

**HINDCAST OF HURRICANE STORM SURGE FOR
PUERTO RICO USING A TIGHT COUPLING
UNSTRUCTURED CURRENT MODEL SELFE (SEMI-
IMPLICIT EULERIAN-LAGRANGIAN FINITE ELEMENT)
AND THE WWM II (WIND WAVE MODEL II)**

by

Ernesto J. Rodriguez Fernandez

A thesis submitted in fulfillment of the requirements for the degree of

MASTER OF SCIENCE
in
MARINE SCIENCES
PHYSICAL OCEANOGRAPHY

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2013

Approved by:

Aurelio Mercado, M.S.
President, Graduate Committee

Date

Julio Morell, M.S.
Member, Graduate Committee

Date

Miguel Canals, PhD
Member, Graduate Committee

Date

Victor Huerfano, PhD
Representative of Graduate Studies

Date

John M. Kubaryk, PhD
Chairperson of the Department of Marine Science

Date

Abstract

A state-of-the-art, semi-implicit Eulerian-Lagrangian finite element model SELFE and a spectral wave model (WWM II) were tested in Puerto Rico. The research was focused mainly in validating the coupled model in a complex island environment. In this thesis, a fully coupled wave-current interaction model, SELFE+WWM II is used to hindcast the storm surge, water levels and wave fields of two hurricanes that impacted Puerto Rico during 1998 and 2011. Hurricane Georges in 1998 and Hurricane Irene in 2011 were the last two hurricanes that made landfall over mainland Puerto Rico. In general, the results from SELFE+WWM II indicate a good agreement with the observed data for both cases. Overall, the study showed that SELFE+WWM II has huge potential to be implemented as an operational model to forecast storm surge, wave field and coastal inundation when the user provides the best possible representation of the hurricane track and the intensity of the winds.

Resumen

Un modelo no-estructurado semi-implícito de circulación (Semi-implicit Eulerian-Lagrangian Finite Element model (SELFEE)), acoplado con un modelo espectral de oleaje (Wind Wave Model II (WWM II)) fue probado en Puerto Rico. Este proyecto estuvo enfocado mayormente en validar el modelo acoplado en un ambiente complejo, en este caso una isla. En esta tesis, el modelo acoplado de circulación y oleaje fue SELFEE+WWM II, el cual fue usado para recrear la marejada ciclónica, los niveles del agua y los campos de olas para dos huracanes de impactaron a Puerto Rico para el 1998 y el 2011. Los últimos dos huracanes que se movieron sobre Puerto Rico fueron el huracán Georges en el 1998 y el huracán Irene en el 2011. En general, los resultados del modelo SELFEE+WWM II indicaron una buena correlación con los datos observación para cada uno de los casos. Este estudio se demostró que el modelo SELFEE+WWM II tiene un gran potencial para ser implementado como un modelo operacional para pronosticar la marejada ciclónica, el campo de olas y la inundación costera, si el usuario provee la mayor representación de la trayectoria e intensidad del ciclón tropical.

Acknowledgement

I would like to thank my advisor, Aurelio Mercado for his guidance and direction during my graduate study and in this research. I would also like to thank my other committee members: Julio Morell and Miguel Canals who gladly offered help and suggestion to me. I felt extremely lucky be around such a group of elite professors during my graduate studies. The successful completion of this thesis would not have been possible without the scholarly knowledge and technical support given by the model developers Yinglong J. Zhang and Aaron Roland.

Finally I would like to thank my family, especially my wife, my daughter and my mother for their encouragement and support throughout my studies.

Table of Content

LIST OF FIGURES	vi
LIST OF EQUATIONS.....	vii
LIST OF TABLES.....	vii
1 Introduction.....	1
1.1 Objectives.....	3
2 Literature Review	4
3 Methodology	5
3.1 Models description	5
3.1.1 SELF E model.....	7
3.1.2 Wind Wave Model II.....	7
3.1.3 Atmospheric Model	8
3.2 Computational domain.....	11
3.3 Model setup	12
4 Results.....	13
4.1 Tidal Validation.....	13
4.2 Wind model	20
4.3 Wave model results	24
4.4 Water Level.....	28
4.4.1 Hurricane Georges	28
4.4.2 Hurricane Irene.....	31
5 Discussion.....	34
6 Conclusion & Reccomendations.....	35
7 References	37
APPENDIX A: SELF E Input File.....	41
APPENDIX B: WWM II Input File.....	50
APPENDIX C: MATLAB Script to adjust the intensity of the cyclone	57

LIST OF FIGURES

FIGURE 1: TROPICAL CYCLONES THAT HAVE MOVED ACROSS THE NORTHEAST CARIBBEAN FROM 1850 TO 2012. IMAGE CREDIT: NOAA.....	1
FIGURE 2: HURRICANE GEORGES (YELLOW LINE) AND HURRICANE IRENE (CYAN LINE) TRACKS. ABBREVIATION INSIDE OF THE IMAGE SUCH AS TS AND HU REPRESENT TROPICAL STORM AND HURRICANE, RESPECTIVELY. BACKGROUND IMAGE CREDIT: BING.....	3
FIGURE 3: SCHEMATIC REPRESENTATION OF THE COUPLING (INFORMATION EXCHANGE) BETWEEN SELFE AND WWM II.....	6
FIGURE 4: SCHEMATIC REPRESENTATION OF SELFE+WWM II MODELING SYSTEM.....	6
FIGURE 5: IMAGES ABOVE SHOW THE ATMOSPHERIC FORCING FOR HURRICANE GEORGES AND HURRICANE IRENE JUST BEFORE EACH HURRICANE MADE LANDFALL OVER MAINLAND PUERTO RICO. THE IMAGES OF THE LEFT REPRESENT THE WIND SPEED (M/S) & DIRECTION. THE IMAGES OF THE RIGHT REPRESENT THE SURFACE PRESSURE FIELD IN MILLIBARS.....	10
FIGURE 6: UNSTRUCTURED MESH CREATED FOR THE 2007 FEMA FLOOD INSURANCE STUDY. FILLED CONTOURS OF WATER DEPTH IN METERS.....	11
FIGURE 7: AVERAGE SEASONAL CYCLE FOR SAN JUAN. SOURCE: NOAA.....	14
FIGURE 8: AVERAGE SEASONAL CYCLE FOR MAGUEYES ISLAND. SOURCE: NOAA.....	14
FIGURE 9: IMAGE ABOVE SHOWS THE HURRICANE GEORGES TRAJECTORY (YELLOW LINE) AND THE AVAILABLE STATIONS (SAN JUAN AND MAGUEYES) IN SEPTEMBER 1998. BACKGROUND IMAGE CREDIT: BING.....	15
FIGURE 10: IMAGE ABOVE SHOWS THE HURRICANE IRENE TRAJECTORY (YELLOW LINE) AND THE STATIONS (TIDE GAUGES IN GREEN AND BUOYS IN CYAN) IN AUGUST 2011. BACKGROUND IMAGE CREDIT: BING.....	16
FIGURE 11: TIDAL SIMULATION AT SAN JUAN STATION DURING SEPTEMBER 14-29, 1998.....	17
FIGURE 12: TIDAL SIMULATION AT MAGUEYES ISLAND STATION DURING SEPTEMBER 14-29, 1998.....	18
FIGURE 13: TIDAL SIMULATION AT SAN JUAN DURING AUGUST 15-30, 2011.....	19
FIGURE 14: TIDAL SIMULATION AT MAGUEYES ISLAND DURING AUGUST 15-30, 2011.....	19
FIGURE 15: WIND COMPARISON AT THE LUIS MUNOZ MARIN INTERNATIONAL AIRPORT IN SAN JUAN, P.R. DURING THE HURRICANE GEORGES 1998. THE CORRECTED WIND SPEED REPRESENTS THE OBSERVED WIND SPEED ADJUSTED AT 10-METER HEIGHT.....	21
FIGURE 16: WIND COMPARISON AT THE BUOY 41053 (JUST NORTH OF SAN JUAN) DURING THE HURRICANE IRENE, 2011. THE CORRECTED WIND SPEED REPRESENTS THE OBSERVED WIND SPEED ADJUSTED TO MARINE EXPOSURE AT 10-METER HEIGHT.....	22
FIGURE 17: WIND COMPARISON AT THE BUOY 42085 (JUST SOUTH OF PONCE) DURING THE HURRICANE IRENE, 2011. THE CORRECTED WIND SPEED REPRESENTS THE OBSERVED WIND SPEED ADJUSTED TO MARINE EXPOSURE AT 10-METER HEIGHT.....	22
FIGURE 18: WIND COMPARISON AT THE BUOY 41052 (JUST SOUTH OF ST. JOHN) DURING THE HURRICANE IRENE, 2011. THE CORRECTED WIND SPEED REPRESENTS THE OBSERVED WIND SPEED ADJUSTED TO MARINE EXPOSURE AT 10-METER HEIGHT.....	23
FIGURE 19: CONTOUR FILLED OF WWM II SIGNIFICANT WAVE HEIGHT (METERS) AND VECTORS OF WIND SPEED IN PUERTO RICO, CULEBRA AND VIEQUES ISLAND DURING HURRICANE GEORGES IN 1998.....	25
FIGURE 20: COMPARISON BETWEEN THE SIMULATED SIGNIFICANT WAVE HEIGHT AND PEAK PERIOD AND THE OBSERVATIONS AT THE BUOY 41053 (NEAR SAN JUAN, PUERTO RICO) DURING HURRICANE IRENE IN 2011.....	26
FIGURE 21: COMPARISON BETWEEN THE SIMULATED SIGNIFICANT WAVE HEIGHT AND PEAK PERIOD AND THE OBSERVATIONS AT THE BUOY 42085 (NEAR PONCE, PUERTO RICO) DURING HURRICANE IRENE IN 2011.	26
FIGURE 22: COMPARISON BETWEEN THE SIMULATED SIGNIFICANT WAVE HEIGHT AND PEAK PERIOD AND THE OBSERVATIONS AT THE BUOY 41052 (NEAR ST. JOHN, USVI) DURING HURRICANE IRENE IN 2011.....	26
FIGURE 23: CONTOUR FILLED OF WWM II SIGNIFICANT WAVE HEIGHT (METERS) AND VECTORS OF WIND SPEED IN PUERTO RICO, CULEBRA AND VIEQUES ISLAND DURING HURRICANE IRENE IN 2011.....	27
FIGURE 24: OUTPUT OF SELFE+WWM II MODEL DURING LANDFALL OF HURRICANE IRENE OVER MAINLAND PUERTO RICO. UPPER LEFT PLOT SHOWS WATER ELEVATION IN METERS. UPPER RIGHT PLOT SHOWS WIND	

SPEED IN METER PER SECOND. LOWER LEFT PLOT SHOWS SIGNIFICANT WAVE HEIGHT IN METERS. LOWER RIGHT PLOT SHOWS PEAK WAVE PERIOD IN SECONDS.	27
FIGURE 25: RESIDUAL WATER ELEVATIONS AFTER REMOVE THE TIDE CONTRIBUTION. OBSERVED AND MODELED WATER ELEVATION DURING HURRICANE GEORGES AT SAN JUAN, PUERTO RICO.....	29
FIGURE 26: RESIDUAL WATER ELEVATIONS AFTER REMOVE THE TIDE CONTRIBUTION. OBSERVED AND MODELED WATER ELEVATION DURING HURRICANE GEORGES AT MAGUEYES ISLAND, PUERTO RICO.....	29
FIGURE 27: RESIDUAL WATER ELEVATIONS AFTER REMOVE THE TIDE CONTRIBUTION. OBSERVED AND MODELED WATER ELEVATION DURING HURRICANE GEORGES AT LIME TREE, USVI.....	30
FIGURE 28: SIMULATED MAXIMUM STORM SURGE DURING HURRICANE GEORGES IN SEPTEMBER 1998.	30
FIGURE 29: SIMULATED MAXIMUM STORM SURGE AT VIEQUES ISLAND DURING HURRICANE GEORGES IN SEPTEMBER 1998.	31
FIGURE 30: RESIDUAL WATER ELEVATIONS AFTER REMOVING THE TIDE CONTRIBUTION. OBSERVED AND MODELED WATER ELEVATION DURING HURRICANE IRENE AT SAN JUAN, PUERTO RICO.....	32
FIGURE 31: RESIDUAL WATER ELEVATIONS AFTER REMOVING THE TIDE CONTRIBUTION. OBSERVED AND MODELED WATER ELEVATION DURING HURRICANE IRENE AT ESPERANZA (SOUTH COAST), VIEQUES ISLAND.	32
FIGURE 32: RESIDUAL WATER ELEVATIONS AFTER REMOVING THE TIDE CONTRIBUTION. OBSERVED AND MODELED WATER ELEVATION DURING HURRICANE IRENE AT FAJARDO, PUERTO RICO.....	33
FIGURE 33: SIMULATED MAXIMUM STORM SURGE DURING HURRICANE IRENE 2011.	33

LIST OF EQUATIONS

EQUATION 1: WAVE ACTION EQUATION (WAE). TAKEN FROM ROLAND, 2009.	8
EQUATION 2 : MEAN ABSOLUTE ERROR (MAE) EQUATION, WHERE N IS THE LENGTH OF THE DATASET, M_i IS THE MODEL OUTPUT AND O_i IS THE OBSERVATIONS.	16
EQUATION 3: ROOT MEAN SQUARED ERROR (RMSE) EQUATION, WHERE N IS THE LENGTH OF THE DATASET M_i IS THE MODEL OUTPUT AND O_i IS THE OBSERVATIONS.....	16

LIST OF TABLES

TABLE 1: MAJOR TIDAL CONSTITUENTS USED TO FORCE SELFIE DURING HURRICANE GEORGES (SEPTEMBER 14-29, 1998) AND HURRICANE IRENE (AUGUST 15-30, 2011).	13
TABLE 2: SIMULATED TIDE ERRORS DURING HURRICANE GEORGES AND HURRICANE IRENE AT EACH STATION.	18
TABLE 3: SUMMARY OF ERRORS IN WIND SPEED DURING HURRICANE GEORGES AND HURRICANE IRENE AT EACH STATION.	23

1 Introduction

The Northeastern Caribbean region is one of the most active tropical cyclone areas in the world (Figure 1), particularly during August, September and October. Tropical Cyclone hazards such as strong winds, heavy rainfall, storm surge, and related wind waves and runup, produce widespread damage across the coastal areas. Emergency managers, coastal planners and coastal engineers are interested in studying the impact of the hurricanes to make important decisions. Coastal hazards that take place in the surf zone region during hurricanes impact life and property, including coastal flooding and coastal erosion caused by storm surge.

In this case, Puerto Rico lying along the northeast boundary of the Caribbean Sea, it is exposed to different types of waves, such as wind waves, winter swells and tropical cyclone forced waves. Another challenge is the complex bathymetry across Puerto Rico and the local islands as well as the large population density along the coastal areas. Irregular coastlines, steep bathymetry gradients and narrow shelf characterized the coastal morphology across the regional waters of Puerto Rico.

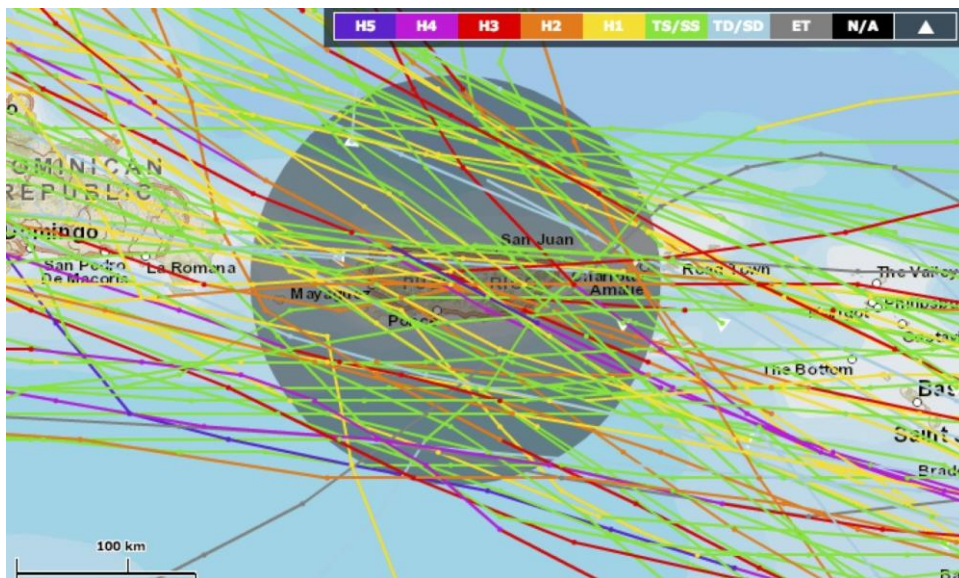


Figure 1: Tropical cyclones that have moved across the Northeast Caribbean from 1850 to 2012. Black circle represents 100 nautical miles centered at 66.37W and 18.22N. Image credit: NOAA

Currently, Caribbean islands such as Puerto Rico and the US Virgin Islands have limited guidance available to estimate the impacts of the hurricane induced storm surge. Local and federal emergency management use this limited information to plan the evacuation along coastlines when the islands are threatened by a tropical cyclone.

In this thesis, a fully coupled wave-current interaction model, Semi-implicit Eulerian-Lagrangian Finite Element (SELFE+WWMII) is used to hindcast the storm surge, water levels and wave fields of two hurricanes that impacted Puerto Rico during 1998 and 2011 (Figure 2). Georges, a Category 2 hurricane, was the most destructive hurricane to strike the entire island of Puerto Rico since Hurricane San Ciprian in 1932 (NWS San Juan). Hurricane Georges traversed the island of Puerto Rico from east to west on September 21, with its estimated maximum sustained winds of up to 115 mph and gusts of 150 mph. On the other hand, Irene made landfall over southeastern Puerto Rico as a tropical storm on Monday August 22, intensified overland and became a hurricane over northern Puerto Rico, before exiting into the Atlantic. Sustained winds of 52 mph with a gust to 71 mph were reported over Vieques Island (a small island municipality east of mainland Puerto Rico) while a tidal gauge south of Vieques Island reported a gust to 66 knots. The highest storm surge was measured in Vieques and Fajardo, where it reached 1.6 feet (NOAA).

SELFE is being used in its 2- and 3-dimensions versions at many locations (Zhang and Baptista, 2008; Shen, 2009; Roland et al., 2012; Teng, 2012; NTHMP, 2012). Its hydrostatic depth integrated version has been validated for tsunami use as part of the National Tsunami Hazard Mitigation Program requirements (NTHMP, 2012) since it is the tsunami model adopted by the state of Oregon. And its non-hydrostatic version has also been tested. Having an unstructured mesh model validated for both tsunamis and storm surges, both using the same mesh, is a great advantage. The coupled

models ADCIRC+unSWAN were tested in Puerto Rico a few years ago (Gonzalez et al., 2011), and the results of this implementation of ADCIRC+unSWAN in Puerto Rico came across problems due to the relatively low resolution of the adopted FEMA unstructured mesh (see below) at the abrupt shelf break around Puerto Rico (Gonzalez et. al 2011, Dietrich et al., 2012; <http://www.caseydietrich.com/2009/10/28/wave-refraction-on-coarse-meshes/>). The problem was traced to the unSWAN model, while the structured version of SWAN had no problems. These unSWAN problems required the use of limiters on spectral propagation velocities in order to solve the problems.

1.1 Objectives

The objective of this thesis is to validate the hurricane-forced storm surge and wave fields associated with tropical storms and hurricanes, and to expand and improve the coastal inundation model guidance now available for Puerto Rico. Another motivation is to test whether SELFE, coupled with a state-of-the-art new unstructured wave model (WWM II) could circumvent the problems that unSWAN had with wave refraction in water depths of less than 20 meters.



Figure 2: Hurricane Georges (yellow line) and Hurricane Irene (cyan line) tracks. Abbreviation inside of the image such as TS and HU represent tropical storm and hurricane, respectively. Background image credit: BING.

2 Literature Review

Storm Surge is defined by the NOAA National Hurricane Center (NHC), as an abnormal rise in sea level accompanying a hurricane or other intense storm, and whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone (NHC Glossary, NWS, 2009). Numerous models have been developed in the last few decades to simulate the impacts of the hurricane-forced storm surge along vulnerable coastlines (Zhang and Baptista, 2008; Qi et al., 2009; Dietrich, et al. 2010; NTHMP, 2012). In these days model developers make codes that resolve the conservation of momentum and continuity equations to simulate physical processes that occur in a particular region of the ocean during an impact of a tropical cyclone. Inside of this vast catalogue of codes, models based on unstructured grids (meshes, or Finite Elements) are becoming more frequently used because of their capability to resolve a broad spectrum of space scales without the necessity of using nested grids. They resolve complex bathymetry and irregular coastlines quite well without using nest grids. The most notable models of this kind are SELFЕ+WWM II (Zhang and Baptista, 2008), ADCIRC+unSWAN (Dietrich, et al. 2010 – the prefix “un” is used to distinguish between the structured and unstructured versions of SWAN) and FVCOM+SWAVE (Qi et al., 2009). For this study, we have selected the state-of-the-art semi-implicit model SELFЕ (Zhang and Baptista, 2008) coupled with the spectral wave model WWM II (Roland, 2009). Although the physics inside of the models are similar, ADCIRC+unSWAN had some problems with wave refraction in regions inside of the unstructured domain where the resolution of the bathymetry is insufficient (Gonzalez, 2011). To resolve this issue, Dietrich et. al (2012) includes limiters based on the Courant–Friedrichs–Lewy (CFL) criteria for the spectral propagation (refraction and frequency shifting) velocities in

ADCIRC+unSWAN. The aims of our study is to evaluate the performance of SELFE+WWMII in a complex island environment as well as to verify if SELFE+WWMII has the same problems that ADCIRC+unSWAN had in areas of low resolution inside of the FEMA 2007 unstructured grid.

