The National Air Quality Forecast Capability Using the NOAA Global Forecast System: Model Developments and Community Applications

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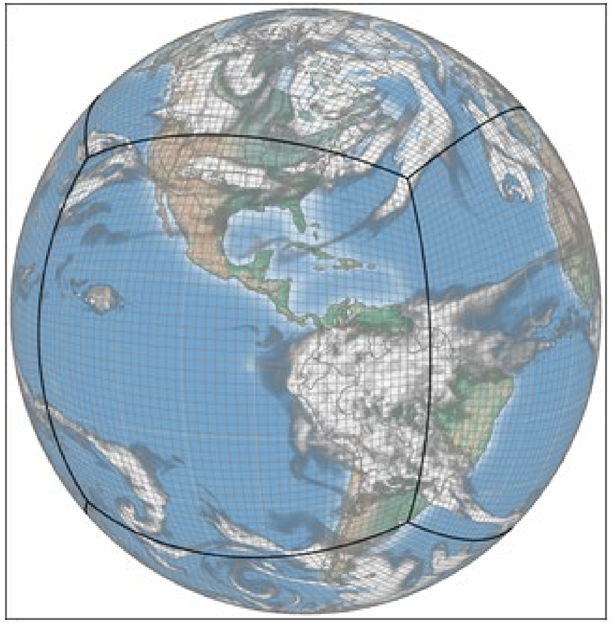
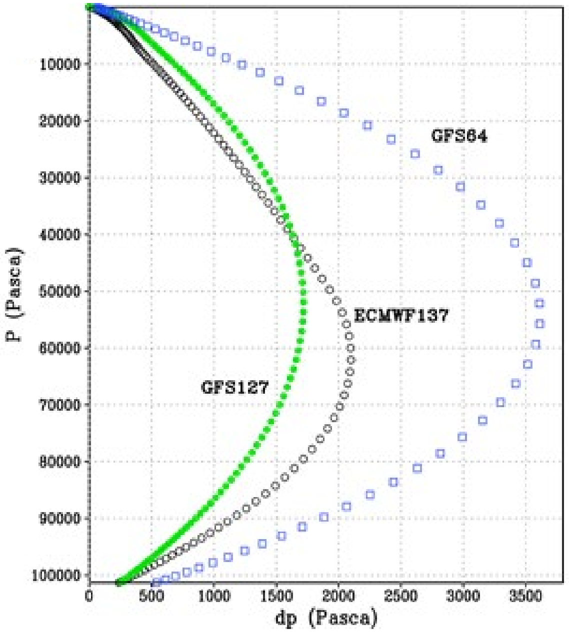
Introduction & Motivation

- The National Air Quality Forecast Capability (NAQFC) has been operational since 2004.
- The Finite Volume Cubed-Sphere (FV3) dynamical core is used in the NOAA Global Forecast System (GFS).
- NOAA is running GFS Version 16 (GFSv16) operationally.
- Streamlined development to use GFSv16 for a next-generation, state-of-the-science, NAQFC.
- Improve community options to use NOAA GFSv16 products for air quality applications.



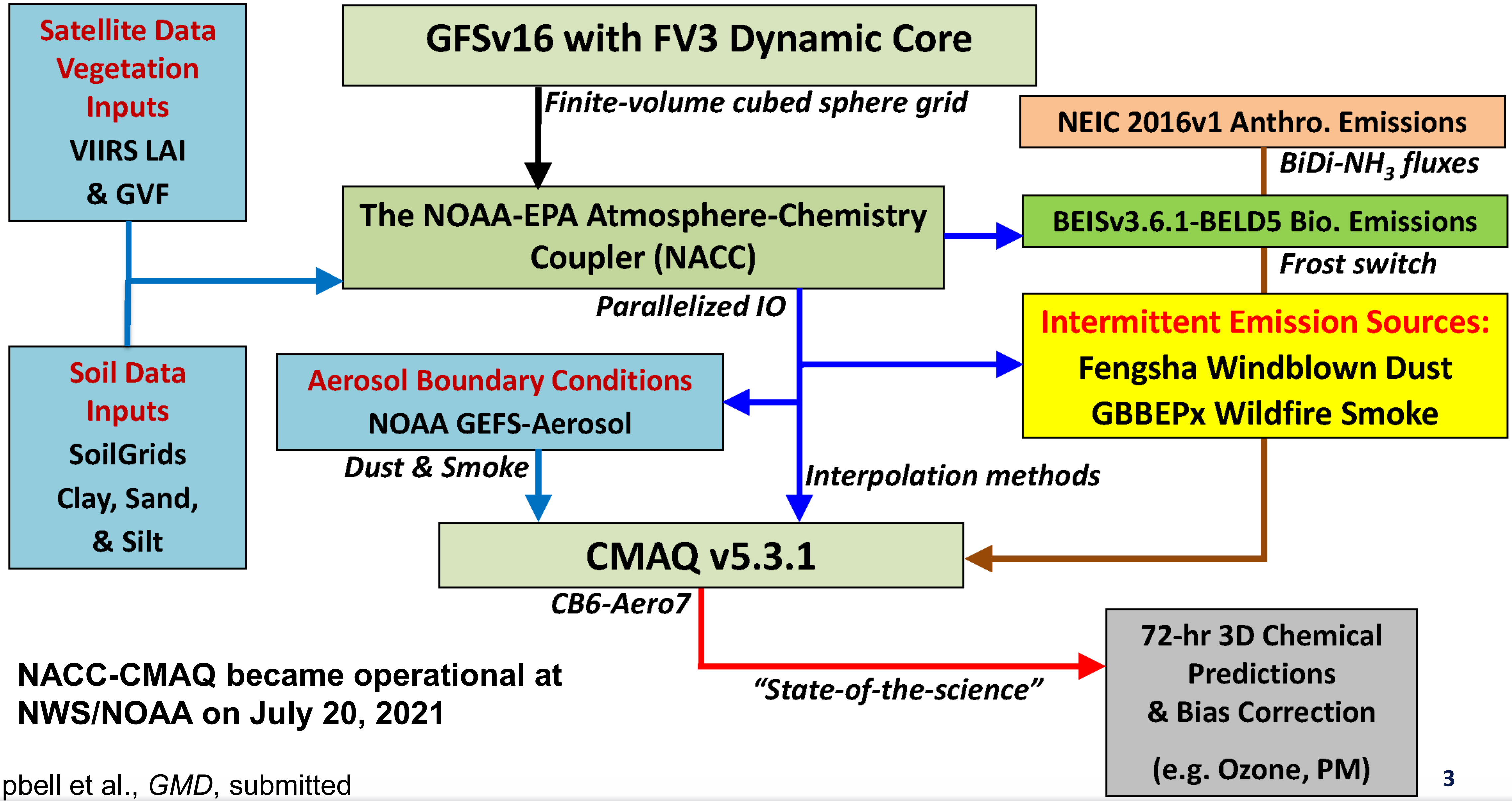
FV3 gnomonic cubed-sphere grid



GFSv16 127L vertical structure

Campbell et al., *GMD*, submitted

The Advanced NAQFC: NACC-CMAQ



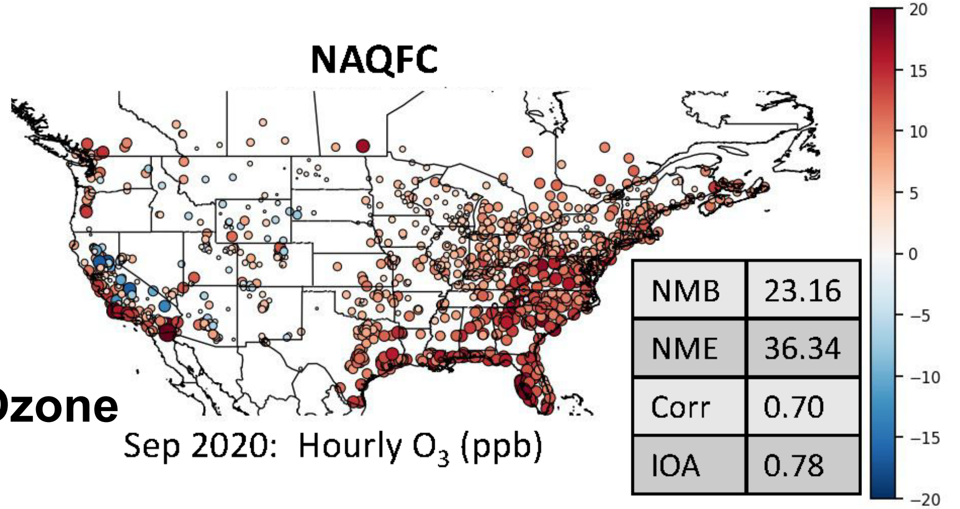
NACC-CMAQ became operational at NWS/NOAA on July 20, 2021

