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Integrated Wind Wave Modeling at NWS

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Integrated Wind Wave Modeling at NWS

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APPENDICES

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1. Introduction

WInd waves are the chaotic surface gravity waves created by airflow over open water. WInd wave prediction supports Safety of Live and Property at open water and on the coast. It also supports the Blue Economy by supporting daily operations of industries such as fisheries, marine transportation, marine recreation, and offshore oil, gas and wind energy exploration.

Wind wave modeling has been an integral part of National Weather Service (NWS) Operations since 1956. Traditionally, wind wave modeling covers all main ocean bodies and the Great Lakes, with ever increasing coastal resolutions as computational resources allow. What is missing from these operational efforts is modeling at smaller spatial scales, in particular for a large number of freshwater lakes. The latter was pointed out in a Ken's Connection request from May 2024 that is reproduced here in Appendix A. This request highlighted the need for developing a more formal Wind Wave Modeling strategy for NWS operations. This internal NOAA report presents an overview of relevant aspects of wind wave modeling and an outline for a general wind wave modeling strategy for the NWS in NOAA. Due to the present uncertainty of resources for modeling in general at NOAA, the strategy will focus on critical activities, but not on a time line, or "valid period" for the underlying strategy. This document has been developed by contributors identified in Appendix D. The vetting and approval process is also discussed in Appendix D.

Section 2 of this report presents background information relevant for wind wave modeling at NWS. Section 3 explores space and time scales of wind waves relevant for operational modeling and forecasting. Section 4 describes dominant wave processes loosely associated with the above scales. Section 5 provides a review of modeling approaches, with a focus on approaches used for and suitable for operations. Section 6 provides a consensus set of wave model applications loosely ordered by priority, based on the team discussions documented in Appendix D. Finally, in Section 7 summarized and prioritized actions are gathered for all applications identified in the previous section.

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2. Background

The 1974 International Convention for the Safety of Life at SEA (SOLAS) identified waves as a critical factor concerning the safety of life and property at sea. SOLAS addresses these threats through standards for ship construction, stability, and life-saving appliances, and by mandating that meteorological services provide wave forecasts.

The NWS provides several marine products focused on waves to protect life and property through Impact Based Decision Support (IDSS) grounded in guidance provided by modeling. "Hazardous Seas Warnings" are paramount, signaling imminent danger from high waves, while coastal and offshore forecasts offer detailed wave height, period, and direction information for voyage planning. "Small Craft Advisories," with their wave height component, aim to protect smaller vessels from dangerous sea states. The Marine Weather Messages (MWW) provide quick access to hazardous seas “watches” and “warnings”, where a "watch" means hazardous weather is possible, and a "warning" means it is happening or imminent. Gridded, text, and graphical products from the Ocean Prediction Center and the National Hurricane Center/Tropical Analysis and Forecast Branch further enhance situational awareness with visual wave data, all contributing to safer maritime navigation and the prevention of wave-related accidents. The above products cover traditional SOLAS activities. More recently, the range of NWS products has expanded, in particular with products for rip currents, when it became clear that rip currents are in the top five of weather related conditions with respect to annual fatality rates (see the description of the NWPS in the following section).

Internationally, operational wind wave modeling started with wind wave predictions for the June 6, 1944 D-Day landings in Normandy (Sverdrup and Munk, 1946, 1947). The NWS provided their first wind wave numerical guidance in July 1957 (Hubert 1957). A review of early operational wind wave modeling at the NWS can be found in Tolman et al. (2002).

In the first wave modeling approaches used at NWS, a significant wave height H_s was computed from a local wind speed using empirical parametric relations. Such “growth curves” (e.g., Kahma and Calkoen 1992) are still used in wave model development. In more modern wave models, the inherently stochastic wave field is described using a (deterministic) spectrum following Rice (1944), typically describing the wave energy density distribution as a function of a wave number and wave direction. The first spectral wind wave models were developed by Gelci et al (1956, 1957). In the 1960s and 1970s, a plethora of spectral wind wave models were developed. The SWAMP study (SWAMP Group 1985) provided an intercomparison of existing models. It was concluded that so-called first- and second-generation wind wave models using a heuristic description of spectral wave growth were not generally applicable. The SWAMP study recommended developing third-generation (3G) wind wave models where the spectral evolution of wind waves was based on first principles without assumptions on the spectral shape other than in the parametric spectral tail used for high frequencies. This resulted in the development of the WAM model (WAMDI Group1988) as the first community-based 3G model suitable for operations. The development of WAM led to the development of WAVEWATCH III ® at NOAA (Tolman 1991, Tolman et al. 2002) and SWAN at Delft University of Technology (Booij et al.

1999, Ris et al. 1999). These two models now are popular community models, and are both used in NOAA operations.

Initial operational wind wave guidance focused on oceans, with a review of early work given in Tolman et al. (2002). The corresponding global wave model was augmented with "downstream" regional models for areas of general interest for the USA, and for specialized hurricane wave modeling (e.g., Chao et al. 2005, Chao and Tolman 2010). The global and regional wave models were subsequently integrated in a single "multi-grid" model (Tolman 2008, Chawla et al. 2013). The regional hurricane wave models have now been integrated in the coupled hurricane models, in particular the Hurricane Analysis and Forecast System (HAFS) model, as a continuation of the HWRF model (e.g., Alaka et al., 2024).

Wind wave guidance for the Great Lakes was initially provided by the Great Lakes Environmental Research Laboratory (GLERL) of Oceanic and Atmospheric Research (OAR) of NOAA, based on the GLERL-Donelan second-generation wind wave model (Schwab et al. 1984). Note that this is a computationally inexpensive wind wave model that has been used locally at Weather Forecast Offices (WFOs) as outlined in the Ken's Connection request reproduced in Appendix A, and as originally supported by Greg Mann from Weather Forecast Office (WFO) Detroit. Operational wind wave guidance was transitioned from OAR to NWS, replacing the GLERL-Donelan model with the more accurate WAVEWATCH III (WW3) model (Alves et al. 2014). Note that the GLERL-Donelan model was recently re-introduced in operations as part of the coupled SLOSH-Waves probabilistic tropical storm surge model PSURGE[1] (e.g., Rhome et al., 2019).

Wind waves away from the coast generally change at scales of tens of km or more. As the waves approach the coast, the spatial scales of changes collapse to being as small as 10-100m. Moreover, most human impact of waves is on the coast, where most "people meet waves". This was the driving force for developing the operational Nearshore Wave Prediction System (NWPS, e.g., Van der Westhuysen et al, 2013). The NWPS predicts wave conditions in nearshore areas. It provides guidance on wave height, direction, period, and other related factors. The latest version (NWPS v1.3)[2,3] also includes guidance on rip currents, erosion, and overwash probabilities. A draft charter for the NWPS v1.5 can be found here[3].

Note that the development of the NWPS included various approaches to "local" modeling. First, it was intended to focus on local modeling on dedicated hardware at individual WFOs. This evolved into using AWIPS hardware available at each WFO. It finally became a fully independent local solution run and maintained on central hardware. As such, the NWPS is an example for NWS deciding to move away from local modeling at WFOs (see also Section 5). Another unique technology developed for the NWPS is that it allows for local WFO forecasters to submit model runs at the NOAA central computer through their local AWIPS software.

[1] SLOSH is the underlying storm surge model, and PSURGE is the operational application. Note that wind wave coupling is not yet used in other SLOSH-based applications like the probabilistic extra-tropical storm surge mode (P-ETSS).

[2] The present operational version is NWPS v1.4. Version 1.4 differs from version 1.3 only due to changes needed to port the system to a new operational supercomputer.

[3] Internal NOAA document, visible to individuals with a NOAA google account only.

The most recent operational model that is under development is the Regional Wave Prediction System (RWPS). Addressing the NWS requirement CaRDS[4] 17-005, RWPS aims to provide a capability similar to the Nearshore Wave Prediction System (NWPS) but for offshore and high seas areas in addition to the nearshore domains covered by NWPS. The development plan was completed in FY21Q4 by the STI Marine Working Group with representation from various NWS regions and centers. Due to resource constraints, it has not yet been implemented, although the development process has now been started formally. RWPS is intended to be a single large oceanic domain model, as a "downstream" component of the UFS[5], and based on WW3. The proposed domain for RWPS covers the Oceanic National Blend of Models (NBM) domain and NWS marine responsibilities, including high seas, offshore waters, and coastal areas. The latest plans for the RWPS can be found here[6].

What is still missing from operational modeling systems is a systematic approach to providing relevant wave guidance for smaller lakes. A limited set of such guidance is provided by regional modeling at WFOs, or has been considered for potential newer implementations of the NWPS[7]. Both the need for a wave modeling strategy for lakes and possibly for local modeling was outlined in the Ken's Connection request. With that, the present document will suggest such a strategy for lakes as an integral part of a global and regional wind wave modeling strategy.

