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NOAA's Great Lakes Wave Prediction System

A Successful Framework for Accelerating the Transition of Innovations to Operations

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ABSTRACT: The establishment of the Great Lakes wave forecast system is an early success story inspiring the introduction of open-innovation practices at the U.S. National Oceanic and Atmospheric Administration (NOAA). It shows the power of community modeling to accelerate the transition of scientific innovations to operational environmental forecasting. This paper presents an overview of wave modeling in the Great Lakes from the perspective of its societal benefits. NOAA's operational wave modeling systems and development practices are examined, emphasizing the importance of community- and stakeholder-driven collaborative efforts to introduce innovations such as using advanced spatial grid types and physics parameterizations, leading to improved predictive skill. The success of the open-innovation approach, set in motion at NOAA by initiatives such as the Great Lakes wave forecasting system, accelerated the transition of innovations to operations. The culture change to operational modeling efforts became part of the foundation for establishing the Unified Forecast System and, more recently, the Earth Prediction Innovation Center. Open-innovation initiatives will improve operational weather and climate forecast systems through scientific and technical innovation, reducing the devastating impacts of hazardous weather and supporting NOAA's mission of protecting life and property and enhancing the national economy.

KEYWORDS: Oceanic waves; Numerical weather prediction/forecasting; Operational forecasting; Wind waves; Ocean models; Community

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The concepts of open development and open innovation have been successfully used in private industry to accelerate the transition of innovative ideas into new products. Public services in Europe, Southeast Asia, and, more recently, the United States have followed suit. In this paper, we document the development and implementation of the Great Lakes wave (GLW) forecast system as one of the success stories that inspired organizational change in the recent transition of numerical weather prediction systems to open development at the National Oceanic and Atmospheric Administration (NOAA). New practices introduced in the GLW development process helped inspire culture change at NOAA, showing the power of community modeling to accelerate the transition of innovations to operations.

In the early 2000s, NOAA introduced community modeling practices at its National Centers for Environmental Prediction (NCEP). Among the trailblazing community models adopted by NCEP were the WAVEWATCH III wave modeling framework (Tolman 1991; Tolman et al. 2002), the Community Radiative Transfer Model (CRTM; Weng et al. 2005), the Great Lakes Operational Forecast System (GLOFS; Chu et al. 2011), the Hurricane Weather Research and Forecasting Model (HWRF; Tallapragada et al. 2014, 2015), and the SWAN model (Booij et al. 1996) as part of NCEP's Nearshore Wave Prediction System (NWPS). New development practices in these systems inspired a new vision for NOAA's modeling enterprise and operational production suite road map (Tolman and Cortinas 2020a,b), leading to the advent of the Unified Forecast System (UFS) and the creation of NOAA's Earth Prediction Innovation Center (EPIC). All these initiatives reflect an agencywide effort to transform NOAA's model development paradigm to a community-driven, open-development framework, as reflected in recent papers by Jacobs (2021) and Uccellini et al. (2022).

Here we will use the development of the GLW forecast system, an implementation of the WAVEWATCH III (henceforth denoted as WW3) model, to illustrate these changes in the paradigm of operational model development. The establishment of community modeling practices in the WW3 model and application development was part of a National Oceanographic Partnership Program (NOPP) project (Tolman et al. 2013), supported by the Office of Naval Research (ONR). NOPP funded several projects that improved general wind-wave modeling and introduced modern code and application development techniques to accelerate the transition from the modeling community innovations to NOAA operations.

Using the wave model as a scientific inquiry tool, Ardhuin et al. (2010) developed a novel empirical parameterization of wind input to waves and dissipation mechanisms that significantly improved the predictive skill of NOAA's wave models. The newly developed technology was introduced into NCEP's global deterministic wave model, becoming operational in 2012 (Chawla et al. 2013). Thanks to the interplay of an open-source WW3 code and emerging open-development practices adopted during the NOPP project, innovations transitioned to operations in less than two years.

The successful ideas introduced in the NOPP wave projects were adopted by the wave modeling team at NCEP in a stakeholder-driven model development approach further established in the GLW system development. The result led to an accelerated flow of innovations into the NOAA's wave modeling systems and the fast transition of innovations such as advanced unstructured meshes and physics parameterizations. Below, we explore the effectiveness of open development for accelerating the innovations-to-operations (I2O) transition at NOAA by describing the implementation process for the GLW, from ideation to operational implementation.

The second section provides an overview of wave modeling in the Great Lakes and its societal benefits. The third section summarizes NOAA's operational wave modeling systems and development practices. We examine the collaborative effort to develop and innovate the GLW system in the fourth section, considering the impact of spatial grid types and physics parameterizations on predictive skill. The fifth section provides a brief discussion of new initiatives made possible thanks to the success of the open-innovation approach introduced to the future of wave model development and accelerating the innovations-to-operations process within NOAA. The sixth section provides concluding remarks. Note that the manuscript focuses on the transition process of innovation to operations. In this context, we refer to actual innovations as examples of benefits to operational applications without a complete discussion of scientific merits beyond the scope of this paper.

Societal benefits of wave forecasts in the Great Lakes region

The Great Lakes basin aggregates more than 1/10th and 1/4th of the U.S. and Canadian populations. Sixty million people live in what is the largest megaregion in America. Large cities sprawl their coasts, and their inhabitants intensively use lake waters and shorelines for work and leisure. Drownings are frequent. According to the Great Lakes Surf Rescue Project,[1] about 1,000 people perished on the Great Lakes' shores between 2010 and 2019. Rip currents and persistent currents become stronger when large storm waves reach the coast, causing more than 90% of these incidents.

Several states with significant contributions to the American economy surround the Great Lakes. Commercial shipping constitutes one of the most cost-effective means of transporting raw materials and goods to and from the states of New York, Pennsylvania, Ohio, Michigan, Indiana, Illinois, Wisconsin, and Minnesota. The Great Lakes Shipwreck Museum estimates that around 6,000 shipwrecks have caused the death of 30,000 people.[2] The most famous is the loss of the ship *Edmund Fitzgerald* on Lake Superior on 10 November 1975. An intense storm produced winds with gusts stronger than hurricane force on Lake Superior, generating waves with significant wave heights larger than 7.5 m (Hultquist et al. 2006). The *Edmund Fitzgerald* sank, and all 29 crew members perished.

