EPIC as a Catalyst for NOAA’s Future Earth Prediction System
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ABSTRACT: NOAA has launched the Earth Prediction Innovation Center (EPIC) in partnership with the Weather Enterprise (academia, government, and industry) to bring the power of distributed innovation to bear on one of the greatest challenges of our time. EPIC provides a collaborative framework building upon the community-driven Unified Forecast System (UFS) to accelerate innovative improvements to the nation’s forecast system in order to save lives, protect property, and enhance the economy. This article describes NOAA’s strategic, tactical, and organizational approaches to utilize EPIC to transform the world-leading U.S. national forecast systems into an even stronger and more effective community-based, computationally advanced Earth prediction system to meet the expanding and pressing needs of national and international societies.

KEYWORDS: Numerical weather prediction/forecasting; Software; Community

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The National Oceanic and Atmospheric Administration (NOAA) is responsible for producing world-leading observations, information, forecasts, and warnings to protect life and property and enhance the nation’s economy. NOAA’s National Weather Service (NWS), and its predecessor organizations, have been meeting this mission successfully for over 150 years. Increasing vulnerability to extreme events caused by climate change and socioeconomic insecurity has escalated the demand for reliable weather, water, and climate services. This has led to the introduction of Information Decision Support Services (IDSS) to NWS responsibilities. The U.S. economy has encountered nearly $2 trillion in weather-related costs since 1980, with $95 billion in damage occurring in 2020 alone—shattering the previous annual record (NCEI 2021). The costs of severe weather events are escalating in the United States due to a combination of increasing exposure of assets in weather-prone regions (Ashley and Strader 2016), aging infrastructure, and the growing incidence of multiple hazards (Melillo et al. 2014). Furthermore, there is a trend of increasing intensity and frequency of extreme weather events such as heavy rainfall, large tropical cyclones, fires, and droughts (USGCRP 2018; IPCC 2021).

Our society relies on NOAA forecasts to predict hazards at various time scales and spatial dimensions to mitigate impacts associated with increased extreme events. The addition of numerical forecast model resolution and complexity aims to increase lead time and precision, but model skill continues to be challenged by the frequency and intensity of extreme events. Historically, NOAA has provided forecast information for tornadoes, tropical storms, extreme heat, cold, precipitation, droughts, floods, air pollution, and winter weather. It has been widely recognized that an Earth system approach is needed to solve tomorrow’s forecast challenges, as described in numerous recent reports and publications (e.g., Shapiro et al. 2010; National Academies of Sciences, Engineering, and Medicine 2020; Ruti et al. 2020). Shapiro et al. (2010) defines Earth system as “[t]he atmosphere and its chemical composition, the oceans, land/sea ice and other cryosphere components as well as the land surface, including surface hydrology and wetlands, lakes, and human activities. On short time scales, it includes phenomena that result from the interaction between one or more components, such as ocean waves and storm surges. On longer time scales (e.g., climate), the terrestrial and ocean ecosystems, including the carbon and nitrogen cycles and slowly varying cryosphere components (e.g., the large continental ice sheets and permafrost), are also part of the Earth system.” We would amend this definition to also include space weather on short time scales. An Earth system approach helps to improve forecast skill, to extend forecast lead time, and provides Earth-system-related products and services.

To meet these challenges, NOAA must craft the best environmental information for the U.S. population using large datasets of observations, high-performance computing (HPC), advanced numerical weather prediction (NWP) systems, and the expertise of its technical
and scientific staff. For shorter forecast time scales, trusted forecasters must deliver accurate, meaningful forecast products and decision support services to inform the nation and empower public safety officials at every level of government and our larger society with actionable information for hazardous weather response. On longer time scales, environmental information and forecasts must be available to predict changes in our climate and how those changes affect physical and natural systems.

Over the last two decades, NOAA developed a “seamless suite” of models (spanning time scales from minutes to months to address weather and climate prediction challenges serving a number of sectors; Fig. 1), following the Grand Challenge associated with the “climate–weather linkage” brought forward by global leaders from both communities in a joint meeting of the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP) in 2010 (Brunet et al. 2010; Shapiro et al. 2010). At the time, covering the large spatial, temporal, and sectoral space required a relatively large set of specialized models, including the addition of ensembles and multimodel ensembles to enhance prediction skill and address predictability issues at longer time scales which expanded this suite even further (WMO 2015; National Academies of Sciences, Engineering, and Medicine 2020). Figure 1 illustrates the enormous progress made over the past 20+ years to develop and apply an operational seamless suite of models within the NOAA/NWS covering the temporal domain from hours to subseasonal to seasonal (S2S); it also illustrates the challenges facing the weather, water, and climate research communities interested in systematically improving/changing the current operational model suite. Clearly, unification and simplification of this modeling suite is required to support the enterprise to access, use, and improve the operational models, while applying a unified framework as a strategic basis for future advancements across the entire Earth system from both research and operational perspectives.

