NOAA Technical Memorandum NOS 35
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Whitepaper on the Development of a Unified Forecast System for Coastal Total Water Level Prediction

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Executive Summary

The UFS Coastal Applications Team (CAT) for Water Quantity (i.e. physical properties) is developing model evaluation recommendations for selecting NOAA's next-generation coupled coastal models. Under UFS CAT Water Quantity, plans were developed for three applications: (a) Total Water Level (TWL) prediction, (b) Risk reduction, and (c) Safe and efficient navigation. The present white paper describes the design of the first of these applications, namely TWL prediction on weather scales. This model aims to provide TWL predictions for an estimated 40% of the U.S. population that live under the threat of inundation ranging from nuisance flooding to compound flooding from tropical cyclones and extratropical storms.

Users of this proposed TWL prediction system include the NOAA/National Weather Service's National Centers, Coastal Weather Forecast Offices (WFOs), and River Forecast Centers (RFCs). Using this model guidance, they will provide TWL forecasts to the Federal Emergency Management Agency (FEMA), state and local emergency managers, local coastal managers (county and city level), the U.S. Army Corps of Engineers (USACE) Districts, and the U.S. Geological Survey (USGS) Water Science Centers and Storm Team. In addition, an active development community exists, including the USGS's Coastal-Marine Hazards and Resources Program, USACE's Engineer Research and Development Center, Navy, DOE, and academia. The requirements of these user groups can be met by a coupled coastal system that provides 1-hourly estimates of tides, waves, and compound flooding out to 7-10 days. Streamflow, stage, inundated area, and flood level duration will be provided hourly out to 3-5 days, 4 times/day for a 10-day outlook, and once/day for a 30-day outlook.

These user requirements will be met by a UFS model that uses the **ESMF/NUOPC coupling infrastructure**, **data assimilation in the JEDI framework**, and features **wave, sea ice, coastal ocean, and hydrology** components. Initially, a data model will be used for atmospheric forcing (one-wave coupling). ***WAVEWATCH III*** and ***CICE6***, which are widely-used within UFS, were selected as the wave and sea ice models for this TWL effort, respectively. Coastal ocean model candidates are: ***ADCIRC, SCHISM, D-FLOW,*** *and* ***FVCOM***. Hydrology component candidates are: ***NextGen National Water Model*** *and* ***WRF Hydro***. It is important to note that although Noah-MP is widely-used within UFS, it includes only a land surface model (no streamflow component), and its current subsurface representation has limited utility for hydrologic modeling. Thus, Noah-MP is considered unsuitable for the present application. In addition, downstream models for **urban inundation**, **wave runup, morphology**, and **rip currents** are proposed.

From these candidates, a final set of coupled components will be determined by means of quantitative model inter-comparison, using a set of historical tropical and extratropical storms, and evaluation metrics derived from user requirements. Using the final selection of model components, the operational coupled TWL system will be developed in two phases - in the first, a **deterministic coupled model** and workflow will be established; in the second phase, this model will be extended to an **ensemble/probabilistic TWL system**. A challenge in this regard is the computational expense of the large number of ensemble members. Solutions will be sought in improved numerical efficiency and the use of AI-based surrogate models.

1. Introduction

According to the U.S. Census Bureau, 127 million people, or about 40% of the U.S. population, lived in coastline counties in 2017, which is a 15.3% increase since 2000 (Cohen, 2019). This significant portion of the U.S. population is vulnerable to the threat of coastal inundation ranging from regular nuisance flooding to compound flooding from tropical cyclones which appear to display increasing intensity (Knutson et al, 2021). This vulnerable population requires actionable information on the timing and magnitude of flood levels arising from various sources, including tides, wind-driven surge, wave-driven surge, and rainfall run-off. There are a number of key stakeholders who provide the general public with the forecasts and emergency response needed to ensure their safety and the protection of their property. These are the National Weather Service's (NWS) National Centers, Weather Forecast Offices (WFOs) and River Forecast Centers (RFCs), the emergency managers at federal (Federal Emergency Management Agency, FEMA), state and local levels, the U.S. Army Corps of Engineers (USACE), and U.S. Geological Survey (USGS). These stakeholders in turn rely on guidance provided by numerical weather models of the various physical processes involved.

Traditionally, the National Oceanic and Atmospheric Administration (NOAA) has developed individual, stand-alone models to address the requirements of these users as they arise. In this way, NWS's Meteorological Development Lab (MDL) developed the Probabilistic Surge model (P-Surge, Jelesnianski et al. 1992; Zachry et al., 2015), NOAA National Ocean Service's (NOS) Office of Coast Survey developed the Extratropical Surge and Tide Operational Forecast System (ESTOFS, Funakoshi et al. 2013; Xu and Feyen 2016), NWS's National Centers for Environmental Prediction (NCEP) developed the Nearshore Wave Prediction System (NWPS, Van der Westhuysen et al. 2013) and NWS's Office of Water Prediction developed the National Water Model (NWM, OWP, 2016). However, recent storms such as Hurricane Harvey (2017) and Hurricane Florence (2018) have shown the importance of compound flooding, and hence the need to develop coupled coastal flooding models that take into account all relevant factors, including sources from both the ocean and land. This means that NOAA's current separate coastal modeling systems need to be replaced by an integrated coastal modeling system that can dynamically link all contributing processes to provide a Total Water Level (TWL) prediction that would meet all user requirements. See Wilkin et al. (2017) and Fringer et al. (2019) for a further discussion on this topic.

This effort forms part of a larger development within NOAA and its partners, namely the Unified Forecast System (UFS). It was found by external reviews that NOAA needs to consolidate its individual modeling systems (global and regional atmosphere, ocean, land, etc.) into a smaller set of coupled Earth System models that would continue to serve its various stakeholders. For this purpose, it has adopted a common coupling framework, the Earth System Model Framework (ESMF) with which to connect individual models. This has led to the development of various coupled UFS applications ("apps") to address well defined modeling needs. Examples are global modeling on weather scale (UFS Weather Model) and on sub-seasonal to seasonal scale (UFS S2S Model). The present white paper is part of an effort by the UFS Coastal Application Team

(CAT) to develop similar coupled applications for the coastal environment. Within the UFS CAT, models are being developed for water quantity (i.e., the physical properties of the models) and water quality (i.e., biological-chemical properties of the models). Under UFS CAT Water Quantity, model development plans were compiled for three application themes: (a) Total Water Level prediction, (b) Risk reduction, and (c) Safe and efficient navigation. The present white paper describes the design of the first of these applications, namely TWL prediction on a weather scale of 1-2 weeks.

A second important principle of the UFS is the partnership between NOAA and the community. In the past NOAA tended to develop its modeling systems in-house. The current UFS applications are meant to be conceived, developed, and continually improved in collaboration with community partners in academia, at other federal agencies, and other international weather centers. As a result, this white paper is co-authored between NOAA and these partners in the coastal community, and model candidates will be assessed together with the community, as is described in the sections below. Furthermore, NOAA has recently launched the Earth Prediction Innovation Center (EPIC), which will facilitate community collaboration by making NOAA’s UFS models and its operational infrastructure available on a cloud platform for experimentation and improvement.

UFS has defined a number of general system requirements across all applications (UFS, 2019). Following from the community principle of UFS is the key requirement that all model components be community-developed and maintained. This implies open source software which is supported by an active group of developers and users. This guarantees that the developed Earth System applications will also be open source and community-based. For operational purposes, additional system requirements of numerical stability and efficiency, and adherence to prescribed coding standards are required, as is detailed below.

This paper is structured as follows: Section 2 presents the various users of TWL models and/or information, and their requirements in terms of output quantities and quality metrics. Section 3 discusses the model components and general coupled system architecture needed to meet these requirements. Section 4 describes the operational requirements, including deterministic versus probabilistic modeling, numerical stability, efficiency, and licensing. Sections 5 to 7 discuss the coupled model candidates and the methodology for their evaluation. Sections 8 to 9 detail the development strategy of the operational TWL coupled application, including the potential benefit of leveraging Artificial Intelligence/Machine Learning (AI/ML) for ensemble modeling. Section 10 describes the strategy for ongoing improvement of the future coupled model, as a partnership between NOAA and the coastal modeling community. Section 11 closes the paper with conclusions and recommendations.

2. Users and their requirements

In this section, we identify the various user groups of TWL modeling. Two types of users are distinguished: The first comprises users of TWL model guidance for the purpose of issuing forecasts, emergency management, or other operational activities. The second comprises expert users, representing the modeling community who will be involved in co-developing this TWL modeling system.

2.1 Primary users of TWL model guidance

(a) NOAA/NWS National Centers and Coastal Weather Forecast Offices

Weather forecasters at NOAA/NWS' National Centers and Coastal Weather Forecast Offices are the primary users of NOAA's forecast model guidance. On a state level, coastal Weather Forecast Offices (WFOs) have the local responsibility for marine forecasting (<60 nmi from the shore). Over offshore regions, the Ocean Prediction Center (OPC), National Hurricane Center (NHC) and Central Pacific Hurricane Center (CPHC) have forecast responsibility. NHC, CPHC and OPC also have forecast coordination responsibility during hurricane events, including the associated storm surge. The National Water Center (NWC) collaborates to support a nationally-consistent and unified national hydrologic program. NWC works across the weather forecasting enterprise to deliver actionable water resources information from national to street-level across all time scales, provide minutes-to-months water forecasts that quantify both atmospheric and hydrologic uncertainty, and deliver forecasts of flood inundation that depict the areal extent and depth of floodwaters.

(b) NOAA/NWS River Forecast Centers

River Forecast Centers (RFCs) provide river and flood forecasts, watches, and warnings to support protection of life and property. RFCs provide hydrologic forecasts for time scales that vary from hours to months. RFCs support local communities, decision makers, and emergency management officials by providing forecast information and impact-based decision support services related to the severity, extent, and duration of floods.

(c) USACE Districts

U.S. Army Corps of Engineers (USACE) Districts make decisions on operating flood risk management measures such as navigation gates and pump stations, based on predicted total water levels and the timing of those flood waters. Decisions related to where to stage assets for post-storm operations and for locations with critical infrastructure that might require additional fortification to prevent or lessen flood damage, require reliable estimates for total water levels. The duration of flooding in an area is also important to know for estimating when post-storm operations can begin and the potential for damages from longer duration inundation, such as bridge and floodwall scouring and levee saturation.

(d) USGS Water Science Centers and Storm Team

U.S. Geological Survey (USGS) Water Science Centers use NOAA's model guidance and forecasts to determine scope of storm response and placement of USGS Storm Team instrumentation prior to landfall and planning post-storm highwater mark surveys. In particular, total water level elevations are used to determine instrument placement along the coast. River flood forecasts from NOAA/NWS' Advanced Hydrologic Prediction Service (AHPS), 1-3 day forecasts of quantitative precipitation forecasts (QPF), and seven day flood hazards from the NOAA/NWS' NWC are used to determine placement of rapid-deployment stream gauges. Forecasts of arrival of tropical storm force winds are used to assess safety for Storm Team members. In turn, the USGS Storm Team provides a valuable contribution to the community with this collection of various types of observations, which include nearshore and overland water levels, high water marks, streamflow and significant wave height (USGS, 2021).

