Advancements in the National Air Quality Forecast Capability

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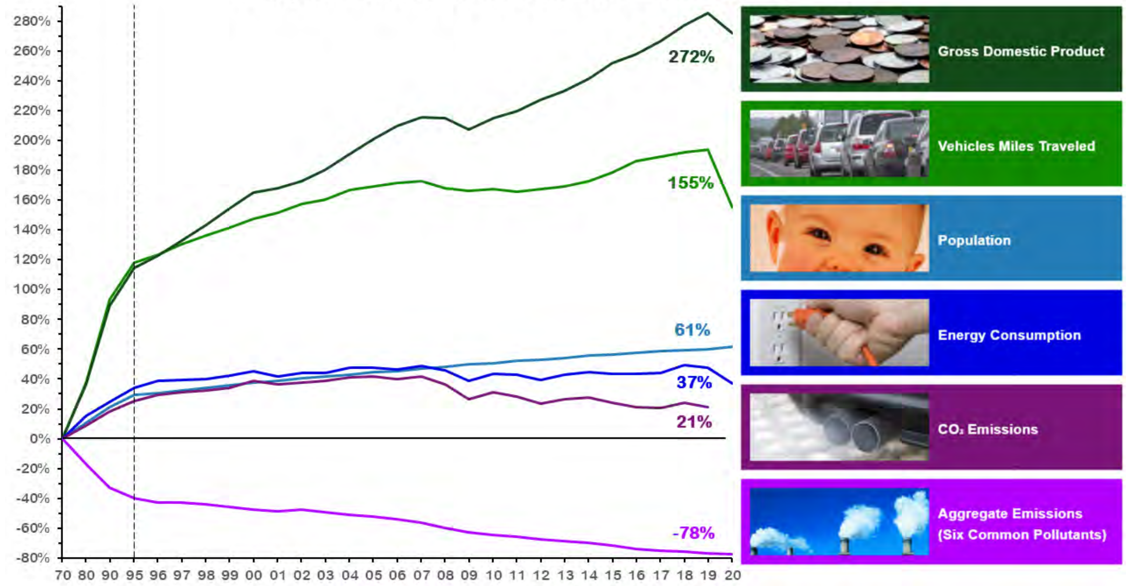
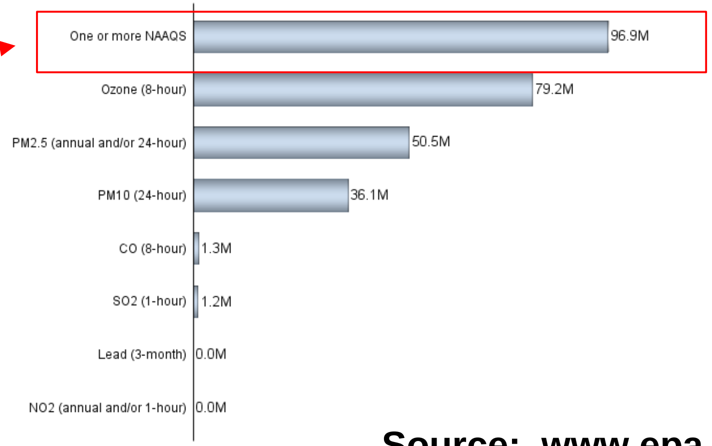
March 22, 2022

The Nation’s Air Quality: Why do we care?

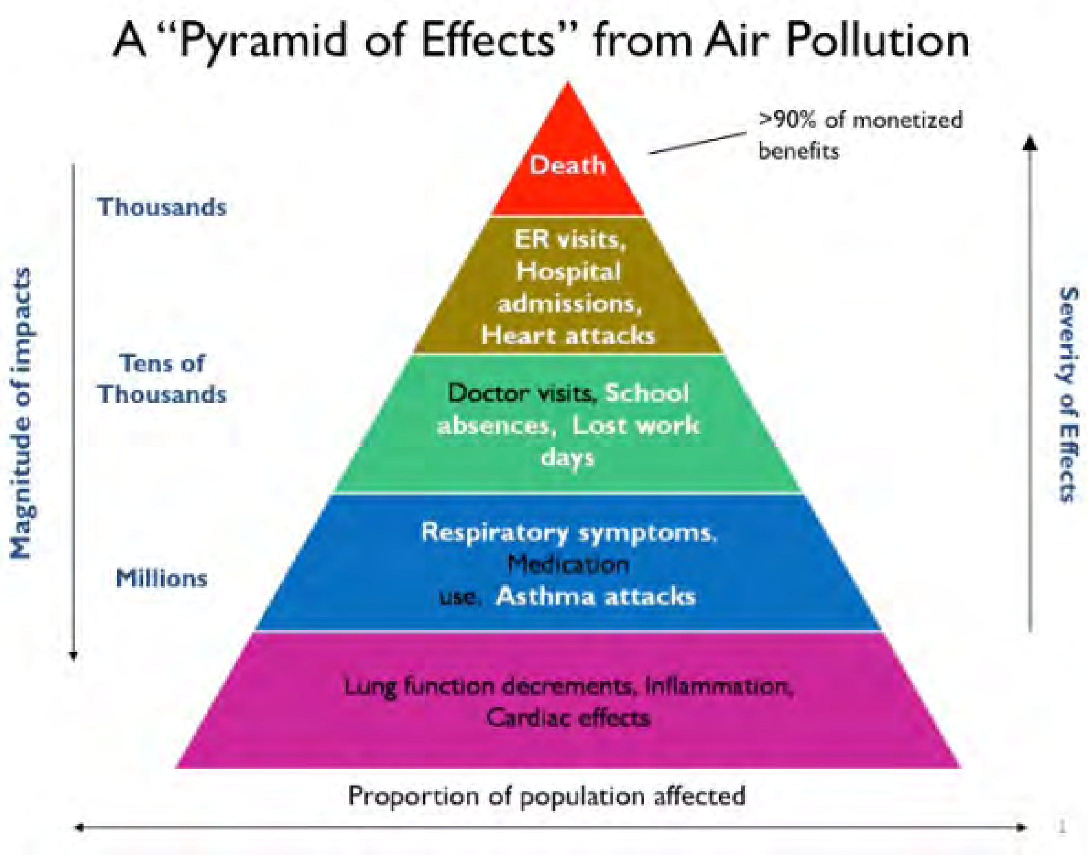
Comparison of Growth Areas and Emissions, 1970-2020



Number of People Living in Counties with Air Quality Concentrations Above the Level of the NAAQS in 2020



~ 100 million people in the U.S. still live in areas with poor air quality.



Outdoor air pollution is responsible for ~ 107,000 early deaths and ~ $886 billion each year in the U.S. (Goodkind et al., *PNAS*, 2019)

Source: www.epa.gov

The National Air Quality Forecasting Capability (NAQFC)

Overview

The NAQFC develops and implements operational air quality forecast guidance for the U.S., thus improving the lives of Americans and saving billions of dollars per year.