In response to this need, NOAA has endeavored to create a Unified Forecast System (UFS) in collaboration with the larger public–private weather, water, and climate research and
academic enterprise, following the unified modeling system approach of centers such as the U.K. Meteorological Office, and the community modeling approach of groups such as NCAR’s Weather Research and Forecasting (WRF). NOAA’s community modeling strategy is particularly bold and high risk/high reward, with an expectation that community collaborations and contributions will transform operational forecast skill. Furthermore, the UFS’s open-source, open-development stance exposes the model code to potential forecast system competitors throughout the international public and private forecast community.

NOAA’s path to simplification, unification and community numerical weather prediction modeling started in 2008, when NOAA invited the University Corporation for Atmospheric Research (UCAR) to conduct a review of their National Centers for Environmental Prediction (NCEP). The UCAR Community Advisory Committee for NCEP (UCACN) recommended simplification of the NCEP modeling systems. In line with these recommendations, NOAA developed the Research to Operations (R2O) initiative (Office of Management and Budget 2013), a 5-year plan to develop NOAA’s Next-Generation Global Prediction System (NGGPS). In 2015, NOAA asked UCACN to form a subcommittee, the UCACN Modeling Advisory Committee (UMAC), to provide a technical review of the NCEP Production Suite (NPS) strategy. The resulting report stressed not only simplification but also the creation of a community-based, unified modeling suite to enable seamless prediction across all time and space scales (Blumberg et al. 2015). NOAA then selected the NOAA Geophysical Fluid Dynamics Laboratory (GFDL)-developed Finite-Volume on a Cubed Sphere (FV3) as the dynamic core in the implementation of NGGPS. The R2O initiative matured into a multiyear strategic implementation plan (Tolman and Cortinas 2020), establishing a co-development framework between NOAA and the extramural community toward a national integrated Earth modeling system for operations and research—the UFS. The UFS is initially focused on Earth system prediction on shorter weather time scales as described in the definition above, but could be expanded to address environmental prediction challenges on longer time scales in the future.

The UFS is a major component of the NOAA/NWS Weather-Ready Nation vision, building partnerships across the Weather Enterprise (henceforth Enterprise) to create a nation that is ready, responsive, and resilient to extreme weather, water, and climate events (Uccellini and Ten Hoeve 2019). Addressing the vision of simplifying NOAA’s operational forecast model suite by 2025, the NWS will have reduced its 21 stand-alone operational forecast systems into eight major forecast systems sharing the UFS framework (Fig. 2).

The Earth Prediction Innovation Center (EPIC) is mandated by Congress and is essential to fuel the UFS community modeling strategy. The Weather Research and Forecasting Innovation Act of 2017\(^1\) states that NOAA is to prioritize improving weather data, modeling, computing, forecasting, and warnings to protect life and property and enhance the national economy. Specific calls were subsequently made in the National Integrated Drought Information System Reauthorization Act of 2018\(^2\) for creating EPIC to accelerate community-developed scientific and technological improvements into NOAA’s operational weather model. In 2021, NOAA’s Science Advisory Board (SAB) was charged by Congress to inform federal investment priorities for weather research for the coming decade. In response, the SAB published the Priorities for Weather Research (PWR),\(^3\) in which they advocated for a community, multiscale, coupled Earth system model to become the backbone of community modeling.

EPIC is designed to catalyze community modeling by attracting, uniting, and supporting the UFS community to advance more rapidly. One way EPIC accomplishes this is by creating a common codebase and modeling infrastructure for both research and operational forecasts. Through software and user support, EPIC enables the incorporation of research innovations

\(^1\) www.congress.gov/115/plaws/publ25/PLAW-115publ25.pdf

\(^2\) www.govinfo.gov/content/pkg/PLAW-115publ423/pdf/PLAW-115publ423.pdf

into operations (R2O), extending ultimately to include other needs for environmental information or product applications (R2X). EPIC also provides a framework to communicate operational and stakeholder requirements to the research community. As described in a companion paper (Jacobs 2021), EPIC is designed to leverage funding lines to foster collaboration, following the open innovation business model (Chesbrough 2003). In this manuscript, we explore EPIC’s strategic and tactical approaches, organizational support, and societal benefits.

**Strategic basis for EPIC**

EPIC’s vision is to enable the most accurate and reliable operational Earth system forecast model in the world. EPIC’s mission is to be the catalyst for community research and modeling focused on informing and accelerating advances in our nation’s operational NWP forecast modeling systems. NOAA is evolving and expanding these forecast systems to include Earth prediction systems. Initially, EPIC’s focus will be on the UFS, including all model elements needed for NWP forecast production: data assimilation, ensemble design, coupling, physical and Earth system components and metadata protocols, tools, and algorithms to facilitate postprocessing of model outputs.