Any new operational modeling strategy for NOAA needs to be built around the Unified Forecast System (UFS) approach. In the UFS, operations and research focus on a small set of modeling approaches. This set is designed to be small enough to have critical mass with respect to resources, and large enough to cover the entire NOAA mission. Such an approach was initially explored by the Unified Modeling Task Force of the NOAA Research council, and its findings are presented in Link et al (2017a,b). The initial UFS vision of such a Unified Approach was approved by senior NOAA leadership in Tolman and Cortinas (2020a,b). Furthermore, this unified approach is documented in a series of BAMS articles, covering its basic benefits (Jacobs 2021), its support by the Earth Prediction Innovation Center (EPIC, Uccellini et al., 2022), and examples of successful community modeling with a UFS approach (Alves et al. 2023, Tolman 2025a).

The UFS has a shared software stack consisting of community-based environmental models and modeling tools. WW3 is an active UFS component model, and SWAN is a suitable UFS wind wave model that has been used in the NWPS. The software stack by itself does not provide any products. To provide (measurable) products from this software stack, the UFS also consists of applications. Such applications are the subject of this proposed strategy. UFS applications are inherently coupled (real time interactions between atmosphere, oceans, wind waves, etc.). Whereas this makes individual components more complicated, it also results in a much more consolidated production suite of applications. Moreover, UFS applications should be

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[4] "*Capabilities and Requirements Decision Support*", NWS Policy Directive 10-103.
[5] That is, this model is run in the production suite after the core coupled UFS models are run.
[6] Internal NOAA document, visible to individuals with a NOAA google account only.
[7] An unpublished NWPS plan for NWPS v1.4 from ca. November 2022 identifies domains for Moosehead Lake (WFO Caribou), Lake Mead (NV/AZ), Lake Mojave (NV/AZ), Havasu Lake (AZ), Lake Tahoe (CA/NV) Pyramid Lake (NV). As possible additions the plan identifies Canyon Ferry Lake (MT), Holter Lake (MT), Lake Elwell (MT), Lake Frances (MT), Fort Peck Lake (MT). American Fork Reservoir (ID) and Bear Lake (ID/UT).

ensemble-based to address both the forecast and its uncertainty (see next paragraph), and, in particular for outlook products, have an associated reanalysis and reforecast to allow for systematic error assessments and corrections.

A good forecast addresses both the accuracy and the reliability of a model (e.g., Murphy, 1993). The latter is generally addressed by expressing the forecast in probabilistic terms, which in turn is traditionally achieved by providing an ensemble forecast (National Research Council, 2006). This implies that wave models, like all environmental models, should produce ensemble forecasts.

Wind waves interact with the atmosphere, ocean, ice, and riverine outflow. An overview of the associated processes at longer time scales can be found in, for instance, Cavaleri et al. (2012) or Bidlot et al. (2024). This implies that the wave model inherently is coupled to other component models in UFS applications.

Artificial Intelligence and Machine Learning (AI/ML) have recently gained much attention in particular with the rise of data-driven weather models. AI/ML has been applied to wind wave modeling for several decades, for instance with both early and more recent attempts to emulate physics in wave models (Tolman and Krasnopolsky 2004, Tolman et al. 2005, Krasnopolsky et al. 2008, Olawale et al. 2025), with using Genetic Optimization for object parameter estimates in nonlinear wave-wave interactions (Tolman and Grumbine 2013), and in obtaining more accurate information from wave ensembles (e.g., Campos et al. 2019, 2020). Note that we are on the verge of having data driven wind wave models that are competitive with traditional physics-based numerical models (e.g., Shen et al. 2024, Wang and Jiang 2024, Wang et al. 2024, Bodnar et al., 2025). Note, furthermore, that there are insufficient wave observations to generate a data-dominated wind wave field for most regions. Hence, AI/ML is more likely to be successful in creating wave model emulators, than in creating fully data-driven AI/ML wave models.

From a mathematical perspective wind waves represent a forced and damped problem. This implies that the accuracy of the model depends on the accuracy of the forcing, and that model errors related to initial conditions dampen during the forecast cycle. This, furthermore, implies that an accurate wave forecast can be made by cycling initial conditions in the absence of data assimilation (DA). This is in stark contrast with (chaotic) initial value problems such as weather and ocean circulation problems. For the latter problems DA is critical for obtaining accurate forecasts. In contrast, wave DA is not always used at operational forecast centers. With the move to coupled DA, however, wave DA becomes more interesting as wave data then can impact initial conditions for the atmosphere and ocean. Note that even without DA in wave models, it remains essential to maintain the present set of real-time wind-wave observations, in particular from buoys and altimeters, in order to be able to validate and further develop wind-wave models. As DA represents an expansion of needed base capabilities of wave models, and is most interesting for coupled DA, wave DA is not considered in detail here. Interested parties should instead see the EMC DA plan for more details (Kleist et al. 2023, 2024).

3. Scales

As its name implies, wind waves are the surface waves on water that are or have been generated by surface winds. Note that this excludes other wave events like meteo-Tsunamies, infra-gravity waves, solitons, tides, storm surges and Tsunamis. The latter wave phenomena are therefore out of scope from the present assessment. Local wave fields can incorporate scales as small as those of capillary waves (`ripples') with a wavelength as small as 2.5 cm, to wave components with wavelengths of more than 1km. Corresponding wave periods are as small as a fraction of a second to approximately 30s.

Wind wave theory assumes that the forcing of the wind waves (wind, currents, bathymetry, ice) varies at scales much larger than those of individual waves. This implies that the deep ocean spatial scales of wind wave models should be of the order of 10 km or larger. However, decades of practical experience has shown that wave models can be accurate if this scale separation is violated, with successful coastal wave model applications with spatial resolutions of the order of 100 m.

Wind waves act like a low pass filter with respect to wind forcing (Tolman 2025c). This implies that waves do not directly respond to gustiness and small scale features like water spouts. Instead, (dominant) wave growth is associated with mesoscale weather features with its associated temporal and spatial scales. Some of the smallest mesoscale weather features that create significant wind waves are small but intense tropical cyclones.

When winds subside, the actively generated wind seas transition into freely propagating swells. In the deep ocean, wind sea components disperse[8] in different directions and with different speeds (longer wave components travel faster), creating wave fields with much larger spatial scales than the spatial scales of wind seas. On the Pacific Ocean, relevant swells can travel for up to two weeks before being dissipated at shorelines. This dispersion and the associated travel time increases the time scale associated with swells compared to time scales associated with wind seas, with the latter being typically of the order of a day or less. Even though swells have been created by winds, they are often no longer under a significant influence of the local winds, and hence wave prediction at these scales is inherently non-local.

When wind waves reach shallow water, typically near coastlines, waves become sensitive to the bottom due to refraction[9] and wave-bottom interactions that dissipate wave energy. A first collapse of scales occurs at the shelf break. For mariners, the shelf break is generally associated with water depths of approximately 200m. Depending on the width of the continental shelf, this usually results in spatial scales of tens to hundreds of kilometers[10]. The corresponding time scale is associated with the time it takes for the dominant waves traveling across these spatial scales, and is generally measured in hours. A second collapse of scales occurs in the transition from the continental shelf to the coastal zone. Mariners typically associate this

[8] Note that in the transition of wind seas to swell wave height reduces rapidly due to this dispersion, ***much less so*** due the dissipation of wave energy.
[9] Waves change direction and potentially focus in a process similar to Snel's law in optics.
[10] Note that persistent boundary currents in the deep ocean such as the Gulf Stream and the Kuroshio as well as mesoscale ocean eddies can also result in wave field signatures at corresponding scales.

transition with the 10 fathom or 20m depth line on sandy shores. This area is typically associated with spatial scales of tens of kilometers or less, and with time scales smaller than 1h. A third collapse of scales occurs at the surf zone where waves rapidly dissipate their remaining energy due to depth-induced wave breaking in the surf zone. The scales associated with the surf zone are of the order of hundred of meters and tens of seconds.

For lakes in general, the enclosing coastline limits the spatial scales, and, through the propagation time of a typical wave field across the lake, the temporal scales. When spatial scales of a lake are larger than those of relevant weather patterns, a lake will see both wind seas and swell. This is generally the case for the Great Lakes, and lakes like Lake Victoria. When lakes are significantly smaller than the dominant spatial feature of weather patterns, no mature swell can develop, and effectively the lake is subject to wind seas only (including decaying wind seas). Note that wide rivers could be considered as lakes in this context as well.

4. Processes

At the largest scales of oceans most wind waves are swell rather than locally generated wind seas. This makes wind wave modeling at oceanic scales inherently non-local.

