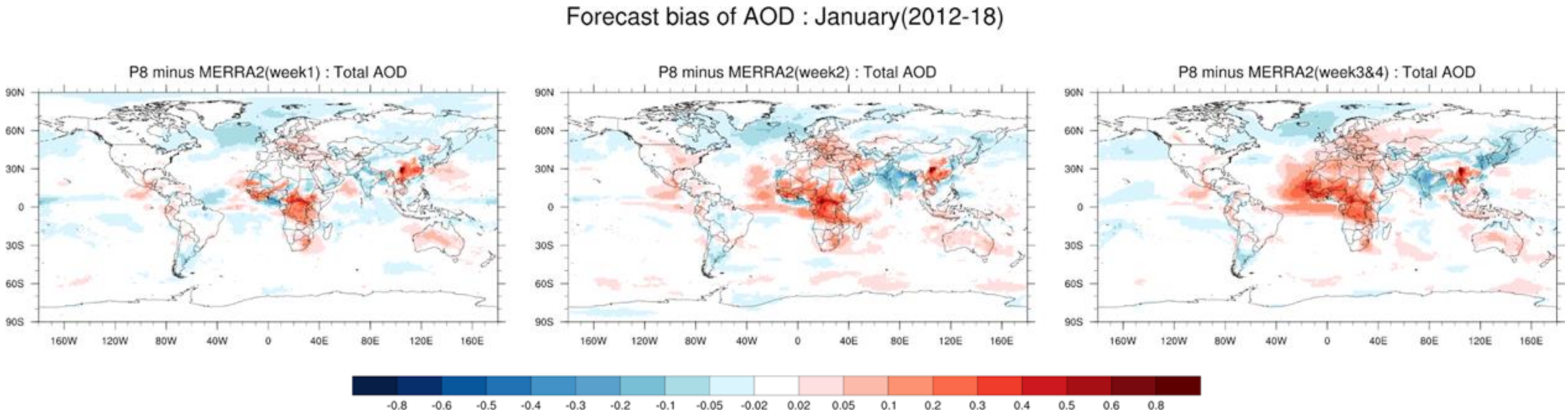
S2S: Fully coupled with ocean, sea ice and wave, online aerosol prediction for direct radiative feedback

Global aerosol data assimilation (DA)

Application in Subseasonal to Seasonal (S2S) Predictions

UFS Prototype 8 (P8) experiments 201204-201803, twice per month for 35-day forecast

- UFS is fully coupled with ocean (includes sea ice), wave and aerosol components.
- Use MERRA-2 reanalysis aerosol data as the initial conditions to drive UFS-Aerosols model for 35 days free run predictions, starting from 1st and 15th of each month (no aerosol feedback from aerosol component in P8 experiments).
- Only single control member, QFED fire emission, CEDS 2019 anthropogenic emission, FENGSHA dust scheme (2022).

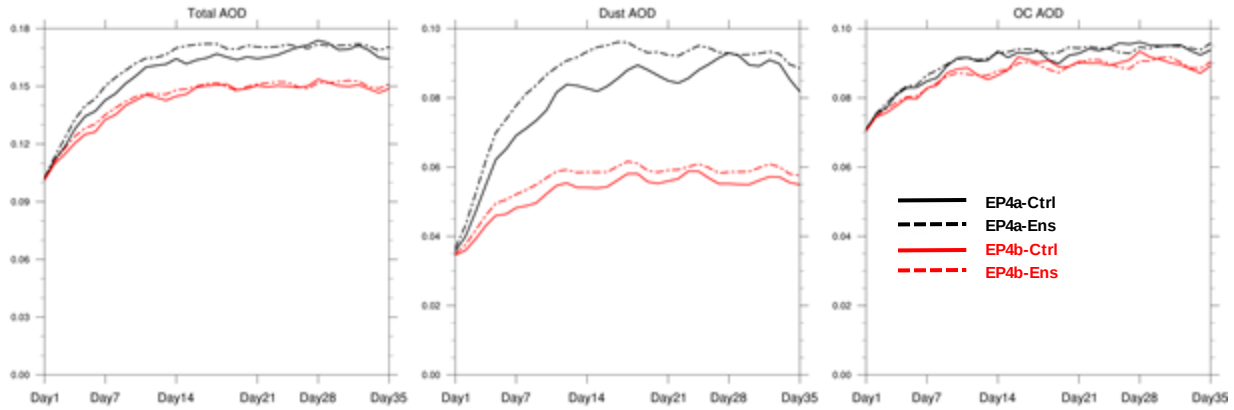


Application in Subseasonal to Seasonal (S2S) Predictions

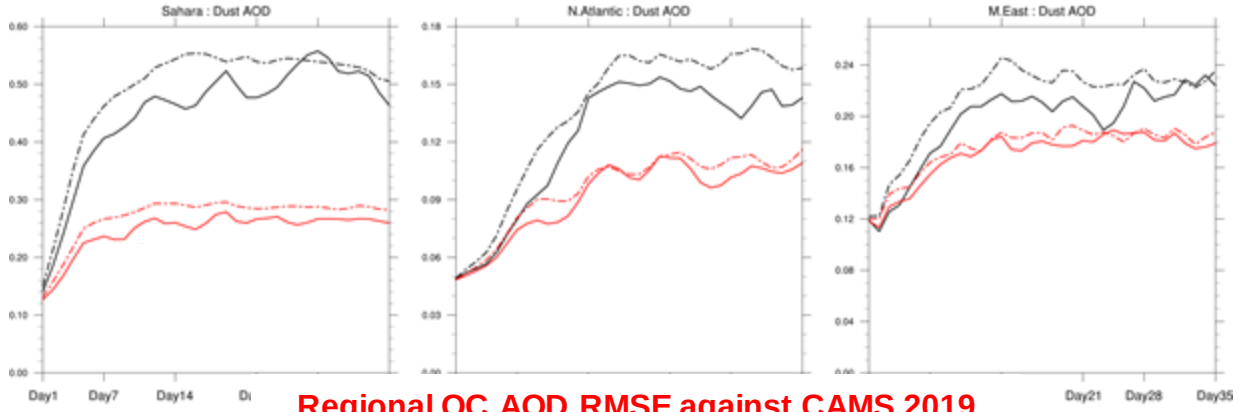
Ensemble Prototype 4 (EP4) experiments 201710-201909, once per week for 35-day forecast

- 10 ensemble members with perturbations in Met. Fields. Model configurations for EP4a are the same as previous P8 experiments. Updated FENGSHA dust scheme and scaled QFED is used in EP4b.
- Online aerosols prediction from aerosol component are used for direct radiative feedback in EP4a and EP4b experiments