The UFS provides the codebase that is the foundation of NOAA’s next-generation forecast systems. The codebase is packaged into forecast applications that address prediction scales ranging from short-range severe weather and hurricane models to subseasonal-to-seasonal systems. Ultimately, the UFS will include applications that effectively provide forecasts for the range of phenomena facing the United States, including fires, air quality, space weather, ocean biogeochemistry, storm surge and flooding, and extended-range forecasts of droughts and floods.

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4 The UFS community refers to forecast systems as forecast applications, e.g., the hurricane application. In other contexts the NWP community uses the term application to indicate a downstream product that may not be an operational product. Throughout this paper we use the word “forecast application” to indicate the former and “product application” to indicate the latter.
As described in Jacobs (2021), these aspirations require an energized and committed community that includes researchers from the full Enterprise—academia, government, and industry—ultimately engaged with NOAA in a partnership to improve scientific understanding and forecasting through innovation. EPIC is a mechanism to catalyze that community engagement—the success of EPIC depends on a united Enterprise collaborating to improve the UFS, as proposed by Cikanek et al. (2019), Tolman and Cortinas (2020), Lapenta et al. (2020), and Jacobs (2021).

EPIC will embody four of NOAA’s foundational principles—a commitment to scientific integrity, a drive to transition innovative research to operations and product applications, a need to provide critical environmental data that are reliable, on time, and ensure our society and economy are safe and prosperous, and a goal to build an open and dynamic collaboration empowering the Earth sciences community.

The EPIC Vision Paper (Cikanek et al. 2019) proposes the value system upon which EPIC is built, establishing its seven core investment areas: software engineering, software infrastructure, user support services, cloud-based HPC, scientific innovation, management and planning, and external engagement and community (Fig. 3). EPIC’s seven pillars are essential to opening the UFS codebase to the community, partners who have insights into how to transform the forecast systems. NOAA remains 100% committed to the EPIC vision and is now inviting partners from across the Enterprise through its web portal and community workshops to engage in this unified effort for the benefit of society.

Central to the NOAA vision embedded in EPIC is the value proposition to drive and sustain the community partnerships built as part of the UFS development process in the last few years. EPIC will facilitate the expansion of the UFS to an Earth system prediction model, extending the current R2O (operations) paradigm to R2X (product applications, commercialization). The expanded partnerships will give more individuals the opportunity to make meaningful contributions to benefit the Enterprise and the public. EPIC applies an open-innovation and open-development software framework to amplify the respective benefits to private, public, and government stakeholders.
academic, and public sectors alike. Jacobs (2021) summarizes the co-benefits, indicating that private companies will have greater opportunity for customization, back-end value-added companies will have more accurate and reliable products, and cloud service providers (CSPs) will have a rapidly growing customer base. There is certainly risk to open development, but there are numerous examples of modern, open, community code development activities, where sophisticated and motivated developers understand that keeping codes aligned, with regular commits back to the code trunk, is the most efficient approach for software development, such as PANGEO (pangio.io). Furthermore, there is the expectation that an outstanding common product will be branded and recognized. For the academic sector, the UFS has joined other community NWP systems such as WRF and the open version of the European Centre for Medium-Range Weather Forecast’s (ECMWF’s) Integrated Forecasting System (IFS) in becoming a tool for classroom teaching and for basic research leading to new knowledge and scientific journal publications. The public sector, through NOAA, will ultimately benefit through improvements to the accuracy and confidence of the forecaster from better model skill.

**Tactical approaches**

NOAA has embarked on a unified approach to its forecast systems, drawing from the seamless suite of operational deterministic and ensemble weather and seasonal UFS-based prediction systems (Fig. 1). EPIC supports NOAA’s unification strategy by rolling out a single coupled modeling infrastructure with a select number of component models addressing both operational and research requirements, using an optimized software architecture. A high-level view of how EPIC will accomplish its value proposition is provided in Fig. 4.

EPIC’s goals to modernize software practices through cloud strategies and to use HPC resources more efficiently are foundational components to advance the UFS. Forecast improvements depend upon an optimal combination of more effective assimilation of observations, finer-scale model resolution, larger ensemble number, and coupled and complex systems.