Campbell et al., *GMD*, submitted

Model Evaluation Versus Prior NAQFC

Day 1 Mean Bias (Model-AirNow) Plots and Domain-Wide Statistics

NAQFC

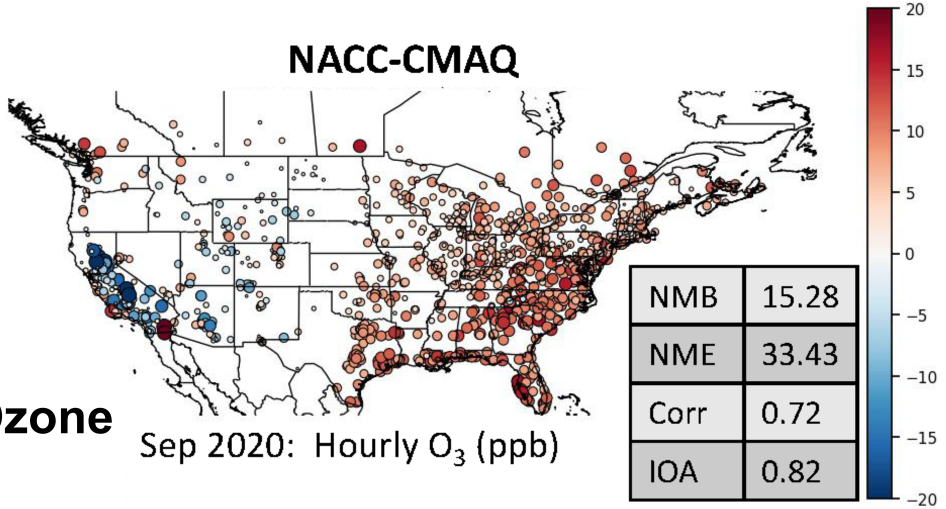


Ozone

Sep 2020: Hourly O_3 (ppb)

NMB	23.16
NME	36.34
Corr	0.70
IOA	0.78

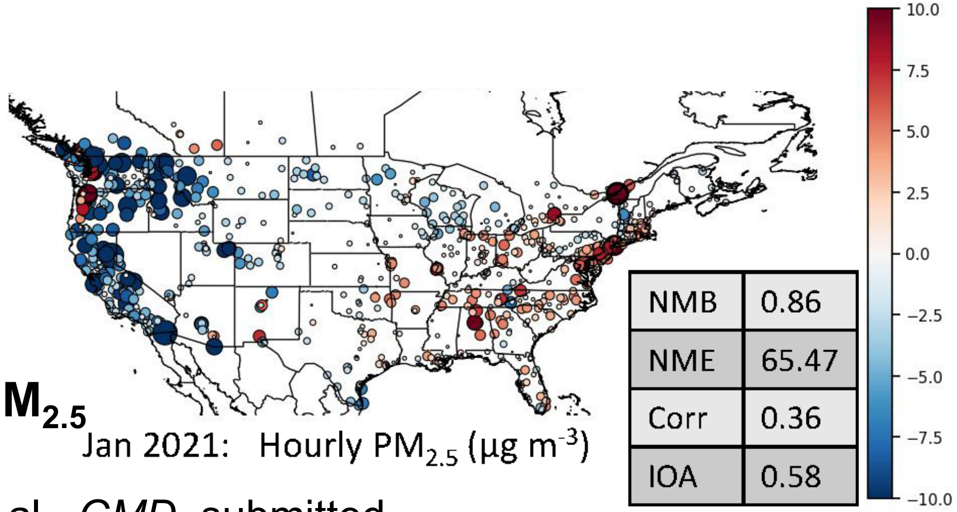
NACC-CMAQ



Ozone

Sep 2020: Hourly O_3 (ppb)

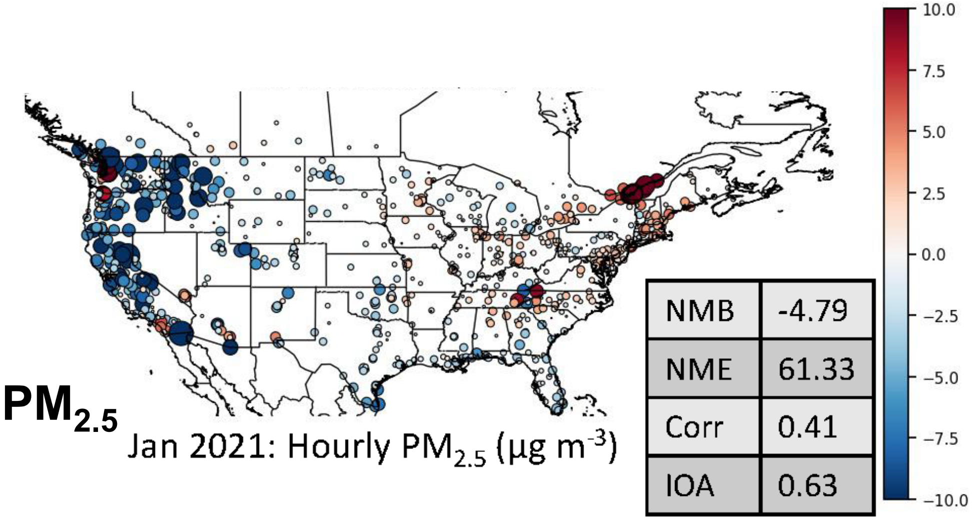
NMB	15.28
NME	33.43
Corr	0.72
IOA	0.82



$PM_{2.5}$

Jan 2021: Hourly $PM_{2.5}$ (μg m^{-3})

NMB	0.86
NME	65.47
Corr	0.36
IOA	0.58



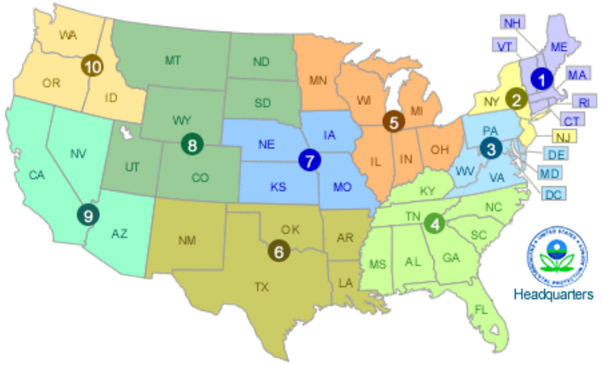
$PM_{2.5}$

Jan 2021: Hourly $PM_{2.5}$ (μg m^{-3})