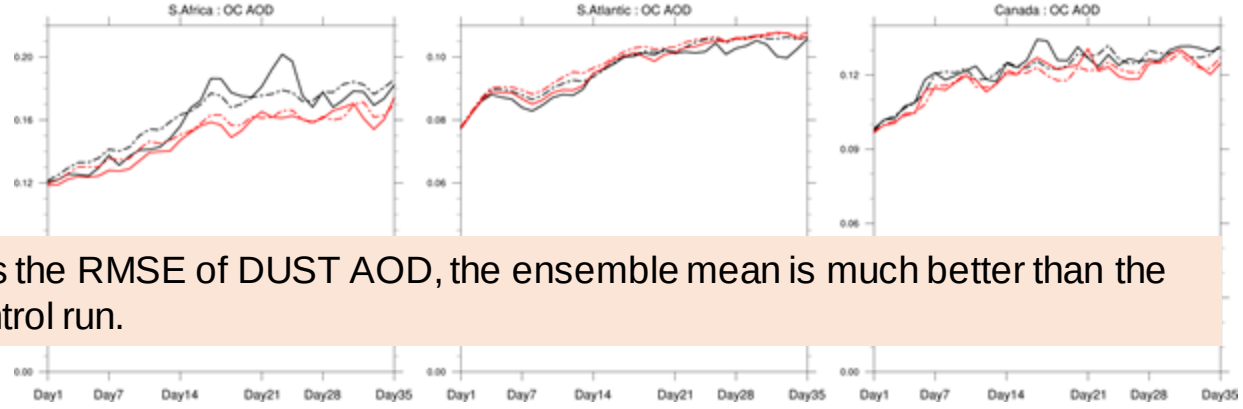
Global AOD RMSE against CAMS 2019



Regional Dust AOD RMSE against CAMS 2019

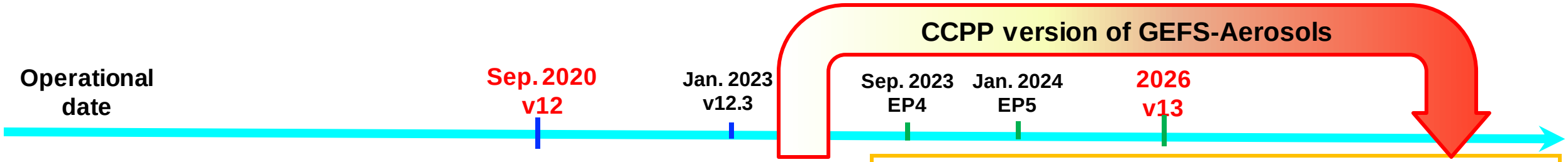


Regional OC AOD RMSE against CAMS 2019



Updated FENGSHA dust scheme (Sep. 2023) significantly reduces the RMSE of DUST AOD, the ensemble mean is much better than the control run.

NOAA's Global Aerosol/Chemistry Forecast Systems



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Aerosol/Chem Components	1st NASA GOCART	GSL GOCART (based on WRF-Chem)	2nd NASA GOCART	GSL GOCART/AM4 Other aerosol and gas-phase schemes

Ensemble members

Atmospheric model only, direct radiative feedback is coming from climatological aerosol reanalysis data

S2S: Fully coupled with ocean, sea ice and wave, online aerosol prediction for direct radiative feedback

Global aerosol assimilation (DA)

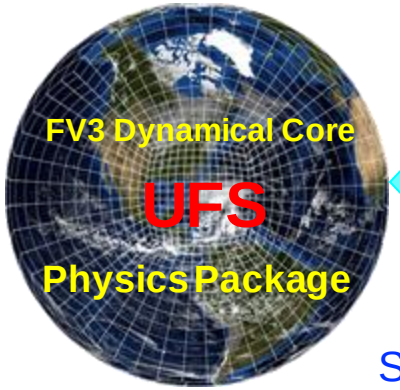
UFS-Chem Framework

Wave component

Ocean & Sea ice components

Land Surface Model

Fully coupled



Capability of radiative feedback

Short/Medium-range weather and Subseasonal to Seasonal (S2S) forecasts

Coupled chemistry suites

CCPP/NUOPC

Emission System (NEXUS)

- Anthropogenic emission
- Biomass burning (fire)
- Biogenic emission
- Volcanic emission
- Lighting/Ocean
- Historical & Future projections

Aerosol Schemes

- Smoke/dust (RRFS-Smoke-dust)
- GOCART (GSL) (CCPP version GEFS-Aerosols)
- CRACMM (CMAQ)
- Complex research schemes

Gas-phase mechanisms

- Greenhouse Gases
- REDHC-RAP-Chem
- AM4 (GFDL)
- Complex research mechanisms

NCAR Model Independent Chemistry Module (MICM)

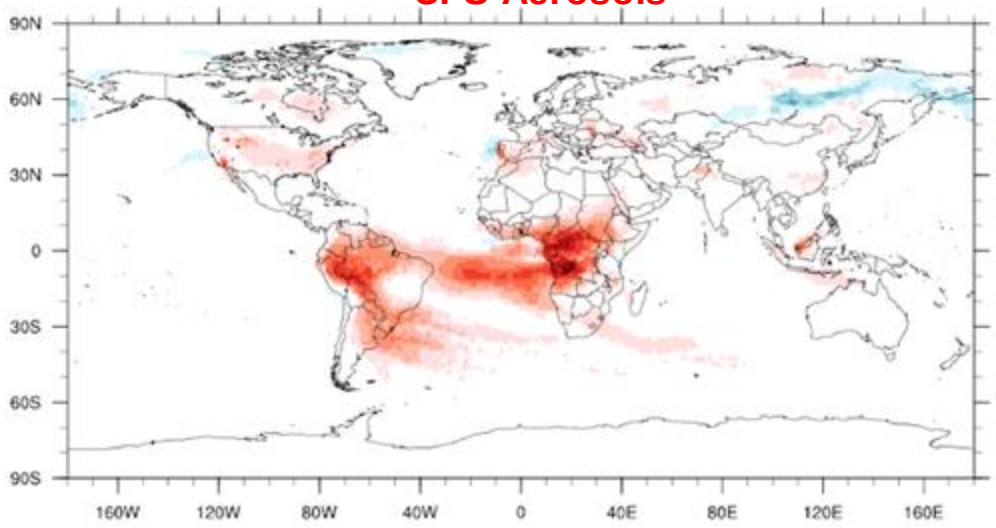
CATChem (Configurable ATmospheric Chemistry)

Post-validation

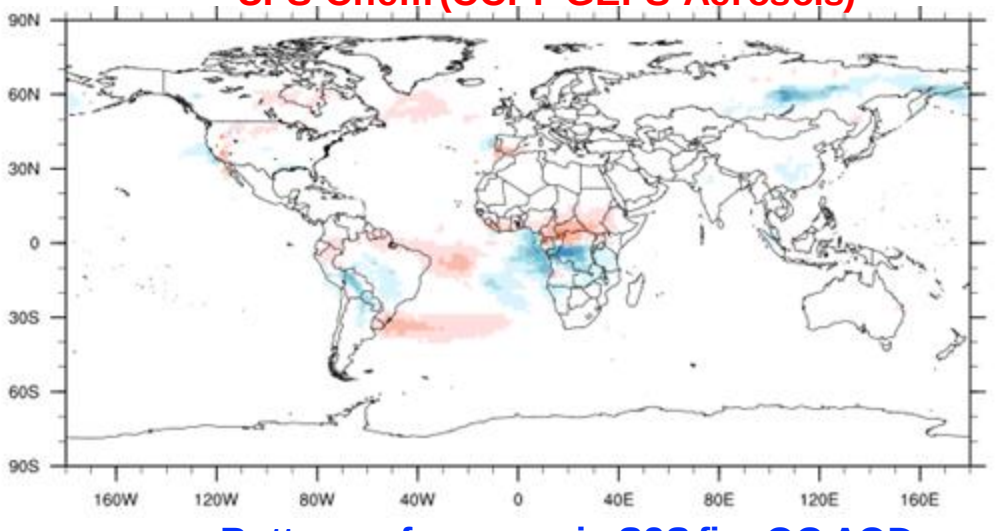
- MELODIES-MONET
- MET
- Other research tools

Organic Carbon (OC) AOD biases with respective to MERRA-2,
August 2016 (GBBEPx v003)