**UFS Model and Infrastructure Ports to Cloud Service Providers**

User Support and Community Engagement to Accelerate Innovation

![Diagram showing the proposed EPIC approach for accelerating community innovations toward the development of the UFS.](image)

**Fig. 4.** Proposed EPIC approach for accelerating community innovations toward the development of the UFS.
all of which require keeping stride with advanced HPC technologies and methods. Industry practices that promote portable, efficient code to utilize complex computer architectures must build upon thoroughly documented and well-tested software. Programming (portability) models must be explored and employed that permit necessary flexibility between FORTRAN and more modern languages. To accommodate transition to operations, a hierarchy of hardware testing will be needed, with scientific testing in the research and development (R&D) environment, followed by testing within an emulated operational computational environment. Expanded utilization of modular and hierarchical codes, libraries, and machine learning tools will also facilitate development of more efficient approaches for model physics, data assimilation, and postprocessing.

EPIC embraces agile code management, in which incremental and iterative code improvements are subject to continuous testing and improvement, often within brief development sprints. EPIC will leverage the UFS code repository on GitHub and build out infrastructure to support code innovation and will transition select code innovation into NOAA by introducing DevOps collaboration and automation using Continuous Integration/Continuous Deployment (CI/CD) pipelines. DevOps is a practice of bringing development and operations teams together, focusing on constant testing and delivery. CI/CD pipelines offer an improved and automated approach that transitions the UFS toward modern software development methods. This framework allows community developers to track and demonstrate the status of their contributions and provides NOAA operational centers awareness of possible new methods and innovations. The agile approach underpins teamwork across the community to expedite code work. EPIC will provide training for users and developers, community partners who may run and test the code. These users need not worry about the agile development process. For developers that would prefer to hand off code developed within a distinct code branch or system, integration is still possible, but will be slower.

EPIC’s network of CI/CD pipelines will ensure that developer changes are frequently pushed to the shared repository. Automated code-management capabilities will facilitate rapid incorporation of innovation by implementing consistent and transparent, standardized and community-driven validation and verification (V&V) tests. Testing must occur on multiple levels: first, to ensure that the code accurately represents the intended calculation; second, unit tests routinely check each piece of code and monitor that new developments have not broken the intended calculation; third are test cases of the relevant model configurations and their datasets on selected on-premise HPCs, cloud service providers, and limited test environments; fourth, larger sections of code are tested against observations to check whether the system is accurately representing the Earth system.

Mediation strategies for monitoring the flow of innovative research through the R2O “funnel” (Fig. 5) are required for allowing the modeling community to develop and deploy criteria for selecting mature algorithms. As stated in Jacobs (2021), “EPIC should serve as the R2O funnel that aggregates development from the broader community, including NOAA, and manages layers of testing and refinement with the objective of improving NCEP’s operational UFS. This will be done through an open and transparent process, where the community plays a role in the development and validation of new ideas.” NOAA operations, at the base of the funnel, shares and incorporates its criteria that are applied increasingly as codes approach operations (Tolman and Cortinas 2020). As NOAA’s modeling increasingly addresses other product applications in addition to operational systems, the funnel construct is expanded to apply to R2X. The funnel model for research to operations/applications transition helps the UFS specify steps to identify the maturity of innovative and iteratively improved code and facilitates NOAA’s transition to an automated CI/CD approach entailed in EPIC’s DevOps and agile practices. To assist mediation, the maturity of community innovations as they journey from research to operations are identified using NOAA’s readiness levels (Cernter et al. 2020),
with low levels depicting new research and innovations and high levels depicting implementation into operations/applications.

An example of early UFS infrastructure improvement is EPIC’s management of UFS workflow—the software utility that drives the constellation of coupled models that make up the UFS codebase. Working with the broader UFS community, EPIC is developing UFS structure and standards. Lack of communication and coordination in developing UFS forecast application-specific workflows has led to completely different workflow systems that do not follow the same standards (UFS Workflows Workshop Report 2020⁷). As a result, the UFS has a proliferation of workflow styles that is impeding collaboration and community engagement. A harmonized workflow will help integrate many shared components across community models and forecast application scales. A wide array of forecast application- and platform-agnostic tools in object-oriented Python will be developed. Any forecast application can assemble a unique suite of these tools for its needs. Such a unified workflow framework will follow the agile methodology of iterative development, where requirements and solutions will evolve through collaboration between the development and forecast application teams.

Figure 6 illustrates EPIC’s strategic base and tactical approach. The constant flow of communication between research and operations and transparent testing mirroring operational requirements are critical for community engagement leading to accelerated operational improvements. At the heart of this process is a community infrastructure with codes made publicly available on GitHub. UFS infrastructure and virtually all its component models, supporting datasets, and test cases are available to the public. This includes two self-contained forecast applications—the Medium- and Short-Range Weather Apps, MRW and SRW, respectively. EPIC will expand these features, ensuring the UFS code is portable to cloud and standard HPC environments. The community will not only have access to UFS codes—EPIC empowers everyone to create new code, using the tools and data needed to innovate.