Accurate forecasts of wind waves are a critical service for ensuring the safety of people, coastal property, and maritime operations in the Great Lakes. Since 1974, marine forecasting in the Great Lakes region has been performed systematically following the creation of NOAA's Great Lakes Environmental Research Laboratory (GLERL). In association with researchers at the Ohio State University, GLERL developed technology for producing wave forecasts for the Great Lakes in the early 1980s. The early approach used a parametric, first-generation wave model described by Schwab et al. (1984) and integrated GLERL's Great Lakes Coastal Forecasting System (GLCFS; Schwab and Bedford 1996). With the advent of third-generation wind-wave models in the late 1980s, a next-generation forecast system was codeveloped

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[1] https://glsrp.org

[2] www.shipwreckmuseum.com/underwater-research/shipwrecks/

successfully within NOAA's operational wave model framework as part of the official suite of operational environmental forecast models at NCEP. The effort brought together GLERL's experience and new technologies available at EMC to better address forecasters' needs.

NOAA's wave models and development practices

Operational wave models at NOAA have provided forecast guidance to the National Weather Service (NWS) since 1956 [see Tolman et al. (2002) for a review of early efforts]. In the 1990s, the agency developed a third-generation spectral wind-wave model (Tolman 1998) which became operational in 2000. The WW3 model evolved from an institutional model to an open-source package (Tolman 2007), setting the stage in the 2000s for the transition in NOAA's numerical weather prediction (NWP) model development paradigm toward a community modeling approach.

WW3's version 1.18 (Tolman 1999), the first operational implementation of NOAA's new wave model, was made available to the general public as "freeware" several months before its first operational implementation at NCEP. Its third public release (version 3.14; Tolman 2009) introduced a custom-designed formal open-source license. The original WW3 model effectively became a community model[3] with several thousand users in more than 100 countries. At that time, the transition of a new model from research to operations would typically take between five and seven years. NOAA's wave model is now available on GitHub, as described below.

The latest publicly released WW3 package, version 6.07.1,[4] includes state-of-the-art scientific advancements in wind-wave modeling and dynamics. The wave model solves the random phase spectral action density balance equation for wavenumber-direction spectra, including options for shallow-water applications, the surf zone, and the wetting and drying of grid points. Propagation of a wave spectrum can be solved using rectilinear or curvilinear (regular), triangular (unstructured), and spherical multiple-cell (SMC) grids, individually or combined into multigrid mosaics. Options to use quadtree adaptive grids developed via external collaboration are also available (Popinet et al. 2010). The model package user manual (WW3DG 2019)[5] provides a comprehensive description of model features.

Alongside HWRF and CRTM, WW3 became one of the first models at NCEP to transition toward an open-development paradigm, starting with a custom open-source license. From 2015 to 2019, community development of the wave model was enabled through code management using Subversion (Pilato et al. 2008) and NOAA's Virtual Laboratory (VLab; Burks et al. 2019). In 2019, WW3 was the first model at NCEP to have its code management moved to GitHub.[6] Code management tools like the Apache Subversion versioning system (SVN) and GitHub allow developers to add features to the existing framework, including new science, technological advancements, improved performance, and bug fixes. Coding standards ensure a practical collaborative framework by setting clear rules and coding ethics. The latest code management approach used in the wave model follows the GitFlow model (Driessen 2010).

GitHub is a user-friendly implementation of the free, open-source distributed version control system git.[7] Code management in git evolves within projects inside version-controlled repositories—directories in a server that can be either a personal computer or the cloud. NOAA's wave model has one central repository, the so-called authoritative repository, part of the NOAA organization maintained by EMC at NCEP. Currently, the WW3 code-management system has

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[3] Export regulations at this time prohibited sharing the code with five specific countries. Once EMC established that the request did not come from these countries, the code was shared free and open in a full-access SVN repository. This restriction is no longer enforced with NOAA's use of GitHub for code management.

[4] https://github.com/NOAA-EMC/WW3/releases/tag/6.07.1

[5] Note that parts of WW3 are also used with different grid approaches as in Popinet et al. (2010).

[6] Without the export restrictions applied to the original WW3 custom license as outlined in footnote 3.

[7] https://git-scm.com/

three additional "trusted" repositories hosted by the French Institute for Ocean Research (Ifremer), the Met Office, and the U.S. Army Corps of Engineers (USACE).

NOAA's authoritative WW3 repository[8] is used to produce public releases and is the central reference to all code copies. A developer may choose to create a GitHub fork from the authoritative or trusted institutional repositories. In the end, approved code changes become part of the central wave model repository managed by NOAA. Approval of code changes by code managers of the authoritative repository depends on passing rigorous regression tests prepared to scrutinize the code package with different numerics and physics options. If the modified code passed all regression tests and did not result in compilation or runtime errors relative to the stable master version, it becomes the new master.

NOAA's wave model development community includes collaborators from all over the world. WW3 has over 3,000 users in more than 120 countries and over 200 developers. It is also the operational wave model used by several leading international public weather service organizations, including the NWS, U.S. Navy, Met Office, the Australian Bureau of Meteorology (BoM), the Indian National Center for Ocean Information Systems (INCOIS), and the Canadian Meteorological Center (CMC), among others.

Great Lakes wave forecast innovations

The initial development of a Great Lakes wave forecasting system at NCEP using WW3 began in late 2004 as a collaboration between GLERL and EMC to upgrade the wave models to a third-generation approach and to move support for this model from NOAA research (GLERL) to NOAA/NWS operations. Since its early development stages, the team adopted a stakeholder-driven approach that favored the inclusion of key partners, in particular forecasters and science operations officers (SOOs) from 11 Weather Forecast Offices (WFOs) in the Great Lakes region (Fig. 1). All steps of the development process, including prioritizing requirements, developing design strategies, prototyping, and scientific testing, involved stakeholders.