UFS-Aerosols

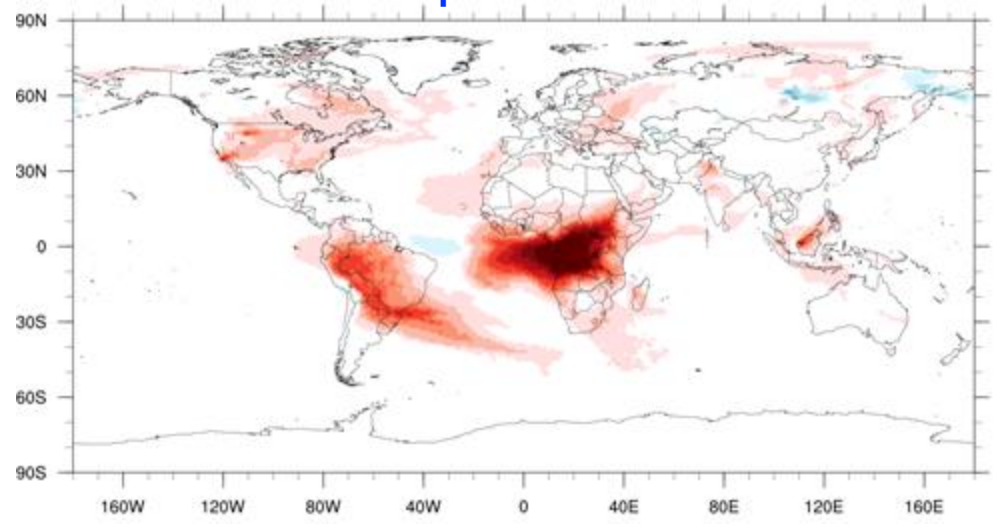


UFS-Chem (CCPP GEFS-Aerosols)



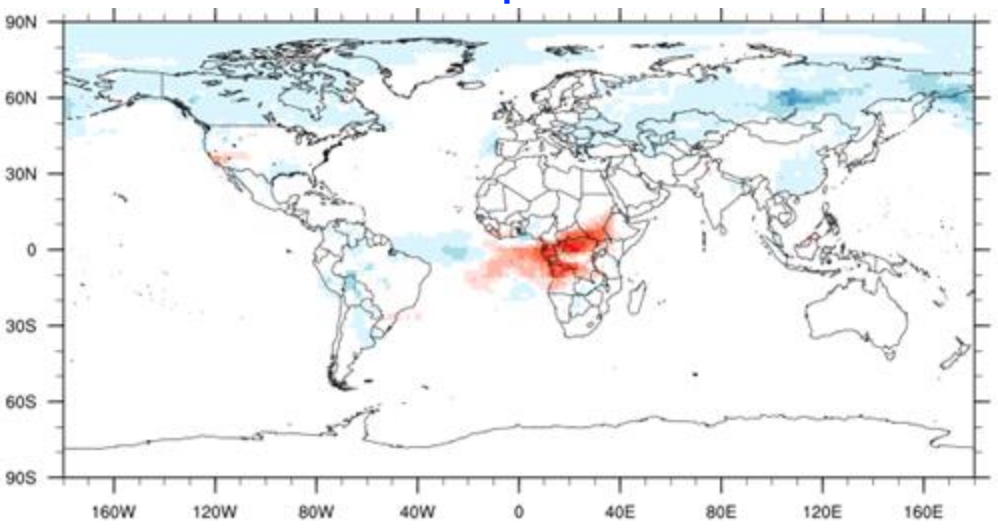
Fully coupled S2S predictions

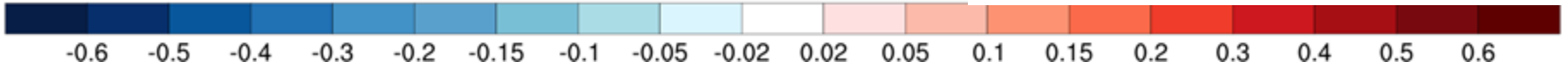
Larger biases over fire regions no online plume-rise module



Atmos. only 24hr-cycling

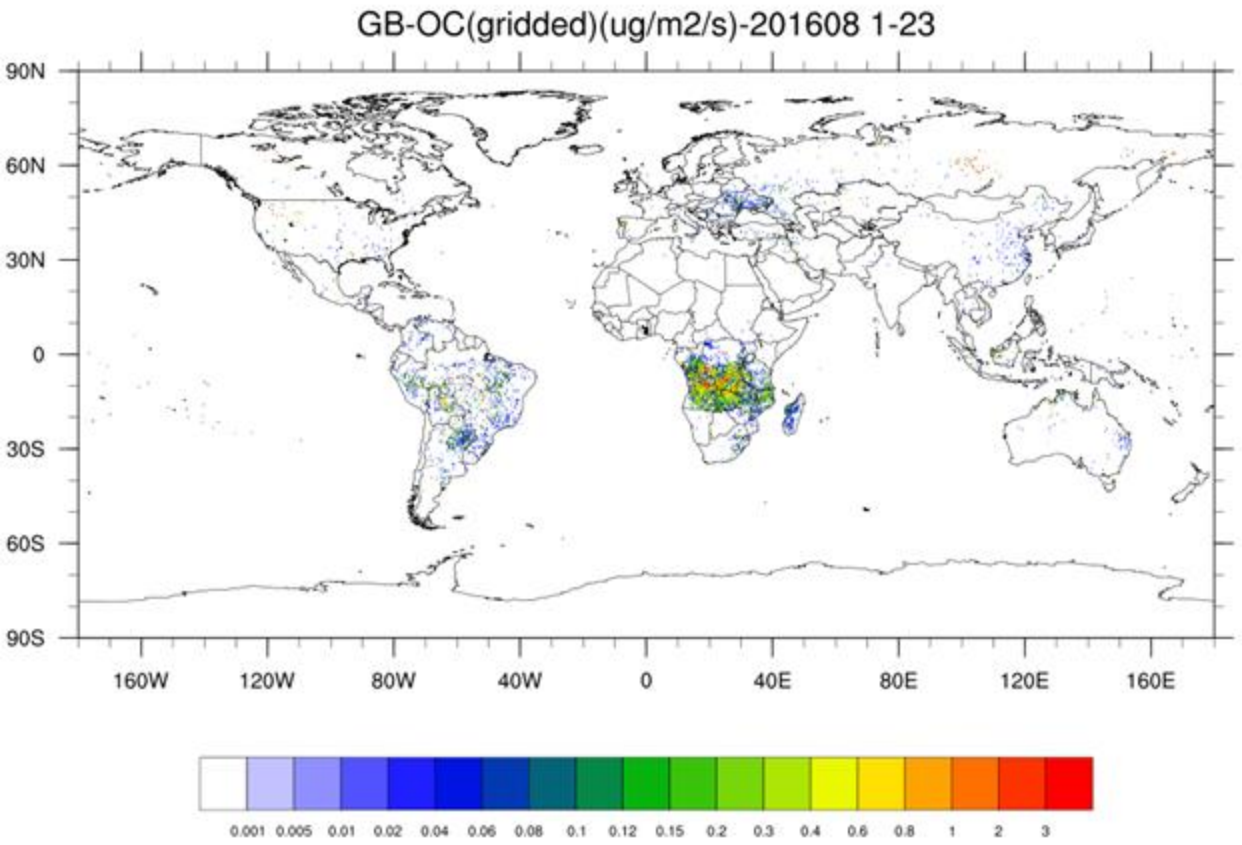
Better performance in S2S fire OC AOD with online plume-rise module





