

SURGE AND COASTAL INUNDATION STUDY OF SEPTEMBER 2014
STORM IN GİRESUN, BLACK SEA

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DENİZ CAN AYDIN

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STORM IN GİRESUN, BLACK SEA**

submitted by **DENİZ CAN AYDIN** in partial fulfillment of the requirements for
the degree of **Master of Science in Civil Engineering Department, Middle East
Technical University** by,

Prof. Dr. Gülbin Dural Ünver
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. İsmail Özgür Yaman
Head of Department, **Civil Engineering**

Prof. Dr. Ahmet Cevdet Yalçın
Supervisor, **Civil Engineering Department, METU**

Assist. Prof. Dr. Gülizar Özyurt Tarakcıoğlu
Co-Supervisor, **Civil Engineering Department, METU**

Examining Committee Members:

Assist. Prof. Dr. Elçin Kentel
Civil Engineering Dept., METU

Prof. Dr. Ahmet Cevdet Yalçın
Civil Engineering Dept., METU

Assist. Prof. Dr. Gülizar Özyurt Tarakcıoğlu
Civil Engineering Dept., METU

Assist. Prof. Dr. Cüneyt Baykal
Civil Engineering Dept., METU

Assist. Prof. Dr. Melih Çalamak
Civil Engineering Dept., TED University

Date: 05.09.2016



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Name, Last name : Deniz Can Aydın

Signature :

ABSTRACT

SURGE AND COASTAL INUNDATION STUDY OF SEPTEMBER 2014 STORM IN GİRESUN, BLACK SEA

Aydın, Deniz Can

M.S., Department of Civil Engineering

Supervisor: Prof. Dr. Ahmet Cevdet Yalçın

Co-supervisor: Assist. Prof. Dr. Gülizar Özyurt Tarakcıoğlu

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In Turkey, due to the fact that the Black Sea coast is vulnerable to storms and coastal hazards, further comprehensive studies for storm surge and consequent coastal inundation are necessary. The aim of this study is to investigate wave formation under storm conditions and analyze coastal flooding in Giresun during the storm event occurred between 23-26 September 2014. For this purpose numerical studies are carried out in two phases. In phase 1, coupled ADCIRC+SWAN model is used for examining wave generation and in phase 2, wave parameters obtained from these runs are used to investigate coastal flooding.

In phase 1, sensitivity of the coupled model is investigated by altering the shared information among circulation and wave models. It is observed that preventing water elevation and current information passing from ADCIRC to SWAN leads to decreased wave heights and among them, current information is found to be more effective. Moreover disregarding wave effects result in negligible difference in water elevations which is attributed to relatively low wind speeds. At Giresun cape, significant wave heights obtained from ADCIRC+SWAN simulations range between 4.5m and 7.5m with peak periods around 11.25s.

In phase 2, shallow water numerical model NAMI-DANCE is used. Coastal inundation and flow depths are computed for three selected wave heights. Maximum inundated area is computed to be close to 0.095km². Major

inundation is computed at Giresun cape, its west and east, and also at the breakwater and harbor. The results are compared with observations and fairly well agreement is obtained.

Keywords: storm surge, waves, inundation, Black Sea, coastal flooding



ÖZ

GİRESUN, KARADENİZ İÇİN EYLÜL 2014 FIRTINASI SIRASINDAKİ FIRTINA KABARMASI VE KIYIDAN SU BASKINI ÇALIŞMASI

Aydın, Deniz Can
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Ahmet Cevdet Yalçın
Ortak Tez Yöneticisi: Yard. Doç. Dr. Gülizar Özyurt Tarakcıoğlu
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Türkiye'de Karadeniz kıyısının fırtınalara ve kıyı tehlikelerine karşı savunmasız olmasından ötürü fırtına kabarması ve kıyıdan gelen su baskını için kapsamlı çalışmalara ihtiyaç bulunmaktadır. Bu çalışmanın amacı 23-25 Eylül 2014 tarihleri arasında meydana gelen fırtına sırasında fırtına koşulları altındaki dalga oluşumunu ve Giresun'da meydana gelen su baskınını incelemektir. Bu amaçla sayısal model çalışmaları 2 evrede yürütülmüştür. 1. evrede dalga oluşumunu araştırmak için bileşik ADCIRC-SWAN modeli kullanılmıştır ve 2. evrede bu çalışmalardan elde edilen dalga parametreleri kullanılarak kıyısal su baskını incelenmiştir.

1. evrede sirkülasyon ve dalga modelleri arasındaki veri paylaşımı değiştirilerek bileşik modelin hassasiyeti araştırılmıştır. Su seviyesi ve akıntı bilgilerinin ADCIRC'den SWAN'a geçişini önlemenin dalga yüksekliklerini düşürdüğü ve bu iki bilgi arasında akıntı bilgisinin daha etkili olduğu görülmüştür. Ayrıca dalga etkisini dikkate almamanın su seviyesinde yarattığı fark gözardı edilebilir seviyede olmuştur. Bu durum düşük rüzgar hızlarına bağlanmıştır. Giresun burnunda Giresun burnu önünde ADCIRC-SWAN simülasyonlarından elde edilen temsili dalga yükseklikleri 4.5m ile 7.5m arasında ve pik periyot değerleri de yaklaşık 11.25s bulunmuştur.

2. evrede sıđ su sayısal modeli NAMI-DANCE kullanılmıřtır. Su altında kalan alanlar ve akıntı derinlikleri seilen üç dalga yükseklikleri için hesaplanmıřtır. Su altında kalan maksimum alan 0.095 km²'ye yakın bulunmuřtur. Su altında kalma daha ok Giresun burnunda, burnun dođu ve batı taraflarında ve de dalgakıran ile limanda gözlemlenmiřtir. Sonular gözlemlerle karřılařtırılmıř ve iyi bir uyum elde edilmiřtir.

Anahtar kelimeler: fırtına kabarması, dalga, su baskını, Karadeniz, kıyı baskını





Dedicated to my beloved family...

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TABLE OF CONTENTS

ABSTRACT	v
ÖZ.....	vii
ACKNOWLEDGEMENTS	x
TABLE OF CONTENTS	xi
LIST OF FIGURES.....	xiii
LIST OF TABLES	xvi
LIST OF SYMBOLS	xvii
1. INTRODUCTION.....	1
2. LITERATURE SURVEY	5
2.1 Storm Surge Description.....	5
2.2 Circulation Models	7
2.3 Coupled Studies	8
2.4 Black Sea Studies	12
3. NUMERICAL MODEL DESCRIPTIONS.....	15
3.1 ADCIRC	15
3.1.1 Governing Equations	15
3.1.2 Surface Stress	17
3.1.3 Bottom Stress.....	20
3.2 SWAN.....	21
3.2.1 Governing Equations	22
3.2.2 Generation by Wind.....	23
3.2.3 Nonlinear Wave-Wave Interactions	25
3.2.4 Whitecapping.....	29
3.2.5 Bottom Friction.....	29
3.2.6 Breaking.....	30
3.3 ADCIRC-SWAN Coupling	31
3.4 NAMI-DANCE.....	33
3.4.1 Governing Equations	34

4.	DATA ACQUISITION AND PROCESSING	37
4.1	Study Area and Selected Event.....	37
4.2	Input Data.....	39
4.3	Mesh Generation.....	44
4.3.1	Mesh for ADCIRC + SWAN Simulations.....	44
4.3.2	Mesh for NAMI-DANCE Simulations	46
5.	RESULTS AND DISCUSSIONS	47
5.1	Storm Simulation Results	47
5.1.1	Case 1 Results	48
5.1.2	Case 2 Results	53
5.1.3	Case 3 Results	55
5.1.4	Case 4 Results	56
5.1.5	Case 5 Results	57
5.1.6	Case 6 Results	59
5.2	Discussion of the Storm Study Results	60
5.3	Inundation Study Results	63
5.3.1	Case A Results	65
5.3.2	Case B Results	67
5.3.3	Case C Results	69
5.4	Discussion of the Inundation Study Results	71
6.	CONCLUSION AND FUTURE RECOMMENDATIONS	73
	REFERENCES	75

LIST OF FIGURES

Figure 1.1: World population along coastlines (GRID-Arendal, 2006).....	2
Figure 1.2: Estimated population rise (GRID-Arendal, 2016).....	3
Figure 2.1: Storm tide (EMU Park Online, n.d.).....	7
Figure 3.1: Wind energy transfer (Kamphuis, 2000)	18
Figure 3.2: Rear sector (151-240 degrees relative to the storm motion vector) 2) Right sector (21-150 degrees) , and 3) Left front sector (241- 020 degrees) (Dietrich, n.d.1)	19
Figure 3.3: Wind drag coefficients (Dietrich, n.d.2).....	20
Figure 3.4: Triad(a) and quadruplet(b) wave interactions (Holthuijsen,2007) .	25
Figure 3.5: Frequency shifting due to triad interactions (Holthuijsen,2007)	26
Figure 3.6: Frequency shifting due to quadruplet interactions (Holthuijsen,2007).....	28
Figure 3.7: Breaking parameter related to bottom slope n and dimensionless depth kd	31
Figure 3.8: Shared information among ADCIRC and SWAN models	32
Figure 3.9: Inundation parameters (WACOP, n.d.)	34
Figure 4.1: Study area, red box in the upper picture covers the ADCIRC+ SWAN domain boundaries and red bow in the lower picture covers the NAMI- DANCE domain boundaries.....	38
Figure 4.2: Photographs of flooding in Giresun.....	39
Figure 4.3: Bathymetry contours in meters.....	40
Figure 4.4: Bathymetry contours in meters in the area of interest	41
Figure 4.5: Wind velocity vectors and atmospheric pressure contours in	

meters of water at a) September 22,2014 12:00 e)September 23,2014 00:00	
f)September 23,2014 12:00	42
Figure 4.6: Grid spacing contours in meters	45
Figure 4.7: Grid spacing contours in meters around the shoreline	45
Figure 4.8: elevation contours in meters	46
Figure 5.1: Maximum significant wave heights with contours in meters and wind velocity vectors for a) September 24,2014 00:15am b) September 24, 2014 02:45am c) September 24,2014 06:30am	50
Figure 5.2: Maximum current velocities for Case 1 with contours in meters per second	51
Figure 5.3: Maximum water elevations for Case 1 with contours in meters.....	51
Figure 5.4: Maximum significant wave height distribution for Case 1 with contours in meters.....	52
Figure 5.5: Maximum peak period distribution for Case 1 with contours in seconds	53
Figure 5.6: Maximum significant wave height distribution for Case 2 with contours in meters.....	54
Figure 5.7: Maximum peak period distribution for Case 2 with contours in seconds	54
Figure 5.8: Maximum significant wave height distribution for Case 3 with contours in meters.....	55
Figure 5.9: Maximum peak period distribution for Case 3 with contours in seconds	56
Figure 5.10: Maximum water elevations for Case 4 with contours in meters...	57
Figure 5.11: Maximum significant wave height distribution for Case 5 with contours in meters.....	58
Figure 5.12: Maximum peak period distribution for Case 5 with contours in seconds	58
Figure 5.13: Maximum significant wave height distribution for Case 6 with contours in meters	59

Figure 5.14: Maximum peak period distribution for Case 6 with contours in seconds	59
Figure 5.15: % Differences in maximum significant wave heights between Case 1 and Case 2, dark purple areas indicate where Case 1 results are higher.....	60
Figure 5.16: % Differences in maximum significant wave heights between Case 1 and Case 5, blue areas indicate where Case 1 results are higher.....	61
Figure 5.17: % Differences in maximum significant wave heights between Case 1 and Case 6, darker blue areas indicate where Case 1 results are higher.....	62
Figure 5.18: % Differences in maximum significant wave heights between Case 3 and Case 1, darker green areas indicate where Case 3 results are higher.....	63
Figure 5.19: Snapshots from video recording taken during the storm, two consecutive waves are marked with red ellipse	64
Figure 5.20: The input of irregular wave fluctuations for CASE A as $H_s=6\text{m}$ $T_s=11\text{s}$	66
Figure 5.21: The distribution of maximum water elevations near the coast computed during the simulations (upper plot) and computed inundated areas (lower plot).....	67
Figure 5.22: The input of irregular wave fluctuations for CASE B as $H_s=5.5\text{m}$ $T_s=12\text{s}$	68
Figure 5.23: The distribution of maximum water elevations near the coast computed during the simulations (upper plot) and computed inundated areas (lower plot).....	69
Figure 5.24: The input of irregular wave fluctuations for CASE B as $H_s=4.5\text{m}$ $T_s=10\text{s}$	70
Figure 5.25: The distribution of maximum water elevations near the coast computed during the simulations (upper plot) and computed inundated areas (lower plot).....	71

