NOAA Technical Memorandum NOS CS 41

DEVELOPMENT OF A FLEXIBLE COUPLING INTERFACE FOR ADCIRC MODEL FOR COASTAL INUNDATION STUDIES

Silver Spring, Maryland
June 2019

noaa **National Oceanic and Atmospheric Administration**

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory

Office of Coast Survey National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The Office of Coast Survey (OCS) is the Nation's only official chartmaker. As the oldest United States scientific organization, dating from 1807, this office has a long history. Today it promotes safe navigation by managing the National Oceanic and Atmospheric Administration's (NOAA) nautical chart and oceanographic data collection and information programs.

There are four components of OCS:

> **The Coast Survey Development Laboratory develops new and efficient techniques to accomplish Coast Survey missions and to produce new and improved products and services for the maritime community and other coastal users.**
>
> **The Marine Chart Division acquires marine navigational data to construct and maintain nautical charts, Coast Pilots, and related marine products for the United States.**
>
> **The Hydrographic Surveys Division directs programs for ship and shore-based hydrographic survey units and conducts general hydrographic survey operations.**
>
> **The Navigational Services Division is the focal point for Coast Survey customer service activities, concentrating predominately on charting issues, fast-response hydrographic surveys, and Coast Pilot updates.**

NOAA Technical Memorandum NOS CS 41

DEVELOPMENT OF A FLEXIBLE COUPLING INTERFACE FOR ADCIRC MODEL FOR COASTAL INUNDATION STUDIES

Saeed Moghimi, Sergey Vinogradov, Edward P. Myers, Yuji Funakoshi
Office of Coast Survey, Coast Survey Development Laboratory
Silver Spring, Maryland

Andre Van der Westhuysen, Ali Abdolali, Zaizhong Ma
National Centers for Environmental Prediction College Park, Maryland

Fei Liu
ESMF developer team
Metuchen, New Jersey

June 2019

noaa **National Oceanic and Atmospheric Administration**

U. S. DEPARTMENT OF COMMERCE
Wilbur Ross,
Secretary

National Oceanic and Atmospheric Administration
Benjamin Friedman,
Deputy Under Secretary

National Ocean Service
Nicole R. LeBoeuf
Acting Assistant Administrator

Office of Coast Survey
Rear Admiral Shepard Smith

Coast Survey Development Laboratory
Neeraj Saraf
Acting Division Chief

NOTICE

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

To enable flexible model coupling in storm surge studies, a coupling cap for ADvanced CIRCulation model (ADCIRC) was developed. The cap is essentially a wrap-around ADCIRC model which enables the model to communicate seamlessly with other model components, e.g., surface wave and numerical weather prediction models. All the model components advertise their imported and exported fields at the runtime and connect to each other for exchanging data based on the availability of the advertised fields. Models can operate on structured or unstructured grids and the regridding capability will be provided by Earth System Modelling Framework (ESMF) and National Unified Operational Prediction Capability (NUOPC) infrastructures. We implemented the coupled application including ADCIRC cap as well as NUOPC compliant caps to read WaveWatchIII and Hurricane Weather Research and Forecasting Model (HWRF) generated forcing fields. We validated the coupled application for hurricane Ike on very high resolution mesh that covers the entire U.S. Atlantic coastal water. We also showed that inclusion of the surface waves improves the model performance of both total water level and coastal inundation. Also shown how the maximum wave set-up and maximum surge regions may happen at various time and locations depending on the storm track and its landfalling region.

Key Words: Strom surge, tides, coupling, ADCIRC, WaveWatch III, modeling, circulation model, wave model, ESMF, NUOPC

1. INTRODUCTION

The pace of emerging issues in our global environment such as sea-level rise, precipitation pattern change, and the increase in frequency of landfalling hurricanes is unprecedented. Multiple international, national and regional studies point to the possibility of increasing frequency and severity of extreme weather events, including coastal flooding (Ezer and Atkinson, 2014). To establish a reasonable coastal flooding prediction system, several model components based on the target geographical region need to be combined. To accurately predict total water level in a tropical hurricane landfalling inundation study, a dynamically coupled system of numerical models including storm surge, surface waves, inland river flooding and hurricane prediction components is necessary. For instance, to set-up an efficient coastal flooding prediction system for the Alaska region, inclusion of a sea-ice model is also essential. In an Earth System Model (ESM), components are connected using the same coupling architecture. Flexible coupling strategy is adopted, in which the model components are able to exchange required variables in a generic and seamless manner.

In recent years, Earth System Models were proven to be invaluable tools that enabled us to better understand and more accurately predict our environment. Each system includes a coupled application consists of several model components to represent the relevant physical processes. The model components also take into account their interactions similar to what takes place in nature. There are several Earth System Model software backbones implemented that enable model components to communicate their imported and exported variables (Jacob et al, 2005; Valcke et al, 2012; Hill et al, 2004). The Earth System Modelling Framework (ESMF) has been utilized to develop several earth system coupled applications. To increase interoperability among such applications, the National Unified Operational Prediction Capability (NUOPC) consortium developed a layer consisting of a set of generic components (Theurich et al, 2016). NUOPC is the backbone of The National Oceanic and Atmospheric Administration (NOAA) Environmental Modeling System (NEMS). NUOPC layer is a wrap-around ESMF and was developed collaboratively by several research and operational centers. Coupling several components using NUOPC/ESMF infrastructure leads to a single executable containing all the model components and coupling infrastructure.