(e) FEMA, State and Local Emergency Managers

The Federal Emergency Management Agency (FEMA) has roles both in flood risk management and flood response. Examples of the former are the regulatory Flood Insurance Rate Maps (FIRMs) that show special flood hazard areas and the risk premium zones. Since these products are developed using hindcast modeling, this user requirement is addressed in the accompanying UFS Coastal Application Team's Coastal Risk Reduction effort. On the other hand, the flood response role of FEMA, state and local emergency managers require accurate forecast information to inform which zones to evacuate ahead of a landfalling storm, and also to plan mitigation, recovery, and survey activities during and after the event. NOAA/NWS' NHC and WFOs work closely with this user group to provide them with the available forecast information and products to aid their evacuation decisions. These decisions are driven, for an important part, by accurate model estimates of total water level during tropical and extratropical events.

(f) Local coastal managers (County and city level)

Knowing risks of flood hazards and locations of inundation at a city, county, or regional level, can determine flood warning procedures, escape routes, inform media outlets, and recommendations on transportation, protecting the public and property prior to flood events. Real-time gauge information is used by the public as well as local managers to make decisions and for information dissemination on flood preparedness.

Table 1: Variables of interest and quality metrics per user group

User group	Variable of interest	Lead time	Quality metric
NOAA National	Water level	7-10 days	**Hs**: Bias < 0.3 m (or

Centers and WFOs	Maximum inundation height and extent Significant wave height Wave direction Wave period Uncertainty estimates of these variables.	7 days for tropical	10%); SI: < 0.3 **WL:** Bias < 0.1 m; RMSE < 0.2 m
NOAA RFCs	Streamflow Precipitation data Stage Inundated area Duration of flood level Feeds into AHPS	AHPS out to 3 to 5 days. NWM short term: 18 hours (issued hourly based on HRRR). Medium term: 10 day (issued 4 times/day based on GFS) Long term: 30 day (issued once/day based on CFS)	Difference between USGS measured and model discharge. Water level depends on rating curve. NWS maintains separate rating curves from USGS at some sites. Categorical metric
FEMA, State, and Local Emergency Managers	Peak surge, total inundation area, high water mark, Hs, time series water levels and current, morphology changes, breaching, overtopping/overwash, precipitation data (for operating storm drains). Capture uncertainties - what happens at days 3, 2, 1?	Up to 7 days. Varies by EM, based on evacuation times for the particular state, county/parish, region, city, or other.	Aid decision on whether to order evacuations.
Local coastal managers	Water level for inundation of city infrastructure (e.g. storm water pipes). Local warnings of flooding. Flooding extent.	6-24 hours	Water level <0.5 foot
USACE Districts	Peak water levels, duration of inundation, timing of flood levels (when will it reach a certain flood stage), post event recoveries, flood	2-3 days minimum	Decision on if and when to close navigation or flood gate. Water level accuracy/uncertainty and timing window.

	control. WLs relative to different vertical datums. Water velocity and wave energy are also important quantities.		
USGS Coastal Change Viewer	WL, Hs, Tp, Dir, tidal and longshore currents, water level relative to dune toe and crest	6 days	Water level relative to dune toe/crest < 50 cm
USGS Storm Team	Landfall location (peak surge and wave height), streamflow, QPF. What elevation to deploy instruments?	4-5 days	Go/No go decision for deployments based on storm surge uncertainty and guidance from NHC

2.2 Community users of TWL model

A second group of users of the envisaged TWL model exists, namely modelers and code developers. These are expert users, who will take the role of co-developers of the coupled model and its components, thus creating an Operations to Research (O2R) and a Research to Operations (R2O) cycle. The most prominent community users are the U.S. Geological Survey (USGS), the U.S. Army Corps of Engineers (USACE), the U.S. Navy, the U.S. Department of Energy (DOE), and academia. The contributions of each of these community users are described below.

(a) USGS Coastal-Marine Hazards and Resources Program

The USGS Coastal-Marine Hazards and Resources Program partners with NOAA to develop new capabilities for forecasting ocean-driven total water levels and coastal change. Forecasts of the probability of coastal change describing collision, overwash, and inundation for named storms (developed over the last decade) currently rely on NOAA's P-Surge and GFS-Wave models. The present state-of-the-art Total Water Level and Coastal Change prediction is based on significant wave height and period predictions at the 20 m isobath from the NWPS model, tide and wind-driven surge predictions from the ESTOFS model, combined with coastal elevation thresholds along 1D transects. In future, the goal is to base such coastal change predictions on the output of a coupled model that provides predictions of both the water level and wave characteristics in the nearshore. Additional efforts within a National Ocean Partnership Project (NOPP) are described under subsection (c) below.

(b) USACE Engineer Research and Development Center

The USACE civil works mission includes aspects of flood risk management, navigation and environmental ecosystems that rely on accurate total water level estimates. The USACE uses many community-based numerical modeling tools and is an active partner in their development. In addition, USACE develops and maintains many other numerical tools related to hydrodynamics. The US Army Engineer Research and Development Center's Coastal and Hydraulics Laboratory (CHL) mission is to deliver solutions to our Nation's most challenging coastal and hydraulic problems through research, development and application of cutting-edge science, engineering and technology.

CHL has adopted a community-based numerical technology modernization strategy to guide how it develops, maintains, applies and transitions into general practice numerical tools for both civil works and military applications. Many of the tenets of the strategy are aligned with the UFS, in particular the establishment of common systems and standardized methods for numerical technologies development and applications as well as to use component-based community software and to have seamlessly integrated data and models. These components are reinforced and interconnected with an integrated verification, validation and uncertainty quantification process and common data and metadata standards.

Working with partner agencies and academia in a collaborative process and with common goals, such as the UFS, resources from individual groups can be better utilized to advance the state of science, instead of duplicating efforts and creating competing technologies. Through these efforts, USACE will be able to leverage models and technologies that are part of the UFS and the UFS itself to better predict and model total water level for both storm and non-storm events. USACE district offices that manage and operate many flood risk management structures and water resources will benefit from enhanced and standardized workflows and improvements in not only the extent of flooding but the timing and duration of flood events.

USACE will be able to contribute to the UFS efforts as a direct development partner for models and data. Data collected by the USACE for flood events and at project sites will be valuable in validating UFS models and systems. Further, USACE has large computing resources and has used those resources to execute high-fidelity numerical models in a probabilistic framework to develop databases of regional flood risk hazard estimates quantifying annual exceedance probabilities, for example for water levels and wave conditions for coastal and inland areas. The next leap forward is to consider compound coastal flooding events which will need integrating even more numerical models and expanding the probabilistic approach to account for total water levels regardless of the source of the flooding, be it rainfall/runoff or coastal storm surge. The same models and model coupling requirements for the UFS are needed for these new estimates.

(c) U.S. Navy

The Office of Naval Research's (ONR) National Ocean Partnership Project (NOPP) aims to develop real-time forecasting systems that predict coastal impact from land-fall hurricanes of wave, surge, sediment transport (erosion and accretion above and below mean sea level), structure interaction and damage. Many modeling systems are being used in several configurations such as cross-shore profile, 2D (depth-integrated), and 3D (layers) fully-gridded approaches to compare methodologies and performance. Attention will focus on effects of vegetation and infrastructure on local scale impacts, with strong interaction amongst teams collecting high resolution land use data and oceanographic information. Approaches will test operability on the cloud and approaches to feed into the R2O cycle.

(d) DOE

The Department of Energy (DOE) is leading the development of an Integrated Hydro-Terrestrial Modeling (IHTM) and data infrastructure that will enhance knowledge, understanding, prediction, and management of the nation's diverse water challenges (Community Coordinating Group on Integrated Hydro-Terrestrial Modeling, 2020). This effort encompasses operational tools for forecasting and research to identify and resolve knowledge and data gaps that lead to forecast uncertainties. It thus fosters close coordination across scientific, operational, and resource management communities. Three "Priority Water Challenge" domain areas for initiating development of the IHTM were identified. One of which, namely "Extreme weather-related water hazard", agrees closely with the TWL coupled model development goals presented here. These water challenges span agency mission boundaries and encompass a broad range of geographies, complex system dynamics and feedbacks. The following technical challenges and opportunities for enhanced integration of capabilities were identified: (1) Standardization of data and models to allow interoperability and reuse, (2) Development of shared testbed problems to evaluate existing and new code, (3) Development and sharing of data-model integration workflows to increase the efficiency of hydro-terrestrial modeling across scales and agencies. This call for standardization, shared testbeds and workflows closely reflects the approach of UFS. There is therefore scope for significant collaboration between these two efforts.

(e) Academia

Universities rely on access to forecast data and modeling systems to support basic, applied and interdisciplinary research on a wide range of topics that intersect coastal processes and hazards. Access to advanced modeling systems used operationally will afford researchers the broader perspective (e.g., understanding of sensitivities and interdependence among models) needed to frame the most important research questions and focus research activity on topics that offer the greatest potential for new scientific knowledge and broad impact. Moreover, in support of UFS goals for damage avoidance and public safety, participation by universities is critical for educating the next generation of researchers and practitioners and for fostering innovation in the private sector. Meeting these user needs underscores the importance of numerous entry points of varying levels of sophistication for university users including: an ability to experiment with the underlying formulation and coupling of models within the TWL modeling framework, an ability to contribute and test new models and theories, an ability to access TWL forecast data at a range of scales in real time, and an ability to recover historical forecast data for retrospective studies.

3. System components and architecture

3.1 Vision for complete system

In order to meet the diverse user requirements identified above, the Total Water Level application would need to encompass an extensive number of physical processes. This will require a coupled system of interdependent models that operate from blue water and atmospheric interactions down to coastal surge, waves and sea ice, down further to overland flows. On the atmospheric side, the modeling system should include atmospheric surface stress, pressure and precipitation. On the ocean side, the modeled processes should include ice field concentration, tides, tidal dissipation, wind-driven surge, 3D baroclinic effects, ice impact on storm surge, wind wave generation, propagation, scattering (due to ice) and dissipation (due to topography, bed roughness, vegetation, and ice), and the associated wave-driven surge. On the land side, the processes should include groundwater infiltration and soil moisture, riverine discharge, runoff and inundation dynamics (2D flood routing, especially in urban environments), human infrastructure and the built environment (levees/gates/pumps/dams releasing water, stormwater infrastructure). In the nearshore and overland region, the necessary processes include estuarine circulation, morphological changes and overwashing/breaching from the sound side towards the ocean. In capturing these processes, topographic, land use, and building uncertainty is typically the biggest source of uncertainty.

In terms of geographical coverage, this coupled application would need to provide model output over the coastal zones of all US regions and territories, including CONUS, Alaska, Hawaii, Puerto Rico, the Great Lakes, amongst others. We note that the first generation of the planned system would not necessarily cover all these regions (e.g. Alaska and outlying territories), but that expansion to these domains should be possible with the selected system. In order to deliver model products over this extent, the modeling system could be configured with regional domains with boundary conditions from global models, or defined over a global extent. Considering the small spatial scales of flooding and inundation processes in the coastal zone, the application should ideally have a flexible mesh with a resolution of O(10 m) in the nearshore and inundated areas, and expand to O(100 m) to O(1 km) in the offshore and over the shelf. Within vulnerable inundation areas, it is important to account for all significant hydraulic structures such as levees and dams, for example as provided by USACE (2021). Areas further inland will need to resolve topographic features at a scale necessary and sufficient to describe the dominant processes in the hydrologic calculations, with element sizes of O(10 m) to O(1 km) and channel computational reach lengths O(100 m) to O(3000 m) depending on stream size and local conditions. In the future, the ambition is to describe flooding at a street level resolution. In this regard, a dual modeling approach could be considered, in which a high-resolution mode could be turned on only when required (Sanders and Schubert 2019).