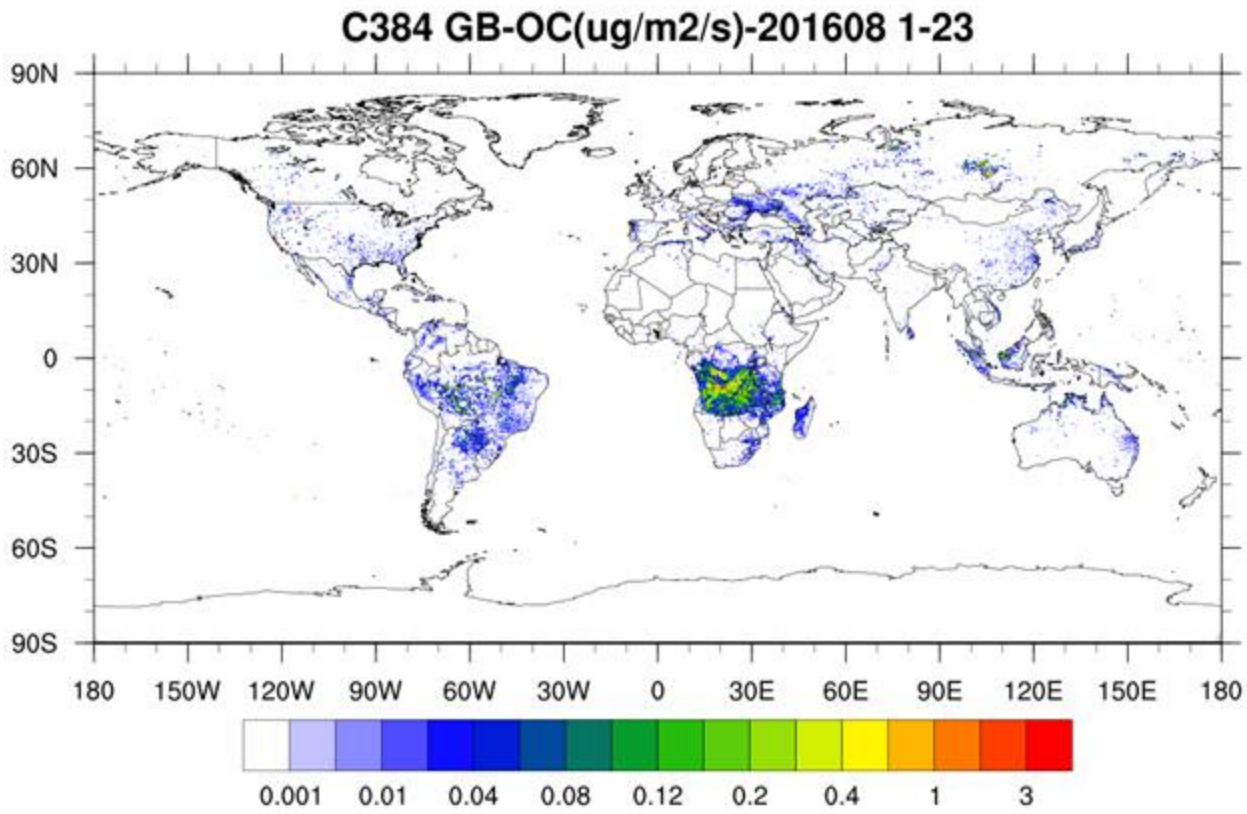
Uncertainties of GBBEPx v003 fire emission at different horizontal resolutions (201608)

UFS-Aerosols 0.1x0.1 degree gridded data



Based on 0.1x0.1 gridded GB fire emission input, it uses the ESMF/MAPL mass conservative method to interpolate into UFS-Aerosols model resolution of C384 (~25km). Much higher over broad areas.

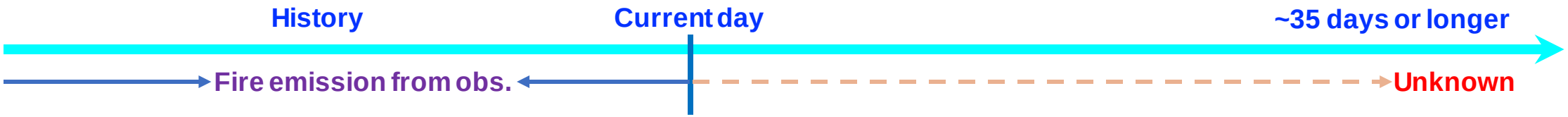
GEFS-Aerosols C384 grid (~25 km) data



The product on C384 (~25km) FV3 grid of GB fire emission is used as direct input for GFES-Aerosols.

Fire emission uncertainties in operational and real-time forecast

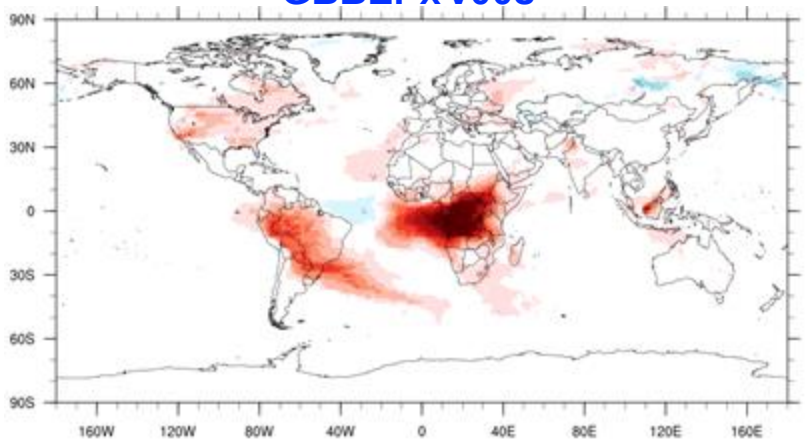
- Resolution uncertainties when gridded from satellite observation.
- Diversities in different fire emission products (GBBEPx v3 & v4, QFED, GFAS…..)
- How to get better estimate of the fire emissions in operational or real-time forecasts for medium weather or S2S predictions?



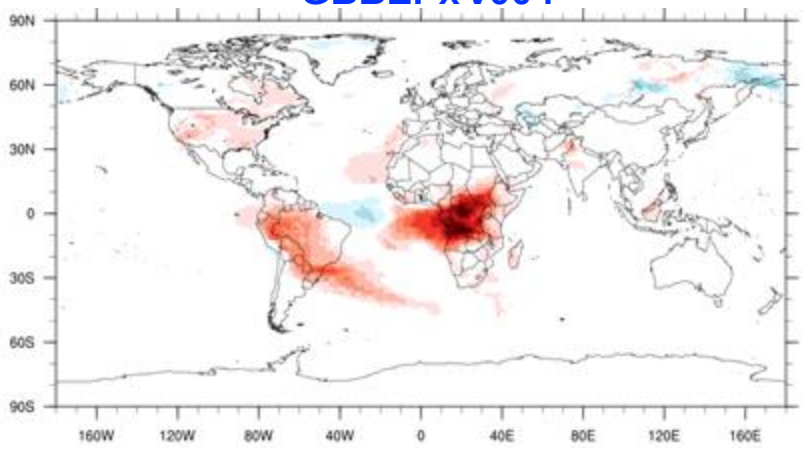
Funded WPO Project

Improving Subseasonal to Seasonal Fire Emissions and Weather Forecasts

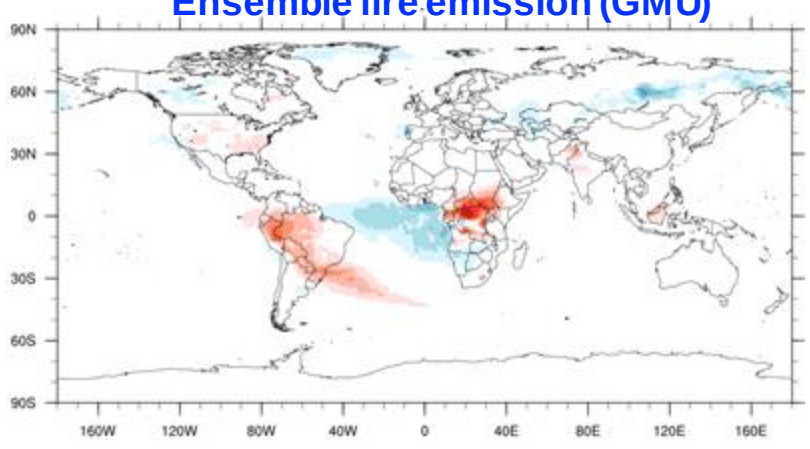
GBBEPx v003



GBBEPx v004



Ensemble fire emission (GMU)



