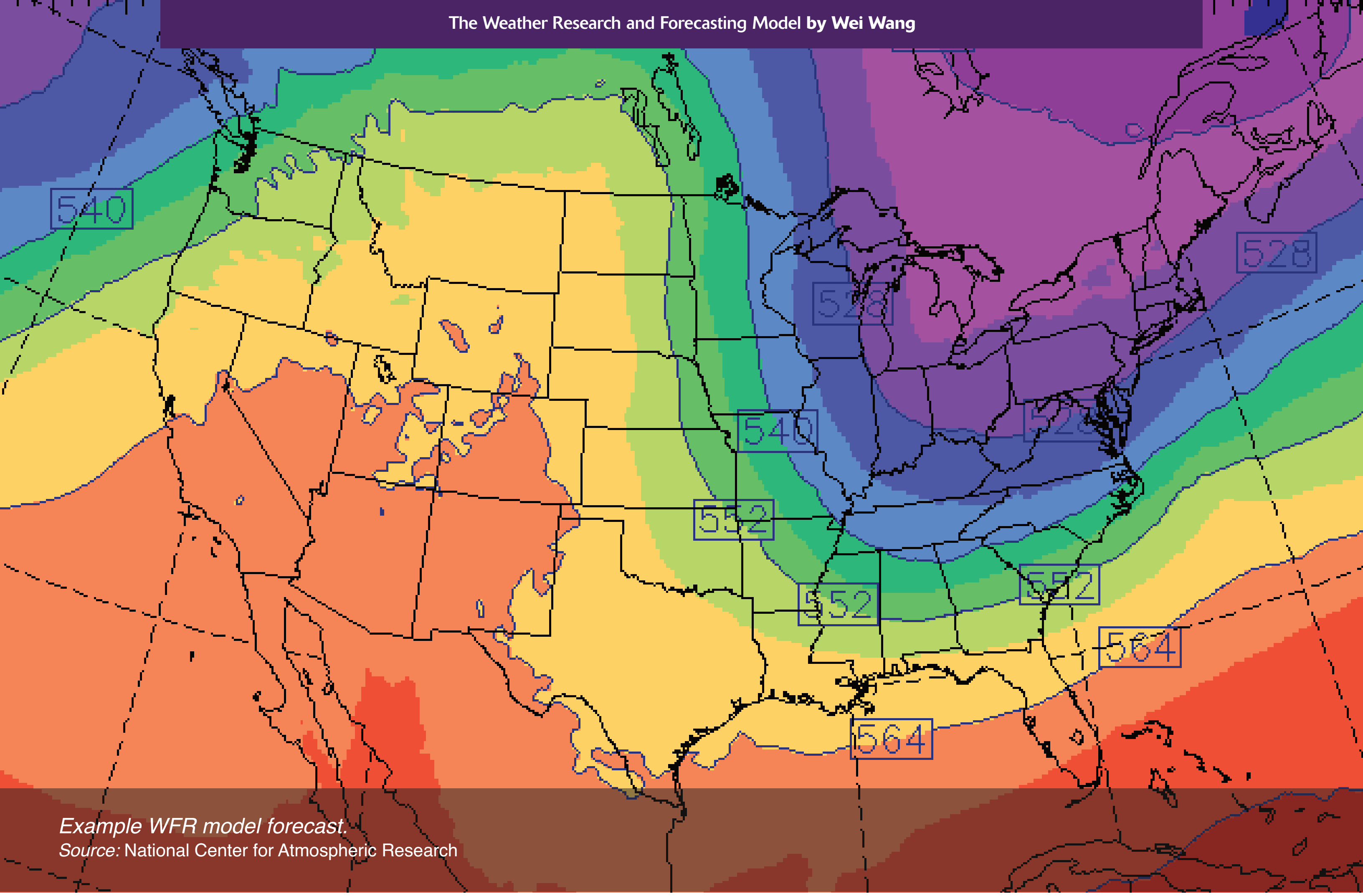

Example WFR model forecast.
Source: National Center for Atmospheric Research

Supporting the Weather Research and Forecasting Model as a Community Resource

by Wei Wang

A look at the development of the Weather Research and Forecasting (WRF) model as a research community resource. WRF has been used as the primary meteorology driver for the Community Multiscale Air Quality model since 2012.