NMB	-4.79
NME	61.33
Corr	0.41
IOA	0.63

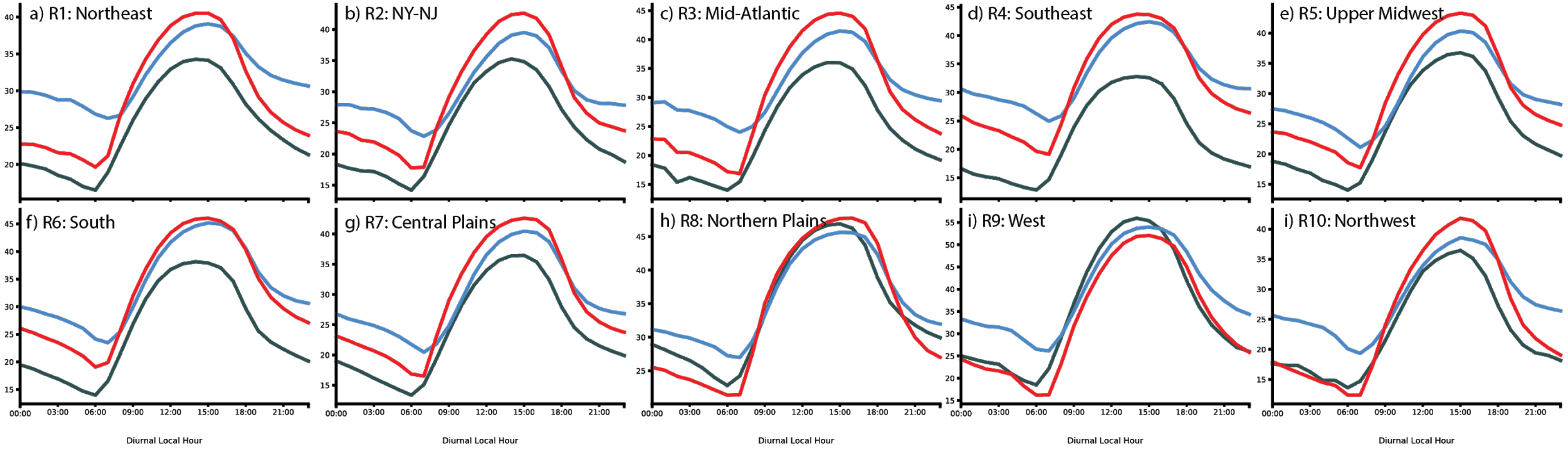
Campbell et al., *GMD*, submitted

Model Evaluation Versus Prior NAQFC



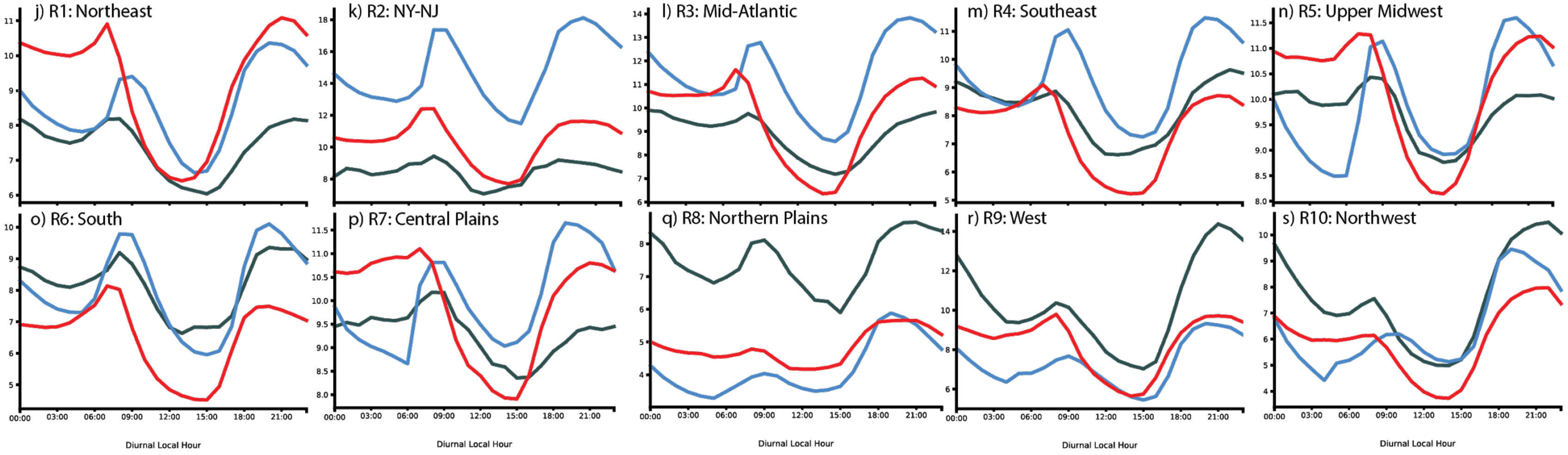
AirNow
NAQFC
NACC-CMAQ

September 2020 Average Diurnal Ozone (ppb)



Average O_3 Correlation:
Prior NAQFC = 0.67
NACC-CMAQ = **0.73**

January 2021 Average Diurnal PM2.5 (ug m^{-3})

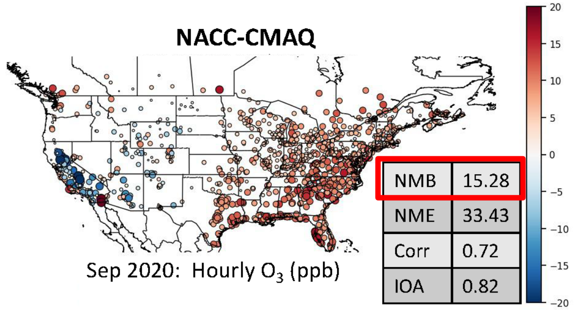


Average $PM_{2.5}$ Correlation:
Prior NAQFC = 0.50
NACC-CMAQ = **0.59**

Campbell et al., *GMD*, submitted

Testing In-Canopy Effects in NACC-CMAQ

- Systematic ozone overpredictions in CTMs are linked to distinct vertical gradients of ozone measured within dense forest canopies of the U.S. → NACC-CMAQ incorporates canopy parameters associated with the attenuation of light (Makar et al., 2017).



NMB	15.28
NME	33.43
Corr	0.72
IOA	0.82

$$P(\theta) = e^{-\frac{G(\theta)\,\Omega(\theta)\;LAI}{cos(\theta)}}$$

Probability of beam penetration (i.e., fractional light penetration; Nilson, 1971; Monsi and Saeki, 1953) depends on LAI, leaf projection (G), clumping index (Ω), and solar zenith angle (θ).

- In-canopy vertical diffusivity is also modified based on the Raupach (1989) near-field theory for turbulence within the forest canopy (Makar et al., 2017):

$$K_{\mathrm{can}}(z) = \frac{K_{\mathrm{mod}}(z_1)}{K_{\mathrm{est}}\left(\frac{z_1}{h_c}\right)} K_{\mathrm{est}}\left(\frac{z}{h_c}\right),$$

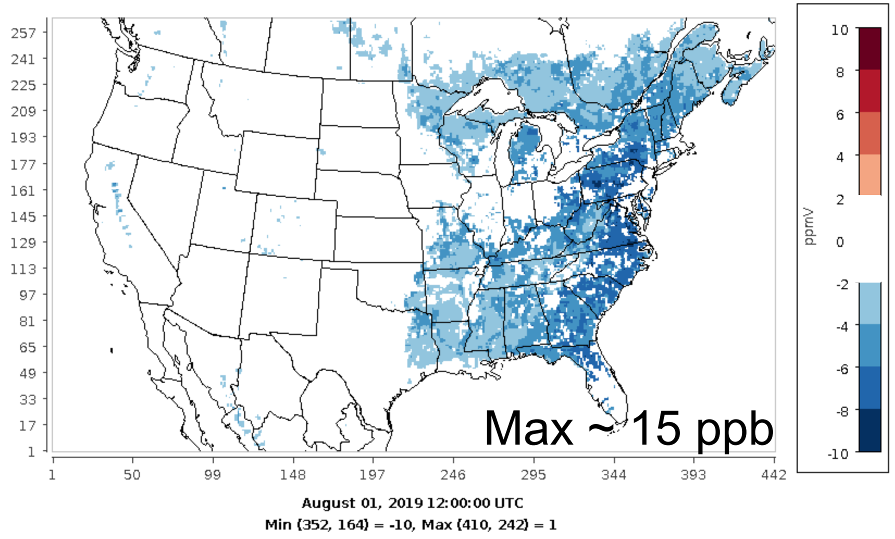
Modified turbulent diffusivity is scaled to 1st model layer and depends on variance in Eulerian vertical velocity (σ_w^2) and turbulent length scale (T_L)

$$K_{\mathrm{est}}\left(\frac{z}{h_c}\right) = \sigma_{\mathrm{w}}^2\left(\frac{z}{h_c}\right) T_{\mathrm{L}}\left(\frac{z}{h_c}\right),$$