Summary

- The implementation of GEFS-Aerosols shows great improvement compared to the previous NGACv2, which has been operational since Sep. 2020 to provide kinds of applications.
- UFS-Aerosols, as the 2nd generation global aerosol forecast system, is still under development, preliminary results from UFS-Aerosols in forecasting are nonetheless encouraging. The ensemble prototype 4b (EP4b) experiment shows significant improvement in dust predictions with updated FENGSHA dust scheme compared to EB4a and UFS prototype 8 (P8) experiments.
- The development of UFS-Chem model has been launched; an innovative community model that incorporates chemistry online coupled with UFS. Its initial development involved a collaboration between NOAA OAR laboratories and NCAR, utilizing the CCPP infrastructure to connect the gas and aerosol chemistry modules with the rest of the model.
- There are larger overpredictions of OC AOD over southern African fire regions compared to the CCPP version of GEFS-Aerosols (UFS-Chem) when using GBBEPx v003 fire emission , which maybe partly due to uncertainties of fire emissions.
- Recognizing the uncertainties associated with fire emission, a key factor impacting the model performance, we have initiated further studies to improve fire emission for S2S predictions. This effort will benefit both the operational implementation of GEFSv13 and the development of UFS-Chem.

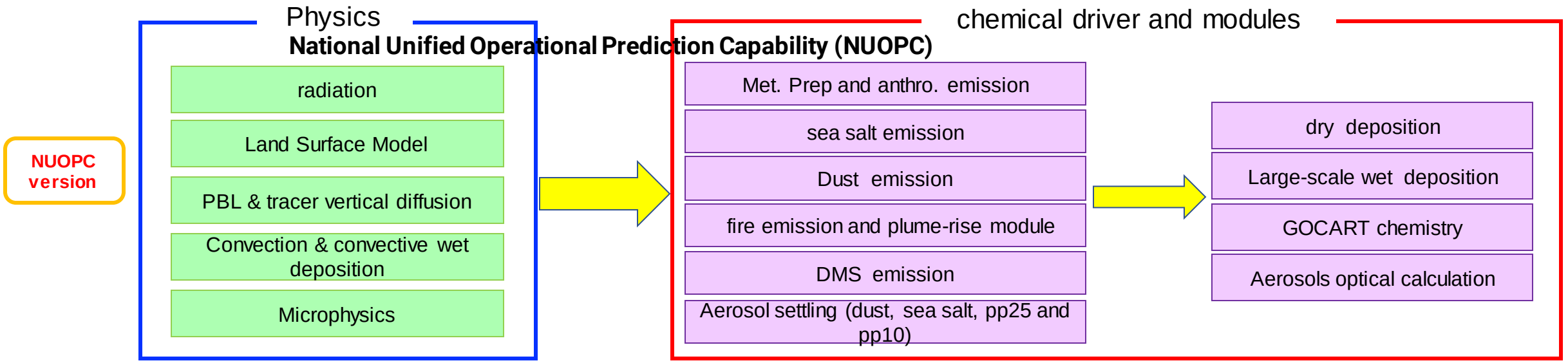
Thank you!

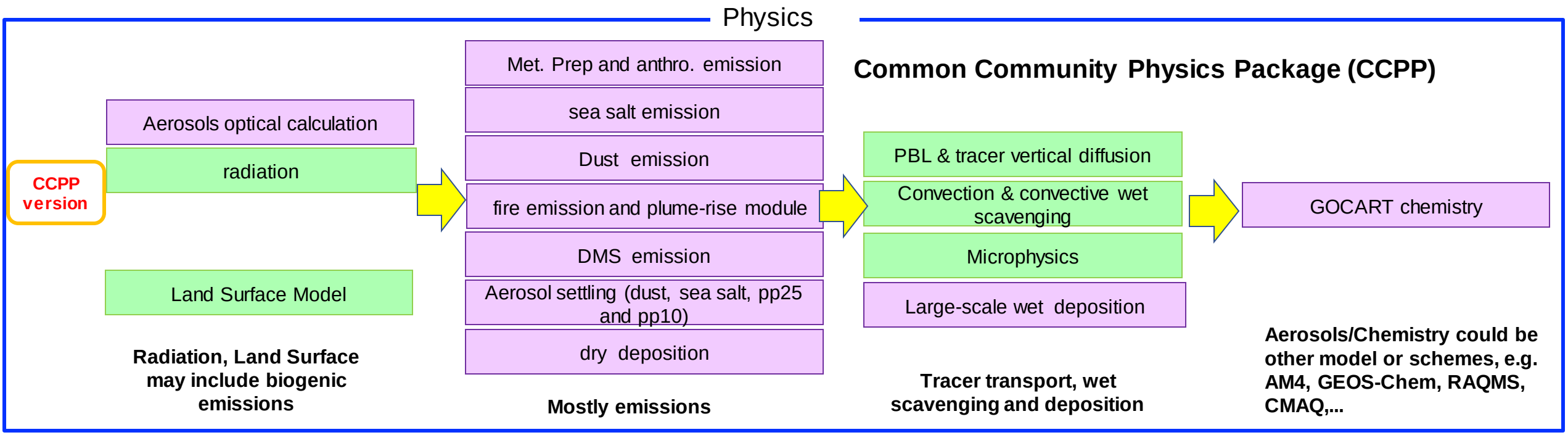
References:

1. Zhang, L., Montuoro, R., McKeen, S. A., Baker, B., Bhattacharjee, P. S., Grell, G. A., Henderson, J., Pan, L., Frost, G. J., McQueen, J., Saylor, R., Li, H., Ahmadov, R., Wang, J., Stajner, I., Kondragunta, S., Zhang, X., and Li, F.: Development and evaluation of the Aerosol Forecast Member in the National Center for Environment Prediction (NCEP)'s Global Ensemble Forecast System (GEFS-Aerosols v1), Geosci. Model Dev., 15, 5337–5369, https://doi.org/10.5194/gmd-15-5337-2022, 2022.

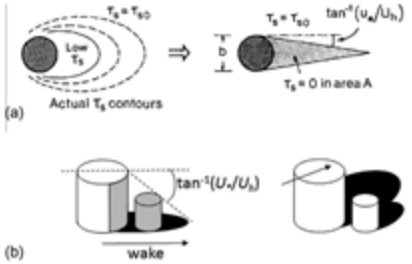
2. Bhattacharjee, S. P., **Zhang, L.,** Baker, B., Pan, L., Montuoro,R., Grell, G. A. and McQueen, J.T.: Evaluation of Aerosol Optical Depth Forecasts from NOAA's Global Aerosol Forecast Model (GEFS-Aerosols), Weather and Forecasting, 38(2), 225-249. Retrieved Feb 2, 2023, https://doi.org/10.1175/WAF-D-22-0083.1, 2023.