Wind wave models receive their primary input from the bathymetry of the modeled area, atmospheric models (surface winds or stresses including atmospheric stability information) and ice models (in first order dynamically adjusting the effective layout of a basin). Secondary inputs and processes at large scales include mean ocean currents and local wave-ice interactions for areas with partial sea ice coverage. With wind waves also influencing their forcings through their impact on oceanic surface fluxes, wave-current interactions and wave-ice interactions, wave modeling at oceanic scales requires a fully coupled dynamic wave model as a part of an integrated environmental modeling system.

In coastal areas, scales of wind wave fields and modeling collapse as described in the previous section. Coastal wind wave fields are dominated by propagation of offshore wave conditions into the area, as well as by local wind forcing. Due to tidal, wave- and wind-driven currents, wave-current interactions are important in such areas. Arguably the most important coupling aspect in such regions is the linkage between coastal waves and coastal surge. It has long been known in the coastal engineering community that “storm-surge” is often, in fact, driven by wind waves rather than solely by (local) winds, and that local wave heights are extremely sensitive to the local mean water depth. In practical forecasting, this effectively became indisputable after the publication of the Interagency Performance Evaluation Team (IPET) report for hurricane Katrina in 2005[11]. Strongly coupled wave-surge interactions, including freshwater runoff and precipitation is a must for accurate wave-surge prediction. In such conditions the impact of waves on other environmental components is not yet clear. For instance, the transition of over-land to over-water boundary layers is essential to describing coastal transitions of wind fields, but it is not clear if this is a local process that can be addressed with heuristic approaches, or whether this needs full coupling of component models with larger scale implications.

The largest lakes like the Great Lakes represent enclosed basins without considering wave penetration from outside the region. Nevertheless, such lakes are large enough so that a storm may create waves over a selected part of the basin. Thus the life cycle of a wind wave includes a relevant swell stage, and wind waves have a distinct non-local aspect and require a full wind-wave model approach. Here, high fidelity 3G models provide significantly better results than simpler and older modeling approaches (e.g., Alves et al. 2014).

Considering increasingly smaller lakes, the (spatial) scale of the dominant wind forcing eventually becomes much larger than the spatial scale of the lake. In such conditions wind waves can be considered as local wind seas, and a local approach can be considered. The complexity of the local wave field is then dominated by the complexity of the layout of the lake. For complex lake geometries like that of Flathead lake, an argument can be made for using a

[11] https://biotech.law.lsu.edu/katrina/ipet/ipet.html

physical wave model. For simple geometries like Lake Tahoe, an argument can be made that it is sufficient to only produce a representative wave height directly from the local wind speed and a representative fetch. Furthermore, for increasingly small lakes it is less likely that coupling processes back to the atmosphere will have a significant impact on the atmosphere. Thus, estimation of wave conditions can be considered as a “downstream” or “postprocessing” product of a larger coupled environmental model.

5. Models / Software approaches

Since 1999, the WW3 wind wave model has been the model of choice for (large scale) operational wind wave modeling at NOAA (Tolman et al. 2002). As this model is designed as a framework rather than a single model, WW3 applications with NOAA can have different physical and numerical approaches. With that, the operational global models at NOAA use different grid approaches and numerics than, for instance, the Great Lakes operational wave model. Note that WW3 models run at other agencies also use different numerical and physical options, and therefore would previously have been considered as different models, rather than as different realizations of the same model. (See the discussion on frameworks and models in Alves et al. 2023).

The WW3 model, like most traditional wave models, solves a set of hyperbolic equations forward in time effectively along characteristic trajectories. Whereas this allows for solutions at arbitrary scales, it also implies that computational cost increases dramatically as the spatial resolution of models is increased. This makes such models often prohibitively expensive for representing the spatial scales of coastal applications, although this is somewhat mitigated by the more recent development of numerical implicit unstructured grid approaches. The latter allowed running an operational WW3 Great Lakes wave model with 250m coastal resolution hourly.

In coastal engineering, prohibitive costs of the above modes for coastal applications has led to the development of quasi-stationary wave models. In quasi-stationary conditions, the governing equations become elliptic in nature, requiring the inversion of a large matrix. In early quasi-stationary models like HISWA (Holthuijsen et al. 1989) the matrix inversion was made economical assuming a dominant wave direction allowing for a single-sweep matrix inversion. In a full third-generation quasi-stationary approach as developed in the SWAN model (Booij et al. 1999), the matrix is inverted using a limited number of iterations. In more recent versions of the latter model, time evolution was reintroduced by considering time derivatives as a “source function”, allowing application of SWAN on larger domains and for wave fields evolving in time. Due to its economy for high-resolution coastal domains, SWAN is used in operations at NOAA in the Nearshore Wave Prediction System.

As models have evolved, WW3 and SWAN can now effectively be used at overlapping and arbitrary scales. WW3 still has a preference on large scales (economy, more flexibility with physics development). SWAN is still used extensively at the coast (economy, more extensive surf-zone physics), in particular where wave conditions can be considered as quasi-stationary. With WW3 becoming more suitable for coastal application, in particular with the availability of implicit unstructured grid options, NWS had been considering removing SWAN out of NWPS operations and replacing it with WW3. This work was paused as work now focuses on RWPS, which will be based on WW3. Note that both models have mature coupled wave-surge capabilities.

NOAA presently has no established approach for providing wind wave guidance for smaller lakes (Appendix A), which was one of the triggers for developing this comprehensive documentation and strategy. As suggested above, when lakes are small enough, a full wave model is not needed, and mature parametric relations can be used to compute wave heights from a representative wind speed (e.g., Kahma and Calkoen, 1992). Similar simplified / parametric approaches are also used for ice and surface temperatures of smaller lakes in our weather models (see Appendix B). Note that a simple approach is often also justified as there is virtually no objective validation data for wave heights on smaller lakes. Furthermore, parametric relationships and/or custom AI/ML models for individual lakes could be developed potentially by research partners, by tuning such relationships to selected retrospective full model hindcasts. Finally, the GLERL-Donelan model is used operationally at the Missoula WFO for Flathead Lake. This model is locally maintained and run at this WFO. Note that the WFO will lose the capability to run this model locally when AWIPS shifts to the cloud, which is presently scheduled for September 2026.

A somewhat unique question for NOAA/NWS with over 100 WFOs is that of local modeling performed at the WFOs versus central modeling performed at NCEP. The practice of local modeling at WFOs was a trigger for the Ken's Connection request at the core of the development of this document. In this context it is relevant that the development of NWPS was initially envisioned as a local modeling capability running on AWIPS hardware at local WFOs. After several iterations, it was found that the cumulative nature of local modeling at many locations made this prohibitively expensive and risky from a Continuity of Operations (COOP) perspective without standardization and central support. Moreover, a national drive to reduce the number of data centers in the government drove the NWPS design towards running local models on NOAA's central operational supercomputer on demand. The NWPS experience was crucial in NWS leadership explicitly moving away from local modeling at WFOs. Instead, the NWS prefers to focus on sustainable centrally supported generation of local products.

6. Towards a comprehensive Strategy

A comprehensive wave strategy has to be embedded in a larger production suite strategy based on the UFS. Following Tolman and Cortinas (2020b), the future production suite is intended to be centered around a small set of products covering a range of guidance time scales as outlined in Fig. 6.1 (Their Figure 2). This approach is embedded in the first ever formal NOAA modeling strategy (Morgan et. al., 2024). The NWS is making progress with moving to this envisioned structure of the production suite with WW3 already embedded in the global coupled modeling systems and the hurricane forecast system. Note that the National Ocean Service (NOS) also recently published its modeling strategy[12], which is consistent with the UFS and with NOAA strategies. When considering coupled wave-surge products, NWS and NOS plans need to be aligned. Linkages with NOS are called out here where appropriate, and as complimentary information NOS' relevant coastal modeling efforts are described in Appendix C.