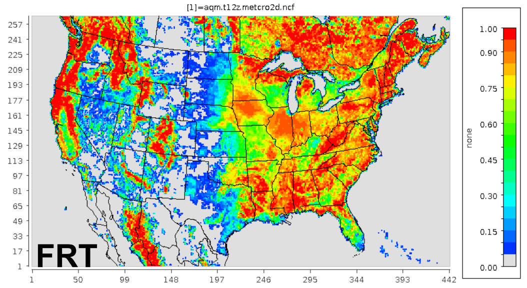
$$T_{\mathrm{L}}\left(\frac{z}{h_c}\right) = \frac{h_c}{u^*}\left[0.256\left(\frac{z-0.75h_c}{h_c}\right) + 0.492\exp\left(\frac{-0.256z/h_c}{0.492}\right)\right],$$

Impacts of In-Canopy Effects on Ozone

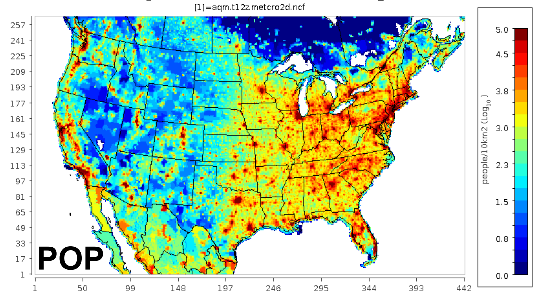
August 2019 Ozone (ppb)
Canopy – No Canopy



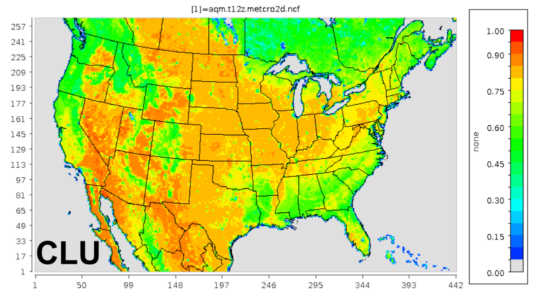
Forest Fraction



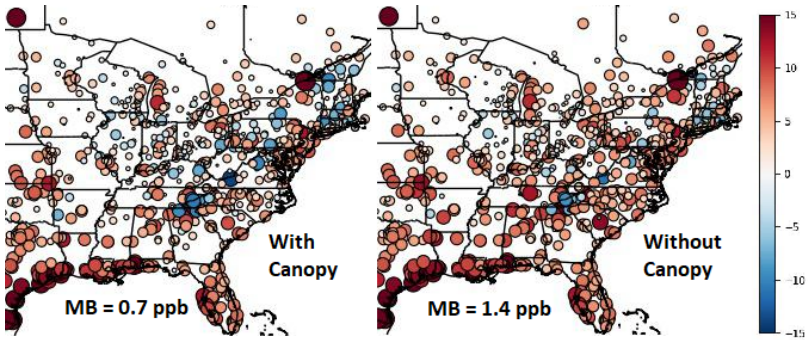
Population Density



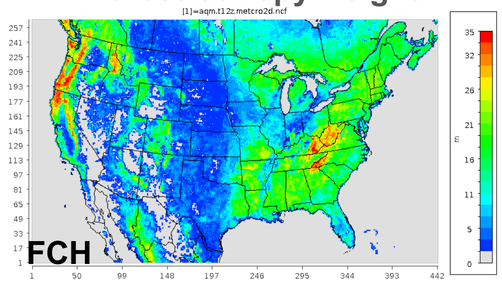
Clumping Index



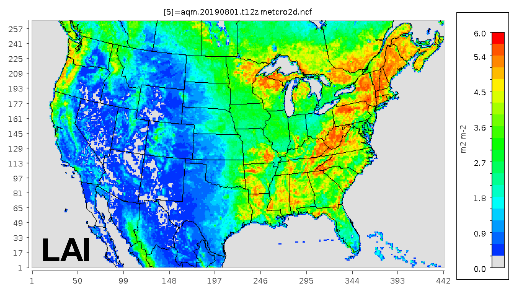
August 2019 Ozone (ppb)
Mean Bias (AirNow)

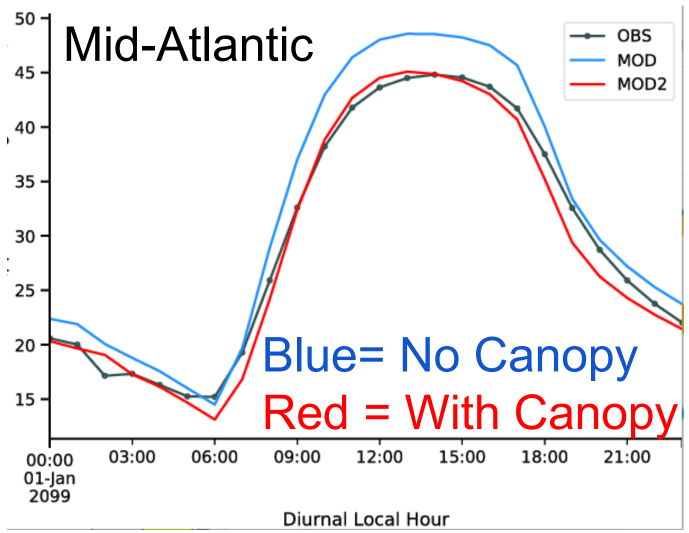


Forest Canopy Height



Leaf Area Index





Conditions for contiguous forest canopy: FCH > 10 m & LAI > 0.1 & FRT > 0.5 & POP < 10000 people/10km^2
& P (θ) < 45 % & FCH > 18 m (Makar et al., *Nature*, 2017)

Community Applications and Research

- Developing a prototype for NACC data to be available "In the Cloud" (2021-2022).

- Facilitates GFS-driven CMAQ applications for the greater research community:

1. Access CMAQ-ready NACC outputs for NAQFC domains (e.g. 12km CONUS).
2. Access GFS inputs to run "NACC-in-the-cloud" for any user-defined domain globally.

- Potential Benefits:

✓ Interface directly with a NOAA operational GFSv16 global dataset (no data download required).

✓ New research tool for any regional domain globally and avoid downscaling/running WRF.

✓ Rapid applications of CMAQ-ready meteorology for recent air quality events/applications.

- Tests of NACC-CMAQ vs. WRF-CMAQ have been performed (up next…).

NACC-CMAQ vs WRF-CMAQ

NACC-CMAQ and WRF-CMAQ are analyzed for wildfire and non-wildfire events during FIREX-AQ in August 2019.