Comparison of Coupling structure between NUOPC and CCPP





Fengsha - Updates (in a nutshell)



Friction Velocity

Threshold Velocity

Area

Density

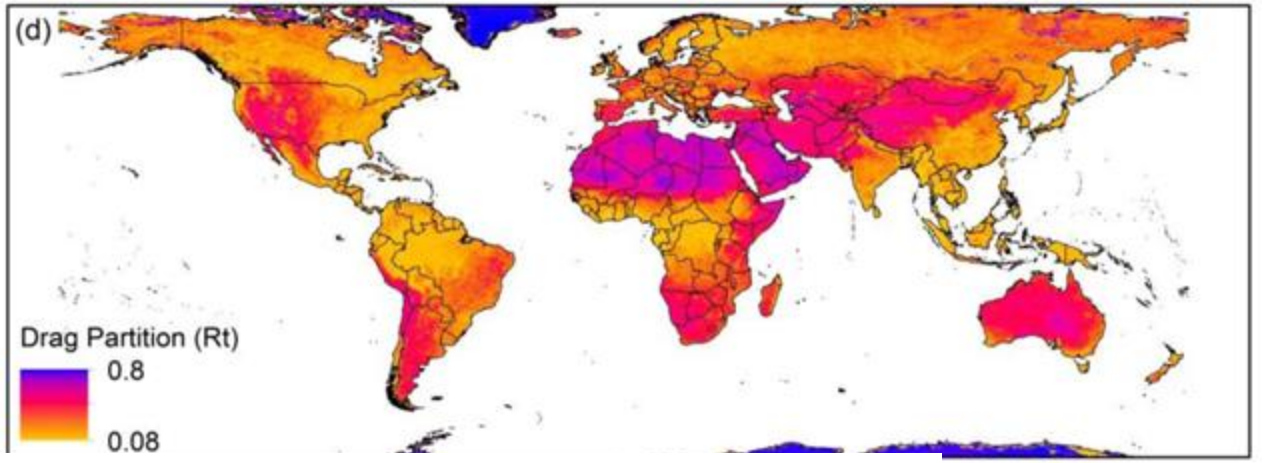
$$F = \alpha A \frac{\rho_a}{g} \left(Ru_*^3\right) \left(1 - \frac{u_{*t}^2}{u_*^2}\right) \left(1 + \frac{u_{*t}^2}{u_*^2}\right)$$

Vertical To Horizontal Flux Ratio

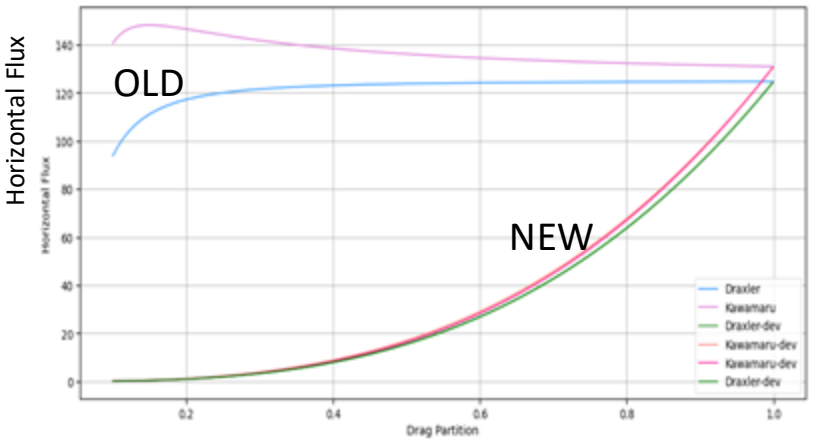
Gravity

Drag Partition

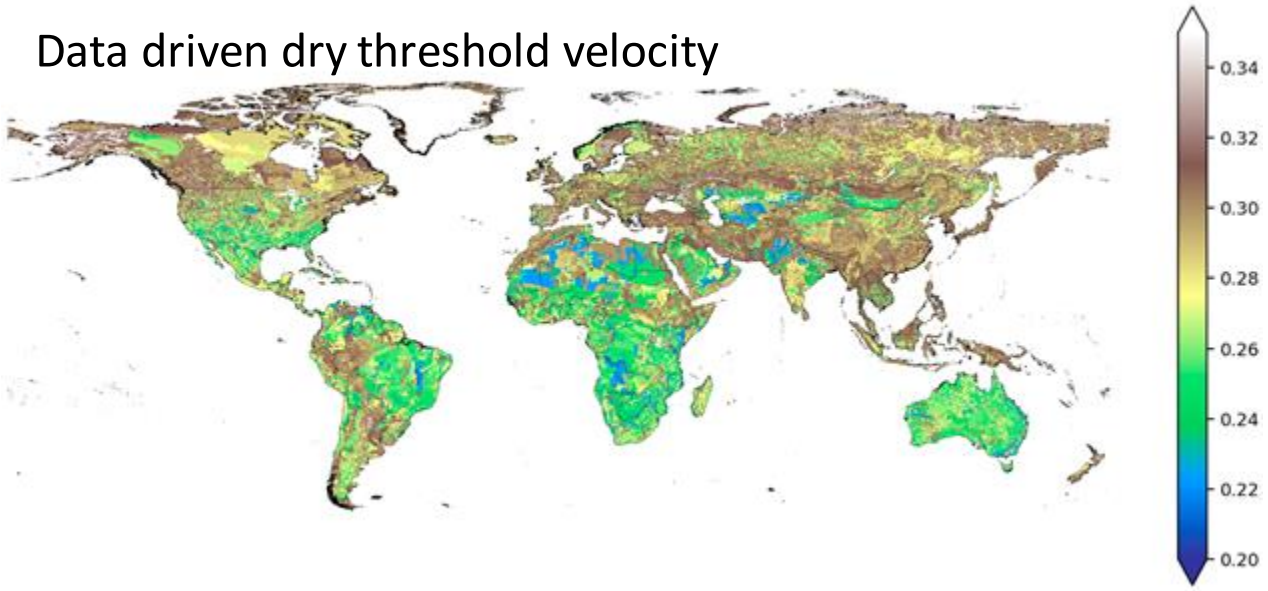
Update the drag partition to Chappel and Webb 2016



Webb et al. 2020



Data driven dry threshold velocity



RMSE and correlation coefficients of GEFS-Aerosols AOD (v12 and v12.3) with respect to AERONET