It is important to mention that SELFE uses Garrat's parameterization of the wind stress (Garrat, 1977), which increases monotonically with the wind speed. This is the only option right now. But a consensus is being reached amongst experts that the wind stress reaches a plateau near the start of hurricane winds, and may even decrease (Powell, 2006). The capability of using a limited wind stress may improve the skill of the models, but it is a topic of further research.

3 Methodology

3.1 Models description

In this study, a fully coupled wave-current interaction model based on a circulation model (SELFE) and the spectral wave model (WWM II) was used to simulate storm surge on an unstructured grid. SELFE and WWMII use the same domain decomposition scheme. The same sub-domains in the two models eliminate the interpolation between models and simplify the exchange of information, resulting in better efficiency. Basically, WWMII is a subroutine inside SELFE. During the information exchange (Figure 3), the sea surface elevation, wet/dry nodes, and surface horizontal velocities are passed from SELFE to WWMII, and the calculated wave radiation stress, total surface stress, and the wave orbital velocity are returned to SELFE. Since SELFE has no internal hurricane wind model, in this thesis the atmospheric forcing necessary to force SELFE+WWMII was generated by a deterministic model WRF-NMM, Version 3 (Janjic et al, NOAA/NCEP), which was initialized using GFS (Sela, 1980; NOAA/NCEP) and NOAA CFSR (Saha et. al,

2006) Reanalysis. To summarize the coupling process, a schematic representation of the modeling system is provided in Figure 4.

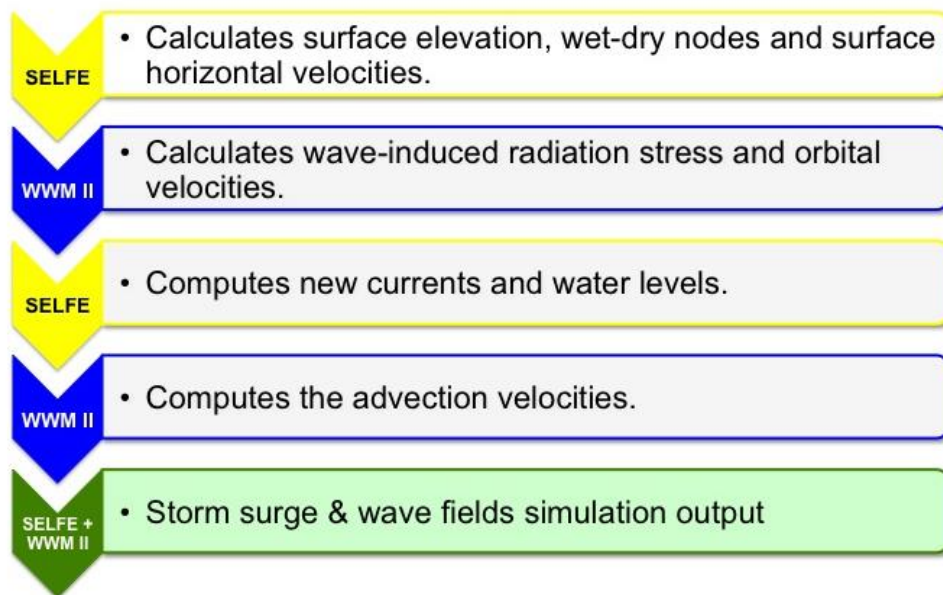


Figure 3: Schematic representation of the coupling (information exchange) between SELFE and WWM II.

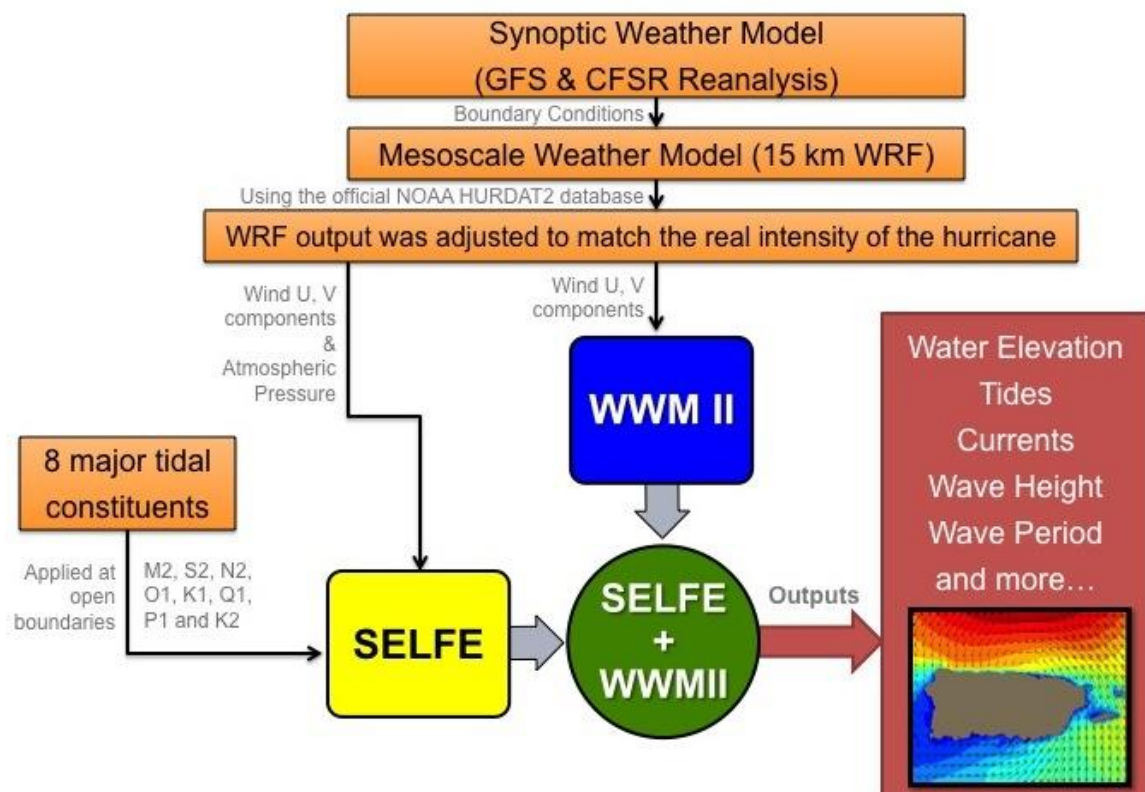


Figure 4: Schematic representation of SELFE+WWM II modeling system.

3.1.1 SELFE model

The SELFE (Semi-implicit Eulerian-Lagrangian Finite Element) model uses a semi-implicit finite-element algorithm (Casulli and Walters, 2000) to solve the primitive equations in hydrostatic form, to realistically address a wide range of physical processes and of atmospheric, ocean and river forcing. The advection is computed with the Eulerian-Lagrangian method (ELM) in the momentum equations. The orthogonality of the unstructured triangular grid cells is not necessary since finite element discretization is used in SELFE. The numerical algorithm is high-order, and stable and computationally efficient. It also incorporates a natural inundation scheme where at each time step, the interfaces between wet and dry regions are computed to determine if the shoreline advanced or retreated. Further details of SELFE numeric beyond the description given above can be found in Zhang and Baptista (2008). SELFE has been extensively tested against standard ocean/coastal benchmarks and applied to a number of bays/estuaries around the world, in the context of general circulation, tsunami and storm surge inundation, internal waves, and recently, oil spill, sediment transport, coastal ecology, and wave-current interaction. In this thesis, SELFE along with WWMII was employed to hindcast the hurricane induced storm surge.

3.1.2 Wind Wave Model II

The spectral wave model WWM II (Wind Wave Model II; Roland, 2009) uses the Wave Action Equation (WAE) (Equation 1) to describe the growth, decay, advection and refraction of wind waves due to varying depths and currents. The WAE in the WWM II is similar to that used in the SWAN model. The first term in the equation (Eq. 1) represents the change of wave action in time, the second term in spatial space, the third term represents refraction due to currents and depths, and the

last term represents the frequency shifting due to variation in depths and/or the presence of currents.

$$\underbrace{\frac{\partial}{\partial t} N}_{\text{Change in Time}} + \underbrace{\nabla_{\mathbf{x}} (\dot{\mathbf{X}} N)}_{\text{Advection in horizontal space}} + \underbrace{\frac{\partial}{\partial \sigma} (\dot{\theta} N) + \frac{\partial}{\partial \theta} (\dot{\sigma} N)}_{\text{Advection in spectral space}} = \underbrace{S_{tot}}_{\text{Total Source Term}}$$

Equation 1: Wave Action Equation (WAE). Taken from Roland, 2009.

The S_{tot} term in the right side of the equation represents the wave growth and wave dissipation due to wave breaking, bottom friction and white-capping as well as non-linear wave-wave interactions such as triad and quadruplet interactions. Basically, the model uses the same parameterizations for wave growth and white-capping as used in the latest version of the well-known NOAA Wave Watch III model 3.14 (Tolman, 2009). In WWM II, the friction velocity required to compute the surface stresses is calculated according with the formulation addressed in detail by Tolman (2009) where the mean wind profile has a logarithmic shape near the surface of the ocean.

3.1.3 Atmospheric Model

For this project, the next-generation mesoscale numerical weather prediction system, Weather Research and Forecasting (WRF, NOAA/NCEP) model was configured to produce wind and pressure fields since SELFE has no internal hurricane wind. The WRF non-hydrostatic (NMM) Version 3 developed by the NOAA National Center of Environmental Prediction (NCEP) was setup for these hindcast runs. The WRF computational domain extends from 5N to 23N and from 76W to 54W, with a spatial resolution of approximately 15 kilometers (see Figure 5). The NOAA Climate Forecast System Reanalysis (CFSR) and the Global Forecast System (GFS) were used as boundary conditions for the high-resolution runs of WRF. For Hurricane Georges, the WRF model was initialized with the 40-km CFSR reanalysis. In contrast, for

Hurricane Irene, the WRF model was initialized with the 32-km GFS because at the time of the study the CFSR reanalysis was only available until March 2011. Both low-resolution models, the 40-km CFSR and 32-km GFS, did a good job with the trajectory of the cyclones; however they are deficient in resolving detailed wind fields when the hurricane interacts with the topography of the islands. Therefore, the high-resolution WRF model was required to provide detailed surface winds over the islands and surrounding waters.

Although, WRF resolved fairly well the wind and surface pressure fluctuations, the model was not good enough matching the real intensity of the hurricanes. Since WRF winds under-predicted the wind speed compared with the official intensity from NOAA HURDAT2 database (<http://www.nhc.noaa.gov>), the winds were corrected to match approximately the official intensity. This was made using a MATLAB® script that corrected it using the official information from NOAA. The values were corrected every 3 hours as given in the official information from NOAA. After the corrections were made, these winds and surface pressure were used as atmospheric forcing in SELFE+WWM II.

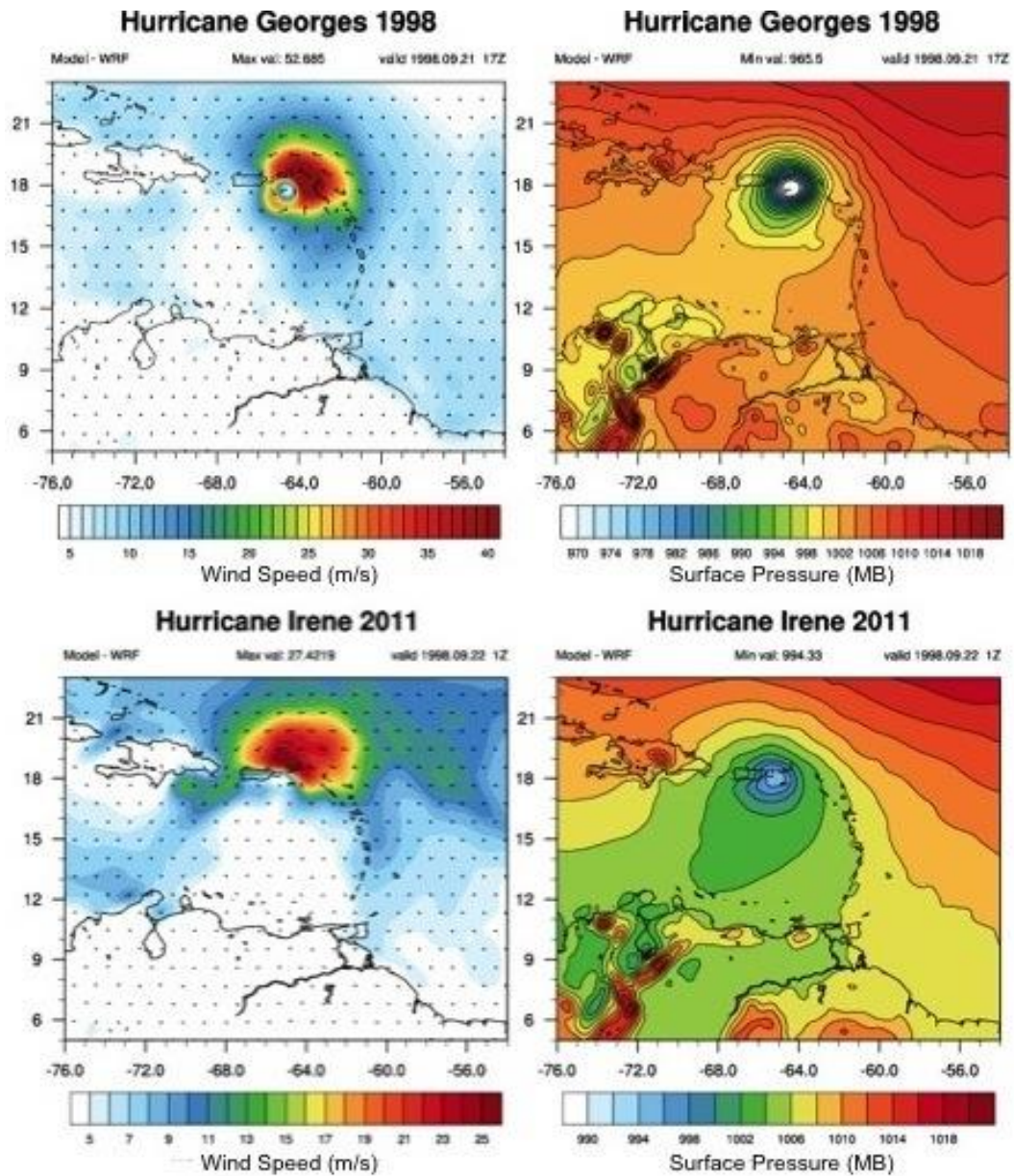


Figure 5: Images above show the atmospheric forcing for Hurricane Georges and Hurricane Irene just before each hurricane made landfall over mainland Puerto Rico. The images of the left represent the wind speed (m/s) & direction. The images of the right represent the surface pressure field in millibars.

3.2 Computational domain

The unstructured mesh created for the 2007 Puerto Rico FEMA Flood Insurance Study was used for all the model simulations. This mesh has 124,815 nodes and 242,976 triangular elements, and its spatial resolution ranges from 60 kilometers at the boundaries to a minimum of 50 meters in the nearshore and inland. The mesh covers the Eastern Caribbean region and parts of the Tropical Atlantic. The spatial coverage of the FEMA unstructured domain extends approximately from 6°N - 22°N and 55°W - 75°W.

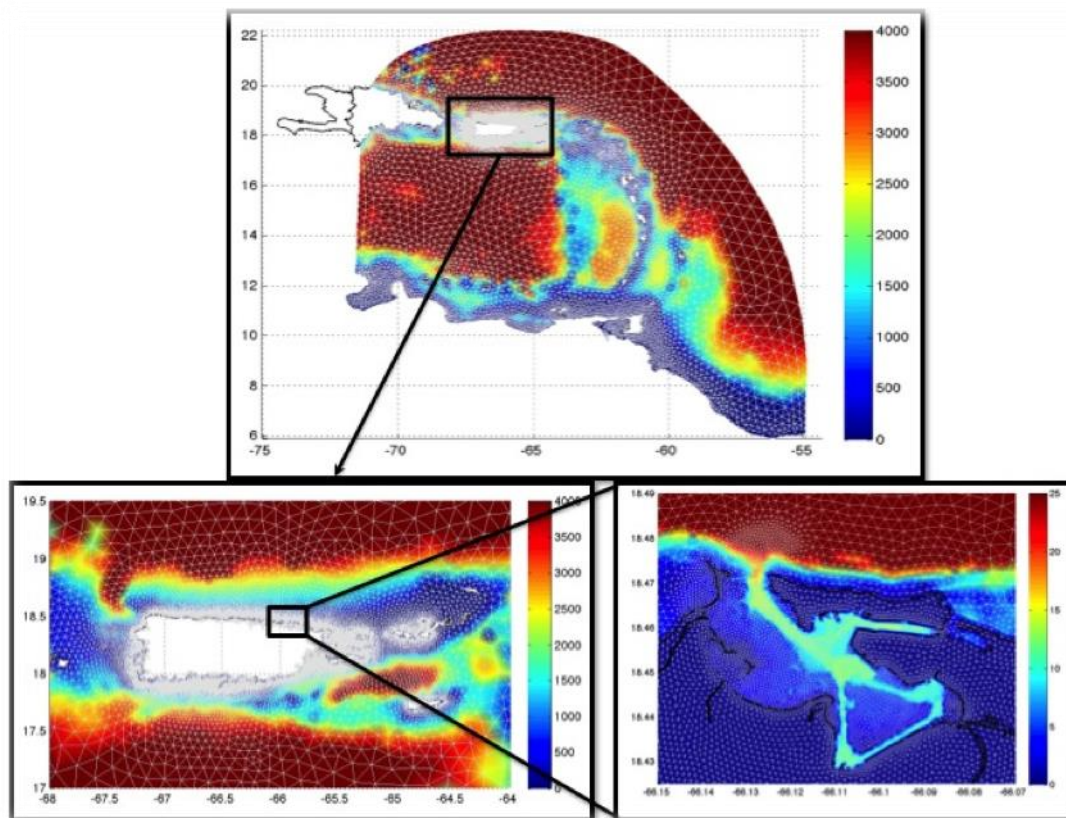


Figure 5: Unstructured mesh created for the 2007 FEMA Flood Insurance Study. Filled contours of water depth in meters.

3.3 Model setup

SELFE was used in hydrostatic, 2-dimensional horizontal barotropic mode. The time step for SELFE was 150 seconds. In contrast, WWM II had a time step of 600 seconds (10 minutes). This means that every 4 calculations, SELFE exchanged the sea surface elevation, wet/dry nodes, and surface horizontal velocities with WWM II. Then WWM II calculates the wave-induced radiation stress and the wave orbital velocity and sends back the results to SELFE. Then, new current and water level distributions are computed by SELFE. These new current and water level passed back to the WWM II where the advection velocities in the different phase spaces are recalculated using the new values of the current velocities and water levels, closing the coupling cycle between the two models. The total run time for Hurricane Georges was 3 days or 72 hours; on the other hand, the run time for Hurricane Irene was 2 days or 48 hours. Boundary conditions such as surface pressure and winds had a temporal resolution of one hour, which were accessed by the model via NetCDF files. SELFE applied the quadratic stress at the bottom boundary and, for this project; a fixed uniform Manning coefficient of 0.025 was used over the entire domain (equivalent to flow over bare earth).

SELFE was run without wind-wave forcing to validate the model output with NOAA's predicted tidal signal. This also serves to test the bathymetry since any differences in the phases and amplitudes between the observed and computed astronomical tides will be due to differences between the real and the model-fed bathymetry. After the tidal validation, wind and pressure fields from the WRF model were used to force SELFE. At this point, simulated winds were compared with available weather stations across Puerto Rico and US Virgin Islands. Finally, SELFE+WWM II was forced using tides, winds and surface pressure to calculate the

storm surge for each hurricane. Simulated water elevations were compared with the NOAA tidal gauges for hindcast purposes.

4 Results

4.1 Tidal Validation

In order to validate the model, the SELFE output was compared to NOAA's harmonic tide predictions. The NOAA's harmonic tide predictions are calculated using 26 tidal constituents while SELFE was forced with the principal constituents. For this step, the model was forced using the eight major tidal constituents (M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 and Q_1) applied at the open boundaries. The elevation forcing for these constituents was obtained from the *USACE Eastcoast 2001: Tidal Constituent Database* (A. Y. Mukai & J. J. Westerink, 2002). Table 1 summarizes the nodal factors and equilibrium arguments used to force SELFE to simulate the tides for each hurricane.

Table 1: Major tidal constituents used to force SELFE during Hurricane Georges (September 14-29, 1998) and Hurricane Irene (August 15-30, 2011).