By June 2023, EPIC will have released cloud-ready versions of the MRW and SRW. EPIC will initially focus particularly on the SRW system (Fig. 7) and the land component and will develop an end-to-end, research-to-operations process for these forecast applications before turning attention to the other systems. The UFS land component is relatively immature, and it has been widely acknowledged that the choices of land surface processes and their coupling with atmospheric components for UFS applications are critical for UFS forecast skill at various scales. EPIC can provide a hierarchical development framework, including offline and coupled land–atmosphere interaction cases at various resolutions, to foster a unified collaboration approach.

Within 5 years, EPIC will also expand cloud and user support to include the subseasonal-to-seasonal forecast system and some of the highest-priority NOAA Earth system components, such as coastal, fire, and atmospheric composition. EPIC also aims to establish an integrated community development environment using in-cloud and on-premise HPCs to accelerate the flow of innovation all the way to operations, including harmonization of data and testing environments to continuously integrate with operational centers.

**Steps to Support UFS Short-range Weather Application in the EPIC Framework**

- SRW release in the cloud with documentation and necessary data for testing
- Library of test cases for challenging forecast environments
- Training for SRW users and developers
- Benchmarking against verified baselines for skill and computation
- Seamless transition to operations by harmonizing research and operational CI/CD pipelines

Fig. 6. EPIC’s facilitation of a constant flow of communication between research and operations and transparent testing mirroring operational requirements is critical for community engagement leading to accelerated operational improvements.

Fig. 7. EPIC’s steps to support the UFS Short-Range Weather Application.
Key success indicators or metrics for EPIC include the number of community contributors to UFS, the speed at which a new code contribution is delivered to operations or product application, and the improvement to the skill of the forecast system. As these metrics are further refined, they will appear on the EPIC Community Portal for easy reference by the community.

It will take time to observe the fruits of the EPIC vision in terms of model advances. Establishing the process and technological elements of the community modeling framework will be critical for success, as will the cultural accommodation of serving an operational entity. Equally as important, however, is the continuous engagement needed with the community to gain buy-in to the EPIC vision and incentives to work within the community modeling framework. In the long run, this new paradigm will accelerate the pace of modeling advancements. The EPIC program is establishing metrics to quantify the integration of innovations into the UFS and the rate of innovation transition toward operations by taking advantage of statistics in code commitments, merges from community code repositories, and automating and tracking the clearance of testing hurdles.

Organizational support
EPIC aspirations require alignment across NOAA as a firm basis for engagement to external community partners. This section first describes NOAA’s internal support for EPIC followed by some of the key external partnerships already in place with EPIC.

EPIC itself is a modestly sized program within NOAA’s Weather Program Office (WPO), part of NOAA/Oceanic and Atmospheric Research (OAR). The contract to support EPIC, or “virtual center,” was awarded to Raytheon Intelligence and Space, a division of Raytheon Company. The Raytheon contract includes subcontracts to several private companies with extensive experience in NWP, and the team brings proven expertise in scientific leadership, software engineering, software infrastructure, and delivery of support services to government, academia, and industry researchers who will collaborate within the EPIC framework. Over the next five years, EPIC’s virtual center has a contract ceiling of $45 million. Additional EPIC program resources support infrastructure for data assimilation and for engagement with community partners. Additional partnerships come through other programs and projects within OAR and NWS, where the next-generation forecast system is under development. Partner project opportunities are already available within WPO’s annual Notices of Funding Opportunities (NOFOs). These and similar NOFOs are now allowing applicants to budget for cloud computing, which will be vital for engaging with EPIC.

OAR’s Laboratories and Cooperative Institutes (CIs) are among the early EPIC partners. The majority of NOAA’s current Earth system and NWP modeling comes from the OAR laboratories, which benefit from colocated CI partnerships (Ackerman 2007). CIs are academic and nonprofit research institutions that conduct research in support of shared goals and strategic plans. NOAA currently supports 20 CIs and 70 universities/research institutes across 28 states and the District of Columbia.

NOAA’s NWS is a key partner for EPIC, since this is where most of NOAA’s NWP forecast systems are finalized and delivered into operations. Preparations for operations occur at the Environmental Modeling Center (EMC) and other centers within National Centers for Environmental Prediction (NCEP) and are supported by NWS’s Office of Science and Technology Integration (STI). In recent years, NWS and OAR have been jointly sponsoring projects to develop next-generation forecast models by teams of scientists from both inside and outside of NOAA. Examples include the Unified Forecast System Research to Operations (UFS R2O) Project, the Hurricane Forecast Improvement Program (HFIP), and various supplemental projects. The final testing and
delivery of innovations into operations occurs at NWS/NCEP Central Operations (NCO); EPIC will work with NWS and NCO to help ensure that community innovations can pass NCO’s rigorous testing and implementation standards.