The idea of providing an atmospheric model for a broader research community took root in the mid-1980s. A group of scientists at National Center for Atmospheric Research (NCAR) and Pennsylvania State University began to share the Penn State/NCAR Mesoscale Model Version 4 (MM4) to the scientific community with the support of the U.S. Environmental Protection Agency's (EPA) Regional Acid Deposition Modeling project. Since then, the effort has evolved to supporting MM5, a follow-on model to MM4, and later to the Weather Research and Forecasting (WRF) model.

Toward the middle of the 1990s, more powerful computer resources became available and the interest of applying numerical models in atmospheric research blossomed. Researchers realized that in order to move the atmospheric modeling research forward, it would require a redesign of the numerical model and, in particular, its software framework so as to take advantage of the advancement of the parallel computing technology. The other motivation for a new development was to involve the federal weather forecasting agencies, so that a common modeling framework could be used by both the research and operational communities. This helped form a partnership among a number of federal agencies and NCAR, who shared funding for the initial WRF modeling system development.

The WRF Model Is Born

The first version of the WRF model[1] was released in December 2000. The model solves equations of motion and thermodynamics for the atmosphere based on fluid dynamics, conservation of mass and scalars and knowledge of atmospheric physics. The WRF software is designed to be flexible and portable. It allows the model to run on diverse high-performance computing platforms while making it easy for scientists to program. The real-data application was initially supported by a pre-processing software package called Standard Initialization (SI), which supported the functions to design the limited area domain, and prepare static terrestrial input (e.g., terrain, land use, and soil category fields) and time-varying meteorological data. A separate model initialization program took the data processed by SI and generated initial and lateral boundary condition files for the model.

In its Version 2 release four years later, the height-based vertical coordinate dynamic core was removed, and mass-based vertical coordinate became the only dynamic core in the model until today. The other significant addition was the nesting capability, which allowed for a higher resolution domain to run inside its parent domain. The WRF-Chemistry extension was added in Version 2.1. By the time Version 2.2 was released in December 2006, the function to constrain the simulation toward observations via "nudging" was added, which is a popular capability in the air quality community.

WRF Version 3, released in April 2008, came with the global capability and the newly developed pre-processing programs, named the WRF pre-processing system or WPS. The WPS package includes three separate programs: geogrid, ungrib and metgrid. The geogrid program is used for configuring model domains, computing map projection factors, and interpolating terrestrial fields onto the defined domains. The ungrib program processes the General Regularly distributed Information in Binary form, or GRIB data, from various sources, including forecast and reanalysis data from meteorological centers like National Centers for Environmental Prediction and European Centre for Medium-Range Weather Forecasts. The metgrid program interpolates the data from external source onto the designed domain grids and combines static fields from geogrid and time-varying data from ungrib. WPS serves the same purposes as the previous SI, but is written in modern Fortran and has more flexibility. For example, the generality of the geogrid program allows adding another data source and combining different datasets easily. At the same time, WRF three-dimensional variational data assimilation (3DVAR) code was integrated into Version 3 too.

WRF Version 3 lasted for 10 years, during which time the modeling system and user base experienced the fastest growth, especially in the area of physics. When WRF Version 3 was first released, the model had six cumulus schemes (CPS), nine microphysics (MP), five planetary boundary layer (PBL) schemes, four land-surface models (LSM), and four radiation options. By Version 3.9, the model had 16 CPS, 19 MP, 13 PBL, six LSM, and eight radiation options. The model also added more advanced physics modules related to urban, lake, and ocean environments. Most of the physics packages are contributions from the user community.

In June 2018, WRF Version 4.0 was released. The release adopted a hybrid vertical coordinate as opposed to the traditional terrain-following coordinate, similar to that used by many global models. The capability potentially helps to improve simulations above and downstream of mountain ranges. WRF 4DVAR code was also added to the software framework. A coupled WRF-CMAQ function was contributed to the WRF repository in the Version 4.4 release.

Supporting Atmospheric Models for Community Research

When WRF was first conceived, it was clear to all involved that this was going to be a community resource. Based on the experience of MM5, the support for WRF generally covers the following areas: web pages, training and workshops, user inquiries, and code releases and management.

