NOAA Technical Memorandum NOS 33
NOAA Technical Memorandum NWS 01
NOAA Technical Memorandum OAR 01

Risk Reduction Sub-Group Models Model Evaluation Report

Silver Spring, Maryland
June 2022

noaa National Oceanic and Atmospheric Administration

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Risk Reduction Sub-Group Models Model Evaluation Report

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Executive summary

Coastal areas are especially vulnerable to hazards, now and in the future, posed by waves, tsunamis and surges associated with sea level rise and coastal storms. Changing climate, geological processes and continued urbanization and economic investment have increased the vulnerability of coastal areas to natural disasters.

This sub-application team defined ***risk reduction*** as a ***risk management technique*** that involves reducing the damaging consequences in the form of human or financial loss. In order to better understand past coastal hazard events and also potential coastal exposure to specific hazards, ***hindcast reanalysis*** is used to support the development of products such as hazard maps and coastal flooding return periods.

As such, hindcast coastal applications are grouped into two main time-scale groups:

> ***Short term:*** disaster mitigation, coastal resiliency and support local and federal authorities (e.g. COASTAL Act) on the order of weeks to months.
>
> ***Long term:*** reanalysis studies that use time scales on the order of years and typically greater than 25 years, including probabilistic hazard analysis.

Even with two time-scale groups, it is impossible to use one model for all risk reductions applications within a certain group. As such, the team focused on two main applications:

Consumer Option for an Alternative System to Allocate Losses (COASTAL) Act: The COASTAL Act was designed to mitigate future legal issues by requiring NOAA to produce detailed "post-storm assessments" in the aftermath of a damaging tropical cyclone that strikes the U.S. or its territories. Using output from a hindcast model (termed the "Named Storm Event Model" (NSEM) by the Act), the assessments will indicate the strength and timing of damaging winds and water at a given location in the area impacted by the tropical cyclone.

Tsunami applications: Hindcasting of past tsunami events includes:

> 1) **Post-event analysis**: This modeling activity refers to tsunami modeling and analysis in the immediate aftermath of tsunami impact.
>
> 2) **Long-term hindcasting** of tsunami modeling that can extend from decades to thousands of years.

The report includes Model Evaluation recommendations for short-term and long-term risk reduction applications and a summary of current model capabilities as follows:

- ***a.*** **Resolution**
- ***b.*** **Stability, Accuracy and computational efficiency**
- ***c.*** **Code management**
- ***d.*** **Coupling**
- ***e.*** **Data Assimilation (DA)**

f. **NOAA Readiness Levels**
g. **Geographic coverage**
h. **License**

The selected models to participate in the model evaluation for COASTAL Act applications are **ADCIRC**, **DFLOW**, **FVCOM**, **SCHISM**, **ROMS**, **SLOSH.** The models to participate in the model evaluation for Tsunami Application are **FUNWAVE-TVD**, **GEOCLAW**, **MOST**, **NEOWAVE**, and **TSUNAMI-HySEA.**

1. Introduction

Coastal areas in the U.S. are economic drivers for the whole country, supporting port commerce, valuable fisheries, and multiple revenue streams for state and local governments. However, coastal areas are especially vulnerable to hazards, now and in the future, posed by waves, tsunamis and surges associated with sea level change and coastal storms. Changing climate, geological processes and continued urbanization and economic investment have increased the vulnerability of coastal areas to natural disasters.

In this document, we define **risk reduction** as a **risk management technique that involves reducing the damaging consequences of human or financial loss**. This encompasses a whole range of actions including reducing the severity of a loss, reducing its frequency, or making it less likely to occur overall.

In order to better understand past coastal hazard events and also potential coastal exposure to specific hazards, hindcast analysis is used to support the development of products such as hazard maps and coastal flooding return periods. The use of hidcast analysis also lays the foundation for possible future climate studies (i.e., decades up to centuries). As such, this report classifies the hidcast coastal application into two main groups:

- ***Short term:*** *disaster mitigation, coastal resiliency and support local and federal authorities (e.g. COASTAL Act) on the order of weeks to months.*
- ***Long term:*** *multi-year analysis, typically 25 ~ 40 years reanalysis studies, including probabilistic hazard analysis.*

The Unified Forecast System (UFS) is the process for selecting a reasonable minimum number of models to properly cover all modeling needs and requirements. The UFS is designed to meet the National Oceanic and Atmospheric Administration’s (NOAA) operational forecast mission to protect life and property and improve economic growth. The UFS numerical applications span local to global domains and predictive time scales from sub-hourly analyses to seasonal predictions. It is designed to support the Weather-Water-Climate Enterprise and to be the source system for NOAA's operational numerical weather and ocean prediction applications. The challenges of a community-based Unified Forecast System, addressing a portfolio of applications, compels a more formalized, organized, documented, and transparent implementation of the Research to Operations (R2O) functions. The strategy is to have the ability to conduct a community-based, coupled comprehensive Earth system model-based analysis and prediction system.

It is important to note that there is already a R2O process in NOAA and other government agencies. Different groups apply and document the R2O process with different levels of rigor. What is apparent is that the process of moving from research to operations is one of focusing and narrowing research efforts to contribute to specific applications. The selection process, which considers a portfolio of research contributions to be part of a UFS application, is not linear. Rather, it is an iterative process that occurs again and again as knowledge is gained from application-based experience.

The components of the configuration (Physics, Coupling, Dynamics, Data Assimilation, Initialization and boundary conditions, Tools, and Suite of products for dissemination) of the Candidate for Operations is evaluated and tested at different levels up to in a real-time forecast environment. At each level, different groups determine if the model is suitable for operations. If the candidate is not suitable for operations, it may be rejected or incremental changes might be made and the testing continues.

Even with two time-scale groups, the group identified multiple coastal applications with very different requirements that cannot be lumped into one list or operated using one model. As such, the team focused on two main applications in order to create a model evaluation recommendations for short-term and long-term risk reduction applications:

Consumer Option for an Alternative System to Allocate Losses (COASTAL) Act: The COASTAL Act was designed to mitigate future legal issues by requiring NOAA to produce detailed "post-storm assessments" in the aftermath of a damaging tropical cyclone that strikes the U.S. or its territories. Using output from a hindcast model (termed the "Named Storm Event Model" (NSEM) by the Act), the assessments will indicate the strength and timing of damaging winds and water at a given location in the area impacted by the tropical cyclone.

Tsunami applications: Two key risk reduction applications include:

A. Development of community specific tsunami inundation maps that will, in turn, inform the creation of evacuation routes, appropriate use and installation of signage and other informational products designed for the at-risk population.

B. Hindcasting of past tsunami events includes:

   1) Short-term hindcasting for post-event analysis in the immediate aftermath of tsunami impact.

   2) Long-term hindcasting of tsunami modeling that can extend from decades to thousands of years.

2. Common Risk Reduction Applications - COASTAL Act Application: the Named Storm Event Model (NSEM)

2.1 Overview and modeling components

The Consumer Option for an Alternative System to Allocate Losses (COASTAL) Act was signed into law on July 6, 2012. The purpose of the COASTAL Act is to lower costs to FEMA's National Flood Insurance Program (NFIP) by better discerning wind versus water damage in the case of "indeterminate losses;" that is, where little tangible evidence beyond a building's foundation ("slab") remains for the proper adjustment of insurance claims for homes totally destroyed by a tropical cyclone. Indeterminate losses became an issue following Hurricane Katrina, when private home insurance providers disagreed with their policyholders over the loss-allocation between flood as a cause of loss (covered by NFIP) and wind peril (covered by private home insurance). These disagreements led to backlogs in the judicial system.

The COASTAL Act was designed to mitigate future legal issues by requiring NOAA to produce detailed "post-storm assessments" in the aftermath of a damaging tropical cyclone that strikes the U.S. or its territories. Using output from a hindcast model (termed the "Named Storm Event Model" (NSEM) by the Act), the assessments will indicate the strength and timing of damaging winds and water at a given location in the area impacted by the tropical cyclone. The NSEM model components will be **initiated from operational products** (e.g, Hurricane Weather Research Forecast Model - HWRF, High Resolution Rapid Refresh - HRRR, and Unrestricted Mesoscale Analysis - URMA). NSEM will be executed over an updated mesh generated from digital elevation models (DEMs) with most recent updates before the hurricane season. The atmospheric models will be run iteratively to achieve the **90% accuracy** as much as possible over a **90-day period**. Blended atmospheric fields will be generated for wind, gust, and surface pressure passed over to NSEM as the forcing. NSEM will be run iteratively to achieve the 90% accuracy as much as possible. All final outputs from the models will be shared with the FEMA and the general public via Coastal Wind and Water Event Database (CWWED).