LIST OF TABLES

Table 5.1: Case description for storm simulations	48
Table 5.2: Input wave parameters.....	65
Table 5.3: Inundated areas for each case	72



LIST OF SYMBOLS

ζ	free surface elevation (relative to the geoid)
U, V	depth integrated water velocities in the x, y directions respectively
p_s	atmospheric pressure on the surface
g	gravitational acceleration
ρ_0	reference density of water
τ_{bx}, τ_{by}	bottom stresses in the x and y directions
B_x, B_y	depth integrated baroclinic pressure gradient terms in the x and y directions
Z	total water depth $Z=h+\zeta$
h	bathymetric water depth
f	Coriolis parameter
D_x, D_y	depth integrated diffusion/dispersion terms
η	Newtonian tidal potential
Υ	self attraction and load tide
τ_{sx}, τ_{sy}	surface stresses in the x and y directions
C_d	wind drag coefficient
U_{10}	wind velocity at 10m elevation
E	wave energy
N	wave action density
Q_x, Q_y	discharge fluxes in x and y directions ($Q_x=UZ, Q_y=VZ$)



CHAPTER 1

INTRODUCTION

Coastal areas have always been popular for habitation as they provide food supply and allow higher economic activity through ports. This popularity led to high concentrations of world population on 10% of the earth's land surface resulting in around 3.2 billion living on 200 km wide coastal strip (Hinrichsen, 1999). In Figure 1.1 population living among the coasts and in Figure 1.2 estimated rise in coastal population are shown. In the USA more than 120 million people corresponding to 39% of the population are residents of counties adjacent to a shoreline which results in a population density in coastal areas six times higher than the inland population density (NOAA, 2013). In Europe 40.8% of the population live on coastal areas (Collet & Engelbert, 2013). This continuing popularity of coastal areas puts more and more people and property under the risks of coastal hazards. Therefore understanding of coastal related hazards and planning according to have utmost importance. Storms are among the most important causes of coastal hazards leading to destruction of coastal defense structures, infrastructures, inland properties and endangering human life.

One of the most vulnerable places on earth is the Bay of Bengal in Indian Ocean. Out of the 30 deadliest tropical cyclones in the world, 22 of them were experienced here due to high population density. The most deadliest of these disasters is the Great Bhola Cyclone that caused around 400,000 live loss with

up to 10 m high storm tides ("Deadliest World Tropical Cyclones | Weather Underground", 2016).

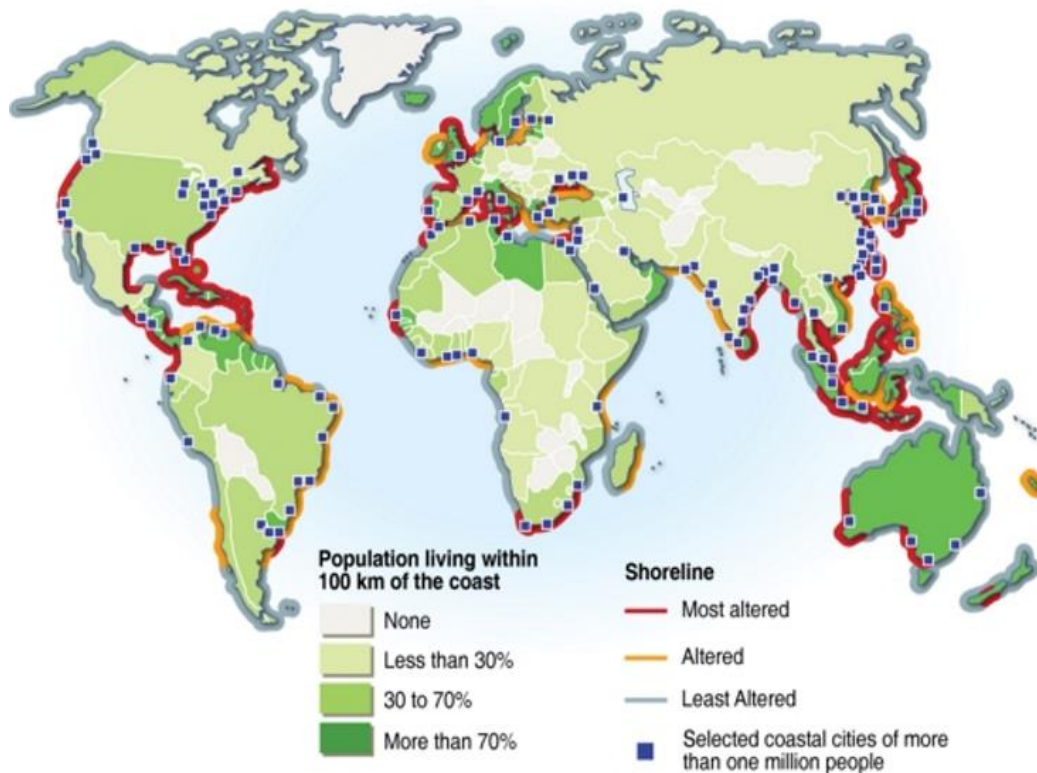


Figure 1.1: World population along coastlines (GRID-Arendal, 2006)

The most deadliest storm related disaster in the US history is due to Galveston Hurricane that occurred in 1900 over tropical Atlantic and moved to Gulf of Mexico and Texas. This category 4 hurricane resulted in inundation of the entire Galveston Island and some parts of the Texas coast with storm tides up to 4.5 m high. Around 8,000 people lost their lives and estimated property damage was 30million\$ which makes it the second costliest hurricane ("Hurricanes in History", 2016).

Our closeness to the oceans

- population of coastal cities continues to expand

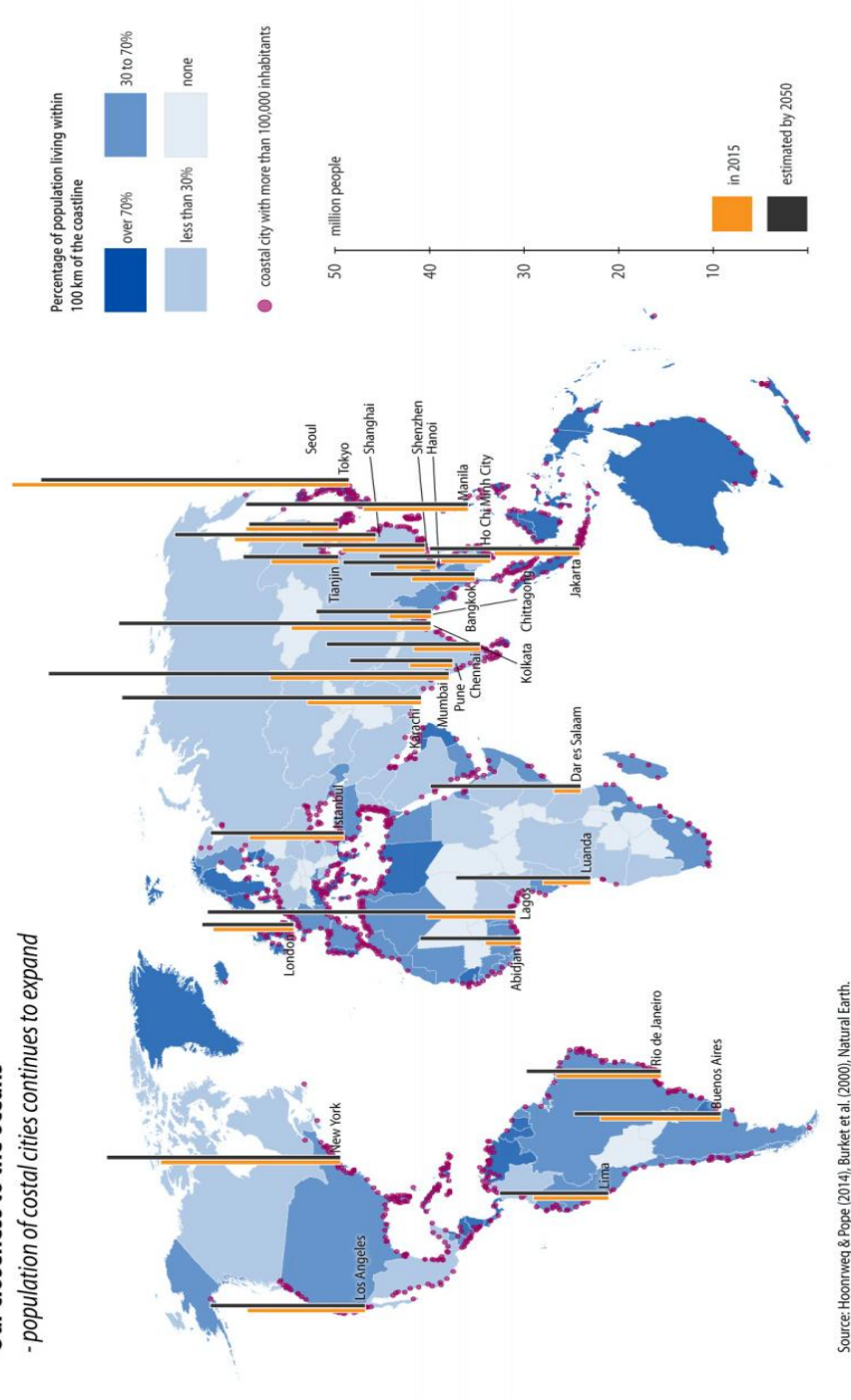


Figure 1.2: Estimated population rise (GRID-Arendal, 2016)

The category 5 Hurricane Katrina that strike the New Orleans in 2005 caused one of the most devastating disasters in the USA history. The storm surge height reached 8.5 m along the Mississippi coast and 80% of the New Orleans was flooded. In total, around 1200 deaths were reported and the estimated damage was 75billion\$ ("Hurricanes in History", 2016).

In 2008 the Cyclone Nargis hit Myanmar and resulted in one of the most deadliest disasters in Asia. Storm surges reached 40km inland causing more than 138,000 deaths in the low-lying Irrawaddy delta and more than 10billion\$ damage.

Despite the lack of hurricanes like mentioned above in Turkey due to its geographical location, storms that generate surges and waves high enough to result in coastal flooding are experienced frequently. These storm related hazards cause damage to the coastal protection structures, harbors, ships and endanger human life. One of these storms occurred between 23-25 September 2014 in Black Sea and the Giresun province was one of the affected cities in Turkey. In this study, storm surge and coastal inundation due to the 2014 September storm event in Giresun province is investigated by numerical modeling.

In Chapter 2, a brief information on storm surge is given and available circulation models are introduced. Moreover wave-surge coupled studies that have been conducted by different researchers are described. Chapter 3 provides detailed information on the numerical models selected for the study which are ADCIRC for circulation, SWAN for wave affects and finally NAMI-DANCE for inundation study. In chapter 4 numerical model study is explained and continued with results and discussion of the studies in Chapter 5. Finally in Chapter 6 conclusion and future recommendations are presented.

CHAPTER 2

LITERATURE SURVEY

2.1 Storm Surge Description

Storm surge is the rise in water elevation induced by wind and pressure fields over the water body. It consists of wind setup, wave setup and inverse barometer effect. A decrease in the atmospheric pressure above the water surface reduces the vertical force acting on the water column therefore sea surface adjust this barometric change with a increase in the surface elevation which is called inverse barometer effect. A drop of 1mb in the atmospheric pressure leads to 1cm increase in the water level. This adjustment of the water level can occur if water flow towards the low pressure area is not restricted thus it is observed on open oceans where water depth is not a concern (Schwartz, 2005).

As pressure differences in the atmosphere lead to generation of winds, this barometric effect is rarely exactly observed in nature. The other major driving force for storm surge generation is the shear stress generated on the water surface by the interaction of the water and the wind blowing over. This interaction leads to energy transfer from wind to water and cause an increase on the water surface on downwind -a meteorological term defining the direction wind blows toward- area which is known as wind setup (Schwartz, 2005). Effect of the wind depends on the wind speed, water depth and direction of the wind. The stronger the wind is, the higher resulting shear stress is exerted on the water surface thus leading to higher increase in surface elevation. The effect of the

wind increases also inversely proportional to water depth. Furthermore the direction of the wind is also an important factor. A strong wind blowing towards the shoreline tend to create higher surge than winds with a direction parallel to the shore.