Vision

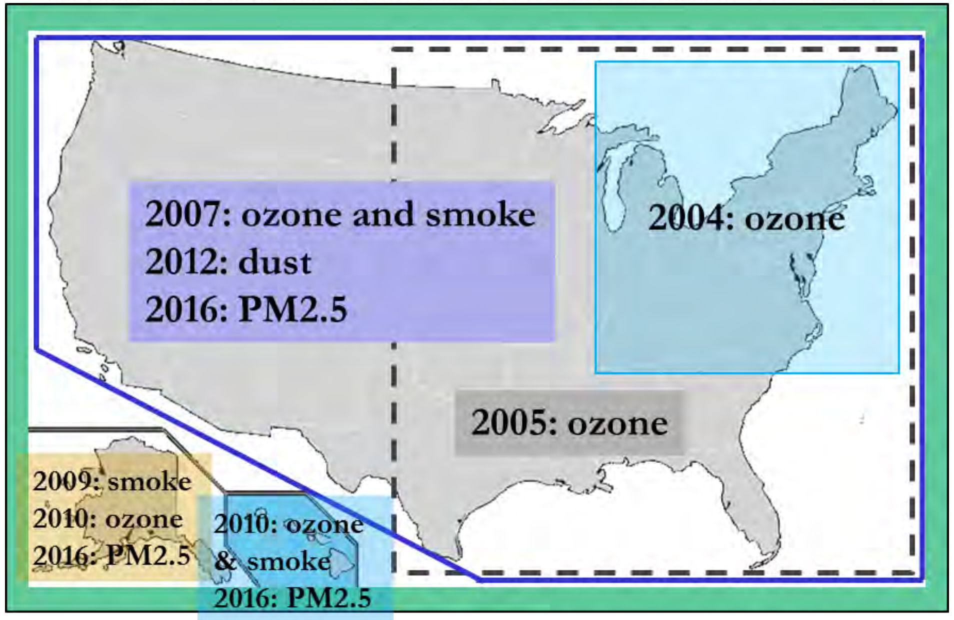
The NAQFC provides the U.S. with ozone, particulate matter and other pollutant forecasts with enough accuracy and advance notice to take action to prevent or reduce adverse effects.

Strategy

Multi-agency collaborative effort to work with federal, state, and local air quality agencies and private sector to develop end-to-end air quality forecast capability for the U.S.

NAQFC Operational Predictions

Products	Implementation Date	Operational Readiness Review Briefings
Ozone (NE U.S.)	September 2004	Initial implementation of ozone predictions for northeastern U.S.
Smoke (CONUS)	February 2007	Initial implementation of smoke predictions for 48 contiguous states
Ozone (CONUS)	September 2007	Expansion of ozone predictions to 48 contiguous states
Smoke (Alaska)	September 2009	Expansion of smoke predictions to Alaska
Smoke (Hawaii)	February 2010	Expansion of smoke predictions to Hawaii (nationwide)
Ozone (nationwide)	September 2010	Expansion of ozone predictions to Alaska and Hawaii (nationwide)
Dust (CONUS)	January 2012	Initial implementation of dust for 48 contiguous states
PM2.5 (nationwide)	February 2016	Initial implementation of PM2.5 predictions nationwide

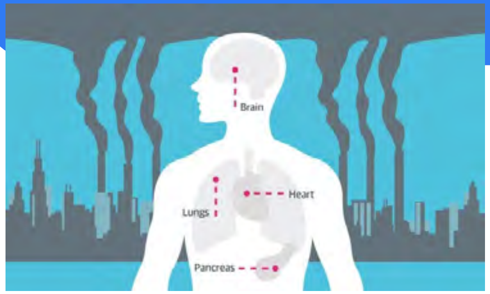


https://www.weather.gov/sti/stimodeling_airquality_predictions

Relevance of the NAQFC to NOAA's Mission

"The Commerce Department's National Oceanic and Atmospheric Administration (NOAA) is dedicated to enhancing national safety, economic security, and environmental stewardship through analysis, ***prediction*** *and research of weather, water and climate-related events."*

Air pollution is dangerous to health and is costly in the U.S.



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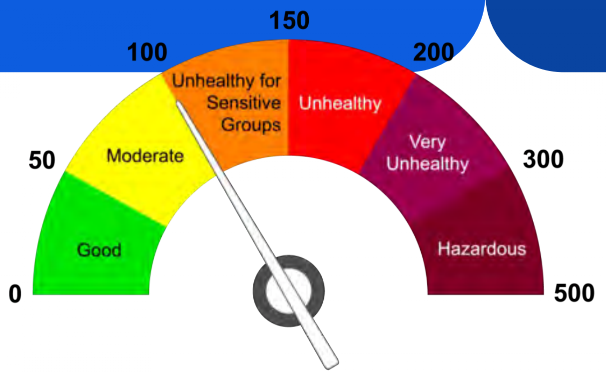
Need for a national air quality forecasting capability.



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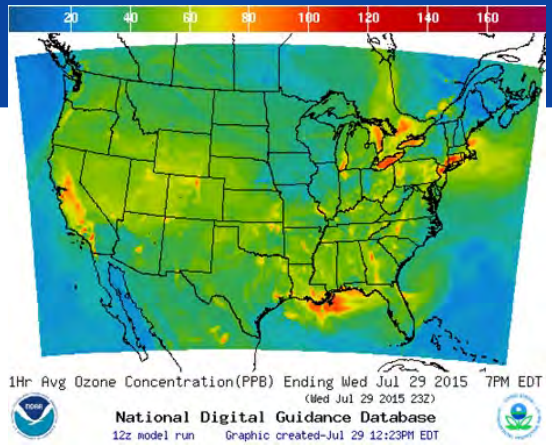
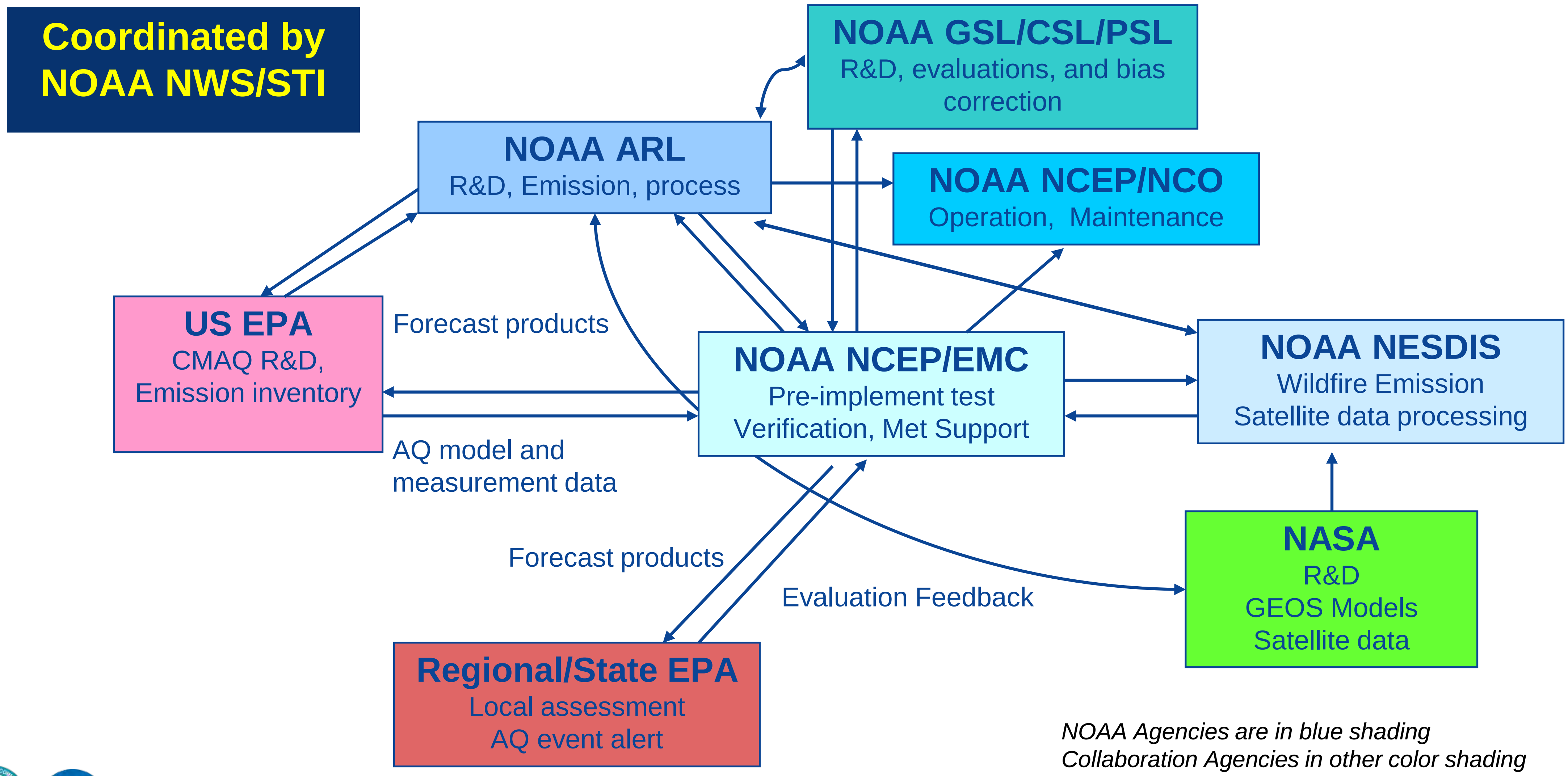
The NAQFC is relevant and thereby improves the lives of Americans while saving billions of dollars per year.

