

Challenges and Opportunities in Numerical Weather Prediction

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The AMS 2022 Summer Community Meeting: The Current State, Challenges, and Next Steps in NWP

What: One hundred fifty-six participants discussed current trends, challenges, and next steps to advance numerical weather prediction across the U.S. weather enterprise.

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Where: Boulder, Colorado

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In 1922 Lewis Fry Richardson published *Weather Prediction by Numerical Process* (Richardson 1922), a vision for how atmospheric dynamical equations could be used to predict weather. Selling for about \$2 with a print run of 750 copies, the book was not a commercial success; Richardson’s vision was impractical at the time (Lynch 2006). Decades before the development of high-speed telecommunication, satellites, and computers, a global forecast required use of a “forecast factory” with a workforce of 64,000 human “computers” calculating the algorithms by hand in unison. And even if that were available, a full understanding of how best to apply the dynamical equations was not yet fully understood, and indeed, Richardson failed to remove high-frequency waves from his own calculations, leading to an unrealistic, unstable forecast solution (Lynch 2006). Nevertheless, Lewis Fry Richardson understood the feasibility of numerical weather prediction (NWP) and demonstrated how it could be done.

The AMS Summer Community Meeting (SCM) is hosted annually by the Board on Enterprise Communication, part of the Commission on the Weather, Water, and Climate Enterprise, with the goal of providing a platform for sharing information and generating conversation across the public, commercial, and academic sectors. This year’s SCM celebrated the 100th anniversary of Richardson’s book with the goal of identifying the challenges and opportunities to advance NWP in the United States. Specifically, each speaker was charged with identifying the current state of the science, the remaining fundamental challenges, and the next steps needed to advance NWP across the weather, water, and climate enterprise. What follows is a collective summary of those assessments, challenges, and recommendations posed by meeting attendees.

Current state of NWP

The speakers discussed how the U.S. weather, water, and climate enterprise supports a broad array of microscale to global models serving a variety of end users. NOAA’s National Centers for Environmental Prediction (NCEP) Production Suite (NPS) currently includes over 20 operational weather forecast systems, providing forecasts from the mesoscale to global seasonal outlooks. In an effort to optimize resources, the NPS is being simplified to far fewer systems within the Unified Forecast System (UFS) framework that nevertheless span NOAA’s weather prediction mission: short-range regional and atmospheric composition (RRFS, WoF), medium-range subseasonal (GEFS) to seasonal (SFS), marine and coastal (GFS, GEFS,

NWPS, GLWU), hurricanes (HAFS), on-demand atmospheric dispersion (HySPLIT), hydrology (NWM), and space weather (WAM/IPE) (see appendix for a full list of abbreviation definitions). The military operates a similar suite of operational models for their weather services: the Navy supports the NAVGEM, COAMPS, NAAPS, NIMO, NEPTUNE, and MEPS models, while the Air Force runs the GALWEM model from the British Met Office. In general, the private sector builds upon these operational models by running similar versions in-house (e.g., MM5, CCMS, MPAS, WRF-ARW) and through additional postprocessing of model output. The public, commercial, and academic sectors share in the research and development (R&D) of community models such as WRF, MPAS, CESM, and the UFS suite.

Recent advances in observations have contributed to model improvement. An international constellation of low-Earth-orbit and geosynchronous-equatorial-orbit satellites are expanding our Earth intelligence; for example, polar-orbiting satellites now provide 85% of the data used in global weather models. Additional private investment has expanded the variety and resolution of observations now available. For example, commercial global positioning system radio occultation data from Spire and GeoOptics provide about 6,000 vertical atmospheric profiles per day as part of NOAA's Commercial Weather Data Pilot. WindBorne is launching long-range global sounding balloons to collect vertical thermodynamic and wind profiles across remote land and ocean regions with the intent to eventually provide them for assimilation into numerical models. Climavision is deploying surface-based X-band radars to fill critical data gaps in the atmospheric boundary layer. Additional targeted observations are addressing known data gaps; for example, airborne radio occultation is being used for targeted data collection during atmospheric river events. The internet of things (IoT) and uncrewed in situ platforms are expanding local weather observations worldwide. The current global observing system is diverse, robust, and rapidly evolving.