2.2 Requirements

In October 2012, FEMA communicated to NOAA that 90% accuracy (as it pertains to the COASTAL Formula) shall be achieved for a Named Storm when all of the following criteria are met:

A. **Data for boundary and forcing conditions -** Sufficient quantity and quality of Covered Data are gathered, in the area between the shoreline and the limit of coastal flooding during a Named Storm, to allow successful application of the COASTAL Formula. In addition to the definition of "Covered Data" as defined by the Act, that term shall also include the magnitude and timing of overland wave conditions required to accurately model and assess damage from a Named Storm; and further, the definition of "Named Storm Event Model" as defined by the Act shall include the magnitude, timing, and spatial variation of overland wave conditions associated with a specific Named Storm to be used in the COASTAL Formula.

B. **Correlation with observations -** The NSEM replicates measured wind speed, still water elevation, and wave height data within +/- 10% across the flooded area.

C. **Successful application** - The COASTAL Formula is considered successfully applied when the COASTAL Formula is calibrated against at least an undefined number of adjusted claims of past determined losses from the Named Storm, such that the COASTAL Formula predicts within +/- 10% the percent of wind damage and the percent of flood damage determined by insurance claims adjusters for determined losses certified under the NFIP in consultation with engineers and using Covered Data.

NOAA offered the following expanded set of covered data to serve as input to the COASTAL Formula, down to approximately parcel scale to permit application to individual structures:

- Time series of **water levels**, at indeterminate damage sites distributed across the storm's inundation zone, including combined contributions of tides, storm surge, wave set-up, and riverine flooding from the coastal watershed;
- Time series of **wave heights and periods**;
- Time series of the **wind speed and direction** for a standard averaging time and height applicable to the exposure of the site; and
- Time series of **rainfall** to estimate potential interior losses from wind-driven water penetration.

While static observations (i.e., snapshots of physical phenomena at a site) will be informative, time-series data are essential for establishing the relative timing of the wind and flood peaks. This information will influence engineering assumptions about the timing and severity of potential damage associated with each peril, (e.g., flooding, wind, rainfall).

2.3 Guidelines for model evaluation - The Named Storm Event Model

Addressing these requirements, the COASTAL Act program adapts the following general methodology for assessing the accuracy level of the NSEM. FEMA stipulates an accuracy level of 90% for two gridded output product groups: Wind and Water (water level, wave height, precipitation, and river flooding) and can be evaluated for accuracy in two ways, using wind as an example:

Method 1: The gridded wind analysis can be compared with all input observations (of acceptable quality) to provide an analysis error at each observation location. If the ratio of analysis difference from the observation to the analyzed wind is less than 10% (with some correction for the expected observation error) then the analysis can be described as 90% accurate in the region surrounding the observation.

Method 2: An ensemble of wind analyses can be generated from statistically representative sub-samples of acceptable input observations. At each grid point, the spread of this ensemble provides an estimated analysis uncertainty that can be compared with the analyzed wind to test the 90% accuracy criterion. This method provides accurate information in regions far away from observations.

3. Common Risk Reduction Applications - Tsunami Risk reduction

3.1 Overview and modeling components

In the context of tsunami hazard, a comprehensive risk reduction plan involves a series of modeling activities directed towards reducing the risk of coastal communities in sustaining damage from tsunami impact. These activities include but are not limited to:

A. Development of community specific tsunami inundation maps that will, in turn, inform the creation of evacuation routes, appropriate use and installation of signage and other informational products designed for the at-risk population.

B. Hindcasting of past events serves three well-defined objectives:

   1. **Post-event analysis:** This modeling activity refers to tsunami modeling and analysis in the immediate aftermath of tsunami impact (orders of hours). These studies are crucial in: Assisting search and rescue efforts focus on areas shown to have been hardest hit by the event, inform the collection of perishable scientific data for model validation and refinement and help Emergency Management with rapid loss estimations of the event.

   2. **Long-term hindcasting:** This type of tsunami modeling involves geological time scales that can extend from decades to thousands of years. In this regard, long-term hindcasting for tsunamis differs from typical time scales associated with other climate or weather driven hazards. In the case of tsunamis, hindcast modeling involves careful analysis of historical and ancient tsunami evidence, ranging from eye-witness accounts in the oral or written literature to paleo-tsunami studies of pre-historical events to the identification of potential sources and return periods based on seismic records. These data are then used to calibrate local hydrodynamical models and gain a better understanding of hazard exposure for a particular community. Long-term hindcasting can be approached from either a deterministic or probabilistic viewpoint.

The activities listed above work together in reducing the risk of losses and respond to the Congressional mandate reflected in the Weather Act, Public Law 115–25—APR. 18, 2017 directing the NOAA Administrator to:

“...operate a program to provide tsunami detection, forecasting, and warnings for the Pacific and Atlantic Ocean region including the Caribbean Sea and the Gulf of Mexico...”

and to:

"... in coordination with the Administrator of the Federal Emergency Management Agency and the heads of such other agencies as the Administrator considers relevant, [the Administrator] shall conduct a community-based hazard mitigation program to improve tsunami preparedness and resiliency in at-risk areas of the United States and the territories of the United States."

3.2 Requirements

The National Tsunami Hazard Mitigation Program (NTHMP) is a federal/state partnership dedicated to the mitigation of the tsunami hazard in the United States. The NTHMP has been closely involved with coastal states in the design of Tsunami Evacuation Maps for at-risk, coastal communities, and has invested a significant amount of effort in creating consensus amongst the scientific community on establishing standards and benchmarks for tsunami simulation codes. In addition to the NTHMP efforts, PMEL and the NWS Tsunami Warning Centers (TWCs) defined together key requirements for the Tsunami models. The requirements are a product of workshops involving NOAA and academic partners, and other NOAA internal meetings.

In the field of Tsunami numerical modeling, there have been a number of initiatives at the national level to establish standards and criteria that would identify baseline requirements for operational use of tsunami numerical models. Of particular interest was the use of these models for real-time tsunami forecasting in combination with DART (Meinig et al. ,2005) buoy data was the driver behind these initiatives. However, results from these early studies were later expanded to evaluate numerical models for Hazard Assessment applications.

A thorough review of the literature and existing benchmark problems that could be used for model evaluation, verification and validation was initiated at the Pacific Marine Environmental Laboratory (PMEL) and crystallized with the publication in 2007 of a NOAA Technical Report (Synolakis et al., 2007) proposing a model validation framework that included verification of model results with analytical solutions, laboratory experimental data and field observations of real tsunami events.

This NOAA Technical report served as the basis for three separate efforts by the National Tsunami Hazard Mitigation Program (NTHMP) to validate additional models for use by the Program in the design of Tsunami Evacuation Maps for at-risk, coastal communities. To this end, a first workshop was organized by the NTHMP in Texas A&M University at Galveston, TX in 2011. During this workshop, different tsunami models were evaluated for their ability to accurately reproduce tsunami inundation extents in some of the benchmark problems identified in the 2011 NOAA report.

A second workshop took place in Portland, OR in 2015, designed to gage the ability of the models in forecasting tsunami-induced currents, which had, by then, been identified as largely contributing to harbor damage. For the evaluation of tsunami currents, the NTHMP committee provided a new set of benchmark problems primarily from experimental and field observations. Results of that workshop along with a description of the benchmarks problems proposed for validation were published in Lynett et al. (2017).

One last workshop was organized by the NTHMP, once again in Texas A&M University at Galveston, TX in 2018 with the purpose of evaluating the ability of the models to accurately simulate tsunamis generated by both subaerial and submarine landslides. Model results for this exercise were validated almost exclusively against experimental laboratory data and published as a report (Kirby et al, 2018).

In addition to these evaluation efforts, PMEL and the NWS Tsunami Warning Centers (TWCs) came together in 2013 to agree on a set of metrics that would address the accuracy improvement in tsunami forecasts brought about by the use of numerical models. This effort looks beyond the individual performance of a particular tsunami model and evaluates the overall ability of the code to produce accurate and timely forecasts within the forecasting framework used by the TWCs. The metrics used in the study were mostly based on tide gage observations and the underlying metric required predicted results to be on average within 70% accuracy of the maximum tsunami amplitude (of the **Tsunami waves**) observed at a set of tide gages in a number of recent real tsunami events. There were also requirements on the computational speed of the tsunami codes for their use in real-time forecast operations to ensure timely forecasts.