The WRF web page (https://www2.mmm.ucar.edu/wrf/users/) provides all resources related to the WRF model. It hosts the download page for the modeling system software, as well as input data, records of each release, documentation (e.g., technical notes and user guides), tutorial and workshop presentations, and additional learning materials. Communications with the user community also happen via a subscription email list, through which the model-related announcements are made.

Training for the WRF model began as early as 2001, several months after the initial model release. It started with one tutorial per year and grew to two per year in 2006. The tutorial is typically a week-long program that offers a mix of lectures and hands-on sessions. During the past 23 years, around 2,500 participants have attended these tutorials at NCAR's facility in Boulder, CO (see Figure 1).

In addition to the training, the annual users' workshop in Boulder is another venue for the community to gather to share new developments and discussions about the model (see Figure 2). During the early years, these workshops were particularly effective in moving the model development forward. For example, whether the nudging function should be included in WRF was one of the lively discussion topics at the time. The workshops are also places for the community to learn more about atmospheric modeling. Lectures on atmospheric physics and dynamics, best practices for using the model, and new tools to perform model analysis are provided by experts at NCAR and from within the community. These presentations usually take place the day before the official workshop.

Part of the success of the WRF model is its help desk (https://www2.mmm.ucar.edu/wrf/users/supports/support.html). The number of users grew significantly after the Version 3 release. Along with this growth has been the number of emails the help desk receives each month. It averaged around 350–400 per month for many years, peaking at 450 per month in 2013. Many inquiries come from new and/or inexperienced users who need help to start their modeling applications. But some emails also come from diligent scientists who discover and sometimes find fixes to model issues and bugs. Some user inquiries point to unclear documentation and lack of safeguard in the code. These exchanges help improve the science and software in the modeling system. The help desk has also evolved in time, from email to wrfhelp to a public forum today. The public forum (https://forum.mmm.ucar.edu) allows users to search common questions and answers and encourages community members to participate in supporting fellow members.

Another challenge to support a complex modeling system software to the community is a philosophy about how to develop code that can be used by a community and code management. The scientists and software engineers who develop the WRF software are keen on making the software easy and user friendly. Since 2004 and the WRF Version 2 release, the code has been managed via version control system, and it has evolved to today's use of Git via Github (https://github.com/wrf-model/WRF). The use of a version control system allows tracking of code development, collaboration, and contributions from a broad community. The relative ease and generality of the software framework has allowed the extensions of model functions to chemistry, data assimilation, hydrology modules, and coupling with ocean and wave components. Today, through the use of Github, the community can directly contribute to the development of modeling system software.

Figure 1. A WRF model tutorial in progress in January 2020.

Figure 2. A group photo from the 17th WRF Users' Workshop in 2016.

Looking Ahead

It has been 23 years since the first public release of the WRF model, and the modeling system has made significant impact on the atmospheric research community and extended its applications to many other disciplines.[2] WRF has been adopted as an operational model by several agencies both nationally and internationally. WRF is also widely used for air quality studies and has been used as the primary meteorology driver for community multiscale air quality (CMAQ) model since 2012. Other important application areas are high-resolution regional climate and urban studies, along with a growing interest in renewable energy applications. The user community continues to grow and publications using the WRF modeling system has accumulated to over 10,060 as of the end of 2022. NCAR will continue to support and maintain the WRF modeling system in the foreseeable future.

Among the motivations to develop a new limited area model back in the 1990s was to meet the need for explicit convection forecasting at a few kilometers. To extend that goal to global scale, the Model for Prediction Across Scales (MPAS) has been in development over the past 10 years.[3] In the same software framework, a regional MPAS has also been made available recently. Learning a few lessons from the WRF model, MPAS is formulated on an unstructured spherical centroidal Voronoi meshes which enables computational scaling on global meshes. It also allows variable mesh configuration that enables coarser to fine resolution change in a single mesh. MPAS employs a general height-based, hybrid vertical coordinate and split dynamic and physics time steps, which potentially permits a larger time step for physics. The MPAS development team and its collaborators are actively exploring the Graphics Processing Unit (GPU) deployment to enhance its computing efficiency. Looking into the future of the atmospheric modeling research, MPAS opens many new opportunities and new sciences. The variable resolution mesh and the capability to use GPU could make MPAS a favorite tool for many regional atmospheric applications. The NCAR team will be there to support the community as we explore the new science frontier together. **em**

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