NEMS is a coupled modeling infrastructure designed to address increasing needs for prediction of the earth environment at a range of time scales. NEMS includes several external model components that have a primary source code outside NOAA. NOAA only maintains and develops the model component coupling interfaces (i.e., model caps). NEMS ecosystem allows connecting various combinations of model components into a number of different coupled model applications to address specific environmental phenomena on at specific time scales.

This application, designed to perform coastal flooding and total water level hindcast and forecast, is currently under development and will include the ADvanced CIRCulation model (ADCIRC) as the hydrodynamic component (Luettich Jr et al, 1992), WaveWatchIII as the wave model (Tolman, 2002), Hurricane Weather Research and Forecasting Model (HWRF) as the atmospheric component (Tallapragada et al, 2014), and National Water Model (NWM) as the inland hydrological component (Gochis et al, 2013) under The Consumer Option for an Alternative System to Allocate Losses (COASTAL) Act project (Fig. 1).

The present research goals are to develop and test a flexible and generic coupling cap for ADCIRC and to provide an infrastructure for future development and inclusion of additional model components, such as those for river and inland flooding. At the current stage of development, the cap can perform dynamical coupling of ADCIRC, surface wave, and weather prediction models. The cap is capable of importing atmospheric forcing and surface wave fields, and exporting water surface elevation and current velocity to the connected model components.

The structure of this report is as follows. First, we describe the envisioned design of the NSEModel coupled application and the methodology. Then a detailed description of the ADCIRC cap implementation and available coupling options is given. Finally, we present results of the application of the coupled system to a storm surge inundation event during hurricane Ike, 2008 in the US Gulf of Mexico coastal region.

2. STRUCTURE OF THE COUPLED APPLICATION

A typical NUOPS application includes a number of generic components that provide an interface to the underlying ESMF infrastructure for generating and operating a coupled application in a fairly straight forward and seamless manner. The generic components are defined as follows:

- The driver manages all the components to initialize, run, finalize and keep track of time for exchanging information among model components
- The connector is used to execute field matching, grid remapping and data redistribution among model components
- The model (cap) wraps the model component code (e.g. ADCIRC) to provide a generic interface and standard metadata suitable to be plugged into the driver and form a multi-model coupled application
- The mediator wraps the custom coupling code to calculate quantities that include data from several model components or require operations like time averaging

The system includes methods and utilities for time management, error handling, high performance inputs/outputs (I/O), grid remapping and field interpolation. Since NUOPC is a layer around ESMF library, function calls to both NUOPC and ESMF are always possible and sometimes are necessary.

In this research, we developed a NUOPC application that includes a driver, three NUOPC enabled model components and four connectors. The components are not allowed to directly access each other’s data. The only way the data moves in or out of a component is via instances of an ESMF state class. The state is a container that wraps native data and also includes a metadata to let the other components know about name, coordinates and decomposition of the actual packed data. Model components are accessible only via their SetServices() method. The main program of the coupled application includes to initialize, start and finalize of the driver and the log files.

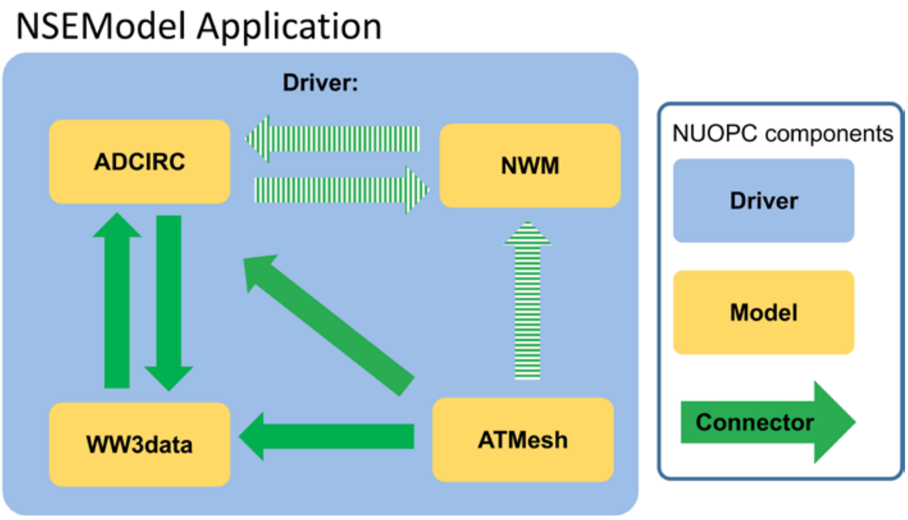


Fig. 1: Design of the coupled application for coastal flooding inundation studies (NSEModel).

The driver component accesses ADCIRC, ATMesh and WW3data model components via their SetServices() methods. It reads basic information for how to initialize and run the model components from a configuration text file (Fig. 2). The configuration file contains information about name of the model components, number of processes to be associated to each model component, the coupling time intervals, and the order of data exchange among the components. The driver also initializes the number of connectors by providing the name of the sending and receiving model components. Therefore, for a dynamical two-way coupling between two model components, two connectors are required.