NTHMP plans to update some of the standards and benchmarks for tsunami numerical models that have been used and published to date with new and existing data, and to design new benchmarks that will address the specific model application. We note here that the model requirements in tsunami application are presently designed for earthquake- or landslide-generated tsunamis. Model standards for tsunamis generated by meteorological events have not been well established due to premature modeling and observational technology in this particular application.

3.3 Guidelines for model evaluation - Tsunami Application

While the NTHMP has published a series of reports identifying relevant problems where model results can be validated with known solutions of either tsunami wave elevation or flow speeds. Most of the proposed validation tests are focused on the validation of tsunami wave elevation, as existing measurements of tsunami flow speeds are rare.

In PMEL’s consensus with the NWS Tsunami Warning Centers (TWCs), the consensus was that an average accuracy in maximum tsunami wave elevation at tide-gages, over a statistically significant set of observations should not fall below **70% accuracy** of the maximum tsunami amplitude in the simulated models compared to the observed values at the tide gages, for sites with a large enough signal to noise ratio. Additional criteria includes:

- **Minimum Processing time -** For computation of TWCs inundation models for forecasting. In the past, sufficient computational speed to compute 4 hours of tsunami activity in 10 minutes of wall clock time was required, but this metric is obsolete now and needs to be updated.
- **Stability -** No metrics have been clearly defined for this requirement, but it is expected that tsunami codes are robust enough for the computation of tsunami inundation without the threat of a disruption to TWC operations.

Models for tsunami risk reduction studies are required to follow the standards and criteria established by Synolakis et al. (2007), NTHMP (2012 and 2015), Lynett et al. (2017), and Kirby et al. (2018). These standards ensure sufficient quality of the tsunami risk assessment and a basic level of consistency between efforts in terms of products.

- Procedure

  A model to be adopted for hindcast application needs to be put through a benchmarking process in which numerical results, such as tsunami water surface, inundation limit, runup height, and current speed, were analyzed and compared with well-established analytical solutions, laboratory experiments, and observed field data. Currently there are no targeted accuracy requirements, however it is recommended that one model should achieve the average accuracy of all tested models listed in the NTHMP documents (NTHMP, 2012 and 2015; Kirby et al., 2018).

  A model to be adopted for forecast application is required to, besides the above benchmarking process, engage an additional Operational Testing & Evaluation (OT&E) process set forth by the NOAA's Tsunami Warning Centers (Gately and Fryer, 2013), which further evaluates the accuracy and robustness of the model against observational data at multiple tide gauges for four historical events and synthetic data for one hypothetical scenario. An average accuracy of 70% for the maximum tsunami amplitude between model results and observations is deemed as the passing criterion.

- Standard NOAA and NTHMP benchmarking problem (BP). Details of the datasets, initial conditions, and boundary conditions are provided in Synolakis et al. (2017), NTHMP (2012 and 2015), Kirby et al., 2018), and Gately and Fryer (2013).

Table A. Model evaluation BPs for tsunami water surface, inundation limit, and runup heights

Benchmark test	Category	Description
BP1	Analytical solution	Single wave on a simple sloping beach
BP2		Solitary wave on a composite beach
BP3		Sub-aerial 2D landslide on simple sloping beach
BP4	Laboratory experiment	Solitary wave on a simple sloping beach
BP5		Solitary wave on a composite beach
BP6		Solitary wave on a conical island

BP7		Tsunami runup onto a complex 3D beach: Monai Valley
BP8		Tsunami generation and runup due to a 3D landslide
BP9	Field measurements (Reference case studies)	Okushiri Island tsunami (runup measurements)
BP10		Rat Island tsunami (tide gauge)

Table B. Model evaluation BPs for tsunami currents

Benchmark test	Category	Description
BP1	Laboratory experiment	Steady flow over submerged obstacle
BP2	Field measurements	Tsunami currents in Hilo Harbor from the 2011 Japan tsunami
BP3	Field measurements	Tsunami currents in Tauranga Harbor, New Zealand from the 2011 Japan tsunami
BP4	Laboratory experiment	Flow through a city building layout

Table C. Model evaluation BPs for landslide-generated tsunamis

Benchmark test	Category	Description
BP1	Laboratory experiment	2D submarine solid blocks
BP2		3D submarine solid blocks
BP3		3D submarine/subaerial triangular solid block
BP4		2D submarine granular slide
BP5		2D subaerial granular slide
BP6		3D subaerial granular slide

BP7	Field observation	Slide at Port Valdez, AK during 1964 Alaska earthquake

A. Historical and hypothetical events for model Operational Testing & Evaluation. Datasets of tide-gauge observational data and initial source solutions are available in Gately and Fryer, 2013.
    - Samoa M8.1 September 29, 2009
    - Kuril M8.1 January 13, 2007
    - Tohoku M9.1 March 11, 2011
    - Chile M8.8 February 27, 2010
    - Fajado: hypothetical

- Model Recommendation:

    In this document, five models that have been benchmarked in NTHMP workshops are recommended for Tsunami Application based on their capability in offering a complete coverage of modeling tsunamis from the source generation, regional-scale wave propagation to high-resolution inundation at local community scale. These models are **FUNWAVE-TVD**, **GEOCLAW**, **MOST**, **NEOWAVE**, and **Tsunami-HYSEA**.

    Many other models benchmarked in NTHMP workshops are also potential candidates for future UFS Tsunami Application. However, the authors could not find enough detail for comparing the model mentioned above (namely, for the criteria that is summarized in Tables A to H). As such, it is hard for the authors to recommend the following model for evaluation: ALASKA GI'-T, Alaska Tsunami Model, BOSZ, Cliffs, NAMI DANCE, pCOULWAVE, SCHISM Tsunami, THETIS, TSUNAMI3D.

4. Anticipated reporting (tables) for model evaluation results

4.1 Guidelines for model evaluation (COASTAL Act)

- *Present as an example how the pros and cons for each model in table format*
    - ***A. Resolution:***
        - *Possibility to produce model results to resolve inland/coastal hydraulic connections (25 m)*
        - *Time step limit requirement (e.g. CFL criterion)*
    - ***B. Stability, Accuracy and computational efficiency***
        - *Sensitivity to bottom slope or requirement topobathy smoothing*
        - *Given required accuracy and time window for providing final results per requirements of the application (e.g. in COASTAL Act results should be provided within 90 days)*
        - *Accuracy and computational efficiency*
        - *Numerical Mixing*[1]
    - *C. **Code management:** community and support through GitHub or similar git platforms, i.e.,feasibility of making the model available to community developers and to be integrated into the UFS code base.*
    - *D. Coupling: ocean, wave, inland hydrology, atmosphere, sea ice*
    - *E. Data Assimilation (DA)*
    - *F. NOAA Readiness Levels (e.g. code readiness for operations, RL higher than 4/5)*
    - *G. Geographic coverage: national/global Atl/GoM/PAC, Great Lakes, West Coast*
    - *H. License: NOAA strongly encourages CC0 license for the codes developed with its support.*

Hindcast configuration:

- **Hindcast length (period) -** Run the models in hindcast mode for a period of time appropriate for the application: short term, e.g. the COASTAL Act (~weeks) and long term, e.g. return period (~years).
- **Hindcast turnaround time -** Hindcast results should be available within **90 days** from a named storm event.
- **Locations - Tropical cyclones for OCONUS** and islands/atolls in the Pacific (e.g. Hawaiian Islands and Guam), and US Caribbean territories (e.g., PR and USVI).
- **Spatial reference system -** Vertical is NAVD88 and Horizontal is WGS-84.
- **Horizontal resolution -** 25 m to 120 m, depending on the elevation source data.

Requirements:

- **Water level accuracy (within 90% accuracy) -** *Skill assessment of water levels will be calculated against:*

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[1] *Lock exchange or similar, see Burchard and Rennau,* https://www.sciencedirect.com/science/article/pii/S146350030700128X

- *Water level observation time-series from NWLON, PORTS and USGS gages.*
- *High Water Marks*

- **Product formats** - NetCDF and CSV, depending on FEMA requirements.