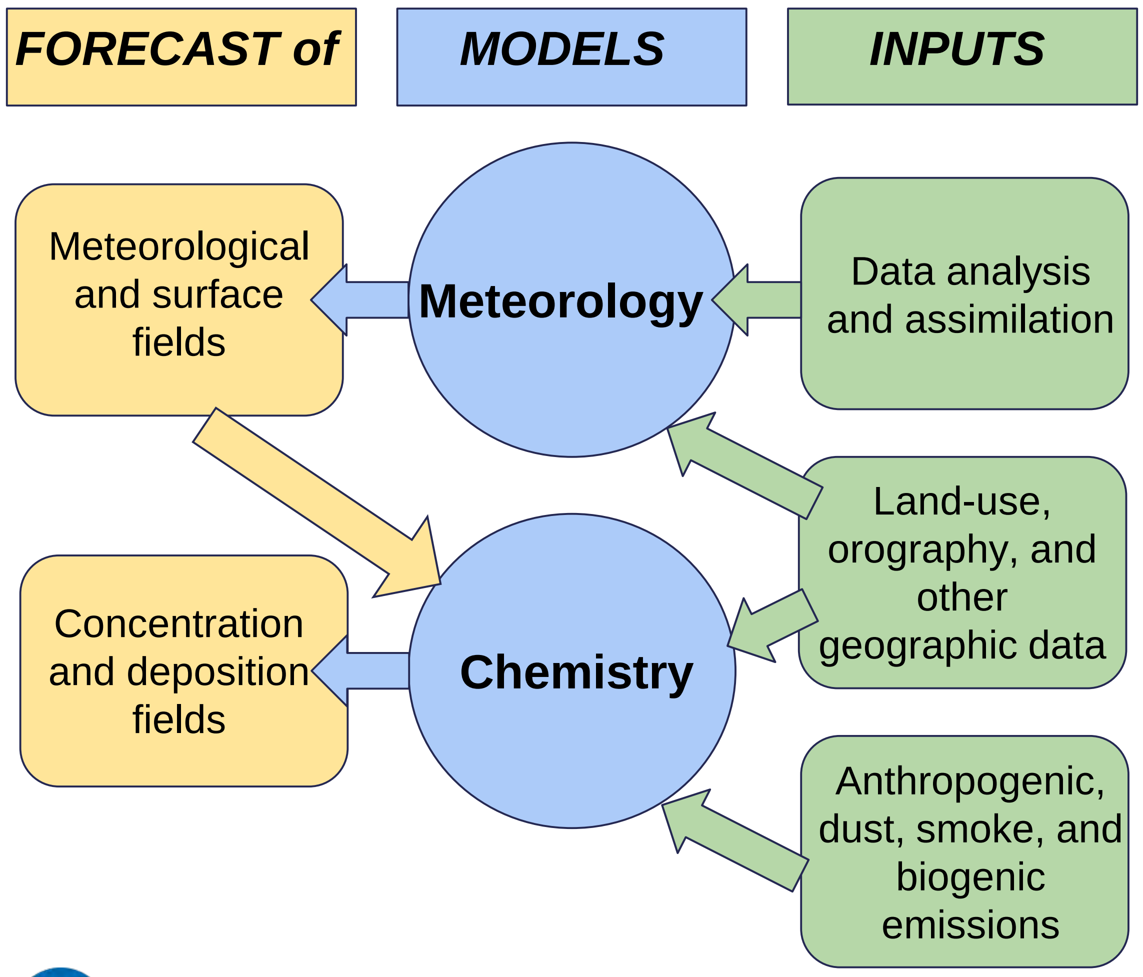


Description of the Multi-Agency NAQFC Collaboration



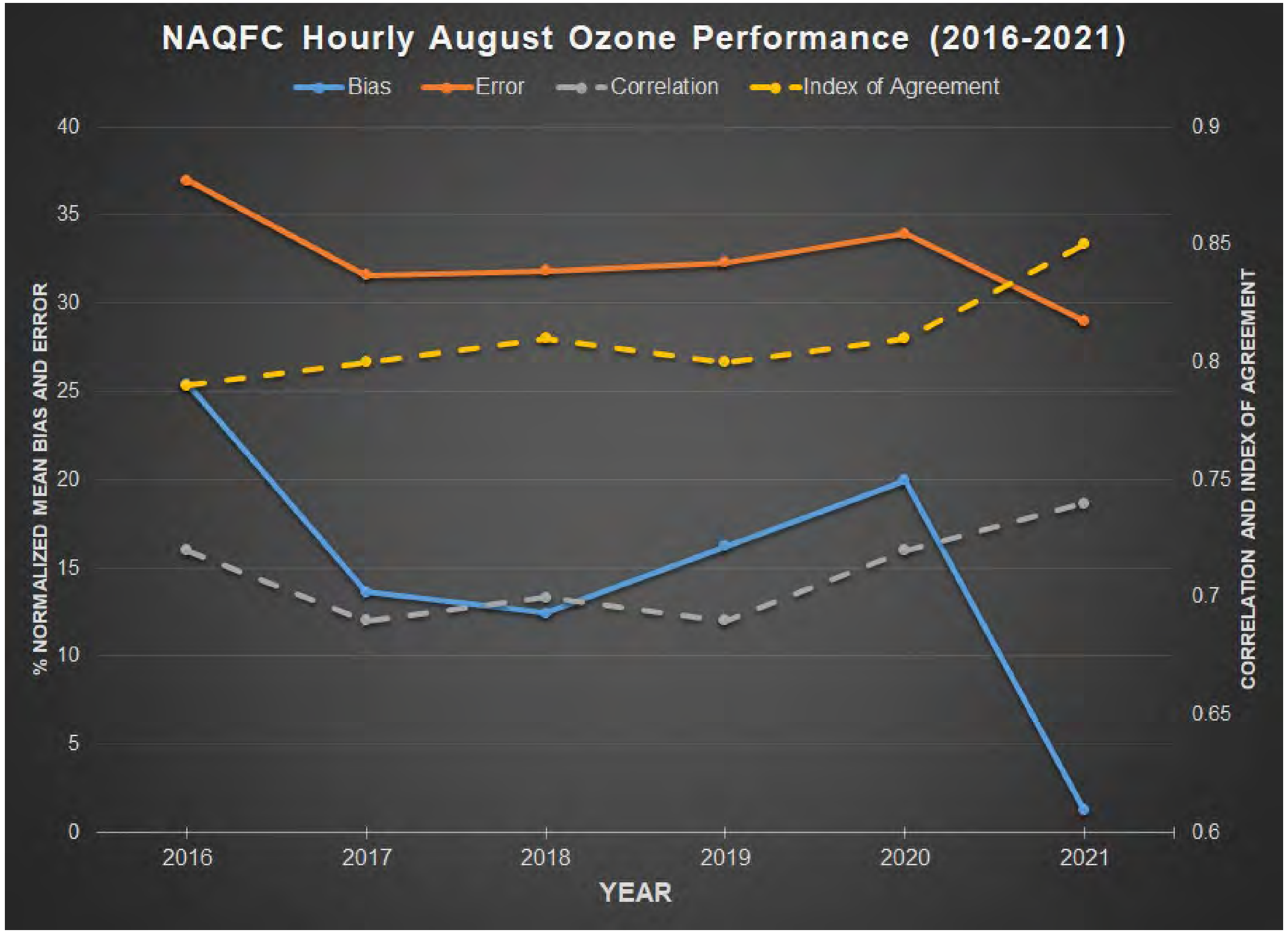
General Overview of the NAQFC Modeling Framework