The connector component initializes at the run time by matching the list of available import and export fields advertised by the model components. The connector establishes the connection based on matched import and export fields. The connector also has access to the domain decomposition and computational domain discretization of the connected model components. It will generate a remapping and necessary weight matrices for interpolation of the fields among model components at the initialization phase. In other words, the connector receives exported data in the form of an ESMF_state in the native grid or mesh from the exported model component and passes it to the importing model components in its own native grid or mesh definition.

ATMesh and WW3data model components were developed as the placeholders for weather prediction and surface wave model caps. These caps read weather prediction and wave model standard outputs, initialize required NUOPC/ESMF objects and provide requested data and information to ADCIRC cap through NOUPC/ESMF backbone (Fig. 1). The NWM hydrological model component and its associated connectors are not yet implemented.

3. ADCIRC MODEL

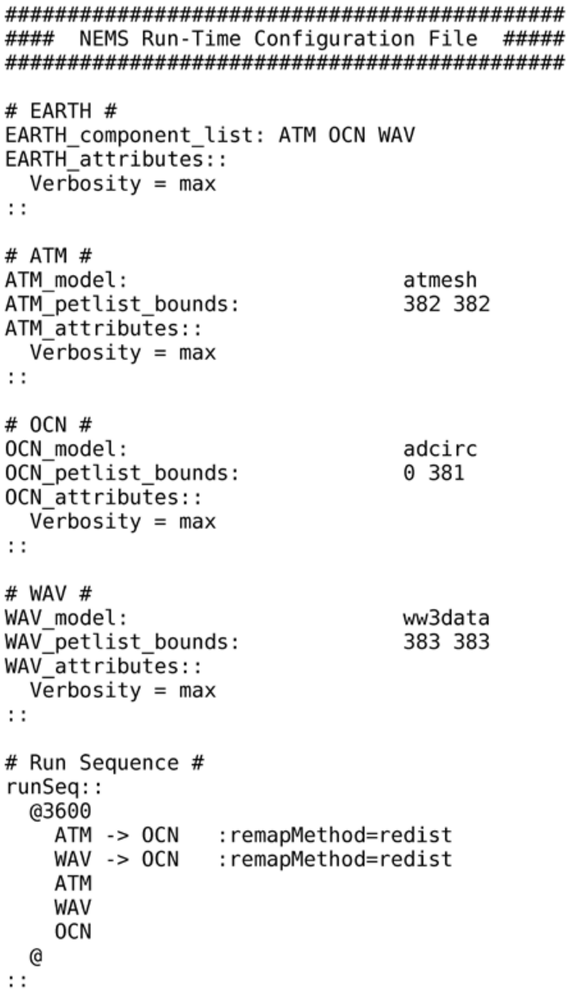
The ADvanced CIRCulation model (ADCIRC) is a finite element hydrodynamic community model originally developed by Luettich et al (1992). ADCIRC is undergoing continuous development by groups of scientists and engineers. Its natural finite element unstructured mesh capability, and several modules specifically addressing various aspects of the coastal flooding and tropical cyclone forcing, made it one of the best tools available for the coastal inundation studies. ADCIRC operates in either two-dimensional (2D) depth averaged (barotropic) and three dimensional (baroclinic) modes. In the 2D mode, it solves equations for both water surface elevation and the depth-averaged velocity field. For more details about ADCIRC governing equations, numerical methods and wave forcing implementation please see (Luettich et al, 1992; Dietrich et al, 2011). ADCIRC is written in modular FORTRAN and supports parallel execution on massive supercomputers using MPI architecture. The code structure is partitioned in three distinct initializing, running and finalizing phases ready for the ESMF coupling. The model initializes by a call to ADCIRC_Init() which also receives a MPI communicator from the driver. The subroutine reads necessary input files for constructing the computational mesh including nodes location and connectivity. It also builds a local and global nodal map to reference which nodes reside on which MPI process, and to identify their global relationships. It reads input information to constrain the model such as bathymetry, meteorological forcing, and freshwater inflow and open boundary conditions. As a part of initialization, ADCIRC also checks and connects to all requested output files that will be used as containers to fill in the model results.

ADCIRC enters the run phase by a call to ADCIRC_Run() subroutine, which also receives an argument for the number of time steps (NTIME_STP) for that specific run request. The start time and end time of the simulation is determined during the initialization phase. The model run takes place via a time loop in which, for each time step, a single call to the TIMESTEP() subroutine occurs. All the computational steps for applying forcing and boundary conditions to produce the final results are being performed in this subroutine.

The ADCIRC conclude its run by a call to ADCIRC_Final() subroutine where some of the final post-processing and check for MPI finalizing are performed.