List of Models that were evaluated in this report are provided in Appendix A. Based on the guideline in the beginning of this section, we have communicated with the developers and publications and summarized the results in the following tables:

Table D.1. Resolution

- Possibility to produce model results to resolve inland/coastal hydraulic connections (25 m)

Model	Pros	Cons
ADCIRC	• Unstructured mesh allows flexible and high resolution in order to resolve relevant physical processes in space.	• Model starts to be more sensitive and prone to instability for mesh sizes below 250 m. Need more careful assessment.
DFLOW	• Unstructured mesh allows higher flexibility, with higher resolution only for required areas and conversely • Combination of unstructured grid elements consisting of triangles, quadrangles, pentagons and hexagons • Vertical coordinate resolved using a σ- or z-layer coordinate approach	• Mesh requires orthogonalizing, which may be time consuming if the mesh consists of many elements • Mesh checking (especially in shallow areas with complex features) is crucial and it might require an investment of time (DFLOW's adjustable time step functionality does not ensure quality of results).
FVCOM	• Unstructured mesh allows flexible and high resolution for areas of interest • Resolution can be up to O(1m) to simulate inland flooding and coastal inundation	• The model is better suited for 3D applications, and seems unnecessarily expensive for 2D applications (e.g., COASTAL Act).
ROMS	• Nesting and grid refinement to allow increased resolution. • Easy grid generation.	• Structured mesh not well suited for deep inland boundary fitting. The gridded format, where the shoreline features are more complex at large scales (i.e., at 25 m resolution).
SCHISM	• Unstructured mesh allows flexible	• Further is required to confirm any

	and high resolution only for required areas ● Combination of Quadrilateral and triangular mesh allow seamless coupling to inland hydrology ● Resolution up to 1 m without strict limit on time step	operational issues at 10m resolution.
SLOSH	● Uses a polar grid system that can capture the coastal area of impact with high resolution, and save computational cost with lower resolution towards the offshore. ● Allows for large ensemble due to low computational costs, allowing for focus on modeling uncertainty where necessary	● Polar grid system is less flexible than an unstructured mesh. It can only focus its high resolution on a limited area. Makes it challenging to cover a large region. Typically uses a series of polar grids for regional coverage.

Table E.1. Stability, accuracy and computational efficiency

- Sensitivity to bottom slope or requirement topobathy smoothing
- Given required accuracy with respect to water surface elevation and time window for providing final results per requirements of the application (e.g. in COASTAL Act results should be provided within 90 days)
- Accuracy and computational efficiency. (**Note:** we only provide a qualitative description of accuracy and efficiency in this report - a quantitative calculation will be provided after a model evaluation is conducted).

Model	Pros	Cons
ADCIRC	● 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
DFLOW	● Self-adjusting time step results in stable model setups which are not sensitive to gradients in topobathy ● Excellent parallel computing efficiency	● Explicit scheme results in short time steps and long runtimes for high resolution meshes
FVCOM	● Model is based on 3D primitive equations	● Subject to Courant-Friedrich

	with high accuracy in simulating tidal and storm surge total water level ● Excellent parallel computing efficiency	Levy (CFL) stability criterion ● Bottom topography smooth to reduce numerical diffusion
ROMS	● Highly accurate advection schemes (3rd or 4th order) ● Very computationally efficient ● Many advanced features for testing of physical processes. ● Modern adjoint for data assimilation.	● Sensitive to very steep topography
SCHISM	● 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 3D mode ● Stable and efficient (see large time steps, inverse CFL below in model characteristics table; and skew element tolerance, scalability in geographic coverage table)	● In 2D mode model need more care to increase skill and accuracy
SLOSH	● Has shown to be highly stable in operational environment, with long track record of guidance to NHC. ● High computational efficiency, allowing for large ensembles for probabilistic guidance.	● Individual members are considered to be less accurate than peer models, due to the omission of some physical processes.

Table F.1. Code management

- Community and support through GitHub or similar git platforms, i.e. feasibility of making the model available to community developers and to be integrated into the UFS code base.

Model	Pros	Cons
ADCIRC	• Code management through git workflow	• Code is not fully open source. Registration via email required to access.
DFLOW	• Code management through svn workflow.	• Code is not fully open source. Registration via email required to access.
FVCOM	• Code management through git workflow	• Code is managed by the developer (U-MASS), not through a community platform • Code is not fully open source. Registration via email required to access.
ROMS	• Code management through svn workflow	• Code is managed by the developers (Rutgers), not through a community platform • Code is not fully open source. Registration via email required to access.
SCHISM	• Model is fully open source at GitHub.com (no user/pass needed for access to code) • Code management through git workflow	
SLOSH	• Code currently managed in git repo under VLab. Could be made available to the UFS community. • As of Oct. 2021, code is being disseminated via GitHub	• Has been developed internally by NOAA/NWS, with no strong external developer community. • GitHub access requires acknowledgement of licensing (see table H) and a GitHub account (which is provided read access to the repo)

Table G.1. Coupling: ocean, wave, inland hydrology, atmosphere, sea ice

- Model is NUOPC ready (has NUOPC cap)
- Model is being coupled using NOAA/NEMS driver
- The coupling cap and test cases are available

Model	Pros	Cons
ADCIRC	• NUOPC cap written for coupling to other models, including wave and sea ice model • Model is fully tested for coupling to wave models through NOAA/NEMS NUOPC, • Coupling infrastructure is accessible through NOAA OCS GitHub repo at: https://GitHub.com/noaa-ocs-modeling/CoastalApp	• Model connection to inland hydrology is in development
DFLOW	• NUOPC cap is being developed/validated • The hydrodynamic model can be coupled with D-Waves (SWAN), real-time control and water quality (delwaq) models. Additional information can be found in https://content.oss.deltares.nl/delft3d/manuals/D-Flow_FM_User_Manual.pdf	• Direct coupling via NUOPC cap (and UFS standards) is not currently possible without code tweaking. • Component coupling is achieved through Basic Model Interface (BMI)
FVCOM	• NUOPC cap is developed and being validated • Model is internally embedded with wave (based on SWAN), sediment transport model (based on USGS), sea-ice (based on CICE) • Model is one-way connected with hydrology and atmospheric inputs	• Wave model is not regularly updated to the new development in SWAN
ROMS	• NUOPC cap is developed and being validated by developers • Coupled to atmosphere models with wave (based on SWAN), wave model (WAVEWATCH III) and sea-ice (based	• Structured mesh grid - potential challenge with coupling to hydrologic models • ROMS cap not yet tested using NOAA/NEMS driver

	on CICE)	
SCHISM	• NUOPC cap is developed and being validated • Model is well suited to coupling to inland hydrology • Model is being tested for coupling to wave and atmospheric models through NOAA/NEMS • Coupling infrastructure is accessible through NOAA OCS GitHub repo at: https://GitHub.com/noaa-ocs-modeling/CoastalApp	
SLOSH	• The model contains an internal coupling to an efficient wave model (SLOSH-FW version) but is not yet operational.	• Is not ESMF/NUOPC compliant, and can thus not currently be integrated into an ESMF/NUOPC coupled framework. • It is recommended that wave models should be used for internal coupling purposes only. This model seems to have low fidelity compared to present operational wave models at NOAA.

Table H.1. Data Assimilation (DA)

- Are there any relevant processes that are not included in the model (e.g., Tem. and Salinity) that require DA? If so, does the model have any DA capability? Is the model's DA implementation JEDI compliant?

Model	**Pros**	**Cons**
ADCIRC	• Bias correction of water surface elevation via pseudo pressure term	• Effect of bias correction on other variables, e.g. current velocities, not yet fully tested • Not JEDI compliant
DFLOW	• Data assimilation through OpenDA (https://www.openda.org/). Deltares' optimized OpenDA code can be accessed	• Not JEDI compliant

	from: https://svn.oss.deltares.nl/repos/openda/	
FVCOM	• Nudging/OI assimilation • Kalman filter • Adjoint assimilation	• Not JEDI compliant
ROMS	• Advanced 4DVAR being used in operations (WCOFS - SSH, SST, HFRadar) • Funded work on improving 4DVAR within ROMS • Funded work integrating ROMS 4DVAR into JEDI	
SCHISM	• DA via PDAF (Parallel Data Assimilation Framework) in active development	• Not JEDI compliant
SLOSH	• SLOSH's Extra-Tropical Storm Surge (ETSS) and Probabilistic ETSS (P-ETSS) operational systems contain a bias correction based on recent water level observations.	• Not JEDI compliant

Table I.1. Operational Readiness

- With respect to operations at NOAA (i.e. NOAA operational requirements) and/or at a National Center in another country

Model	Status
ADCIRC	• RL 9 - ADCIRC 2D is running operationally on WCOSS by NCEP
DFLOW	• RL 7 - The East/Gulf Coast NWM/DFLOW system has been demonstrated in a relevant environment
FVCOM	• RL 9 - Great Lakes OFS using FVCOM are running operationally on WCOSS by NCEP
ROMS	• RL 9 - Several OFS (such as, WCOFS and DBOFS) are running operationally on WCOSS by NCEP