In terms of the temporal resolution of model products, 1-hourly output would be required out to 18 h, with 6-hourly output for the remainder of the forecast. Internally, each model component will have its own integration time step, and will communicate with the other coupled components at intervals of ~10-20 min to capture the temporal variability of the fluxes.

3.2 Coastal ocean model

The coastal ocean model component (also known as a coastal hydrodynamic model) is required to compute tides and coastal surge on both basin- and regional/local scale domains. Considering these large spatial domains, and the short processing window required for operational application, a RANS-type approach is preferred for the coastal ocean model component (as opposed to DNS/LES type). In order to interact with other earth systems components, the coastal ocean model needs to be able to receive wind, pressure, tidal, wave, sea ice, and discharge inputs. For detailed representation of the coastal environment, canopy information and bed roughness needs to be accounted for. Baroclinicity can be important in tropical regions and in the vicinity of western intensification currents (e.g. The Gulf Stream), and thus needs to be included. The baroclinic effects can account for up to 10-15% of the total water level (Ye et al., 2020). The model evaluation therefore needs to consider the advantages/disadvantages of whether the model includes baroclinic effects, if those effects are incorporated in a one-way manner in 2D simulations, or if they are included dynamically in fully 3D simulations. In order to represent the various hydraulic conditions in inundated regions, sub-grid features, such as levees, gates need to be included. The coastal ocean model needs to extend landward to cover full inundation, and to connect to a hydrological model. In order to resolve this range of geographic features, the model evaluation should consider the advantages/disadvantages of using unstructured or structured grids, as well as using hybrid elements (e.g. triangular, quadrilateral, 1-D mixed capabilities). For a seamless connection to this inland modeling, the coastal ocean model needs to be able to run on various vertical datums such as NAVD88 and MSL.

3.3 Wave model component

Wind-generated ocean waves contribute to the severity and impact of coastal storms in two major ways: indirectly by transferring radiation stress to the mean flow, thus increasing the total water level, and directly via the destructive effect of breaking waves on property in inundated areas. Two broad approaches for wind-wave modeling exist in the literature: The first approach is phase-resolved modeling (e.g. Mild-slope equation and Boussinesq approximation), in which the individual wave crests and their phases are resolved in time and space. This approach is the more accurate alternative, since it is able to explicitly describe important nearshore processes such as diffraction and shallow water three-wave nonlinear interaction (responsible for wave crest skewness and asymmetry). However, this class of wave models is prohibitively expensive, since nonlinearities are explicitly computed, typically requiring sub-meter spatial steps and sub-second time steps. Thus, this type of model is typically only run on small geographic domains in the nearshore.

The second approach is phase-averaged or spectral modeling (e.g. Action-balance equation) in which the Fourier transform of the wave field is modeled statistically. Instead of modeling individual waves, this approach considers the sources (e.g. forcing by the atmosphere), sinks (e.g. steepness- and depth-induced breaking, bed friction and vegetation dissipation), propagation (e.g. refraction), and interaction (e.g. three- and four-wave interaction) of wave energy within the carrier frequencies of the wave spectrum. Due to the statistical nature of phase-averaging, this model type can be deployed over large domains, and is commonly applied over both global and coastal domains. Since wave processes occur over varying spatial scales, coastal wave modeling typically employs variable resolution unstructured meshes to resolve offshore wave generation at scales of O(1 km) to O(10 km), and nearshore wave transformation at scales of O(10 m). Although the phase information is typically dropped during the Fourier transform, the phase-averaged approach allows for the modeling of wind-wave generation over large domains in the offshore, nearshore wave transformation, and finally the contribution to the total wave level due to dissipation-induced radiation stress transfer on a regional or national scale. It is thus well-suited as a coupling component in a TWL prediction model.

3.4 Sea ice model component

In the interest of predicting TWL, nearshore representation of sea ice processes are most critical. Ice cover nearshore directly or indirectly modifies the momentum transfer between air and water, and therefore impacts coastal surge and high waves. These processes include landfast ice (i.e., immobile ice cover attaching to the shoreline), ice deformation by wind convergence, and ice-wave interactions. For landfast ice, key processes to be modeled are tensile stress in ice internal stress and anchoring of ice keels on the seafloor. Ice deformation, such as ridge formation, increases the form drag and therefore air-ice wind stress, potentially resulting in more intense coastal surges. In TWL prediction, a sea ice model would require accurate representations of air-ice and ice-water drag coefficients to simulate such events, such as the ability to parameterize the form drag associated with ice deformation and thickening. For ice-wave interactions, the capability to represent ice breakage by waves is desired as they impact the melt rate in spring and overall stability of nearshore ice cover. Another desired capability is to represent dampening, scattering, dissipation of waves by ice through the coupling infrastructure.

Many sea ice models employ continuum body assumption, where sea ice is treated as a large continuum body with a representative rheology (e.g., viscous-plastic, elastic-anisotropic-plastic). For a sea ice model to accurately represent nearshore processes associated with TWL, the spatial resolution needs to be high enough to resolve coastline characteristics and nearshore bathymetry. However, continuum body models face a dilemma in pursuing smaller grid sizes because they require that a grid size needs to be sufficiently larger than a representative size of ice floes, which can be 100 m to 1 km in size in coastal areas. For example, a grid size of 10^1 m, which hydrodynamic and wave models often use, may violate the continuum body assumption. However, continuum body models often demonstrate good performance both in prediction skill and computational efficiency and are well suited for TWL prediction applications. In the future, discrete element models may provide an alternative to continuum body models but the development of for integrating into the coupled model system is not matured yet in terms of coupling it with other Eulerian model components at sufficient computational performance.

3.5 Hydrologic model component

For the purpose of forecasting Total Water Level in coastal areas, the critical consideration is the interaction of streamflow with tides, surge, and waves in estuaries, bays and tidal channels. This system represents a downstream boundary condition for freshwater models and an inland boundary condition for hydrodynamic model domains. Both systems overlap and contribute to compound water surface profiles (e.g., Moftakhari et al. 2019, Santiago-Collazo et al. 2019). Streamflow forecasting is a principal output of the National Water Model (NWM), which will be a NOAA-specific operational configuration of the interagency Next Generation Water Resources Modeling Framework (NextGen). NextGen represents an important platform for advancing the TWL forecasting system.

For the purpose of providing the input to the Total Water Level projections, the hydrologic model needs to provide forecast information for a full suite of water budget variables, including soil moisture, snowpack, stage, groundwater storage, and hydrologic/hydraulic channel routing as appropriate, to the coast. An operational configuration of the National Water Model utilizing the Next Generation framework (NextGen NWM) is needed that is capable of resolving these variables across a range of landscapes and hydrologic conditions. The NextGen framework enables a heterogeneous hydrologic modeling approach, allowing for evidence-based selection of the most appropriate process/module/model formulation for local conditions. The NextGen framework is designed to allow flexibility in formulation. Any land surface model, such as Noah-MP, could be utilized with other process modules to enable the selection of the right model formulation for the right reasons. Additionally, the NextGen framework design anticipates integration of complete models in an interoperability framework. Operational constraints favor fast, reliable and robust approaches that meet accuracy standards in terms of discharge, water level and timing.

Current OWP efforts to improve channel routing in the National Water Model include evaluation/comparison of different hydrologic and hydraulic channel routing methods. Results to date show that backwater effects do not strongly affect discharge in most inland situations. However, backwater produces pronounced effects on stage, as expected in coastal, low-gradient and constricted reaches, and at junctions where one or both channels are in flood. This results in significant hysteresis in the relationship between stage and discharge. In coastal areas, tides and surge causing flow reversal necessitate dynamic-wave hydraulic routines. Many hydraulic boundaries in coastal areas require two-dimensional equations. This suggests that there is no universally applicable boundary condition between the purely freshwater domain and the purely saltwater domain. For the purposes of resolving saltwater impacts on freshwater systems, the boundary needs to be set far enough into the saltwater domain to minimize the impacts of freshwater contributions on stage. For the purposes of resolving freshwater impacts on saltwater systems, the boundary needs to be set far enough into the freshwater domain to minimize the impacts of saltwater contributions on flow rate. Inevitably, there will be overlapping modeling domains in the coastal transition zone.

Hydraulic routing for inland applications for the purposes of predicting out-of-bank conditions requires knowledge of the bankfull flow capacity of each reach within the domain of interest. If this quantity is either not known or highly uncertain, then the utility of the model to predict out-of-bank flow conditions becomes limited. The importance of accurate topo-bathy information for hydraulic routing cannot be understated.

Flood losses are concentrated in urban areas (Galloway et al. 2018, National Academies 2019, Rainey et al. 2021) and there is a pressing need for actionable forecast information capable of depicting street-level and household level threats including depth and velocity (Ivanov et al. 2021). Urban flood simulation requires ~3 m resolution topographic data to resolve differences in flow between streets and land parcels and time steps of seconds or smaller for accuracy and stability purposes (Schubert and Sanders 2012, Saleh et al. 2019). For continuous forecasting of flooding across US regions and territories, the data storage and computational workload required would pose extraordinarily high costs that could be far more easily managed with a threshold-based approach whereby regional flood hazard models are activated selectively and forced using model variables (e.g., precipitation, streamflow and total water level) that are continuously forecast within the complete system (Schumann et al. 2013, Sanders and Schubert 2019). There are also opportunities to use a mix of mechanistic and surrogate models developed through machine learning methods, especially for propagating uncertainty in hazard drivers (Ivanov et al. 2021). Additionally, recent research points to novel map types and graphical formats useful for meeting the differing needs of residents, public works managers, and emergency responders (Luke et al. 2018, Sanders et al. 2020). Finally, recognizing that urban flooding may be sensitive to site-specific flood control infrastructure for which data and operational knowledge is localized, use of regional model domains for flood hazard forecasting represent important opportunity for collaboration with end-users who contribute data and knowledge so the forecast system is optimized with respect to geographical idiosyncrasies and community needs (Sanders et al. 2020).

3.6 Morphology model component

Geomorphic changes in the coastal zone occur continuously and are induced by both natural processes and human induced activities. Natural events such as hurricanes, tropical cyclones, and NorEaster storms create impacts from waves and currents that can cause increased sediment transport, resulting in erosion, overwash, and even barrier island breaching. Human-induced changes are often an immediate response to natural events and for reduction of longer term impacts such as beach nourishment, channel dredging, and breach closures. These morphological changes can alter the hydrodynamic character of the system, modifying the flows, and influencing the total water levels both on the open coast and inside adjacent bays.

The prediction of morphological change (Sherwood et al., 2021) is extremely difficult because the changes in hydrodynamics and morphology are coupled (i.e. feedback to each other). The main natural processes that cause change are from waves and currents, with variability in the resulting change due to sediment grain size distribution, cohesive vs non-cohesive, bed armoring. The initial state of the system including merged bathymetry and topography is critical to provide an accurate prediction and during inundation events the land cover such as vegetation type, built structures, roads, etc all have an influence on the coastal response to storms. Accurate prediction of the currents and waves (more increasingly the infra-gravity wave response), is needed to have increased skill in morphological prediction. Spatial resolution required for morphologic modeling is meter-scale, and the coupled nature of hydro- and morpho-dynamics requires wave-by-wave temporal resolution, improved parameterization, or surrogate models for the coupled processes.