The stakeholder-driven approach streamlined the development process and more closely addressed the needs of NOAA's marine forecaster community. The inclusive development

Fig. 1. NOAA's National Weather Service Weather Forecast Offices (red pins) in the North American Great Lakes. Gray lines illustrate NWS marine forecast zones and boundaries.

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[8] https://github.com/NOAA-EMC/WW3

framework spearheaded by the GLW inspired by a broader cultural change in EMC's wave model development process made it work as an incubator for new ideas, allowing for a documented conversion of field requirements into scientific and operational innovations. The focus on user requirements identified the need for high-resolution coastal wave model guidance and the need for addressing low biases in the wave model as the top two user priorities. Both issues were addressed in a community approach, as discussed below.

Spatial grids. The first WW3-based GLW system became operational in August 2006, featuring a traditional rectilinear single-grid domain with ~4-km resolution, including all five major Great Lakes basins—Erie–Saint Clair, Ontario, Huron, Michigan, and Superior (Alves et al. 2014). The GLW system ran eight daily operational forecast cycles alternating forcing wind fields from two sources: a regional deterministic atmospheric model and the forecaster-enhanced winds from the NOAA's National Digital Forecast Database (NDFD; Glahn and Ruth 2003).

Seeking a higher-resolution grid that would address requirements for storm wave forecasting, a Lambert-conformal spatial grid with a 2.5-km resolution was proposed leveraging research enabled by a community partnership between NOAA and the U.S. Navy (Rogers and Campbell 2009). After successful testing, the new grid became operational in January 2015, making the GLW the first operational wave forecasting system in a major international operational center to use a curvilinear grid. The higher-resolution grid improved the quality of wave forecasts due to a better representation of the complex lake-basin wind fetch geometry during rapidly changing conditions, a critical weather feature in the Great Lakes.

The next challenge was predicting wave conditions in the nearshore to improve small-craft advisories and coastal wave prediction. Most life-threatening nearshore hazards affecting the large transient population associated with recreational watercraft and beachgoers (including the rip currents mentioned above) are associated with moderate to high waves near the coast. Subtle changes in wave height [e.g., 0.3 m (1 ft)] can dramatically impact swimmer safety or the ability to operate a small boat safely. While such small changes in wave height can be challenging to represent due to the complexity of the nearshore physical characteristics, it is nonetheless a critical component of assessing risk for operational marine weather services.

An international collaboration team worked together to develop unstructured meshes with higher coastal resolution. Benchmark tests and code sprints, including engineers across multiple time zones, quickly proved the feasibility of using WW3 with a triangular mesh for Lake Michigan with competitive computational performance, good skill in predicting significant wave heights, and a better description of transformations near the coast. The international "tiger team" operated in an agile approach without formal help from NOAA other than existing WW3 code management support. The effort is a clear example of the power of community-driven open development for leveraging resources and sharing benefits among all participants.

After a brief proof-of-concept stage using a single Lake Michigan mesh, a prototype triangular mesh for the entire Great Lakes basin was successfully tested within NOAA's operational high-performance computing environment, with resolutions ranging from 250 m at the coast to 2.5 km in deeper offshore regions of lake basins. The differences in grid approaches are illustrated in Fig. 2 for the Leelanau Peninsula, Beaver and North Manitou Islands, Lake Michigan. In contrast, Fig. 3 illustrates the effects of the grid choices on small-scale wave features near the coast for the Green Bay area. In the latter, it is seen that the unstructured mesh resolves focusing areas where wave heights become significant, providing a much-improved depiction of nearshore features and wave transformation characteristics in the nearshore zone. Note that the largest wave height values in deep water