SCHISM	• 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	• RL 9 - The model is running operationally on WCOSS by NCEP

Table J.1. Operational geographic coverage

- Global, ocean basin, regional, or local

Model	**Status**
ADCIRC	• Regional and local coverage validated. • Ocean basin scale (PAC and ATL) coverage validated. • Global scale with high resolution insets in US waters fully validated and implemented operationally.
DFLOW	• Regional and local coverage validated. • Global Storm Surge Information System (GLOSSIS) based on Delft3D-FM and Delft-FEWS
FVCOM	• Regional and local coverage validated. • Ocean basin scale (Arctic) coverage validated. • Global scale validated. • Regional coverage for Great Lakes and NY. There are plans for a regional New England coverage.
ROMS	• Regional coverage (e.g. US West coast, Gulf of Maine, Cook Inlet, Chesapeake Bay, among many others) • Ocean basin scale (ATL) coverage validated.
SCHISM	• Regional and local coverage validated. • Basin scale (PAC and ATL) coverage validated. • Global scale 2D and 3D coverage is being developed.
SLOSH	• Regional and local coverage through ETSS and P-ETSS (e.g. Gulf of Mexico, US East Coast, US West Coast, Puerto Rico, US VI, Hawaii, and Am. Samoa, and Alaska)

Table K.1. License

- NOAA strongly encourages CC0 license for the codes developed with its support.

Model	**Status**
ADCIRC	The ADCIRC source code is copyrighted, 1994-2016, by: R.A. Luettich, Jr. and J.J. Westerink
DFLOW	License type: GNU AGPL (GNU Affero General Public License) https://www.gnu.org/licenses/agpl-3.0.en.html
FVCOM	http://fvcom.smast.umassd.edu/FVCOM/Source/agreement.htm
ROMS	• MIT open-source license (https://www.myroms.org/index.php?page=License_ROMS)
SCHISM	• Apache-2.0 License (https://GitHub.com/schism-dev/schism)
SLOSH	License cleared by NOAA General Council - Apr 23, 2014. Summary: • Provided "as is" • NOAA assumes no legal liability • NOAA with not provide technical support or training unless a separate agreement is in place • SLOSH software is not subject to copyright protection and is considered in the public domain • NOAA requests that recipient acknowledge NOAA's contribution to SLOSH in technical documentation • NOAA encourages recipient to provide NOAA with any improvements

4.2 Guidelines for model evaluation - Tsunami Applications

Hindcast configuration:

- Ability to perform a hindcast - Short term 12 - 48 hours after the source origin time; Long term: different return periods between 50 and 10,000 years
- Forecast turnaround time - Short-term hindcast results are expected to be available within days (less than one week) of the event
- Temporal resolution of output - Onetime effort
- Hindcast range - depends on the application: 1) Post-event analysis range is on the order of hours, and 2) Long-term analysis involves geological time scales that can extend from decades to thousands of years
- Reliability - 99%
- Locations - U.S. coastlines, Pacific (e.g. Hawaiian Islands, Guam, and American Samoa), OCONUS, U.S. Caribbean territories, Department of States overseas posts
- Spatial reference system - Mean High Water (e.g. tidal or astronomical observation), and Horizontal is WGS-84.
- Horizontal resolution - 10-60 m depending on the elevation source data. 10 m is required if the source DEM has a horizontal resolution of 10 m or finer.

Requirements:

- **Water level accuracy (within 70% accuracy)** - Skill assessment of water levels will be calculated against:
    - Maximum tsunami wave amplitude from NOS and GTS gauges
- **Product formats -** NetCDF, ASCII, and CSV

Table D.2 Resolution - Possibility to produce model results to resolve inland/coastal hydraulic connections (~10 m or finer)

Model	Pros	Cons
FUNWAVE-TVD	• Multiple structured grids • Explicit scheme requiring time step to satisfy the CFL condition	• One-way grid nesting
GEOCLAW	• Adaptive mesh refinement to several nested levels with arbitrary refinement ratios at each level. • Refinement is done based on wave height and specification of the areas of interest. • Time step needs to satisfy CFL condition	•
MOST	• Telescoped structured grids with an	• The number of telescoped

	arbitrary ratio of grid resolutions between the inner and outer grids ● Resolution can be up to <5m to resolve inland/coastal hydraulic connections with time step satisfying the CFL condition	grids needs to be exactly three
NEOWAVE	● Multiple number of two-way, nested grids ● Resolution can be up to <5m to resolve inland/coastal hydraulic connections with time step satisfying the CFL condition	● The resolution multiple between inner and outer grids needs to be an integer
Tsunami-HySEA	● Infinite number of two-way, nested grids ● Resolution can be up to <5m to resolve inland/coastal hydraulic connections	● The resolution multiple between inner and outer grids needs to be an integer

Table E.2. Stability, Accuracy and computational efficiency

- Sensitivity to bottom slope or requirement topobathy smoothing
- Given required accuracy and time window for providing final results per requirements of the application (e.g. model results should be made available within hours to days, usually less than a week, after the event for short-term forecast)
- Accuracy and computational efficiency. (**Note:** we only provide a qualitative description of accuracy and efficiency in this report - a quantitative calculation will be provided after a model evaluation is conducted).

Model	Pros	Cons
FUNWAVE-TVD	● Model is based on highly nonlinear Boussinesq equations capable of fully addressing wave dispersion using a hybrid finite volume and finite-difference-MUSCL-TVD scheme ● Improved linear dispersive properties are achieved up to the deep water limit. ● Fully parallelized for computational efficiency	● One-way grid nesting that may impact the accuracy near the coast
GEOCLAW	● Model is based on the shallow water equations in conservative form with nonlinear limiters for shock-capturing ● Adaptive mesh refinement to several nested levels with arbitrary refinement ratios at each level makes the model efficient in computation speed ● Stable to Courant number 1 and very robust.	● No inclusion of dispersive terms in the equations, and is not capable of addressing wave dispersion.

	• Require no smoothing due to the well-balanced scheme	
MOST	• Model is based on the depth-integrated shallow water equations, and is highly accurate for long waves, especially in deep water. • Model approximates the physical wave dispersion using numerical methods, and is capable of simulating weakly dispersive waves. • Model utilizes the GPU technology and is highly efficient in terms of computational speed.	• Model is sensitive to bathymetry with steep slope and one-node topography. Grid smoothing is needed under these circumstances. • One-way grid nesting that may impact the accuracy near the coast
NEOWAVE	• Model is a shock-capturing, dispersive model solving the shallow water equations in conservative form with the non-hydrostatic terms and the momentum-conserved advection scheme. • Model is highly accurate in terms of shock-capturing and mass conservation. It is one of the models achieving the best model accuracy among all NTHMP-benchmarked models for tsunami	• Not parallelized, the computational efficiency is relatively low, particularly with the non-hydrostatic terms turned on • Occasionally, the model requires smoothing to treat singularities in the bathymetry or topography • Not suitable for forecast due to slow computation
Tsunami-HySEA	• Model is based on the depth-integrated shallow water equations, and is highly accurate for long waves, especially in deep water. • Model utilizes the GPU technology and is highly efficient in terms of computational speed. • Model is highly stable and requires no smoothing for topography and bathymetry	• A version including dispersive terms in the equations is available, as well as a coupled-multilayered version that can provide some depth variation.

Table F.2. Code management:
Community and support through GitHub or similar git platforms, i.e. feasibility of making the model available to community developers and to be integrated into the UFS code base.

Model	Pros	Cons
FUNWAVE-TVD	• Model is fully open source through the website and GitHub • Code management through GitHub workflow	
GEOCLAW	• Model is fully open source through the CLAWPACK website and GitHub • Code management through CLAWPACK website and Git workflow	
MOST	• The community interface of MOST (ComMIT) is available by request after participation in a ComMIT training course • Code is not fully open source. Training via email required to access.	• ComMIT training can only be provided once or twice a year due to lacking of funding and staff
NEOWAVE	• Code is not fully open source. Email request is required to obtain access.	• Codes are entirely managed by the developers.
Tsunami-HySEA	• Model is fully open source through the EDANYA research group • One without GPU computational resources can ask for an account in the ENDANYA GPU-cluster for running *Tsunami-HySEA* code.	

Table G.2. Coupling: ocean, wave, inland hydrology, atmosphere, sea ice

Model	Pros	Cons
FUNWAVE-TVD	• Model has a meteo module to couple atmospheric and wave models for storm surge and metro-tsunami modeling	
GEOCLAW		• Currently no coupling capabilities.