An "Offline-Coupled" Meteorology and Chemistry Model System



- Meteorology based on NOAA's weather models (e.g., NAM, GFS)
- Chemistry based on the U.S. EPA's Community Multiscale Air Quality (CMAQ) model
- First implemented into operations in September 2004
- Current configuration (based on GFSv16) is at 12 km, 35 levels, to 72 hrs, 4x/day
- 2D and 3D air quality predictions for ozone, PM, dust, and smoke

Overview of NAQFC Performance Progress from 2016-2021



Observations based on the U.S. EPA AirNow Network
Results are daily (24-hr forecast) averages over the entire CONUS domain
Results are based on raw model output (not bias corrected)

NAQFC Progress for Hourly Ozone Predictions

- The model bias (solid blue) and error (solid orange) have generally decreased from 2016-2021.
- The model correlation coefficient (dashed gray) and Index of Agreement (dashed yellow) have generally increased from 2016-2021.

NAQFC Changes by Year (not comprehensive)

- **2016:** Minor CMAQ model updates from v4.6.5 → v4.7.2, and updates to model structure and emissions
- **2017:** Major NAM met model updates to V4 and major CMAQ model update from v4.7.2 → v5.0.2
- **2018:** Moderate updates to both anthropogenic and natural (e.g., wildfire) emissions
- **2019:** Major updates to entire anthropogenic emissions inventory
- **2020:** Minor updates to both anthropogenic and natural point source emissions
- **2021:** Major updates to the entire NAQFC system, i.e., the GFS-driven NACC-CMAQv5.3.1 (see next slides)

NCEP Operational Air Quality Forecast Model Change Log

2021 Multi Model Air Quality Performance Indices (AQPI)

Domain: NAQFC–RAQDPS intersection (Southern Canada and cont. US)

Agency	System	O_3 Jul	O_3 Aug	O_3 Sep	NO_2 Jul	NO_2 Aug	NO_2 Sep	$PM_{2.5}$ Jul	$PM_{2.5}$ Aug	$PM_{2.5}$ Sep
ECCC	RAQDPS	88	86	89	**66**	66	**71**	36	35	45
ECCC	RAQDPS-FW	88	87	89	**66**	66	**71**	70	73	**68**
NOAA	NAQFC	**91**	**90**	**91**	-	-	-	64	67	62
ECMWF	IFS-CAMS	85	85	88	60	60	64	**76**	**75**	66
NASA	GEOS-CF	80	76	83	58	61	63	53	48	43
FMI	IFS-SILAM	85	86	87	65	**67**	68	64	70	65

Analysis Period: 2021/07 - 2021/09
Analysis and slide courtesy of Environment and Climate Change Canada (ECCC)

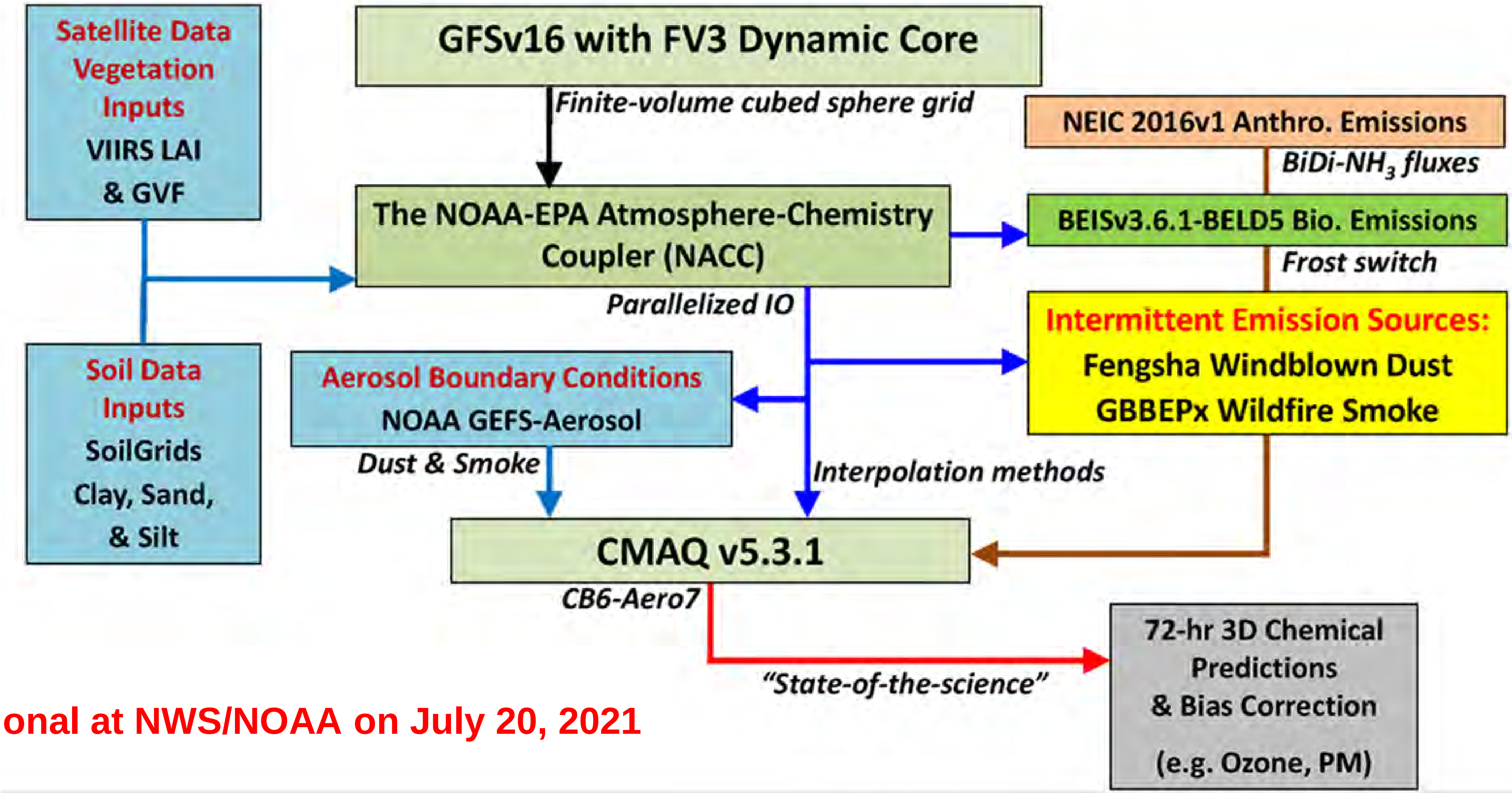
Legend	AQPI (%)
Excellent	[90, 100]
Very Good	[80, 89]
Good	[70, 79]
Acceptable	[60, 69]
Poor	[50, 59]
Very Poor	≤ 49

- O_3: Most systems have a very good performance. NAQFC has the best performance for all three months.
- NO_2: RAQDPS and RAQDPS-FW have the best performance in July and September and IFS-SILAM has the best performance in August.
- $PM_{2.5}$: IFS-CAMS has the best performance in July and August. RAQDPS-FW has the best performance in September. The range of monthly scores is large for this quarter due to wildfires in Western USA and Canada.