FV3-GFSv16 Configuration

- Microphysics: GFDL 6-cat scheme
- PBL: sa-TKE-EDMF
- Cumulus: SAS
- Radiation: RRTMg
- Land Surface/LU Data: Noah/21-cat MODIS
- Surface Layer: M-O

<u>August 2019 Simulation: </u> GFSv16/NACC direct interpolation for input to CMAQv5.3.1

WRFv4.0.3 Configuration

- Microphysics: Morrison 2-moment
- PBL: YSU
- Cumulus: Multiscale KF
- Radiation: RRTMg
- Land Surface/LU Data: Noah/21-cat MODIS
- Surface Layer: M-O

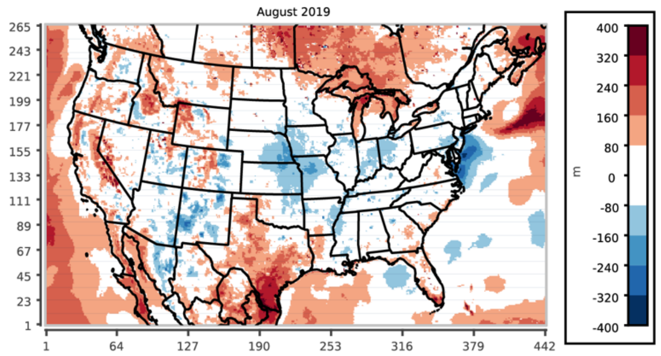
<u>August 2019 Simulation: </u> GFSv16 downscaled to WRFv4.0.3 simulation for input to CMAQv5.3.1

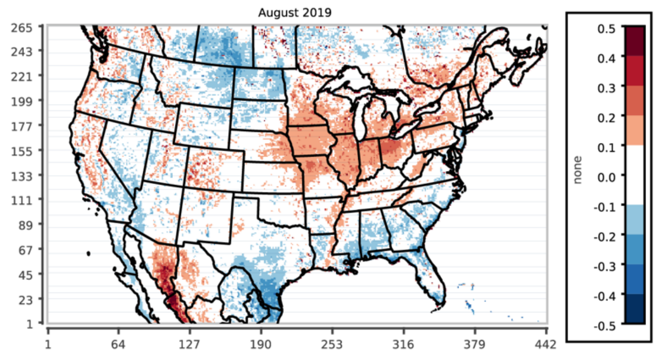
FDDA Nudging: Enabled for T and Q for whole domain, but only outside the PBL for U, V.

Note: Both the emissions and CMAQ configurations are identical.

GFSv16 vs. WRFv4.0.3 Meteorology

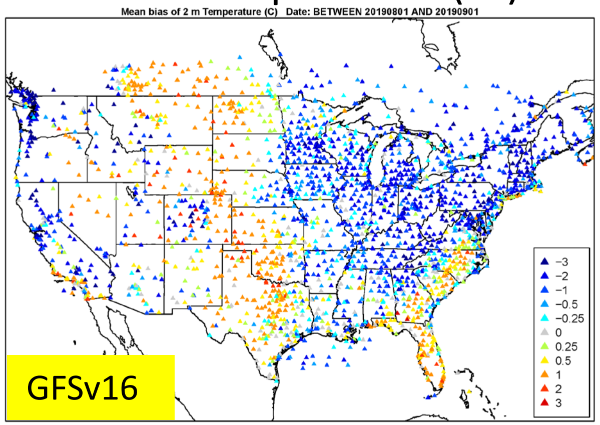
August 2019
GFSv16/NACC - WRF

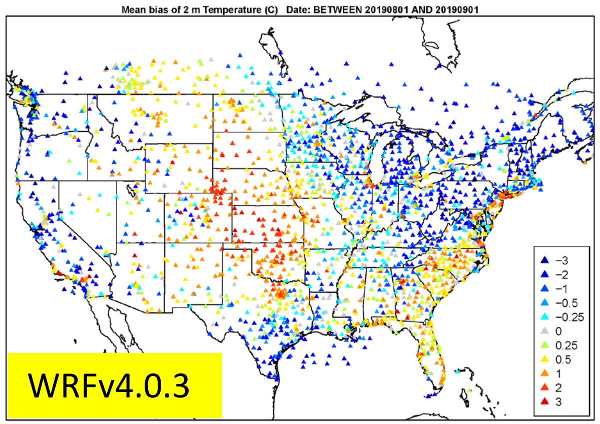




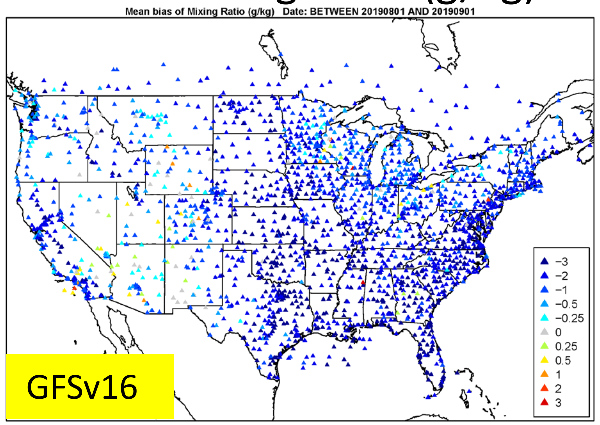
August 2019

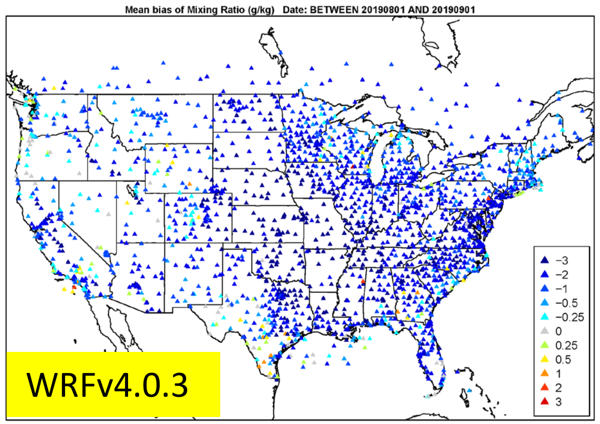
2-m Temperature (°C)



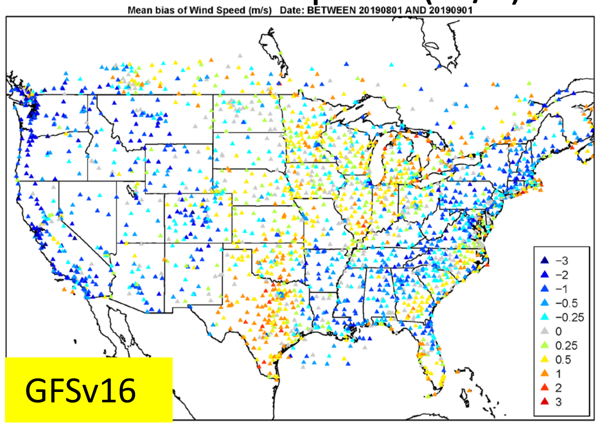


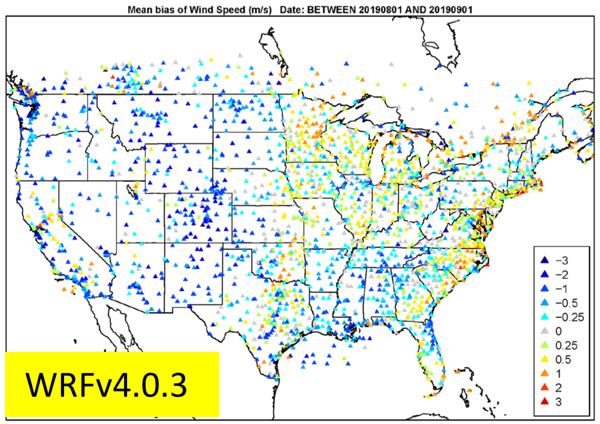
2-m Mixing Ratio (g/kg)





10-m Wind Speed (m/s)