Another key collaborator is the NOAA/National Environmental Satellite, Data, and Information Service (NESDIS), where much of the observational data required to drive the forecast systems are collected and prepared. NESDIS is also pioneering the use of cloud computing as a mechanism to rapidly and securely transmit observations and will collaborate with EPIC to gain efficiencies in cloud data optimization and computing efforts. EPIC also works with NOAA’s Office of the Chief Information Officer (OCIO) on computing, data, and software components. Computing resources and data storage for EPIC, both on premises and cloud, are provided with and by OCIO. EPIC objectives to advance in software standards and model performance will be pursued in partnership with OCIO.

As the UFS forecast systems evolve toward Earth prediction systems, the collaborations with NOAA’s National Ocean Services (NOS) and National Marine Fisheries Services (NMFS) are also essential. NOS supports community coastal ocean systems that are joining the UFS to provide a coastal application that will be appropriately coupled with other UFS components. In time, the UFS will also be coupled with NWS’s Office of Water Prediction (OWP) NextGen National Water Model to provide hydrologic elements of the Earth system. Even longer term, and as appropriate to the needs of weather and ecosystem forecasting requirements, careful coupling among physical and ecological ocean systems developed by OAR, NOS, and NMFS may be included in the UFS.

In recent months, NOAA established a NOAA Modeling Board (NMB) to align and coordinate modeling efforts across its Line Offices, which will be instrumental for adopting the full vision of EPIC. The NMB includes representatives from all the NOAA line offices engaged in modeling, including OAR, NWS, NESDIS, NOS, and NMFS. The NMB has interests in numerous community activities, each with its own business and organizational practices. Under the NMB, there is opportunity to better understand and consider opportunities and challenges for optimal integration of the various forecast systems under development across NOAA. The NMB will become the central touchpoint connecting NOAA to the broader modeling community and other government agencies.

We shift focus now to some of the existing external partnerships that EPIC inherits from the UFS. UFS data assimilation is developed in partnership with UCAR’s Joint Center for Satellite Data Assimilation (JCSDA), where NOAA and several other agencies collaborate to fund and develop the Joint Effort for Data Assimilation Integration (JEDI; Tremolet and Auligne 2020). Support for infrastructure, testing and evaluation, multiagency software, and various community activities occurs through the Developmental Testbed Center (DTC). Jacobs (2021) describes additional infrastructure developed in partnership with NCAR, based on the NOAA–NCAR 2019–24 Memorandum of Agreement (MOA). Support backing the MOA has resulted in several powerful software and infrastructure collaborative developments, including the Common Community Physics Package (CCPP; Zhang et al. 2021), the Model Evaluation Tools (METplus; Jensen et al. 2019), sustained support to the Earth System Modeling Framework (ESMF; Hill et al. 2004), and the Community Mediator for Earth Prediction Systems (CMEPS). These software packages are examples among many in which the UFS and EPIC share modeling infrastructure with other community Earth system scientists, making it easier to integrate community innovations into NOAA’s forecast systems. Furthermore, essentially every component of the UFS is being developed collaboratively with other federal, academic, and private partners. Beginning in 2022, leadership of the UFS is provided through UCAR, who selected and employed a UFS Chief Science Advisor for a 3-year term.
To support community engagement from an organizational perspective, EPIC is facilitating the establishment of a UFS community board, somewhat complementary to the NMB. While EPIC, through its website EPIC Community Portal (ECP), addresses and incorporates technical requirements from the community, this Community Modeling Board (CMB) will engage UFS partners at a high level, provide oversight to the UFS, and represent community interests to the NMB. The CMB may include representation from the NMB to ensure effective communication and alignment. The coupled NMB–CMB system (Fig. 8) provides transparent, two-way visibility and mutual understanding of environmental modeling priorities, helping converge efforts across governmental and nongovernmental modeling communities toward outcomes that benefit all.

In addition to establishing priorities, the boards will oversee tactical challenges such as determining the decision processes for the movement of innovations through the R2O/R2X funnel toward operations and product applications. Although NOAA must retain responsibility for the operational system choices (at the base of the R2O funnel), the broader community will have considerable influence on the processes and decision points for the UFS research and development (higher in the funnel).

**EPIC Community Portal**

The EPIC Community Portal (ECP), EPIC.NOAA.gov, is a web-based system that is improving collaboration, engagement, and inclusion toward innovating the UFS (Fig. 9). Since launching in January 2022, the ECP has attracted more than 7,000 new users. The ECP is already actively providing access to code and development tools and UFS-focused information. It will enable validation of innovative code contributions and interactive collaboration.