4. ADCIRC COUPLING INTERFACE (CAP)

The ADCIRC NUOPC cap performs the coupling in all the three phases: initialize, run and finalizing. In the development of the NUOPC cap for ADCIRC, extreme care and attention were paid to minimize changes to the original ADCIRC code. At the initialization of the NUOPC application, a global MPI communicator is created by ESMF infrastructure and a dedicated set of processes passes to ADCIRC via a MPI communicator based on the number of processes requested for ADCIRC in the configuration file. At the initialization, ADCIRC cap also gets connected to available import and export field matches accepted by the communicators.



```
#############################################
####  NEMS Run-Time Configuration File  #####
#############################################

# EARTH #
EARTH_component_list: ATM OCN WAV
EARTH_attributes::
  Verbosity = max
::

# ATM #
ATM_model:                      atmesh
ATM_petlist_bounds:             382 382
ATM_attributes::
  Verbosity = max
::

# OCN #
OCN_model:                      adcirc
OCN_petlist_bounds:             0 381
OCN_attributes::
  Verbosity = max
::

# WAV #
WAV_model:                      ww3data
WAV_petlist_bounds:             383 383
WAV_attributes::
  Verbosity = max
::

# Run Sequence #
runSeq::
  @3600
    ATM -> OCN   :remapMethod=redist
    WAV -> OCN   :remapMethod=redist
    ATM
    WAV
    OCN
  @
::
```

Fig. 2: Coupled application configuration file.

After the information exchange among the model components, the ModelAdvance() subroutine of the ADCIRC cap calls the ADCIRC_Run() subroutine to perform the next run interval. Tab. 1 and Tab. 2 show the list of the exported and imported fields currently accepted by the ADCIRC cap. ADCIRC preprocessing and main model code were modified and tested to accommodate various coupling arrangements. The NWS input parameters in fort.15 input file are described in Tab. 3.

Tab. 1: Exported fields from ADCIRC.

Data field	Units	Variable
Eastward sea water velocity	ms^{-1}	UU2
Northward sea water velocity	ms^{-1}	VV2
Sea surface height above mean sea level	m	ETA2

Tab. 2: Imported fields to ADCIRC.

Data field	Units	Variable
Eastward radiation stress	m^2s^{-2} ($N\ m^{-2}/\rho$)	ADCIRC_SXX
Northward radiation stress	m^2s^{-2} ($N\ m^{-2}/\rho$)	ADCIRC_SYY
Cross radiation stress	m^2s^{-2} ($N\ m^{-2}/\rho$)	ADCIRC_SXY
Eastward wind at 10m height	ms^{-1}	WVNX2
Northward wind at 10m height	ms^{-1}	WVNY2

Tab. 3: Implemented and tested options in fort.15 input file of ADCIRC Option Meteorological forcing Wave forcing.

NWS parameter	Meteorological forcing	Wave forcing
17	ATM ∗	None
517	ATM ∗	WAV ∗∗
500	None	WAV ∗∗
519	Best Track (Holland Model)	WAV ∗∗
520	Best Track (Generalized Asymmetric Holland Model)	WAV ∗∗

∗ Any NUOPC enabled numerical weather prediction model providing required data fields e.g. ATMesh cap.

∗∗ Any NUOPC enabled wave model providing required data fields e.g. WW3data cap.

Breaking waves transfer their momentum to ocean currents. Mathematically, this forcing is expressed in the circulation model as the divergence in the radiation stresses, as described in some detail below. From spectral wave models (i.e, WaveWatch III), the radiation stress vectors can be evaluated from wave energy density.

$$S_{XX} = \rho_w g \iint (n - 0.5 + n\ \cos^2\theta)\ F(k,\theta) d\theta dt$$

$$S_{XY} = \rho_w g \iint n\ \sin\theta \cos\theta\ \ F(k,\theta) d\theta dt$$

$$S_{YY} = \rho_w g \iint (n - 0.5 + n\ \sin^2\theta)\ F(k,\theta) d\theta dt$$

where ρ_w is the water density, g is the gravitational acceleration, $F(k,\theta)$ is the directional wave energy density spectrum, k is the absolute wave number determined by the Doppler shifted dispersion relation, θ is the spectral direction and n is the ratio of the group to phase speeds for a given depth, d, and frequency.

$$n = \frac{1}{2} + \frac{kd}{\sinh(2kd)}$$

In order to evaluate the local wave forces, F_X and F_Y, that satisfy the rate of wave momentum, the spatial gradient of radiation stress per unit area can be calculated as

$$F_X = -(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y})$$

$$F_Y = -(\frac{\partial S_{yy}}{\partial y} + \frac{\partial S_{xy}}{\partial x})$$

Tab. 4: Cases with various forcing conditions.

Cases	Cases	Cases
GFS05d OC	GFS05d OC	GFS05d OC
GFS05d OC_Wav	GFS05d OC_Wav	GFS05d OC_Wav
GFS05d OC_DA	GFS05d OC_DA	GFS05d OC_DA
GFS05d OC_DA_Wav	GFS05d OC_DA_Wav	GFS05d OC_DA_Wav

5. RESULTS

We verified the coupled application in a step-by-step manner. In the first step, we saved all the ESMF exchange ESMF state fields before sending and after receiving in the model components. Then we performed a basic verification using a small toy set-up. In the final verification step, we switched to a full scale hurricane inundation test case.

We utilized the existing Hurricane Surge On-demand Forecast System (HSOFS) unstructured triangular mesh as the base of the computational domain for our case study. The HSOFS mesh covers the entire Gulf of Mexico and extends into the Atlantic Ocean to the approximate longitude of 65W, allowing for appropriate generation of storm surge from atmospheric effects over a large region. The mesh covers the shallow coastal regions up to a topographic height of 10m with the mesh resolution of approximately 200m. We force the model with main tidal constituents at the open boundaries (Fig. 3).