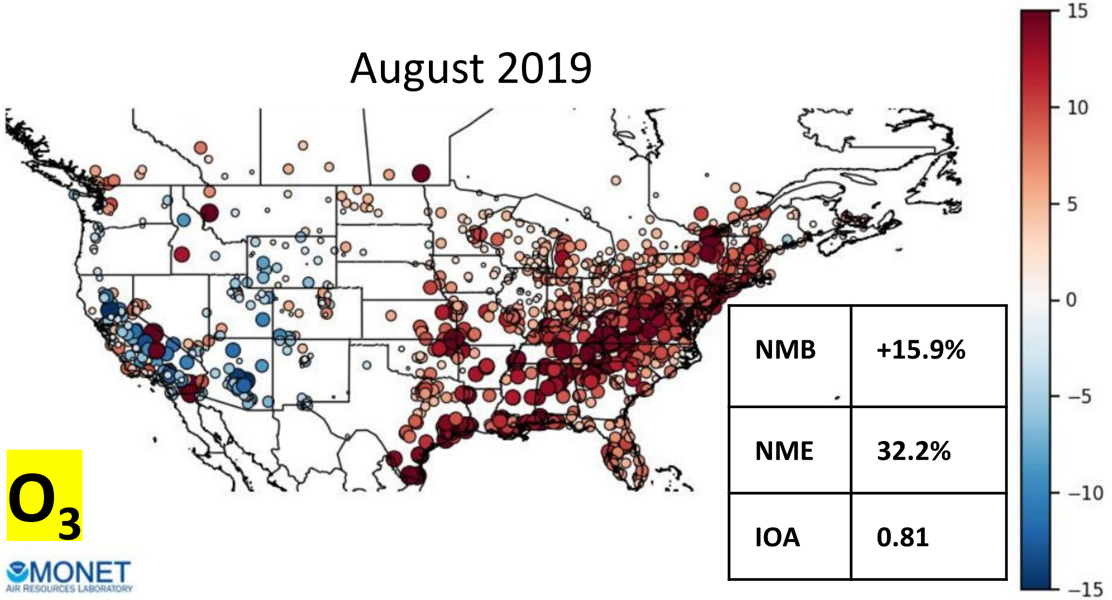


Model physics & LU data differences lead to PBLH differences → Rather similar met model performance (against METAR)

Tang et al., *GMD*, in prep.

WRF-CMAQ vs. NACC-CMAQ Ozone

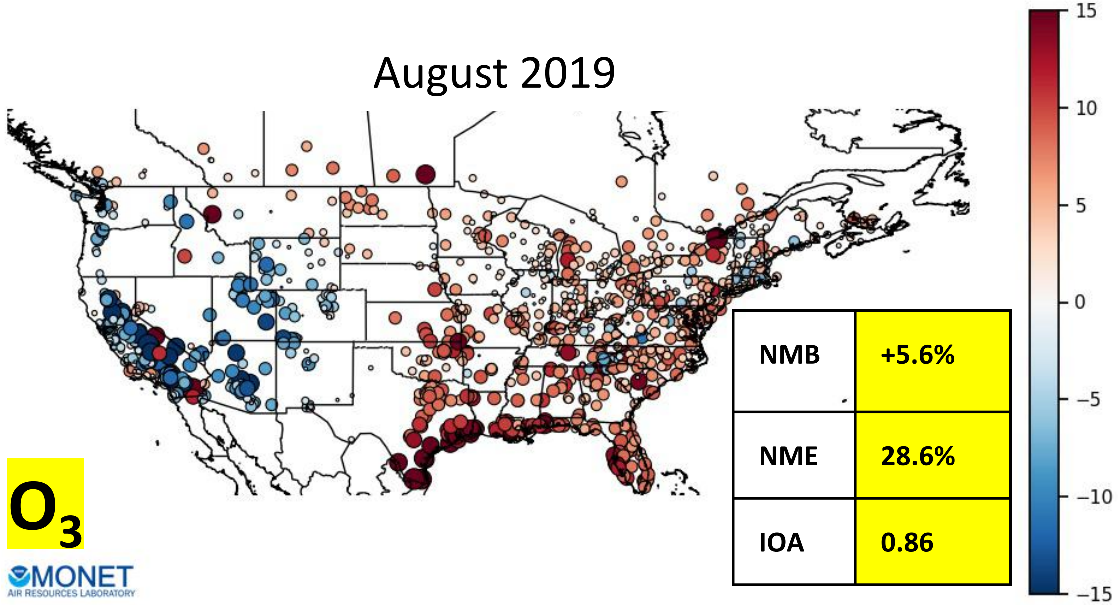
GFSv16/WRFv4.0.1-CMAQv5.3.1



NMB	+15.9%
NME	32.2%
IOA	0.81

WRF downscaling with different GFS vs. WRF physics to CMAQ

GFSv16→NACC-CMAQv5.3.1



NMB	+5.6%
NME	28.6%
IOA	0.86

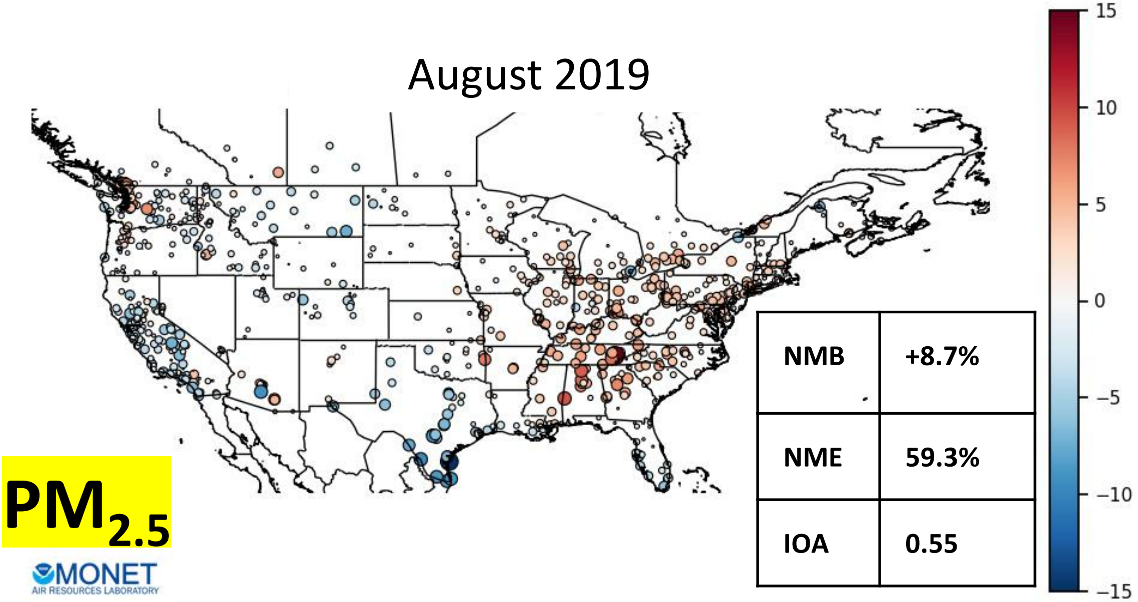
No downscaling, direct GFSv16 physics interpolation to CMAQ

Demonstrates generally improved model performance of NACC-CMAQ compared to WRF-CMAQ.

Tang et al., *GMD*, in prep.

