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

Patrick C. Campbell\textsuperscript{1,2}, Youhua Tang\textsuperscript{1,2}, Pius Lee\textsuperscript{1}, Barry Baker\textsuperscript{1,2}, Daniel Tong\textsuperscript{1,2}, Rick Saylor\textsuperscript{1}, Ariel Stein\textsuperscript{1}, Jianping Huang\textsuperscript{3,4}, Ho-Chun Huang\textsuperscript{3,4}, Edward Strobach\textsuperscript{3,4}, Jeff McQueen\textsuperscript{3}, Ivanka Stajner\textsuperscript{3}, Jameese Sims\textsuperscript{5}, Jose Tirado-Delgado\textsuperscript{5,6}, and Youngsun Jung\textsuperscript{5}, Fanglin Yang\textsuperscript{3}, Tanya L. Spero\textsuperscript{7}, Robert C. Gilliam\textsuperscript{7}, Michael Neish\textsuperscript{8}, and Paul Makar\textsuperscript{8}

1. NOAA Air Resources Laboratory (ARL), College Park, MD.
2. Center for Spatial Information Science and Systems, George Mason University, Fairfax, VA.
3. NOAA National Centers for Environmental Prediction (NCEP), College Park, MD
4. I.M. Systems Group Inc., Rockville, MD
5. NOAA NWS/STI
6. Eastern Research Group, Inc (ERG)
7. U.S. Environmental Protection Agency, Research Triangle Park, NC
8. Environment and Climate Change Canada (ECCC)
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.

Campbell et al., *GMD*, submitted
The Advanced NAQFC: NACC-CMAQ

Satellite Data Vegetation Inputs
VIIRS LAI & GVF

Soil Data Inputs
SoilGrids
Clay, Sand, & Silt

GFSv16 with FV3 Dynamic Core
Finite-volume cubed sphere grid

The NOAA-EPA Atmosphere-Chemistry Coupler (NACC)
Parallelized IO

Aerosol Boundary Conditions
NOAA GEFS-Aerosol
Dust & Smoke

Interpolation methods

CMAQ v5.3.1
CB6-Aero7
“State-of-the-science”

72-hr 3D Chemical Predictions & Bias Correction (e.g. Ozone, PM)

NEIC 2016v1 Anthro. Emissions
BiDi-NH$_3$ fluxes
Frost switch

BEISv3.6.1-BELD5 Bio. Emissions

Intermittent Emission Sources:
Fengsha Windblown Dust
GBBEPx Wildfire Smoke

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

**Ozone**
- Sep 2020: Hourly $O_3$ (ppb)
- NAQFC: NMB 23.16, NME 36.34, Corr 0.70, IOA 0.78
- NACC-CMAQ: NMB 15.28, NME 33.43, Corr 0.72, IOA 0.82

**PM$_{2.5}$**
- Jan 2021: Hourly PM$_{2.5}$ ($\mu g$ m$^{-3}$)
- NAQFC: NMB 0.86, NME 65.47, Corr 0.36, IOA 0.58
- NACC-CMAQ: NMB -4.79, NME 61.33, Corr 0.41, IOA 0.63

Campbell et al., GMD, submitted
Model Evaluation Versus Prior NAQFC

Average O₃ Correlation:
Prior NAQFC = 0.67
NACC-CMAQ = 0.73

Average PM₂.₅ 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).

- 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):

\[
P(\theta) = e^{-\frac{G(\theta) \frac{\Omega(\theta)}{\cos(\theta)} \text{LAI}}{}}
\]

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).

Modified turbulent diffusivity is scaled to 1st model layer and depends on variance in Eulerian vertical velocity \(\sigma_{z}^{2}\) and turbulent length scale \(T_{L}\):

\[
K_{\text{can}}(z) = \frac{K_{\text{mod}}(z)}{K_{\text{est}}(\frac{z}{h_{c}})} \frac{K_{\text{est}}(\frac{z}{h_{c}})}{K_{\text{est}}(\frac{z}{h_{c}})},
\]

\[
K_{\text{est}}\left(\frac{z}{h_{c}}\right) = \sigma_{w}^{2}\left(\frac{z}{h_{c}}\right) T_{L}\left(\frac{z}{h_{c}}\right),
\]

\[
T_{L}\left(\frac{z}{h_{c}}\right) = \frac{h_{c}}{u^{*}} \left[ 0.256 \left( \frac{z - 0.75h_{c}}{h_{c}} \right) + 0.492 \exp \left( - \frac{0.256 z/h_{c}}{0.492} \right) \right]
\]
Impacts of In-Canopy Effects on Ozone

August 2019 Ozone (ppb)
Canopy – No Canopy
Max ~ 15 ppb

Population Density
Forest Fraction

Forest Canopy Height Leaf Area Index Clumping Index

Conditions for contiguous forest canopy: FCH > 10 m & LAI > 0.1 & FRT > 0.5 & POP < 10000 people/10km² & 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

August 2019 Simulation: 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

August 2019 Simulation: 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.
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

August 2019

WRF downscaling with different GFS vs. WRF physics to CMAQ

<table>
<thead>
<tr>
<th></th>
<th>NMB</th>
<th>NME</th>
<th>IOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>+15.9%</td>
<td>32.2%</td>
<td>0.81</td>
</tr>
</tbody>
</table>

GFSv16 → NACC-CMAQv5.3.1

August 2019

No downscaling, direct GFSv16 physics interpolation to CMAQ

<table>
<thead>
<tr>
<th></th>
<th>NMB</th>
<th>NME</th>
<th>IOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>+5.6%</td>
<td>28.6%</td>
<td>0.86</td>
</tr>
</tbody>
</table>

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**

WRF downscaling with different GFS vs. WRF physics to CMAQ

<table>
<thead>
<tr>
<th></th>
<th>NMB</th>
<th>NME</th>
<th>IOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>+8.7%</td>
<td>59.3%</td>
<td>0.55</td>
</tr>
</tbody>
</table>

**GFSv16→NACC-CMAQv5.3.1**

No downscaling, direct GFSv16 physics interpolation to CMAQ

<table>
<thead>
<tr>
<th></th>
<th>NMB</th>
<th>NME</th>
<th>IOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>-6.5%</td>
<td>56.9%</td>
<td>0.53</td>
</tr>
</tbody>
</table>

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

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

NACC-CMAQ and WRF-CMAQ capture gas chemistry signals well, but both underestimate O₃, CO, and SO₂ in similar regions as dry bias in boundary layer.

DC-8 Flight over the central California valley.

Tang et al., GMD, in prep.
Overall predictions are good for O₃ 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/](https://airquality.weather.gov/) (NWS Air Quality Forecast Guidance)
  

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