Continued advancements in data assimilation (DA) are making the most of these observations to improve NWP skills. For example, the ensemble-variational (EnVar) method, which is a hybridization of the variational method and the ensemble transform Kalman filter (ETKF)/local ETKF (LETKF), or ensemble square-root filter (EnSRF), has been adopted by the U.S. NWS operational global and regional model suites. Advancement of multiscale DA (MDA) approaches, methods to distinguish model and observation errors, methods that leverage machine learning in DA, and methods that treat non-Gaussianity demonstrate the potential to more appropriately combine forecast and observational data. In addition to the advancement of DA research, the Joint Effort for Data assimilation Integration (JEDI), operated by the UCAR Joint Center for Satellite Data Assimilation (JCSDA), provides a common software infrastructure for full community engagement in the testing, research, and development of new observations and DA methods.

Recent work in model dynamics, parameterizations, and ensemble prediction are furthering model accuracy and value, extending model range, and providing users with more reliable probabilistic information to aid in decision-making for a wide variety of activities. Methods that identify “forecasts of opportunity” such as linear inverse models (LIMs) are extending predictability during some periods of highly anomalous activity. Updated reanalyses and reforecasts are improving community understanding of atmospheric processes and relationships and greatly facilitate the statistical postprocessing necessary to generate reliable, skillful forecast products. The application of ensemble prediction at ever-higher resolutions is increasing the accuracy, confidence, and applicability of local forecasts. NCEP's Global Ensemble Forecast System (GEFS) has seen an average of 2 days decade⁻¹ improvement in model skill (from 6 to 10 days equivalent) for predicting 500 hPa heights. Skill in predicting the Madden-Julian oscillation (MJO) has been extended from 13 to 22 days with v.12 of the GEFS. Test results show significant improvement in convection-allowing hurricane and

severe weather prediction achieved with convective-scale DA. New tools for analyzing model output, such as the extreme forecast index (EFI), aid end users in the application of models in preparing for extreme events.

Speakers pointed out that a critical step in the application of NWP is downscaling and statistically adjusting the model output to satisfy specific user needs. Artificial intelligence and machine learning (AI/ML) are now key tools applied in the postprocessing of model output for downscaling and calibration. These are further improved by large samples afforded by long time series of reforecasts. Operationally, humans can adjust forecasts using advanced tools such as AI/ML. Social science is integral to merging AI/ML into the forecast process, and new programs such as the NSF AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography (AI2ES) are working to facilitate this integration.

Getting model output to the user is a final and essential step; the public weather community continues to work to “democratize” access, making NWP output readily available to all users regardless of their location, knowledge, abilities, or resources. Federal agencies are beginning to utilize the cloud to increase storage and accessibility. Real-time distributions of data are made possible via LDM, THREDDS, AWIPS, Science Gateway in the Cloud, and MADIS, among others. Open-sourced code offer opportunities for specialization and growth.

Perhaps most importantly, the weather modeling community is now focused on collaborating across sectors to advance our collective NWP goals. National NWP programs now place a much greater emphasis on collaboration, with cross-sector, community engagement in model system R&D at all stages. For example, the UFS and the Earth Prediction Innovation Center (EPIC) were recently developed to focus the community’s work and energy into a single community modeling effort. In 2016, the Space Weather Operations, Research and Mitigation (SWORM) Interagency Working Group (IWG) was formed to organize space weather research and operations across agencies, and in 2017, the Interagency Council for Advancing Meteorology Services (ICAMS) was formed at the White House Office of Science and Technology Policy (OSTP) to improve coordination of weather policy and programs across federal agencies. Cross-agency and cross-sector collaborations between such agencies as NOAA, NASA, USGS, FEMA, U.S. government laboratories, the university community, and private sector industries are now common across the enterprise.