In addition to barometric effect and wind setup, wave setup is also another process constituting storm surge that has a high impact on the mean surface elevation in nearshore. As waves in deep water approach to shore, they start to steepen until they break and dissipate energy due to the bottom effect in shallow water. This energy dissipation leads to a decrease in radiation stress which is defined as "the excess flow of momentum due to the presence of the waves." (Longuett-Higgins and Stewart, 1964). The change in radiation stress creates a positive force on the water column towards the shore thus results in rising of the mean water surface elevation. The wind setup with wave setup usually contributes to 80-90% of the storm surge height (Walton and Dean, 2009).

The rotation of the Earth also causes currents to accelerate to the right in Northern Hemisphere and to the left in Southern Hemisphere which is a phenomenon known as Coriolis effect. This effect leads to amplification or lessening of surge heights depending on whether the coast is at the right side or left side of the currents.

Moreover the timing of the storm occurrence also plays a vital role in the water elevation rise. If the storm coincides with high tide the results can be much more devastating (Fig. 2.1).

Beside the meteorological processes there are also other factors highly affecting the surge behavior during the storms like bathymetry and coastal features. Low sloping continental shelves results in higher surge levels than sea bottom with steep slopes. Coastal features and manmade structures like breakwaters also affect the water flow.

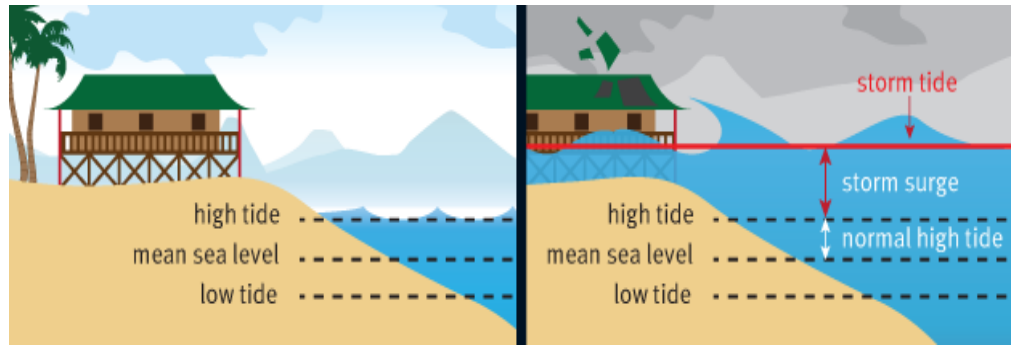


Figure 2.1: Storm tide (EMU Park Online, n.d.)

2.2 Circulation Models

Complex physical processes make it necessary to use an efficient numerical model to study storm surge. There are different numerical models used either by governmental organizations or academics for this purpose and most of them solve conservation of mass and momentum to resolve the corresponding circulation generated by storm surges. One of these models is the widely known SLOSH -Sea, Lake and Overland Surges from Hurricanes- model (Jelesnianski, Chen and Shaffer, 1992) developed by the National Weather Service of the USA primarily for forecasting surge heights before a hurricane makes landfall and evacuate people in the areas at risk to safer zones. The model allows overtopping and inundation however does not incorporate wind waves.

Princeton Ocean Model -POM- is a 3D primitive numerical ocean model developed at Princeton University by Blumberg and Mellor (1987). The model can be triggered by tides, surface wind stress, outflows/inflows, heat/salt fluxes and surface elevations at inflow boundaries. Wetting and drying scheme is included in the POM by Xie et al. (2004) which is then used to simulate the storm surge and inundation in the Croatan-Albemarle-Pamlico Estuary System in eastern North Carolina under hypothetical category 2 and 3 hurricane events

(Peng, Xie & Pietrafesa, 2004) and for Hurricane Hugo in Charleston Harbor, South Carolina (Peng, Xie & Pietrafesa, 2006).

CH3D -Curvilinear Hydrodynamics in 3D- solves 3D hydrostatic equations of water motion using boundary fitted curvilinear grid using finite volume method. The model is developed by Sheng (1986,1989) and later wetting drying calculation is implemented (Sheng et al., 2002).

FVCOM - The Unstructured Grid Finite Volume Community Ocean Model- is a finite volume model that runs on unstructured grid solving primitive equations. It is developed by UMASSD-WHOI joint efforts for coastal circulation studies and estuarine wetting-drying process. Examples of model application can be find in storm surge studies in North Captiva Island due to Hurricane Charley (Weisberg and Zheng, 2005) and in Tampa Bay for hypothetical hurricanes (Weisberg and Zheng, 2006).

ADCIRC -Advanced Circulation Model for oceanic, coastal and estuarine waters- (Luettich et al., 1992) solves the equations of fluid motion on an unstructured grid and has been used for modeling circulation and surge problems for over twenty years. Other areas that the program can be used include larval transport studies, dredging analysis and near shore marine operations. The model has both two dimensional or three dimensional versions. Two dimensional version solves the depth integrated shallow water equations, Detailed information about ADCIRC is given in Chapter 3.

2.3 Coupled Studies

Although storm surges are separated in the energy spectrum from wind driven short waves that have periods up to 25 seconds, they can interact with each other. Water levels are effected by radiation stress gradients generated due to

wave transformation, whereas bottom friction is effected by the wave motion in shallow waters. Moreover waves alter sea surface roughness which in return effect the surge generation. Due to this interaction between surges and waves, coastal inundation studies should take into account both phenomena.

Liu et al. (2006) examined the effects of ocean waves on storm surge and coastal flooding by using POM model and SWAN -Simulating WAVes Nearshore-model. The authors simulated Hurricane Hugo (1980) in Charleston Harbor for 5 cases with different coupling mechanism and compared results. The cases were as follows: Case 1 did not incorporate any wave affect, Case 2 included only wave induced surface stress, Case 3 included only wave induced bottom stress, Case 4 considered only radiation stresses and finally Case 5 incorporated all of the wave affects mentioned above. Comparison of the results yielded that among the 3 wave affects, wave induced stress have the largest impact on inundation followed by radiation stresses. Moreover this impact was not the same across the whole domain. The surface currents with altered direction due to surface stress resulted in both increase in flooded areas in some locations and decrease in some other locations.

Sun et al. (2013) have used FVCOM coupled with SWAVE to investigate the storm surge experienced during Hurricane Bob (1991). It is observed that the effect of current wave interaction on the maximum water levels varied spatially and temporally. Also model studies for a smaller domain shows that coupling increases the net maximum flux by 14%.

Sheng et al. (2010) developed a modeling system using ADCIRC coupled with Wavewatch III for regional simulations which provide boundary conditions for the local simulations that are run with CH3D coupled with SWAN model. Including wave affects resulted in over 20% increase in the peak surge heights compared to simulations that do not incorporate any wave affect. Also

maximum inundation area determined to be much larger. The authors also compared 2D and 3D simulation results and the difference between calculated peak surge heights were less than 15%, 3D simulations providing slightly higher surge heights.

In 1997 unusual coastal flooding occurred on the west coast of Korea during Typhoon Winnie that cannot be attributed to storm surge solely. Moon et al. (2003) investigated this by using a two way coupling system between POM model and Wavewatch II model. The authors concluded that enhanced tidal forcing, water mass transported into the Yellow Sea and the resonance coupling of the sea and the tide were major causes of the unexpected coastal flooding rather than the storm surge itself.

Niedoroda et al. (2010) studied the storm surge behavior in Mississippi coasts using different models to capture different processes. The authors applied WAM model -Wave Action Model- in deep water, SWAN model with a finer mesh in coastal water for waves and for storm surge simulation ADCIRC is applied. In the study was conducted in two steps. First ADCIRC was run on a coarser mesh without wave effects and resulting water elevations are provided for WAM. From WAM simulations wave behavior and radiation stress gradients were obtained which are then used to define boundary conditions for SWAN run. In the second step of the study, radiation stresses estimated from SWAN simulation are imposed in the new ADCIRC run with a higher resolution grid.

Besides the studies mentioned above, there are also several coupled studies performed by using ADCIRC and SWAN models. Hereafter some of these studies are introduced.

Bender et al. (2012) applied the coupled model of ADCIRC+SWAN to study water level elevations and wave heights for Hurricane Hugo (1989) and Ophelia (2005) as part of the South Carolina Surge Study (SCSS) project. The team run

the coupled model with third generation mode for SWAN and default Komen parameters. Whitecapping is calculated using Komen formulation, default parameters are used for considering breaking process and triad wave interactions which did not have major effect on wave heights during sensitivity analysis are turned off during computations. After the validation of the coupled model with measured data for both hurricanes, the team applied the model for calculations of still water levels with different occurrence possibilities. The results were to be used for Flood Insurance Rate Maps of FEMA for South Carolina counties.

Kerr et al. (2013) studied the mesh resolution and friction effects on model during simulation of Hurricane Ike (2008) in Gulf of Mexico. The authors used two unstructured meshes, a coarser mesh that contains 826,866 triangular elements named 'ULLR' and the finer mesh with 18,300,169 elements (SL18TX33). The study revealed that at deep ocean water levels are similar for both meshes however at inland locations the finer SL18TX33 mesh was able to capture surge propagation better. However under the effects of long sustained winds mesh size did not create much difference in the water levels,

Sebastian et al. (2014) modeled storm surge for Hurricane Ike (2008) in Galveston Bay and after validation of the model they analyzed storm surge behavior for synthetic storms. During their study the authors observed that increasing wind speeds by 15% lead to around 23% increase in water levels in and around the Galveston Bay.

Kennedy et al. (2012) have studied the inundation risk from cyclones in Hawaiian Islands Oahu and Kauai for hypothetical cyclone scenarios. The authors applied BOUSS1D model after ADCIRC+SWAN simulations, to determine wave run-up process. The results of the study yielded that the absence of continental shelf and presence steep slopes of volcanic islands yield to decrease of the storm surge height. On the other hand this type of bathymetry

results in much higher wave heights at near shore and wave run-up and wave setup become major factors for coastal inundation.

Bashkaran et al. (2014) examined coastal inundation due to Thane cyclone (2011) in Bay of Bengal and compared computed results with observations for 40 selected locations. The model results showed good agreement with the observation. For some locations with flat beaches, the model inundation results were underestimated which was attributed to quality of GEBCO bathymetric data for near shore regions by the authors. The results also showed that inundation distance is decreased with increasing beach slopes.

2.4 Black Sea Studies

In this sections studies performed over the Black Sea region are introduced. To begin with Van Vledder and Akpinar (2015) studied the sensitivity of the SWAN model to wind data source in Black Sea. They used data from NASA MERRA, NCEP CFSR, JRA-25, ECMWF Operational, ECMWF ERA-Interim and ECMWF ERA40. They compared computed waves by SWAN to the wave data obtained from NATO TU-WAVES project. Comparing the results, the authors concludes that JRA-25 inputs result in the worst performance for wave hindcasting by SWAN and CFSR data driven model perform best among the all compared wind inputs.

Kuznetsov et al. (2005) investigated the extreme waves and their formation in the Gelendzhik area (northwestern part) of Black Sea based on the wave data obtained from buoy measurements recorded between years 1996 and 2003. The authors compiled the frequency spectrum for the storm in 2003 during which the maximum average of maximal waves is observed with 11m height. The spectrum has two lateral peaks beside the main maximum which are attributed

to nonlinear instability if waves in deep water. Examining the different frequency wavelets the authors conclude that extreme waves appear when maximums of these waves coincide.

Finally Rusu and Butunoiu (2015) studied the wave propagation around the Sacalin Island which is next to Danube delta in Black Sea using SWAN wave model and incorporating Danube River outflow. It is revealed that two patterns are effective in the area. First one is the dominant one which is defined as constructive process. This process represents 50% of the total incoming waves which are directed from northeast. This pattern in combination with the river input and sediment transport determines the extension of the Sacalin Island in the southeastern part. In the second pattern named as the destructive process the waves come from southeast. Although this pattern is less frequent, waves coming from southeast observed to be stronger and carry the risk of destructing sediment accumulation.

To conclude although several studies are performed, there have not been much research carried out regarding to coastal flooding during storm events for Black Sea. The need for comprehensive studies in this topic becomes one of the motives of this study.