August 2021

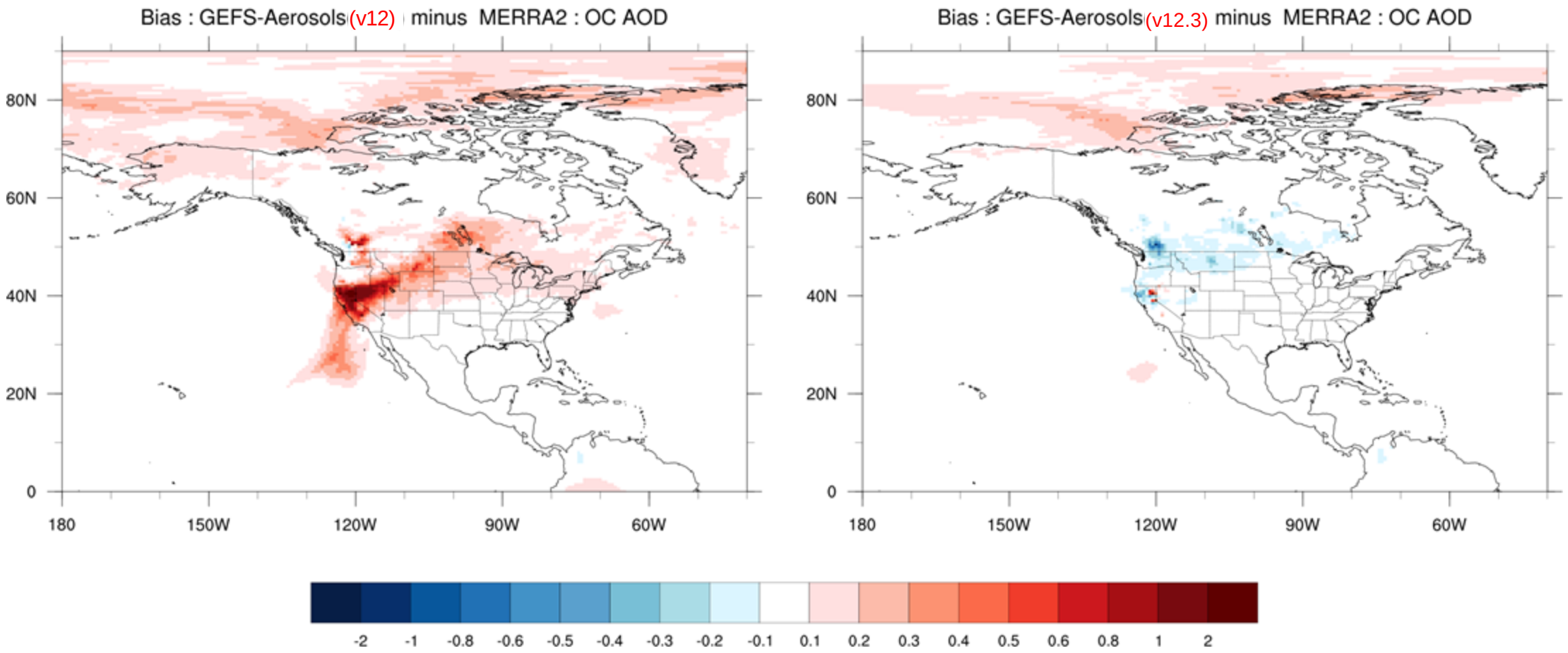
	RMSE			Correlations		
	GEFSv12	GEFS (v12.3)	MERRA2	GEFSv12	GEFS (v12.3)	MERRA2
Univ. of Reno	2.44	0.844	0.637	0.601	0.546	0.665
Neon_Wref	0.314	0.348	0.3058	0.8425	0.858	0.862
PNNL	1.282	0.455	0.499	0.365	0.721	0.656
Meridian	0.77	0.552	0.552	0.599	0.724	0.553
Cascade Airport	0.65	0.63	0.627	0.498	0.575	0.539
Taylor Ranch	1.6	0.66	0.61	0.411	0.686	0.684
Lewis Clark	1.14	0.64	0.506	0.42	0.56	0.67
Pinehurst	0.769	0.602	0.5752	0.507	0.69	0.608
Missoula	0.541	0.455	0.4305	0.61	0.675	0.643
Bozeman	2.19	0.4898	0.29	0.588	0.677	0.789
Rexburg Idaho	3.414	0.473	0.465	0.493	0.697	0.661

	RMSE			Correlations		
	GEFSv12	GEFS (v12.3)	MERRA2	GEFSv12	GEFS (v12.3)	MERRA2
Bakersfield	1.19	0.288	0.257	0.729	0.734	0.745
Monterey	1.52	0.4	0.32	0.814	0.847	0.87
NASA AMES	1.64	0.32	0.28	0.863	0.828	0.838
Railroad Valley	0.954	0.418	0.478	0.395	0.732	0.538
Neon Wood	0.643	0.336	0.228	0.482	0.751	0.757
U. of Wisconsin	0.28	0.213	0.1	0.76	0.64	0.86
GSFC	0.172	0.12	0.09	0.485	0.575	0.8
Cartel (NY)	0.255	0.253	0.138	0.648	0.69	0.9
Toronto	0.311	0.179	0.09	0.45	0.55	0.92
Appalachian	0.097	0.097	0.06	0.737	0.719	0.726
Tucson	0.05	0.05	0.04	0.52	0.54	0.62

- For most of the sites over western US, the RMSEs have reduced significantly, some sites are even up to 80%.
- The correlation coefficients also show some improvements, which have increased by almost 50% at some sites.

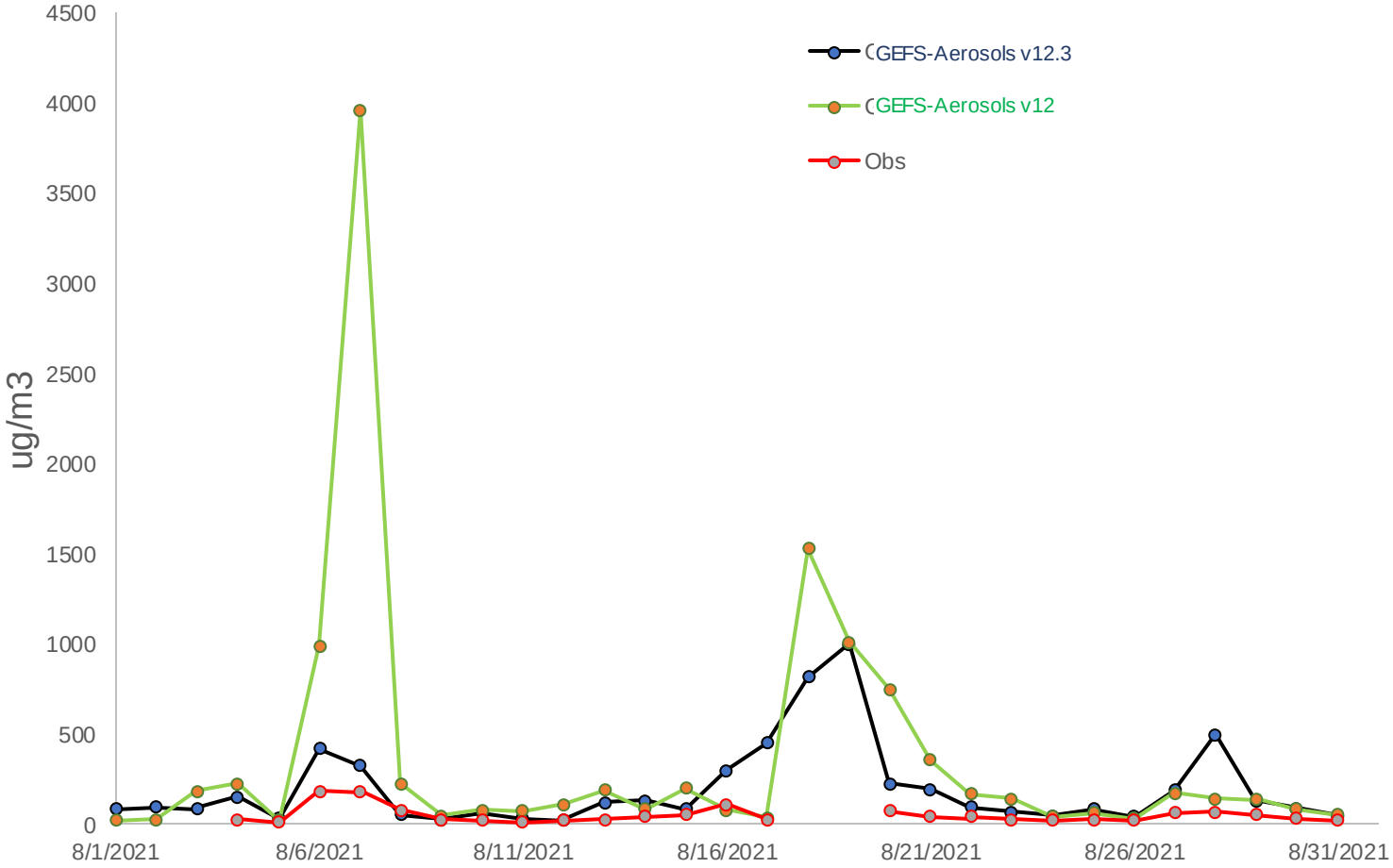
(Correlation coefficients are at the 95% confidence interval)