3.7 Atmospheric forcing component

All of the model components described above are forced - either directly or indirectly - by the atmosphere. Over the ocean, the atmospheric forcing on the storm surge and wave models includes u- and v-wind speed and pressure. For the sea ice model, additional forcings include the sensible heat flux, latent heat flux, turbulent exchange, long-wave and short-wave radiation. Over land, the atmospheric forcing provides temperature, mixing ratio, surface pressure, u- and v-wind speed, longwave and shortwave radiation, and precipitation rate, required across all the hydrologic model basins. These forcings can either be provided by an active atmospheric model component, coupled with two-way exchanges with other the other components, or via stored output from an offline atmospheric model, fed to the other coupled component via a so-called data cap, e.g. the Community Data Models for Earth Predictive Systems (CDEPS, NSF 2020).

3.8 Domains, Dependencies, and Boundaries

In order to create the Total Water Level prediction system envisioned in Section 3.1, the various model components described in Sections 3.2-3.7 need to be set up on model domains, their dependencies on the other coupled components need to be defined, and the boundary locations and information flow need to be established.

In terms of model domains, the coastal ocean model and wave model components should be defined over the same U.S. coastal water extent, in order to exchange water levels, currents and radiation stresses. These can either be regional domains with offshore tide and wave boundary conditions, or global models with high resolution in these coastal regions. These models could either share the same mesh to reduce interpolation errors when exchanging states, or meshes with optimized resolution to best describe coastal surge and wave processes respectively. The sea ice model should be defined over the Arctic Regions and Alaska, with high coastal resolution, in order to account for interactions with waves and storm surge. The hydrology model should cover all of the Contiguous United States, and also its drainage basins that extend into Canada and Mexico. In addition, drainage basins should ultimately be included for Alaska, Hawaii and all U.S. OCONUS territories. Atmospheric model forcing should extend over the domains of all of these coupled components. Spatial and temporal scales of atmospheric data should be adequate to resolve the storm event of interest, such as small-scale hurricanes. As detailed in Section 3.7, the specific forcing variables required for the surge, wave, sea ice and hydrology processes vary by model.

Drawing on an extensive literature review of compound flooding models, Santiago-Collazo et al. (2019) discuss various configurations of model dependencies and boundary condition placement. The most critical choice is the coupling strategy and boundary location between the hydrology and the coastal ocean models. Based on Santiago-Collazo et al. (2019), we consider the following coupling alternatives:

- **Linked hydrology/hydraulic routing model:** Here the hydrology model is the central component that provides freshwater flow information to the TWL computation, and its boundary condition with the coastal ocean model is located near the coastline. It is forced by an offline atmospheric model that provides precipitation, etc. over its drainage basins, and offline (coupled) coastal ocean and wave models that provide the downstream coastal water level. This configuration is possible if the hydrologic model includes hydraulic routing, which can account for the backwater effect from the ocean boundary condition. A cited example is USACE's Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) hydrologic model (Downer and Ogden, 2004, 2006) coupled to the ADCIRC coastal ocean model and the SWAN wave model (Araya et al., 2018). A hydraulic routing capability will be deployed with version 3.0 of the National Water Model in 2023.

- **Linked coastal ocean model:** Here the central component is the coastal ocean model which is responsible for providing information on tides, surges, and waves to the TWL computation. The coastal ocean model's boundary condition with the hydrologic model is located at each river draining into the coastal basin, ideally upstream of where any tidal or coastal surge effects are found, although model spatial resolution may preclude extending the ocean model that far inland. In addition, extending the ocean models that far inland also require consideration of runoff and routing of precipitation if the ocean model does not directly account for precipitation. The coastal ocean model is forced by the river discharge from an offline hydrologic model and a coupled wave model, which together are forced by the atmospheric fields.

- **Loosely-coupled models:** Here the hydrology and surge models are run concurrently and exchange information via a software infrastructure. One example from the literature is cited, namely Cheng et al. (2010), who set the boundary condition for these exchanges at the downstream coastline.

- **Tightly-coupled models:** Here the physics of the hydrology and coastal ocean models are integrated into a single source code, and run as a single model, so that no distinct boundary conditions are defined.

From the above options, the alternative that is the closest to the ESMF/NUOPC coupling approach is that of loosely-coupled models, in which information exchange occurs between two or more live models. The tightly-coupled alternative, in which models are integrated at the source code level, falls outside of the ESMS/NUOPC paradigm. However, as noted above, the final choice of coupling strategy and associated boundary condition will be dependent on the type of routing available in the selected hydrologic model.

3.9 System architecture

As discussed in Section 1, ESMF/NUOPC is the software framework selected for the UFS, so that it will be used to combine the coupled model components described above. The ESMF/NUOPC framework identifies a number of different components that make up a coupled earth system model (ESMF, 2021): (a) models, (b) connectors, (c) a driver, and (d) a mediator. Each participating model is associated with a given regular/unstructured mesh, which forms the basis of its interactions with the other model components. Connectors are used to pass the export state from one gridded component to another. The driver keeps the overall timing of the coupled model and schedules the passing of states between models. A mediator can be included to perform merging or blending operations between model components. In order for a model to be included within this framework, a software interface of "cap" needs to be present. This cap translates the model's native variables to standard export/import states, provides information on the mesh and parallelization scheme, and receives timing information from the driver.

Figure 1 shows the proposed ESMF/NUOPC coupling between the atmospheric, sea ice, wave, coastal ocean and hydrologic modeling components. The atmospheric component provides the primary forcing to all the models. This component can either be a live model or a data model which provides one-way forcing. It is recommended that the initial implementation feature one-way forcing for simplicity, but that coupling to a live model such as NOAA's Rapid Refresh Forecast System (RRFS, currently under development) be considered for future generations. The sea ice model in turn forces both the wave and coastal ocean models with sea ice concentration one way. This sea ice can dissipate, scatter and affect the dispersion of wind-generated waves, and enhance storm surge in the coastal ocean model. An additional interaction is possible, namely the break-up of sea ice by wave action. The wave and coastal ocean models exchange water levels, currents, and radiation stresses two-way.

As discussed in Section 3.8, the interaction between the coastal ocean model and the hydrologic model will depend on the routing scheme available in the latter. Assuming that hydrologic routing is applied in the latter (only continuity considered, no backwater effects included), the connection between these components will be one-way, including only discharge from the hydrologic model exported to the coastal ocean model. This part of the coupled system will thus correspond to the "linked coastal ocean model" of Santiago-Collazo et al. (2019) reviewed above. However, if hydraulic routing would be available (i.e. backwater effect included), an export state of the water level at a coastline boundary condition can be included (see dashed arrow in Figure 1). As with all ESMF/NUOPC applications, Figure 1 symbolically shows that the driver serves to coordinate all of these one- and two-way interactions.

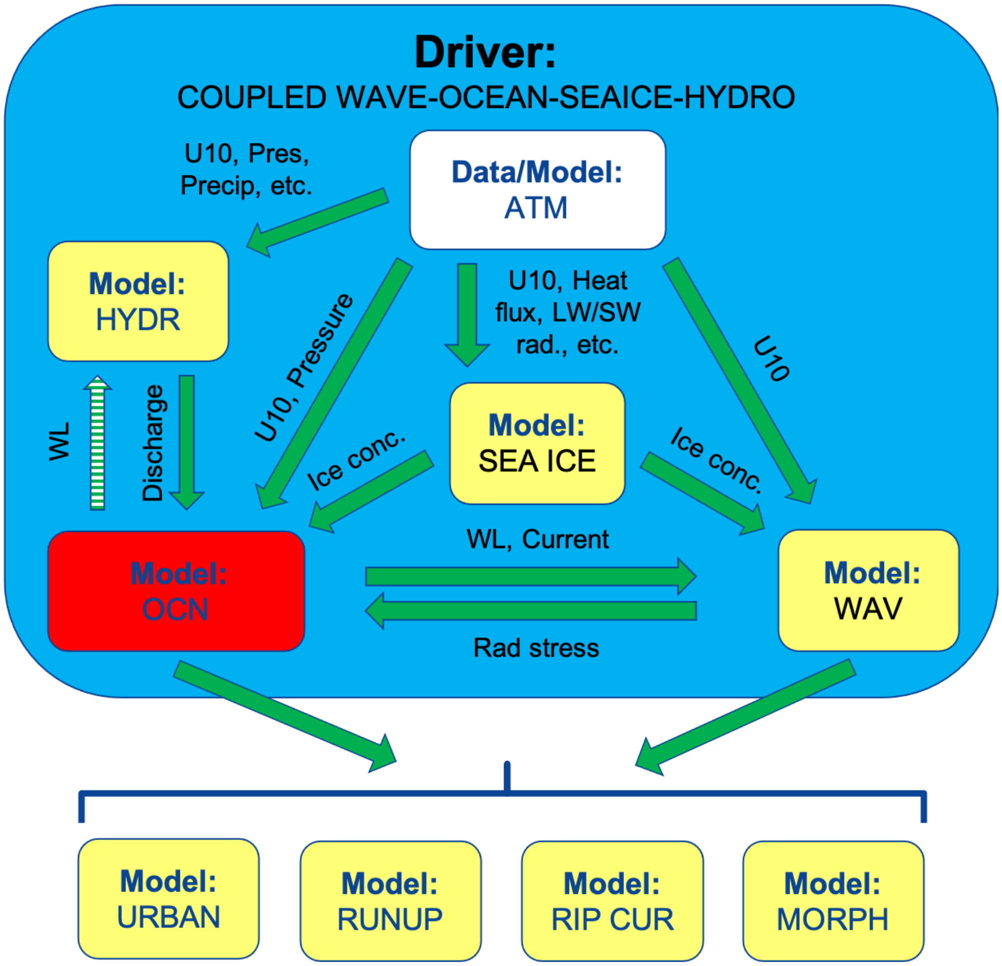

Fig 1: Example of the architecture of a coupled total water level application within the ESMF/NUOPC framework, indicating gridded components (yellow boxes), connectors (green arrows) and a driver (blue box). Dashes green arrows represent a possible connection between the OCN and HYDR components. Downstream models appear below the blue NUOPC driver box.

4. Operational requirements

4.1 Deterministic versus Ensemble versus Probabilistic

The uncertainty in tropical flood and inundation modeling is driven primarily by uncertainties in the atmospheric forcing, topographical information, channel bathymetry, and land surface characteristics (e.g. percent impervious). As a result, there is a strong need for ensemble or probabilistic TWL information, in particular for tropical applications. An example of a probabilistic storm surge system is P-Surge (e.g. Zachry et al. 2015). This adds an additional requirement of high computational speed on the coupled modeling system, or alternatively a large investment in parallel computing resources. It also requires an approach to force the individual members with perturbed atmospheric forcing fields. This could either be done through the use of existing members of upstream models (e.g. 21 HWF members) or perturbations based on historical model errors (e.g. ~500 best track perturbations of P-Surge).