CHAPTER 3

NUMERICAL MODEL DESCRIPTIONS

Theoretical background of all used numerical models are described in this chapter along with the basic information about the contributing factors of sea level elevation. Firstly formulation for ADCIRC is introduced and continued with SWAN model. Then coupling mechanism of these two model is described and finally theoretical background of NAMI-DANCE model is presented.

3.1 ADCIRC

3.1.1 Governing Equations

ADCIRC uses the finite element method and computations are governed by the primitive continuity equation and the non-conservative momentum equations that are shown below (Eq 1,2,&3).

primitive continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial UZ}{\partial x} + \frac{\partial VZ}{\partial y} = 0 \quad (1)$$

non-conservative momentum equations:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = \quad (2)$$

$$- \frac{\partial}{\partial x} \left[\frac{p_s}{\rho_0} + g\zeta - g(\eta + Y) \right] + \frac{\tau_{sx}}{\rho_0 Z} - \frac{\tau_{bx}}{\rho_0 Z} + D_x - B_x$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} - fU = \quad (3)$$

$$- \frac{\partial}{\partial y} \left[\frac{p_s}{\rho_0} + g\zeta - g(\eta + Y) \right] + \frac{\tau_{sy}}{\rho_0 Z} - \frac{\tau_{by}}{\rho_0 Z} + D_y - B_y$$

Where U and V represent velocities in x and y directions respectively. ζ is free surface elevations, Z is total water depth, f is Coriolis parameter, p_s is atmospheric pressure, ρ_0 is density of water, g represents gravity, η represents Newtonian tidal potential and Y represents self attraction and load tide. Other parameters are as follow:

τ_{bx}, τ_{by} : bottom stresses

τ_{sx}, τ_{sy} : surface stresses

D_x, D_y : depth integrated diffusion/dispersion terms

B_x, B_y : depth integrated baroclinic pressure gradient terms in the x and y directions

The two dimensional depth integrated (2DDI) version of ADCIRC solves the Generalized Wave Continuity Equation (GWCE) along with the momentum equations (2) and (3). The GWCE is obtained by taking the time derivative of the primitive continuity equation and adding the primitive continuity equation multiplied by τ_0 . The form of GWCE is shown below (Eq.4).

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} - UZ \frac{\partial \tau_0}{\partial x} - VZ \frac{\partial \tau_0}{\partial y} = 0 \quad (1)$$

In the equation above τ_0 is a spatially variable numerical parameter that is used to weight the primitive vs the wave forms of the continuity equation in the GWCE. As it reaches zero, the equation becomes a pure wave equation, and when it goes to infinity, the equation becomes the primitive continuity equation.

A_x and A_y are as follows:

$$\begin{aligned} A_x &\equiv \frac{\partial UZ}{\partial t} + \tau_0 UZ \\ A_y &\equiv \frac{\partial VZ}{\partial t} + \tau_0 VZ \end{aligned} \quad (2)$$

3.1.2 Surface Stress

When wind blows over water, it causes disturbances on the water surface, eventually leading the formation of waves. The resulting shear stress on the water surface due to the energy transfer from wind to water causes water to move toward the water crest. The wave form leads to effective negative pressure on crest which increases the crest height whereas on trough positive pressure is formed further pushing water downward. Relative pressures on water surface is shown in Figure 3.1.

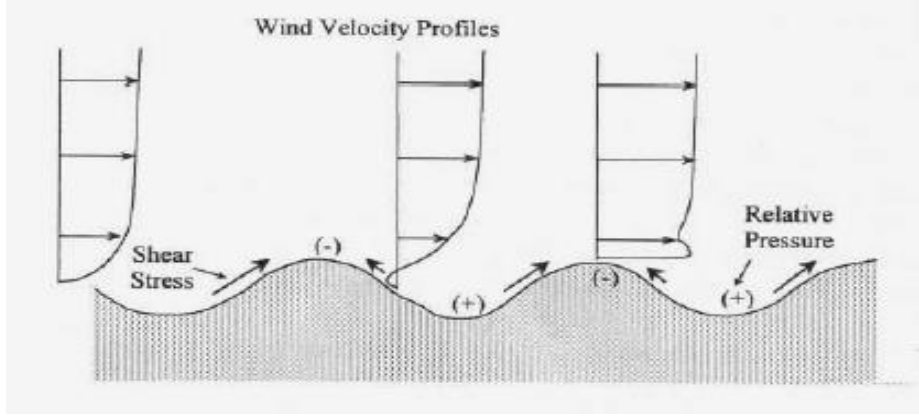


Figure 3.1: Wind energy transfer (Kamphuis, 2000)

Momentum transfer from winds to water is defined by the stress at the interaction surface as follows:

$$\tau = \rho C_d U_{10}^2 \quad (6)$$

In the equation above U_{10} represents the wind velocity at 10m elevation, and C_d is the wind drag coefficient. For the empirical determination of wind drag coefficient, the following relationship proposed by Garrat (1977) is incorporated in ADCIRC calculations.

$$C_d = (0.75 + 0.067U_{10}) \times 10^{-3} \quad (7)$$

Whereas the relationship proposed by Wu (1982) is shown below.

$$C_d = (0.8 + 0.065U_{10}) \times 10^{-3} \quad (8)$$

The proposed formulae both by Garrat and Wu are very close to each other and they show that the drag coefficient therefore surface stress increases with increasing wind velocity due to the presence of waves.

Besides the wind velocity, wind drag is also affected by the direction of waves as in nature wind and wave directions may not always coincide. Black et al. (2007) investigated this relationship between the wave direction and wind drag by dividing the storm into three sectors according to wave characteristics. In Figure 3.2 these sectors are represented. Right sector and rear sector includes waves moving with the wind. Wavelengths in rear sector are shorter whereas shifting to longer wavelengths observed in right sector. However in left sector where the longest wavelengths exist and waves move counter to the wind direction.

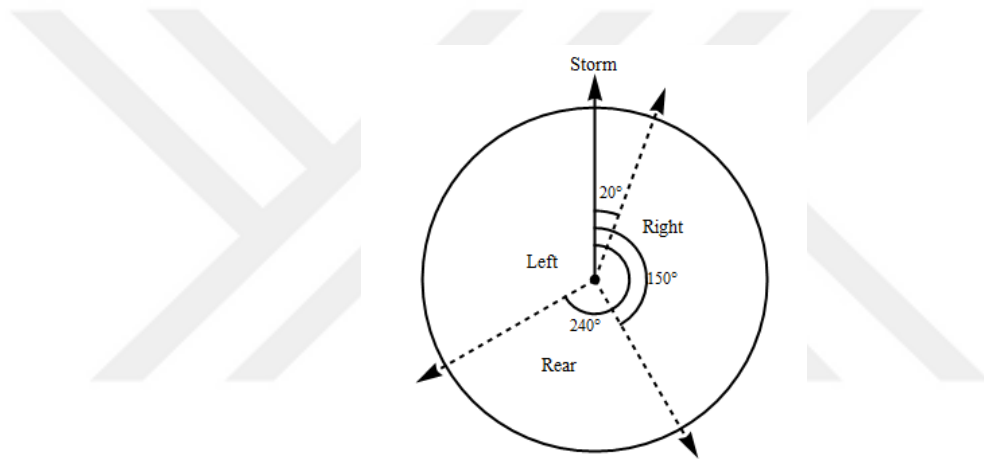


Figure 3.2: Rear sector (151-240 degrees relative to the storm motion vector) 2) Right sector (21-150 degrees) , and 3) Left front sector (241- 020 degrees) (Dietrich, n.d.1)

From the proposed relationship that is presented in Figure 3.2, it can be seen that the C_d values for rear and right sectors are almost same for wind speeds below 35m/s. At higher winds drag coefficient for both left and rear sectors decrease while in the right sector a increase is observed.

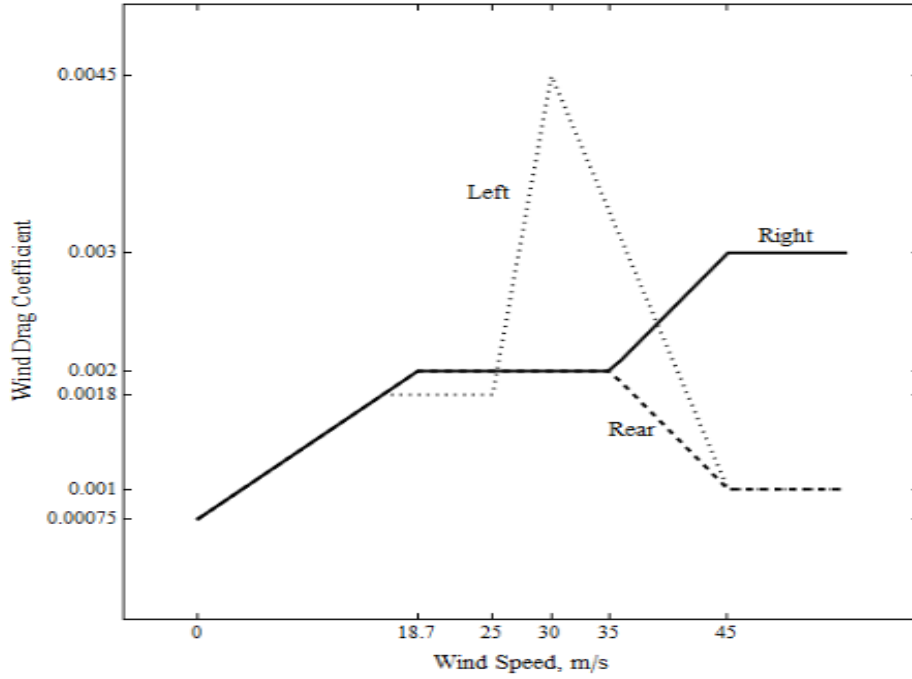


Figure 3.3: Wind drag coefficients (Dietrich, n.d.2)

3.1.3 Bottom Stress

In 2DDI version of ADCIRC model, the bottom stress is incorporated with the following relationship (Luettich and Westerink, 2004).

$$\frac{\tau_{bx}}{\rho_0} = K_{slip} U \quad (9)$$

The model allows three approaches for bottom friction consideration which are i) linear ii) quadratic and iii) hybrid function of depth averaged water velocity.

In the linear approach, a drag coefficient K_{slip} is determined by the user which is constant in time but may vary within the domain and read as model input. The recommended approach for most coastal applications is the quadratic approach

where K_{slip} value depends on the velocity magnitude and drag coefficient for which the recommended value is $C_d=0.0025$.

$$K_{\text{slip}} = C_d \sqrt{U^2 + V^2} \quad (10)$$

The third hybrid bottom friction approach requires user to provide breaking depth- H_{break} -, f_{min} , θ and γ values to provide in the model input file and calculates drag coefficient depending on the water depth.

$$C_d = C_{\text{fmin}} \left[1 + \left(\frac{Z_{\text{break}}}{Z} \right)^\alpha \right]^{\gamma/\alpha} \quad (11)$$

Exponent α determines how quickly C_d value reaches its limits as the depth increases or decreases and term γ scales how friction coefficient increases with increasing depth. In deep water where water column thickness is larger than the breaking depth ($Z \gg Z_{\text{break}}$), the C_d value approaches to the user determined C_{fmin} value.

Recommended values are as follows:

$$\begin{array}{ll} C_{\text{fmin}}=0.0025 & Z_{\text{break}}=1.0\text{m} \\ \alpha=10 & \gamma=1/3 \end{array}$$

3.2 SWAN

SWAN -Simulating WAVes Nearshore- is a third-generation phase-averaged model that is used extensively for estimation of wind generated wave parameters and currents in coastal water. Unlike phase resolving models where each wave is represented individually with a high resolution grid, phase averaged models uses statistics of the sea surface by computing energy or action density spectrum on

grid points. Computations are driven by bottom, wind, and current conditions given by user. Simulations can be carried out either stationary or nonstationary on both Cartesian and spherical coordinate systems.

3.2.1 Governing Equations

An irregular sea state can be represented by energy density $E(\sigma, \theta)$ over frequencies; σ and direction of propagation; θ . However in presence of currents wave energy is not conserved whereas wave action is. Spectral wave models therefore determine the action density $N(\vec{x}, t; \sigma, \theta)$ in space $\vec{x}$ and time t which is defined as $N=E/\sigma$. SWAN solves the wave action balance equation incorporating source and sink terms to compute random, short-crested wind-generated waves in coastal regions (Eq.12).