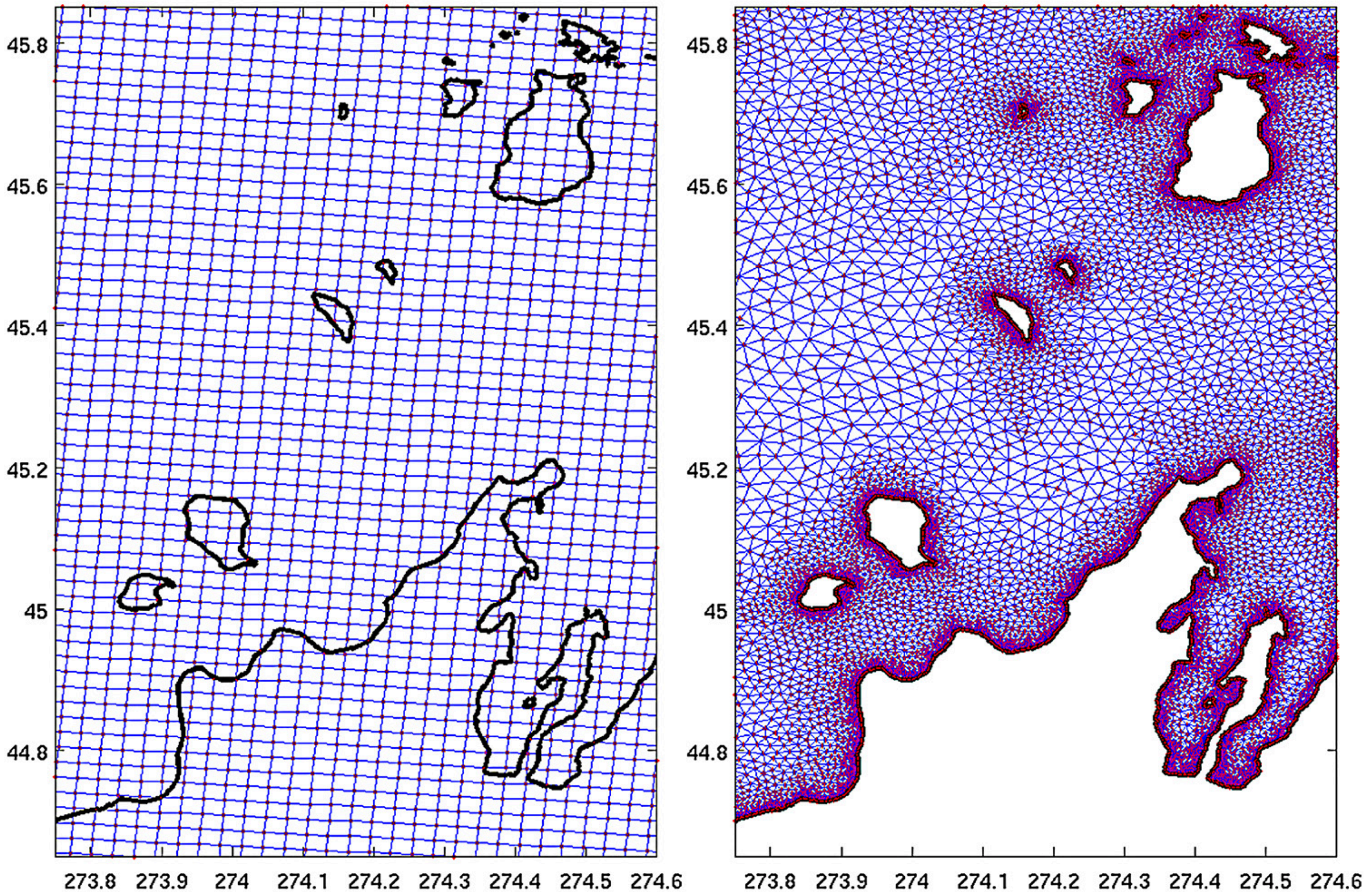

Fig. 2. Resolution differences between (left) curvilinear (Lambert conformal) grid at ~2.5-km resolution and (right) the unstructured mesh at ~2.5 km offshore and ~250 m at the coast. Leelanau Peninsula, Beaver and North Manitou Islands, Lake Michigan.

result from the effects of new physics parameterizations used in the upgraded system and that the purpose of the figure is to illustrate how the unstructured mesh allows resolving nearshore features more effectively.

The region's unavailability of nearshore measurement platforms precludes quantitative validation of nearshore improvements seen in Fig. 3. However, qualitative feedback from NWS forecasters confirms that the higher-resolution data improved their ability to identify observed regions of higher waves near the coast, with associated higher confidence in issuing small-craft advisories. Further testing performed at NCEP revealed that the unstructured mesh technology allowed enhancements in wave-field resolutions in the nearshore zone without exceeding the available high-performance computing resources but satisfying runtime for making forecasts available on time. The demonstrated improvements led to the operational implementation of the GLW system in 2017, making it the first operational wave model in a major international forecasting center to use unstructured triangular meshes. With this community approach to modeling using the operational code as a starting point, the transition of what is effectively a new model into operations only took about a year, a roughly fivefold reduction of the time needed to implement it operationally.

Parameterizations of physical processes. The continuous stakeholder engagement process supporting the development of new spatial grids allowed the identification of new priority features to be developed, addressing forecaster needs. One such priority affecting nearshore wave predictions in the Great Lakes was a systematic low wave-height bias

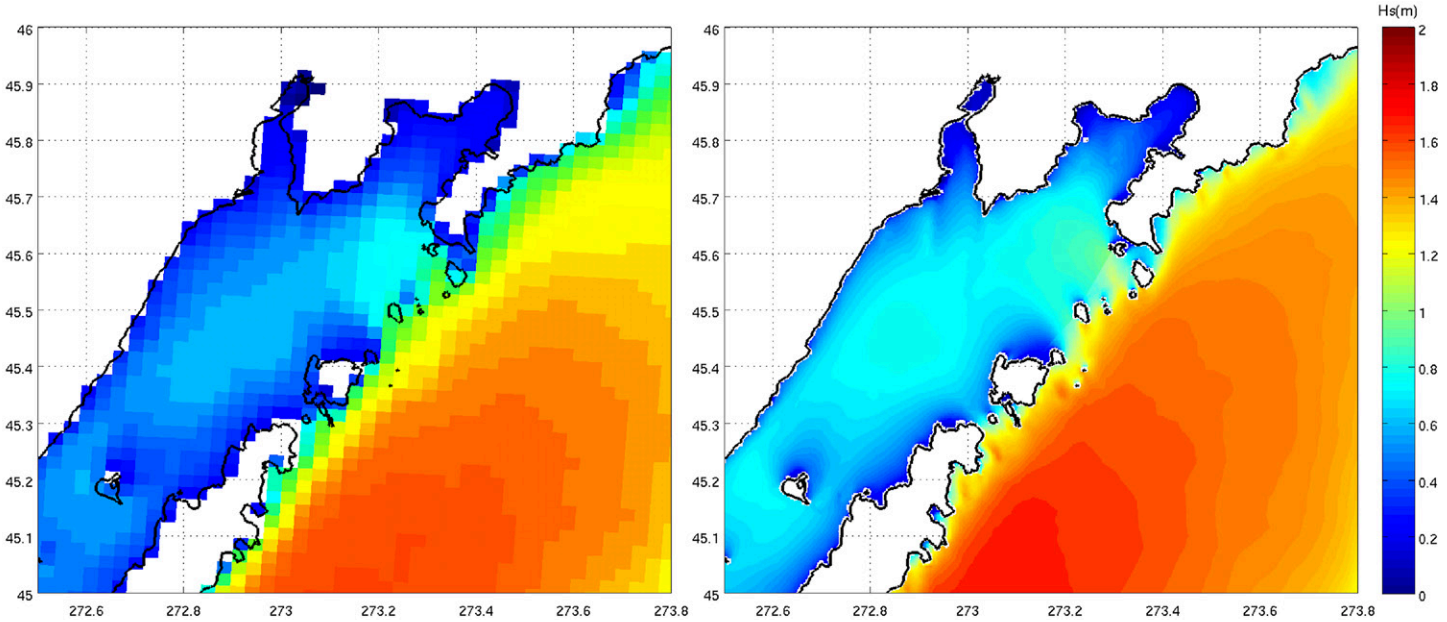

Fig. 3. Wave-height pattern resolution near Green Bay, Lake Michigan, illustrating the significant improvement in quality of simulated wave forecasts in the nearshore zone. (left) Original Lambert conformal grid and (right) upgraded unstructured mesh.

during persistent long-fetch events observed near the coast. During such events, wave fields propagate over long distances parallel to the coast. The low bias scores suggested a problem with wave generation and dissipation source terms. The working hypothesis was that lateral energy loss to coastal boundaries in the Great Lakes basins was damping wave growth, a known limitation of the discrete interaction approximation (DIA) for computing nonlinear wave–wave interactions that govern wave evolution (Hasselmann and Hasselman 1985).