4.2 Model robustness

Model robustness is a key requirement for operational use. Operational grade models are expected to run reliably, and provide guidance for each cycle without fail. This is quantified by NCEP Central Operations as the successful delivery of 99.9% of all model products. This also requires that delivered products are free from erroneous behavior such as spurious water level or wave height peaks.

4.3 Computational speed

Timely product delivery is a second key operational requirement. Computation and delivery of model products need to be fast enough to provide forecasters and users actionable information in a timely manner. For storm surge applications, the delivery time is typically less than 1h. It is also important that operational models have predictable run times, with minimal variability from cycle to cycle (< 5 min).

4.4 Community modeling

As discussed in Section 1, a central principle of UFS is community modeling. Therefore, all coupled model components are required to be community models that are open source and supported by an active user community. Licenses are thus required to be open source, or at least have open source/open access to government and not-for-profit groups, allowing changes to be made and distributed.

5. Model candidates

In Sections 3 and 4 we described the design of a coupled community model for the forecasting of total water level. This design takes into account the user requirements presented in Section 2, recent literature, the community modeling paradigm on the UFS, and various operational considerations. In Section 3 we described the coupled model components in general terms from the point of view of required functionality. We now turn to evaluating specific model candidates in order to assess how well they meet these requirements. The process started by selecting a number of model candidates from the categories of coastal ocean, waves, sea ice, and hydrology, and then evaluating them in terms of their strengths (pros) and weaknesses (cons) with respect to the following criteria:

- Mesh type and model coverage
- Physics included
- ESMF/NUOPC compatibility
- Numerical speed and stability
- Community support and license type
- Operational readiness level
- Data assimilation capability

The detailed results of this evaluation are presented in Tables A.1-A.6 in the Appendix. Based on this analysis, the writing team members assigned a numerical suitability score to each model, in terms of each of the above categories, for inclusion into a coupled TWL system, using the following four-point scale:

- **Limited (1):** Model has a fundamental limitation that would make inclusion as a coupled component challenging.

- **Suitable with major revisions/development (2):** Model has a significant limitation (but not fundamental), requiring major development to make it suitable as a coupled component.

- **Suitable with minor revisions/development (3):** Model lacks some functionality, requiring minor development to make it suitable as a coupled component.

- **Suitable (4):** Model is currently suitable for inclusion as a coupled component.

These expert judgment ratings were aggregated to averaged scores, and then rounded off to values greater than or equal to 3 (suitable in the short term), and values less than 3 (limited or not suitable in the short term). The short term is defined here as model characteristics that could be applied to coupled modeling within the next year. Table 2 shows the rounded results of this assessment for each model. In the group of coastal ocean models, ADCIRC, SCHISM, D-Flow and FVCOM are recommended as being generally suitable for inclusion as coupled model components. It is noted, however, that isolated drawbacks were flagged, including numerical speed and stability (SCHISM) and operational readiness level (D-Flow). The SLOSH and SFINCS models were deemed not suitable based on a number of factors. The wave model WAVEWATCH III and the sea ice model CICE are used widely within UFS, and they are also considered to be generally suitable for application to the TWL problem. However, the lack of a data assimilation interface in WAVEWATCH III is noted.

The group of hydrology models shows a range of suitability. In terms of mesh type, model coverage and included physics, the Next-Generation NWM shows full suitability, and WRF-Hydro model partial suitability. By contrast, both Noah-MP and FEWS lack the full range of mesh type and physical processes to serve as the inland hydrology component to a TWL system. Details are provided in Table A.2, showing that Noah-MP includes only a land surface model, and does not include a streamflow component. Also, its current subsurface representation has limited utility for hydrologic modeling. Thus, even though Noah-MP is widely-used within UFS, and scores well on a number of our criteria, it is considered unsuitable for the present application. WFR-Hydro is considered generally suitable in terms of the remaining categories. Next-Gen NWM is rated low in terms of NUOPC compatibility, numerical speed and stability, operational readiness level and data assimilation mainly because it is a new model still in development. However, it is recommended for inclusion based on its superior attributes regarding flexible model formulational physics included. The recommended models are thus (see shaded rows in Table 2): ADCIRC, SCHISM, D-Flow and FVCOM (coastal ocean), WAVEWATCH III (waves), CICE (Sea ice), Next-Gen NWM and WRF-Hydro (hydrology).

Table 2: Summary of model suitability comparison, using a four-point scale. Recommended models in shaded rows.

Model	***Type***	***Mesh type and model cove-rage***	***Physics inclu-ded***	***ESMF/ NUOPC compat i-bility***	***Numeri-cal speed and stability***	***Commu -nity support and license type***	***Opera-tional readine ss level***	***Data assimi-lation capabi-lity***
ADCIRC	Ocean	✓	✓	✓	✓	✓	✓	✓
SCHISM	Ocean	✓	✓	✓	✓	✓	✓	✓
SLOSH	Ocean	✗	✗	✗	✓	✗	✓	✗
SFINCS	Ocean	✗	✗	✗	✓	✗	✗	✗
D-Flow	Ocean	✓	✓	✓	✓	✓	✗	✓
FVCOM	Ocean	✓	✓	✓	✓	✓	✓	✓

WAVEWATCH III	Wave	✓	✓	✓	✓	✓	✓	✓
CICE	Sea ice	✓	✓	✓	✓	✓	✓	✓
NextGen NWM	Hydrology	✓	✓	✗	✓	✓	✗	✗
WRF Hydro	Hydrology	✓	✗	✓	✓	✓	✓	✗
Noah-MP	Hydrology	✗	✗	✓	✓	✓	✓	✓
FEWS/CHPS/ AHPS	Hydrology	✗	✗	✗	✓	✗	✓	✓

6. Downstream applications

As discussed in Section 3.9, in addition to the core ESMF/NUOPC coupled model components listed in the previous section, the UFS application will feature a number of downstream models to serve specific user needs. The distinction is that these downstream models need not be ESMF/NUOPC compliant, and will typically receive inputs from the coupled application without passing any exchange fields back. Table 3 lists these downstream models, indicating the model type, the inputs from the coupled model used, and the user needs addressed.

Table 3: Downstream models

Model	Type	Coupling needs	User need addressed
Total Water Level and Coastal Change (Stockdon et al. (2006, 2007). Pearson et al. (2017)	Wave runup (regression model)	1-way coupling, using wave height, period, and water level extracted at 20 m isobath.	Identify locations along the coast where beach erosion and dune overtopping will occur.
XBeach Surfbeat	Long waves, mean flow, sediment transport	1-way coupling, waves, currents, and water levels	Morphologic change, elevation and volumetric change, beach erosion, dune erosion, overwash, breaching
COAWST/InWAVE	Long waves, mean flow, sediment transport	1-way coupling, waves, currents, and water levels	Morphologic change, elevation and volumetric change, beach erosion, dune erosion, overwash, breaching
CSHORE	One-dimensional nearshore model for predicting hydrodynamics and profile changes from depth of closure into the swash zone.	1-way coupling of waves, currents and water levels	Predicts cross-shore distribution of wave height, setup and overtopping, water velocities, transport quantities and morphology change.
Sanders and Schubert (2019)	Urban flood hazard model	1-way coupling with forcing from precipitation, streamflow, wave-driven overtopping flows, and	Flood inundation dynamics (Depth, velocity) at household and street-level resolution.

		total water level data	
Mario Morales-Hernández et al. (2021)	Urban flood hazard model	1-way coupling with forcing from precipitation, streamflow, and total water level data	Flood inundation dynamics (depth, velocity)
Kim et al. (2012)	Coupled soil moisture/urban flooding model	1-way coupling with forcing from precipitation, streamflow, and total water level data	Flood inundation dynamics (depth, velocity) and soil moisture distribution.
Dusek & Seim (2013)	Rip current (logistic regression model)	1-way coupling, using wave height, direction, period, and water level extracted at 5 m isobath.	Identify locations along beaches where hazardous rip currents will occur.

7. Quantitative model evaluation

On the basis of a number of qualitative metrics, Section 6 identified model candidates that are considered to be generally suitable to serve as components of a UFS community coupled system for TWL prediction. The next step is a quantitative comparison of these candidates, in order to arrive at a final set of components to make up the coupled system. This selection will take the form of a testbed comparison, similar to previous testbeds conducted by the NOAA National Ocean Services' Coastal and Ocean Modeling Testbed (COMT), e.g. Kerr et al. (2013) and Joyce et al. (2019). Within this testbed framework, a number of candidate coupled systems will be constructed using the general system architecture presented in Section 3.9. As noted there, the exact nature of some connections will be determined by the specific model candidates making up that system, for example whether the coupling between the hydrologic and coastal ocean models will be one- or two-way. Each of these candidate coupled systems evaluated using a series of idealized and field cases featuring coastal coupling and compound flooding. These cases and their description are given in Table 4.

Table 4: Testbed case selection

Case	**Description**
Boers (1999)	Idealized wave-current interaction in a laboratory flume.
Hurricane Harvey (2017)	Field case featuring compound flooding with significant local precipitation.
Hurricane Florence (2018)	Field case featuring compound flooding with significant local precipitation.
Hurricane Maria (2017)	Wave-surge interaction in a reef-fringed island environment.
March 2018 Nor'easter	Major storm with hurricane-force wind gusts and coastal flooding.
January 2017 storm	Alaska storm featuring sea-ice interaction and inundation.

Each of the test cases in Table 4 features a significant number of observations of various types (waves, water level, high water mark, streamflow) with which to assess the model performance. These are available from various sources, including the NWS National Data Buoy Center (NDBC), NOS Center for Operational Oceanographic Products and Services (CO-OPS), and the USGS Flood Event Viewer. These observations and model results will be used to compute the various error metrics in e.g. water level, wave parameters, and streamflow that have been identified from user needs in Section 2. In addition, each coupled model system will be assessed on the basis of computational speed and stability (spurious numerical results). These metrics are detailed in Table 5. The coupled model system that achieves the highest overall score across all test cases and metrics will be selected as the preferred candidate.

Table 5: Testbed evaluation metrics

Category	**Metric**
Significant wave height	Bias, RMSE, Taylor diagram, QQ plot
Mean wave period	Bias, RMSE, Taylor diagram, QQ plot
Water level	Bias, RMSE, Taylor diagram, QQ plot
Streamflow	Long term (monthly, seasonal, annual, multi-year) bias, RMSE, MAE, Nash-Sutcliffe efficiency, Kling-Gupta coeff., event time-scale metrics including error in peak discharge, time-of-peak, event volume, inter-event recession characteristics, statistical flood frequency measures comparing modeled vs. observed distributions
Computational speed	Walltime, for given number of processors
Parallel scalability	Scaling characteristics (how close to linear)
Model stability	Presence of spurious numerical results

8. Model development strategy

Having identified the most suitable prototype based on user needs and operational criteria (Sections 5-7), the next stage is the development of the operational TWL guidance system. As done in the quantitative model inter-comparison (Section 7), the selected model components will be coupled with the ESMF modeling framework and their NUOPC caps (Figure 1). In addition, this final system will feature downstream models for high-resolution urban inundation, wave runup (erosion and overwash), rip currents, and morphology. The code and coupling infrastructure for the model components will be maintained in a single UFS application code repository ("UFS Coastal"), with external dependencies to the authoritative repositories of each of the components. The development will occur in two phases - in the first a deterministic model will be created, and in the second this system will be extended to an ensemble/probabilistic model.