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (12)$$

First term in the above equation represents rate of action density change with respect to time. Propagation of wave in the x and y coordinates are denoted by the second and third terms with velocities c_x and c_y respectively. The fourth term represents the shifting in frequency due to changes in depth and current while the fifth term represents refraction with c_σ and c_θ corresponding to propagation velocities in spectral space (σ, θ) . S_{tot} represents the combination of all source and sink terms which contribute to generation, dissipation or redistribution of the wave energy. Source and sink terms included in SWAN are wave generation by wind, triad and quadruplet wave-wave interaction, whitecapping, bottom friction and depth-induced breaking (Eq.13).

$$S_{\text{tot}} = S_{\text{in}} + S_{\text{nl3}} + S_{\text{nl4}} + S_{\text{ds,w}} + S_{\text{ds,b}} + S_{\text{ds,br}} \quad (13)$$

3.2.2 Generation by Wind

As in the ADCIRC, main driving input for SWAN model is the energy transfer from atmosphere to water determined from the user given wind data. Computations are driven by the 10m height wind speed and the model uses this value to calculate friction velocity U_* as follows:

$$U_*^2 = C_d U_{10}^2 \quad (14)$$

Where the drag coefficient C_d is obtained using the relationship presented by Wu (1982).

$$C_d = \begin{cases} 1.2875 \times 10^{-3}, & U_{10} < 7.5 \text{ m/s} \\ (0.8 + 0.065 \times U_{10}) \times 10^{-3}, & U_{10} \geq 7.5 \text{ m/s} \end{cases} \quad (15)$$

Furthermore as explained in section 3.1.2 the form of the generated wave leads to changes in the wind profile that results pressure differences along the crest and trough which further cause growth of wave. In SWAN this process is expressed in the summation of linear and exponential wind growth terms (Eq.16).

$$S_{\text{in}}(\sigma, \theta) = A + BE(\sigma, \theta) \quad (16)$$

where σ and θ represent the frequency and direction respectively.

The term A is the linear growth term taken from Cavaleri and Malanotte-Rizzoli (1981).

$$A = \frac{1.5 \times 10^{-3}}{2\pi g^2} (U_* \max[0, \cos(\theta - \theta_w)])^4 k, \quad (17)$$

$$k = \exp\left(-\left(\frac{\sigma}{\sigma_{PM}^*}\right)^{-4}\right), \quad \sigma_{PM}^* = \frac{0.13g}{28U_*} 2\pi$$

where θ_w is the direction of wind and σ_{PM}^* is the peak frequency of the fully developed sea state according to Pierson and Moskowitz (1964). k is the filter term used for eliminating wave growth at frequencies lower than the Pierson-Moskowitz frequency (Tolman, 1992a).

For the exponential wind growth representation SWAN allows two options to user. First approach uses the expression proposed by Komen et al. (1984):

$$B = \max\left[0, 0.25 \frac{\rho_a}{\rho_w} \left(28 \frac{U_*}{c_{ph}} \cos(\theta - \theta_w) - 1\right)\right] \sigma \quad (18)$$

where c_{ph} : phase speed and

ρ_a and ρ_w : density of air and water, respectively.

Second approach for exponential wind growth utilizes the equation proposed by Janssen (1989, 1991a):

$$B = \beta \frac{\rho_a}{\rho_w} \left(\frac{U_*}{c_{ph}}\right)^2 \max[0, \cos(\theta - \theta_w)]^2 \sigma \quad (19)$$

in which β is the Miles constant which is estimated from the non-dimensional critical height λ by Janssen's (1991a) theory.

3.2.3 Nonlinear Wave-Wave Interactions

Another process that affects the wave growth is the energy transfer among the waves. When two waves with different directions and frequencies combine with each other creating a wave which has its own wave length and direction, this wave may interact with a third freely propagating wave if it has the same wave length and direction with the resultant wave. This interaction is called resonance and the interaction of three propagating waves is known as triad wave-wave interaction (Holthuijsen,2007) (Fig.3.4). This interaction among the waves leads some wave components to gain energy while other wave components lose, however the total energy of all the wave components would remain the same.

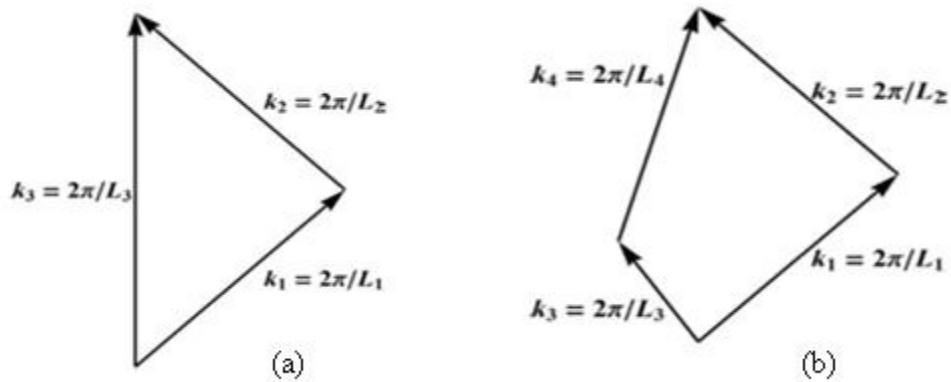


Figure 3.4: Triad(a) and quadruplet(b) wave interactions (Holthuijsen,2007)

Due to the reason that the matching of the same wave speed, wave length and direction which are the requirements for resonance cannot occur with three wave components in deep water, triad wave-wave interactions are experienced in

shallow water. The process shift energy to higher frequencies and may lead to formation of a multiple peaked spectra from single peaked spectra (Fig.3.5).

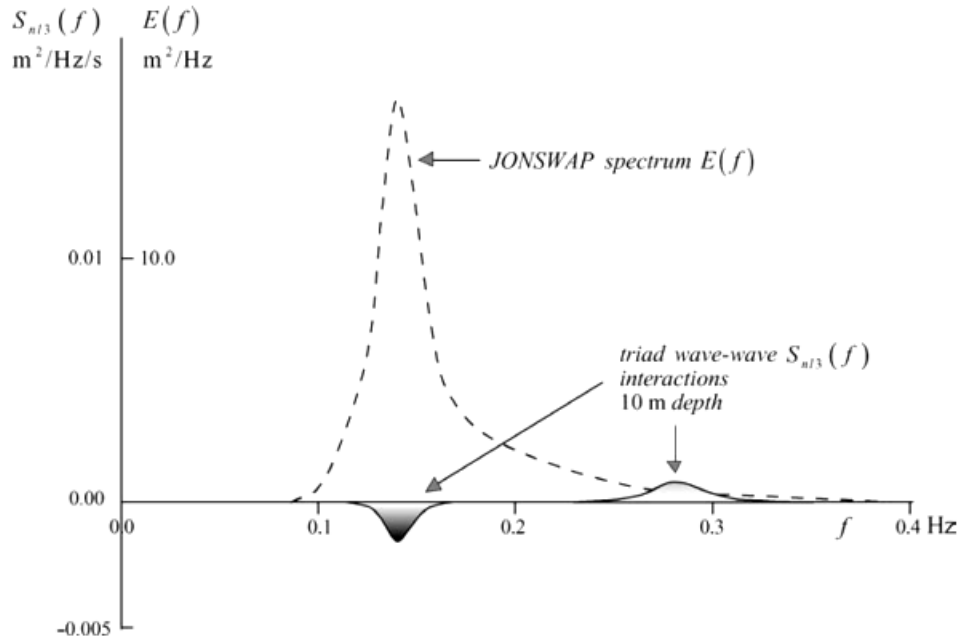


Figure 3.5: Frequency shifting due to triad interactions (Holthuijsen,2007)

In SWAN calculations, Eldeberky's (1996) Lumped Triad Approximation (LTA) is used in each direction for incorporating triad wave interactions:

$$S_{nl3}(\sigma, \theta) = S_{nl3}^{-}(\sigma, \theta) + S_{nl3}^{+}(\sigma, \theta) \quad (20)$$

$$S_{nl3}^{+}(\sigma, \theta) = \max[0, \alpha_{EB} 2\pi c_g J^2 |\sin \beta| \{E^2(\sigma/2, \theta) - 2E(\sigma/2, \theta)E(\sigma, \theta)\}] \quad (21)$$

$$S_{nl3}^{-}(\sigma, \theta) = -2S_{nl3}^{+}(2\sigma, \theta) \quad (22)$$

where α_{EB} is proportionality coefficient and J is the interaction coefficient.

In deep water, two pairs of waves can interact with each other which is called as quadruplet wave-wave interactions (Fig.3.4). This kind of interactions shift considerable amount of energy from the peak of the spectrum to lower frequencies and a small amount of energy is shifted to higher frequencies (Fig.3.6). The energy shifted to higher frequencies is dissipated by whitecapping and the resultant spectrum has a lower peak frequency. The quadruplet wave-wave interaction can be the dominating reason for spectrum change in deep water if wind is not varying strongly. It tends to stabilize the spectrum shape of steep waves and becomes the reason for observing Jonswap spectrum in storms (Holthuijsen, 2007).

The main factor differentiating third generation models from first and second generations is the inclusion of the quadruplet wave-wave interaction calculations where the discrete-interaction approximation (DIA) of Hasselmann et al. (1985a) is used. Two configurations are used for quadruplet wave numbers with frequencies presented below.

$$\begin{aligned}\sigma_1 &= \sigma_2 = \sigma \\ \sigma_3 &= \sigma(1 + \lambda) = \sigma^+ \\ \sigma_4 &= \sigma(1 - \lambda) = \sigma^-\end{aligned}\tag{23}$$

where λ is a constant with default value of 0.25.

And source terms are as shown:

$$S_{nl4}(\sigma, \theta) = S_{nl4}^*(\sigma, \theta) + S_{nl4}^{**}(\sigma, \theta)\tag{24}$$

in which S_{nl4}^* represents the first quadruplet and S_{nl4}^{**} represents the second quadruplet

The variance change due to quadruplet interaction is expressed as follows:

$$\begin{pmatrix} \delta S_{nl4}^*(\sigma, \theta) \\ \delta S_{nl4}^*(\sigma^+, \theta^+) \\ \delta S_{nl4}^*(\sigma^-, \theta^-) \end{pmatrix} = \begin{pmatrix} 2 \\ -1 \\ -1 \end{pmatrix} C_{nl4} (2\pi)^2 g^{-4} \left(\frac{\sigma}{2\pi} \right)^{11} \times \left[E^2(\sigma, \theta) \left\{ \frac{E(\sigma^+, \theta^+)}{(1+\lambda)^4} + \frac{E(\sigma^-, \theta^-)}{(1-\lambda)^4} \right\} - 2 \frac{E(\sigma, \theta) E(\sigma^+, \theta^+) E(\sigma^-, \theta^-)}{(1-\lambda^2)^4} \right] \quad (25)$$

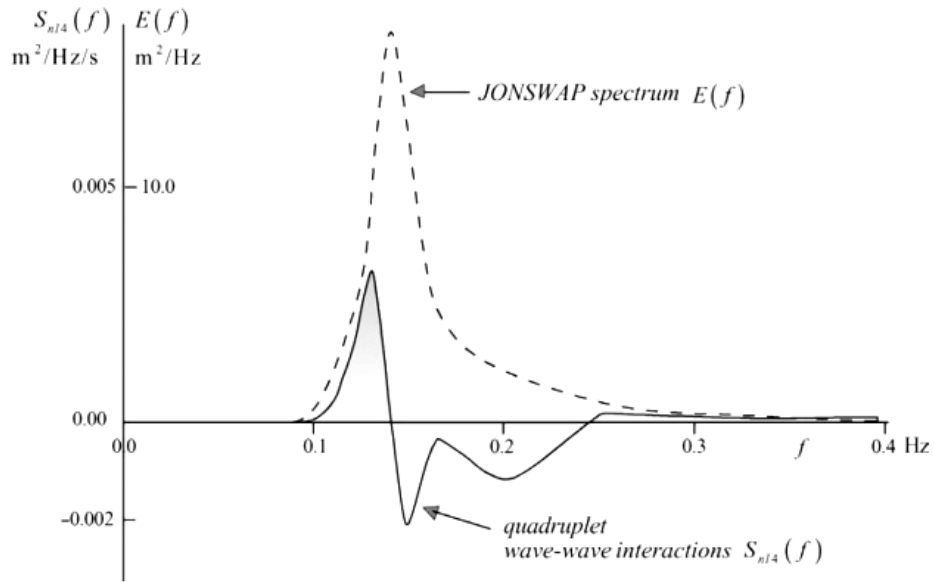


Figure 3.6: Frequency shifting due to quadruplet interactions (Holthuijsen,2007)

3.2.4 Whitecapping

Breaking of waves in deep water which is called white-capping is the least understood phenomenon among the physical processes that affects waves (Holthuijsen,2007). In SWAN Komen et al.(1984) approach is used with the reformulation of Hasselmann(1974) model that depends on the wave number, steepness and wave energy (Eq.26).

$$S_{ds,w}(\sigma, \theta) = -\Gamma \tilde{\sigma} \frac{k}{\tilde{k}} E(\sigma, \theta) \quad (26)$$

in which $\tilde{\sigma}$ and $\tilde{k}$ are the mean frequency and mean wave number respectively and the Γ is a coefficient depending on the overall wave steepness.