A well-known feature of the DIA is the production of directional wave spectra that are too wide in both frequency width and directional spread. Therefore, wave growth in the narrow Great Lakes basins could be constrained laterally by the proximity of coastal boundaries due to the exaggerated directional spread imposed by the DIA. A more advanced wave–wave interactions parameterization would be a potential remedy for reducing low energy biases in nearshore regions. The generalized multiple DIA (GMD) wave–wave interactions source term developed by Tolman (2013), and optimized by Tolman and Grumbine (2013), produces narrower spectra more consistent with the “exact” but prohibitively expensive interaction formulations. Therefore, it was considered a promising candidate to remediate the GLW growth issue.

Figure 4 illustrates the impact of DIA and GMD on simulations of the wave spectrum. The figure shows the two-dimensional wave energy density spectrum at NDBC buoy 45170, in the nearshore zone near Chicago in southwestern Lake Michigan, during a strong fetch-limited event associated with a northerly wind flow on 1 July 2016. Note the significant difference in directional spread between DIA (left) and GMD (right) spectra,[9] as well as lower peak frequency and larger energy densities. The latter is narrower, leading to an integrated growth effect across the lake basin, which results in more focused wave heights near the coast and lower wave-height errors. Normalized standard deviations improve from 0.73 to 0.92, biases are reduced from −10 to −5 cm, and RMS error falls from 0.22 to 0.18. Improvements obtained in simulated wave heights are indirect evidence that the DIA produces directional spectra that are too broad relative to observations (Rogers and Wang 2007), and that narrower spectra provide a closer representation of observed long-fetch wave fields.

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[9] Using GMD configuration G13d from Tolman and Grumbine (2013).

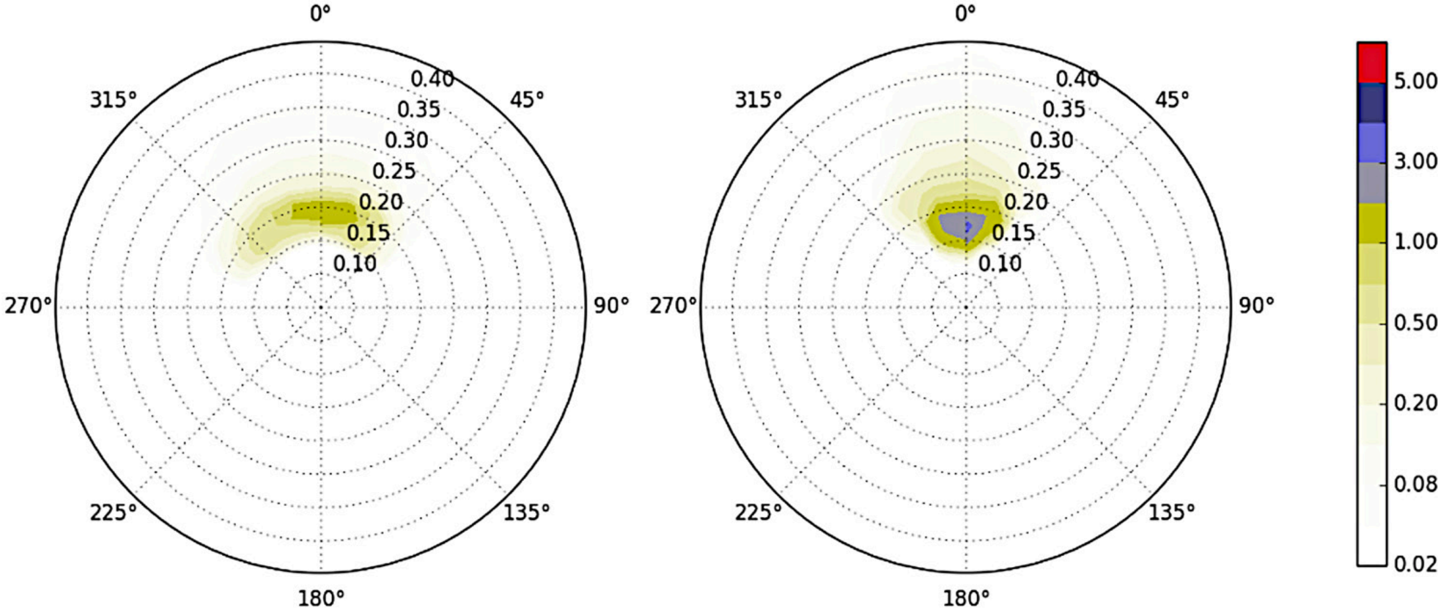

Fig. 4. Comparison of wave spectra using the (left) DIA and the (right) GMD at NDBC buoy 45170 in Lake Michigan.

We hope these assumptions will soon be validated quantitatively as new directional wave measurement platforms become available at the Great Lakes basin.

Impact of community innovations. Extended tests verified community innovations' impact and satisfied the requirements of transitioning them to the operational GLW system at NCEP. The validation effort consisted of comparing simulations from a hindcast period of six months in 2016 about data obtained from NOAA National Data Buoy Center (NDBC) buoys deployed in both nearshore (four buoys) and deep-water (six buoys) regions across all Great Lakes basins. Improvements in all validation statistics were consistent in deep and nearshore locations. On average, wave-height biases reduced from 5 to 0 cm, root-mean-square errors reduced from 25 to 20 cm, scatter indices fell from 20% to 18%, and normalized standard deviations against buoy data increased from 0.81 to 1.01 (where 1 represents perfect model behavior). The ratio of 95th wave-height percentiles between the model and buoy data went from 0.87 to 1.0. Validation statistics pointed to the improved skill of the upgraded system not only in terms of ambient conditions but also in predicting extreme wave conditions.