NOAA's NAQFC outperforms all other model systems for 2021 ozone forecasts, and achieves the "excellent" level.

$$AQPI[O_3, NO_2, PM_{2.5}] = 100 \cdot avg[\,FAC2, R, 1 - |MFB/2|\,]$$

Description of the Advanced NAQFC at NOAA-ARL



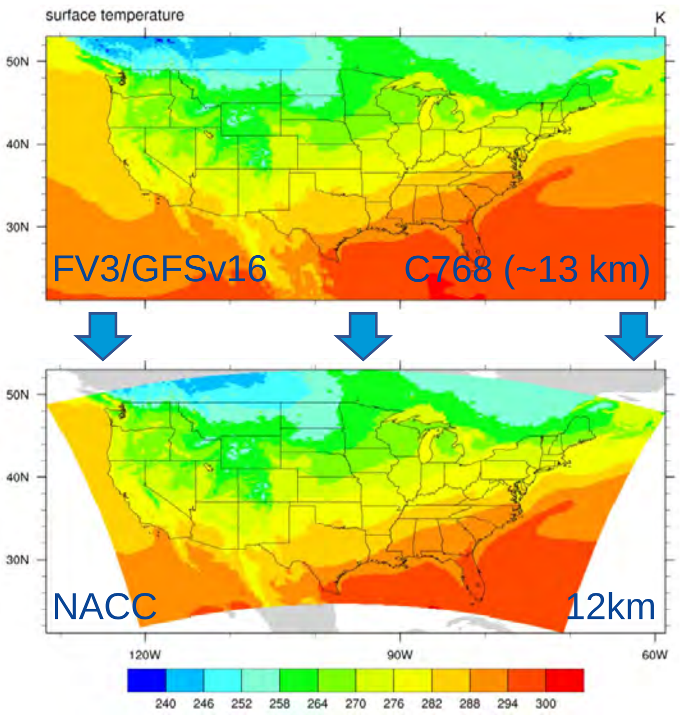
Operational at NWS/NOAA on July 20, 2021

Campbell et al., *GMD*, under review.

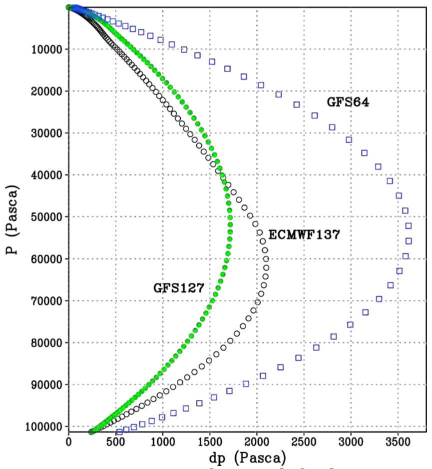
The NOAA-EPA Atmosphere Chemistry Coupler

- The **N**OAA-EPA **A**tmosphere-**C**hemistry **C**oupler (NACC) (i.e., *“knack”: meaning an acquired skill*) is adapted from EPA’s Meteorology-Chemistry Interface Processor (MCIP) version 5 (Otte and Pleim, 2010).

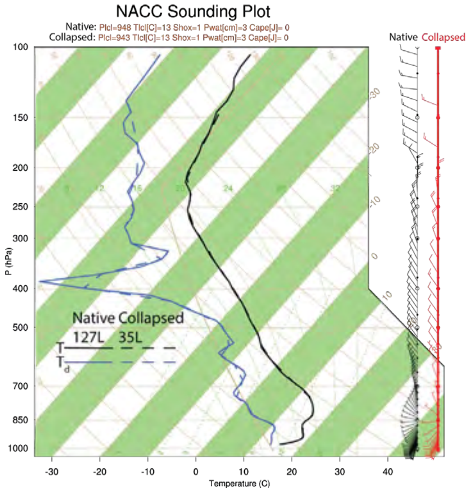
Directly Interpolated Fields



Redefined Vertical Structure



GFSv16 has higher vertical resolution with 127L and thinner 1st layer (20 m thick) than previous GFS.



NACC uses either native or collapsed GFSv16 layers, and there is good agreement in structure.

- NACC is used for NOAA’s latest operational NAQFC and is available to the greater scientific community at: https://github.com/noaa-oar-arl/NACC.

Campbell et al., *GMD*, under review.

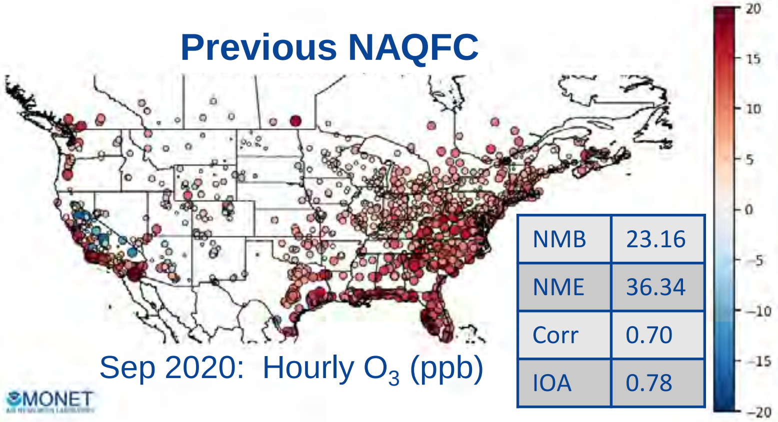
Benefits of the Advanced NAQFC: NACC-CMAQ

- Interfaces NOAA’s global FV3-GFSv16 meteorological to latest CMAQv5.3.1.
- Processes high-resolution satellite vegetation and soil data inputs for CMAQ.
- User-defined vertical layers; run CMAQ with native GFS or collapsed layers.
- Github integration allows for streamlined future updates to NACC-CMAQ.
- Advanced intermittent emissions sources and aerosol boundary conditions.
- NACC parallelization speeds up I/O and is easily portable.
- Direct interpolation of FV3-GFSv16 to CMAQ forms a new research option.

Improved Performance of the Advanced NAQFC: NACC-CMAQ

Summer (September) Surface Ozone

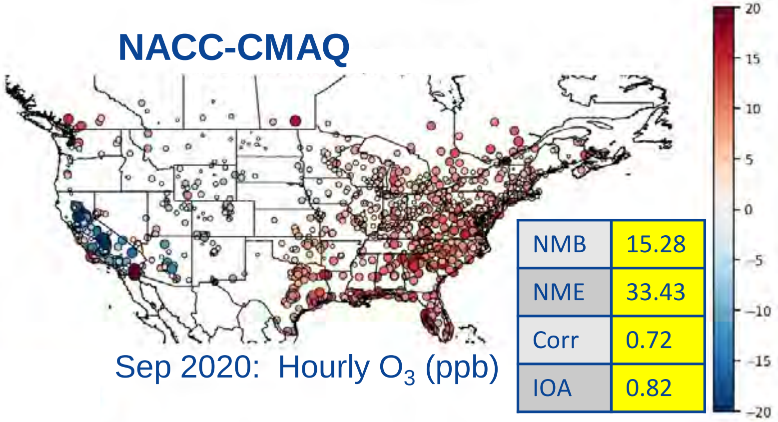
Previous NAQFC



Sep 2020: Hourly O_3 (ppb)

NMB	23.16
NME	36.34
Corr	0.70
IOA	0.78

NACC-CMAQ

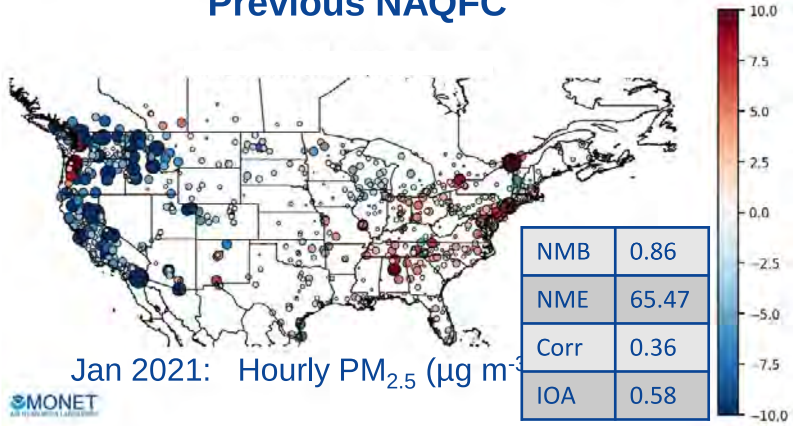


Sep 2020: Hourly O_3 (ppb)