3.2.5 Bottom Friction

As waves approach to shore, particle motions on the surface of shallow water extend to the sea bottom leading an interaction between the surface waves and sea floor. This interaction results in the loss of energy depending on the wave field and bottom characteristics. There are three approaches utilized in SWAN for bottom friction calculations that can be expressed in the following form:

$$S_{ds,b} = -C_b \frac{\sigma^2}{g^2 \sinh^2 kd} E(\sigma, \theta) \quad (27)$$

C_b is the bottom friction coefficient that depends on the root mean square of the bottom orbital velocity at sea bottom.

In SWAN the default option is the JONSWAP model (Hasselmann et al.,1973) with a constant friction coefficient of $C_b = 0.038 \text{ m}^2\text{s}^{-3}$ which can be decreased for smooth sea floors.

Collins (1972) option uses presented a drag law model with the following friction coefficient calculation:

$$C_b = C_f g U_{\text{rms}} \quad (28)$$

And finally Madsen et al.(1988) approach uses the following relationship where the bottom friction coefficient depends on the bottom roughness height and wave conditions:

$$C_b = f_w \frac{g}{\sqrt{2}} U_{\text{rms}} \quad (29)$$

in which f_w is a dimensionless factor depending on near bottom excursion amplitude and bottom roughness length scale.

3.2.6 Breaking

As waves propagate toward the shore the wave height increases with decreasing water depth. Eventually the waves become so steep that they cannot propagate further and start to break releasing energy. SWAN uses the Battjes and Janssen (1978) model to incorporate the energy dissipation related to breaking during computations. Mean rate of energy dissipation D_{tot} is expressed as:

$$D_{\text{tot}} = -\frac{1}{4} \alpha_{\text{BJ}} Q_b \left(\frac{\tilde{\sigma}}{2\pi} \right) H_{\text{max}}^2 = -\alpha_{\text{BJ}} Q_b \tilde{\sigma} \frac{H_{\text{max}}^2}{8\pi} \quad (30)$$

where $\alpha_{BJ} = 1$ and Q_b is the fraction of breaking waves determined by:

$$\frac{1 - Q_b}{\ln Q_b} = -8 \frac{E_{tot}}{H_{max}^2} \quad (31)$$

The maximum wave height is $H_{max} = \gamma Z$, in which γ is the breaker index and Z is the total water depth. The model allows user to choose a constant γ for the whole domain or compute it related to bottom slope and dimensionless depth (Fig.3.7). This second approach proposed by Salmon and Holthuijsen (2011) is shown to produce better results for waves travelling over horizontal slopes such as lakes or reefs.

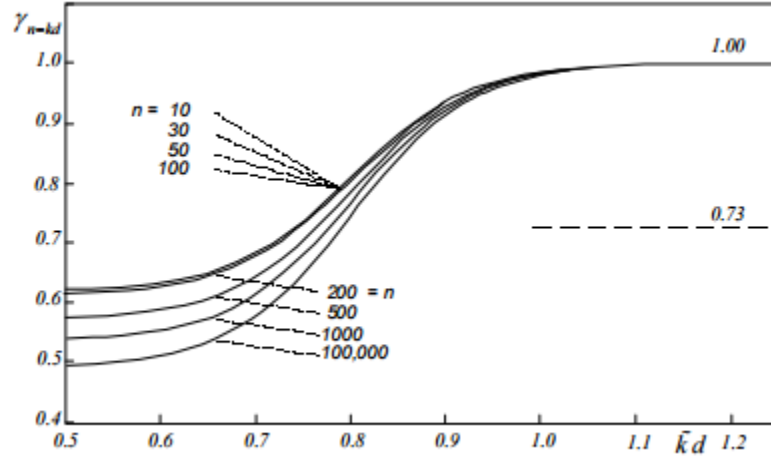


Figure 3.7: Breaking parameter related to bottom slope n and dimensionless depth kd

3.3 ADCIRC-SWAN Coupling

In deep sea the total water level is determined by both short waves like wind waves and seiches that have periods ranging from 0.5s-25s and longer waves

such as tsunami waves. Seiches or tides with a period of minutes to weeks. The waves with different period are separated in the energy spectrum which forces use of different approaches in modeling. Despite this separation, short waves and long waves can interact with each other. For this reason, ADCIRC developers have enabled tightly coupling of the model with the SWAN wave model on the same unstructured mesh (Dietrich et al.,2011).

The coupling mechanism works this way: after ADCIRC part of the simulation is complete, water levels, currents and wind speeds for the beginning and end of the current coupling interval are accessed by SWAN which are then averaged to be used in the radiation stress gradients. Then SWAN provides the radiation stress gradients at the beginning and end of the previous coupling interval to ADCIRC, which are then used to extrapolate the gradients corresponding to ADCIRC's own time steps in the present coupling interval. Figure 3.8 shows the shared information among the models.

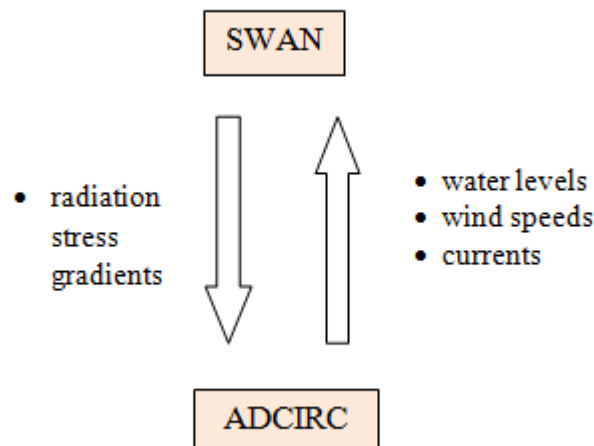


Figure 3.8: Shared information among ADCIRC and SWAN models

3.4 NAMI-DANCE

Due to the fact that ADCIRC considers only surge heights not wave heights for wetting and drying process, another numerical tool, NAMI-DANCE is used for coastal flooding analysis.

NAMI DANCE is developed by Profs Andrey Zaytsev, Ahmet Yalciner, Anton Chernov, Efim Pelinovsky and Andrey Kurkin using C++ programming language and designed especially for tsunami modeling and visualization (NAMIDANCE,2016). It has been developed using the same calculation procedures of TUNAMI N2 (Shuto et al., 2006) that has been developed by Professors Shuto and Imamura. Capabilities of NAMI-DANCE involves determination of tsunami source from rupture or wave form given by user, computation of propagation, coastal amplification, inundation, current velocity direction and distribution. Moreover water surface elevations for whole domain and also at selected gauge locations can be computed. it has been applied to several tsunami events (YALCINER et al. 2001, 2002, 2003, 2004; ZAHIBO et al. 2003; ZAITSEV et al. 2008; YALCINER and PELINOVSKY 2007; YALCINER et al. 2010, 2014, Kian 2015, Aytore et al., 2015, Cankaya et al., 2015, Kian et al., 2016, Zaytsev et al., 2016).

Since this study is focused on coastal flooding, related parameters computed by NAMI-DANCE should be mentioned specifically. Inundation distance is the horizontal distance measured from the original shoreline to the furthest point water reaches inland. Correspondingly the elevation difference between this point and sea level is called the run-up height. In Figure 3.9 these parameters are represented.

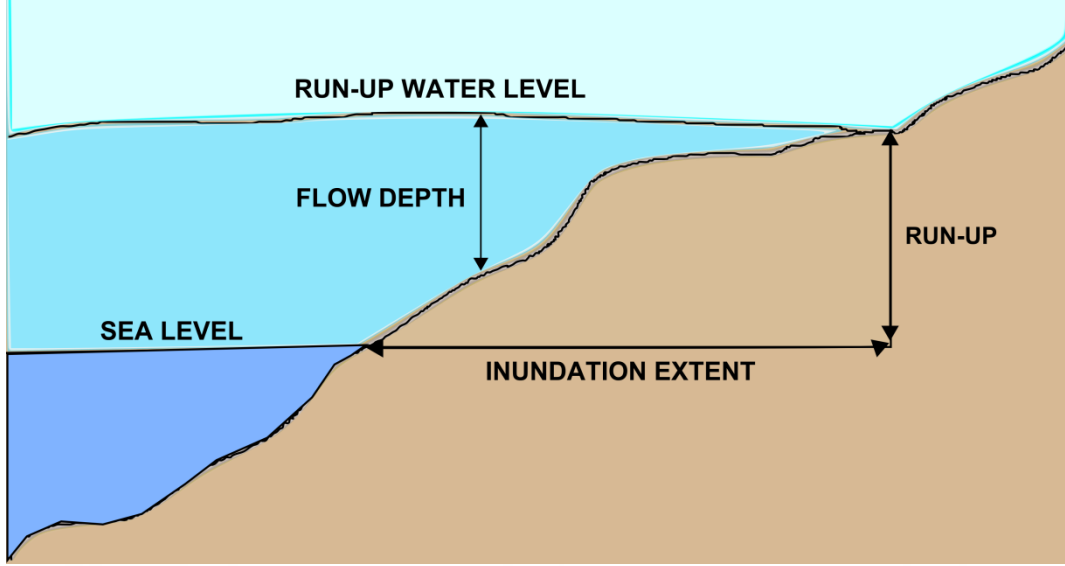


Figure 3.9: Inundation parameters (WACOP, n.d.)

3.4.1 Governing Equations

Like ADCIRC, NAMI-DANCE also solves two dimensional shallow water equations but uses a structured rectangular grid instead of an unstructured grid. Nonlinear shallow water equations assume that the water depth is small compared to the wave length and the horizontal water velocity does not change with depth.

$$\frac{\partial \zeta}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0 \quad (32)$$

$$\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q_x^2}{Z} \right) + \frac{\partial}{\partial y} \left(\frac{Q_x Q_y}{Z} \right) + gZ \frac{\partial \zeta}{\partial x} + \frac{\tau_x}{\rho} = A \left(\frac{\partial^2 Q_x}{\partial x^2} + \frac{\partial^2 Q_x}{\partial y^2} \right) \quad (33)$$

$$\frac{\partial Q_y}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q_x Q_y}{Z} \right) + \frac{\partial}{\partial y} \left(\frac{Q_y^2}{Z} \right) + gZ \frac{\partial \zeta}{\partial y} + \frac{\tau_y}{\rho} = A \left(\frac{\partial^2 Q_y}{\partial x^2} + \frac{\partial^2 Q_y}{\partial y^2} \right) \quad (34)$$

Equations 33 and 34 seem similar to the equations 2 and 3 that ADCIRC solves, however it can be noticed that pressure effects are not included in NAMIDANCE calculations. Also bottom shear stresses in x and y directions are defines as shown below.

$$\begin{aligned}\frac{\tau_{bx}}{\rho} &= \frac{1}{2g} \frac{f}{Z^2} Q_x \sqrt{Q_x^2 + Q_y^2} \\ \frac{\tau_{by}}{\rho} &= \frac{1}{2g} \frac{f}{Z^2} Q_y \sqrt{Q_x^2 + Q_y^2}\end{aligned}\tag{35}$$

f in the above equations corresponds to bottom friction coefficient and it is related to the Manning's roughness n with the following relationship.

$$n = \sqrt{\frac{fZ^{1/3}}{2g}}\tag{32}$$



CHAPTER 4

DATA ACQUISITION AND PROCESSING

In this chapter selected study area and the storm event are introduced. Selection of input data sources and mesh generations for storm and inundation simulations are also described in details.