MOST	• Model can couple wind pressure and stress for meteorologically-generated tsunamis	• Only a few cases have been tested for meteorological tsunamis
NEOWAVE	• Model can adopt atmospheric conditions for storm surge modeling	
Tsunami-HySEA		• Currently no coupling capabilities.

Table H.2. Data Assimilation (DA)

- Does the model have any DA capability? Is the model's DA implementation JEDI compliant?

Model	Pros	Cons
FUNWAVE-TVD		
GEOCLAW		
MOST	• Data assimilation is mostly used to constrain the Initial tsunami source. Model needs to be re-run	DA implementation is not JEDI compliant
NEOWAVE		
Tsunami-HySEA		

Table I.2 NOAA Readiness Levels
(e.g. code readiness for operations, RL higher than 4 and 5)

Model	Pros
FUNWAVE-TVD	• RL 6 - (potential demonstrated)
GEOCLAW	• RL 6 -(potential demonstrated)
MOST	• RL 9 (operationally implemented)
NEOWAVE	• RL 6 - (potential demonstrated)
Tsunami-HySEA	• RL 6 - (potential demonstrated)

Table J.2. Geographic coverage:

national/global Atl/GoM/PAC, Great Lakes, West Coast

Model	Coverage
FUNWAVE-TVD	● Regional scale: Pacific, Atlantic, and Indian Ocean ● Global scale not fully evaluated ● Model has capabilities allowing it to run efficiently over large areas ● High-resolution inundation modeling performed at local or regional scale
GEOCLAW	● Regional scale: Pacific, Atlantic, and Indian Ocean ● Global scale not fully evaluated ● Model has capabilities allowing it to run efficiently over large areas ● High-resolution inundation modeling performed at local or regional scale
MOST	● Global scale ● Regional scale: Pacific, Atlantic, Indian Ocean, and Antarctica ● Model is capable of efficient computation over large areas ● High-resolution inundation modeling performed at local or regional scale
NEOWAVE	● Regional scale: Pacific, Atlantic, and Indian Ocean ● Global scale not evaluated ● High-resolution inundation modeling performed at local or regional scale ● Model has capabilities allowing it to run efficiently over large areas
Tsunami-HySea	● Regional scale: Pacific, Atlantic, and Indian Ocean ● Global scale not fully evaluated yet ● Model has capabilities allowing it to run efficiently over large areas ● High-resolution inundation modeling performed at local or regional scale

Appendix A: Models considers for the COASTAL Act evaluation

A.1 ADCIRC

The Advanced CIRCulation (ADCIRC) model is an unstructured triangular grid continuous Galerkin finite-element method (FEM) coastal ocean model that has been extensively used for detailed hurricane inundation studies at local and regional scales (e.g., Westerink et al., 2008; Bunya et al., 2010; Hope et al., 2013), as well as for NOAA's Extratropical Surge and Tide Operational Forecast System (Funakoshi et al., 2011; Vinogradov et al., 2017), which is now fully global. ADCIRC makes use of the Generalized Wave Continuity Equation (GWCE) formulation to remove spurious oscillations in the FEM solution to the shallow water equations (ref: ADCIRC Theory Report). ADCIRC can be solved on global, regional or local domains using spherical coordinates, which are transformed into an equivalent set of equations in Cartesian coordinates using a standard cylindrical projection such as the Mercator projection (Pringle et al., 2021). The unstructured mesh FEM solver enables flexibility in mesh design, and a large range in element sizes can be used to conform to geographical shapes and topographical features.

ADCIRC has mostly been used in 2D barotropic mode, without much development in 3D, although it technically has had 3D capabilities from the beginning (Luettich and Westerink, 1992), and the 3D baroclinic mode was used most recently to study a river-dominated estuarine environment (Cyriac et al., 2020). Instead the focus of ADCIRC has long been on hurricane surge and hence on providing accurate wind forcing through unique built-in hurricane vortex models, complex surface and bottom roughness formulations, wind reduction factors overland, and coupling to wave models to get coastal wave setup effects. However, storm surge forerunners and baroclinic components of water levels are not well- or- at all captured by the 2D barotropic formulation. Artificially reducing bottom roughness coefficients (Kennedy at al., 2011) and coupling to 3D baroclinic models (Pringle et al., 2019), or the application of a low-frequency pseudo-pressure forcing (Asher at al., 2019), have been used to circumvent this problem when using the 2D barotropic model in practice.

A.2 DFLOW

D-Flow FM is a multi-dimensional (1D, 2D and 3D) hydrodynamic (and transport) simulation model which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on structured and unstructured, boundary fitted grids. The term Flexible Mesh in the model name refers to the flexible combination of unstructured grids consisting of triangles, quadrangles, pentagons and hexagons. In 3D simulations, the vertical grid uses the σ coordinate approach. A fixed z layers approach is also possible as an alternative. The 2D functionality in D-Flow FM has been fully released, while the functionality for 3D and 1D is in development at the time of writing this document.

The D-Flow FM Graphical User Interface provides a powerful and integrated environment for setting up D-Flow FM models and inspecting model input, such as time-dependent forcings (e.g. boundary conditions and barrier control). Another improvement within the User Interface is the use of scripting for running and live interaction with a model.

D-Flow FM implements a finite volume solver on a staggered grid. The continuity equation is solved implicitly for all points in a single combined system. Time integration is done explicitly for part of the advection term, and the resulting dynamic time-step limitation is automatically set based on the Courant criterion. The possible performance penalty that may result from this approach can often be remedied by refining and coarsening the computational grid at the right locations. In D-Flow FM, the advection scheme is suitable for both sub-critical and critical flows. The scheme is 'shock proof', i.e. capable of reproducing correct bore propagation velocities.

Areas of application for D-Flow FM include, among others: tide and storm surge, stratified and density-driven flows, river flow simulations, rural channel networks, rainfall-runoff in urban environments, simulation of tsunamis, hydraulic jumps, bores and flood waves, freshwater riverine discharges in bays, saline intrusion, cooling water intakes and wastewater outlets, transport of dissolved materials and pollutants.

Model features include: tidal forcing, Coriolis' force, density driven flows (pressure gradients terms in the momentum equations), advection-diffusion solver included to compute density gradients, space and time varying wind and atmospheric pressure, four turbulence models to account for the vertical turbulent viscosity and diffusivity based on the eddy viscosity concept, time varying sources and sinks (e.g., river discharges), simulation of thermal discharge, effluent discharge and intake of cooling water at any location and any depth, robust simulation of drying and flooding of inter-tidal flats and river winter beds, heat exchange through the free water surface, wave induced stresses and mass fluxes, influence of waves on the bed shear stress and special structures such as pumping stations, bridge piers, fixed weirs and controllable barriers.

A.3 FVCOM

The Finite Volume Community Ocean Model (FVCOM) is a unstructured-grid coastal ocean model for simulating nearshore flooding/drying process, tidal, buoyancy and wind-driven circulation in estuaries and coastal oceans. It is best suited to estuarine and coastal systems that are featured with complex coastlines and requirement of high-resolution i. FVCOM is integrated with a number of modules for broader coastal and global applications, including sea-ice, sediment transport, wave, general ocean turbulent model and data assimilations.

A.4 ROMS

The Regional Ocean Modeling System (ROMS) is a three-dimensional, free surface, terrain-following hydrodynamic model that solves the Reynolds-Averaged Navier Stokes equations assuming hydrostatic equilibrium and Boussinesq approximations, using a finite differences method on an Arakawa C grid (Haidvogel et al., 2000, 2008; Shchepetkin and McWilliams, 2005; Warner et al., 2008). The modeling system solves the hydrostatic primitive equations for momentum using a split-explicit time-stepping scheme. The system has various options for advection schemes subgrid scale mixing. There are several options for air-sea interaction, biological submodules, sediment transport, and sea-ice. The system has been used extensively for over 20 years of applications and continued development. The model is used extensively for development and testing of new physics that explain ocean-wave coupling, air-sea interactions, and coastal morphological changes.

There is a massive data assimilation capability for this system, including 4D variational data assimilation and tangent linear adjoint. The model has the most recent version of ESMF and NUOPC caps and has been successfully coupled to other components of the UFS.