The ECP amplifies outreach and community engagement through documentation, training opportunities, and a comprehensive set of tools for users to access underlying software infrastructure components supporting the UFS, such as the GitHub repository and the CI/CD pipeline. User-support services available through the ECP enable real-time interaction with EPIC’s community infrastructure users to quickly resolve issues, escalating urgent requests to code managers and engineers supporting the UFS. The ECP provides statistics on UFS code engagement, including total number of code contributions, which at the time of this writing...
are 247 and 285 for the weather and short range applications, respectively, since the first major UFS code release in March 2021.

Community feedback obtained through the ECP facilitates incorporation of code user and developer perspectives and requests to align future EPIC directions with technology advancement, changing guidelines, and shared opportunities. This openness maximizes flexibility and encourages broad diversity of thought to produce the best outcome for the Earth sciences community.

The ECP will also support scientific code hackathons, code sprints, and workshops, providing additional opportunities for bringing community innovations into the UFS codebase. A cloud cost calculator will enable researchers to estimate the cost of running the UFS on various platforms using tunable parameters, directly supporting UFS applications for research. A dashboard will allow users to monitor community engagement with the UFS, such as GitHub activity and the effectiveness of the R2X/X2R process in transitioning innovations into the UFS codebase. Through the ECP, UFS users and developers can create communities of interest and practice to open more avenues for innovation with NOAA and the Enterprise. Access to the ECP ensures responsiveness to the needs of all community members, reducing barriers to innovation and accelerating the emergence of groundbreaking research.

The ECP is part of a communications and outreach ecosystem connected to the UFS Community Portal (UFS.community.org), a complementary engagement web presence that provides public information about the UFS community, access to UFS governance documents, and publications such as news items of interest and the quarterly bulletin of the UFS community. The launch of the ECP has stimulated renewed interest in the UFS website, with the number of new users accessing both websites growing steadily. The websites provide UFS code developers, forecasters, scientists, students, and the general public access to a wealth of information, including a usability test—the Graduate Student Test (GST)—designed to measure the usability of the UFS code and engage the broader community in NOAA’s model development process.

Fig. 9. The EPIC Community Portal, EPIC.NOAA.gov, forms a complete ecosystem for community interaction across the broad objectives of EPIC, ensuring a coordinated approach for developing the UFS and supporting NOAA’s R2X/X2R mission.
Societal benefits

Murphy (1993) proposed that “forecasts have no intrinsic value. They acquire value through their ability to influence the decisions made by users of the forecasts.” For EPIC to successfully contribute to the vision of a Weather-Ready and a Climate-Ready Nation, forecast advancements generated through the program must be deployed operationally and connected to decision-makers of all types. Model forecasts in turn must be understandable and trusted by forecasters across NOAA and the Enterprise, who are in turn trusted by end users.

As shown in Fig. 10, taken from Uccellini and Ten Hoeve (2019), observations and numerical weather prediction provide the basis for accurate and actionable forecast products and services for forecasters. Forecasters then develop impact-based decision support services (IDSS) for core partners based on these forecasts. In turn, along with a strong community engagement, IDSS becomes the linchpin for the societal outcomes embedded in the Weather-Ready Nation vision, including lives saved, property damage mitigated, and a more ready, responsive, and resilient nation. It is essential for EPIC to also receive input from the forecasters. In 2019, NWS convened three workshops13 including both UFS modelers and forecasters to discern the greatest concerns of the forecasters regarding the forecast models (Sims et al. 2021). In addition to periodically convening workshops such as these, EPIC will directly engage forecasters as model users and developers.

The promise of EPIC is to bring together the broader research community to advance NWP and eventually Earth system prediction. With its successful implementation, EPIC will improve NOAA’s public safety mission and make forecast advancements that the entire Enterprise can use to tailor forecasts for a variety of economic sectors. Therefore, EPIC should become a critical component of the weather value chain (Fig. 11), improving numerical models to meet society’s growing needs for better weather, water, and climate products, services, and decision support. As societal and physical changes exacerbate the impacts of extreme weather,
these improved forecasts will result in significant societal benefits for the nation, ranging from improved preparedness and response to extreme weather to economic growth, risk mitigation, and service equity.

Numerous studies have shown that the return on investment of better weather forecasts and climate information is substantial. For instance, the World Bank estimates that highly weather-sensitive sectors could benefit by over $160 billion from improved weather forecasts and climate projection, with a cost–benefit ratio of 1:26 for certain observational systems (Linn et al. 2021). Willingness-to-pay studies have shown that the value of better weather or climate forecasts, when applied to the U.S. population, is in the hundreds of millions to billions of dollars per year (Wehde et al. 2021). For example, NOAA found that the value provided by weather forecasts is 6.2 times the cost of producing them, with $5.1 billion in spending (both private and public sector) creating $31.5 billion in economic benefit.

