The GFDL Variable-Resolution Global Chemistry-Climate Model for Research at the Nexus of US Climate and Air Quality Extremes

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A cross-division development effort at GFDL started in 2021

W Division: M. Zhao, L. Harris, S. Garner, L. Zhou
Modeling S: N. Zadeh and many others
DOE/PNNL: S. J. Smith and H. Ahsan

Paper: J. of Advances in Modeling Earth Systems, 2023MS003984
Challenges in Predicting U.S. Air Quality in a Changing Climate

Challenges:
- More frequent hot & dry weather
- Large land-biosphere feedbacks
- Transported plus local pollution
- Diverse air basins & complex terrain

Limitations in current tools:
- X Prescribed vegetation characteristics
- X Issues with imposing global model BCs on regional models
- X The “stationarity” assumption in statistical downscaling

Future:
- ✓ Need a seamless modeling system that can provide detailed info over a targeted region, while still integrating global Earth system components
- ✓ Increased coupling of atmospheric composition with dynamic vegetation

Lin et al. (2012ab, 2015ab, 2017, 2019, 2020); Jaffe et al. (2018, 2020); Ginoux et al. (2012); Xie et al. (2022)
The GFDL Variable-Resolution Global Chemistry-Climate Model (AM4VR) for Research at the Nexus of U.S. Climate and Air Quality Extremes

Key Features:
- GFDL FV3 Dynamical Core with regional grid refinement to 13 km over CONUS; sub-grid tiles for land surface heterogeneity
- Retuned moist physics from GFDL AM4.0
- Comprehensive gas-phase & aerosol chemistry from AM4.1
- High-resolution anthropogenic emissions from CEDS-2021-04-21 (0.1°x0.1°), 1980-2020
- Interactive dust emissions from a dynamic vegetation land model (LM4.0), with retuned params
- Interactive dry deposition of gases, responding to hydroclimate, land cover, and photosynthesis in a dynamic vegetation model
- Revised interactive BVOC emissions (MEGAN2.1), with revised hi-res emission potential maps and land cover data
- Revised biomass burning emissions from GFED4s (0.25°x0.25°), with reactive nitrogen partitioning, increased OVOCs, and MISR injection height

1990-2020 AMIP simulations with prescribed ocean
50% of the computational cost for a 25 km uniform-res grid

Illustrated by Linjiong Zhou

Lin M. et al. [JAMES, 2023MS003984]
AM4VR maintains a good simulation of global-scale circulation and climate comparable to AM4.1 (CMIP6) at uniform 100 km resolution.
Marked improvements in U.S. regional precipitation patterns

1990-2020 ANN Precip [mm/day]

- Notably reducing the central US dry bias that has persisted in many generations of weather forecast and climate models.
Improved skill in simulating the central US warm-season precipitation from mesoscale convective systems

- Limited skill from recent models at 25 km resolution, e.g. DOE E3SM (Tang et al., 2019; 2023); CMIP6 (Dong et al., 2023)

AM4VR at 13 km resolution exhibits:
→ superior fidelity in representing the nocturnal peak of precipitation driven by mesoscale convective systems
→ reduced drizzling bias and increased rainfall extremes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IMERG OBS</th>
<th>AM4VR 13 km</th>
<th>AM4 25 km</th>
<th>AM4 100 km</th>
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<tr>
<td>q50</td>
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<td>q90</td>
<td>6.9</td>
<td>6.9</td>
<td>5.2</td>
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</table>

Seasonal cycle

Diurnal cycle (JJAS)

Daily distribution (JJAS)
Improved precipitation affects ozone removal by vegetation

**JJAS Precipitation Bias**

100 km (C96 – OBS)

$ r = 0.80$

$\text{BIAS} = -0.39$

$\text{RMSE} = 0.97$

13 km (AM4VR – OBS)

$ r = 0.90$

$\text{BIAS} = 0.01$

$\text{RMSE} = 0.63$

**Difference in JJA daytime $V_d [O_3]$**

JJA daytime $V_d [O_3]$ in AM4VR

OBS (Table 1 in Lin et al., GBC2019)

Lin M. et al. [JAMES, 2023MS003984]
Reduced ozone removal by drought-stressed vegetation worsens ozone air pollution extremes during heatwaves

- The Wesely scheme (used in CMAQ/WRF-Chem/GEOS-Chem) does not account for stomatal closure induced by soil drying or rising atmospheric CO$_2$ concentrations.
  - A new, mechanistic scheme in GFDL models yields process insights.
  - Offer novel opportunities to study vegetation feedbacks in future climate.

Lin M. et al. (Nature Climate Change, 2020; GBC2019)
Summer ozone pollution in the western US

Lin M. et al. [JAMES, 2023MS003984]

Improved representation of:
1) air pollution meteorology
2) urban-rural chemical regimes
3) BVOC emissions
4) drought
5) ozone removal by vegetation

MDA8 O₃ [ppb]

Lin M. et al. [JAMES, 2023MS003984]
Winter Haze and Formation of Tule Fog in the Central Valley

- Strong temperature inversion
- \(\text{NH}_4\text{NO}_3\) aerosol as an efficient CCN

Impacts from large-scale circulation and climate change?

Lin M. et al. [JAMES, 2023MS003984]
ENSO → Southwest US Hydroclimate and Dustiness

La Niña

AM4VR driven by observed SSTs captures SWUS dust variability, implying seasonal forecast potential
Impacts of local & transported wildfire plumes on US urban air quality

PM$_{2.5}$ (μg/m$^3$) in Pacific Northwest, Aug-Sep

Xie Y. and Lin M. et al. (PNAS 2022); Lin M. et al. (in prep)
Improved representation of fire weather

Lin M. et al. [JAMES, 2023MS003984]
TAKE-HOME MESSAGE:
Towards seamless prediction of climate – air quality interactions

- Integrating the global Earth System components within a seamless variable-resolution framework
- Increased coupling and interactivity of atmospheric composition with land-biosphere
- Improved representation of US regional precipitation, drought, and air quality extremes

→ Develop seasonal air quality forecasting
→ Multidecadal projections from global to urban scales
→ Impact-oriented research

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Lin M. et al. [J. of Advances in Modeling Earth Systems, 2023MS003984]
AM4VR features vastly improved representation of aerosols from AM4.1 CMIP6 simulation

- Improved representation of biogenic VOC emissions and secondary organic aerosols
- Improved representation of dust
- Improved representation of nitrate aerosols due to interactive dry deposition of nitric acid + NH$_3$ to land

Midwestern US

![Graph showing NH$_4$NO$_3$ concentration over months]