In the first development phase, the coupled components will be assembled into a high-resolution deterministic model for TWL prediction. This system will be forced by an atmospheric data model from a single deterministic source. It is proposed that this single source be the Global Forecast System (GFS) over the ocean and the High-Resolution Rapid Refresh (HRRR) over the mainland (and in the future the Rapid Refresh Forecast System, RRFS). During tropical events, the forcing will be switched to the future Hurricane Analysis and Forecast System (HAFS). In turn, the downstream models will be forced with the output from this single deterministic coupled TWL model. In addition to the core UFS application code, a workflow will be developed for this operational system with which to automatically prepare, execute, and postprocess model runs according to the standards of NCEP Central Operations (NCO, 2019). This workflow will contain, amongst others, topo-bathy data and benthic data of the highest detail and accuracy possible with which to constrain the model. In addition to the workflow for the complete end-to-end system, a series of unit tests will be configured with which component processes can be assessed (e.g. tide-only runs, wave-surge interaction, and discharge-surge interaction). This deterministic model will be validated using at least a full year of meteorological conditions (four seasons), as well as a series of significant historical tropical conditions.

The second development phase will address the prediction uncertainty presented by the atmospheric forcing, in particular during tropical storms. For this purpose, the deterministic TWL model will be expanded to an ensemble system. This ensemble system will comprise the same coupled model components of the deterministic TWL system, but will feature additional ensemble members with perturbed atmospheric forcing. Outside of tropical storms, it is proposed to force this ensemble model with the members of the Global Ensemble Forecast System (GEFS). For tropical conditions, it is proposed to apply the Automated Tropical Cyclone Forecasting System (ATCF) best track data, and perturb these with statistical spread from historical forecast errors, similar to the approach for P-Surge (e.g. Zachry et al., 2015). One significant challenge in this regard is the computational load of the large number of ensemble members required (order of hundreds) to provide probabilistic storm surge guidance to NHC. One avenue is to improve the numerical efficiency of the selected physics-based models in order to reduce run times, or to allocate sufficient computational resources to enable such a large ensemble. An alternative approach is to develop and apply Artificial Intelligence-based surrogate models based on these physics-based models, as is discussed in Section 9 below. This ensemble system will have a similar workflow to the deterministic model, but expanded to accommodate the ensemble members.

To optimize the accuracy of this TWL model, a coupled data assimilation (DA) module will be developed using the infrastructure provided by the Joint Center for Satellite Data Assimilation's JEDI framework (JCSDA, 2021) and its interface to the UFS. Both remote sensed and in situ observations will be leveraged in this DA module, including satellite altimetry, water level stations, wave buoys, and stream gauges.

Upon completion of the operational workflows, DA module development, and extensive model validation, the final performance of this UFS-based TWL model will be assessed by NCEP for suitability to be included in the NOAA operational suite.

9. Machine Learning/Artificial Intelligence Approaches

Artificial Intelligence (AI) and Machine Learning (ML) can be used to improve the fidelity and computational efficiency of coupled river, ocean, wave and morphologic modeling; to QA/QC and extract information from both observations and model output; to post-process system output for feature detection and extreme event prediction; and to produce new value-added water intelligence products. One approach to integrating AI with models that already use known physical laws is to replace computationally expensive pieces of the numerical model (e.g., turbulence parameterization, drags, fluid-sediment interaction) with highly efficient AI/ML-based emulators. Improving simulation speed means models can be run at a higher resolution or for a longer period of time, providing more accurate and useful ensemble predictions. A second approach that can facilitate scientific discovery is to use AI to identify novel features in model output and gain new insights into the dynamics of nonlinear processes (e.g., frontal insatiability, morphologic change) associated with river-ocean and fluid-sediment interactions. We expect applications of AI and marine learning will be particularly valuable to ocean observations and sub-grid model parameterizations. Oceanographic observations are limited by spatial coverage and sampling rate, while models are limited by finite resolution and uncertainty. We can take advantage of a large number of observations and model outputs to train the AI and ML techniques to explore how they can be used to identify novel aspects of total water level prediction system improvement.

10. Operations to Research (O2R) and Research to Operations (R2O) cycles

Once included in NOAA operations, the TWL models described above will provide daily guidance, which will be continuously monitored for accuracy and resource usage. In striving for a cycle of constant improvement, these performance statistics will be shared with the primary users and the model development community. In addition, the code repositories of both the UFS coupled application and the associated workflows will be made available to the research community. In this way, the exact NOAA operational model and environment can be replicated by the model community, thereby establishing the Operations to Research (O2R) cycles. This access to operational repositories and environments will furthermore be facilitated by the EPIC program. Using these modeling resources, community users will develop aspects of the model based on either identified shortcomings, improved understanding of physical processes and theoretical advancements, or numerical improvements. Using the operational configuration as basis, these partners can then contribute their development back to the operational model for consideration in future upgrades, thereby completing the Research to Operations (R2O) cycle.

11. Conclusions and Recommendations

This white paper presented the need for a coupled operational Total Water Level (TWL) model as part of the UFS suite of models. This model aims to provide TWL guidance for those living in vulnerable coastal counties, namely an estimated 127 million people (40% of the U.S. population) in 2017. This significant proportion of the U.S. population is under the threat of inundation ranging from regular nuisance flooding to compound flooding from tropical cyclones and extratropical storms. The proposed model forms part of a wider collection of next-generation coupled coastal models, developed by the UFS Coastal Application Team, that focus on either the quantity or quality of water in the coastal zone. This white paper first identified the various user groups for this TWL modeling system and their requirements of this system. It then discussed the overall system design and the required functionalities of the individual coupled model components. Based on these requirements, a number of candidate models were discussed, from which a set of suitable candidates were identified. The white paper subsequently describes the procedure for the qualitative selection of the final set of coupled components, the development strategy for this coupled system, the potential need for AI-based surrogate models, and the envisaged O2R and R2O development cycles following the initial operational implementation. From the results of this writing effort, the following can be concluded:

1. The primary users of model guidance from the proposed TWL prediction system have been identified as the NOAA/National Weather Service’s National Centers, Coastal Weather Forecast Offices (WFOs), and River Forecast Centers (RFCs). Using this model guidance, they will provide TWL forecasts to the Federal Emergency Management Agency (FEMA), state and local emergency managers, and local coastal managers (county and city level). Other important users of TWL forecasts include the U.S. Army Corps of Engineers (USACE) Districts, and the U.S. Geological Survey (USGS) Water Science Centers and Storm Team. The requirements of these user groups have been quantified in Table 1.

2. Community users of the proposed TWL prediction system include the USGS’s Coastal-Marine Hazards and Resources Program, USACE’s Engineer Research and Development Center, Navy, DOE, and academia. These are expert users and future co-developers of the TWL prediction system, who will contribute to the model improvement via O2R and R2O cycles.

3. The requirements of these users will be best met by a regional ensemble/probabilistic coupled TWL model that includes the following components: (a) coastal ocean, (b) ocean waves, (c) sea ice, (d) hydrology, and (e) atmospheric forcing. ESMF/NUOPC will provide the coupling infrastructure, and this coupled application (Figure 1) will form part of the UFS code repository. For the initial implementation, the atmospheric forcing will be provided via a “data cap”, with data from models such as GFS, GEFS, HRRR and RRFS. In subsequent generations two-way coupling to a regional model such as the RRFS will be considered.

4. In addition to ESMF/NUOPC coupled components, a number of one-way coupled ("downstream") models were identified that serve specific user needs (Table 3): (a) statistical rip current models, (b) statistical wave runup models, (c) morphological models, and (d) high-resolution urban inundation models.

5. Potential model components for this coupled system were evaluated based on the following criteria (Tables A.1-A6): mesh type and model coverage, physics included, ESMF/NUOPC compatibility, numerical speed and stability, community support and license type, operational readiness level, and data assimilation capability. The recommend model candidates are:

a. Coastal ocean:	***ADCIRC, SCHISM, D-FLOW, FVCOM***
b. Ocean waves:	***WAVEWATCH III***
c. Sea ice:	***CICE6***
d. Hydrology:	***NextGen National Water Model, WRF Hydro***

6. A final set of coupled components will be determined by means of quantitative model inter-comparison, using a set of historical tropical and extratropical storms (Table 4), and evaluation metrics derived from user requirements (Table 5).

7. Using the final selection of model components, the operational coupled TWL system will be developed in two phases - in the first phase, a deterministic coupled model and associated workflow will be established; in the second phase, this model will be extended to an ensemble/probabilistic TWL system. A challenge in this regard is the computational expense of the large number of ensemble members. Solutions will be sought in improved numerical efficiency and the use of AI-based surrogate models.

References

Cheng, J.C., Hunter, R.M., Lin, H. (2010). Demonstration of a Coupled Watershed-Nearshore Model. Vicksburg, MS.

Cohen, D. (2019). About 60.2M Live in Areas Most Vulnerable to Hurricanes. America Counts: Stories Behind the Numbers, U.S. Census Bureau. Retrieved on August 24, 2021 from: https://www.census.gov/library/stories/2019/07/millions-of-americans-live-coastline-regions.html

Community Coordinating Group on Integrated Hydro-Terrestrial Modeling (2020), “Integrated Hydro-Terrestrial Modeling: Development of a National Capability,” report of an interagency workshop held September 4-6, 2019 with support from the National Science Foundation, the U.S. Department of Energy, and the U.S. Geological Survey, https://doi.org/10.25584/09102020/1659275

Downer, Charles W., and Fred L. Ogden (2004). "GSSHA: Model to simulate diverse stream flow producing processes." Journal of Hydrologic Engineering 9, No. 3: 161-174.

Downer, C.W., and F.L. Ogden (2006), Gridded Surface Subsurface Hydrologic Analysis (GSSHA) User's Manual, Version 1.43 for Watershed Modeling System 6.1, System Wide Water Resources Program, Coastal and Hydraulics Laboratory, U.S. Army Corps of Engineers, Engineer Research and Development Center, ERDC/CHL SR-06-1, 207 pp. Available on-line at: http://gsshawiki.com/gssha/GSSHA_User%27s_Manual

ESMF (2021). NUOPC Interoperability Layer. Accessed on November 26, 2021 at https://earthsystemmodeling.org/nuopc/

Fringer, O., C. Dawson, R. He, D. Ralston, and Y. Zhang (2019). The future of coastal and estuarine modeling: Findings from a workshop, Ocean Modelling, 143:101458 doi: 10.1016/j.ocemod.2019.101458

Funakoshi, Y., J. C. Feyen, F. Aikman, A. J. van der Westhuysen, and H. L. Tolman (2013). The Extratropical Surge and Tide Operational Forecast System (ESTOFS) Atlantic Implementation and Skill Assessment. NOAA Tech. Rep. NOS CS 32, 155 pp. [Available online at https://repository.library.noaa.gov/view/noaa/16917.]

Galloway, E. G., Reilly, A., Ryoo, S., Riley, A., Haslam, M., Brody, S., ... & Parker, S. (2018). The Growing Threat of Urban Flooding: A National Challenge 2018. University of Maryland and Texas A&M University.

Ivanov, V. Y., Xu, D., Dwelle, M. C., Sargsyan, K., Wright, D. B., Katopodes, N., ... & Bras, R. L. (2021). Breaking Down the Computational Barriers to Real-Time Urban Flood Forecasting. Geophysical Research Letters, e2021GL093585.