The atmospheric forcing is provided by the Hurricane Weather Research and Forecasting (HWRF) modeling system empowered by a movable multilevel nesting technology (Zhang et al, 2016). The model grid is a triple-nested using telescopic, two-way interactive horizontal grid resolutions from synoptic with 0.18° resolution as the outer box (spanning about 75° × 75°), to moving storm box with 0.06°◦ resolution (10° × 10°) and core with 0.02° resolution (spanning 6° × 6°). These boxes follow the hurricane best track, ensuring the highest resolution around the eye of a hurricane. In this study, we have interpolated the hourly HWRF model outputs from multiple cycles initiated with analysis data and 9 forecast time steps. Every 6 hours, reanalysis data from the next cycle are smoothly ramped into the wind and pressure fields. The atmospheric forcing has been validated against National Data Buoy Center (NDBC) and satellite altimeter data. We extracted wind velocity at 10 m height and surface pressure from the original GRIB2 output files and saved them in NetCDF format. The ATMesh NUOPC cap reads the meteorological forcing from NetCDF file and provides it to ADCIRC cap on every coupling time step. For this study, we used atmospheric fields generated by HWRF coupled to HYCOM ocean model. The HWRF model was forced with initial and boundary conditions provided by Global Forecast System (GFS) with half degree spatial grid resolution.

The wave induced forcing is provided by WaveWatchIII model, which solves the random phase spectral action density balance equation for wavenumber-direction spectra. The wave model uses the same HSOFS mesh as the computational domain and was forced with the same meteorological forcing. ADCIRC accesses wave forcing fields through WW3data NUOPC cap at every coupling time step. The wave forcing information in the form of radiation stress components are a direct output of unstructured WaveWatchIII model in NetCDF format. The model results forced with various meteorological forcing with and without wave effects are defined in Tab. 4.

We validated the coupled model results against two sets of water level observations. The tidal gauge time series was measured by the NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) and High Water Marks (HWM) measured and provided by United States Geographical Survey (USGS).

Comparison between the total water surface elevation from ADCIRC and tidal gauges time series (Fig. 4a-d), shows that the maximum water level is reproduced accurately for almost all of the presented stations. For the first three stations the inclusion of the waves does not show a significant contribution to the final maximum water surface elevation. However for the Fig. 4d, a considerable enhancement (about 0.4m to the maximum surge) due to wave forcing (wave set-up) is presented.

High Water Marks are an important source of observations for validation and enhancement of the storm surge and flood inundation studies. After significant flooding due to a landfalling hurricane, a rapid high water mark (HWM) data collection by USGS takes place to document the event and to help improve future disaster preparedness activities. Fig. 6 shows the results for statistical metrics for comparing ADCIRC total water levels and modeled HWM data given in Tab. 4. Definition of the statistical metrics are given in the Appendix. All modeling results show an underestimation of the model in comparison to observations. An improvement on the error measures, such as the relative bias (RB) and root mean square error (RMSE) after inclusion of the wave forcing is shown. However a significant enhancement in total water level in comparison with observations occurs when HWRF model performs is run data assimilation. The locations of the HWMs data and their values for the GFS05d_OC_DA_Wav case are shown in Fig. 7.

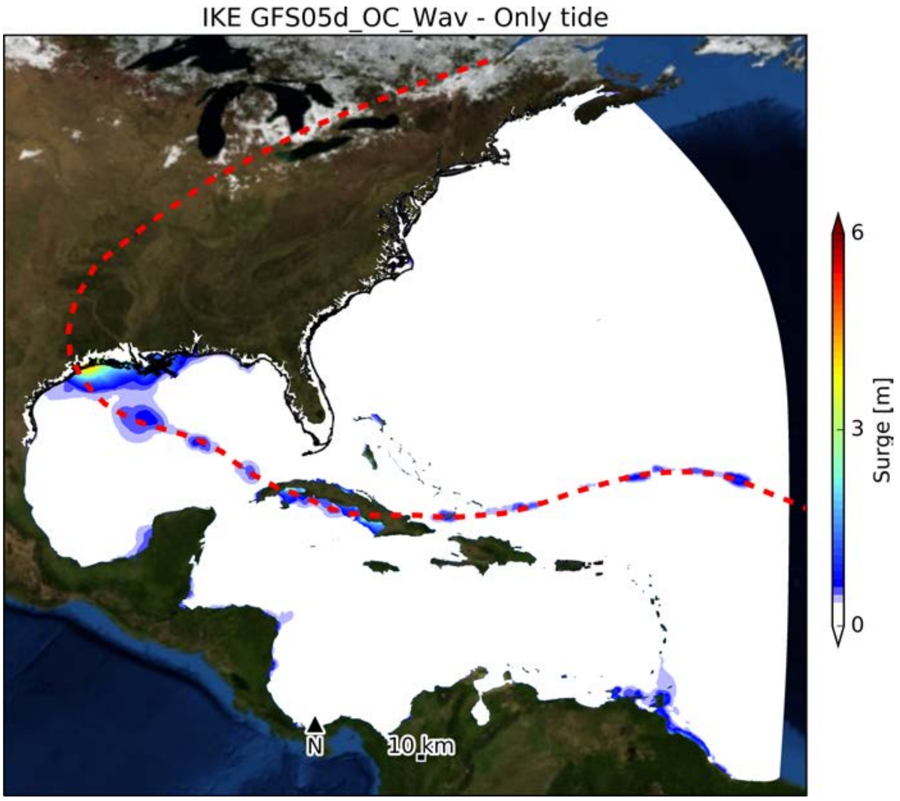


Fig. 3: Surge level is computed by subtraction of tide elevation from maximum total water level for the whole HSOFS mesh. Hurricane Ike best track is shown by a red dashed-line (preliminary results).