A.5 SCHISM

SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model) is a derivative product of SELFE v3.1dc (Zhang and Baptista 2008). It is a next-generation, open-source, community-supported, innovative modeling system, based on hybrid triangular-quadrangular unstructured grids in the horizontal and a very flexible coordinate system in the vertical (Zhang et al. 2015), designed for the effective simulation of 3D baroclinic circulation across creek-to-ocean scales in a single grid without resorting to grid nesting or bathymetry smoothing. The combination of flexible gridding systems in the horizontal and vertical dimensions results in highly desirable “polymorphism” (Zhang et al. 2016) that allows a single SCHISM grid to seamlessly morph between full 3D and 2DH/2DV and quasi-1D modes (e.g., with full 3D representation for the deep ocean and channels, 2DH/2DV/1D for shallow tidal flats and upstream rivers and watersheds), thus maximizing accuracy and efficiency. SCHISM employs a highly efficient semi-implicit finite-element/finite-volume method together with a Eulerian-Lagrangian method (ELM) to solve the Navier-Stokes equations. As a result, numerical stability and robustness are greatly enhanced. The implicit scheme used in SCHISM often allows the use of ‘hyper resolution’ (on the order of a few meters; Bertin et al., 2014; Liu et al. 2018; Nunez et al. 2021) with little penalty on the time step, thus allowing users to focus more on physics instead of numerics.

SCHISM already showed strong predictive skills to simulate short waves, storm surges and coastal flooding (e.g., in the US east coast (Ye et al. 2020; Zhang et al. 2020), Gulf of Mexico (Huang et al. 2021), the Bay of Biscay (Bertin et al., 2014; Guérin et al., 2018), the Bay of Bengal (Krien et al., 2017) etc). The model's ability to simulate baroclinic instability and large-scale eddying regime has been documented in some recent publications (Zhang et al. 2016; Stanev et al. 2017). It has also been extensively tested as an operational model at multiple agencies around the world (e.g. http://tidesandcurrents.noaa.gov/ofs/creofs/creofs.html; http://cwb.gov.tw/V7e/forecast/nwp/marine_forecast.htm by Taiwan’s Central Weather Bureau); California Department of Water Resource (DWR) also disseminates a Bay-Delta SCHISM package (http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/bay_delta_schism/) that is being used as part of their Decision Support System. The model has been rigorously benchmarked for inundation problems and officially certified by National Tsunami Hazard Mitigation Program as a tsunami inundation model (NTHMP 2012). Recently, the model is being evaluated (1) by NOAA as the three-dimensional modeling engine for ESTOFS that encompasses the US east coast and Gulf of Mexico, up to 10m above sea level, and (2) by EPA Chesapeake Bay Program as their new regulatory model. An on-demand web-based forecast/hindcast system (OPENCoastS) has been set up that allows users to create their own forecast/hindcast system for any parts of world’s ocean with the ‘engine’ running on EOSC-HUB supported cloud platform (https://opencoasts.ncg.ingrid.pt/), and operationalization of the model has also been done by a few EU agencies (e.g. Joint European Research Centre (JRC); Helmholtz-Zentrum Hereon). More information about the model and its application cases around the world can be found at schism.wiki, including a complete list of 170+ journal papers for SCHISM and its predecessor SELFE.

The SCHISM modeling system consists of a suite of tightly coupled (not via external couplers) modules that share the same 3D grid with the hydrodynamic core, including the 3D sediment transport and wind wave modules. The entire modeling system is fully parallelized using domain decomposition with hybrid MPI and openMP paradigm with good scalability. In addition, the entire modeling system has been checked into ESMF and can be coupled to other earth-system models that have ESMF components. The official version of SCHISM is managed using GitHub with active contributions from ~20 developers worldwide, and the repository includes regression tests that are carried out on a regular basis.

A.6 SLOSH

The Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (Jelesnianski et al. 1992) is a 2D barotropic surge model consisting of a set of equations derived from the Newtonian equations of motion (shallow water equations) and the continuity equation applied to a rotating fluid with a free surface. The model is defined on a polar grid system that allows for greater resolution in the nearshore and overland region of interest, and reducing resolution further offshore. The coastline is represented as a physical boundary. Subgrid-scale water features (cuts, chokes, sills, and channels), and vertical obstructions (levees, roads, spoil banks, etc.) are parameterized. The model accounts for astronomical tides in two different ways. For potential storm surge products (e.g., MEOWs and MOMs), an initial tide level is used, as the storms are assumed to coincide with high tide. For real-time products, a gridded tide field is coupled to the storm surge field. SLOSH does not include rainfall amounts or riverflow. Recently, an efficient wave model based on Schwab et al. (1984) was coupled to the surge and tide fields, allowing the modeling of wave-driven setup (Joyce et al. 2019).

A significant characteristic of the SLOSH model is its low computational cost, which allows the execution of a large number of ensemble members. This makes it possible to account for the typically large uncertainty in the atmospheric forcing in surge and inundation predictions in real-time. The Probabilistic Extra-Tropical Storm Surge (P-ETSS) model does so by replacing SLOSH's parametric wind model with the U, V, and Pressure fields from the US's 31-member Global Ensemble Forecast System (GEFS) and the Canadian 21-member Global Ensemble Prediction System (GEPS). Similarly, the Probabilistic storm Surge (P-Surge) model does so by permuting NHC's official forecast based on its historical errors. Thus, generating approximately 630 perturbations of atmospheric forcing which are run through SLOSH to generate probabilities of inundation products.

Appendix B: Models considered for the Tsunami applications

B.1 FUNWAVE-TVD

The FUNWAVE tsunami propagation and runup model is based on fully nonlinear and dispersive Boussinesq equations, retaining information to leading order in frequency dispersion O[(kh)2] and to all orders in nonlinearity (Wei and Kirby, 1995; Wei et al., 1995). Instead of tracking the moving boundary during wave run-up/run-down on the beach or coastlines, FUNWAVE treats the entire computational domain as an active fluid domain by employing an improved version of the slot or permeable-seabed technique, i.e., the moving shoreline algorithm proposed by Chen et al. (2000) and Kennedy et al. (2000) for the runup simulation. The basic idea behind this technique is to replace the solid bottom where there is little or no water covering the land with a porous seabed or to assume that the solid bottom contains narrow slots. This is incorporated in terms of mass flux and free surface elevation in order to conserve mass in the presence of slots. The model includes bottom friction, energy dissipation to account for the wave breaking and a subgrid turbulence scheme too. The bottom friction is modeled by the use of the quadratic law with bottom friction coefficient. The subgrid turbulence is modeled in terms of Smagorinsky-subgrid turbulent mixing type to account for the effect of the underlying current field. The energy dissipation due to wave breaking in shallow water is treated by the use of momentum mixing terms. The associated eddy viscosity is essentially proportional to the gradient of the horizontal velocity, which is strongly localized on the front face of the breaking wave.

FUNWAVE-TVD is an extension of FUNWAVE, formulated in both Cartesian coordinates (Shi et al., 2012) and in spherical coordinates with Coriolis effects (Kirby et al., 2009; 2012) for application to ocean basin scale problems. This new model uses a hybrid finite-volume and FDM-MUSCL-TVD scheme. As in FUNWAVE, improved linear dispersive properties are achieved, up to the deep water limit, by expressing the BM equations in terms of the horizontal velocity vector at 0.531 times the local depth. Additionally, wave breaking is more accurately modeled by switching from the Boussinesq equations to the NSWE, when the local height to depth ratio exceeds 0.8. FUNWAVE-TVD's latest implementation is fully parallelized using MPI-FORTRAN, for efficient use on distributed memory clusters. One-way grid nesting was implemented to allow for grid refinement near tsunami sources and near the coast. This latest version was used for running the tsunami benchmarks.

FUNWAVE-TVD has been used to model landslide or co-seismic tsunamis. A pre-processor allows the user to specify the initial tsunami source condition in terms of a hot start, either from the underwater landslide (slides or slumps) solution of Grilli et al. (2002), Grilli and Watts (2005) and Watts et al. (2005), or for co-seismic tsunamis based on the standard Okada (1985) solution. More recently, both landslide and co-seismic tsunamis have also been dynamically generated (as a space and time-varying bottom boundary condition), using the non-hydrostatic, sigma coordinate model NHWAVE (Ma et al., 2012), whose solution is then interpolated into FUNWAVE's Cartesian or spherical grid.

B.2 GEOCLAW

The GeoClaw model is based on the NSWEs and uses a finite volume method on adaptively refined rectangular grids (Cartesian or lat-long). The method exactly conserves mass (except near the shoreline when refining or de-refining grids) and conserves momentum over a flat bottom. This method is based on Godunov's method: at each cell interface a one-dimensional Riemann problem is solved normal to the edge, which reduces to a one-dimensional shallow water model with piecewise constant initial data, with left and right values given by the cell averages on each side. The jump in bathymetry between the cells is incorporated into the Riemann solution in a manner that makes the method “well balanced": the steady state of the ocean at rest is exactly maintained. The shoreline is handled by allowing dry cells to have depth 0 and to dynamically change between wet and dry. The method is second order accurate in smooth regions but nonlinear limiters are used to create “shock-capturing” methods (LeVeque, 2002) that maintain sharp non-oscillatory solutions and non-negative depth even in the nonlinear regime. The method is stable to Courant number 1 and very robust. The Manning friction term is incorporated using a fractional step method.