Jelesnianski, C. P., J. Chen, and W. A. Shaffer (1992). SLOSH: SEA, Lake, and Overland Surges from Hurricanes. NOAA Tech. Rep. NWS 48, 71 pp. [Available online at http://slosh.nws.noaa.gov/sloshPub/pubs/SLOSH_TR48.pdf.]

Joyce, B. R., J. Gonzalez-Lopez, A. J. van der Westhuysen, D. Yang, W. J. Pringle, J. J. Westerink, A. T. Cox (2019). U.S. IOOS Coastal and Ocean Modeling Testbed: Hurricane-Induced Winds, Waves, and Surge for Deep Ocean, Reef-Fringed Islands in the Caribbean, Journal of Geophysical Research: Oceans, 124(4), 2876-2907, https://doi.org/10.1029/2018JC014687

JCSDA (2021). Joint Effort for Data assimilation Integration (JEDI). Accessed on Jan 3, 2022 at https://www.jcsda.org/jcsda-project-jedi

Kerr, P. C., A. S. Donahue, J. J. Westerink, R. A. Luettich, L. Y. Zheng, R. H. Weisberg, Y. Huang, H. V. Wang, Y. Teng, D. R. Forrest, A. Roland, A. T. Haase, A. W. Kramer, A. A. Taylor, J. R. Rhome, J. C. Feyen, R. P. Signell, J. L. Hanson, M. E. Hope, R. M. Estes, R. A. Dominguez, R. P. Dunbar, L. N. Semeraro, H. J. Westerink, A. B. Kennedy, J. M. Smith, M. D. Powell, V. J. Cardone, and A. T. Cox (2013). U.S. IOOS coastal and ocean modeling testbed: Inter-model evaluation of tides, waves, and hurricane surge in the Gulf of Mexico, Journal of Geophysical Research: Oceans, 118(10), 5129–5172, doi:10.1002/jgrc.20376.

Kim, J., Warnock, A., Ivanov, V. Y., & Katopodes, N. D. (2012). Coupled modeling of hydrologic and hydrodynamic processes including overland and channel flow. Advances in water resources, 37, 104-126.

Knutson, T.R., Chung. M.V., Vecchi, G., Sun, J., Hsieh, T.-L., Smith, A.J.P. (2021). Climate change is probably increasing the intensity of tropical cyclones. Understanding Climate, Climate.gov. Retrieved on August 24, 2021 from: https://www.climate.gov/news-features/understanding-climate/climate-change-probably-increasing-intensity-tropical-cyclones

Luke, A., Sanders, B. F., Goodrich, K. A., Feldman, D. L., Boudreau, D., Eguiarte, A., ... & Matthew, R. A. (2018). Going beyond the flood insurance rate map: insights from flood hazard map co-production. Natural Hazards and Earth System Sciences, 18(4), 1097-1120.

Moftakhari, H., Schubert, J. E., AghaKouchak, A., Matthew, R. A., & Sanders, B. F. (2019). Linking statistical and hydrodynamic modeling for compound flood hazard assessment in tidal channels and estuaries. Advances in Water Resources, 128, 28-38.

Morales-Hernández, M., Sharif, M. B., Kalyanapu, A., Ghafoor, S. K., Dullo, T. T., Gangrade, S., ... & Evans, K. J. (2021). TRITON: A Multi-GPU open source 2D hydrodynamic flood model. Environmental Modelling & Software, 141, 105034

National Academies of Sciences, Engineering, and Medicine. (2019). Framing the challenge of urban flooding in the United States. National Academies Press.

NCO (2019). NCO High Performance Computing (HPC) Implementation Standards. Implementation Standards version 10.2. Accessed on January 1, 2022 at https://www.nco.ncep.noaa.gov/idsb/implementation_standards/

NSF (2020). CDEPS documentation, Accessed on November 23, 2021 at https://escomp.github.io/CDEPS/html/index.html

OWP (2016). National Water Model - Improving NOAA's Water Prediction Services. Weather-Ready Nation, National Oceanic and Oceanographic Administration, August 2016. Available at https://water.noaa.gov/documents/wrn-national-water-model.pdf

Pearson, S. G., Storlazzi, C. D., van Dongeren, A. R., Tissier, M. F. S., & Reniers, A. J. H. M. (2017). A Bayesian-based system to assess wave-driven flooding hazards on coral reef-lined coasts. *Journal of Geophysical Research: Oceans*, 122, 10,099– 10,117.

Rainey, J. L., Brody, S. D., Galloway, G. E., & Highfield, W. E. (2021). Assessment of the growing threat of urban flooding: a case study of a national survey. Urban Water Journal, 18(5), 375-381.

Saleh, F., Ramaswamy, V., Georgas, N., Blumberg, A. F., Pullen, J., Chen, S., ... & Schmidt, J. (2019). An integrated weather–hydrologic–coastal–stormwater framework to model urban-coastal interactions: City of Hoboken application. Journal of Flood Risk Management, 12(4), e12477.

Sanders, B.F. and J.E. Schubert (2019). PRIMo: Parallel raster inundation model, Advances in Water Resources, 126, 79-95, https://doi.org/10.1016/j.advwatres.2019.02.007.

Sanders, B. F., Schubert, J. E., Goodrich, K. A., Houston, D., Feldman, D. L., Basolo, V., Luke, A., Boudreau, D., Karlin, B., Cheung, W., Contreras, S., Reyes, A., Eguiarte, A., Serrano, K., Allaire, M., Moftakhari, H., AghaKouchak, A., Matthew, R. A. (2020). Collaborative modeling with fine-resolution data enhances flood awareness, minimizes differences in flood perception, and produces actionable flood maps. Earth's Future, 8(1), https://doi.org/10.1029/2019EF001391.

Santiago-Collazo, F. L., Bilskie, M. V., & Hagen, S. C. (2019). A comprehensive review of compound inundation models in low-gradient coastal watersheds. Environmental Modelling & Software, 119, 166-181.

Schubert, J. E., Luke, A., AghaKouchak, A. & Sanders, B. F. A framework for mechanistic urban flood forecasting at the metropolitan scale. Manuscript in review.

Schubert, J. E., and Sanders, B. F. (2012). Building treatments for urban flood inundation models and implications for predictive skill and modeling efficiency. Advances in Water Resources, 41, 49-64.

Schumann, G. P., Neal, J. C., Voisin, N., Andreadis, K. M., Pappenberger, F., Phanthuwongpakdee, N., ... & Bates, P. D. (2013). A first large-scale flood inundation forecasting model. Water Resources Research, 49(10), 6248-6257.

Sherwood, C.R., van Dongeren, A., Doyle, J., Hegermiller, C.A., Hsu, T.J., Kalra, T.S., Olabarrieta, M., Penko, A.M., Rafati, Y., Roelvink, D., van der Lugt, M., Veeramony, J.,and Warner, J.C. (2021). Modeling the Morphodynamics of Coastal Responses to Extreme Events: What Shape Are We In? Annual Review of Marine Science, 14:5.1-5.36.

Silva-Araya, W., Santiago-Collazo, F., Gonzalez-Lopez, J., Maldonado-Maldonado, J. (2018). Dynamic modeling of surface runoff and storm surge during hurricane and tropical storm events. Hydrology 5, 13. https://doi.org/10.3390/hydrology5010013.

Stockdon, H. F., et al. (2006). Empirical parameterization of setup, swash, and runup. Coastal Engineering, 53, 7, 573-588.

Stockdon, H. F., et al. (2007). A simple model for the spatially-variable coastal response to hurricanes. Marine Geology, 238,1-4, 1-20.

Torres, J.M., Bass, B., Irza, N., Fang, Z., Proft, J., Dawson, C., Kiani, M., Bedient, P. (2015). Characterizing the hydraulic interactions of hurricane storm surge and rainfall-runoff for the Houston-Galveston region. Coast. Eng. 106, 7-19. https://doi.org/10.1016/j.coastaleng.2015.09.004.

UFS (2019). Unified Forecast System Overview. Available at https://ufscommunity.org/wp-content/uploads/2019/10/201903xx_UFS_Overview.pdf

USACE (2021). National Levee Database, Website Version 3.13.0, API Version 3.13.1. Accessed on November 23, 2021 at https://levees.sec.usace.army.mil/#/

USGS (2021). Flood Event Viewer. Accessed on November 28, 2021 at https://stn.wim.usgs.gov/FEV/

Van der Westhuysen, A. J., R. Padilla-Hernandez, P. Santos, A. Gibbs, D. Gaer, T. Nicolini, S. Tjaden, E. M. Devaliere and H. L. Tolman (2013). Development and validation of the Nearshore Wave Prediction System. Proc. 93rd AMS Annual Meeting, Am. Meteor. Soc., Austin, TX. https://ams.confex.com/ams/93Annual/webprogram/Manuscript/Paper222877/AMS2013_Westhuysen-etal_ext_abstr_paper4-5.pdf

Wilkin, J., L. Rosenfeld, A. Allen, R. Baltes, A. Baptista, R. He, P. Hogan, A. Kurapov, A. Mehra, J. Quintrell, D. Schwab, R. Signell, and J. Smith (2017). Advancing coastal ocean modeling, analysis, and prediction for the U.S. Integrated Ocean Observing System, Journal of Operational Oceanography, doi: 10.1080/1755876X.2017.1322026 [PDF]

Xu, J. and J. C. Feyen (2016). The Extratropical Surge and Tide Operational Forecast System for the eastern North Pacific Ocean (ESTOFS-Pacific): Development and Skill Assessment. NOAA Tech. Rep. NOS CS 36, 163 pp. [Available online at https://repository.library.noaa.gov/view/noaa/8441.]

Ye, F., Yinglong J. Zhang, Haocheng Yu, Weiling Sun, Saeed Moghimi, Edward Myers, Karinna Nunez, Ruoyin Zhang, Harry V. Wang, Aron Roland, Kevin Martins, Xavier Bertin, Jiabi Du, Zhuo Liu, Simulating storm surge and compound flooding events with a creek-to-ocean model: Importance of baroclinic effects, Ocean Modelling, Volume 145, 2020, 101526,ISSN 1463-5003, https://doi.org/10.1016/j.ocemod.2019.101526.

Zachry, B.C., Booth, W.J., Rhome, J.R., Sharon, T.M. (2015). A National View of Storm Surge Risk and Inundation. Weather, Climate, and Society, Vol. 7., 109-117. DOI: 10.1175/WCAS-D-14-00049.1

Appendix: Model candidate evaluation

This appendix contains the detailed evaluation of the coupled model candidates for the coastal ocean, wave, sea ice and hydrology components. Each of these candidates is evaluated in terms of their strengths (pros) and weaknesses (cons) in terms of criteria that are important to user needs, coupled community modeling within UFS, and operational considerations presented in the body of this document. These various considerations are presented in the Tables A.1 to A.6 below.