Fundamental challenges inhibiting advancement

Some fundamental challenges were identified at the SCM that continue to thwart efforts to improve U.S. NWP. These challenges span a variety of issues ranging from resource limitations to critical knowledge and workforce gaps.

- *Model accuracy.* U.S. global NWP is roughly third in the world, behind the ECMWF and Met Office models and tied with the Canadian Meteorological Center, as measured by model accuracy (Colman and Glenn 2021). Models have limited ability to forecast rare events, and they often fail to capture large-scale relationships, such as the MJO–QBO. Continuous gap analysis and model verification are essential for diagnosing and addressing errors.
- *High number of supported models.* The long list of supported models operated by the U.S. weather community is both a strength and a weakness of U.S. NWP. While the wide range of models directly supports a broad range of users, the large number of models limits the R&D support (human and financial) for development of any particular system. The number of supported models is being reduced (via the UFS program) to optimize limited resources, but the U.S. community is still divided in the models it supports. For example, NOAA and UCAR currently support different suites of models. An open question is whether a single community super-model with multiple dynamic cores is possible. Finally, limited funding requires balancing resources and prioritization.

- *Data—Volume, gaps, and threatened resources.* As new sensor networks continue to expand and model spatial and temporal resolutions increase, data volume is expected to grow to over 100 TB day⁻¹ within the decade. Observational gaps limit model performance. For example, global precipitation, atmospheric rivers, the lower atmospheric boundary layer, and developing high-impact events are underobserved. Frequency allocation issues remain a considerable threat for the continuance of some critical satellite bands. Furthermore, existing data are underutilized. Finally, an agreed-upon quantitative approach is needed to prioritize investments among possible observing systems.
- *Difficulty assimilating new data with the future landscape of high-resolution models.* Theoretical studies show that multiday improvements in the practical predictability limit can be achieved at subsynoptic scales by reducing the magnitude of the initial errors. But while commercial data streams, microsatellite data, and citizen science are increasing at a rapid pace, assimilation of these new data into NWP to provide accurate multiscale analyses remains challenging. The integration of new data requires acquisition, an observation operator, error characterization, quality control, testing, and optimization. Additional challenges associated with MDA include accurate representation of model errors, multiscale background error interactions, and dealing with non-Gaussian variables. Questions remain on how to handle the ever-increasing volume of data.
- *Lack of a long-term vision for data assimilation priorities.* A long-term mechanism is needed for identifying DA research priorities, establishing funding of such research, and educating the future workforce in DA, where there is a serious lack of expertise.
- *Challenges in ensemble prediction.* Ensemble forecasts require sets of initial conditions that span the range of expected uncertainty in the analysis and thus benefit from the refinement of ensemble-based assimilation techniques. Ensembles can also be improved by increasing the model resolution and improving the stochastic treatment of unresolved processes such as deep convection; this alleviates the common tendency for underspread forecasts. As coupled ensembles are required to provide predictions for subseasonal-to-seasonal forecasts, it is also necessary to properly represent the uncertainty in the ocean, land, and sea ice states and their interactions with the atmosphere. Other needs include optimized code and enhanced distribution and communication of ensemble output. The community at large has difficulty in deriving and communicating risk, and ensembles are an essential tool for improved representation of forecast confidence.
- *Limited high-performance computing (HPC) capacity, especially for research.* The HPC capacity available to the U.S. NWP community for R&D is inadequate in comparison to the need. The two new operational Weather and Climate Operational Supercomputing Systems (WCOS2) are 12.1 PF each, for a total of 24.2 PF. The sum of all of NOAA's research HPC is 16 PF; thus, a research-to-operations (R/O) ratio of 2:3 with a total of about 40 PF. The PWR recommended that NOAA have 100 times more HPC available in 10 years for research and operations combined, with a R/O ratio of at least 3:1.
- *Challenge of dissemination.* Resource challenges persist in the collection and distribution of observations from the field and the real-time dissemination of model output. Increased bandwidth and new paradigms for data dissemination including cloud storage are needed to allow the community full access to the increased volumes of observations and copious amounts of model output.
- *Collaboration and intellectual property.* Legitimate concerns often limit the degree of collaboration across the community. For example, the military must balance “open science” against national security. Private industry must balance competition with community engagement. National advancement is not always compatible with international inclusion.
- *Challenge in identifying national priorities.* Identifying how best to allocate limited resources and investment across the weather enterprise remains a considerable challenge.