Constituent	Hurricane Georges, Sep 1998		Hurricane Irene, Aug 2011	
	Nodal Factor	Equilibrium Argument (deg)	Nodal Factor	Equilibrium Argument (deg)
K1	0.9025	257.64	0.9944	241.96
O1	0.8406	277.34	0.9908	97.42
P1	1.0000	97.22	1.0000	126.94
Q1	0.8406	221.71	0.9908	321.15
N2	1.0326	116.59	1.0067	207.23
M2	1.0326	172.22	1.0067	343.50
S2	1.0000	0.00	1.0000	0.00
K2	0.7802	336.09	0.9658	303.87

The average seasonal cycle correction was applied to the model solution, because the model did not consider changes in mean sea level caused by regular fluctuations in coastal temperatures, salinities, winds, atmospheric pressures, and ocean currents. Figure 7 and Figure 8 show the average seasonal cycle corrections calculated by NOAA at two stations in Puerto Rico, one in the north coast (San Juan) and one in the south coast (Magueyes Island). The seasonal cycle for San Juan is based on approximately 50 years of data and for Magueyes Island is based on approximately 55 years of data.

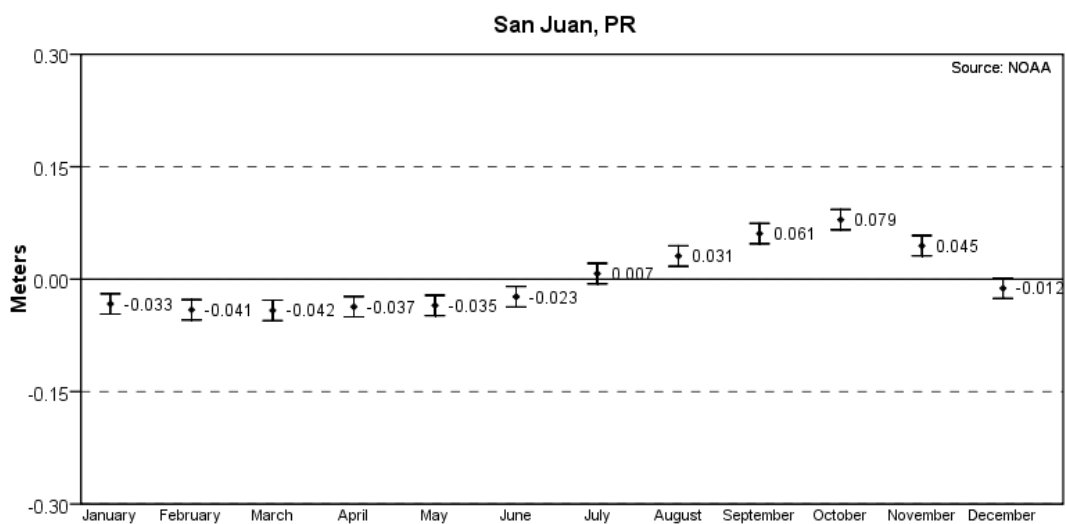


Figure 6: Average seasonal cycle for San Juan. Source: NOAA.

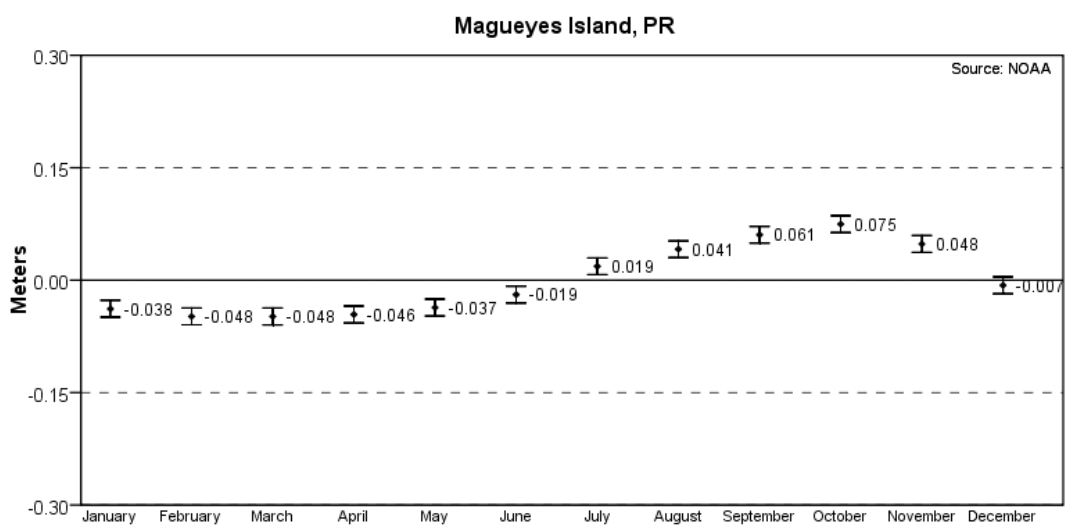


Figure 7: Average seasonal cycle for Magueyes Island. Source: NOAA.

The seasonal cycle is very similar at both stations with the highest monthly water levels of the year occurring in October and the lowest monthly water levels of the year occurring in March.

For Hurricane Georges, only two tidal stations were available for validation in Puerto Rico during September 1998 (Figure 9). The tide gauge in San Juan is located inside of the bay while the Magueyes tide station is located in a small island about 70 meters south of the coast of Lajas, Puerto Rico. In contrast, for Hurricane Irene, there were more than 15 tide gauges and 4 coastal buoys available along the Puerto Rico and U.S. Virgin Islands during August 2011. For continuity, the same stations, San Juan and Magueyes were used in the tidal validation for Hurricane Irene (Figure 10).

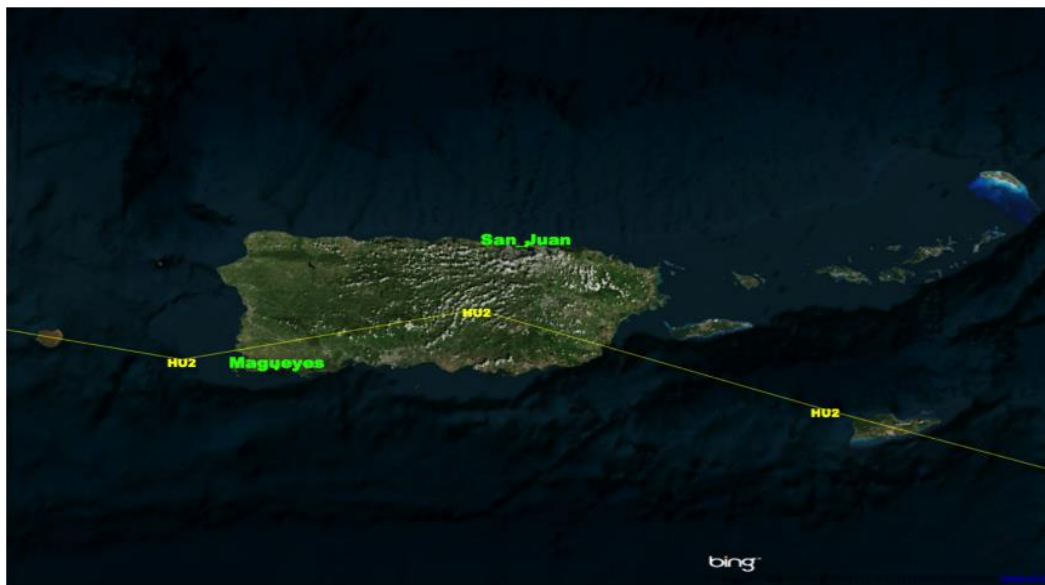


Figure 8: Image above shows the Hurricane Georges trajectory (yellow line) and the available stations (San Juan and Magueyes) in September 1998. Background image credit: BING.



Figure 9: Image above shows the Hurricane Irene trajectory (yellow line) and the stations (tide gauges in green and buoys in cyan) in August 2011. Background image credit: BING.

To verify the skill of the model in simulating tides, the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE) were computed using the model results and the NOAA harmonic tide prediction. Basically, MAE is the mean absolute differences between observations and the forecast. The MAE is defined as:

$$MAE = \frac{1}{N} \sum_{i=1}^N |m_i - o_i|$$

Equation 2 : Mean Absolute Error (MAE) equation, where N is the length of the dataset, m_i is the model output and o_i is the observations.

The Root Mean Square Error (RMSE) is defined as:

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

Equation 3: Root Mean Squared Error (RMSE) equation, where N is the length of the dataset, m_i is the model output and o_i is the observations.

The tidal validation was carried out as follows. The simulation of the tides for both hurricanes was performed using a time step of 150 sec during a 30-day period. The first 15 days of simulations were used to spin-up the model. Consequently, the last 15 days were taken into consideration for the tidal validation for San Juan and Magueyes Island, respectively. Figure 11 and Figure 12 show the tidal simulations during September 14, 1998 and September 29, 1998. In both stations, SELFE did fairly well in replicating the tidal amplitudes and phases. The model in the San Juan station resolved the semi-diurnal and mixed semi-diurnal cycle and the tidal amplitude really well. For San Juan, the MAE and RMSE were only 0.0036 and 0.0238 meters, respectively. Similarly, SELFE predicted the mixed diurnal tide in Magueyes with some inconsistencies when the tidal amplitude is small or during neap tide. For the Magueyes Island station, the MAE and RMSE were 0.0063 and 0.0194 meters, respectively.

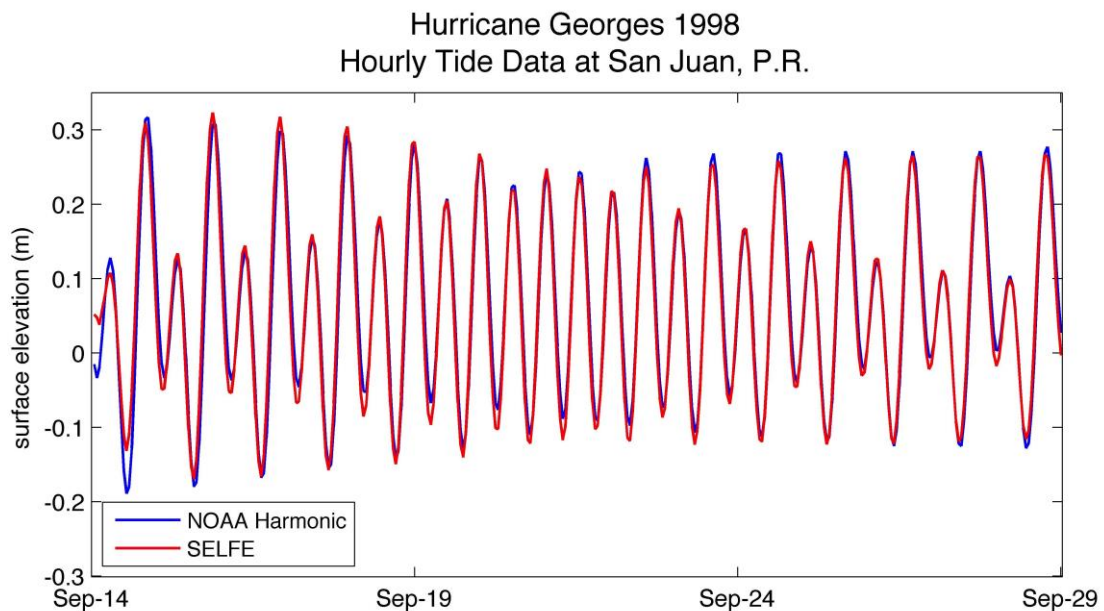


Figure 10: Tidal simulation at San Juan station during September 14-29, 1998.

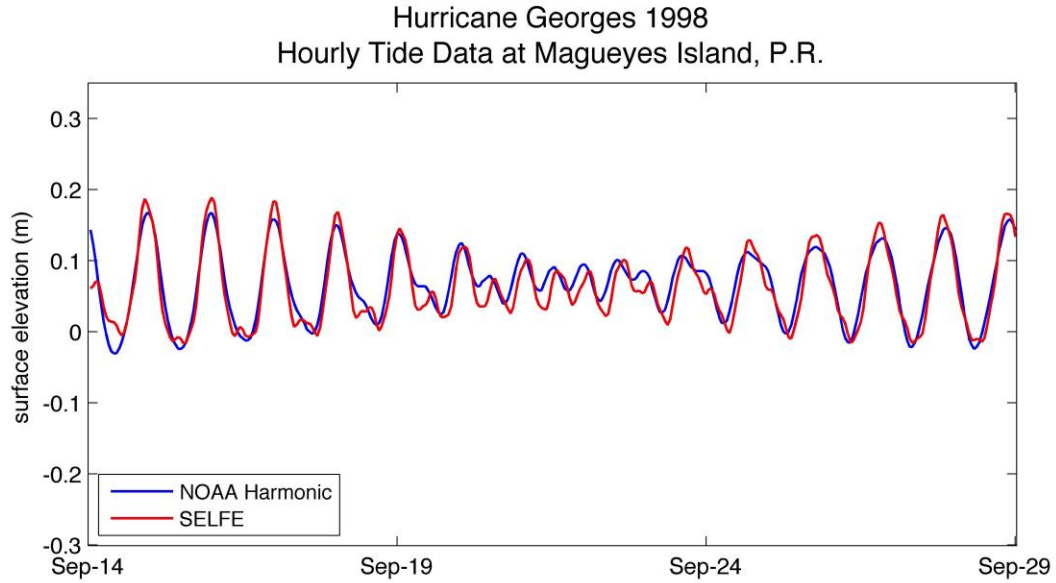


Figure 11: Tidal simulation at Magueyes Island station during September 14-29, 1998.

For Hurricane Irene, the same stations San Juan and Magueyes Island were analyzed between August 15 and August 30 2011. Results (Figures 13 and 14) show a good agreement between simulated tides and tide gauge observations. RMSE errors were around 0.03 meters and the MAE errors were between 0.01 and 0.02 meters. The exact values are presented in the Table 2. In general for both cases, the errors of the simulated tides were small. These small discrepancies could be associated with the number of tidal constituents used to force SELFIE and the poor representation of small islets and reefs in the some areas of the computational domain.

Table 2: Simulated tide errors during Hurricane Georges and Hurricane Irene at each station.

Station	Hurricane Georges		Hurricane Irene	
	MAE	RMSE	MAE	RMSE
San Juan	0.0036 m	0.0238 m	0.0124 m	0.0305 m
Magueyes Island	0.0063 m	0.0194 m	0.0177 m	0.0267 m

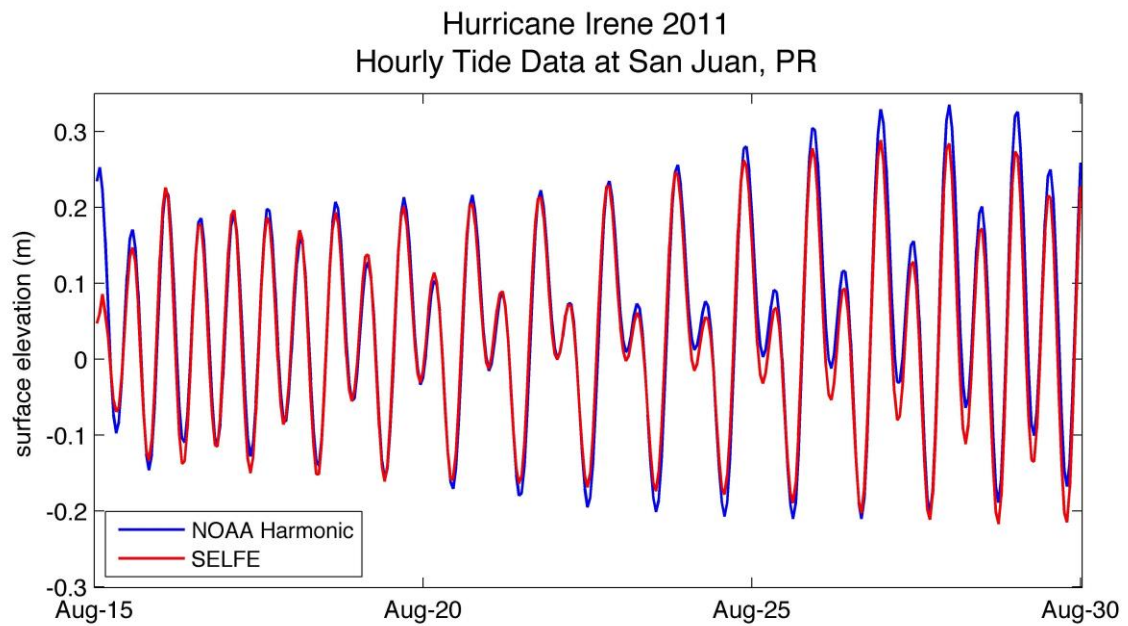


Figure 12: Tidal simulation at San Juan during August 15-30, 2011.

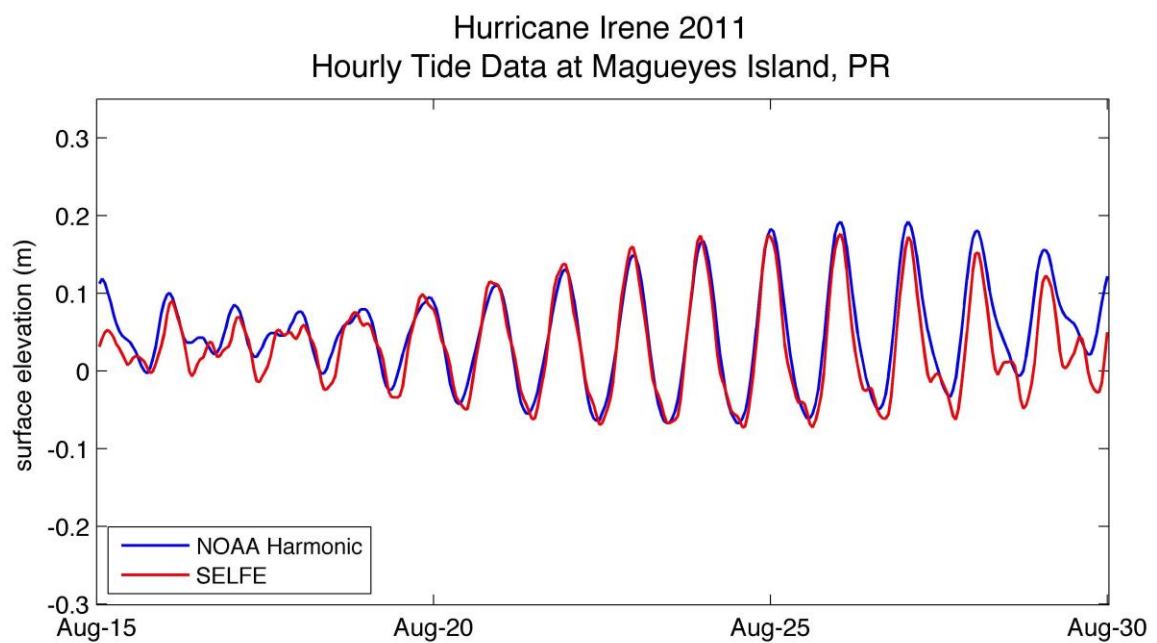


Figure 13: Tidal simulation at Magueyes Island during August 15-30, 2011.

4.2 Wind model

The non-hydrostatic version (NMM) of WRF was used to recreate the meteorological conditions during the September 1998 and August 2011. The WRF model calculated hourly averages of 10-meter wind and surface pressure fields. This sophisticated Numerical Weather Prediction (NWP) model takes into account topographic factors, applying the appropriate adjustment to the velocities depending of the surface roughness and elevation. As it has been previously explained in Section 3.1.3, the model wind speed and surface pressure were adjusted using the official track and intensity information using the NOAA's HURDAT2 database. By doing so, the WRF model output is adjusted to match the official intensity of the cyclone described in HURDAT2. For comparison purpose, all wind observations were referenced to a 10-meter height wind using the conversion proposed by Powell and Houston (1996).

Wind validation for Hurricane Georges was performed using the observed wind data at the Luis Munoz Marin International Airport in San Juan, PR and the simulated meteorological conditions from WRF. At that time, the only reliable station in Puerto Rico was the ASOS (Automated Surface Observation System) at Luis Munoz Marin International Airport. Figure 15 shows the wind comparison between the WRF model and the wind observation at the Luis Munoz Marin (LMM) International Airport. The comparison of the simulated winds and observed winds shows that although WRF captured really well the behavior of the winds at the LMM airport, errors at this station were somewhat high, with a MAE of 2.99 m/s and a RMSE of 4.47 m/s. Such underestimation of the wind speed in the Hurricane Georges simulation could be attributed to the "Land Use dataset" used inside of WRF. The latest "USGS Land Use dataset" was used to force the model, but obviously today

there are many more structures and buildings that increase the roughness of the terrain, when compared with September 1998 (almost 15 years ago). Higher values of roughness may contribute to a decrease in the wind speeds; especially in highly-developed urban areas.