Adaptive mesh refinement to several nested levels is allowed, with arbitrary refinement ratios at each level. Refinement is done by flagging cells for refinement (based on wave height and specification of the areas of interest). The flagged cells at each level are clustered into rectangular patches for refinement to the next level, as described in detail in Berger and LeVeque (1998). The high-resolution methods and adaptive refinement algorithms have been extensively tested in the Clawpack software that has been in development since 1994. GeoClaw includes special techniques to deal with bathymetry data, well-balancing, and wetting/drying, and is an outgrowth of the TsunamiClaw software developed in George (2006). The algorithms and software are described in more detail in Berger et al. (2011) and LeVeque et al. (2011).

For modeling earthquake-generated tsunamis, the co-seismic seafloor motion is modeled by adjusting the bathymetry dynamically each time step. An Okada (1985) model can be used to translate fault models to seafloor motion. For modeling landslide-generated tsunamis, the seafloor motion is modeled by adjusting the bathymetry dynamically each time step. The landslide motion is generally computed first, and GeoClaw has been used with a Savage-Hutter model to simulate the motion of the landslide itself. This has been compared with two-layer fully coupled models and found adequate for landslides in sufficiently deep water.

The main code is written in Fortran, with a Python user interface and plotting modules.All of the code is open source, hosted at https://GitHub.com/organizations/clawpack. Additional documentation is available at http://www.clawpack.org/geoclaw.

B.3 MOST

The MOST model simulates propagation and runup of gravity waves according to depth-integrated NSWEs. The algorithm is based on the method of fractional steps which reduces the 2-D problem to a 1-D problem in each direction. To progress the solution through a time step, two 1-D problems are solved sequentially. Each 1-D problem is formulated in terms of Riemann invariants. MOST's computational algorithm uses a forward difference scheme in time and centered differences for spatial derivatives (Titov and Synolakis, 1998; Burwell et al., 2007).

Friction is represented by a Manning term. The model operates on structured grids given in Cartesian or spherical coordinates. The algorithm is coded in Fortran 95 and parallelized using OpenMP. There are also MPI and highly parallelized CUDA versions of the MOST model.

MOST's inundation algorithm is a 1-D algorithm that uses horizontal projection of the water level in the last wet node onto the beach to move the instantaneous shoreline position (Titov and Synolakis, 1995). The simulation can be initiated given initial seafloor deformation or by providing lateral boundary conditions. The latter facilitates grid nesting with one-way coupling.

The operational version of the MOST model determines source parameters for the tsunami wave itself by incorporating observations into forecast methodology. Just as hurricane forecasts rely on observations (radar, aircraft, satellite, ocean systems) to forecast the path of a hurricane following generation, the operational forecast relies on deep-ocean bottom pressure observations of the tsunami waves after generation. The specific operational procedure is hard-coded for a three-nested-grid configuration forced through the boundary of the outer grid. The boundary input is supplied by the database of an ocean-wide 24-hour-long simulation of tsunami wave propagation, for numerous tsunamis generated by hypothetical Mw 7.5 earthquakes covering worldwide subduction zones. These data sets are linearly combined to imitate an arbitrary tsunami scenario in the deep ocean. Access to the operational version is offered via internet-enabled interface (ComMIT), which allows for the selection of model input data, use of shared databases, display of model output through a graphical user interface (GUI), and sharing simulation results.

B.4 NEOWAVE

The Non-hydrostatic Evolution of Ocean WAVEs (NEOWAVE) model is a shock-capturing, dispersive model in a spherical coordinate system for basin-wide evolution and coastal runup of tsunamis using two-way nested computational grids (Yamazaki et al., 2011). This depth-integrated model describes dispersive waves through the non-hydrostatic pressure and vertical velocity (Stelling and Zijlema, 2003, and Yamazaki et al., 2009). The vertical velocity term also facilitates modeling of tsunami generation from seafloor deformation to account for the time-sequence of the earthquake rupture process (Yamazaki et al., 2011). The semi-implicit, staggered finite difference model captures flow discontinuities associated with bores or hydraulic jumps through the momentum conserved advection (MCA) scheme, which embeds the upwind flux approximation of Mader (1988) in the shock-capturing scheme of Stelling and Duinmeijer (2003).

NEOWAVE builds on the nonlinear shallow-water model of Kowalik et al. (2005) with the non-hydrostatic terms and the momentum-conserved advection scheme (Yamazaki et al., 2009). The grid refinement scheme is implemented in the model to capture tsunami physics in adequate grid resolution. To ensure propagation of dispersive waves and discontinuities across computational grids of different resolution, a two-way grid-nesting scheme utilizes the Dirichlet condition of the non-hydrostatic pressure and both the horizontal velocity and surface elevation at the inter-grid boundary (Yamazaki et al., 2011). The present model tracks the wet/dry interface using the approach based on Kowalik and Murty (1993) to compute the runup and inundation. The wet/dry interface is predicted by horizontal projection of sea level at the adjacent wet cell, and obtained through integration of the momentum and continuity equations (Yamazaki et al., 2009).

B.5 TSUNAMI-HySEA

HySEA (**Hy**perbolic **S**ystems and **E**fficient **A**lgorithms) software consists of a family of geophysical codes based on either single layer, two-layer stratified systems or multilayer shallow water models. HySEA codes have been developed by EDANYA Group (http://edanya.uma.es) from the Universidad de Málaga (UMA) for more than a decade and they are in continuous evolution and upgrading.

Tsunami-HySEA solves the two-dimensional shallow-water system using a high-order (second and third order) path-conservative finite volume method. Values of *h*, *qx* and *qy* at each grid cell represent cell averages of the water depth and momentum components. The numerical scheme is conservative for both mass and momentum in flat bathymetries and, in general, is mass preserving for arbitrary bathymetries. High order is achieved by a non-linear TVD reconstruction operator of the unknowns *h*, *qx*, *qy* and *=h-H*. Then, the reconstruction of *H* is recovered using the reconstruction of *h* and . Moreover, in the reconstruction procedure, the positivity of the water depth is ensured. Tsunami-HySEA implements several reconstruction operators: MUSCL (*van Leer*, *1979*) that achieves second order, the hyperbolic Marquina's reconstruction (*Marquina*, *1994*), that achieves third order, and a TVD combination of piecewise parabolic and linear 2D reconstructions that also achieves third order (Gallardo et al, 2011). The high order time discretization is performed using the second or third order TVD Runge-Kutta method described in *Gottlieb and Shu (1998).* At each cell interface, Tsunami-HySEA uses Godunov's method based on the approximation of 1D projected Riemann problems along the normal direction to each edge. In particular Tsunami-HySEA implements a PVM-type method that uses the fastest and the slowest wave speeds, similar to HLL method (Castro and Fernandez-Nieto, 2012). A general overview of the derivation of the high order methods is performed in Castro et al. (2009). For large computational domains as the case of the complete scenario in benchmark problem 2 and in the framework of TEWS, Tsunami-HySEA also implements a two-step scheme similar to leap-frog for the deep water propagation step and a second-order TVD-WAF flux-limiter scheme for close to coast propagation/inundation step. The combination of both schemes guarantees the mass conservation in the complete domain and prevents the generation of spurious high frequency oscillations near discontinuities generated by leap-frog type schemes. At the same time, this numerical scheme reduces computational times compared with other numerical schemes, while the amplitude of the first tsunami wave is preserved.

Concerning the wet-dry fronts discretization, Tsunami-HySEA implements the numerical treatment described in Castro et al. (2005) and Gallardo et al. (2007), that consists in locally replacing the 1D Riemann solver used during the propagation step, by another 1D Riemann solver that takes into account the presence of a dry cell. Moreover, the reconstruction step is also modified in order to preserve the positivity of the water depth. The resulting schemes are well-balanced for the water at rest, that is, they exactly preserve the water at rest solutions, and are second or third order accurate, depending on the reconstruction operator and the time stepping method. Finally, the numerical implementation of Tsunami-HySEA has been performed on GPU clusters and nested-grids implementation available. These facts allow to speed up the computations, being able to perform complex simulations, in very large domains, much faster than real time.

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