The needs across all components of the NWP system must be considered, but investment needs vary. One successful community effort focused on weather forecasting, the NOAA PWR report, incorporated input from 130 weather, water, and climate experts. However, the PWR report itself recommended that NOAA develop a quantitative prioritization process.

Next steps and opportunities

Despite the above challenges, SCM meeting participants are optimistic as the U.S. weather community is pushing forward on several major initiatives designed to accelerate progress in NWP development, such as JEDI, UFS, EPIC, AI2ES, and a university consortium for data assimilation education and research. Collaboration, communication, and education are key goals of these programs, essential for harnessing the full potential of the broad weather, water, and climate enterprise. A few specific next steps and opportunities include the following:

- *Collaboration.* A common thread across all presenters was the great strides forward in collaboration across the public, commercial, and academic sectors. The UFS is a community set of forecast applications, providing a common platform for operations and R&D, engaging all sectors of the weather enterprise. An EPIC Community Modeling Board is proposed to further engage, encourage, and facilitate the use of UFS applications across the community. Additional collaborative programs include JEDI; EPIC; the National Unified Operational Prediction Capability, a collaboration between the NWS, U.S. Navy, and U.S. Air Force; the North American Ensemble Forecast System (NAEFS), a collaboration between the national weather service programs of Canada, the United States, and Mexico; the NCAR Earth System Prediction working group (ESPWG); the Waves to Weather (W2W) program; and Model Evaluation Tools (MET-Plus) that provide a common assessment methodology. Given the serious lack of data assimilation expertise in the U.S. workforce, increased investment to enable the systematic collaboration between universities and agencies is recommended to allow innovative data assimilation research, workforce development, and operational transition.
- *Community models.* Community models offer a foundation for shared R&D and largely enabled the rapid growth of the academic and private sector involvement in the U.S. weather enterprise. Such models require a community of support, broad adoption, ease of use, extensive documentation, ongoing support infrastructure, and bidirectional engagement with users. For further improvement, the next steps to consider are 1) accelerate innovation with disruption, not incremental improvement; 2) improve communication between operational and research contributors; 3) clarify roadmaps for development, including needed field campaigns to collect observations to advance parameterization schemes; and 4) establish processes for adopting improvements. Community governance boards should be adopted. Finally, all aspects of NWP must be considered, including the continued development of parameterizations, data assimilation, model verification, and utilization of reanalyses and reforecasts. Approaches to identify priorities for each of these areas are needed.
- *Focus on Earth system modeling.* The future of NWP is modeling the full Earth system, as demonstrated by the next-generation GEFS (version 13), a fully coupled ocean–atmosphere–sea ice–land ensemble system, all with a unified code base. Further progress in Earth system modeling requires the integration of additional fields of study such as chemistry, oceans, and sea ice. Next steps include downscaling large-scale signals to local weather, advancing coupled data assimilation, improving outlooks from seasonal to annual time scales, improving prediction of extreme events and their impacts, and translating customer costs and exposure.