The partnership between NOAA, the scientific community, and Great Lakes stakeholders resulted in a transition of innovations to operations that took less than two years. In addition, the new model features allowed NCEP to generate wave guidance from deep to shallow waters with increased accuracy at all scales for average to extreme weather conditions. The resulting improved wave forecast system, employing a flexible framework including unstructured meshes and state-of-the-art physics parameterizations, was praised by the forecasting community as a game changer for its ability to provide more accurate small-craft advisories and nearshore wave forecasts.

Toward next-generation Great Lakes wave forecasts

The flexibility and accessibility of the collaborative open-development process adopted in the development of the GLW system seeded a new funding opportunity for investigating the benefits of implicit schemes to predict rip currents and coastal inundation in the Great Lakes region. As a partnership between NOAA and the USACE, this new initiative was fostered by the enactment of the Consumer Option for an Alternative System to Allocate Losses (COASTAL) Act (U.S. Congress 2011, S.1091). The effort allowed the development of a next-generation implicit numerical integration scheme capable of increasing coastal model resolutions to the order of meters and allowing more efficient parallel computing resources.

By adding a new parallelization algorithm and an implicit numerical solver, the WW3 model became more efficient and accurate, bypassing numerical restrictions (CFL constraints) on very large, high-resolution meshes (Abdolali et al. 2020). The enhancements provided a unique opportunity to incorporate water level and wave–current coupling effects and resolve complicated geometries in shallow water regions (Moghimi et al. 2020). Initial results were further enhanced thanks to recent efficiency improvements in WW3, which have made the code faster and eliminated the limit for the maximum number of CPU threads, allowing the allocation of more computational cores to the wave model.

The new developments expanded the ability to couple WW3 from global-scale systems, a recent NOAA achievement within the realm of the UFS, to coupling waves and nearshore hydrodynamic models. Such breakthroughs have expanded the ability of WW3 to be dynamically coupled with storm surge, hydrological, ice, and atmospheric models, providing opportunities to investigate nearshore wave climate (Bakhtyar et al. 2020). Associated efficiency improvements in WW3 have allowed one- and two-way coupled atmosphere–wave systems to run faster. Benefits have expanded toward evaluating uncertainty via ensemble modeling (Abdolali et al. 2021), which may contribute to existing operational wave ensemble systems at NOAA (Alves et al. 2013).

Concluding remarks

The history of WW3-based operational wave forecasting systems demonstrates the power of developing a modeling framework uniting NOAA and the broader community. The speed of transitioning scientific innovations to operations exemplifies its benefits. Early code development work for GLW took approximately three years in the early 2000s, and its first operational implementation took another five years. The subsequent GLW system development invited community modeling to introduce several innovations, including a new grid approach, parameterizations, and output options. By adopting a community modeling approach, all development work done by external codevelopers had effectively no cost to NOAA.

Once the work was mature, NCEP needed less than a year to do scientific testing of this code and less than a year to implement operationally—less than two years to transition innovations to operations. From NOAA's perspective, the last step in transitioning innovations to operations (the R2O process) for the GLW system was roughly a factor of 4–5 times faster than the first implementation. Note that the complexity of the latter implementation, using entirely new grids, numerics, and physics, is effectively the equivalent of implementing a new model.

The WW3 model is only one of the many components in NOAA's operational production suite. Its successful open-development approach strengthens the ongoing transition of NOAA's operational prediction systems toward the UFS to become a full collaboration with the broader research community.[10] Some of these collaborations precede the UFS effort, particularly concerning model coupling. Examples are the Earth System Modeling Framework (ESMF; Hill et al. 2004) and the National Unified Operational Prediction Capability (NUOPC; Sandgathe et al. 2011). In another example of the effort to strengthen NOAA's fundamental shift toward community modeling, parts of NOAA and the National Center for Atmospheric Research (NCAR) signed in 2019 a formal memorandum of agreement to develop infrastructure for joint model development.[11]

Similarly, data assimilation is moving rapidly to a community-based approach supporting research and operations through the Joint Effort for Data Assimilation Integration

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[10] See https://usfcommunity.org.

[11] See www.noaa.gov/media-release/noaa-and-ncar-partner-on-new-state-of-art-us-modeling-framework.

(JEDI; Tremolet and Auligne 2020). With that, all the components of this coupled UFS approach, including component models, data assimilation, infrastructure, pre-, and postprocessing tools, are managed in a community modeling effort similar to the one started by WW3, where some predate the WW3 community modeling effort. Altogether, these efforts expand and attest to the successful transition model developed within the scope of single-component systems such as the WW3 package and its application to the GLW. A broader discussion on how these advances actively apply to systems with multiple cross-dependent components, such as the UFS, is beyond the scope of this manuscript but may be found in recent papers by Jacobs (2021) and Uccellini et al. (2022).

NOAA's wave modeling approach is an example of a shift from internally focused efforts to a community-based framework. Part of this started with the original code design as a modeling framework with many options rather than a more focused traditional model. With this design, the NWS and partnering operational environmental forecasting centers, such as the U.S. Navy, Met Office, BoM, INCOIS, and CMC, can use different grids, numerics, and physics in their operational systems. Hence, they all use the WW3 framework but run different wave models effectively. Because all these centers refer to their model as WW3, this subtlety is often lost in translation. Nevertheless, it is essential for efforts like the UFS, as the slowly changing framework allows for both rapid transition into operations and the diversity in approaches needed for science simultaneously.

In the mid-2000s, WW3 development shifted to a full-blown community effort through the NOPP project, as mentioned in our introduction. The present manuscript documents the culture change this brought in the development of wave models in NOAA and the acceleration obtained with it for transitioning innovations to operations. Most importantly, it documents how much of the development work needed for operations was done outside of NOAA, often reducing costs at NOAA and sharing the benefits more effectively with the scientific community. It also demonstrates that the time it takes to transition such innovations to NOAA operations can now be done up to 5 times faster thanks to a community modeling approach.