The goal of EPIC is to improve the middle of the weather value chain, optimizing the billions of dollars spent by public and private organizations on global Earth observing systems and numerical weather prediction toward generating more accurate model forecasts and ensembles across a range of phenomena and time and space scales. These improvements will not only generate more accurate near-term weather forecasts, but will also improve the continuum of weather-to-climate forecasts, including those in an extended S2S timeframe. And, through improved reforecasts and reanalyses, these advancements will allow forecasters to put extreme weather events into a climate context for decision-makers. For NOAA and the nation to realize these modeling improvements, it will require corresponding investments in better postprocessing products and tools to create realistic dispersive ensemble forecasts that showcase the range of possible scenarios, training and two-way collaboration with forecasters to build trust in these new models, and social science research to optimize understanding and communication of these forecasts to decision-makers and the public.

Finally, there is also the potential for substantial economic value to be generated by America’s weather and climate industry while adapting UFS source code for their purposes. If the value of a forecast to a user is greater than the publicly available forecast, a market exists for industry to provide a better forecast. The investment in an accurate, state-of-the-art, easy-to-use open source modeling suite, facilitated by EPIC, can lower the barrier to entry for new companies to engage in the UFS and also gain access to the testing requirements for NOAA R2O. Working with and through the CMB, industry can be welcomed into the UFS collaboration community, can adapt and upgrade the code as needed, and in turn generate high levels of economic value across a number of weather-sensitive industries such as agriculture, energy, retail, insurance, and tourism. As of 2017,
it was estimated that the market value of the weather industry was $9B and growing at 10%–15% per year (NWS 2017).

The good news is that the benefits are not entirely one-way from government to industry. The goal of EPIC is to capture some of these innovations over time from industry using the code, while still allowing companies to maintain their competitive advantage. Why would they do this if a company maximizes their profit by maximizing the difference between their proprietary forecast and a publicly available forecast? A company may find it in their best interest not to stray too far from the latest model version in order to take advantage of recent upgrades, to be competitive for funding opportunities and other advantages of keeping alignment with the UFS and CMB community.

Overall, EPIC provides value to the community through 1) providing an effective framework and support for researchers/developers within the entire public–private Enterprise to accomplish their objectives, 2) accelerating the incorporation of community-driven innovation into the operational numerical model suite for the benefit of society, 3) improving the communication between researchers and NOAA operations, and 4) connecting scientists across government, academia, and industry to address operational needs. With and through the CMB, the UFS will be positioned to optimally coordinate with other community NWP activities such as those associated with NCAR’s MPAS and WRF.

**Conclusions and a look forward**

Innovation has been part of NOAA’s services and products throughout its 50 years of history. With the establishment of the EPIC program and the organizational structures within and outside NOAA to support EPIC, NOAA is establishing a new way of advancing numerical weather and relevant Earth system prediction. EPIC enables everyone in the Enterprise to participate to their fullest extent and enables the potential to dramatically accelerate innovative research contributions. The next-generation forecast systems will use a coupled Earth system, driven by coupled data assimilation, and ensembles needed to provide quantitative forecasts of uncertainty. This system will advance forecast information for Earth systems, including coastal systems, fires, ocean ecosystems, and air quality, in addition to extending forecast information for severe weather, tropical storms, heavy precipitation, and extreme temperatures out to subseasonal-to-seasonal time scales.

NOAA is embracing a fundamental change into the development and advancements of the operational model suite based on a fully coupled Earth system science approach and addressing all scales from the mesoscale short range to the seasonal to subseasonal predictions across the linked weather–water–climate domain. EPIC joins and supports a collaborative development and application approach across NOAA and with the larger external research communities. The changes provided by EPIC represent a historic opportunity to work across the Enterprise to create the best operational Earth system model forecast capabilities serving societal needs in the face of increasing vulnerabilities to a wide range of extreme weather, water, and climate events. If challenges are faced head on, understanding rather than fearing risk, the Weather Enterprise will together create a sustainable, collaborative, and well-orchestrated development framework with trust, openness, and engagement.

While the community of developers matures the process of accelerating innovations-to-operations/applications at the research level, EPIC’s vision may eventually extend into the transition of that research into NOAA’s operations and applications. Although presently beyond the scope of EPIC, an end-to-end innovations-to-operations/applications process could result in code updates completed on the order of months or even weeks, instead of years, as is currently the case. These longer-range goals for NOAA and EPIC will be pursued once the initial software engineering groundwork is established and as resources permit. At that stage, the model development community will evolve into a new paradigm where the
Weather Enterprise as a unified entity will be closely collaborating to build together the Earth prediction system of the future, tapping into a yet unrealized additional wealth of scientific community knowledge. This new paradigm and capability could, in theory, help increase the value of the Enterprise by an order of magnitude.

The ensuing success of a unified Weather Enterprise will greatly benefit the nation through unifying the weather community around a shared value proposition—providing the best possible weather forecast for the U.S. population.

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