- *Communication and establishing trust.* More work is needed to understand how best to develop trust with users of model output and how to communicate confidence in the model forecasts. The community must continue to work on making the predictions relevant to the customer.
- *Education of users.* Most of the general public are users of model output, not generators of models or experts in NWP. As such, novel users may be confused by science community language focused on “uncertainty” and misunderstand forecast confidence. Therefore, one of our greatest opportunities to increase the value of NWP output may be through improving the clarity and accessibility of our language while simultaneously educating the users of NWP.
- *Resourcing commensurate with impact.* Given the outsized and growing impact of weather on the economy and public safety and the ability to mitigate these risks with high-quality forecast guidance, the community should support, as one voice, markedly increased and sustained resources for the development of these improved prediction systems.

SCM speakers pointed to the timeliness of the meeting as Congress is now working on a reauthorization of the 2017 Weather Innovation Act, which provides an opportunity to discuss community priorities with lawmakers. Prepared by NOAA’s Science Advisory Board, the Priorities for Weather Report (Colman and Glenn 2021) recommends investments by Congress to directly address many of the challenges listed above—Earth system modeling, advancing data assimilation research, capabilities and workforce, data dissemination, high-performance computing, observing system gaps, and human behavior. Furthermore, the PWR recognizes a need to leverage objective methods to prioritize investment decisions, an elevated focus on water issues, and continued attention to high-impact weather. However, as the PWR captures only the needs of the public sector, a broader “Statement on Community Priorities” is necessary to incorporate the needs of the academic and private sectors. A century of progress, from the advent of NWP to better utilization of observations through advanced data assimilation to high-resolution, operational global Earth system models, is to be celebrated as we continue to follow the example of Lewis Fry Richardson by investing in a vision for the future.

Appendix: Abbreviations

AI2ES	NSF AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography
AI/ML	Artificial intelligence and machine learning
AWIPS	Advanced Weather Interactive Processing System
CCMS	Community Climate Model
CESM	Community Earth System Model
COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System
DA	Data assimilation
ECMWF	European Centre for Medium-Range Weather Forecasts
EFI	Extreme forecast index
EnSRF	Ensemble square root filter
EnVar	Ensemble–variational
EPIC	Earth Prediction Innovation Center
ESPWG	Earth System Prediction working group
ETKF	Ensemble transform Kalman filter
GALWEM	Global Air-Land Weather Exploitation Model
GEFS	Global Ensemble Forecast System
GFS	Global Forecast System
GLWU	Great Lakes Wave Unstructured

HAFS	Hurricane Analysis and Forecast System
HPC	High-performance computing
HySPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory model
ICAMS	Interagency Council for Advancing Meteorology Services
IWG	Interagency Working Group
JCSDA	Joint Center for Satellite Data Assimilation
JEDI	Joint Effort for Data assimilation Integration
LETKF	Local ETKF
LDM	Local Data Manager
MADIS	Meteorological Assimilation Data Ingest System
MDA	Multiscale DA
MEPS	Mesoscale Ensemble Prediction System
MET-Plus	Model Evaluation Tools
MJO–QBO	Madden–Julian oscillation–quasi-biennial oscillation
MM5	Mesoscale Model 5
MPAS	Model for Prediction Across Scales
NAAPS	NRL Aerosol Analysis and Predictions System
NAEFS	North American Ensemble Forecast System
NAVEM	Navy Global Environmental Model
NCEP	National Centers for Environmental Prediction
NEPTUNE	Navy Environmental Prediction System Using the NUMA Core
NIMO	Navy Ionosphere Model for Operations
NWM	National Water Model
NWPS	Nearshore Wave Prediction System
RRFS	Rapid Refresh Forecast System
SCM	Summer Community Meeting
SFS	Subfilter scale
SWORM	Space Weather Operations, Research and Mitigation
THREDDS	Thematic Real-Time Environmental Distributed Data Services
UFS	Unified Forecast System
W2W	Waves to Weather program
WAM/IPE	Whole Atmosphere Model/Ionosphere Plasmasphere Electrodynamics model
WoF	Warn-on-Forecast
WRF	Weather Research and Forecasting Model
WRF-ARW	Advanced Research version of WRF

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