4.1 Study Area and Selected Event

Giresun is located on the eastern part of the Black Sea coast of Turkey with approximately 430,000 residents. During two days storm duration between 23-25 September 2014 in Black Sea, the Giresun province was one of the affected cities in Turkey. The city center faced severe attack of waves in 2 days storm duration. Highest waves were observed to run-up at about 5m elevation at some locations. Those had caused severe damage in harbor structures, coastal defense structures and ships in the harbor and vehicles on the Black Sea Coast Highway which serves as the only route for easy transportation between the eastern and western side of the coast (Fig.4.2). The highway was closed to service due to the storm surge (Milliyet,2014). In this study, storm surge and coastal inundation due to the 2014 September storm event in Giresun province is investigated by numerical modeling. In Figure 4.1 selected study areas for ADCIRC+SWAN simulations and NAMI-DANCE simulations are presented. In Figure 4.2 photographs taken during the flooding event are presented.



Figure 4.1: Study area, red box in the upper picture covers the ADCIRC+SWAN domain boundaries and red bow in the lower picture covers the NAMI-DANCE domain boundaries



Figure 4.2: Photographs of flooding in Giresun ("Giresun'da dev dalgalar sahil yolunu sular altında bıraktı", 2014)

4.2 Input Data

The bathymetric data for deep water is taken from General Bathymetric Chart of the Oceans (GEBCO) of the British Oceanographic Data Centre with a spatial resolution of 1 arc-minute in general (General Bathymetric Chart of the Oceans

GEBCO_08 Grid, 2010). Additionally water depths for near shore are obtained by digitizing the map acquired from Turkish Naval Forces Office of Navigation, Hydrography and Oceanography (SHOD).

For topographic data, The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) and Google DEM data are compared. Google DEM data is used for locations close to shore as it provides the most recent and accurate data of the study area. Elevations are obtained through the free online tool named Terrain Zonum (<http://www.zonums.com/gmaps/terrain.php>). Moreover further inland elevations are taken from the ASTER GDEM data which have 1 arc second resolution (ASTER GDEM V2, 2011). In Figure 4.3 and Figure 4.4 elevation data are shown for all of the domain area and over the area of interest respectively.

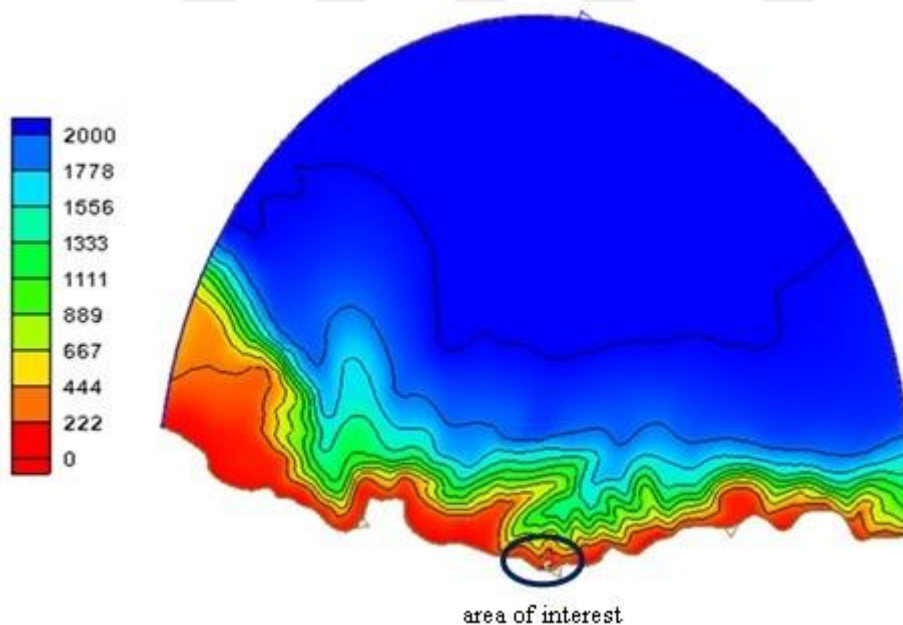


Figure 4.3: Bathymetry contours in meters

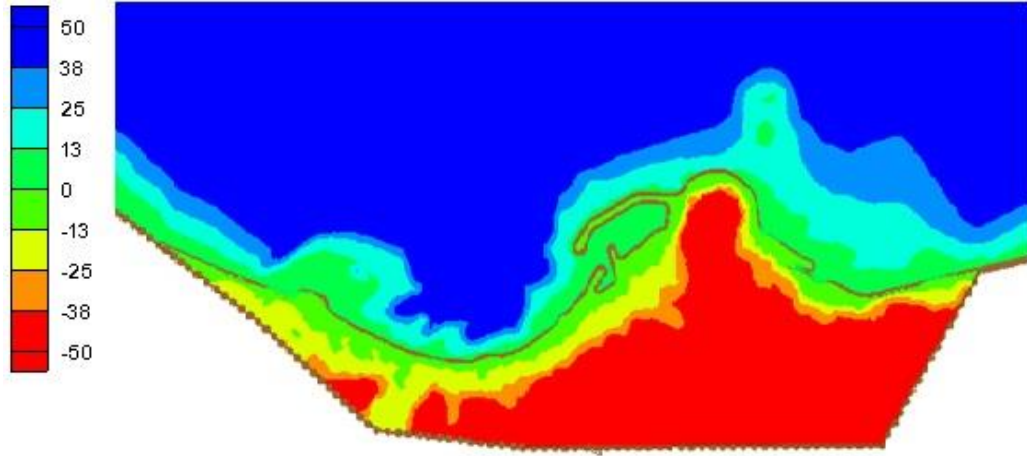


Figure 4.4: Bathymetry contours in meters in the area of interest

The sudden decrease in water depth in front of the cape slightly on the eastern side as it can be seen in the Figure 4.4 should be mentioned especially as this change in bathymetry would affect the simulation results. Here depths drop to as low as 10m.

Furthermore for meteorological input, previous studies of storm events in Black Sea performed by SWAN and WaveWatch III simulations showed that computations with CFSR wind data results in better agreement with observed data rather than ECMWF wind inputs (Tarakcioglu et al,2015). Therefore in this study wind velocity and pressure inputs are taken from NCEP's CFSv2 data which provides hourly data with 0.205 spatial resolution on spherical coordinate system and hourly temporal resolution. Wind velocity vectors and atmospheric pressure contours over the model domain within the simulation time range are presented in Figure 4.5.

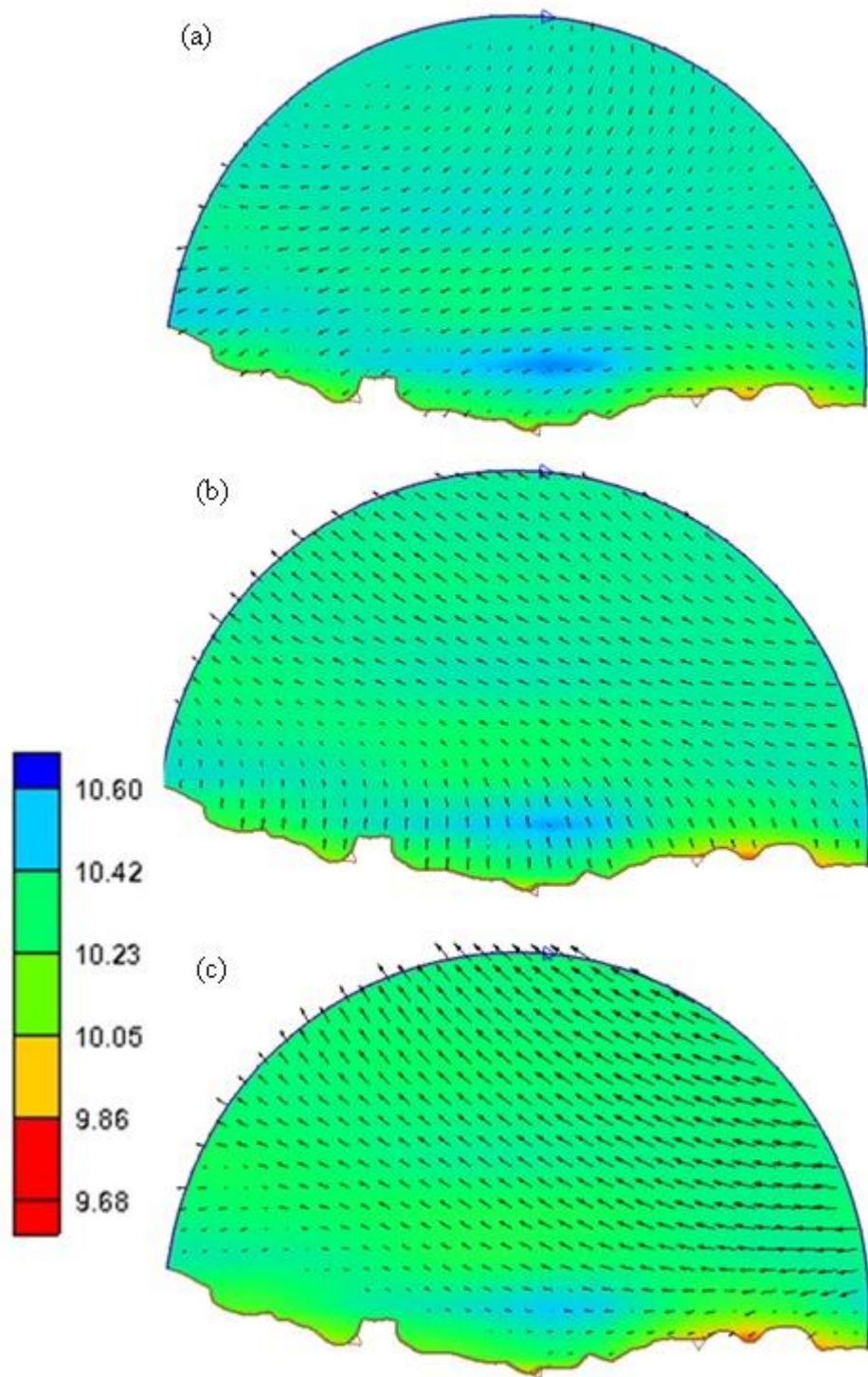


Figure 4.5: Wind velocity vectors and atmospheric pressure contours in meters of water at a) September 22,2014 12:00 e)September 23,2014 00:00 f)September 23,2014 12:00