NMB	15.28
NME	33.43
Corr	0.72
IOA	0.82

Winter (January) Surface $PM_{2.5}$

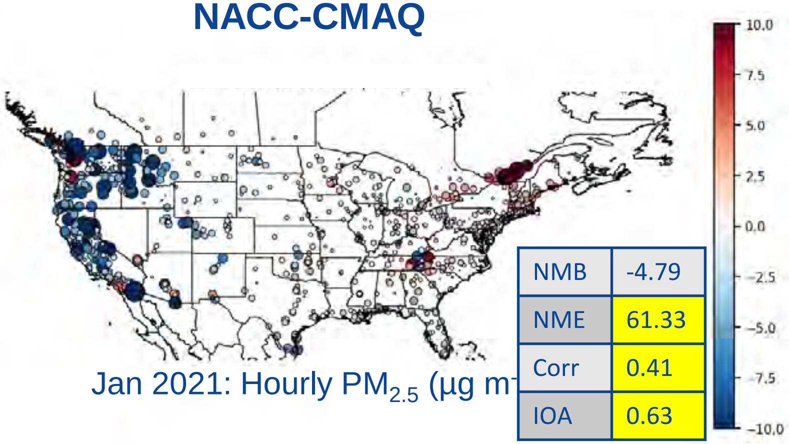
Previous NAQFC



Jan 2021: Hourly $PM_{2.5}$ ($\mu g\ m^{-3}$)

NMB	0.86
NME	65.47
Corr	0.36
IOA	0.58

NACC-CMAQ



Jan 2021: Hourly $PM_{2.5}$ ($\mu g\ m^{-3}$)

NMB	-4.79
NME	61.33
Corr	0.41
IOA	0.63

Overall improved ozone and $PM_{2.5}$ model performance for the updated NAQFC, i.e., NACC-CMAQ, especially in the eastern U.S.

Campbell et al., *GMD*, under review.

Quality and Performance

Operational Implementations and Recognition (not comprehensive)

- Major updates including:

1. Meteorological drivers (e.g., NAMv3 → NAMv4)
2. Chemical model updates (e.g., CMAQv4.6.5 → CMAQv4.7.2 → CMAQv5.0.2)
3. Natural emissions source models (e.g., ARL-developed FENGSHA windblown dust scheme)
4. Anthropogenic emissions inventories (e.g., NEI2005 → NEI2011 → NEI2014v2), including annual point source emissions projections (e.g., Continuous Emissions Monitoring (CEM) data and U.S. DOE projections)

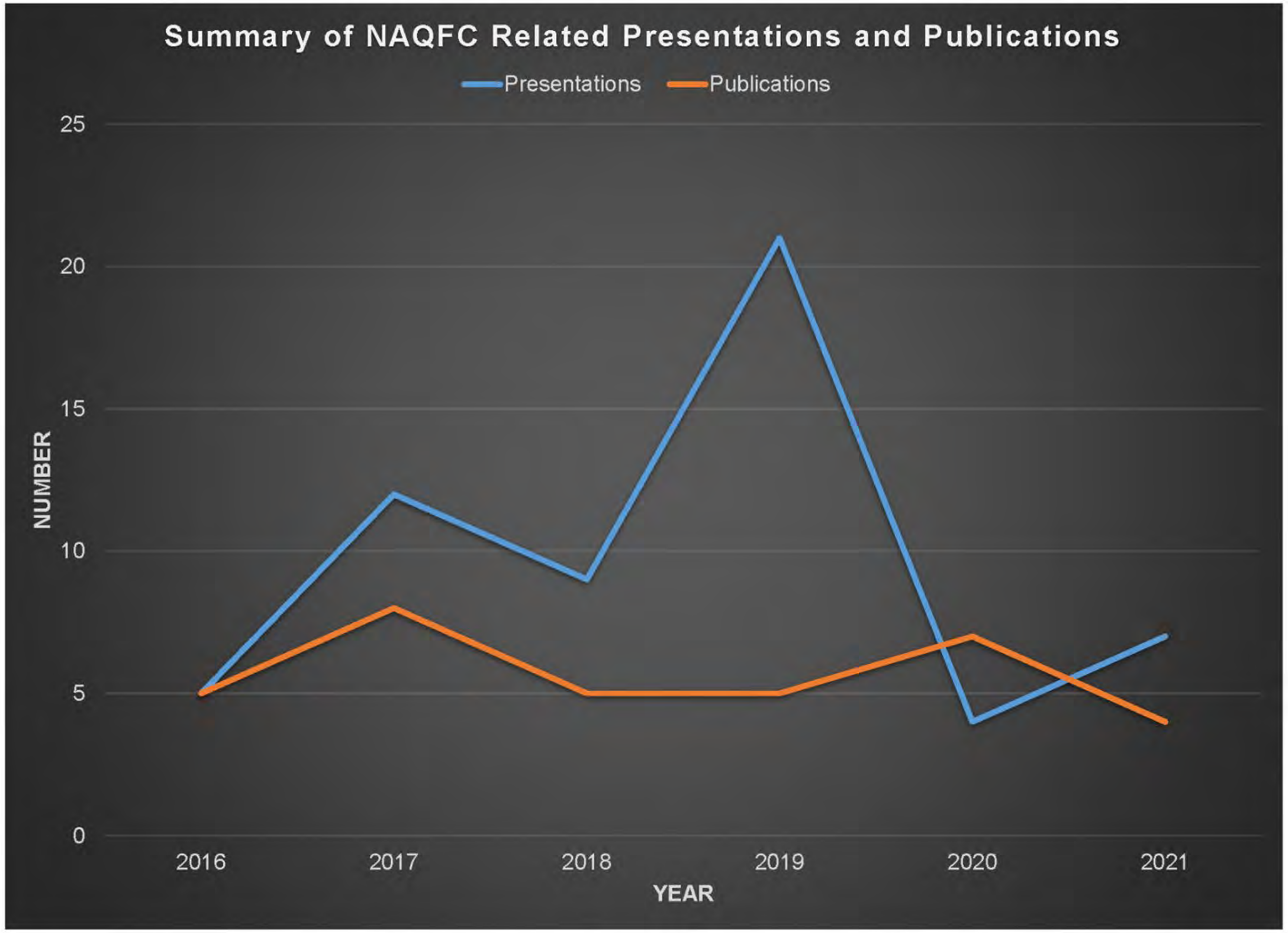
- The advanced NAQFC, based on GFSv16/NACC-CMAQv5.3.1: Updated on July 20, 2021
  NOAA-ARL News Story: NOAA Upgrades Key Air Quality Prediction Model

See the NCEP Operational Air Quality Forecast Model Change Log for a more comprehensive list of implementations.

Awards

- NOAA Administrator's Award in 2019: *"For implementing and upgrading NOAA's Air Quality Forecasting Capability thereby improving the lives of Americans and saving billions of dollars per year."* Drs. Pius Lee and Rick Saylor. ARL Contribution to Air Quality Forecasting Capability Recognized in NOAA Administrator's Awards.
- NOAA Certificate of Commendation in 2020: *"For implementing and upgrading NOAA's Air Quality Forecasting Capability thereby improving the lives of Americans and saving billions of dollars per year."* Dr. Patrick C. Campbell. CISESS Scientists Commended for Air Quality Modeling Work.