Table A.1: Mesh type and model coverage

Model	Type	Pros	Cons
ADCIRC	Ocean	● Unstructured mesh allows flexible and high resolution only for required areas	● Model starts to be more sensitive and prone to instability for mesh sizes below 250 m. Need more careful assessment.
SCHISM	Ocean	● Unstructured mesh allows flexible and high resolution only for required areas. ● Combination of Quadrilateral and triangular mesh allows seamless coupling to inland hydrology. ● Resolution up to 1 m without strict limit on time step.	
SLOSH (P-Surge/PETSS)	Ocean	● Uses polar gridding system (curvilinear grid) with high resolution in coastal area of interest, and coarser resolution further offshore.	● Curvilinear grid makes it difficult to define computational grid over larger areas with adequate resolution. ● Typically applies a series of grids along the coast, each covering one to two coastal WFO domains.
SFINCS (Deltares)	Ocean	● Model uses rectilinear grid	● SFINCS is in the early stages of development and has not yet been deployed at a large scale
D-Flow (Deltares)	Ocean	● Utilizes unstructured grids - triangles,	

		pentagons, and hexagons ● Grids can be refined and coarsened in one model ● D-Flow deployed CONUS and in select OCONUS domains in hindcast mode	
FVCOM	Ocean	● Unstructured mesh allows flexible and high resolution for required areas	
WAVEWATCH III	Wave	● Unstructured mesh (2D) with resolution varying between a few kilometers in the offshore to 10s of meters in the nearshore/overland. ● Can also be nested in structured grid global applications. ● Is currently applied globally, regionally and over lakes.	● Can only use triangular unstructured mesh type (no hybrid).
CICE	Sea ice	● Applied globally in a coupled system with ocean and atmospheric models using ESMF/NUOPC.	● Currently supporting structured grids only. ● Regional applications are at experimental stages.
NextGen NWM	Hydrology	● NextGen framework supports regular and unstructured meshes. ● NextGen framework supports arbitrary discrizations. ● NextGen framework allows for heterogeneous model composition across arbitrary regions within the domain.	
WRF Hydro	Hydrology	● WRF-Hydro has been deployed across the CONUS and selected OCONUS domains	● Can only use regular grids.

		leveraging the NHD+.	
Noah-MP	Hydrology		● Can only use regular mesh ● Designed for coarse discretization as used in general circulation models operating at global climate scales. ● Subsurface discretization and methods not always appropriate for hydrologic applications
FEWS (Deltares) / CHPS (part of AHPS)	Hydrology		● Domain is limited to approximately 110,000 river miles, covering major waterways

Table A.2: Physics included

Model	Type	Pros	Cons
ADCIRC	Ocean	● Solves the equations of motion for a moving fluid on a rotating earth. These equations have been formulated using the traditional hydrostatic pressure and Boussinesq approximations. ● Water levels are obtained from the solution of the depth-integrated continuity equation in Generalized Wave-Continuity Equation (GWCE) form. ● Velocity is obtained from the solution of either the 2DDI or 3D momentum equations.	
SCHISM	Ocean	● 3D baroclinic circulation across creek-lake-river-estuary-shelf-ocean scales	
SLOSH (P-Surge/PETSS)	Ocean	● Wind driven surge. ● Wave driven surge included	● Tides not explicitly modeled.

		with tight coupling to computationally efficient wave model.	
SFINCS (Deltares)	Ocean		● Greatly simplified model physics - neglects advection term.
D-Flow (Deltares)	Ocean	● Includes full 1-, 2-, and 3D hydrodynamic capabilities.	
FVCOM	Ocean	● Includes full 1-, 2-, and 3D hydrodynamic capabilities. ● Internally coupled ice and wave models are available ● An unstructured grid dike and groyne treatment algorithm in a terrain-following coordinate system allows representation of overtopping.	● Weak in winter thermal structure representation and offshore ice cover in deep freshwater (e.g. L Superior), as of version 4.3.
WAVEWATCH III	Wave	● Includes all major physical wave processes in deep and shallow water, including generation, propagation, and dissipation. ● Calculates exchange quantities, e.g. wave radiation stresses.	● Three-wave nonlinear interactions approximately modeled.
CICE	Sea ice	● Ice dynamics and thermodynamics are solved. ● Modifies air-water momentum transfer ● Includes. landfast/shorefast ice (dampen waves/currents) parameterization. ● Floe size distribution (FSD) model allows modeling of ice breakage by waves.	● Not well explored for treatment over floodplain and interactions with breaching/overwash/overtopping. ● The model typically uses a larger grid size than floes. The resolution has to be lower than those of wave/circulation models.
NextGen NWM	Hydrology	● NextGen framework allows for heterogeneous model formulation. Model physical process representation can be selected as appropriate based on local conditions.	

WRF Hydro	Hydrology	• Contains homogeneous (general) description of physical processes.	• Current model formulation only allows for homogeneous process representation across the domain. • Model relies upon adjustable parameters to emphasize dominant physical processes.
Noah-MP	Hydrology		• Land surface model only - does not include streamflow component, etc. • Current subsurface representation has limited utility for hydrologic modeling.
FEWS (Deltares) / CHPS (part of AHPS)	Hydrology	• Routing model includes appropriate physical processes	• Hydrologic components of CHPS based on the Sacramento model - requires the forecaster to be “in the loop”.

Table A.3: ESMF/NUOPC compatibility

Model	Type	Pros	Cons
ADCIRC	Ocean	• ESMF compliant; NUOPC cap	
SCHISM	Ocean	• ESMF compliant; NUOPC cap	
SLOSH (P-Surge/PETSS)	Ocean		• Not ESMF compliant.
SFINCS (Deltares)	Ocean		• Model is in development; NUOPC cap not developed
D-Flow (Deltares)	Ocean	• NUOPC cap developed as part of COASTAL Act	
FVCOM	Ocean	• Active work on NUOPC	

		cap development for coupling with other models.	
WAVEWATCH III	Wave	- ESMF compliant, with existing NUOPC cap.	
CICE	Sea ice	- ESMF compliant, with existing NUOPC cap.	
NextGen NWM	Hydrology	- NextGen NWM is being developed with the goal of full integration into the UFS	- NUOPC cap developed for WRF-Hydro based NWM will need to be evolved
WRF Hydro	Hydrology	- NUOPC cap has been developed for NWM v.2.1 configuration of WRF-Hydro	
Noah-MP	Hydrology	- ESMF compliant; widespread use in UFS	
FEWS (Deltares) / CHPS (part of AHPS)	Hydrology		- Not ESMF compliant

Table A.4: Numerical speed and stability

Model	**Type**	**Pros**	**Cons**
ADCIRC	Ocean	- Model is robust for mesh sizes larger than 250m - Semi-implicit scheme increases computational efficiency and accuracy in comparison with explicit scheme	- Does not always work with topobathy “as is”. The model is sensitive to topobathy and often requires topobathy smoothing for stability reasons
SCHISM	Ocean	- Model is not sensitive to topobathy for stability reasons (no smoothing is required) - Due to implicit implementation model is highly stable with large time steps - Model shows more skill in	- In 2D mode model needs more care to increase skill and accuracy

		3D mode ● Stable and efficient (see large time steps, inverse CFL below in model	
SLOSH (P-Surge/PETSS)	Ocean	● Very fast simulation times. ● Highly stable model. ● Parallel MPI code available.	
SFINCS (Deltares)	Ocean	● Simplified physics yields efficient model performance	
D-Flow (Deltares)	Ocean	● COASTAL Act implementation of DFLOW is robust and efficient	
FVCOM	Ocean	● Running operationally on WCOSS by NCEP. ● Very stable in operations.	
WAVEWATCH III	Wave	● Parallel MPI code ● Scales up to at least 3000 processors ● Highly stable code.	● Tends to be the most expensive component of a coupled Earth System model.
CICE	Sea ice	● Parallel MPI code ● Highly stable code	
NextGen NWM	Hydrology	● Heterogeneous model formulation should allow for optimized efficiency, speed, and stability	
WRF Hydro	Hydrology	● NWM configuration of WRF-Hydro executes within forecast constraints, producing a CONUS-scale short-range forecast in under an hour ● NWM configuration of WRF-Hydro runs stably in NOAA operations	● Some processes in WRF-Hydro, e.g. routing in very small catchments, are computationally expensive
Noah-MP	Hydrology	● Model executes stably and efficiently as part of NWM configuration of WRF-Hydro	
FEWS (Deltares)	Hydrology	● Model executes stably and	

/ CHPS (part of AHPS)		efficiently and supports NWS forecast operations	

Table A.5: Community support and license type

Model	Type	Pros	Cons
ADCIRC	Ocean	● Community model with contributions from many developers ● Code management through git workflow ● The ADCIRC source code is copyrighted, 1994-2016, by: R.A. Luettich, Jr. and J.J. Westerink	● Registration via email required to access code.
SCHISM	Ocean	● Model is fully open source at github.com (no user/pass needed for access to code) ● Code management through git workflow ● Apache-2.0 License (https://github.com/schism-dev/schism)	
SLOSH (P-Surge/PETSS)	Ocean		● Developed in-house at NOAA/NWS/MDL
SFINCS (Deltares)	Ocean		● Model is in development and not yet open source
D-Flow (Deltares)	Ocean	● Open source	
FVCOM	Ocean	● Funding commitment by NOAA with established relationship ($150k/year from NOS base funds). ● Large developer and user community. ● Code available on Github/git workflow.	● Latest user manual in 2013.
WAVEWATCH III	Wave	● Community model with large developer base. ● Open source license	
CICE	Sea ice	● Community model with large developer base	

		- Open source	
NextGen NWM	Hydrology	- Community model with growing developer base - Open source development	- New modeling framework
WRF Hydro	Hydrology	- Open source - Large user community	
Noah-MP	Hydrology	- Open source - Large user community	
FEWS (Deltares) / CHPS (part of AHPS)	Hydrology	- FEWS has Large international user community	- FEWS is not open source

Table A.6: Operational readiness level

Model	**Type**	**Pros**	**Cons**
ADCIRC	Ocean	- RL 9 - ADCIRC 2D is running operationally on WCOSS by NCEP	
SCHISM	Ocean	- RL 7 - with respect to NOAA - RL 9 - with respect to other countries. The model is running operationally in Taiwan Meteorological Office (CWB-OCM surface currents forecast) as well as in New Zealand MetService (e.g. Cook Strait surface currents forecast) and likely Germany (Baltic Sea/North Sea). The models is also running semi-operationally on Frontera	
SLOSH (P-Surge/PETSS)	Ocean	- RL 9: Currently used in NOAA operations as part of P-Surge, ETSS and P-ETSS.	
SFINCS (Deltares)	Ocean		- Model is in development. Estimate TRL to be 5-6.
D-Flow (Deltares)	Ocean	- COASTAL Act implementation of D-Flow is at TRL 7-8	
FVCOM	Ocean	- RL 9: Currently used in	

		NOAA operations (GLOFS).	
WAVEWATCH III	Wave	- RL 9: Both unstructured and regular grid modes currently used in NOAA operations.	
CICE	Sea ice	- RL 9: Currently used in NOAA operations (e.g., Global RTOFS, UFS S2S)	- Regional applications are at experimental stage
NextGen NWM	Hydrology		- Model currently development at TRL 5-6
WRF Hydro	Hydrology	- RL 9: NWM configuration of WRF-Hydro currently used in NOAA operations	
Noah-MP	Hydrology	- RL 9: Currently used in operations as part of the NWM configuration of WRF-Hydro	
FEWS (Deltares) / CHPS (part of AHPS)	Hydrology	- RL 9: Currently used in NWS operations	