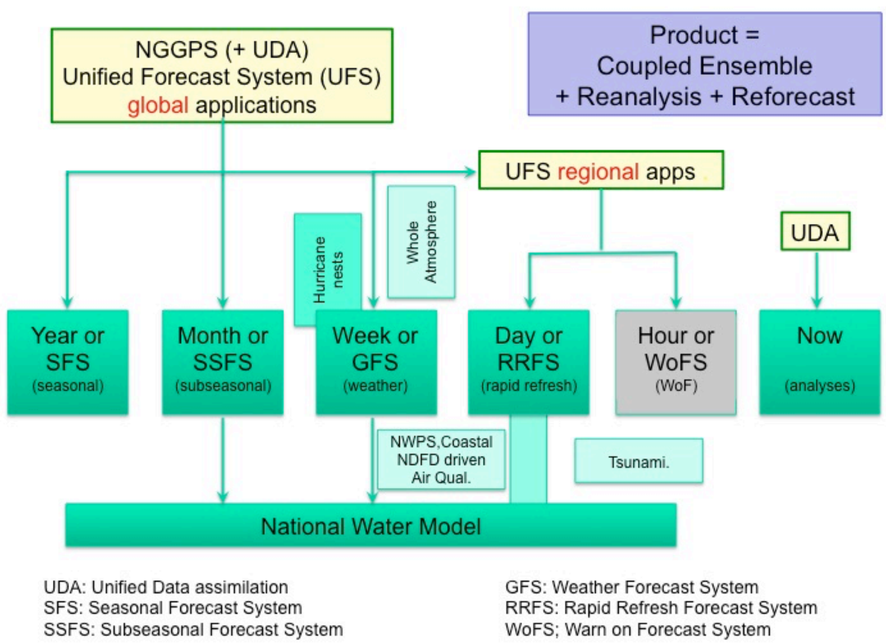

Figure. 6.1: High level vision of future Production Suite Layout (from Tolman and Cortinas 2002b, their Fig. 2)

A basic concept of the UFS is to use the smallest number of component (wave) modeling approaches that support the full mission of the organization. Presently, NWS uses three wave models in operations. These are the WW3, SWAN and GLERL-Donelan models as discussed in the previous Sections. Of these WW3 is integrated in the UFS. As a community model, SWAN

[12] https://cdn.oceanservice.noaa.gov/oceanserviceprod/tools/coastal-predictions/NOS-Modeling-Strategy-2023.pdf

could be considered for full UFS implementation. Without a community supporting it, continued use of the GLERL-Donelan model in operations is inconsistent with the UFS approach.

To map the information provided in Sections 1 through 5 to the UFS paradigm outlined in Fig. 6.1, present and planned wave model applications have been discussed with three focal groups. The groups and their memberships are documented in Appendix D. The discussions identified some general issues shared by most applications focusing on issues with the underlying WW3 model and with the need for accelerated integration of AI/ML into the operational production of wind wave guidance. These issues are gathered here in Section 6.1. The remaining subsections address the various operational applications for wind waves, ordered in the priority that was established in the group discussions.

Each of the latter subsections ends with a set of proposed actions. With current budgetary and organizational uncertainties, scheduling beyond prioritization of these actions or issues is somewhat moot today. Therefore, only prioritization will be addressed here and in summary Section 7.

6.1. General Issues

General issues related to this wave plan can be divided into two categories; one focuses on issues with the present software stack; another focuses on issues associated with the transition of many environmental modeling efforts to a more AI/ML based approach.

Several structural issues must be addressed with respect to the WW3 model. Note that there is presently no viable alternative for WW3 in general UFS applications that could address these issues. NOAA can either lead a team effort to systematically upgrade the WW3 code, or work with partners on a model to replace WW3. General issues include:

A. **Efficiency**: The current WW3 code's parallel and data concepts are outdated, resulting in inefficient use of compute resources. This may require a fundamental re-write of the WW3 code.
B. **Maintainability**: We have reached a point where FORTRAN codes are no longer the most efficient codes on super computers. Moreover, effectively having only a single viable FORTRAN compiler available may become a potential COOP issue for operations (e.g., Tolman 2025b). This suggests a need for transitioning to other languages, for instance, Python or C++.
C. **Specific technical issues**:
    a. **Accuracy**: For several years WW3 appears to systematically underestimate wind waves in general. This requires a systematic re-evaluation of free parameters in existing physics parameterizations, or a scientific re-evaluation of the physics of wind wave growth and attenuation.

b. **GSE**: The Garden Sprinkler Effect (GSE, Booij and Holthuijsen 1987, Tolman 2002)[13] is still an issue that will benefit from a better and more structural solution independent of the grid and numerical approaches used.
c. **North Pole**: The spatial singularity in the lon-lat grid and the directional ambiguity at the North Pole associated with the definition of the wave direction needs to be addressed systematically as an ice-free North Pole is becoming a more common event.

These issues require the following actions:

1. **Code Modernization**: Technical items A and B identify a high-priority need to fully modernize the WW3 code or replace it by a model designed for the present hardware environment (see Tolman 2025b).
2. **Technology development**: Technical items under C identify smaller and more isolated technical requirements that will benefit multiple applications, but that are not as urgent as upgrading the code in general. Tackling these issues need to be prioritized based on available resources.

AI/ML has been considered for and has been used in wind wave modeling for more than 2 decades as documented in Section 2. With the recent spectacular acceleration of the capabilities of data driven weather models, AI/ML has moved into the center of attention of environmental modeling. The wave modeling efforts at NOAA need to be aligned with this acceleration for two main reasons. First, the rapid developments in these fields require operational teams to be embedded in research to most efficiently bring associated and relevant innovations into operations. Second, teams developing AI/ML generally lack expertise in the physics of wind waves, and in the needs of stakeholders in the context of the NOAA mission. The NOAA wave modeling team can fill this gap in expertise as a direct partner in capacity and capability building.

NOAA in general and the EMC wave group in particular have worked for decades on AI/ML, particularly associated with the work of Vladimir Krasnopolsky. This led to a first operational use of AI in NWS operations three decades ago (Krasnopolsky et al., 1995). Since then, however, AI implementations in NOAA operations have been sparse at best. Some of this has been due to a reluctance to use new and poorly understood concepts and techniques in operations. With the rapid recent rise of AI/ML, this cultural issue appears to be dissolving. With that, there is an opportunity to more rapidly implement already proven AI/ML concepts in operations.

The above assessment of AI/ML in general and for wind waves in particular suggests the following high-level actions

1. **Invest in AI/ML**: Identify dedicated resources to work on AI/ML applications for wind wave modeling and product generation to keep up with, and contribute to the rapid development in this field.

[13] That is, a discrete description of the local wind wave spectrum can result in a spurious disintegration of a continuous swell field into small discrete swell fields like individual water drops coming out of a garden sprinkler.

2. **Prioritize focal areas**: The above investment should focus on the following topics, ordered by priority with items b and c of similar priority.
    a. **Data driven models**: We are presently witnessing the birth of the first viable data-driven wave models. The potential impact of such models is particularly important for probabilistic modeling, either using AI models for the generation of large ensembles, or using AI to directly estimate uncertainties in forecast products. Note that due to the lack of sufficient wind wave observations in general, such models are usually trained using hindcasts with or without data assimilation and could therefore also be classified as emulators of the full physical model.
    b. **Postprocessing**: Accelerate the operational implementation of proven AI-based post-processing techniques (e.g., Campos et al. 2019, 2020). Focus on expanding such efforts.
    c. **Optimize model physics**: Explore Genetic Optimization as previously used for optimizing parameters of physics parameterizations (Tolman and Grumbine 2013) to systematically optimize the performance of existing wave model applications.
    d. **Physics emulation**: Revisit efforts to emulate expensive components of the wind wave models such as the nonlinear interactions (e.g., Olawale et al. 2025).

Note that AI/ML could also be beneficial for wind wave Data Assimilation, but this topic has been placed outside of the scope of this assessment (see Section 2).

6.2. Global models

Global wave modeling serves as the foundational layer for NWS wave forecasting operations, providing essential guidance for maritime safety as mandated by SOLAS, and providing boundary forcing for other models. Current development paths, which include transitioning global wave models to a unified, six-way coupled software stack within the production suite, should continue. This approach aligns with the broader Unified Forecast System (UFS) and integrates wave modeling into an Earth System Modeling approach.

There are three main operational or developmental UFS applications with WW3 global wave model components, which are the Global Forecast System (GFS), the Global Ensemble Forecast System (GEFS), and Seasonal Forecast System (SFS). Due to the framework design of WW3, each of these systems can employ different grid definitions, resolutions, and physics parameterizations. This optimizes the wave model for the specific needs and constraints of each modeling system. This is fully consistent with the UFS vision of using a single unification tailored to each application. However, it is also preferred in the UFS approach to minimize the number of approaches if feasible, i.e., use a single grid approach with differences in resolution only.

The SFS, which is still in development, does not explicitly need a wave component from the SOLAS perspective. For this UFS application, adding a wave model component is driven by the scientific belief that it could result in better description of the ocean mixed layer in the ocean component of the UFS, and hence increase accuracy / predictability in the SFS. Further evidence is needed to substantiate these claims for the (developmental) SFS. Additionally, computational cost versus improvement in the forecast should also be considered.

Driven by the need for targeted support of product generation, the global wave model should focus primarily on deep-ocean and shelf-sea scales, but should not target near-shore or inshore areas and their associated need for much higher resolutions. With this, the global wave models in the UFS will benefit from focusing on mature unstructured grid approaches, without pushing unstructured grids to resolve resolutions higher than those of continental shelves.