The community/stakeholder-driven framework adopted by the GLW development team further debunked the perception that community modeling is a risk to operational forecasting systems concerning overhead for community code management and the quality of the resulting software. Instead, our experience has shown that the open partnership resulted in high-quality code that became more portable and easier to transition from innovation to operations. It also demonstrated that additional time spent by NOAA on code management became only a fraction of the time gained by reducing the level of effort needed for underlying code development and debugging and transitioning code to new hardware in general.

The WW3 model was not the only software package at NOAA to go through this culture change, but it was one of the first. Consequently, it served as a strong use case for propagating this culture change to all operational modeling efforts at NOAA. As such, it was part of the foundation for establishing the UFS and, more recently, NOAA's Earth Prediction Innovation Center (EPIC). Together, the UFS and EPIC will improve operational weather and climate forecast systems through scientific and technical innovation, reducing the devastating impacts of hazardous weather and supporting the NWS mission of protecting life and property and enhancing the national economy.

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References

Abdolali, A., A. Roland, A. van der Westhuysen, J. Meixner, A. Chawla, T. J. Hesser, J. M. Smith, and M. D. Sikiric, 2020: Large-scale hurricane modeling using domain decomposition parallelization and implicit scheme implemented in WAVEWATCH III wave model. *Coastal Eng.*, **157**, 103656, https://doi.org/10.1016/j.coastaleng.2020.103656.

——, A. van der Westhuysen, Z. Ma, A. Mehra, A. Roland, and S. Moghimi, 2021: Evaluating the accuracy and uncertainty of atmospheric and wave model hindcasts during severe events using model ensembles. *Ocean Dyn.*, **71**, 217–235, https://doi.org/10.1007/s10236-020-01426-9.

Alves, J. H. G., and Coauthors, 2013: The NCEP–FNMOC combined wave ensemble product: Expanding benefits of interagency probabilistic forecasts to the oceanic environment. *Bull. Amer. Meteor. Soc.*, **94**, 1893–1905, https://doi.org/10.1175/BAMS-D-12-00032.1.

——, A. Chawla, H. L. Tolman, D. Schwab, G. Lang, and G. Mann, 2014: The operational implementation of a Great Lakes wave forecasting system at NOAA/NCEP. *Wea. Forecasting*, **29**, 1473–1497, https://doi.org/10.1175/WAF-D-12-00049.1.

Ardhuin, F., and Coauthors, 2010: Semiempirical dissipation source functions for ocean waves. Part I: Definition, calibration, and validation. *J. Phys. Oceanogr.*, **40**, 1917–1941, https://doi.org/10.1175/2010JPO4324.1.

Bakhtyar, R., and Coauthors, 2020: A new 1D/2D coupled modeling approach for a riverine-estuarine system under storm events: Application to Delaware River basin. *J. Geophys. Res. Oceans*, **125**, e2019JC015822, https://doi.org/10.1029/2019JC015822.

Booij, N., L. H. Holthuijsen, and R. C. Ris, 1996: The "SWAN" wave model for shallow water. *Proc. 25th Int. Conf. on Coastal Engineering*, Orlando, FL, American Society of Civil Engineers, 668–676, https://doi.org/10.1061/9780784402429.053.

Burks, J. E., K. S. Sperow, and S. B. Smith, 2019: NOAA Virtual Lab (VLab) services, an update. *99th Annual Meeting*, Phoenix, AZ, Amer. Meteor. Soc., 11A.2, https://ams.confex.com/ams/2019Annual/webprogram/Paper351312.html.

Chawla, A., and Coauthors, 2013: A multigrid wave forecasting model: A new paradigm in operational wave forecasting. *Wea. Forecasting*, **28**, 1057–1078, https://doi.org/10.1175/WAF-D-12-00007.1.

Chu, P. Y., J. G. Kelley, G. V. Mott, A. Zhang, and G. A. Lang, 2011: Development, implementation, and skill assessment of the NOAA/NOS Great Lakes Operational Forecast System. *Ocean Dyn.*, **61**, 1305–1316, https://doi.org/10.1007/s10236-011-0424-5.

Driessen, V., 2010. A successful Git branching model. nvie.com, https://nvie.com/files/Git-branching-model.pdf.

Glahn, H. R., and D. P. Ruth, 2003: The new digital forecast database of the National Weather Service. *Bull. Amer. Meteor. Soc.*, **84**, 195–202, https://doi.org/10.1175/BAMS-84-2-195.

Hasselmann, S., and K. Hasselmann, 1985: Computations and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum. Part I: A new method for efficient computations of the exact nonlinear transfer integral. *J. Phys. Oceanogr.*, **15**, 1369–1377, https://doi.org/10.1175/1520-0485(1985)015<1369:CAPOTN>2.0.CO;2.

Hill, C., C. DeLuca, M. Suarez, and A. Da Silva, 2004: The architecture of the Earth System Modeling Framework. *Comput. Sci. Eng.*, **6**, 18–28, https://doi.org/10.1109/MCISE.2004.1255817.

Hultquist, T. R., M. R. Dutter, and D. J. Schwab, 2006: Reexamination of the 9–10 November 1975 "*Edmund Fitzgerald*" storm using today's technology. *Bull. Amer. Meteor. Soc.*, **87**, 607–622, https://doi.org/10.1175/BAMS-87-5-607.

Jacobs, N. A., 2021: Open innovation and the case for community model development. *Bull. Amer. Meteor. Soc.*, **102**, E2002–E2011, https://doi.org/10.1175/BAMS-D-21-0030.1.

Moghimi, S., and Coauthors, 2020: Development of an ESMF based flexible coupling application of ADCIRC and WAVEWATCH III for high fidelity coastal inundation studies. *J. Mar. Sci. Eng.*, **8**, 308, https://doi.org/10.3390/jmse8050308.