Biases of Day 1 OC AOD forecast averaged for August 2021 validated against MERRA-2



- Significant positive biases of total AOD have been reduced in GEFS-Aerosols v12.3 compared to v12 over North America; however, it also shows some slightly negative biases.
- The improved OC AOD is the major factor contributing to the positive bias reduction in GEFS-Aerosols v12.3 compared to v12 over North America. The low biases of total AOD over southeastern US is not directly associated to OC.

PM2.5 daily average at Chico-Brutte (near the fire source)



Surface PM2.5 concentrations have been corrected mostly in GEFS-Aerosols v12.3

Enhanced Research Capabilities of UFS-Chem with CATChem (Configurable ATmospheric Chemistry)

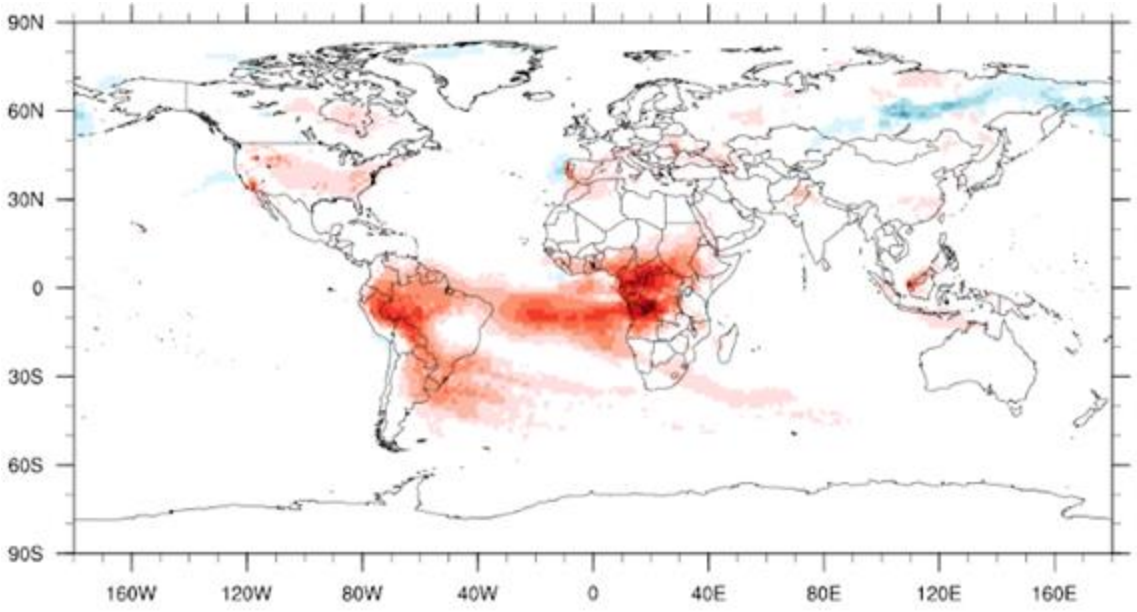
UFS-Chem with CATChem will be flexible and configurable where users can choose different aerosol scheme and gas-phase chemical mechanism using different way to embed into physics package for their desired application or science questions:

1) Options to use gas and aerosol chemical mechanisms of varying complexity.
2) Capabilities to easily couple different chemical mechanisms to different physics options.
3) Flexibilities in emissions processing system.
4) Applications of evaluation/validation tools to efficiently compare model results against a variety of observations.

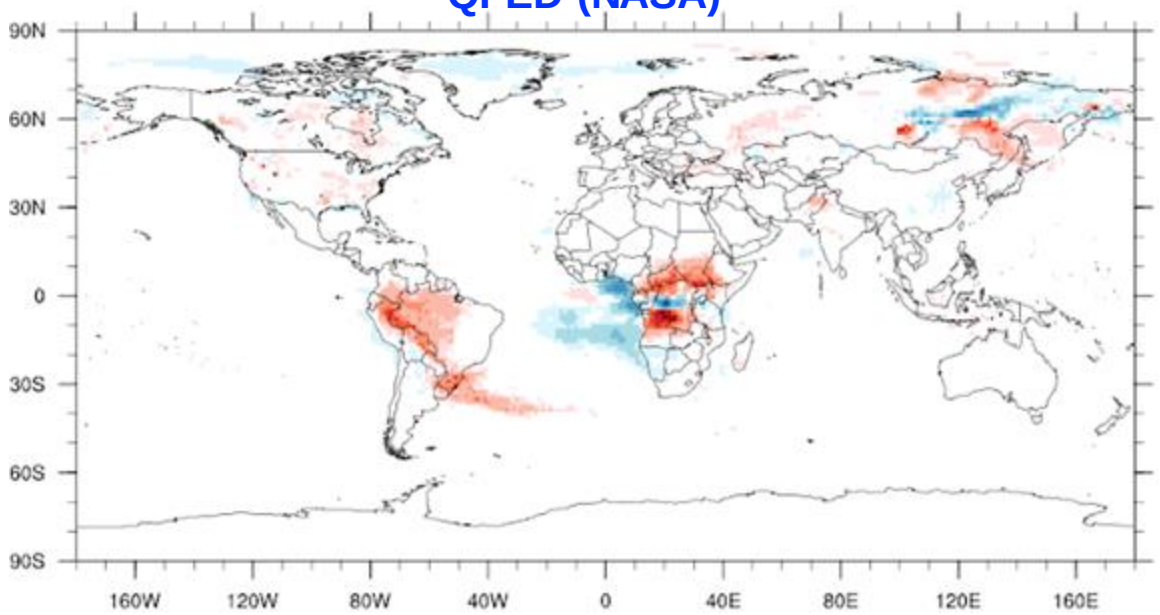
Organic Carbon (OC) AOD biases with respective to MERRA-2, August 2016

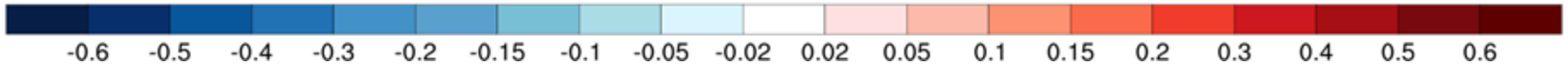
UFS-Aerosols model using different fire emissions
fully coupled S2S predictions

GBBEPx v003 (NESDIS)



QFED (NASA)





The fire emission from various products shows significant differences on S2S AOD predictions, which would undoubtedly impact on the aerosol radiative feedbacks.