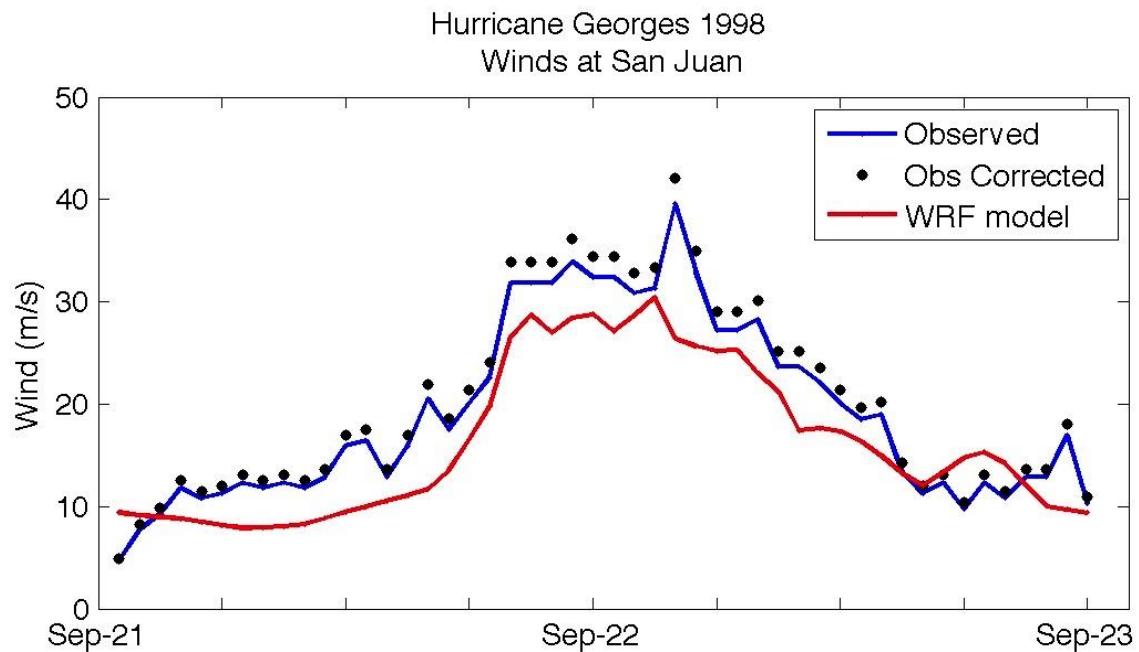


Figure 15: Wind comparison at the Luis Munoz Marin International Airport in San Juan, P.R. during the Hurricane Georges 1998. The corrected wind speed represents the observed wind speed adjusted at 10-meter height.

Figures 16, 17 and 18 illustrate the comparison of WRF simulated winds and the measured winds during Hurricane Irene. The WRF model reproduced the wind field for Irene quite well. At the 4 four stations, the model's errors were less than 1.5 m/s. The simulated data match well with the observed data during August 21. When the storm intensified over Puerto Rico on August 22, winds increased at all stations resulting in a slight overestimation of the winds. Table 3 summarizes the statistical errors (MAE and RMSE) for each station.

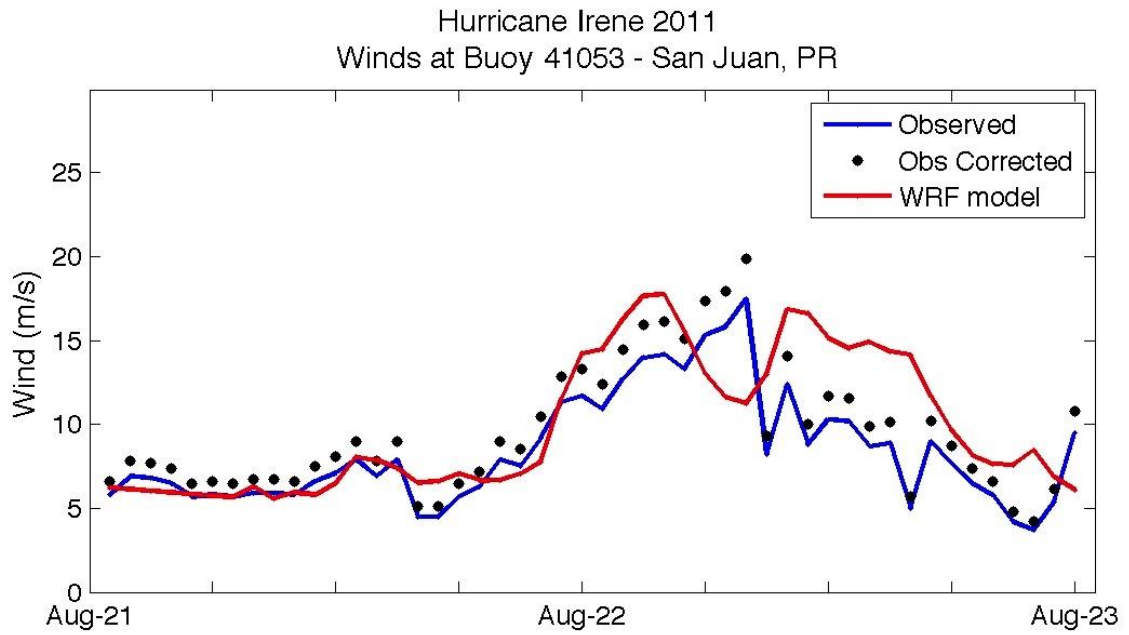


Figure 14: Wind comparison at the buoy 41053 (just north of San Juan) during the Hurricane Irene, 2011. The corrected wind speed represents the observed wind speed adjusted to marine exposure at 10-meter height.

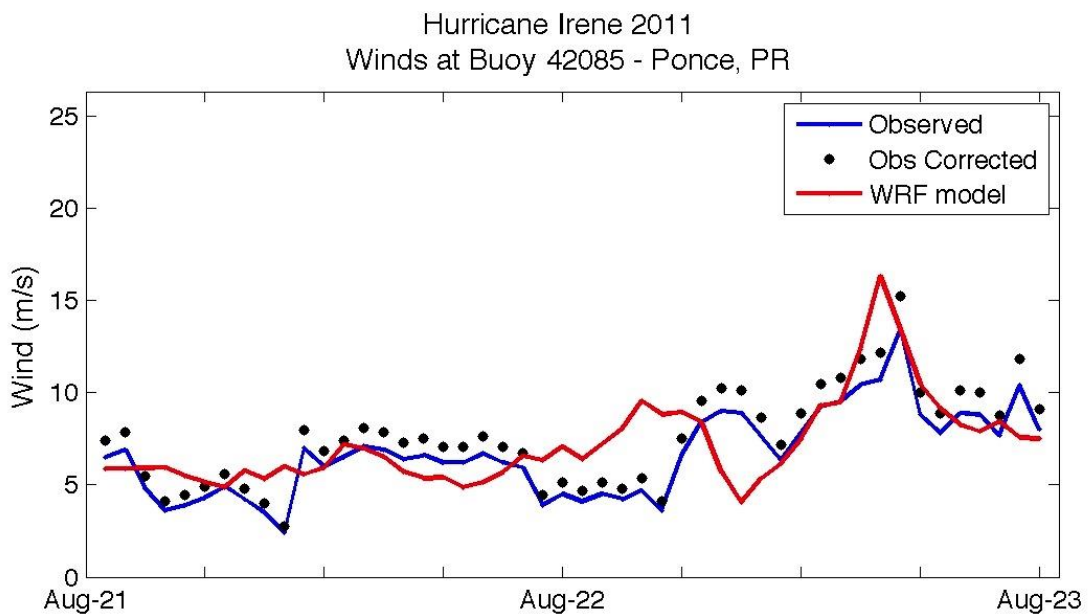


Figure 15: Wind comparison at the buoy 42085 (just south of Ponce) during the Hurricane Irene, 2011. The corrected wind speed represents the observed wind speed adjusted to marine exposure at 10-meter height.

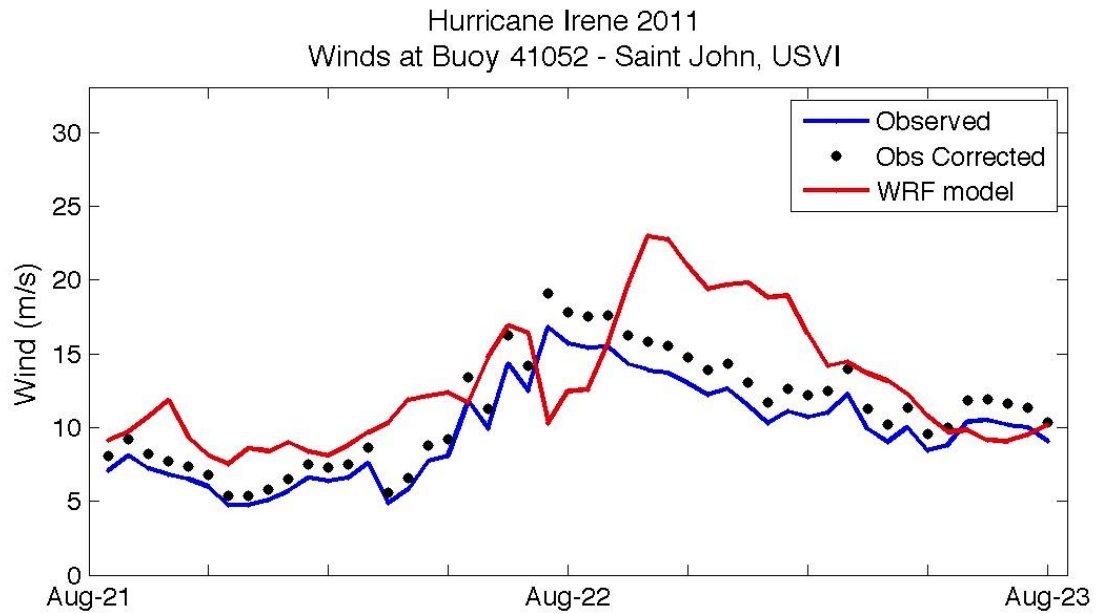


Figure 16: Wind comparison at the buoy 41052 (just south of St. John) during the Hurricane Irene, 2011. The corrected wind speed represents the observed wind speed adjusted to marine exposure at 10-meter height.

Table 3: Errors in winds speeds when compare the observed winds with the WRF simulated winds.

Station	Hurricane Georges		Hurricane Irene	
	MAE	RMSE	MAE	RMSE
San Juan Airport	2.9899 m/s	4.4743 m/s		
San Juan buoy			1.1514 m/s	1.2367 m/s
Ponce Buoy			0.9648 m/s	0.9136 m/s
St. John Buoy			1.4122 m/s	1.3413 m/s
Buoy 41043			1.2367 m/s	1.1514 m/s

4.3 Wave model results

In this section, the result of the WWM II will be compared with the buoy data from the IOOS sponsored Caribbean Ocean Observing System (CarICOOS). All the near-shore buoys across Puerto Rico and U.S. Virgin Islands were installed after August 2009. For this reason, only the waves from Hurricane Irene are validated against the WWM II results. Although, no data of significant wave height were available for Hurricane Georges, Figure 19 is included to display the model performance during September 21-22, 1998. In terms of Hurricane Irene, Figure 10 shows the buoy locations available in August 2011, two buoys across the surrounding waters of Puerto Rico (near San Juan and Ponce) and one buoy just south of Saint John. Significant wave height and peak period at the buoy 41053 (2 miles north of San Juan, PR) during Hurricane Irene are shown in Figure 20. The MAE and the RMSE at this location were 0.7617 meters and 1.3013 meters respectively. Although, WWM II overestimated the wave height at San Juan (Buoy 41053) by approximately 2 meters, the model captured the overall behavior of the wave fields.

It is important to highlight that Tropical Cyclone Irene intensified after it made landfall over mainland Puerto Rico from a strong Tropical Storm to a Hurricane Category #1. This resulted in an increase of the overall wind speed as well as the waves on the right side of the hurricane. Figure 16 and 18; show the wind speed increasing after Irene made landfall, just after midnight on August 22, 2011. The increase in the simulated wind after landfall (Figure 16 and Figure 18) resulted in an overestimation of the significant wave height at San Juan and St. John (Figure 20 and Figure 22). It can be seen in Figure 21 that the model performed at best at the buoy 42085, with a MAE of 0.1581 meters and a RMSE of 0.3829 meters. In this case, the station was located south of the center of Irene. In terms of the wave period, in Figure

20, 21 and 22, it can be observed that the model results were relatively similar to the magnitude of the observed wave periods. The contour filled of significant wave height simulated by WWM II during Hurricane Irene is shown in Figure 23. It can be seen that the WWM II, simulated the wave field reasonably and did not show any problems of wave refraction in areas of low resolution around Puerto Rico, Culebra Island and Vieques Island. Figure 24 shows simulated fields of water elevation, wind speed, significant wave height and peak wave period during Irene's landfall over mainland Puerto Rico in August 2011.

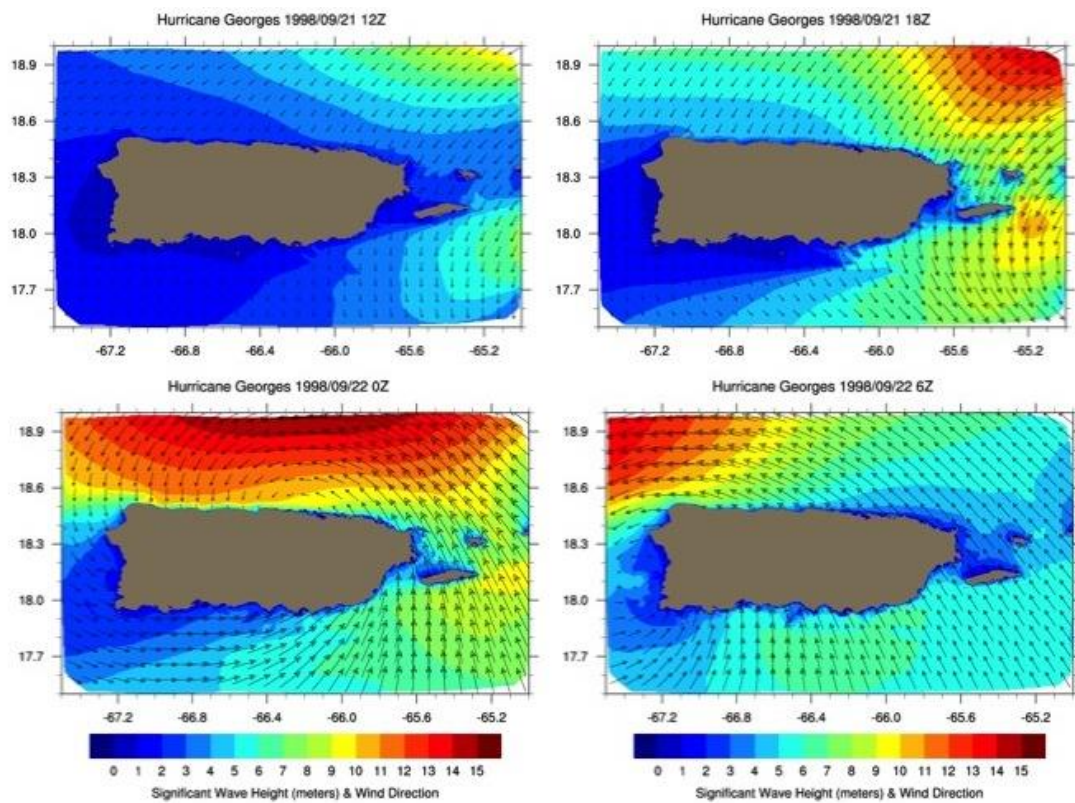


Figure 17: Contour filled of WWM II significant wave height (meters) and vectors of wind speed in Puerto Rico, Culebra and Vieques Island during Hurricane Georges in 1998.

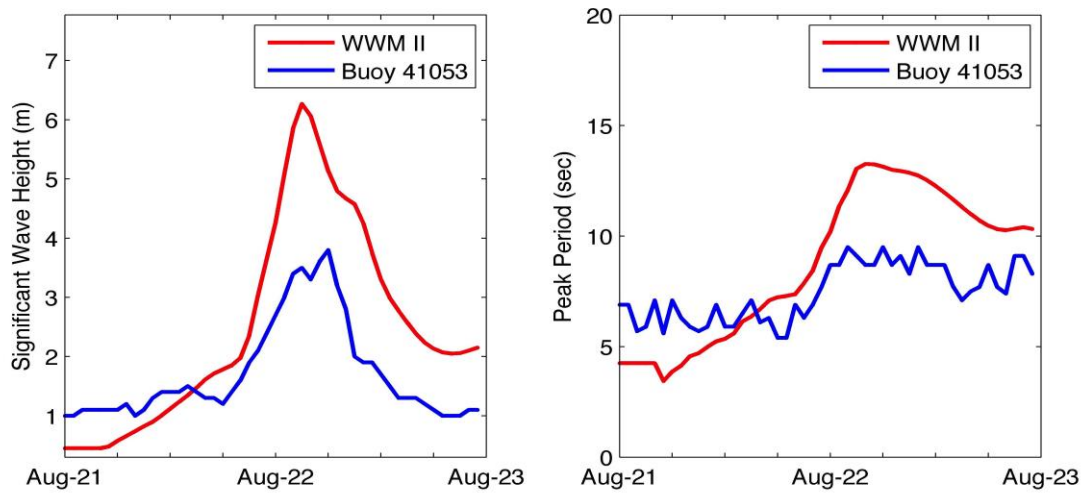


Figure 20: Comparison between the simulated significant wave height and peak period and the observations at the buoy 41053 (near San Juan, Puerto Rico) during Hurricane Irene in 2011.

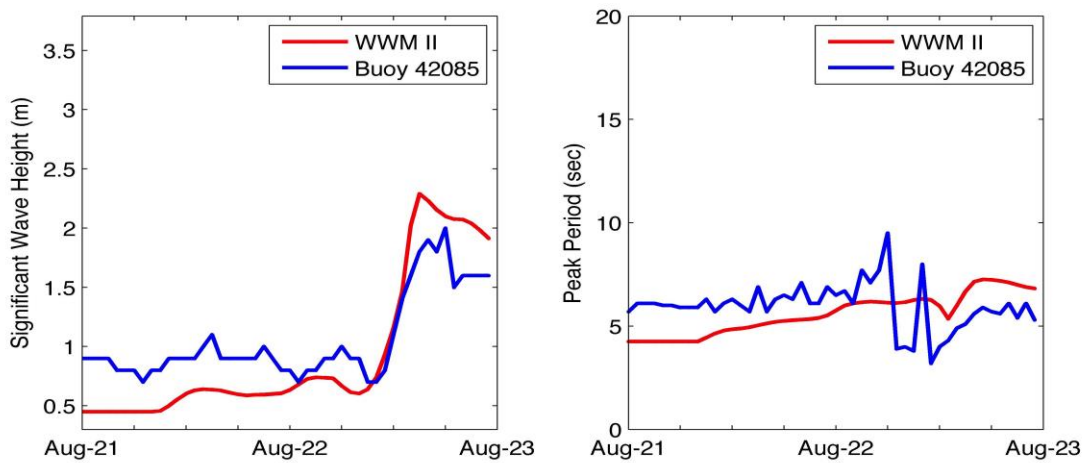


Figure 21: Comparison between the simulated significant wave height and peak period and the observations at the buoy 42085 (near Ponce, Puerto Rico) during Hurricane Irene in 2011.

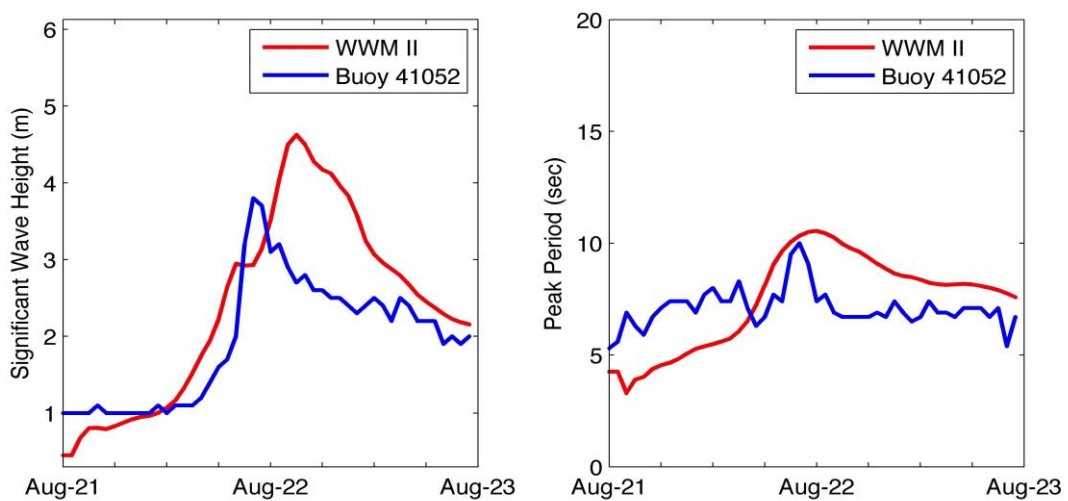


Figure 22: Comparison between the simulated significant wave height and peak period and the observations at the buoy 41052 (near St. John, USVI) during Hurricane Irene in 2011.