The spatial effects of the waves on the final maximum surge level are shown in Fig. 8. The top panel shows the total surge including the wave set-up contribution while the bottom panel shows only the wave set-up contribution. As shown in the top panel of Fig. 8, the maximum surge took place on the east side of the hurricane track. However the maximum wave-set-up contribution is not entirely co-located with the maximum surge. It should also be noted that the maximum wave set-up contribution could differ from the maximum surge location in terms of timing and location. For instance, in terms of the maximum wave set-up region at the Mississippi River delta region close to Devon Energy Facility tide gauge (8760417) shown in Fig. 4d, we see that the maximum wave setup happens more than 12 hours before the maximum surge takes place in the landfall region.

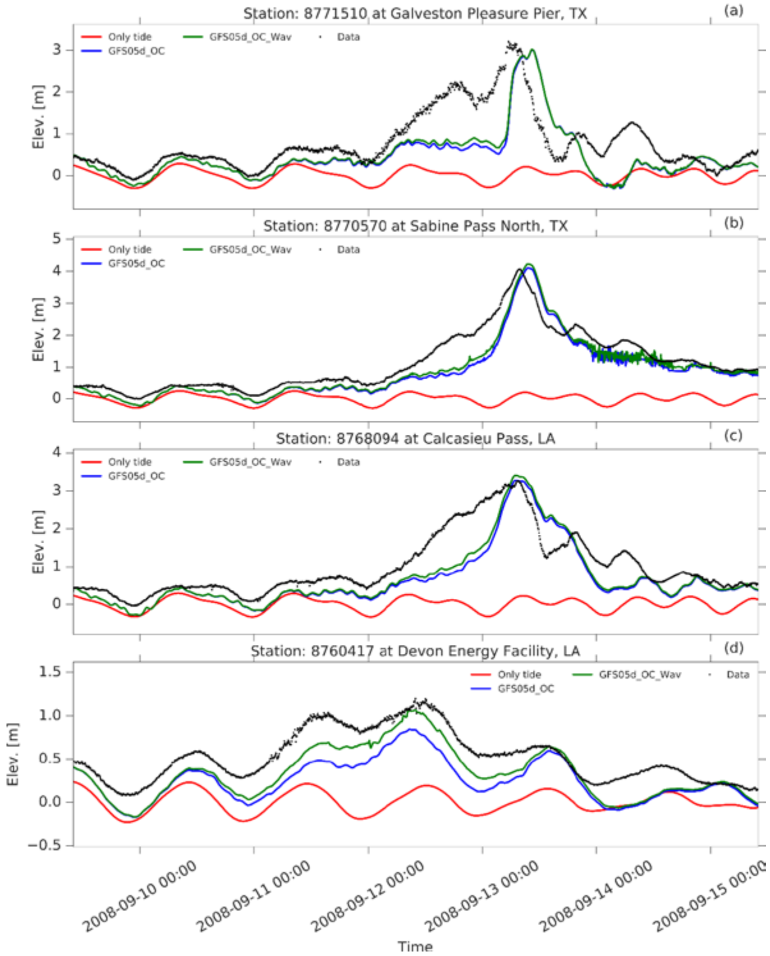


Fig. 4: Time series of the total water level observations at the tidal gauges (locations shown in Fig. 5). Black dots are the observations. Red line is the tide only water level. Blue (GFS05d_OC) and green (GFS05d_OC_Wav) are storm induced total water level without and with wave forcing. Station names and ID numbers are shown in each panel titles (preliminary results).

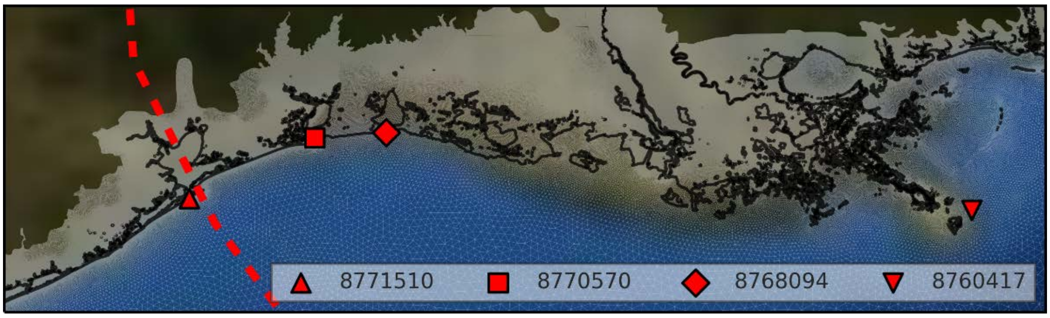


Fig. 5: Locations of the tide gauges used in Fig. 4. Red dashed line is hurricane Ike, 2008 best track. The legend shows the stations ID numbers.