The above view of global wave modeling results in a set of needed actions.

1. **Maintenance**: Due to its foundational nature in the wave modeling suite and in the UFS as a whole, full Operations & Maintenance (O&M) support for the global wave models is a high priority issue.
2. **Generalize the grid approach**: EMC should use the same grid approach for all three global applications albeit at different resolutions. With all applications expected to benefit from different resolutions from the deep ocean to the continental shelves, an unstructured grid approach is preferred.
3. **Generalize the ensemble approach**: Perturbations for a damped and forced problem like wind waves are most naturally started with using perturbed forcing. Due to the low-pass filter behavior of wind waves, the magnitude of perturbations of the wave field for ensemble members depend critically on the details (consistency) of the perturbations of the wind forcing. This aspect of global wave modeling needs additional attention to develop a scientifically solid general approach for perturbing global wave ensembles.
4. **Focus on software modernization**: This action is dependent on the progress of the general software modernization outlined in Section 6.1. Even if this action may be easier to implement in the stand alone RWPS (Section 6.3), its practical impact for the total production suite makes this a high-priority item for the global models.

6.3. The Regional Wave Prediction System (RWPS)

RWPS is a new application that is under development. It is intended to provide both offshore and coastal wave products on basin scales as an "unlock"[14] for marine forecasters and to provide data for a large number of required products as outlined in Section 2, RWPS is also intended to provide products that are presently provided by NWPS, enabling the retirement of the latter model. Leveraging the preparation that has gone into designing the RWPS, action items focus on the initial implementation and the rapid evolution of the RWPS as follows:

1. **Implement:** Execute the most recent development plan[15] with high priority.

[14] Identified here as a specific set of products designed to free up time for forecasters in their normal workflow.
[15] Internal NOAA document, visible to individuals with a NOAA google account only.

2. **Transition NWPS capabilities**: This is of high priority as it enables sunsetting of an obsolescent application. It remains to be seen if this needs to be a requirement for an IOC. Note that this transition invites coordination with NOS as the original source of the rip current products, and the US Geological Survey (USGS) for additional parameterized coastal wave products.
3. **Ensembles**: Consistent with the general UFS approach, evaluate if this system should provide probabilistic information and should include Data Assimilation.
4. **Modernize**: Target this system for development of AI/ML. As an uncoupled "downstream" model in the UFS, it is easier to develop and implement AI/ML techniques here than in fully coupled UFS applications. Note that such development is likely to benefit from extensive retrospective RWPS model output. Potential target areas are:
    a. Inexpensive creation of probabilistic data either as additional AI/ML ensemble components, or by burgeoning AI/ML methods to estimate model uncertainty directly.
    b. More accurate and novel Safety of Life and Property coastal and surf zone products. (possibly in collaboration with NOS as has been done previously for rip-current products).

6.4. Lakes

A wind wave modeling strategy for (freshwater) lakes is new to EMC. Considering the information presented in the previous Sections, a 3-tiered approach is selected to provide a good balance between effort and mission support. The three approaches are described below through categorization of each tier's dominant scales, dominant processes, proposed modeling approaches, and examples.

Tier 1: Largest Lakes

Dominant Scales: Spatial scales are larger than relevant weather patterns, allowing for both wind seas and swell development. Temporal scales are days to weeks.

Dominant Processes: Non-local wave dynamics, including swell propagation, requiring a full wind-wave model approach. Coupled interactions with the atmosphere (lake effect weather, consistent surface fluxes).

Modeling: Modeled using WW3. Eventually should be embedded in global and/or regional coupled models starting with existing stand-alone models and moving towards fully coupled systems (in consultation or collaboration with NOS and GLERL).

Examples: Great Lakes (Superior, Michigan, Huron, Erie, Ontario), Lake Victoria. Note that the NOAA mission has us focus on the US Great Lakes. Note that the impact of such lakes on weather may eventually force us to also include larger lakes outside of the US.

Tier 2: Mid-Sized Lakes/Complex topographies

Dominant Scales: Spatial scales are comparable to or slightly smaller than the spatial scales of dominant wind forcing features. Temporal scales are of hours to a day.

Dominant Processes: Primarily wind seas, with limited swell development. Local wind forcing is dominant, but complex lake geometry may still require a full wave model even for smaller lakes.

Modeling: Requires a wind wave model (model and modeling approach TBD). Run as a downstream or "post-processing" model after the foundational coupled UFS operational runs.

Examples: Flathead Lake.

Tier 3: Smallest Lakes/Simple Geometries

Dominant Scales: Spatial scales are significantly smaller than those of the dominant wind forcing. Temporal scales are of minutes to hours.

Dominant Processes: Local wind seas only. Wave conditions are primarily determined by local wind speed and fetch.

Modeling: Wave data created using parametric relationships such as traditional growth curves, or with AI/ML approaches that can be either general or specific per lake. This can be done either as part of the Unified Post Processor (UPP), or similar to ice and temperature estimates for such lakes inside of full coupled models.

Examples: Lake Tahoe, smaller inland lakes.

In order to implement such a 3-tiered system in operation, the following individual actions and activities have been identified.

1. **Create a Lake Inventory:** Develop an inventory of lakes to be considered in each tier.
2. **Establish Implementation Plans for Tier 1 Modeling:** As these models already exist, short term planning should focus on actual incremental model improvements, and long term planning should focus on a strategy to move toward fully coupled UFS applications.
3. **Select a Model and a Modeling Approach for Tier 2:** Decide on the specific wind wave model and the modeling approach to be used for Tier 2. Community models like SWAN and WW3 are preferred. Note that, unlike for Tier 1, quasi-stationary modeling approaches as used in SWAN may prove adequate and economical. However, maintaining another model comes at an increased cost.
4. **Establish Implementation Plans for Tier 2 Modeling:** Initial plans need to focus on a unified strategy and on replacing legacy solutions. Replacement of legacy solutions should be high priority here, and can be used as “pilot projects” after which a comprehensive plan can be developed. Define how the Tier 2 models will be run as "post-processing" models downstream of the foundational coupled UFS operational runs.
5. **Establish an Modeling Plan for Tier 3:** Determine the specific parametric relationships or AI/ML approaches to be used for Tier 3, and how this data will be integrated into the Unified Post Processor (UPP) or into coupled models.

6. **Establish an Implementation Plan for Tier 3 Modeling:** Plan actual development and implementation of the Tier 3 approach.
7. **Consider Inclusion of Lakes Outside the US:** Evaluate the need to include lakes outside of the US in the modeling strategy at all Tiers.
8. **Establish Verification and Validation Procedures:** Define how the accuracy and reliability of the wind wave models will be verified and validated for each Tier. Note that such procedures are in place for Tier 1, but may be difficult to implement for other tiers due to the general lack of observation data on (smaller) lakes.
9. **Develop a Timeline and Resources Plan:** Create a detailed timeline and resource allocation plan for implementing the three-tiered modeling strategy.

Note that this plan is focusing on a deterministic Initial IOC. Once this IOC is reached, it is natural to start addressing the move to a full probabilistic framework.

6.5. Hurricane Models

Hurricane wind wave modeling at NWS is performed for two applications. One is a WW3 wave model in the UFS Hurricane Analysis and Forecast System (HAFS) as part of a fully coupled atmosphere - ocean - wave model. The other is a GLERL-Donelan wave model as a component in a SLOSH-based hurricane storm surge model. Note that wave products from both systems are not used as a primary source of wave data at NWS. In both cases, the wave model is an essential part of a coupled modeling system. Considering this, the EMC wave modeling group should support both applications, but should not lead its development, or should give these applications as high a priority as is given to wave models that are primary sources of SOLAS-based wave guidance for NWS.

The above view of hurricane wave modeling results in a limited set of needed actions. For HAFS they include:

1. **Maintenance**: The EMC wave group needs to support O&M for the wave component of the HAFS system. EMC should only commit to additional development if available resources allow this.
2. **Development**:
    a. For HAFS applications, WW3 would benefit from the development of either moving grids or adjustable resolutions. As this is a structural development, it could either be targeted for NOAA NOFO funding, or could rely on community developers. As this development is unique for hurricane modeling, it is linked here to the application rather than to core development discussed in Section 6.1.
    b. Note that this application is also historically a focal point and potential future pathfinder for atmosphere-ocean-wave coupling and wave physics development, in particular for extreme wind speeds.
    c. Note that HAFS still lacks an ensemble approach for assessing forecast uncertainty.