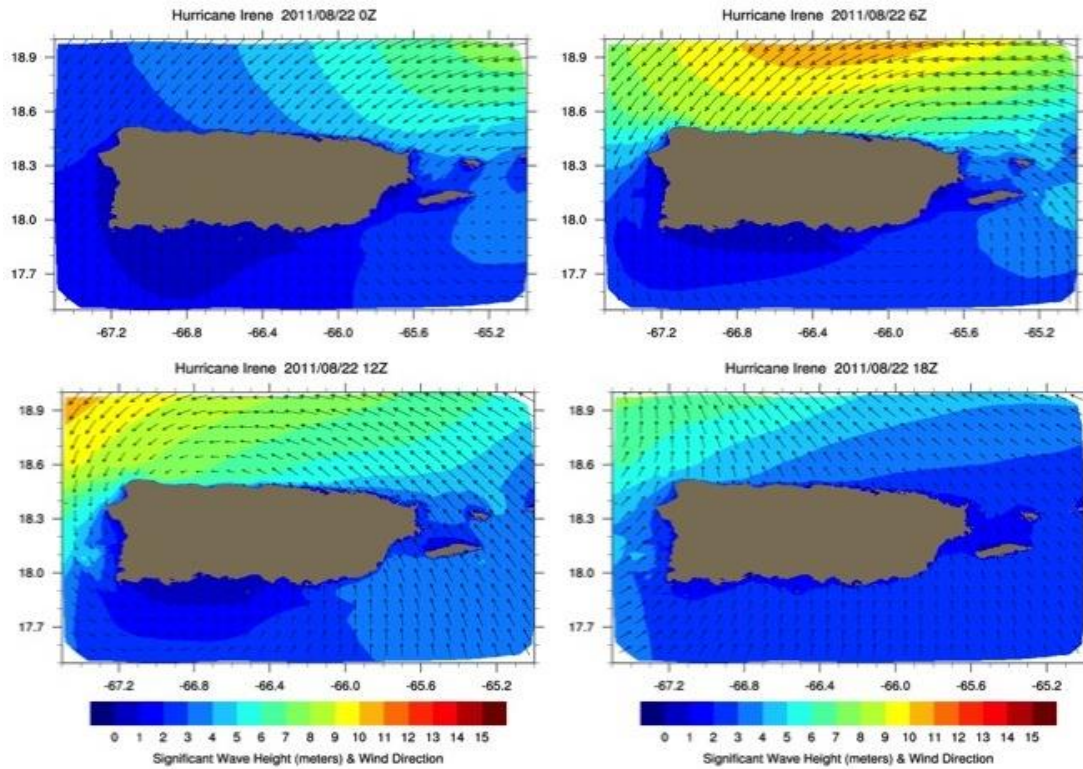


Figure 23: Contour filled of WWM II significant wave height (meters) and vectors of wind speed in Puerto Rico, Culebra and Vieques Island during Hurricane Irene in 2011.

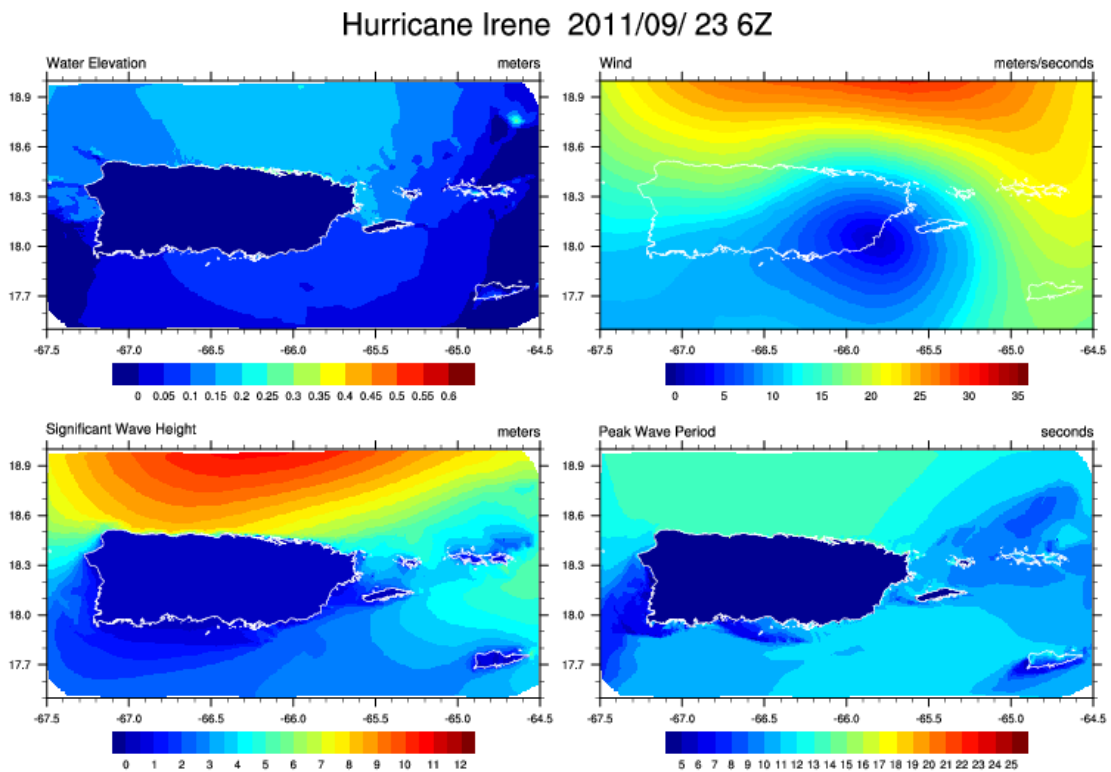


Figure 24: Output of SELFE+WWM II model during landfall of Hurricane Irene over mainland Puerto Rico. Upper left plot shows water elevation in meters. Upper right plot shows wind speed in meter per second. Lower left plot shows significant wave height in meters. Lower right plot shows peak wave period in seconds.

4.4 Water Level

4.4.1 Hurricane Georges

After removing the tidal contribution at each station, the resultant water elevation is equivalent to the storm surge. All the data in this section was referenced to Mean Sea Level (MSL). In the three stations analyzed for Hurricane Georges, the maximum storm surge measured ranged between 0.5 and 0.6 meters. The time series of residual water elevation at San Juan (Figure 25) demonstrated an excellent correlation between the observed and predicted water elevation, with a MAE of 0.08 meters and a RMSE of 0.003 meters. In contrast, the time series (Figure 26) at Magueyes shows that SELFE+WWM II underestimated the storm surge by approximately 0.4 meters (by 66%). Although, the model captured some increment on the water level, the statistical errors at the Magueyes Island station were relatively high compared with San Juan. The MAE is 0.086 meters and the RMSE is of 0.036 meters. The last station analyzed for Hurricane Georges was the Lime Tree, U.S. Virgin Island. Georges crossed the island of St. Croix before it hit Puerto Rico in September 22, 1998. The Lime Tree station is located in the south coast of Saint Croix. Figure 27 illustrated the residual water elevation at Lime Tree. At this station, modeled and observed water elevations were quite similar. Although the model did not capture the peak height of the surge, the results were satisfactory. The error statistics at this station were as follows; the MAE was 0.073 meters and the RMSE was 0.021 meters. For Hurricane Georges Figure 28 shows that the highest values of storm surge occurred north of Vieques Island and along the east portions of Puerto Rico, specifically near Ceiba and Fajardo as well as the northern coast of Culebra Island. Finally, Figure 29 shows the Maximum Storm Surge (in meters) simulated at

Vieques Island during Hurricane Georges. Vieques Island was one of the most affected by the Hurricane Georges' storm surge.

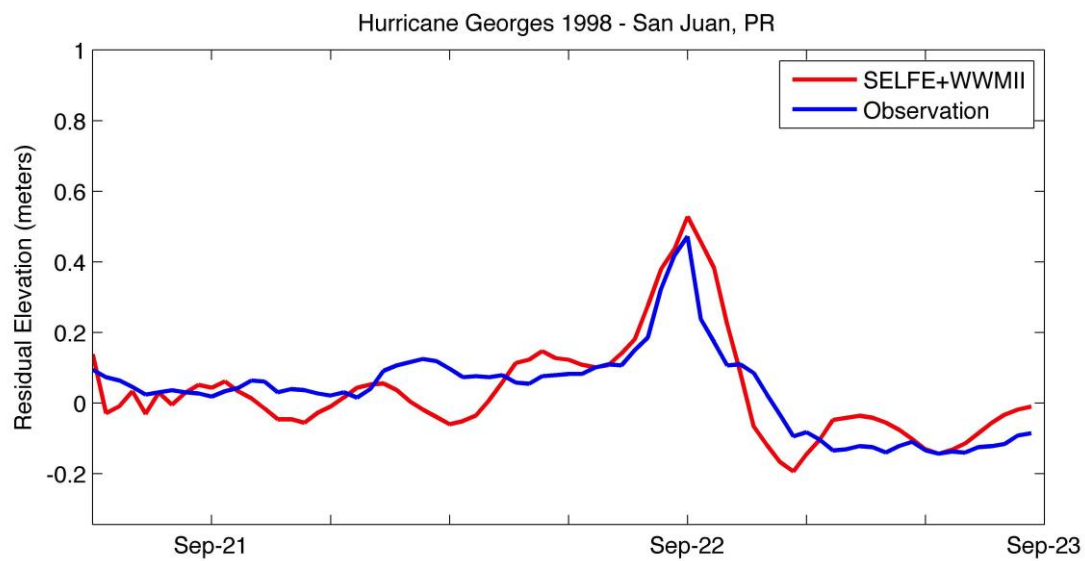


Figure 25: Residual water elevations after remove the tide contribution. Observed and modeled water elevation during Hurricane Georges at San Juan, Puerto Rico.

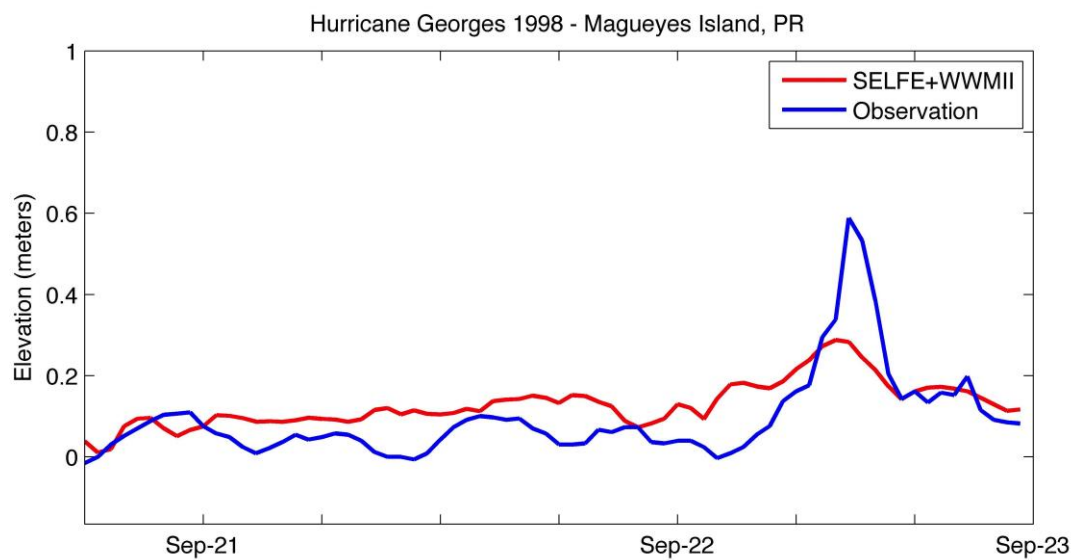


Figure 26: Residual water elevations after remove the tide contribution. Observed and modeled water elevation during Hurricane Georges at Magueyes Island, Puerto Rico.

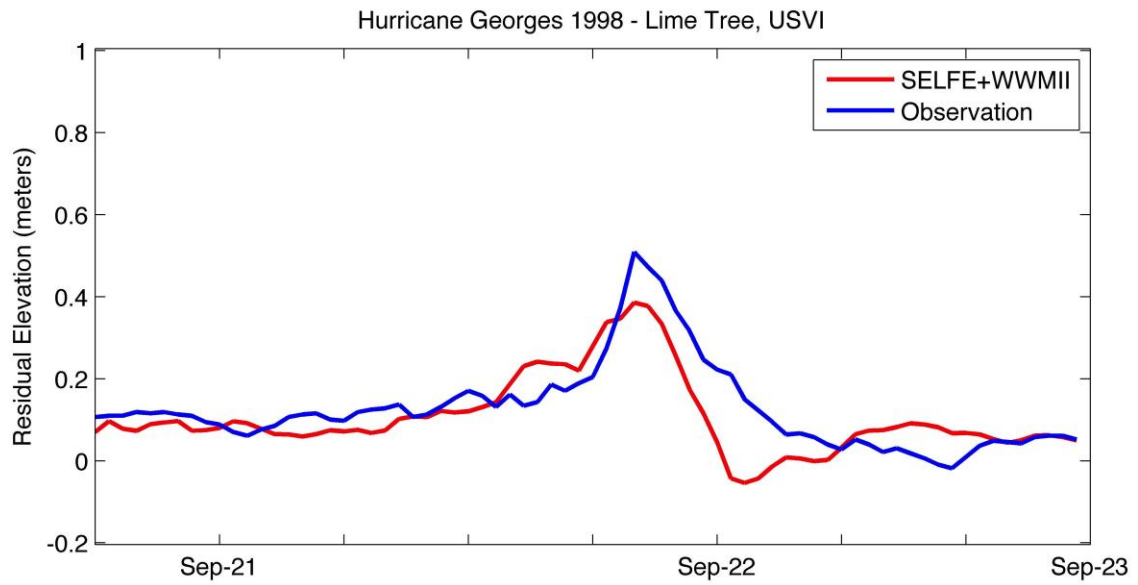


Figure 27: Residual water elevations after remove the tide contribution. Observed and modeled water elevation during Hurricane Georges at Lime Tree, USVI.

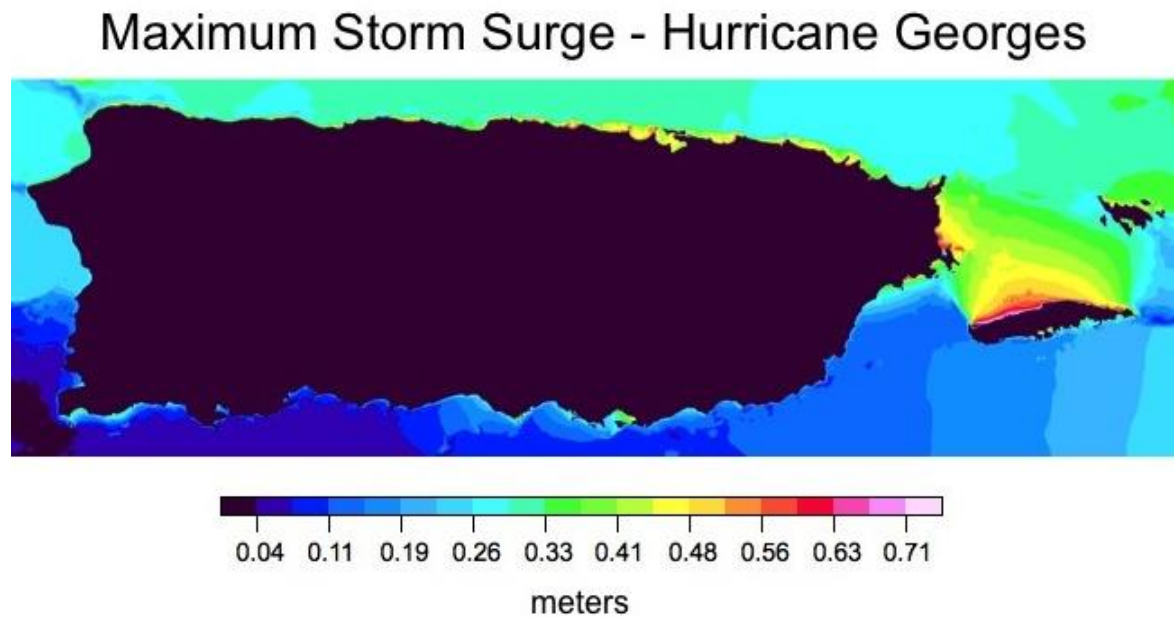


Figure 28: Simulated maximum storm surge during Hurricane Georges in September 1998.

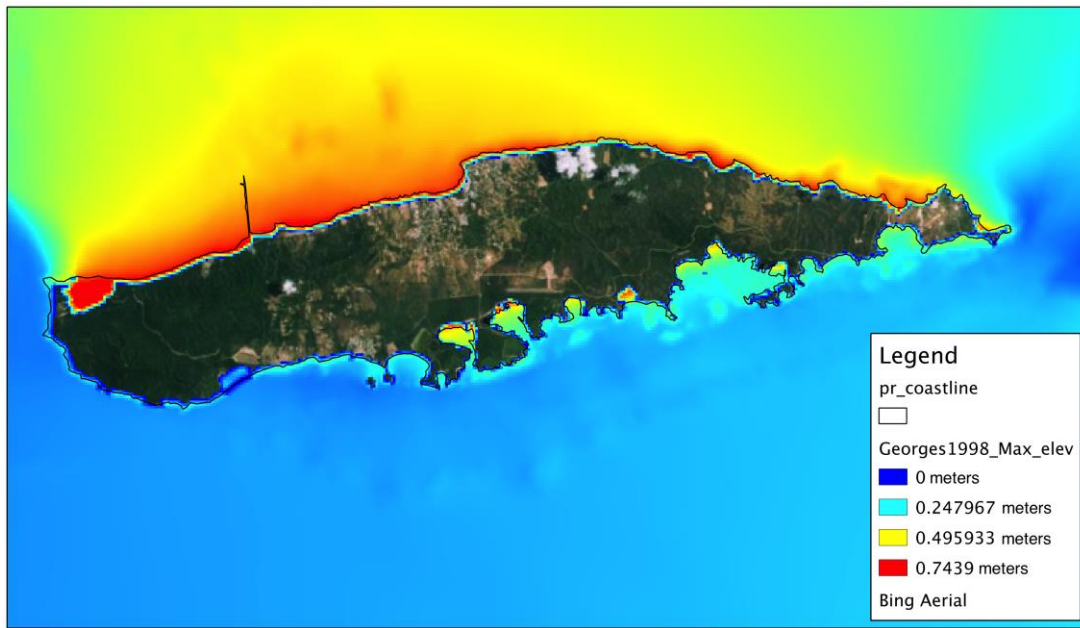


Figure 29: Simulated maximum storm surge at Vieques Island during Hurricane Georges in September 1998.

4.4.2 Hurricane Irene

As shown in Figures 30, 31 and 32, the maximum storm surge measured at the tidal stations during Hurricane Irene was between 0.25 meters and 0.4 meters. At all stations, the storm surge levels are in good agreement with the observed surge. In this case, the statistical errors were small in the range of 0.05-0.07 meters. Figure 33 shows that the highest values of storm surge occurred in portions of northeast Puerto Rico, specifically near Rio Grande.

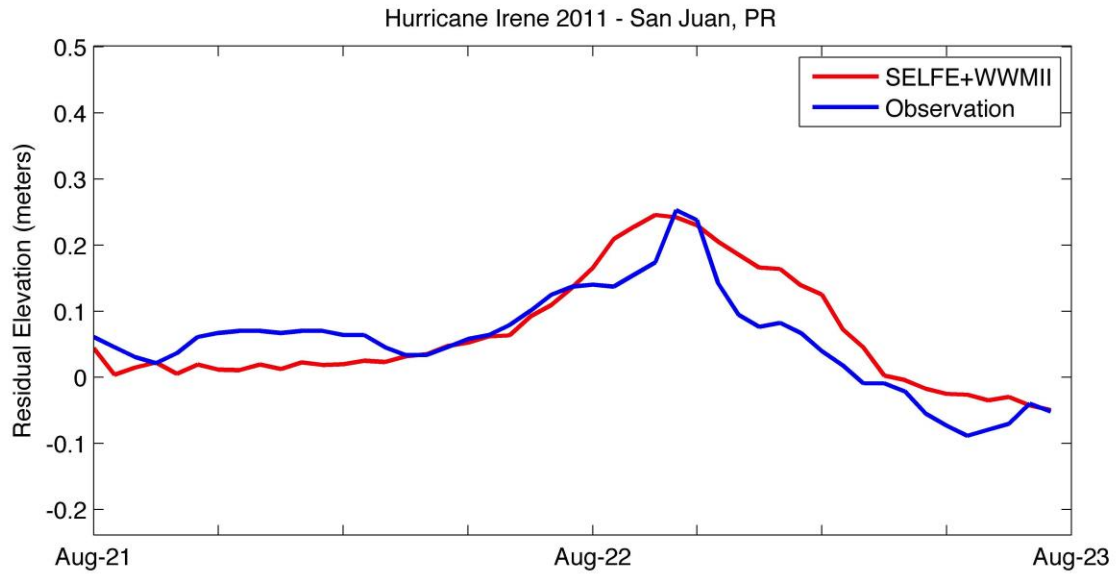


Figure 30: Residual water elevations after removing the tide contribution. Observed and modeled water elevation during Hurricane Irene at San Juan, Puerto Rico.