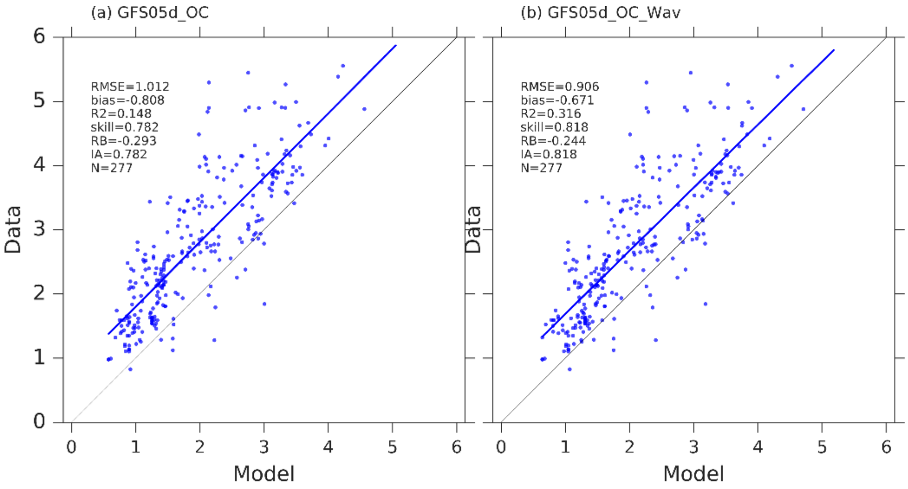


Fig. 6: Statistical comparisons of High water marks observation and model results for cases in Tab. 4. Location of the high water mark observations are shown in Fig. 7 (preliminary results).

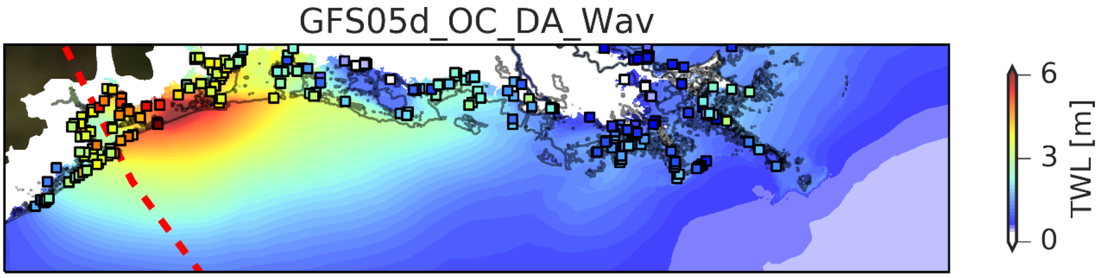
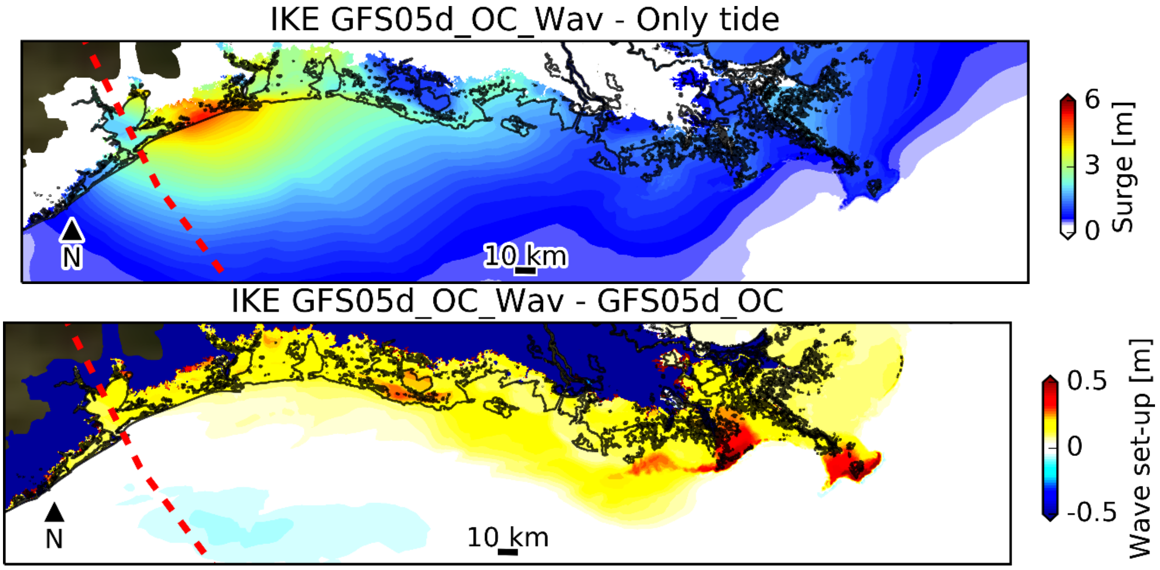


Fig. 7: High water marks observations for hurricane Ike, 2008. The contour plot is the total water level for GFS05d_OC_DA_Wav case (preliminary results).