WRF-CMAQ vs. NACC-CMAQ $PM_{2.5}$

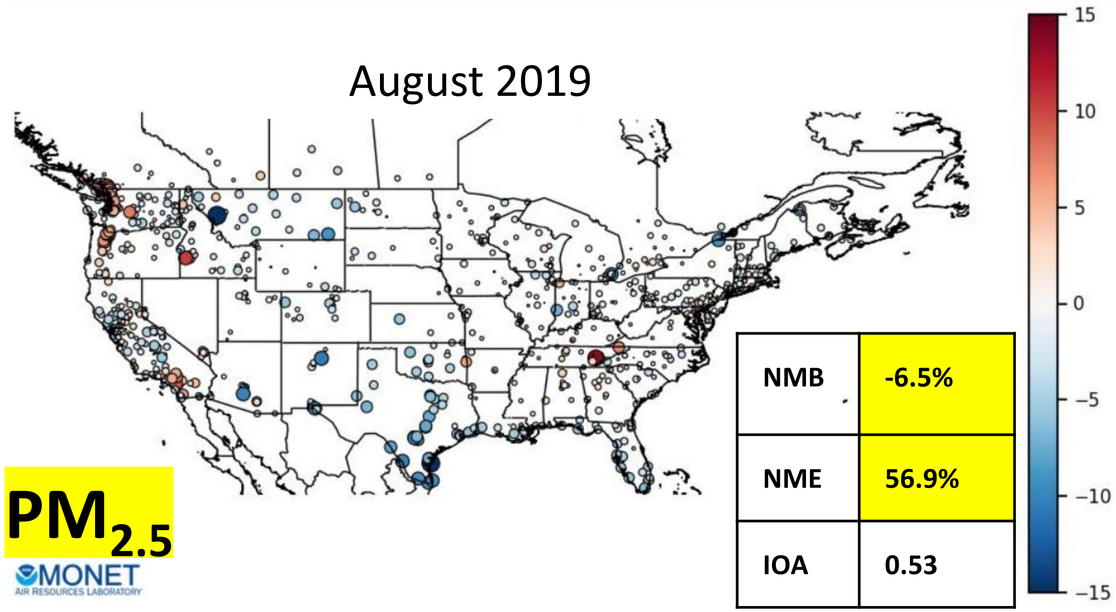
GFSv16/WRFv4.0.1-CMAQv5.3.1



NMB	+8.7%
NME	59.3%
IOA	0.55

WRF downscaling with different GFS vs. WRF physics to CMAQ

GFSv16→NACC-CMAQv5.3.1



NMB	-6.5%
NME	56.9%
IOA	0.53

No downscaling, direct GFSv16 physics interpolation to CMAQ

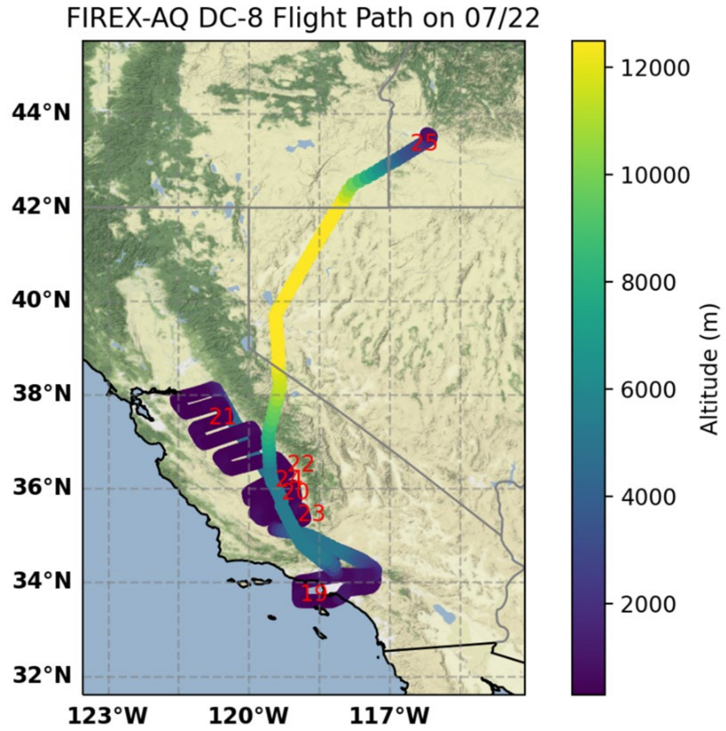
Demonstrates generally improved model performance of NACC-CMAQ compared to WRF-CMAQ.

Tang et al., *GMD*, in prep.

WRF-CMAQ vs. NACC-CMAQ

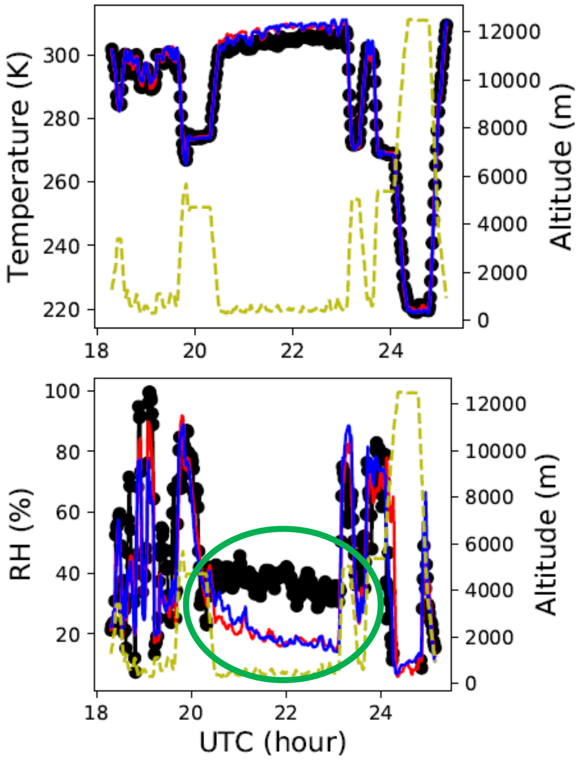
Non-Wildfire Event During FIREX-AQ

Flight Path



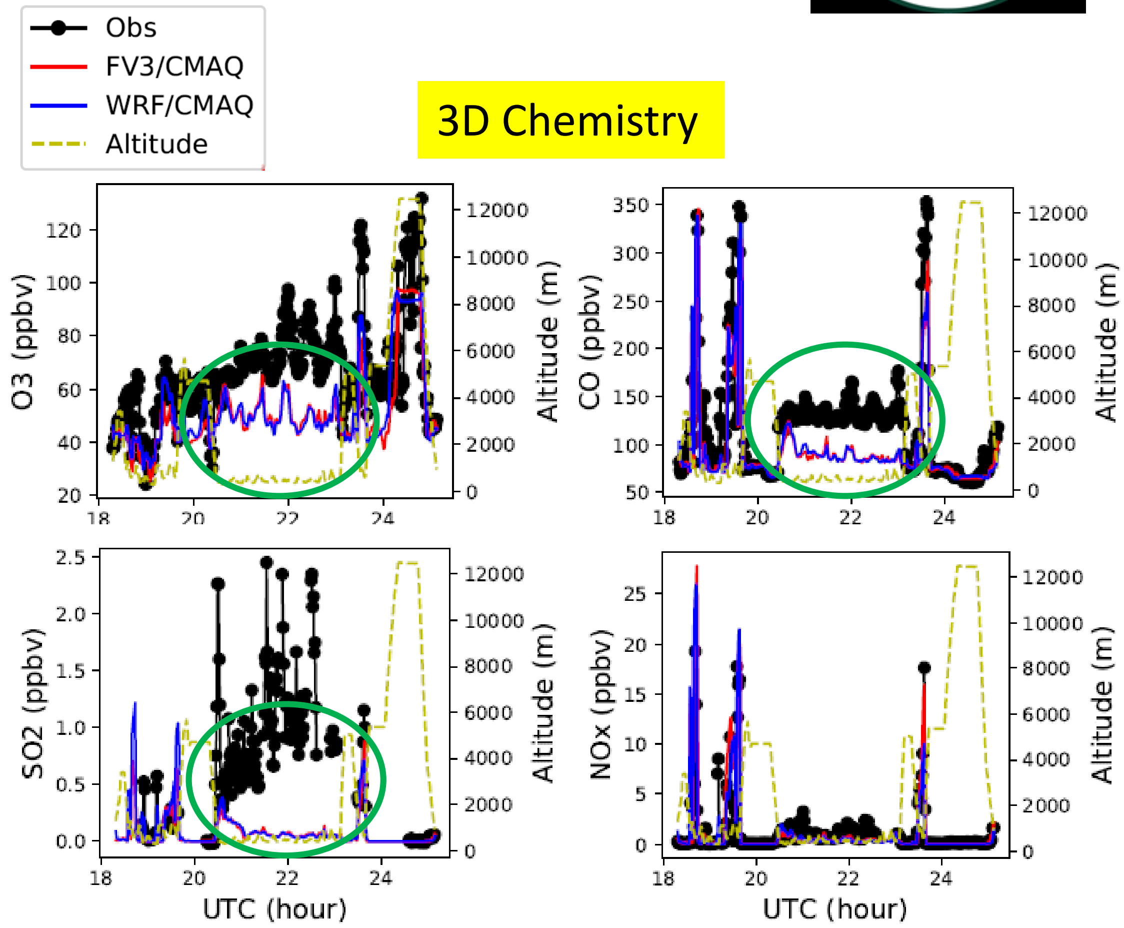
DC-8 Flight over the central California valley.