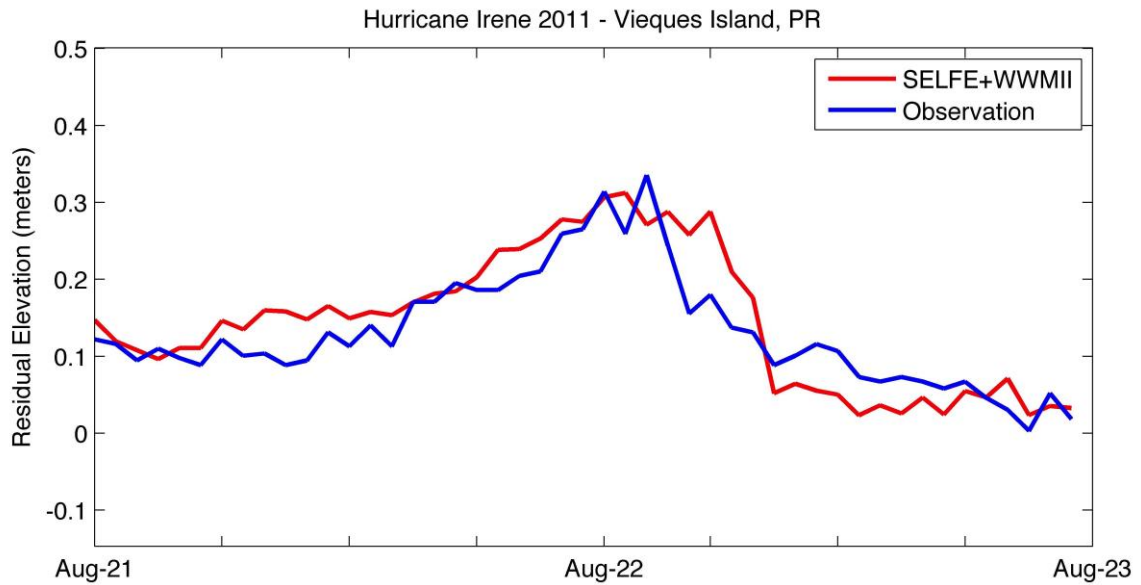


Figure 31: Residual water elevations after removing the tide contribution. Observed and modeled water elevation during Hurricane Irene at Esperanza (south coast), Vieques Island.

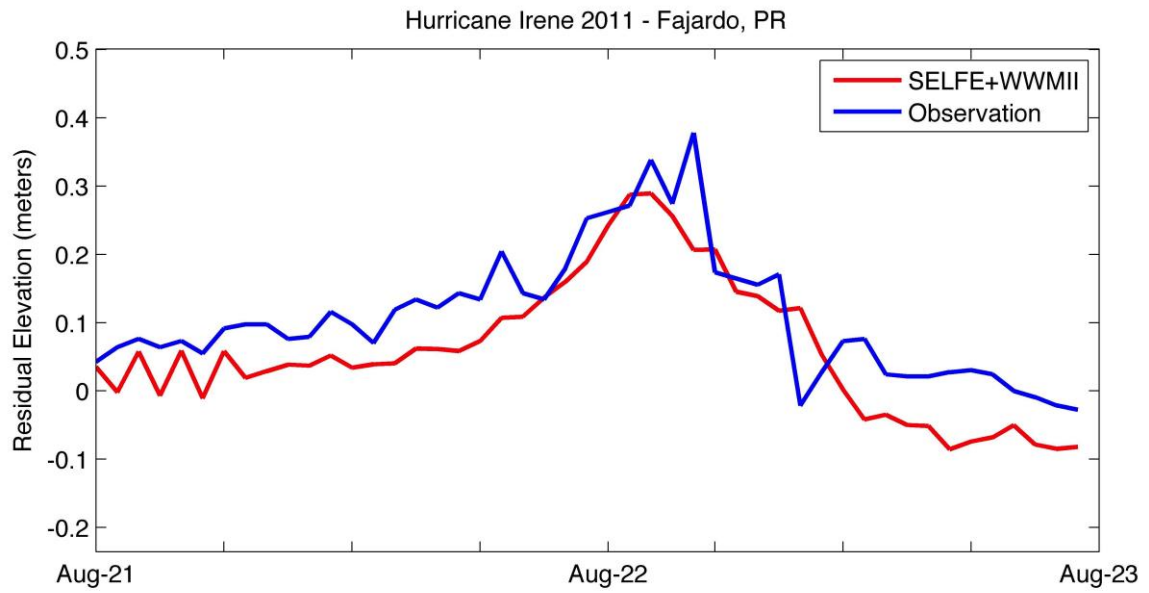


Figure 32: Residual water elevations after removing the tide contribution. Observed and modeled water elevation during Hurricane Irene at Fajardo, Puerto Rico.

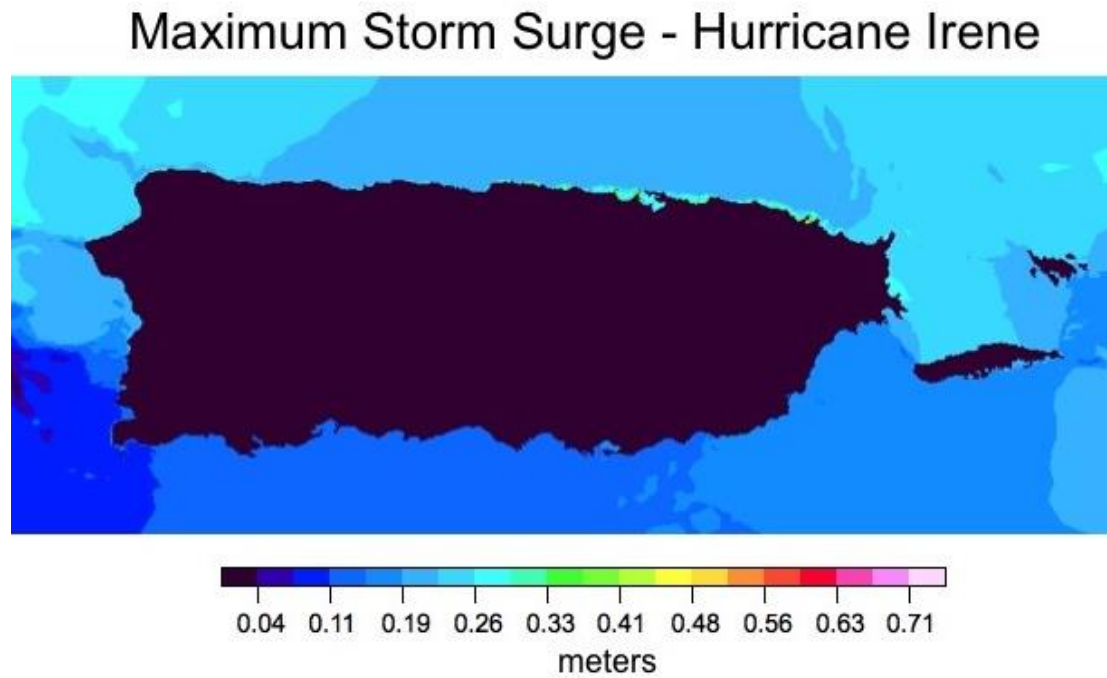


Figure 33: Simulated maximum storm surge during Hurricane Irene 2011.

5 Discussion

When comparing the two case studies as a whole, some general traits become evident. As may be expected, the model overestimates the wave height and water elevation when the wind forcing is greater than the observed data. It is clear in Figures 16, 17 and 18 from TC Irene, during the morning of August 22 when tropical storm Irene became hurricane Category #1 over Puerto Rico, the atmospheric model WRF overestimated the winds over mainland Puerto Rico due to the overall correction of the wind field explained in section 3.1.1. As the NHC's report of Irene stated, the hurricane-force winds only occurred over water north of the center and did not affect directly the island of Puerto Rico (Avila and Cangialosi, NHC Tropical Cyclone Report AL092011). This fact could explain why most of the overestimation of waves occurred on stations in the right side of the cyclone. It can be seen in the water elevation plots (Figure 25 and Figure 30) that the model simulated the storm surge in San Juan very well. The principal factor that contributed to these great results in San Juan was the high-resolution bathymetry along the San Juan area existing in the unstructured computational grid. Conversely, the results of water elevation at Magueyes Island were not as good as expected. The main limiting factor to achieve satisfactory results was the poor representation of the small islands, reefs and coastlines, in the area surrounding the Magueyes Island station. Gonzalez (2011) when simulating Hurricane Georges, encountered the same problem in and around Magueyes Island using the same 2007 FEMA unstructured grid. After refining the bathymetry for this area on the default 2007 FEMA computational unstructured grid, Gonzalez (2011) found much better agreement with the observed water level. There are exceptions to both these tendencies, but the general trend is that the model overestimated the wave height and water elevations when higher winds are used to

force the coupled model. These results agree with previous studies, which demonstrate that the wind stress is the dominant factor in the generation of storm surge and waves in shallow waters (Kohno et al., 2007; Rego and Li, 2010). Clearly, SELFE+WWM II is sensitive to the wind field (Radius of Maximum Winds (RMW)) and trajectory of the system. Further verification of the model is necessary, especially a sensitivity analysis of the wind data.

6 Conclusion & Recommendations

A state-of-the-art, semi-implicit Eulerian-Lagrangian finite element model SELFE and a spectral wave model (WWM II) were tested in the Northeast Caribbean. The research was focused mainly in validating the coupled model in a complex island environment such as the Northeast Caribbean Islands and to verify if SELFE+WWM II had problems with wave refraction in areas of low resolution inside the unstructured grid of FEMA 2007. The unstructured model system was implemented in a regional domain that covers the Eastern Caribbean and portions of the Central Caribbean and the Tropical Atlantic. Various components required to simulated storm surge and hurricane-forced waves were considered in the hindcast process. Hurricane track, tides, wind, surface pressure and waves forcing were crucial to the hindcast process in order to replicate the impacts of each hurricane.

Overall, the results from SELFE+WWM II suggest a good agreement with the observed data and did not show any problem with the wave refraction in areas of low resolution inside the domain. Although, the coupled model performed well, there are some areas for improvement, mainly in the initial conditions. In order to achieve more accurate results, the wind forcing should be improved taking an ensemble approach using various deterministic atmospheric models or a parametric model that takes into

account the topography of the islands. Improving the wind forcing will alleviate the overestimation of the significant wave height, especially on the right side of the tropical cyclone. Another possible way of mitigating the overestimation of significant wave height is adjusting the surface wind drag coefficient inside of WWM II. In terms of the simulated storm surge, the model results were fairly good. The errors can be reduced, improving the computational unstructured domain, specifically refining the bathymetry in areas of high interest. Consequently, if the user refines the unstructured grid in those areas where complex bathymetry features are present, the results of the coastal flooding induced by the storm surge will be more accurate. In general, the study showed that SELFE+WWM II has huge potential to be implemented as an operational model to forecast storm surge, wave field and coastal inundation if the user provides the best possible representation of the hurricane track and the intensity of the winds. A big effort is undergoing in continental United States to improve the storm surge and the coastal inundation modeling skill. The SELFE+WWM II model described in this thesis is participating in a Super-Regional Modeling testbed project (SURA) that was funded by the NOAA IOOS program. This large-scale project will result in an overall improvement of SELFE+WWM II and the other unstructured models participating in this national testbed.

7 References

- Ardhuin, F., Rogers, E., Babanin, A.V., Filipot, J.-F., Magne, R., Roland, A., van der Westhuysen, A., Queffelec, P., Lefevre, J.-M., Aouf, L., Collard, F. (2010): "Semiempirical dissipation source functions for ocean waves. Part I: definition, calibration, and validation". *Journal of Physical Oceanography* 40, 1917–1941.
- Baptista, A.M., Zhang, Y.-L., Chawla, A., Zulauf, M.A., Seaton, C., Myers, E.P., Kindle, J., Wilkin, M., Burla, M., and Turner, P.J. (2004): "CORIE modeling system: status of hindcast simulations as of May 2004" Internal report, Center for Coastal and Land-Margin Research, Oregon Health & Science University.
- Casulli, V., and R.V. Walters (2000): "An unstructured grid, three-dimensional model based on the shallow water equations. *International Journal for Numerical Methods in Fluids*, 32, 331- 348.
- Dietrich, J. C., S. Bunya, J. J. Westerink, B. A. Edersole, J. M. Smith, J. H. Atkinson, R. Jensen, D. T. Resio, R. A. Luettich, C. Dawson, V. J. Cardone, A. T. Cox, M. D. Powell, H. J. Westerink, and H. J. Roberts (2010): "A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and Mississippi. Part II: Synoptic Description and Analysis of Hurricanes Katrina and Rita". *Monthly Weather Review*, 138(2), 378-404.
- Dietrich, J. C., M. Zijlema, J. J. Westerink, L. H. Holthuijsen, C. Dawson, R. A. Luettich Jr, R. E. Jensen, J. M. Smith, G. S. Stelling, and G. W. Stone (2011a): "Modeling hurricane waves and storm surge using integrally-coupled, scalable computations". *Coastal Engineering*, 58(1), 45-65.
- Dietrich, J. C., J. J. Westerink, A. B. Kennedy, J. M. Smith, R. E. Jensen, M. Zijlema, L. H. Holthuijsen, C. Dawson, R. A. Luettich Jr., M. D. Powell, V. J. Cardone, A. T. Cox, G. W. Stone, H. Pourtaheri, M. E. Hope, S. Tanaka, L. G. Westerink, H. J. Westerink, and Z. Cobell (2011b): "Hurricane Gustav (2008): "Waves and Storm Surge: Hindcast, Synoptic Analysis, and Validation in Southern Louisiana". *Monthly Weather Review*, 139(8), 2488- 2522.
- Dietrich, J. C., P-E Alliera, L.H. Holthuijsen, N. Booij, M. Zijlema, J.D. Meixner, J.K. Proft, C.N. Dawson, C.J. Bender, A. Naimaster, J.M. Smith, J.J. Westerink (2012): "Limiters for Spectral Propagation Velocities in SWAN". *Ocean Modelling*, in press, DOI: 10.1016/j.ocemod.2012.11.005.
- Garratt, J.R. (1977): "Review of drag coefficients over oceans and continents." *Monthly Weather Review*, 915-929.
- Gonzalez J. (2011): "Implementation and validation of an unstructured coupled wave-circulation model for hurricane wave and storm surge inundation modeling in Puerto Rico". MS Thesis, University of Puerto Rico, Mayaguez, PR.
- Gonzalez J., A. Mercado, J. Westerink, J. Capella, J. Morell, M. Canals (2011, October): "Effect of Steep and Complex-Featured Shelf on Storm Surge and Wave

Spectra”. Presented at the 12th International Workshop on Wave Hindcasting and Forecasting & 3rd Coastal Hazard Symposium, Waikoloa, HI.

Janjic, Z., T. Black, E. Rogers, H. Chuang, and G. DiMego (2003): “The NCEP Nonhydrostatic Mesoscale Forecasting Model”. 10th Conference on Mesoscale Processes, Portland, OR, Amer. Meteor. Soc.

Kohno, N., K. Kamakura, H. Minematsu, Y. Yorioka, K. Hisashige, E. Shinizu, Y. Sato, A. Fukunaga, Y. Taniwaki, and S. Tanijo (2007): “The mechanism of the storm surges in the Seto inland sea caused by Typhoon Chaba”. 0416 Tech. Rev., 9, Reg. Spec. Meteorol. Cent. Tokyo–Typhoon Cent., Tokyo.

Liau, J.-M., A. Roland, T.-W. Hsu, S.-H. Ou, and Y.-T. Li (2011): “Wave refraction–diffraction effect in the wind wave model WWM”. Coastal Engineering, 58(5), 429–443.

National Hurricane Center, National Weather Service, NOAA (2009).
<http://www.nhc.noaa.gov/aboutgloss.shtml>

National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory (NOAA/AOML). Hurricane Research Division, Hurricane Georges 1998. Retrieved from
http://www.aoml.noaa.gov/hrd/Storm_pages/georges1998/

National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory (NOAA/AOML). Hurricane Research Division, Hurricane Irene 2011. Retrieved from http://www.aoml.noaa.gov/hrd/Storm_pages/irene2011/

National Oceanic and Atmospheric Administration, National Hurricane Center (NHC). Tropical Cyclone Report AL092011, Hurricane Irene 2011. Retrieved from http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf

NTHMP (2012) Proceedings and results of the 2011 NTHMP model benchmarking workshop. Boulder: US Depart. of Commerce/NOAA/NTHMP, NOAA Special Report 436p.

Oliveira, M. Rodrigues, A.B. Fortunato and M. Guerreiro (2011) “Impact of seasonal bathymetric changes and inlet morphology on the 3D water renewal and residence times of a small coastal stream”. J. Coastal Res., SI64, 1555–1559.

Powell, Mark D, and Samuel H Houston (1996): “Hurricane Andrew's Landfall in South Florida. Part I: Standardizing Measurements for Documentation of Surface Wind Fields”. Weather and Forecasting, 304–328.

Powell, M. D. (2006): “Drag coefficient distribution and wind speed dependence in tropical cyclones”. Final report to the NOAA Joint Hurricane Testbed (JHT) Program, 26 pp.

- Qi, J., C. Chen, R. Beardsley, W. Perrie, G. Cowles, and Z. Lai (2009): "An Unstructured-Grid Finite-Volume Surface Wave Model (FVCOM-SWAVE): Implementation, Validations and Applications". *Ocean Modelling*, 28, 153-166.
- Rego, J.L., C. LI (2010): "Nonlinear terms in storm surge predictions: effect of tide and shelf geometry with case study from Hurricane Rita". *Journal of Geophysical Research* 115, C06020.
- Roland, A. (2009): "Development of WWM II - Spectral wave modeling on unstructured meshes". PhD Thesis, Darmstadt University of Technology, Institute for Hydraulic Engineering and Water Resources Management, Darmstadt, Germany.
- Roland, A., A. Cucco, C. Ferrarin, T.-W. Hsu, J.-M. Liao, S.-H. Ou, G. Umgiesser, and U. Zanke (2009): "On the development and verification of a 2-D coupled wave-current model on unstructured meshes". *Journal of Marine Systems*, 78, Supplement(0), S244-S254.
- Roland, A., Y. Zhang, H. V. Wang, Y. Meng, Y.-C. Teng, V. Maderich, I. Brovchenko, M. Dutour, and U. Zanke (2012): "A fully coupled 3D wave-current interaction model on unstructured grids (submitted)".
- Saha, S., and Coauthors (2006): "The NCEP Climate Forecast System". *J. Climate*, 19, 3483–3517.
- Sela, J. (1980): "Spectral modeling at the National Meteorological Center". *Mon. Wea. Rev.*, 108, 1279-1292.
- Shen, J., Zhang, K., Xiao, C. and Gong, W. (2006c): Improved prediction of storm surge inundation with a high-resolution unstructured grid model. *Journal of Coastal Research*, 22, 6, 1309-1319.
- Shen, T. (2009): "Development of a Storm Surge Model Using a High-Resolution Unstructured Grid". MS Thesis, Virginia Institute of Marine Science, College of William and Mary.
- Teng, Y. (2012): "Developing an Unstructured Grid, Coupled Storm Surge, Wind Wave and Inundation Model for Super-regional Applications". PhD Thesis, Virginia Institute of Marine Science, College of William and Mary.
- Tolman, H. L. (2009): "User manual and system documentation of WAVEWATCH III version 3.14". NOAA / NWS / NCEP / MMAB Technical Note 276, 194 pp.+ Appendices
- Zhang, Y.L., Baptista, A.M. and Myers, E.P. (2004): "A cross-scale model for 3D baroclinic circulation in estuary-plume-shelf systems: I. Formulation and skill assessment". *Cont. Shelf Res.*, 24: 2187-2214.
- Zhang, Y.L., and Baptista, A.M. (2008): "Benchmarking a new finite-element tsunami model on unstructured grids". *Pure and Applied Geophysics: Topical issue on Tsunamis*, vol. 165, pp. 2229-2248; NTHMP (2012) Proceedings and results of the

2011 NTHMP model benchmarking workshop. Boulder: US Depart. of Commerce/NOAA/NTHMP, NOAA Special Report 436p.

Zhang, Y.L. and Baptista, A.M. (2008): "SELFE: A semi-implicit Eulerian-Lagrangian finite-element model for cross-scale ocean circulation", *Ocean Modelling*, 21(3-4), 71-96.

APPENDIX A: SELFIE Input File

```
!-----
! SELFIE model parameter inputs.
!-----

!+++++
! Model configuration parameters
!+++++
!-----
! Coordinate option: 1: Cartesian; 2: lon/lat (hgrid.gr3=hgrid.ll in this case,
! and orientation of triangles is outward of earth)
!-----
ics = 2 !Coordinate option

!-----
! Pre-processing option. Useful for checking grid violations.
!-----
ipre = 0 !Pre-processor flag (1: on; 0: off)

!-----
! 2D model flag (0: 3D; 1: 2D)
! For 2D model, the following modules cannot be used:
! USE_ECO, USE_SED, PREC_EVAP, USE_GOTM, USE_NAPZD
!-----
im2d = 1
!-----
! Implicitness factor for Coriolis for 2D model (not used in 3D)
!-----
theta2 = 0. !between 0 and 1

!-----
! If WWM is used, set coupling/decoupling flag. Not used if USE_WWM is distabled in
!Makefile
!   0: decoupled so 2 models will run independently;
!   1: full coupled (elevation, vel, and wind are all passed to WWM);
!   2: 1-way coupling: only R.S. and wind stress from WWM feedback to SELFIE
!-----
icou_elfe_wwm = 1
nstep_wwm = 1 !call WWM every this many time steps ()if /=1, consider using quasi-steady
mode in WWM
iwbl = 0 !1: modified Grant-Madsen formulation for wave boundary layer; used only if
icou_elfe_wwm/=0
msc2 = 24 !same as MSC in .nml ... for consistency check between SELFIE and WWM-II
mdc2 = 30 !same as MDC in .nml

!-----
! Non-hydrostatic model switch (0: hydrostatic model; 1: non-hydrostatic model)
! For non-hydrostatic model, use ihydro_region to indicate if hydrostatic
! region needs to be specified in hydro_region.gr3 (depth=1 in hydrostatic region)
!-----
nonhydro = 0 !must be 0 for 2D model or ics=2 (lat/lon)
ihydro_region = 0 !0: no hydro_region.gr3 needed

!-----
```



```

! # of passive tracers; need to update bctides.in accordingly.
!-----
ntracers = 0 !must =0 for 2D model

!-----
! Bed deformation option (0: off; 1: vertical deformation only; 2: 3D bed deformation).
! If imm=1, bdef.gr3 is needed; if imm=2, user needs to update depth info etc
! in the code (not working for ics=2 yet).
!-----
imm = 0
! ibdef = 10 !needed if imm=1; # of steps used in deformation

!-----
! Center lon/lat for f-plane approximation (not used if ics=2)
!-----
cpp_lon = -67.07 !lon
cpp_lat = 18.95 !lat

!-----
! Baroclinic/barotropic option. If ibcc=0 (baroclinic model), itransport is not used.
!-----
ibcc = 1 !Baroclinic option; must be 1 for 2D model
itransport = 0 !must be 0 for 2D model
nrampbc = 0 !ramp-up flag for baroclinic force
drampbc = 1. !not used if nrampbc=0

!-----
! Hotstart option. 0: cold start; 1: hotstart with time reset to 0; 2:
! continue from the step in hotstart.in
!-----
ihot = 0

!-----
! Hydraulic model option. If ihydraulics/=0, hydraulics.in
! is required. This option cannot be used with non-hydrostatic model.
!-----
ihydraulics = 0

!+++++
! Physical parameters
!+++++

!-----
! Horizontal viscosity option; if ihorcon=1, horizontal viscosity is given in hvis.gr3.
!-----
ihorcon = 0 !must =0 for ics=2 (lat/lon)

!-----
! Horizontal diffusivity option. if ihdif=1, horizontal viscosity is given in hdif.gr3
!-----
ihdif = 0 !!must =0 for 2D model

!-----
! Bottom drag formulation option. If idrag=1, linear drag is used (in this case, itur<0
! and bfric=0); if idrag=2 (default), quadratic drag formulation is used.