Quality and Performance



NAQFC Related Presentations (Blue Line)

- 2016-2021 average = 10 presentations per year
- List of conferences include (not comprehensive):
  Community Multiscale Analysis System Conference
  American Geophysical Union Fall Meeting
  American Meteorological Society Annual Meeting
  International Workshop on Air Quality Forecasting Research
  Meteorology and Climate - Modeling for Air Quality Conference
  NASA Health and Air Quality Applied Sciences Team Meetings
  Annual NOAA General Modeling Meeting and Fair
- Total Number = 34

NAQFC Related Publications (Orange Line)

- 2016-2021 average = 6 publications per year
- List of journals include (not comprehensive):
  AGU Journal of Geophysical Research Letters (*IF=4.720*)
  AGU Journal of Geophysical Research: Atmospheres (*IF=2.799*)
  EGU Geoscientific Model Development (*IF=5.240*)
  AMS Weather and Forecasting (*IF=3.025*)
  Elsevier Atmospheric Environment (*IF=4.012*)
  Journal of the Air & Waste Management Association (*IF=2.906*)
  EGU Atmospheric Chemistry and Physics (*IF=5.414*)
- Total Number = 58

IF = Journal Impact Factor

Detailed list of NAQFC publications and presentations for 2016-2021

Future plans

Continued Development and Improvement of the Advanced NAQFC

- Updating/Evaluating more representative anthropogenic emissions (e.g., projected NEI 2023)
- Refinement of wildfire gas and particulate matter emissions factors, which is also used for supporting RRFS-CMAQ development below
- Further development and tests of in-canopy photolysis and turbulence effects, which is also used for supporting RRFS-CMAQ development below

Rapid Refresh Forecast System (RRFS)-CMAQ

- RRFS-CMAQ development continues – NOAA's Wildfire Supplemental funding
- Machine Learning emulator for CMAQ chemistry under development
- Goal of 3 km horizontal resolution – CONUS domain
- Implementation in NAQFC scheduled for FY24-25
- Near-real-time emissions processing system – ingested satellite and surface data
- Weather-aware emissions – mobile sources, fugitive dust, residential heating, agricultural/ammonia
- Incorporation of canopy effects on chemistry, mixing, emissions and deposition

Detailed List of NAQFC-Related Publications 2016-2021

Quality and Performance

NAQFC Related Publications (Total = 34)

2021

- Campbell, P. C., Y. Tang, P. Lee, B. Baker, D. Tong, R. Saylor, A. Stein, J. Huang, H.-C. Huang, J. McQueen, I. Stajner, J. Sims, J. Tirado-Delgado, Y. Jung, F. Yang, T. Spero, and R. Gilliam (2021). Development and evaluation of an advanced National Air Quality Forecast Capability using the NOAA Global Forecast System version 16. **Geoscientific Model Development**, under review. https://doi.org/10.5194/gmd-2021-316.
- Campbell, P. C., et al., (2021). Impacts of the COVID-19 Economic Slowdown on Ozone Pollution in the U.S. Atmospheric Environment, https://doi.org/10.1016/j.atmosenv.2021.118713.
- Ma, S., D. Tong, L. Lamsal, J. Wang, Y. Tang, R. Saylor, T. Chai, P. Lee, P. C. Campbell, B. Baker, S. Kondragunta, L. Judd, and I. Stajner (2021). Improving predictability of high ozone episodes through dynamic boundary conditions, emission refresh and chemical data assimilation during the Long Island Sound Tropospheric Ozone Study (LISTOS) field campaign. Atmospheric Chemistry and Physics, in press.
- Tang, Y., Bian, B., Tao, Z. Oman, L. D., Tong, D., Lee, P., Campbell, P. C., Baker, B., Lu, C.-H., Pan, L., Wang, J., McQueen, J., Stajner, I., (2021). Comparison of chemical lateral boundary conditions for air quality predictions over the contiguous united states during pollutant intrusion events, Atmospheric Chemistry and Physics, https://doi.org/10.5194/acp-21-2527-2021.

Quality and Performance

NAQFC Related Publications (continued)

<u>2020</u>

- Chen, X., Y. Zhang, K. Wang, D. Q. Tong, P. Lee, Y. Tang, J. Huang, P. C. Campbell, J. T. McQueen, H. O. T. Pye, B. N. Murphy, D. Kang. 2020. Evaluation of the offline-coupled GFSv15-FV3-CMAQv5.0.2 in support of the next-generation National Air Quality Forecast Capability over the contiguous United States. Geoscientific Model Development, Preprint. https://doi.org/10.5194/gmd-2020-272.
- He, H., Liang, X.-Z., Sun, C., Tao, Z., and Tong, D. Q.: The long-term trend and production sensitivity change in the US ozone pollution from observations and model simulations, Atmos. Chem. Phys., 20, 3191–3208, https://doi.org/10.5194/acp-20-3191-2020, 2020.
- Kim, H. C., Kim, S., Lee, S-H, Kim, B-U, Lee, P. (2020). Fine-scale columnar and surface NOx concentrations over South Korea: Comparison of surface monitors, TROPOMI, CMAQ and CAPSS inventory. Atmosphere 2020, 11(1), 101; https://doi.org/10.3390/atmos11010101
- Lee, P., Tong, D., et. al. World Meteorological Organization, Training Materials and Best Practices for Chemical Weather/Air Quality Forecasting, ETR-26; 2020. https://library.wmo.int/doc_num.php?explnum_id=10439
- Li, Y., Tong, D. Q., Ngan, F., Cohen, M. D., Stein, A. F., Kondragunta, S., et al. (2020). Ensemble PM2.5 forecasting during the 2018 Camp Fire event using the HYSPLIT transport and dispersion model. Journal of Geophysical Research: Atmospheres, 125, e2020JD032768. https://doi.org/10.1029/2020JD032768

Quality and Performance

NAQFC Related Publications (continued)

- Pan, L., Kim, H.C, Lee, P., Saylor, R., Tang, Y., Tong, D., Baker, B., Kondragunta, S., Xu, C., Ruminski, M. G., Chen, W., Mcqueen, J., and Stajner, I.: Evaluating a fire smoke simulation algorithm in the National Air Quality Forecast Capability (NAQFC) by using multiple observation data sets during the Southeast Nexus (SENEX) field campaign, Geosci. Model Dev., 13, 2169–2184, https://doi.org/10.5194/gmd-13-2169-2020, 2020.
- Tang, Y., Tong, D. Q., Yang, K., Lee, P., Baker, B., Crawford, A., Luke, W., Stein, A., Campbell, P. C., Ring, A., Flynn, J., Wang, Y., McQueen, J., Pan, L., Huang, J., and Stajner, I.: Air quality impacts of the 2018 Mt. Kilauea volcano eruption in Hawaii: A regional chemical transport model study with satellite-constrained emissions, Atmos. Environ., 227, 117648, https://doi.org/10.1016/j.atmosenv.2020.117648, 2020.