Actions for the wave model in the coupled SLOSH model leads to the following actions:

3. **Maintenance**: The EMC wave group needs to support O&M of the GLERL-Donelan wave model coupled to SLOSH. Additional development should only be committed if available resources allow this.
4. **Development**: The GLERL-Donelan model is selected for its computational cost. It does however, have limited accuracy and limited community support. In this context, selection of an appropriate community model that is cheap enough to operate when coupled with SLOSH is a suitable activity for the EMC wave group. Note that such an activity is also needed for the higher-priority lake modeling efforts. The latter effort may enable upgrading the wave model coupled to SLOSH too.

Note that any coastal wave modeling included here requires long-term coordination on total water prediction and other coastal NOAA requirements with the National Water Center (NWC) and the National Ocean Services (NOS), in particular because the “ownership” of such products and parts thereof lies with multiple organizations. Note, furthermore, that in this context the use of SLOSH as a surge model should also be discussed and coordinated. The latter, however, is outside the scope of the present wave modeling assessment.

6.6. Regional models (GLWU, RRFS)

The NWS presently has one operational stand-alone “downstream” wind wave model. This is the Great Lakes Waves Unstructured application (GLWU, Alves et al. 2014, 2023), which has an offshore resolution of 2,500m, and a coastal resolution of 250m. This model provides critical guidance in the context of SOLAS, and is therefore a high-priority application in the production suite. In the context of the UFS and its simplification of the production suite, a preferred long-term strategy is to absorb the GLWU model in the RRFS application. Note that in the presently suggested wave plan, GLWU becomes a Tier 1 Lake modeling solution, that by nature of Tier 1 solutions can become a part of a coupled modeling system (in this case the RRFS).

The tentative simplified production suite at the core of the UFS (Figure 6.1) includes the regional Rapid Refresh Forecast System (RRFS) and the Warn on Forecast System (WoFS). These systems are envisioned as coupled models, but neither system presently has a wind wave component. The GLWU wave model has tentatively been targeted to become part of the RRFS since its original development, and as outlined in the previous paragraph. The RRFS could also benefit from a coastal wave model associated or coupled with it, either for improved integrated model behavior, or as a tool to unify coastal modeling including wind waves between EMC, NWC, and NOS. Since such a model is presently not intended to provide direct SOLAS support, development of such a wave model does not have the highest priority at EMC. The consensus opinion is that WoFS will not benefit from a wave component due to its application time and space scales, and due to the low-pass filter behavior of wave models.

The above view of regional wave modeling results in a limited set of needed actions. For GLWU and potentially other future Tier 1 wave models for lakes they include:

1. **Maintenance**: The EMC wave group needs to support O&M for GLWU. EMC should only commit to additional development if available upgrades and resources allow this.
2. **Development**: The long term goal is to include the GLWU in the RRFS as a fully coupled component model. Ideally this should also include a sea ice and lake circulation component, which are presently being developed by GLERL and are scheduled for operationalization by NOS. This will require coordination and collaboration between EMC, NOS, and potentially GLERL.

Attaching a wave model to the RRFS requires the following actions:

3. **Short term development**: Develop a stand-alone wind wave model covering the RRFS domain exactly, and with a target coastal resolution similar to that of the GLWU model (unstructured grid approach). Presently, this is a low-priority activity.
4. **Long term development**: Develop coupling strategies, priorities for coupling this wave model with the RRFS, coastal ocean models and the National Water Model. This will require coordination and collaboration between EMC, NWC and NOS.

The WoFS application in the UFS layout of the production suite requires no actions from the EMC wave modeling team.

6.7. The Nearshore Wave prediction System (NWPS)

The NWPS is approaching its end of serviceable life. In terms of product generation, its role is intended to transition to the Regional Wave Prediction System (RWPS, Section 6.3). With that, the following action items have been identified for the NWPS.

1. **Code freeze**: EMC will only provide rudimentary Operations and Maintenance support for the NWPS.
2. **Prioritize RWPS IOC**: The IOC of the RWPS needs to be prioritized by EMC. Ideally, the IOC includes all tag-on products like the rip-current guidance that are presently available from the NWPS. Alternatively, the second RWPS implementation could be the target for being able to sunset the NWPS.
3. **Coordinate**: The final retirement of the NWPS needs to be coordinated with all stakeholders, including OPC, NHC and all WFOs with marine responsibilities.

7. Bringing it together

This section provides a summary of the wave plan with a focus on priorities and links between activities. As stated in the Introduction, uncertainties in resources make it difficult if not impossible to provide realistic time lines.

Primary requirements for wind wave modeling at NWS are derived from the international SOLAS convention and our national commitment to these. SOLAS explicitly requires the NWS to provide wave products for safety of life and property associated with wind waves. What this means in practical terms is generally defined in an interactive process with NWS and its stakeholders. Secondary requirements for wind wave modeling are associated with including wind waves in comprehensive coupled weather and seasonal models to improve their forecasts. Table 7.1 provides an overview and summary of the operational wind wave applications in NWS production in this context.

Application		IOC	O&M	focus	notes
Global	GFS	✔	Level 1	SOLAS	Must have, foundational
	GEFS	✔	Level 1	SOLAS	Must have, foundational
	SFS	✗	TBD	physics / coupling	Evidence driven for total SFS
RWPS		✗	Level 1	SOLAS	Must have, Consolidation effort
Lakes	General	✗	Level 1	SOLAS	Main gap in SOLAS IOC
	GLWU	✔	Level 1	SOLAS	Presently only Tier 1 model in operations
Hurricane	HAFS	✔	Level 1	physics / coupling	Adds value to overall coupled model
	PSURGE	✔	Level 3	physics / coupling	Adds value to overall coupled model
RRFS	GLWU	~	TBD	Lake Effect weather	Needs broader coupling with GL circulation and ice models (GLERL, NOS).
	Coastal	✗	TBD	collaboration	Potential for UFS unification with NOS, NWC
NWPS		✔	Level 3	obsolescent	

IOC: Initial Operational Capability
O&M: Operations and Maintenance support
SOLAS: Safety Of Life At Sea convention

Table 7.1: Operational availability, O&M responsibility and focus of envisioned wind wave applications in operations. See main text for an explanation of O&M levels and cell coloring.

Note that the GLWU model appears twice in this Table. Once as a stand-alone lake model, and once as a coupled component in the RRFS. This does not imply that there are two GLWU models envisioned, instead it implies that the GLWU is intended to evolve from a stand-alone lake wave model to a component of a coupled model, when resources and science dictate this transition.

Table 7.1 presents the main wind wave applications discussed in Section 6 in order of priority. A green background color identifies the highest priority in this context, a yellow background identifies a secondary priority due to association with performance of integrated coupled systems (or additional stakeholder impacts), light red identifies the lowest priority applications, and dark red identifies obsolescent applications.

The second column Table 7.1 identifies if each (sub-) application presently has an IOC in the production suite. Note that the high-priority RWPS and Lakes models still represent a gap in needed IOC.

The third column in Table 7.1 addresses the Level Of Effort (LOE) associated with each application in the context of Operations and Maintenance of each application. Addressing the O&M LOE acknowledges that the highest priority of the EMC team is to provide required products and services both now and in the future.

A level 1 LOE implies that the wave team is fully engaged with the overall support team of the coupled applications throughout its development and implementation cycle, including providing science support to assure a continuous improvement of each application.

Level 2 support focuses fully on keeping all models operationally running, but shares science developments with a broader community. This is the minimum level of support for wave components in applications where the wave model contributes to the overall application quality through coupling, but does not provide a hard SOLAS requirement for products. Examples of this are the HAFS and SFS systems. Note that if resources allow for this, Tier 1 support is preferred for such systems too, and hence called out for the HAFS in Table 7.1.

Level 3 support implies the minimal support needed for keeping the model running in operations. When the wave code is part of a coupled system, ideally such support would be needed only in the case where the main support team for the coupled application critically needs SME support for its wave component.

Whereas the top priority of the wave team is to assure the continued, uninterrupted, and on-time production of wave products in the SOLAS context, a close second priority is to assure that these products are of the highest possible quality, and by representing the leading edge of our scientific and technological understanding of relevant issues. This implies that the wave team needs to supplement the mostly technological expertise associated with basic O&M with scientific skills and development associated with leading edge transition to operations of new techniques and knowledge, and possibly with basic science and technology innovations. Section 6.1 identifies such technological issues associated with the WW3 code and rapid evolution of AI/ML capabilities as such topics that are essential for the evolution and health of the wind wave applications in the NOAA production suite of models.