```

```

!-----
idrag = 2

!-----
! Bottom friction. bfri=0: drag coefficients specified in drag.gr3; bfri=1:
! bottom roughness (in meters) specified in rough.gr3
! If iwbl=1, bfri must =1.
!-----
bfri = 0 !nchi in code; must be 0 for 2D model
!Cmax = 0.01 !needed if bfri=1; 0.01 seems a safe choice for large dt

!-----
! Coriolis. If ncor=-1, specify "latitude" (in degrees); if ncor=0,
! specify Coriolis parameter in "coriolis"; if ncor=1, model uses
! lat/lon in hgrid.ll for beta-plane approximation, and in this case,
! the latitude specified in CPP projection ('cpp_lat') is used.
!-----
ncor = 1 !must be 1 if ics=2
!latitude = 46 !if ncor=-1
!coriolis = 1.e-4 !if ncor=0

!+++++
! Numerical parameters
!+++++
!-----
! Elevation initial condition flag. If ic_elev=1, elev.ic (in *.gr3 format) is needed
! to specify the initial elevations; otherwise elevation is initialized to 0 everywhere
! (cold start only)
!-----
ic_elev = 0

!-----
! Initial condition for T,S. This value only matters for ihot=0 (cold start).
! If icst=1, the initial T,S field is read in from temp.ic and salt.ic (horizontally varying).
! If icst=2, the initial T,S field is read in from ts.ic (vertical varying).
! If ihot=0 && icst=2 || ibcc_mean=1, ts.ic is used for removing mean density profile.
!-----
icst = 1 !must =1 for 2D model

!-----
! Mean T,S profile option. If ibcc_mean=1 (or ihot=0 and icst=2), mean profile
! is read in from ts.ic, and will be removed when calculating baroclinic force.
! No ts.ic is needed if ibcc_mean=0.
!-----
ibcc_mean = 0 !must be 0 for 2D model

!-----
! Methods for computing velocity at nodes. If indvel=-1, non-comformal
! linear shape function is used for velocity; if indvel=0, conformal
! linear shape function is used; if indvel=1, averaging method is used.
! For indvel<=0, Shapiro filter is used for side velocity.
!-----
indvel = 1
shapiro = 0.5 !default is 0.5

```

```

!-----
! Max. horizontal velocity magnitude, used mainly to prevent problem in
! bulk aerodynamic module
!-----
rmaxvel = 10.

!-----
! Following 2 parameters control backtracking
!-----
! min. vel for invoking btrack and for abnormal exit in quicksearch
!-----
velmin_btrack = 1.e-4

!-----
! Nudging factors for starting side/node - add noise to avoid underflow
! The starting location is nudged to: old*(1-btrack_nudge)+btrack_nudge*centroid
! Suggested value: btrack_nudge=9.013e-3
!-----
btrack_nudge= 9.013e-3

!-----
! Wetting and drying. If ihhat=1,  $\hat{H}$  is made non-negative to enhance
! robustness near wetting and drying; if ihhat=0, no restriction is imposed for
! this quantity.
! uninfl=0 is used for normal cases and uninfl=1 is used for more accurate wetting
! and drying if grid resolution is sufficiently fine.
!-----
ihhat = 1 !not used for 2D model
ininfl = 0
h0 = 0.01 !min. water depth for wetting/drying

!-----
! Implicitness factor ( $0.5 < \theta \leq 1$ ).
!-----
theta = 0.6

!-----
! Run time and ramp option
!-----
rday = 2 !total run time in days
nramp = 1 !ramp-up option (1: on; 0: off)
dramp = 1. !needed if nramp=1; ramp-up period in days
dt = 150. !Time step in sec

!-----
! Solver option. JCG is used presently.
!-----
slvr_output_spool = 50 !output spool for solver info
mxitn = 1500 !max. iteration allowed
tolerance = 1.e-12 !error tolerance

!-----
! Advection (ELM) option. If nadv=1, backtracking is done using Euler method;
! nadv=2, using 2nd order Runge-Kutta; if nadv=0, advection in momentum
! is turned off/on in adv.gr3 (the depths=0,1, or 2 also control methods

```

```

! in backtracking as above). dtb_max/min are the max/min steps allowed -
! actual step is calculated adaptively based on local gradient.
!-----
nadv = 1
dtb_max = 30. !in sec
dtb_min = 10.

!-----
! If inter_mom=0, linear interpolation is used for velocity at foot of char. line.
! If inter_mom=1 or -1, Kriging is used, and the choice of covariance function is
! specified in 'kr_co'. If inter_mom=1, Kriging is applied to whole domain;
! if inter_mom=-1, the regions where Kriging is used is specified in krvel.gr3.
! For velocity, additional controls are available in 'blend_internal' and 'blend_bnd',
! two parameters specifying how continuous and discontinuous velocities are blended
! for internal and boundary sides. If indvel=1, code resets blend_internal=blend_bnd=0.
!-----
inter_mom = 0 !must be 0 if ics=2
kr_co = 1 !not used if inter_mom=0
blend_internal = 0.
blend_bnd = 0.

!-----
! Transport method. If iupwind_t=0, ELM is used for T & S (based on inter_st below).
! If iupwind_t=1, upwind method is used. If iupwind_t=2, 2nd-order TVD method is used
! if the total element depth (at all 3 nodes)>=h_tvd and the flag in
! tvd.gr3 = 1 (tvd.gr3 is required in this case); otherwise upwind is used for efficiency.
! If iupwind_t>0, the interpolation method below ('inter_st') does not affect T or S.
!-----
iupwind_t = 1 !not used for 2D model
! tvd_mid = AA !AA (default) or CC (Casulli's formulation); needed only if iupwind_t=2
! flimiter = SB !flux limiter option if iupwind_t=2
! h_tvd = 5. !used only if iupwind_t=2; cut-of depth (m) to
! revert to upwind; used in conjunction with the flags in tvd.gr3

!-----
! Interpolation methods in ELM for salinity and temperature. Used when iupwind_t=0.
! If inter_st=1, split linear
! is used for T,S at foot of char. line. If inter_st=2, quadratic interpolation
! is used there. If inter_st=0, the interpolation method is specified in lqk.gr3.
!-----
inter_st = 1 !formerly lq

!-----
! Atmos. option. If nws=0, no atmos. forcing is applied. If nws=1, atmos.
! variables are read in from wind.th. If nws=2, atmos. variables are
! read in from sflux_files.
! If nws=4, ascii format is used for wind and atmos. pressure at each node (see source code).
! If nws>0, 'iwindoff' can be used to scale wind speed (with windfactor.gr3).
! Stress calculation:
! If nws=1 or 4, or nws=2 and ihconsv=0, or nws=2 and iwind_form=-1,
! the stress is calculated from Pond & Pichard formulation
! If nws=2, ihconsv=1 and iwind_form=0, the stress is calculated from heat exchange
! routine;
! If WWM is enabled and icou_elfe_wwm>0 and iwind_form=-2, stress is calculated by
WWM;

```

```

! otherwise the formulations above are used.
!-----
nws = 2 !must /=3 for 2D model
wtiminc = 150. !time step for atmos. forcing
nrampwind = 1 !ramp-up option for atmos. forcing
drampwind = 1. !needed of nrampwind/=0; ramp-up period in days
iwindoff = 0 !needed only if nws/=0; '1': needs windfactor.gr3
iwind_form = -1

!-----
! Heat and salt exchange. isconsv=1 needs ihconsv=1; ihconsv=1 needs nws=2.
! If isconsv=1, need to compile with precip/evap module turned on.
! For 2D model, both must be 0.
!-----
ihconsv = 0 !heat exchange option
isconsv = 0 !evaporation/precipitation model

!-----
! Turbulence closure.
!-----
itur = 0 !must be 0 for 2D model
dfv0 = 1.e-6
dfh0 = 1.e-6
! turb_met = KL
! turb_stab = KC

!-----
! Sponge layer for elevation and vel.
! If inu_elev=0, no relaxation is applied to elev.
! If inu_elev=1, relax. constants are specified in elev_nudge.gr3
! and applied to eta=0 (thus a depth=0 means no relaxation).
! Similarly for inu_uv (with input uv_nudge.gr3)
!-----
inu_elev = 0
inu_uv = 0

!-----
! Nudging options for T,S. If inu_st=0, no nudging is used. If inu_st=1,
! nudge T,S to initial condition according to relaxation constants specified
! in t_nudge.gr3 and s_nudge.gr3, and vertical relax. specified below.
! If inu_st=2, nudge T,S to values in temp_nu.in
! and salt_nu.in (with step 'step_nu') according to t_nudge.gr3 and s_nudge.gr3
! and vertical relax. specified below. The final relaxation = horizontal relax
! (specified in [t,s]_nudge.gr3) times vertical relax (which varies linearly
! along local depth according to (vnh1,vnf1,vnh2,vnf2)).
! No nudging can be used for 2D model.
!-----
inu_st = 0 !nudging option; must =0 for 2D model
step_nu = 43200. !in sec; only used if inu_st=2
vnh1 = 400 !vertical nudging depth
vnf1 = 1 !vertical relax
vnh2 = 401 !vertical nudging depth
vnf2 = 1. !vertical relax
!-----

```

```

! Cutt-off depth for cubic spline interpolation near bottom when computing horizontal
gradients
! using hgrad_nodes() (baroc. force, radiation stress, and gradients of qnon and qhat in non-
hydro model).
! If depth > depth_zsigma ('deep'),
! a min. (e.g. max bottom z-cor for the element) is imposed in the spline and so a more
! conservative method is used without extrapolation beyond bottom;
! otherwise constant extrapolation below bottom is used.
!-----
depth_zsigma = 100. !h_bcc1

!-----
! Dimensioning parameters for inter-subdomain btrack.
!-----
s1_mxnbt = 0.5
s2_mxnbt = 3.0

!-----
! Global output options.
! For 2D model, the only outputs available are: elev.61, dahv.62, wind.62, wist.62 and hvel.64
!-----
iwrite = 0 !not used
nspool = 24 !output step spool
ihfskip = 288 !stack spool; every ihfskip steps will be put into 1_*, 2_*, etc...

elev.61 = 1 !0: off; 1: on
pres.61 = 0
airt.61 = 0
shum.61 = 0
srاد.61 = 0
flsu.61 = 0
fllu.61 = 0
radu.61 = 0
radd.61 = 0
flux.61 = 0
evap.61 = 0
prcp.61 = 0
wind.62 = 1
wist.62 = 0
dahv.62 = 1
vert.63 = 0
temp.63 = 0
salt.63 = 0
conc.63 = 0
tdff.63 = 0
vdff.63 = 0
kine.63 = 0
mixl.63 = 0
zcor.63 = 0
qnon.63 = 0 !hydrodynamic pressure
hvel.64 = 0
hvel.65 = 0
vert.66 = 0
temp.67 = 0 !T at prism centers
salt.67 = 0 !S at prism centers

```

```

! hvel.67 = 0 !side vel.
! vert.69 = 0 !w at centroids
! temp.70 = 0 !T at prism centers
! salt.70 = 0 !S at prism centers

!-----
! Outputs from WWM (USE_WWM must be on in Makefile)
!-----
wwm_1.61 = 1 !sig. height (m)
wwm_2.61 = 1 !Mean average period (sec) - TM01
wwm_3.61 = 0 !Zero down crossing period for comparison with buoy (s) - TM02
wwm_4.61 = 0 !Mean wave number (1/m)
wwm_5.61 = 0 !Mean wave length (m)
wwm_6.61 = 0 !Mean average energy transport direction (deg)
wwm_7.61 = 1 !Mean directional spreading (deg)
wwm_8.61 = 0 !Peak frequency (Hz)
wwm_9.61 = 1 !Peak period (dominant wave) (sec) - Tp
wwm_10.61 = 0 !Peak phase vel. (m/s)
wwm_11.61 = 0 !Peak n-factor [-]
wwm_12.61 = 0 !Peak group vel. (m/s)
wwm_13.61 = 0 !Peak wave number (1/m)
wwm_14.61 = 1 !Peak wave length (m)
wwm_15.61 = 1 !Peak (dominant) wave direction (degr)
wwm_16.61 = 1 !Peak directional spreading (deg) - few use this
wwm_17.61 = 0 !Discrete peak direction (deg) -Dpeak
wwm_18.61 = 0 !Orbital vel. (m/s)
wwm_19.61 = 0 !RMS orbital vel. (m/s)
wwm_20.61 = 0 !Bottom excursion period (sec)
wwm_21.61 = 0 !bottom wave period (sec)
wwm_22.61 = 0 !Uresell number based on peak period
wwm_23.61 = 0 !Bottom stokes drift (m/s)
wwm_24.62 = 0 !Etot energy vector (m^2)
wwm_25.62 = 0 !Bottom stokes vel. vector (m/s)

!-----
! Tracer outputs (if ntracers/=0)
!-----
trcr_1.63 = 1 !Nitrate
trcr_2.63 = 1 !Ammonium

!-----
! Station output option. If iout_sta/=0, need output skip (nspool_sta) and
! a station.in. If ics=2, the coordinates in station.in must be in lon., lat,
! and z (measured from MSL; not used for 2D variables).
!-----
iout_sta = 0
nspool_sta = 10 !needed if iout_sta/=0

!-----
! Flag for harmonic analysis for elevation. Need to turn on cpp flags
! in Makefile first.
!-----
! iharind = 0

!-----

```

```

! Option for hotstart outputs
!-----
hotout = 1 !1: output *_hotstart every 'hotout_write' steps
hotout_write = 288

!-----
! Conservation check option. If consv_check=1, some fluxes are computed
! in regions specified in fluxflag.gr3.
!-----
consv_check = 0

!-----
! Tracer parameters
!-----
! Time
sim_day = 1
sim_month = 2
sim_year = 2000
sim_hour = 0
sim_minute = 0
sim_second = 0

! Model id (0-for testing; 1-Sediments Model; 2-Ecological Model;
!      3-Oil Spill Model; 4-NAPZD; 5: ICM; -1: for users;
!      need to update the part in elfe_main.F90 - search for
!      "user-defined tracer part")
flag_model = 1

! initial conditions
! 1: needs inputs htr_[1,2,...].ic ('1...' is tracer id); format of each file is similar to salt.ic;
!    i.e. horizontally varying i.c. is used for each tracer.
! 2: needs vtr_[1,2,...].ic. Format of each file (for each tracer) is similar to ts.ic
!    (i.e. level #, z-coord., tracer value). Verically varying i.c. is used for each tracer.
! 3: analytical form for EcoSim
flag_ic = 1

!-----
! Test flags for debugging. These flags should be turned off normally.
!-----
! Williamson test #5 (zonal flow over an isolated mount); if
! on, ics must =2
!-----
izonal5 = 0 !"0" - no test; otherwise on

!-----
! Rotating Gausshill test with stratified T,S (1: on; 0: off)
! Surface T,S read in from *.ic; code generates stratification
!-----
ibtrack_test = 0

nramp_elev = 0

```


APPENDIX B: WWM II Input File

!This is the main input for WWM
!Other mandatory inputs: wwmbnd.gr3 (boundary flag files; see below)
!Depending on the choices of parameters below you may need additional inputs
!
&PROC
PROCNAME = 'pr_wwm_2011_irene' ! Project Name
DIMMODE = 2 ! Mode of run (ex: 1 = 1D, 2 = 2D) always 2D when coupled to SELFE
LSTEADY = F ! steady mode; under development
LQSTEADY = F ! Quasi-Steady Mode; In this case WWM-II is doing subiterations defined as
DELTC/NQSITER unless QSCONVI is not reached
LSPHE = T ! Spherical coordinates
LNAUTIN = F ! Nautical convention for all inputs given in degrees (suggestion: T)
! If T, 0 is _from_ north, 90 is from east etc;
! If F, maths. convention - 0: to east; 90: going to north
BEGTC = '20110821.000000' ! Time for start the simulation, ex:yyyymmdd. hhmmss
DELTC = 600 ! Time step (not used with SELFE)
UNITC = 'SEC' ! Unity of time step
ENDTC = '20110823.000000' ! Time for stop the simulation, ex:yyyymmdd. hhmmss
DMIN = 0.001 ! Minimum water depth. This is not used in selfe; with selfe this is set
automatically to h0 in param.in
&END

&COUPL
LCPL = T ! Couple with current model ... main switch - keep it on
LROMS = F ! ROMS (set as F)
LTIMOR = F ! TIMOR (set as F)
LSHYFEM = F ! SHYFEM (set as F)
RADFLAG = 'LON'
LETOT = F ! Option to compute the wave induced radiation stress. If .T. the radiation stress
is based on the integrated wave spectrum
! e.g. $E_{tot} = \int_0^{\infty} \int_0^{2\pi} [N(\sigma, \theta)] d\sigma d\theta$. If .F. the radiation stress
is estimated as given in Roland et al. (2008) based
! on the directional spectra itself. It is always desirable to use .F., since otherwise the
spectral informations are truncated and therefore
! LETOT = .T., is only for testing and developers!
NLVT = 10 ! Number of vertical Layers; not used with SELFE
LWINDWWM = F ! Wind is coming from the wave model; if false then it comes from the
current model - set it as F when used in SELFE
DTCOUP = 600. ! Couple time step - not used when coupled to SELFE
&END

&GRID
! MNP = 32810, ! Number of nodes of mesh; comment out for SELFE
! MNE = 62774, ! Number of elements of mesh; comment out for SELFE
LCIRD = T ! Full circle in directional space
LSTAG = F ! Stagger directional bins with a half Dtheta; may use T only for regular grid
to avoid char. line aligning with grid line
MINDIR = 340. ! Minimum direction for simulation (unit: degrees; nautical convention; 0:
from N; 90: from E); not used if LCIRD = .T.
MAXDIR = 7.5 ! Maximum direction for simulation (unit: degrees); may be < MINDIR;
not used if LCIRD = .T.
MDC = 30 ! Number of directional bins
FRLOW = 0.03 ! Low frequency limit of the discrete wave period (Hz; 1/period)

```

FRHIGH = 1. ! High frequency limit of the discrete wave period.
MSC = 24 ! Number of frequency bins
IGRIDTYPE = 3 ! Gridtype used. 1 ~ WWM, 2 ~ WWM-PERIODIC, 3 ~ SELFE
FILEGRID = 'hgrid.gr3' ! Name of the grid file. hgrid.gr3 or hgrid.ll if IGRIDTYPE = 3
(SELFE)
LSLOP = F ! Bottom Slope limiter (default=F)
SLMAX = 0.2 ! Max Slope;
LVAR1D = F ! For 1d-mode if variable dx is used; not used with SELFE
&END

&INIT
LHOTR = F ! Use hotstart file
FILEHOT = 'hotfile.dat' ! Hot file name
IHOTPOS = 1 ! Position in the hotstart file ...
LINID = T ! Initial condition; F for default; use T if using WW3 as i.c. etc
INITSTYLE = 2 ! 1 - Parametric Jonswap, 2 - Read from Global NETCDF files, work only if
IBOUNDFORMAT=3
&END

&BOUC
LBCSE = F ! The wave boundary data is time dependent
LBINTER = T ! Do interpolation in time if LBCSE=T (not available for quasi-steady mode
within the subtime steps)
LBCWA = T ! Parametric Wave Spectra
LINHOM = F ! Non-uniform wave b.c. in space
LBCSP = F ! Specify (non-parametric) wave spectra, specified in 'FILEWAVE' below
LINDSPRDEG = .T., ! If 1-d wave spectra are read this flag defines whether the input for the
directional spreading is in degrees (true) or exponent (false)
LPARMDIR = .F., ! If LPARMDIR is true than directional spreading is read from WBDS
and must be in exponential format at this time, only valid for 1d Spectra
FILEWAVE = 'bndfiles.dat' ! Boundary file including discrete wave spectra
LBSP1D = F ! 1D (freq. space only) format for FILEWAVE if LBCSP=T and LINHOM=F
LBSP2D = F ! not functional (freq. + directional space)
BEGTC = '20110821.000000' ! Beginn time of the wave boundary file (FILEWAVE)
DELTC = 1 ! Time step in FILEWAVE
UNITC = 'HR' ! Unit
ENDTC = '20110823.000000' ! End time
FILEBOUND = 'wwmbnd.gr3' ! Boundary file defining boundary and Neumann nodes.
! Flag 0: not on bnd; 3: Neumann (0 gradient);
! 2: active bnd (Dirichlet). Bnd flags imported from SELFE:
! 1: exterior bnd; -1: interior (islands)
IBOUNDFORMAT = 1 ! 1 ~ WWM, 2 ~ FVCOM: 3 ~ WW3. FVCOM and WW3 works
only with LBCWA=T.
! For WW3 boundary input also set LINHOM=T, LBCSE=T and this works only for
spherical coordinates
LMONO_IN = F ! incident wave is defined as monochromatic wave height, which is
Hmono = sqrt(2) * Hs
! The following are needed only if LBCWA=T and LINHOM=F
WBHS = 0.181 ! Hs at the boundary for parametric spectra
WBSS = 2. ! 1 or -1: Pierson-Moskowitz, 2 or -2: JONSWAP, 3 or -3: all in one BIN,
! 4: Gauss. The sign decides whether WBTP below is
! peak (+) or mean period (-)
WBTP = 1.50 ! Tp at the boundary (sec); mean or peak depending on the sign of WBSS
WBDM = 90.0 ! Avg. Wave Direction at the boundary
WBDSMS = 1. ! Directional spreading value in degrees (1) or as exponent (2)