3D Meteorology



GFSv16 and WRF are similar Temp and RH, but both have dry bias in boundary layer.

3D Chemistry



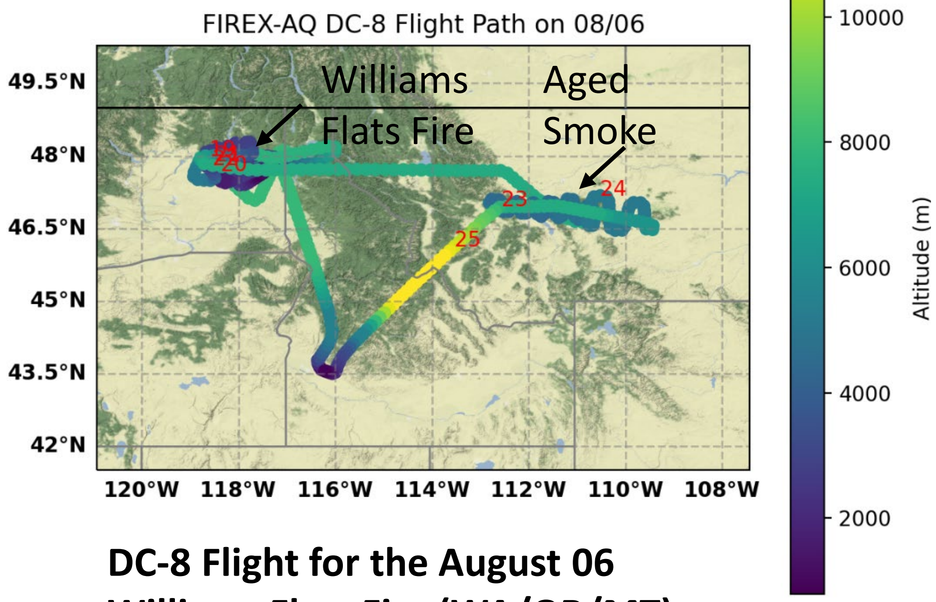
NACC-CMAQ and WRF-CMAQ capture gas chemistry signals well, but both underestimate O_3, CO, and SO_2 in similar regions as dry bias in boundary layer.

Tang et al., *GMD*, in prep.

WRF-CMAQ vs. NACC-CMAQ

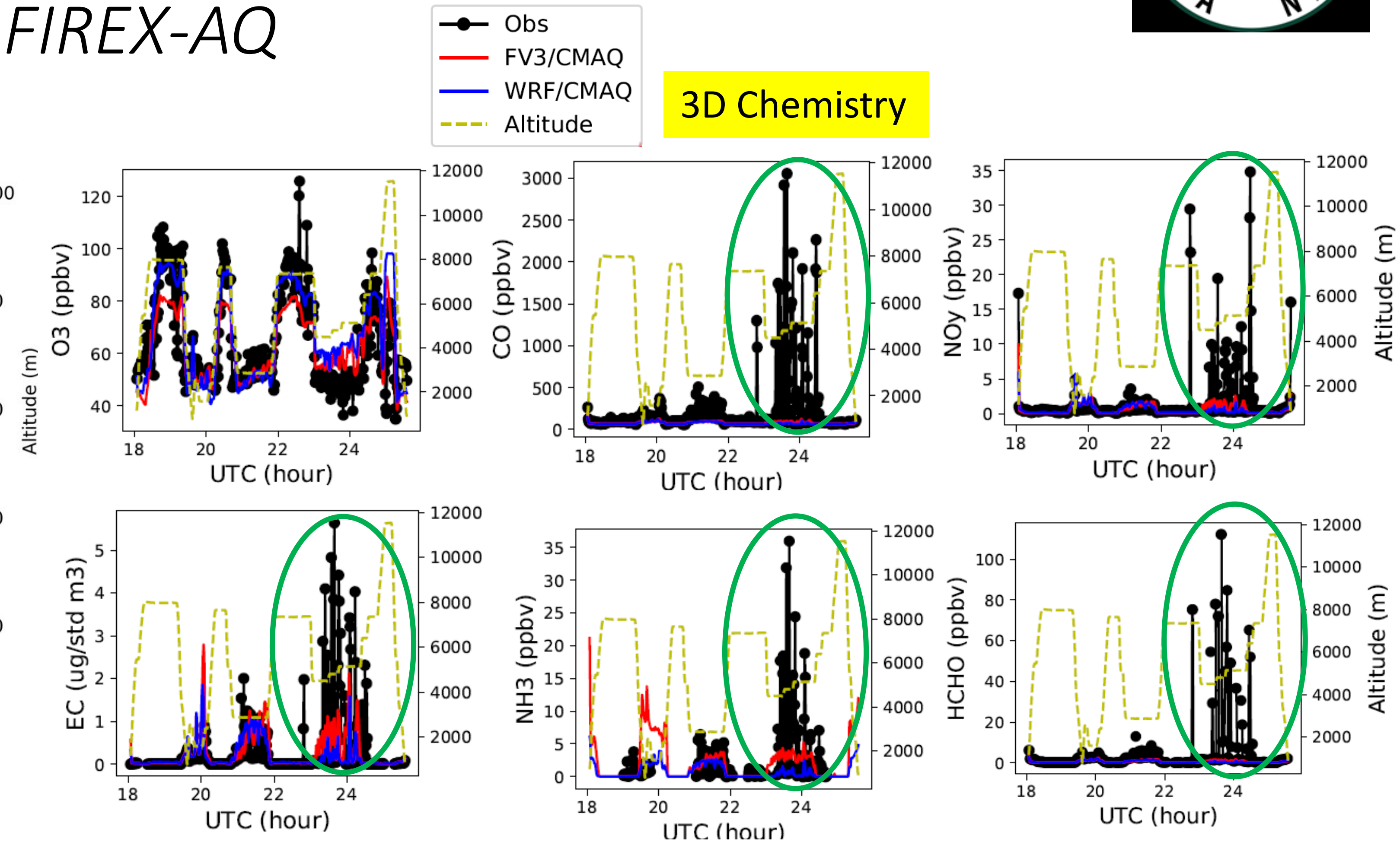
Wildfire Event During FIREX-AQ

Flight Path



DC-8 Flight for the August 06 Williams Flats Fire (WA/OR/MT).

3D Chemistry



Overall predictions are good for O_3 and EC near source and capture timing, but larger underpredictions downwind in the aged smoke.

Tang et al., *GMD*, in prep.

Summary

- An advanced FV3-GFSv16/NACC-CMAQv5.3.1 AQF system is developed.

- The NACC-CMAQ system has advantages over the prior NAQFC.
  -Tested with in-canopy effects on chemistry and scalar transport (reduces ozone overpredictions).

- NACC-CMAQ became operational at NWS/NOAA on **July 20, 2021**.

- NACC-CMAQ may form a new research option to avoid WRF downscaling.

- “NACC-in-the-cloud” for user-defined GFS-driven CMAQ is being developed.

- NACC-CMAQ performance is consistent or better than WRFv4.0.3-CMAQv5.3.1.
  -Compared against 2019 FIREX-AQ campaign for both 3D wildfire and non-wildfire cases.

Acknowledgments and Data Availability

- We would like to acknowledge our colleagues at the U.S. EPA for years of development and collaboration on the PREMAQ and MCIP systems that were pivotal to the development of NACC.

- 2D and 3D GFSv16 and NAQFC output are archived at NCEP/NOAA and can be made available by request (…soon on the AWS Cloud).

- The operational NAQFC output may also be viewed at:

https://airquality.weather.gov/ (NWS Air Quality Forecast Guidance)

https://digital.mdl.nws.noaa.gov/airquality/# (Interactive Air Quality Maps)

- The NACC-CMAQ (Campbell et al.) manuscript has been submitted for publication in GMD, and will hopefully be available soon.