General Development Topic		Priority	Global	RWPS	Lakes	GLWU	HAFS	PSURGE	RRFS	NWPS	Notes
Code ("WW3")	Code Modernization	H	1	1	2	2	2	X	2	X	Foundational, needs partners
	Accuracy (science)	H	1	1	2	2	2	X	2	X	Can be done with old code
	GSE	M	1	1	2	2	2	X	2	X	Wait for new code
	North Pole	M	1	X	X	X	X	X	X	X	Wait for new code
AI/ML	Data driven models (det)	H	2	2	1	2	2	3	2	X	Preferably partnership
	Data driven ensembles	H	2	1	2	2	2	3	2	X	Preferably partnership
	Postprocessing	H	1	2	3	3	3	3	2	X	Mature prototypes available
	Accuracy (par. optim.)	H	2	1	2	2	2	X	2	X	We have expertise
	Physics emulators	M	2	1	2	2	2	X	2	X	High risk (prev. experience)

Table 7.2: Summary of main development foci needed for the wave model suite in operations at NOAA with prioritization and mapping to (initial) focal applications for each focus item. See main text for an explanation of cell coloring.

Table 7.2 represents a summary of the discussion of the basic development outlined in Section 6.1 and a general prioritization in the second column (H: high, M: medium, L: low). Most of the general development foci are of high priority. The exceptions are the GSE and North Pole code issues. These are designated as medium priority, since their systematic solution is likely to benefit from code modernization, if the latter includes architectural choices and features that simplify the (systematic) solution of these issues. In the AI/ML category, physics emulators are identified as medium priority as they are a hot topic in AI/ML in general, with recent progress as outlined in the previous sections. Due to its nature, the latter improvements are equivalent to the detailed technology improvements like GSE alleviate discussed above.

The more fundamental development addressed in Table 7.2 is naturally somewhat removed from operational applications. Measuring the impact of these developments, however, requires its use in an actual application. Effective use of resources dictates that this is done with selected target applications rather than with all operational applications at once. The color coding in Table 7.2 represents a selection of focal applications for the general development topics. Green cells with the number 1 identify such focal applications. Yellow cells with a number 2 identify applications where a positive impact is expected, but that will not be considered only if the initial concept is proven, and resources are available. Light red cells with the number 3 may have a positive impact, but are presently not expected to be considered for development. The dark red cells with the character X will not be considered. For the PSURGE application this acknowledges that the development is not done with the associated wave model. For the North Pole issue, this acknowledges that the North Pole is outside of the domain of this application. For NWPS this acknowledges that this model is obsolescent, and that only Tier 3 support will be provided.

Whereas the basic code modernization and AI/ML research identified above is essential at this juncture of operational wave modeling at EMC, the core research and development work at EMC is always focused on incremental improvement of operational applications, i.e., on the transition of research and technology to operations (R2O). This requires a linkage of the R&D to the R2O process through the assessment of required actions gathered in Section 6.2 through 6.7 for individual operational applications. The last missing link in an integrated wave plan is to bring the actions and needs of individual applications together and to more explicitly address priorities within these applications. This is done in Table 7.3.

For conciseness and to focus on relative priorities between applications, only approximately 3 actions are included per application. The priorities ranging from highest 1/red to lowest 5/blue effectively summarize the text in Section 6. The table also summarized (inter-) dependencies of these top actions, where in each column the “target” application (T, light green cell) depends on an action in a “source” application (S, dark green cell).

The first such column acknowledges that O&M for global models is critical for O&M for other limited area and regional models. The second column implies that the RWPS may be the most convenient model to further develop wave ensemble approaches, after which such developments can be included in other applications. The third and fourth column identify that NWPS capabilities need to be ported to RWPS. Once the transfer has occurred the priority of coordinating the NWPS retirement becomes higher. The fifth dependency column recognizes that developing a Tier 2 lake model is likely enabling the transition of the GLERL-Donelan wave model in SLOSH to a wave model that is more consistent with the UFS approach, which then is likely to increase the priority to replace the former model (column six). Finally, column seven of the dependencies acknowledges that developing a moving grid capability for hurricanes is likely to benefit from general code modernization and hence should have a low priority at the present time.

Finally, the red and blue cells in the code dev. and AI/ML columns reproduce the tentative initial focal applications for R2O for code modernization and AI/ML innovations.

Since the activity of developing this wave plan started with the Ken’s Connection inquiry on modeling in waves at Flathead Lake, it is appropriate to end here with that topic. This lake is a quintessential Tier 2 lake in the lake modeling plan. Since this is the only Tier 2 lake for which wave modeling is presently performed, it is the natural application to transition to a Tier 2 UFS modeling approach, which then in turn should move this operational modeling effort from WFO Missoula to EMC, preferably before the WFO is likely to lose the capability to run their model in-house by September 2026. Until this move is completed, it is consistent with the UFS modeling approach to keep operation of this one lake model at a WFO, as long as the local hard- and software approaches allow this.

Application	Action	Priority	Dependencies							Code	AI / ML	Notes
Global	O&M	1	S							X	X	Foundational
	Generalize grids	2							S			Move to unstructured grid
	Focus on coupling	2										Focus on longer forecast ranges
	Improving ensembles	3		T							X	Requires additional research
RWPS	Initial implementation	1	T							X	X	Unlock (OPC, NWPS retirement)
	Add NWPS capabilities	2			T	S						Likely required for IOC
	Building ensembles	1		S							X	TBD if ensemble is main focus.
Lakes	Create inventory	1										Can be intern activity
	Flathead IOC at EMC	1										Needed by September 2026
	Develop Tier 3 solution	2									X	Can be partners / intern project
	Develop Tier 2 solution	2					S				X	Pursue NOAA funding (e.g. JTTI)
HAFS	O&M	1	T									Foundational
	Building ensembles	4		T								As a community activity
	Focus on coupling	4										As a community activity
	moving grid approach	5							T	X		Link to code modernization
SLOSH	O&M (GLERL-Don.)	4						T				Minimal support of wave part only
	Move to UFS model	3					T	S				Leverage Lakes Tier 2 dev.
GLWU	O&M	1	T									High for SOLAS
	Focus on coupling	4										simplify production suite layout
RRFS	IOC	4	T	T								With NWC, NOS, OAR
	Focus on coupling	5										With NWC, NOS, OAR
NWPS	O&M	2										Keep full capacity until retirement
	Coordinate retirement	3			S	T						With NCO

Table 7.3: Major activities identified for individual operational wind wave applications at the NWS/EMC including the high-level prioritization (ranging from 1/red as highest, to 5/blue as lowest), with the inter-dependencies “target” application = T, light green cell depends on an action in a “source” application = S, dark green cell) and with code modernization and AI/ML focal areas from Table 7.2.

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Appendices

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A. Ken’s Connection request

This is the verbatim Ken’s Connection request regarding wind wave modeling on Flathead Lake in Montana, submitted by David Noble from the Missoula MT WFO:

Problem 1: The NWS does not have an effective way to give adequate lake modeling for smaller lakes in the US.
Problem 2: The NWS is taking away forecast office's ability to run the older Great Lakes wave model(which is already easily installed and run locally via a separate GFE server), or allowing for WFO's to run in-house modeling. This backwards and not forward-thinking decision will cause offices to abandon lake wave forecasts or be forced to use worse invalidated & undocumented empirical GFE scripts. Many tax-paying citizens in the MSO CWA utilize the current GLERL-Donelan 1977 wave model that was coded for GFE by Greg Mann in the early 2000s and the forecasts potentially will be worse off for them.

The output of the GLERL-Donelan 1977 model coded by Mann has been in operation since 2010 with the output being used on the MSO Flathead Lake webpage.

It's in my opinion that the NWS should be offering the same level of quality for wave forecasts for the lesser lakes, than the Great Lakes and Lake Champlain. Do we only put our resources into larger population areas for IDSS? Who is heading up taking care of the smaller lakes in the NWS? Do they have a 5, 10, 20, 30 year plan? I understand that it can be a very costly endeavor to implement the newer WW3 and/or FVCOM models as we have seen for Lake Champlain. But is the only solution to pull the cords of local offices so that our wave forecasts are interrupted?

Suggestion #1: Allow local offices to run the GLERL-Donelan model longer so that in the meantime we can come up with a long-term plan for continuous service to the public. From my understanding, it's easy to set up and run on a separate computer. Does it really cost a lot of money and resources to keep that running? The other alternative is to get MDL involved and get WW3 up and running for millions of dollars.

Suggestion #2: Create a group within the NWS who can meet together to brainstorm how to get the WW3 up and running for the smaller lakes. (Flathead Lake in the MSO CWA is one of the largest freshwater lakes west of the Mississippi River.) I personally am hopefully that we can establish better rapport with the high level users and the University of Montana Biological station located on the lake by educating them in the process of setting up the WW3. Maybe a graduate student may be very interested in taking on the project. Avichal with MDL told me that there may be NSF/NOAA grants available to get the ball rolling. One of the walls that we have encountered with the Bio station is that we haven't been able to offer them any funding to support their buoys in the lake. From my understanding is that we (NWS) can not fund that sort of thing.