IKE GFS05d_OC_Wav - Only tide

IKE GFS05d_OC_Wav - GFS05d_OC

Fig. 8: Total surge level computed by subtracting tides from maximum total water level. The total water level also includes effects of wave forcing. Red line represents best track of the Ike hurricane. Black contour line represents the shoreline, and the areas beyond the black contour line are the inundated regions (preliminary results).

6. SUMMARY

We have developed a flexible and generic coupling cap for ADCIRC to enable future development and seamless inclusion of various additional model components, such as river and inland flooding and sea ice, seamlessly. The current cap development provides the possibility to perform dynamical coupling of ADCIRC, surface waves and weather prediction models. The cap is capable of importing atmospheric forcing and surface wave fields and exporting water surface elevation and current velocity to the connected model components.

We also developed a flexible coupling application for coastal inundation studies using NUOPC/ESMF infrastructure, including NUOPC cap interfaces, to read and provide atmospheric and wave forcing fields to test ADCIRC cap. The coupling application was validated for hurricane Ike, 2008 on the HSOFS triangular mesh. The model skills and improvement due to wave effects on the final inundation were examined and discussed using time series from tide gauges and high water marks observations.

REFERENCES

Dietrich J, Zijlema M, Westerink J, Holthuijsen L, Dawson C, Luettich RA, Jensen R, Smith J, Stelling G, Stone G (2011) Modeling hurricane waves and storm surge using integrally-coupled, scalable computa- tions. Coastal Engineering 58(1):45–65

Ezer T, Atkinson LP (2014) Accelerated flooding along the us east coast: on the impact of sea-level rise, tides, storms, the gulf stream, and the north atlantic oscillations. Earth’s Future 2(8):362–382

Gochis D, Yu W, Yates D (2013) The wrf-hydro model technical description and users guide, version 1.0. NCAR technical document 120

Hill C, DeLuca C, Balaji, Suarez M, Silva Ad (2004) The architecture of the earth system modeling frame- work. Computing in Science & Engineering 6(1):18–28

Jacob R, Larson J, Ong E (2005) M× N communication and parallel interpolation in Community Climate System Model version 3 using the Model Coupling Toolkit. International Journal of High Performance Computing Applications 19:293–307

Luettich Jr RA, Westerink JJ, Scheffner NW (1992) Adcirc: An advanced three-dimensional circulation model for shelves, coasts, and estuaries. report 1. theory and methodology of adcirc-2ddi and adcirc-3dl. Tech. rep., COASTAL ENGINEERING RESEARCH CENTER VICKSBURG MS

Tallapragada V, Kieu C, Kwon Y, Trahan S, Liu Q, Zhang Z, Kwon IH (2014) Evaluation of storm structure from the operational hwrf during 2012 implementation. Monthly Weather Review 142(11):4308–4325 Theurich G, DeLuca C, Campbell T, Liu F, Saint K, Vertenstein M, Chen J, Oehmke R, Doyle J, Whitcomb T, et al (2016) The earth system prediction suite: toward a coordinated us modeling capability. Bulletin of the American Meteorological Society 97(7):1229–1247

Tolman HL (2002) User manual and system documentation of WAVEWATCH-III version 2.22

Valcke S, Balaji V, Craig A, DeLuca C, Dunlap R, Ford R, Jacob R, Larson J, O'Kuinghttons R, Riley G, et al (2012) Coupling technologies for earth system modelling. Geoscientific Model Development 5(6):1589

Zhang X, Gopalakrishnan SG, Trahan S, Quirino TS, Liu Q, Zhang Z, Alaka G, Tallapragada V (2016) Representing multiple scales in the hurricane weather research and forecasting modeling system: Design of multiple sets of movable multilevel nesting and the basin-scale hwrf forecast application. Weather and FORECASTING 31(6):2019–2034

APPENDIX A: METRICS FOR THE EVALUATION OF DATA-MODEL AGREEMENT

In order to assess model performance for model data comparisons, root mean square error (RMSE), BIAS, relative BIAS (RB), Correlation (Cor), Index of Agreement (IA) and peak error (Peak) were used.
The $RMSE$ is given by

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2}$$

where M_i is the modeled data, O_i is the measured data and N is the total number of data.

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)$$

shows the systematic deviation from the observations and is given by Relative BIAS (RB) shows relative systematic deviation from the observations and is given by

$$RB = \frac{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)}{\langle \ O_i \ \rangle}$$

Peak error is calculated by

$$PEAK = \max(O) - \max(M)$$

The Index of Agreement (IA) is formulated as

$$IA = 1 - \frac{\sum_{i=1}^{N}(M_i - O_i)^2}{\sum_{i=1}^{N}(|M_i - \langle O\rangle| \quad - |O_i - \langle O\rangle| \ )^2}$$

where brackets, ⟨°⟩, denote time averaging. IA=1 shows perfect agreement and IA=0 means complete disagreement.
The correlation coefficient (Cor) is calculated by

$$Cor = \frac{\sum_{i=1}^{N}(O_i - \langle O\rangle)(M_i - \langle M\rangle)}{\sum_{i=1}^{N}(O_i - \langle O\rangle)^2 \sum_{i=1}^{N}(M_i - \langle M\rangle)^2}$$