Pilato, C. M., B. Collins-Sussman, and B. W. Fitzpatrick, 2008: *Version Control with Subversion: Next Generation Open Source Version Control.* O'Reilly Media, 493 pp.

Popinet, S., R. M. Gorman, G. J. Rickard, and H. L. Tolman, 2010: A quadtree-adaptive spectral wave model. *Ocean Modell.*, **34**, 36–49, https://doi.org/10.1016/j.ocemod.2010.04.003.

Rogers, W. E., and D. W. Wang, 2007. Directional validation of wave predictions. *J. Atmos. Oceanic Technol.*, **24**, 504–520, https://doi.org/10.1175/JTECH1990.1.

——, and T. J. Campbell, 2009: Implementation of curvilinear coordinate system in the WAVEWATCH-III model. NRL Memo. Rep. NRL/MR/7320-09-9193, 48 pp., https://apps.dtic.mil/sti/pdfs/ADA507120.pdf.

Sandgathe, S., W. O'Connor, N. Lett, D. McCarren, and F. Toepfer, 2011: National Unified Operational Prediction Capability initiative. *Bull. Amer. Meteor. Soc.*, **92**, 1347–1351, https://doi.org/10.1175/2011BAMS3212.1.

Schwab, D. J., and K. W. Bedford, 1996: GLCFS—A coastal forecasting system for the Great Lakes. Preprints, *Conf. on Coastal Oceanic and Atmospheric Predictions*, Atlanta, GA, Amer. Meteor. Soc., 9–14.

——, J. R. Bennett, P. C. Liu, and M. A. Donelan, 1984: Application of a simple numerical wave prediction model to Lake Erie. *J. Geophys. Res.*, **89**, 3586–3592, https://doi.org/10.1029/JC089iC03p03586.

Tallapragada, V., C. Kieu, Y. Kwon, S. Trahan, Q. Liu, Z. Zhang, and I.-H. Kwon, 2014: Evaluation of storm structure from the operational HWRF during 2012 implementation. *Mon. Wea. Rev.*, **142**, 4308–4325, https://doi.org/10.1175/MWR-D-13-00010.1.

——, and Coauthors, 2015: Forecasting tropical cyclones in the western North Pacific basin using the NCEP operational HWRF: Real-time implementation in 2012. *Wea. Forecasting*, **30**, 1355–1373, https://doi.org/10.1175/WAF-D-14-00138.1.

Tolman, H. L., 1991: A third-generation model for wind waves on slowly varying, unsteady and inhomogeneous depths and currents. *J. Phys. Oceanogr.*, **21**, 782–797, https://doi.org/10.1175/1520-0485(1991)021<0782:ATGMFW>2.0.CO;2.

——, 1998: A new global wave forecast system at NCEP. *Ocean Wave Measurements and Analysis*, B. L. Edge and J. M. Helmsley, Eds., Vol. 2, ASCE, 777–786.

——, 1999: User manual and system documentation of WAVEWATCH-III version 1.18. OMB Tech. Note 166, 110 pp.

——, 2007: The 2007 release of WAVEWATCH III: Toward and open source wave model. *Proc. 10th Int. Workshop of Wave Hindcasting and Forecasting*, Oahu, HI, WMO, https://library.wmo.int/pmb_ged/wmo-td_1442_en/WWW/Presentations/Q4_10thwaves.pdf.

——, 2009: User manual and system documentation of WAVEWATCH III version 3.14. MMAB Tech. Note 276, 194 pp.

——, 2013: A generalized multiple discrete interaction approximation for resonant four-wave interactions in wind wave models. *Ocean Modell.*, **70**, 11–24, https://doi.org/10.1016/j.ocemod.2013.02.005.

——, and R. W. Grumbine, 2013: Holistic genetic optimization of a generalized multiple discrete interaction approximation for wind waves. *Ocean Modell.*, **70**, 25–37, https://doi.org/10.1016/j.ocemod.2012.12.008.

——, and J. Cortinas, 2020a: 2017-2018 roadmap for the production suite at NCEP. NOAA Doc., 69 pp., https://ufscommunity.org/wp-content/uploads/2020/06/20200423_2017-2018_Roadmap_for_PSN.pdf.

——, and ——, 2020b: A strategic vision for the NOAA's physical environmental modeling enterprise. NOAA Doc., 9 pp., https://ufscommunity.org/wp-content/uploads/2020/06/20200416_Strategic_Vision_for_Modeling.pdf.

——, B. Balasubramaniyan, L. D. Burroughs, D. V. Chalikov, Y. Y. Chao, H. S. Chen, and V. M. Gerald, 2002: Development and implementation of wind-generated ocean surface wave models at NCEP. *Wea. Forecasting*, **17**, 311–333, https://doi.org/10.1175/1520-0434(2002)017<0311:DAIOWG>2.0.CO;2.

——, M. L. Banner, and J. M. Kaihatu, 2013: The NOPP operational wave model improvement project. *Ocean Modell.*, **70**, 2–10, https://doi.org/10.1016/j.ocemod.2012.11.011.

Tremolet, Y., and T. Auligne, 2020: The Joint Effort for Data Assimilation Integration (JEDI). JCSDA Quarterly, No. 66, Joint Center for Satellite Data Assimilation, Boulder, CO, 46 pp., https://doi.org/10.25923/rb19-0q26.

Uccellini, L. W., R. W. Spinrad, D. M. Koch, C. N. McLean, and W. M. Lapenta, 2022: EPIC as a catalyst for NOAA's future Earth prediction system. *Bull. Amer. Meteor. Soc.*, **103**, E2246–E2264, https://doi.org/10.1175/BAMS-D-21-0061.1.

U.S. Congress, 2011: COASTAL Act. S.1091, 112th Congress.

Weng, F., Y. Han, P. van Delst, Q. Liu, and B. Yan, 2005: JCSDA Community Radiative Transfer Model (CRTM). *Proc. 14th Int. ATOVS Study Conf.*, Beijing, China, WMO, 217–222.

WW3DG, 2019: User manual and system documentation of WAVEWATCH III version 6.07. NOAA/NWS/NCEP/MMAB Tech. Note 333, 465 pp.