2019

- Battye, W. H., Bray, C. D., Aneja, V. P., Tong, D., Lee, P., Tang, Y. (2019) Evaluating Ammonia (NH3) Predictions in the NOAA NAQFC for Eastern North Carolina Using Ground Level and Satellite Measurements. JGR Atmospheres, 124(14), 8242-8259, https://doi.org/10.1029/2018JD029990
- Dreessen, J., Orozco, D., Boyle, J., Szymborski, J., Lee, P., Flores, A., Sakai, R. K. (2019). Observed Ozone over the Chesapeake Bay Land-Water Interface: The Hart-Miller Island Pilot Project, Journal of the Air & Waste Management Association, 69(11), 1312-1330, https://doi.org/10.1080/10962247.2019.1668497
- Kumar, R., Delle Monache, L., Bresch, J., Saide, P., Tang, Y., Liu, Z., da Silva, A., Alessandrini, S., Pfster, G., Edwards, D., Lee, P., Djalalove, I. (2019). Toward Improving Short-Term Predictions of Fine Particulate Matter Over the United States Via Assimilation of Satellite Aerosol Optical Depth Retrievals. JGR Atmospheres, 124(5), 2753-2773, https://doi.org/10.1029/2018JD029009

Quality and Performance

NAQFC Related Publications (continued)

- Saylor, R. D.; Baker, B. D.; Lee, P.; Tong, D.; Pan, L.; and Hicks, B. B. (2019). The particle dry deposition component of total deposition from air quality models: right, wrong or uncertain? Tellus B: Chemical and Physical Meteorology, 71(1), 1-22, https://doi.org/10.1080/16000889.2018.1550324
- Walker, J.T., G. Beachley, H.M. Amos, J.S. Baron, J. Bash, R. Baumgardner, M.D. Bell, et al. (2019). Toward the improvement of total nitrogen deposition budgets in the United States Sci. Total Environ., 691, pp. 1328-1352, 10.1016/j.scitotenv.2019.07.058

2018

- Bray, Casey D.; Battye, William; Aneja, Viney P.; Tong, Daniel Q.; Lee, Pius; Tang, Youhua (2018). Ammonia emissions from biomass burning in the continental United States. Atmospheric Environment, 187, 50-61. https://doi.org/10.1016/j.atmosenv.2018.05.052
- Geng, Guannan; Murray, Nancy L.; Tong, Daniel; Fu, Joshua S.; Hu, Xuefei; Lee, Pius; Meng, Xia; Chang, Howard H.; Liu, Yang (2018). Satellite-Based Daily PM2.5 Estimates During Fire Seasons in Colorado. JGR: Atmospheres, 123: 8159-8171. https://doi.org/10.1029/2018JD028573
- Kim, H. C.; Lee, S.-M.; Chai, T.; Ngan, F.; Pan, L.; Lee, P. A Conservative Downscaling of Satellite-Detected Chemical Compositions: NO2 Column Densities of OMI, GOME-2, and CMAQ (2018). Remote Sens. 10, 1001. https://doi.org/10.3390/rs10071001
- Lee, P.; Saylor, R.; and McQueen, J. (2018). Air Quality monitoring and forecasting. Atmosphere, 9(3), 89. https://doi.org/10.3390/atmos9030089

Quality and Performance

NAQFC Related Publications (continued)

- McNider, Richard T.; Pour-Biazar, Arastoo; Doty, Kevin; White, Andrew; Wu, Yuling; Qin, Momei; Hu, Yongtao; Odman, Talat; Cleary, Patricia; Knipping, Eladio; Dornblaser, Bright; Lee, Pius; Hain, Christopher; and McKeen, Stuart (2018). Examination of the Physical Atmosphere in the Great Lakes Region and its Potential Impact on Air Quality - Over-Water Stability and Satellite Assimilation. Journal of Applied Meteorology and Climatology. https://doi.org/10.1175/JAMC-D- 17-0355.1

2017

- Bray, C. D., W. Battye, V.P. Aneja, D. Tong, P. Lee, Y. Tang, and J.B. Nowak (2017). Evaluating ammonia (NH 3) predictions in the NOAA National Air Quality Forecast Capability (NAQFC) using in-situ aircraft and satellite measurements from the CalNex2010 campaign. Atmospheric Environment. 163, 65-76 https://doi.org/10.1016/j.atmosenv.2017.05.032
- Chai T., H.C. Kim, Li Pan, P. Lee, and D. Tong (2017). Impact of Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) and AirNow PM2.5 assimilation on Community Multi-scale Air Quality (CMAQ) aerosol predictions over the contiguous United States, Journal of Geophysical Research Letters, 122; 5399–5415. doi:10.1002/2016JD026295
- Hong, C., Zhang, Q., Zhang, Y., Tang, Y., Tong, D., & He, K. (2017). Multi-year downscaling application of two-way coupled WRF v3. 4 and CMAQ v5. 0.2 over east Asia for regional climate and air quality modeling: model evaluation and aerosol direct effects. Geoscientific Model Development, 10(6), 2447.

Quality and Performance

NAQFC Related Publications (continued)

- Huang, J., J. McQueen, J. Wilczak, I. Djalalova, I. Stajner, P. Shafran, D. Allured, P. Lee, L. Pan, D. Tong, H. Huang, G. DiMego, S. Upadhayay, and L. Delle Monache, 2017: Improving NOAA NAQFC PM2.5 Predictions with a Bias Correction Approach. Wea. Forecasting, 32, 407–421, https://doi.org/10.1175/WAF-D-16-0118.1
- Lee, Pius, J. McQueen, I. Stajner, J. Huang, L. Pan, D. Tong, H. Kim, Y. Tang, S. Kondragunta, M. Ruminski, S. Lu, E. Rogers, R. Saylor, P. Shafran, H.-C. Huang, J. Gorline, S. Upadhayay, and R. Artz (2017). NAQFC developmental forecast guidance for fine particulate matter (PM2.5), Weather and Forecasting, Volume 32, Issue 1, 343–360, http://dx.doi.org/10.1175/WAF-D-15-0163.1
- Lee, Pius, Jeffery McQueen, Ivanka Stajner, Jianping Huang, Li Pan, Daniel Tong, Hyuncheol Kim, Youhua Tang, Shobha Kondragunta, Mark Ruminski, Sarah Lu, Eric Rogers, Rick Saylor, Perry Shafran, Ho-Chun Huang, Jerry Gorline, Sikchya Upadhayay, and Richard Artz (2017). NAQFC developmental forecast guidance for fine particulate matter (PM2.5), Weather and Forecasting, Volume 32, Issue 1, 343–360, http://dx.doi.org/10.1175/WAF-D-15-0163.1
- Tang, Y., M. Pagowski, T. Chai, L. Pan, P. Lee, B. Baker, R. Kumar, L. Delle Monache, D. Tong, and H. Kim (2017). A Case Study of Aerosol Data Assimilation with the Community Multi-Scale Air Quality Model over the Contiguous United States using 3D-Var and Optimal Interpolation Methods, Geosci. Model Dev., 10, 4743-4758. https://doi.org/10.5194/gmd-10-4743-2017
- Tong, D. Q., J.X. Wang, T.E. Gill, H. Lei, and B. Wang (2017). Intensified dust storm activity and Valley fever infection in the southwestern United States. Geophysical Research Letters, 44(9), 4304-4312. doi:10.1002/2017GL073524

Quality and Performance

NAQFC Related Publications (continued)

2016

- Lei, H., Julian X. L. Wang, Daniel Q. Tong, and Pius Lee (2016). Merged dust climatology in Phoenix, Arizona based on satellite and station data. Climate Dynamics. 47(9-10), 2785-2799. doi: 10.1007/s00382-016-2997-7.
- Shepherd, G., E. Terradellas, A. Baklanov, U. Kang, W. A. Sprigg, S. Nickovic, A. D. Boloorani, et al., (2016). Gemma Shepherd, editor. Global Assessment of Sand and Dust Storms. United Nations Environment Programme, Nairobi. Retrieved from uneplive.unep.org
- Tang, Y., L. Pan, P. Lee, D. Tong, H. C. Kim, J. Wang, and S. Lu (2016). The Performance and Issues of a Regional Chemical Transport Model During Discover-AQ 2014 Aircraft Measurements Over Colorado. In Air Pollution Modeling and its Application XXIV (pp. 635-640, Chapter 103). ISBN:978-3-319- 24476-1, Springer International Publishing, 2016.
- Tong, D., L. Pan, W. Chen, L. Lamsal, P. Lee, Y. Tang, H. Kim, S. Kondragunta, and I. Stajner (2016). Impact of the 2008 Global Recession on air quality over the United States: Implications for surface ozone levels from changes in NOxemissions. Geophysical Research Letters 43 (17); 9280-9288, doi:10.1002/2016GL069885.
- Zhao, H., D. Q. Tong, P. Lee, H. Kim, and H. Lei, 2016: Reconstructing Fire Records from Ground-Based Routine Aerosol Monitoring, Atmosphere, 7(3), 43, doi:10.3390/atmos7030043