CMAQ 25th Anniversary

by Tanya L. Spero and Golam Sarwar

June 2023 marked the 25th anniversary of the U.S. Environmental Protection Agency's (EPA) Community Multiscale Air Quality (CMAQ), the agency's premier modeling system for studying air pollution from global to local scales. The articles presented in this issue of *EM* look back on elements of CMAQ's storied history and offer thoughts on the new directions that drive continued development.

The Community Multiscale Air Quality (CMAQ) modeling system (https://www.epa.gov/cmaq)[1,2] was initially released to the public on June 30, 1998. CMAQ was built as a third-generation air quality modeling system, meant to replace a collection of air pollution modeling tools that were tailored for specific pollutants and applications. Instead, CMAQ would simultaneously and holistically simulate the fate and transport of multiple species within the same model and evolution of atmospheric conditions while leveraging new computing technologies. The new system would provide a consistent platform for both research and applications. It took nearly seven years to design, build, test, document, and launch the initial release of CMAQ.

Today, CMAQ is a powerful computational tool that is used to translate fundamental atmospheric science principles to air quality policy scenarios. CMAQ combines current knowledge in atmospheric science and air quality modeling, advanced computing techniques, and an open-source framework to deliver fast, technically sound estimates of airborne ozone, particulates, toxics, and atmospheric acid and nutrient deposition—that is, concurrent simulation of species that are regulated under the U.S. Clean Air Act. EPA and states nationwide have used CMAQ to support air quality management.

Over the past quarter century, CMAQ has been continually updated to incorporate advances in scientific knowledge and computing power to characterize air quality more accurately and efficiently to protect human health and the environment. CMAQ boasts a community of thousands of users across six continents who use the modeling system for air quality management, forecasting, and research. CMAQ has been the backbone of the National Air Quality Forecasting System (https://airquality.weather.gov) at the National Weather Service since 2004, and it was featured in the inaugural Air Quality Chapter in the National Climate Assessment (https://nca2018.globalchange.gov/chapter/13) in 2018. CMAQ source code is now freely available via GitHub (http://www.github.com/USEPA/cmaq), which broadens the accessibility of the model.

The concept of "community" has been integral to the success of the modeling system. Although the routine development and evaluation of CMAQ occurs at EPA, the community of CMAQ users has contributed scientific ideas and novelties that have advanced the modeling system over the years. In addition, the worldwide userbase for CMAQ has tested the limits of the system, identified areas for improvement, and increased the overall robustness of the science and utility of the system. Furthermore, the interactions within the CMAQ community have facilitated its expansion from simulating week-long episodes of poor air quality in a region of the United States to simulating full annual, decadal, and multi-decadal evolutions of air quality throughout the Northern Hemisphere (with critical supporting emissions estimates) to scenarios of the impacts of climate change on air quality and human health, and much more!

As federal resources for science have gradually declined in the United States, the reliance on collaboration—or *community*—has become increasingly important, not just for sustaining the CMAQ modeling system. In this issue, we highlight the value of modeling communities to strengthen atmospheric science, using the CMAQ community as a microcosm to explore this concept. We contend that a modeling system as complex as CMAQ could not exist in today's world without a community to nurture it.

In this issue, we kick off with a paper by Wei Wang, who describes the mesoscale meteorological modeling community cultivated by the National Center for Atmospheric Research (NCAR; https://www.mmm.ucar.edu). Dr. Wang has been involved with that community going back to the Pennsylvania State University/NCAR Mesoscale Model versions 4 and 5 (MM4 and MM5, respectively) in the 1990s. Many of the concepts of community for CMAQ were patterned after what NCAR had done with MM5, particularly in the realms of providing access to the modeling software, user support, and convening annual meetings. When the science in MM5 transitioned to the Weather Research and Forecasting (WRF) model at NCAR in the mid-2000s, the community followed and continued to grow. CMAQ has relied upon these models from NCAR to provide meteorological data for the air quality simulations. In essence, a subset of the WRF community is also part of the CMAQ community.

In the second article, Sarav Arunachalam reviews the history and functions of the Community Modeling and Analysis System (CMAS; https://www.cmascenter.org) that is hosted at the University of North Carolina at Chapel Hill. The CMAS Center has provided a convenient and critical interface between the CMAQ developers at EPA and the user community for more than 20 years. Although the CMAS Center supports a range of environmental and air quality modeling products, support for the CMAQ model and its peripheral software is arguably their primary function. The CMAS Center also conducts training throughout the world and hosts a data clearinghouse that provides invaluable assets for the CMAQ community. The support of the CMAS Center has been the keystone for growing and supporting the CMAQ community over the years.

Next, Jiani Tan and coauthors provide an overview of some of the CMAQ uses across China. The CMAQ community has gradually expanded throughout China, such that the contingent of CMAQ users in China is ranked second, behind that in the United States. The broad usage of CMAQ throughout East Asia will continue to be critical to address unhealthy air quality in that part of the world. Understanding the contributions and movements of harmful pollutants in China can influence emissions control strategies that synergistically have local benefit within China and far-reaching benefit to citizens of the United States.

The fourth article by Elizabeth Adams and coauthors describes a multifaceted effort to complement local

high-performance computing systems with an extension of CMAQ to operate in cloud computing environments. As a complex scientific model, CMAQ requires a multiprocessor computing environment, often employing hundreds of processors for a model simulation. Cloud computing is a nascent technology that eliminates the need for either expensive access to a major high-performance computing facility or a local computing cluster and the staff to maintain it. However, there are variants of cloud computing private vendors and nuances associated with costs for processing and data exchange that now need to be considered. Adams et al. describe the converging efforts of several teams within the CMAQ community that are tackling computationally efficient and cost-efficient ways to promote the use of CMAQ in the cloud.

Finally, Havala Pye and coauthors offer a high-level introduction to chemical mechanism development and the Community Regional Atmospheric Chemistry Multiphase Mechanism (CRACMM; https://www.epa.gov/cmaq/cracmm), the development of which is fueled by a forward-thinking collaboration between federal, academic, and private researchers. CRACMM epitomizes the community development paradigm, where the current and anticipated needs of the air quality modeling community influence the development of this updated method of describing chemical reactions and interactions within a model. The CMAQ community has recently gotten a taste of CRACMM, and CRACMM is poised to become the default mechanism in the 2026 release of CMAQ and broadly used in other modeling tools throughout the community.

Collectively, these articles highlight a mere sample of the communities of scientists and practitioners that have been effective to strengthen numerical modeling in atmospheric sciences, specifically encompassing the CMAQ modeling system. We hope you will join us as we use this issue to close out the celebration of the 25th anniversary of the initial public release of CMAQ. We thank the authors for highlighting segments of our community, and we extend our gratitude to everyone who has been a part of the CMAQ community over its lifetime. May our communities continue leverage our strengths to better protect human health and the environment. **em**

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References

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