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B. Present lake ice and temperature treatment

For the current operational GFSv16, which is not coupled to ocean and ice models, ice is updated at lake and ocean points using a global 5-minute ice concentration dataset. This dataset is a blend of the NH IMS ice product (yes/no ice flag) and EMC's global 5-minute ice concentration data. At both ocean and lake points, a near-sea surface temperature (NSST) model predicts the skin temperature, which is used by the atmosphere model to compute surface fluxes. NSST requires a foundation temperature, which is updated through data assimilation (GSI). For water bodies not resolved by GSI, the foundation temperature is updated using the trend derived from the RTGSST climatology.

In the new coupled UFS applications, ice is predicted by CICE over ocean points and follows the same method as in GFSv16 for lake points. NSST continues to be applied to both ocean and lake points. For ocean areas, the foundation temperature is derived from MOM6 temperatures, while the same approach used in GFSv16 is maintained for lakes.

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C. Wave Modeling for NOS coastal ocean applications

As NOS advances the implementation of the Unified Forecast System for coastal applications (UFS-Coastal), wave modeling is emerging as an important component in supporting fully coupled coastal earth system prediction applications. An accurate wave model component is key to the success of a suite of coastal applications supporting safe and efficient navigation, search and rescue, pollution transport, and ecosystem health. Primary examples include the South East Coastal Operational Forecast System (SECOFS) and the Three-Dimensional Surge and Tide Operational Forecast System for Alaska (STOFS-3D-Alaska), both currently under development through BIL and NOAA Water Initiative funded projects. These systems utilize a coupled configuration of SCHISM, WW3, and CICE within the UFS-Coastal infrastructure. These examples, alongside other planned activities such as a global-scale surge and wave coupled application (ADCIRC-WW3), reflect a growing operational need for accurate and consistent wave modeling capabilities.

These capabilities will drive reliable forecasts of coastal flooding and support NOAA-wide total water level efforts, particularly in complex coastal environments with high temporal and spatial variability. This also suggests the need to revisit and update key physical parameterizations suitable for three-dimensional wave-current interaction such as Stokes drift, orbital velocity, and atmosphere-wave-ocean momentum and energy transfer mechanisms from shelfbreak to surfzone. Such updates are essential for reliable modeling applications of coastal three-dimensional properties, including vertical mixing and other water column physical processes. The coastal zone is especially sensitive to these processes due to its complex bathymetric and morphological properties, and intricate shoreline geometry. Inaccurate simulation of nearshore wave conditions can result in under- or overprediction of total water levels and other critical modeling variables.

To meet the demands of next-generation coastal forecasting and as an integral part of the UFS-Coastal system, it is essential that the NOAA wave model continue to evolve. This includes development of improved shallow-water and nearshore physics, improved performance for high resolution nearshore applications, and reliable and flexible coupling interfaces with hydrodynamic models. As well as continued investment in GPU-ready models, AI/ML utilization, and upgraded physical parameterizations. As NOS's UFS-Coastal-based applications advance toward operations, the accuracy of wave-derived variables and the fidelity of wind–wave–coastal interactions will directly impact NOAA's ability to provide timely and reliable guidance on storm surge, inundation, total water levels, temperature, salinity, and to provide support to other downstream products. This investment will support coastal resilience, safe and efficient marine navigation, protect human health, enable responses to hazardous spills and search and rescue operations, and facilitate the management of coastal and marine living resources across various spatial and time scales.

D. Development process and contributors

This appendix details the process undertaken to develop this document, including the writing, review, and vetting teams and procedures. It is organized around (the attendees of) fact-finding and discussion meetings. Attendees of these meetings also provided reviews of this document. The Appendix ends with describing the final vetting process.

The following five individuals are the main editors of the document or have contributed the text reproduced in the two of the Appendices. A glossary of abbreviations used in the Tables presented in the Appendix is provided at the end of the Appendix.

Name	organization	Title	Contribution
Hendrik Tolman	NWS / OSTI	Senior Advisor for Advanced Modeling Systems	Lead, Editor
Jessica Meixner	NWS / EMC	Wave modeling lead	Editor
Dave Noble	NWS / Missoula MT WFO	Meteorologist	Appendix A
Fanglin Yang	NWS / EMC	Chief - Model Physics Group	Appendix B
Saeed Moghimi	NOS / OCS / CSDL	Physical Scientist	Appendix C

The development of this plan started with a discussion regarding the Ken's Connection contribution with several employees of the Missoula MT Weather Forecast Office (WFO) as indicated in the Table below (individuals are marked with a checkmark in the column 'I" for initial discussion). Also added to this Table is the initial developer from WFO Detroit of the model that has been run at Missoula. The checkmark in Column "F" indicates that the person provided feedback on the initial wave modeling plan for Lakes, and the column "R" indicates that the individual reviewed the final document. The latter two columns represent key elements of the review process.

Name	organization	Title	I	F	R
Dave Noble	Missoula MT WFO	Meteorologist	✓	✓	†
Daniel Zumpfe	Missoula MT WFO	Science and Operations Officer	✓	†	†
Ryan Leach	Missoula MT WFO	Lead Meteorologist		†	✓
Greg Mann	Detroit MI WFO	Science and Operations Officer		✓	

† manuscript shared, no comment provided or deemed necessary

After the initial drafts of the "background" Sections 1 through 5 were completed, these sections were reviewed for accuracy by the wave modeling team at EMC. Members of this team are identified in the Table below. The wave modeling team met for the initial review of Sections 1-5, and for a discussion about the target applications. Attendance at these two meetings is indicated by the checkmarks in columns "I" and "F" in the Table below.

Name	**organization**	**Title**	**I**	**F**	**R**
Jessica Meixner	EMC	Wave modeling lead	✓	✓	✓
Saeideh Banihashemi	Lynker @ EMC	Contractor	✓	✓	✓
Ming Chen	Lynker @ EMC	Contractor	✓	✓	✓
Matthew Masarik	Lynker @ EMC	Contractor	✓	✓	ǂ
Ali Salimi	Lynker @ EMC	Contractor	‡	✓	✓
Keston Smith	Lynker @ EMC	Contractor	✓	✓	✓

‡ unavailable for meeting, but provided comments virtually
ǂ no longer with the EMC team

After the initial steps of development and review described above, a discussion was initiated with key stakeholders within NOAA. Those involved in this part of the review process are presented in the table below. These discussions were held and attendance at the meeting is recorded in column 'F'.

Name	organization	Title	F	R
Pat Burke	NOS / COOPS /OD	Supervisory Oceanographer		✓
Logan Dawson	NWS / OPC /OAB	Science and Operations Officer	✓	✓
Gregory Dusek	NOS / COOPS	Chief Scientist	✓	✓
Judy Ghirardelli	NWS / OSTI / MDL	Division Chief	✓	‡
Christopher Landsea	NWS / NHC / TAFB	Branch chief	✓	✓
Avichal Mehra	NWS / OPC	Deputy Director		✓
Jessica Meixner	NWS / EMC	Wave modeling lead	✓	✓
Saeed Moghimi	NOS / OCS / CSDL	Physical Scientist		✓
Joseph Sienkiewicz	NWS / OPC / OAB	Branch Chief	✓	‡
Mark Willis	NWS / OSTI / WIAD	Division Chief	✓	✓

‡ retired during development of plan

After the above fact finding meetings had been completed, their outcomes were gathered in Appendix D, and a first full draft of this manuscript was produced. This version of the manuscript was then reviewed by the individuals identified in the above green tables in column “R”.

After the general review cycle was completed, a final red-flag and approval review was performed by senior leadership of STI and EMC as identified in the table below. After this review, the document was published as an internal NOAA report in the NOAA Institutional Repository

Name	organization	Title
Stephan Smith	NWS / STI	Director
Kevin Garrett	NWS / STI	Head, Modeling Program Team
Richard Bandy	NWS / EMC (MDL)	Acting Director
Daryl Kleist	NWS / EMC	Acting Deputy Director
Vijay Tallapragada	NWS / EMC	Chief Scientist
Monica Youngman	NWS / STI	Chief Scientist / AI lead

Glossary for this Appendix:

COOPS	:	Center for Operational Oceanographic Products and Services.
EMC	:	Environmental Modeling Center
MDL	:	Model Development Laboratory
NHC	:	National Hurricane Center
NOS	:	National Ocean Services
NWS	:	National Weather Service
OAB	:	Ocean Applications Branch
OPC	:	Ocean Prediction Center
STI	:	Office of Science and Technology Integration
TAFB	:	Tropical Analysis and Forecast Branch
WIAD	:	Weather Information Applications Division
WFO	:	Weather Forecast Office

E. Revision history

The Table below documents revisions of this document.

Version	Date	Description
1.00	8/6/2025	Approved for publication