```

```

WBDS = 10. ! Directional spreading at the boundary (degrees/exponent)
WBGauss = 0.1 ! factor for gaussian distribution if WBSS=1
! End section for LBCWA=T and LINHOM=F
WBPken = 3.3 ! Peak enhancement factor for Jonswap Spectra if WBSS=2
NCDF_HS_NAME = 'hs' ! NETCDF var. name for the significant wave height (normally it
is just 'hs')
NCDF_DIR_NAME = 'dir' ! NETCDF var. name for the mean wave direction (normally it is
just 'dir')
NCDF_SPR_NAME = 'spr' ! NETCDF var. name for the mean directional spreading
(normally it is just 'spr')
NCDF_FP_NAME = 'fp' ! NETCDF var. name for the peak freq. (normally it is just 'fp')
NCDF_F02_NAME = 't02' ! NETCDF var. name for the zero down crossing freq. (normally
it is just 't02')
&END

```

```

&WIND ! This is now used in selfe
LWINDFROMWWM = F, ! wind is coming from WWM (true) or from SELFЕ(false).
This is under development. If F, the following parameters in this section are ignored. For
SELFЕ users, use F.
LSEWD = .F., ! Time dependend wind input
BEGTC = '20110821.000000', ! Beginn time
DELTC = 60.0, ! Time step
UNITC = 'MIN', ! Unit
ENDTC = '20110823.000000', ! End time
LINTERWD = .T., ! Interpolate linear within the wind input time step
LSTWD = .T., ! Steady wind
LCWIN = .T., ! Constant wind
LWDIR = .T., ! Define wind using wind direction rather than vel. vectors
WDIR = 140.0 ! Wind direction if LWDIR=T
WVEL = 10.0, ! Wind velocity ...
CWINDX = 30.0, ! wind x-vec if LWDIR=F
CWINDY = 0.0, ! wind y-vec
FILEWIND = 'wind.dat', ! wind input data file; input file format: write(*,*)
curtx; write(*,*) curty
IWINDFORMAT = 1 ! ! 1 - ASCII, 2 - DWD_NETCDF, 3 - NOAA CFRS,
4 - NOAA - NARR; everything in NETCDF except ascii files
&END

```

```

&CURR !not used with SELFЕ
LSECU = .F., ! Time dependend currents
BEGTC = '20110821.000000', ! Beginn time
DELTC = 600, ! Time step
UNITC = 'SEC', ! Unit
ENDTC = '20110823.000000', ! End time
LINTERCU = .F. ! Interpolate linear within the wind input time step
LSTCU = .F., ! Steady current
LCCUR = .F., ! Constant current
CCURTX = 0.0, ! current x-vec
CCURTY = 0.0, ! current y-vec
!FNFL1 = 'current.dat', ! Current file name; input file format: write(*,*) curtx;
write(*,*) curty
LERGINP = .F. ! read timor file for input ... ergzus.bin
&END

```

```

&WALV !not used with SELFЕ

```

```

LSEWL = .F. ,           ! Time dependend currents
BEGTC = '' ,           ! Beginn time
DELTC = 1 ,           ! Time step
UNITC = 'HR' ,         ! Unit
ENDTC = '' ,          ! End time
LINTERWL = .F.         ! Interpolate linear within the wind input time step
LSTWL = .T. ,          ! Steady water level
LCWLTV = .T. ,         ! Constant water level
CWATLV = 0.0 ,         ! elevation of the water level [m]
! FNFL1 = '' ,         ! water level file name; input file format: write(*,*) eta
&END

&ENGS !source terms
MESNL = 1 ! SNL4; MESNL = 0 , MESNL = 1, (Discrete Interaction approx.)
MESIN = 1 ! Wind input: Arduin et al (1), Cycle 4 (2), Makin & Stam (3); Babanin et al.
(4), Cycle 3 (5), no wind (0) (default = 1; all others are just for rearch and explicitly not
supported at all!!!)
IFRIC = 1 ! Formulation for atmospheric boundary layer, (IFRIC = 1 for MESIN = 1, IFRIC
= 4 for MESIN=3); only used if MESIN .GT. 2
MESBF = 1 ! Bottomg friction: JONSWAP(1) (Default at 1); 2 - Madsen
FRICC = 0.067 ! Cjon - Bottom friction coefficient (always positive)
MESBR = 1 ! Shallow water wave breaking; 0: no; 1: BJ78 (Default at 1)
ICRIT = 1 ! Wave breaking criterion: set as 1 - SWAN, 2 - Dingemans - default = 2
ALPBJ = 0.5 ! Dissipation proportionality coefficient (0.5 is default)
BRHD = 0.78 ! Wave breaking coefficient for Const. type wave breaking criterion; range:
0.6-0.83 (suggested 0.78)
LMAXETOT = T !Limit shallow water wave height by wave breaking limiter (default=T)
MESDS = 1 ! Formulation for the whitecapping source function; usually same as MESIN
MESTR = 1 !Formulation for the triad 3 wave interactions (MESTR = 0 (off), MESTR = 1
(Lumped Triad Approx. (LTA) like SWAN) (Default at 1)
TRICO = 0.1 ! proportionality const. (\alpha_EB); default is 0.1
TRIIRA = 5. ! ratio of max. freq. considered in triads over mean freq.; 2.5 is suggested
TRIURS = 0.1 !critical Ursell number; if Ursell # < TRIURS; triads are not computed
LPRECOMPST4 = .T. ! Precompute the indices and weightings for the Arduin et al.
formulation and save to disk, if it is .F. then the saved
! values are read from disk
&END

&NUMS
ICOMP = 0,
! This parameter controls the way how the splitting is done and whether implicit or explicit
schemes are used for spectral advection
! ICOMP = 0
! This means that all dimensions are integrated using explicit methods. Similar
! to WW3, actually the same schemes are available in WW3 4.1.
! ICOMP = 1
! This mean that advection in geographical space is done using implicit
! Methods, source terms and spectral space are still integrated as done in
! WW3.
! ICOMP = 2
! This means that the advection is done using implicit methods and that the
! source terms are integrated semi-implicit using Patankar rules and linearized
! source terms as done in SWAN. Spectral part is still a fractional step
!
AMETHOD = 1,

```

```

! AMETHOD controls the different Methods in geographical space
! AMETHOD = 0
!           No Advection in geo. Space
! AMETHOD = 1
!           Explicit N-Scheme for ICOMP = 0 and Implicit N-Scheme for ICOMP > 0
! AMETHOD = 2
!           PSI-Scheme for ICOMP = 0 and Implicit
!           Crank-Nicholson N-Scheme for ICOMP > 0
! AMETHOD = 3
!                                     LFPSI Scheme for ICOMP = 0 and Implicit two
time level N2 scheme for ICOMP > 0
!
! AMETHOD = 4
!           Like AMETHOD = 1 but using PETSc
!
SMETHOD = 1,
! This switch controls the way the source terms are integrated. 0: no source terms;
! 1: splitting using RK-3 and SI for fast and slow modes 2: semi-implicit;
! 3: R-K3 (if ICOMP=0 or 1) - slow; 4: Dynamic Splitting (experimental)
!
DMETHOD = 2,
! This switch controls the numerical method in directional space.
! DMETHOD = 0
!           No advection in directional space
! DMETHOD = 1
!           Crank-Nicholson (RTHETA = 0.5) or Euler Implicit scheme (RTHETA = 1.0)
! DMEHOD = 2
!           Ultimate Quickest as in WW3 (usually best)
! DMETHOD = 3
!           RK5-WENO
! DMETHOD = 4
!           Explicit FVM Upwind scheme
!
RTHETA = 0.5 !Weighing factor for DMETHOD = 1, not really useful since Crank
Nicholson integration can only be monotone for CFL .le. 2
LITERSPILT = F !T: double Strang split; F: simple split (more efficient). Default: F
!
LFILTERTH = .F.,
! LFILTERTH: use a CFL filter to limit the advection vel. In directional space. This is similar
to WW3.
! Mostly not used. WWMII is always stable.
MAXCFLTH = 1.0 ! Max Cfl in Theta space; used only if LFILTERTH=T
FMETHOD = 1,
! This switch controls the numerical method used in freq. space
! = 0
!           No Advection in spectral space
! = 1
!           Ultimate Quickest as in WW3 (best)
LFILTERSIG = F ! Limit the advection velocity in freq. space (usually F)
MAXCFLSIG = 1.0 ! Max Cfl in freq. space; used only if LFILTERSIG=T
LLIMIT = T !Switch on/off Action limiter, Action limiter must mostly be turned on.
!
MELIM = 1
! Formulation for the action limiter
! MELIM = 1 (default)

```

! Limiter according to the WAM group (1988)
! MELIM = 2
! Limiter according to Hersbach Janssen (1999)
! For MESIN = 1 and MESDS = 1, which represents Cycle 3 formulation or Ardhuin, or other formulations except Cycle4, use MELIM = 1 and LIMFAK = 0.1
! For MESIN = 2 and MESDS = 2, which represents Cycle 4 formulation, use MELIM = 2 and LIMFAK = 0.6
!
LIMFAK = 0.1 ! Proportionality coefficient for the action limiter MAX_DAC_DT = Limfak
* Limiter; see notes above for value
LDIFR = F ! Use phase decoupled diffraction approximation according to Holthuijsen et al. (2003) (usually T; if crash, use F)
IDIFFR = 1 ! Extended WAE account for higher order effects WAE becomes nonlinear; 1: Holthuijsen et al. ; 2: Liao et al. ; 3: Toledo et al. (in preparation)
LCONV = F ! Estimate convergence criterion and write disk (quasi-steady - qstea.out)
LCFL = F ! Write out CFL numbers; use F to save time
NQSITER = 1 !# of quasi-steady (Q-S) sub-divisions within each WWM time step (trial and errors)
QSCONV1 = 0.98 ! Number of grid points [%/100] that have to fulfill abs. wave height criteria EPSH1
QSCONV2 = 0.98 ! Number of grid points [%/100] that have to fulfill rel. wave height criteria EPSH2
QSCONV3 = 0.98 ! Number of grid points [%/100] that have to fulfill sum. rel. wave action criteria EPSH3
QSCONV4 = 0.98 ! Number of grid points [%/100] that have to fulfill avg. rel. wave period criteria EPSH4
QSCONV5 = 0.98 ! Number of grid points [%/100] that have to fulfill rel. avg. wave steepness criteria EPSH5
LEXPIMP = F ! Use implicit schemes for freq. lower than given below by FREQEXP; used only if ICOMP=0
FREQEXP = 0.1, !Minimum frequency for explicit schemes; only used if LEXPIMP=T and ICOMP=0
EPSH1 = 0.01, !Convergence criteria for rel. wave height ! EPSH1 < CONVK1 = REAL(ABS(HSOLD(IP)-HS2)/HS2)
EPSH2 = 0.01, !Convergence criteria for abs. wave height ! EPSH2 < CONVK2 = REAL(ABS(HS2-HSOLD(IP)))
EPSH3 = 0.01, !Convergence criteria for the rel. sum of wave action ! EPSH3 < CONVK3 = REAL(ABS(SUMACOLD(IP)-SUMAC)/SUMAC)
EPSH4 = 0.01 !Convergence criteria for the rel. avg. wave steepness criteria ! EPSH4 < CONVK4 = REAL(ABS(KHS2-KHSOLD(IP))/KHSOLD(IP))
EPSH5 = 0.01 !Convergence criteria for the rel. avg. waveperiod ! EPSH5 < REAL(ABS(TM02-TM02OLD(IP))/TM02OLD(IP))
LVECTOR = .T. !Use optimized propagation routines for large high performance computers e.g. at least more than 128 CPU. Try LVECTOR=F first.
IVECTOR = 2 !Used if LVECTOR=T; Different flavours of communications
!LVECTOR = 1; same propagation style as if LVECTOR = F, this is for testing and development
!LVECTOR = 2; all spectral bins are propagated with the same time step and communications is done only once per sub-iteration
!LVECTOR = 3; all directions with the same freq. are propagated using the same time step the communications is done for each freq.
!LVECTOR = 4; 2 but for mixed open-mpi, code has to be compiled with -openmp
!LVECTOR = 5; 3 but for mixed open-mpi, code has to be compiled with -openmp
!LVECTOR = 6; same as 2 but highly optimized with respect to memory usage, of course it is much less efficient than 2

!remarks: if you are using this routines be aware that the memory amount that is used is approx. for LVECTOR 1-5 around
! 24 * MSC * MDC * MNP, so if you are trying this on 1 CPU you get a segmentation fault if your system has not enough memory or
! if your system is not properly configured it may results into the fact that your computer starts blocking since it try's to swap to disk
! The total amount of memoery used per CPU = 24 * MSC * MDC * MNP / No.CPU
!LADVTEST = for testing the advection schemes, testcase will be added soon
LCHKCONV = F !needs to set to .true. for quasi-steady mode. in order to compute the QSCONV_i criteria and check them
&END

&OUTP
BEGTC = '20110821.000000' ! Start simulation time, yyyyymmdd. hhmmss; must fit the simulation time otherwise no output
DELTC = 600 ! Time step for output; if smaller than simulation time step, the latter is used (output every step for better 1D 2D spectra analysis)
UNITC = 'SEC' ! Unit
ENDTC = '20110823.000000' ! Stop time simulation, yyyyymmdd. hhmmss
OUTSTYLE = 'NO' !output option - use 'NO' to maximize efficiency!
FILEOUT = 'misc.dat'
LOUTITER = F
LOUTS = F ! station output flag
IOUTS = 8 ! Number of output stations
NOUTS = 'P-1','P-2','P-3','P-4','P-5','P-6','P-7','P-8' ! Name of output locations
XOUTS = 7280., 7257., 7324., 7319., 7302.,7270.,7958.,8663. ! X-Coordinate of output locations
YOUTS = 19574., 18549., 17129., 15549.,14096.,12615.,8669.,5598. ! Y-Coordinate of output locations
CUTOFF = 8*0.44, !cutoff freq (Hz) for each station - consistent with buoys
LSP1D = T ! 1D spectral station output
LSP2D = F ! 2D spectral station output
LNAUTOUT = T ! Nautical conversion for output coordinates (default=T)
LWXFN = T
LSIGMAX = T ! Adjust the cut-freq. for the output (e.g. consistent with buoy cut-off freq.)
LMONO_OUT = F !Output is in mono format (Default=F)
&END

&HOTFILE
BEGTC = '20110821.000000'
DELTC = 3
UNITC = 'SEC'
ENDTC = '20110823.100000'
LCYCLEHOT = T
LHOTF = F ! Write hotfile
FILEHOT = 'hotfile.dat'
&END

APPENDIX C: MATLAB Script to match the real intensity of the cyclone

```
close all
clear all
clc

% pth = 'Georges_1998/';
% yr_mth = '199809';
pth = 'Irene_2011/';
yr_mth = '201108';
ii=0;

% Load the HURDAT2 file that contains the official track, wind speed and pressure
% --- Use ti=0.1667 for 6-hr track or ti=0.3334 for 3-hr track
ti=0.3334;
% data=load('georges_track_Sep20-23.txt');
data=load('irene_track_Aug21-23.txt');

curr_pres = data(:,4)*100;
mwind = (data(:,3))*0.514; % convert to meters/second
mpres = interp1(1:length(curr_pres),curr_pres,1:ti:length(curr_pres));
mwind = interp1(1:length(mwind),mwind,1:ti:length(mwind));

cd(pth)

%% Read the output of WRF model
for day=21:23;

ncid = netcdf.open(['sflux_air_',yr_mth,'_',num2str(day),'.nc'],'NC_NOWRITE');

[varname, xtype, dimids, atts] = netcdf.inqVar(ncid,0);
varid = netcdf.inqVarID(ncid,varname);

time = netcdf.getVar(ncid, 0);
lat = netcdf.getVar(ncid, 1);
lon = netcdf.getVar(ncid, 2);
uwind = netcdf.getVar(ncid, 3);
vwind = netcdf.getVar(ncid, 4);
prmsl = netcdf.getVar(ncid, 5);
stmp = netcdf.getVar(ncid, 6);
spfh = netcdf.getVar(ncid, 7);

for i=1:24
    ii=ii+1;
    [wspd,wdir] = spd_dir(uwind(:,i),vwind(:,i));

% Adjust the WRF values using the HURDAT2 data
wspd1=wspd;
min0=min(min(wspd));
new_wspd = stretch(wspd,min0,mwind(ii));

msl = prmsl(:,i);
prmsl0 = stretch(msl,mpres(ii),max(max(msl)));
```



```

% Calculate the difference between the grids
diff = new_wspd-wspd1;
mn = mean(mean(diff))+(3*std(std(diff)));
is0 = find(diff<mn);
diff(is0) = round(mn);
new_diff = stretch(diff,0,max(max(diff)));

%Convert the speed & dir to u and v components
[uwind(:,i),vwind(:,i)] = uv(n_wspd,wdir);

%Calculate the difference between the grids
diff1 = prmsl0-msl;
new_diff1 = stretch(diff1,-1*max(max(diff1)),max(max(diff1)));
is0 = find(new_diff1<0);
new_diff1(is0) = 0;
prmsl(:,i) = new_diff1+prmsl0;

subplot(121)
pcolor(double(wspd1))
shading interp
colorbar
title(['OLD - Max:',num2str(round(max(max(wspd1))))],
Min:',num2str(round(min(min(wspd1))))])
caxis([0 50])

subplot(122)
pcolor(double(n_wspd))
shading interp
colorbar
title(['NEW - Max:',num2str(round(max(max(n_wspd))))],
Min:',num2str(round(min(min(n_wspd))))])
caxis([0 50])
pause(0.3)

[day,i, mwind(ii)]
end

disp(strcat('Outputting Day: ',num2str(day)));

ncid2 = netcdf.create(strcat('sflux_air_1.0',num2str(day),'.nc'),'CLOBBBER');

dims(1)=netcdf.defDim(ncid2,'nx_grid',length(lon(:,1)));
dims(2)=netcdf.defDim(ncid2,'ny_grid',length(lat(1,:)));
dims(3)=netcdf.defDim(ncid2,'time',length(time));

% Define new variable in the file.
timeid = netcdf.defVar(ncid2,'time','float',dims(3));
lonid = netcdf.defVar(ncid2,'lon','float',dims(1:2));
latid = netcdf.defVar(ncid2,'lat','float',dims(1:2));
uid = netcdf.defVar(ncid2,'uwind','float',dims(1:3));
vid = netcdf.defVar(ncid2,'vwind','float',dims(1:3));
pid = netcdf.defVar(ncid2,'prmsl','float',dims(1:3)); %pressure
tid = netcdf.defVar(ncid2,'stmp','float',dims(1:3)); %air temp.

```

```

hid = netcdf.defVar(ncid2,'spfh','float',dims(1:3)); %humidity

% Leave define mode and enter data mode to write data.
netcdf.endDef(ncid2)

% Write out new nc file
netcdf.putVar(ncid2,timeid,time);
% Re-enter define mode.
netcdf.reDef(ncid2);

% Create an attribute associated with the variable.
netcdf.putAtt(ncid2,timeid,'units',strcat('days since 2011-08-',num2str(day)));
netcdf.putAtt(ncid2,timeid,'base_date',int32([2011 08 day 0])); %must use int32
netcdf.endDef(ncid2)

netcdf.putVar(ncid2,lonid,single(lon));
netcdf.putVar(ncid2,latid,single(lat));
netcdf.putVar(ncid2,uid,single(uwind));
netcdf.putVar(ncid2,vid,single(vwind));
netcdf.putVar(ncid2,pid,single(prmsl));
netcdf.putVar(ncid2,tid,single(stmp));
netcdf.putVar(ncid2,hid,single(spfh));
netcdf.close(ncid2);

end

```