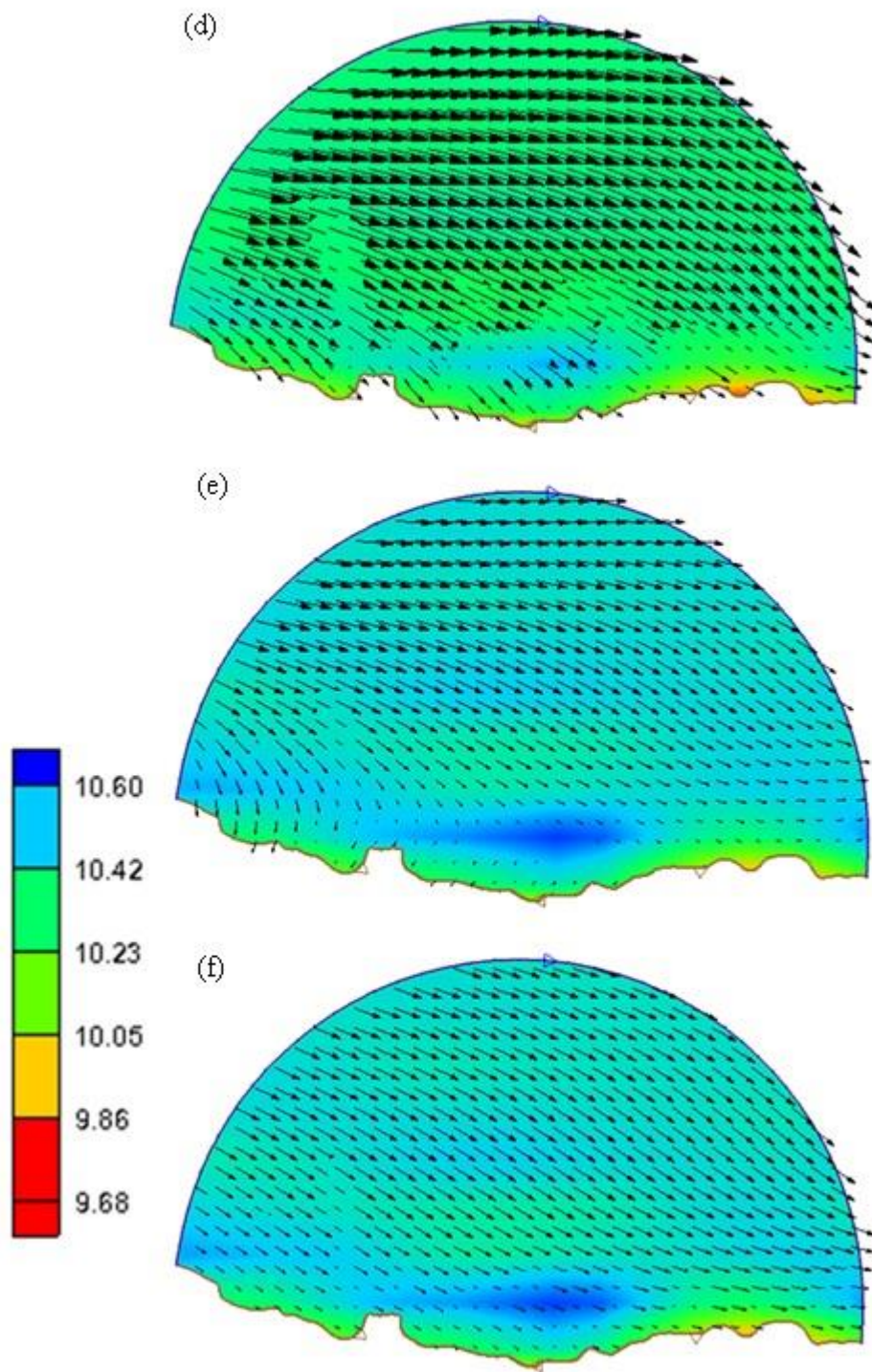


Figure 4.5 (cont'd): Wind velocity vectors and atmospheric pressure contours in meters of water at d) September 24,2014 00:00 e)September 24,2014 12:00 f)September 25,2014 00:00

On 22 September 12:00am (noon) wind speed is around 5m/s blowing from northeast. 12 hours later wind direction is changed to northwest with same magnitudes. On 23 September 12:00pm the wind is still blowing towards northwest with magnitudes of around 3m/s close to shoreline reaching to 10 m/s at the north-northeast part of the domain. Around 2 hours later storm is generated with up to 20m/s wind speeds in the western part of Black Sea but it has not reached study area. Around 24th of September 12:00am the storm has reached the eastern Black Sea and up to 24m/s wind speeds start entering into the domain from northwest blowing towards southeast. Pressures throughout the domain is around 100500 Pa by this time. In the morning of 24 September around 5:00am storm starts leaving the study area from southeast and maximum wind speeds are decreased to 18m/s in the middle part of the domain whereas around 10m/s wind magnitudes are observed close to shoreline. Maximum pressures around 103000 Pa are observed close to shoreline. After that wind speeds decrease gradually until the end of simulation time which is 25 September 2014, 00:00.

4.3 Mesh Generation

4.3.1 Mesh for ADCIRC + SWAN Simulations

Generation of mesh for ADCIRC+SWAN simulations are performed by using the commercial tool named SMS developed by engineering services company, Aquaveo (Aquaveo,2016). Minimum grid spacing is chosen as 30 meters along the shoreline of the area of interest and increased gradually both offshore and onshore. Maximum grid spacing of the generated mesh is 10500 meters along the ocean boundary which is shown as blue line with dots in Figure 4.6. Ocean area covers approximately 35,630 km² whereas the land is incorporated for 8.5 km² area. Maximum distance from the shoreline of the area of interest and the ocean boundary is nearly 195 km. Grid spacing for whole domain and in the area of interest are presented in Figure 4.6 and Figure 4.7 respectively.

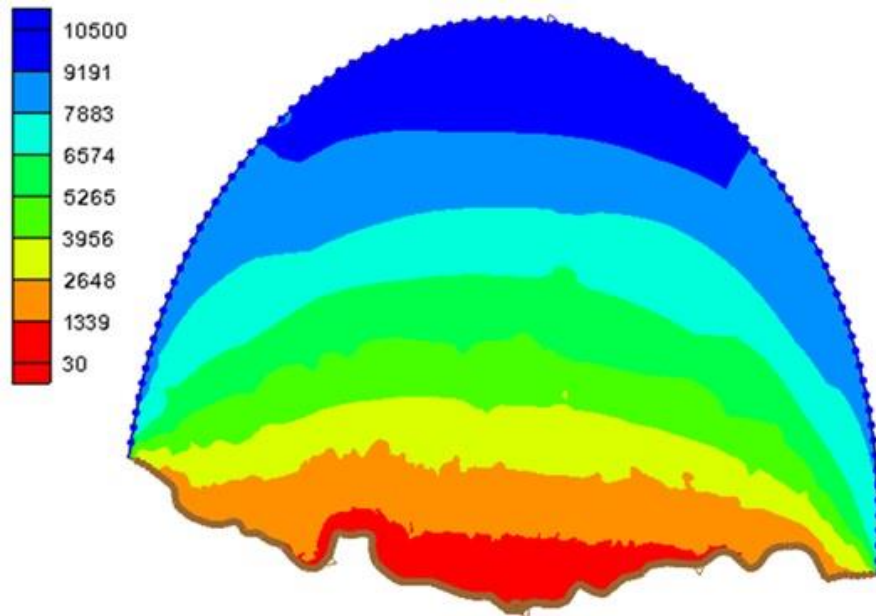


Figure 4.6: Grid spacing contours in meters

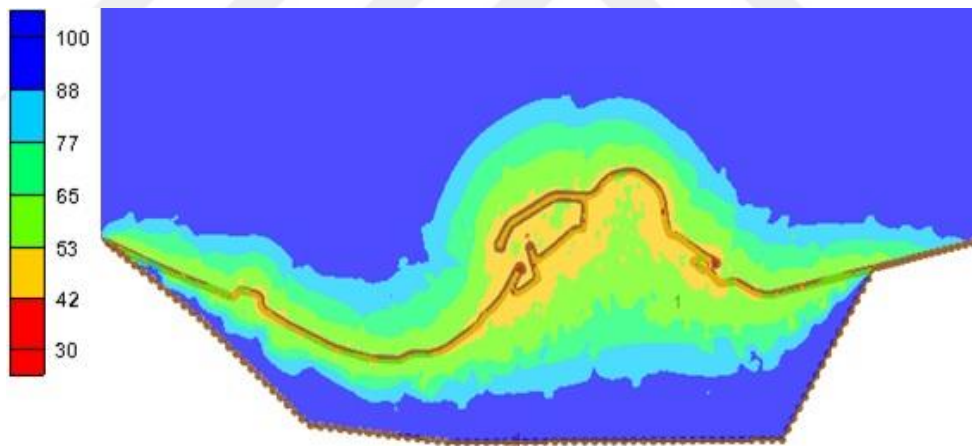


Figure 4.7: Grid spacing contours in meters around the shoreline

4.3.2 Mesh for NAMI-DANCE Simulations

For inundation analysis a high resolution structured grid is generated with around 5.5m grid spacing using Golden Software product Surfer program (www.goldensoftware.com/products/surfer). In Figure 4.8 selected study domain for inundation analysis is presented. North side of the mesh is the ocean boundary where the input forcing is given whereas left and right boundaries of the mesh are open boundaries where wave radiation is allowed.

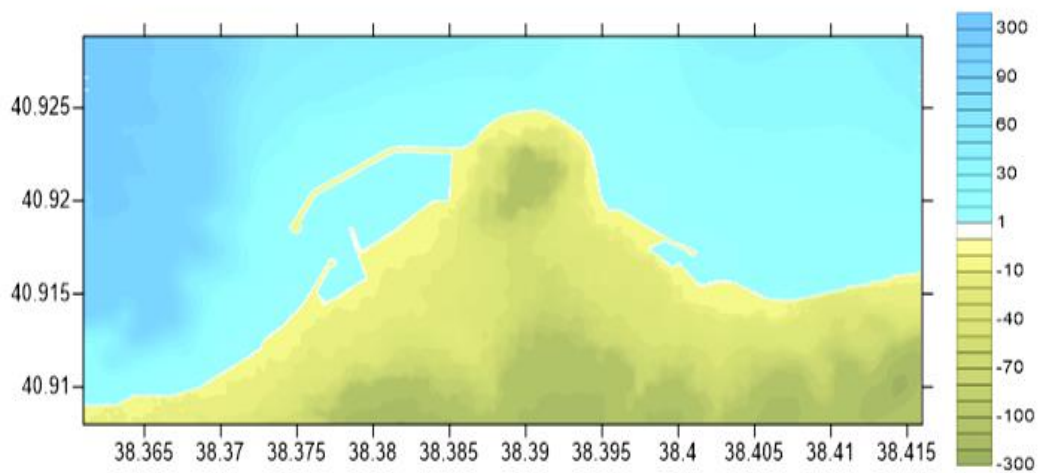


Figure 4.8: Elevation contours in meters

CHAPTER 5

RESULTS AND DISCUSSIONS

In this chapter results of the storm simulations performed by coupled ADCIRC +SWAN model and inundation simulations performed by NAMI-DANCE are presented respectively. Storm simulations are performed for 2.5 days duration starting from 22th of September, 2014 on 12:00pm and lasted on 25th of September 00:00am. Computed maximum significant wave height and period values are then used as input for inundation analysis in NAMI-DANCE. The duration of NAMI-DANCE simulations are chosen to be 15 minutes which is observed to be enough for waves to reach the shoreline.

5.1 Storm Simulation Results

Storm simulations are performed for six different cases. First case is the main simulation that is performed by implementing two way fully coupled ADCIRC + SWAN model. Wave parameters obtained from this case is used for determining input data for inundation analysis. In cases 2, 4, 5 and 6, coupling mechanism is altered for different scenarios to investigate the sensitivity of the resulting wave heights and surge levels to shared data between ADCIRC and SWAN. In case 3 effect of finite amplitude terms and wetting drying mechanism that are incorporated in ADCIRC is studied by closing these parameters. Descriptions of the cases are summarized in Table 5.1.

Spatial distribution of maximum significant wave height and peak periods are drawn for each case results except for the Case 4 where only ADCIRC simulation is performed without any coupling process with SWAN. Therefore any wave related parameters are not computed for this case. However maximum water elevation results are used for comparison with Case 1 to examine wave effects. Furthermore currents and maximum water elevations for the main simulation, Case 1 are also presented. Each figure is drawn by using SMS.

Table 5.1: Case description for storm simulations

Case	SWAN → ADCIRC	ADCIRC → SWAN		Finite amplitude terms and wetting drying in ADCIRC
	Radiation	Water levels	Current	
1	✓	✓	✓	✓
2	✓	x	x	✓
3	✓	✓	✓	x
4	x	x	x	✓
5	✓	x	✓	✓
6	✓	✓	x	✓

5.1.1 Case 1 Results

Examining the wave heights with respect to wind velocities show that occurrence of maximum wave heights and maximum wind velocities effective

in the domain coincides. Maximum winds in the domain area is observed on 24th of September at 00:15 am with magnitudes up to 24m/s. Formation of maximum wave heights with more than 6m height are also observed for that time. Wind velocities more than 20m/s are effective blowing towards southeast until 4:00am on September,24. During this time period wave heights increase over a larger area and then continues to move with wind direction to southeast. In Figure 5.1 wind velocity vectors for the time when the maximum wind velocities of the storm starts effecting the domain area and for the time when the storm starts leaving the study area are presented along with the computed significant wave heights for these moments are presented.

Longshore currents are found to be around 1.5m/s on the western part of the Giresun and reached 2.5m/s behind the break water. On the right part maximum velocities are observed with magnitudes slightly higher than 3m/s. There is a sudden decrease in depth on a limited area in northeast of the cape. As expected this change in bottom leads to sudden increase in current velocities here. Current velocity distributions can be seen in Figure 5.2.

Maximum water elevations are observed behind the breakwater where water elevations reach over 1m height. Along the shoreline water elevations are around 0.7m. Water elevations are decreased with increasing water depth. Distribution of maximum water elevations are presented in Figure 5.3.

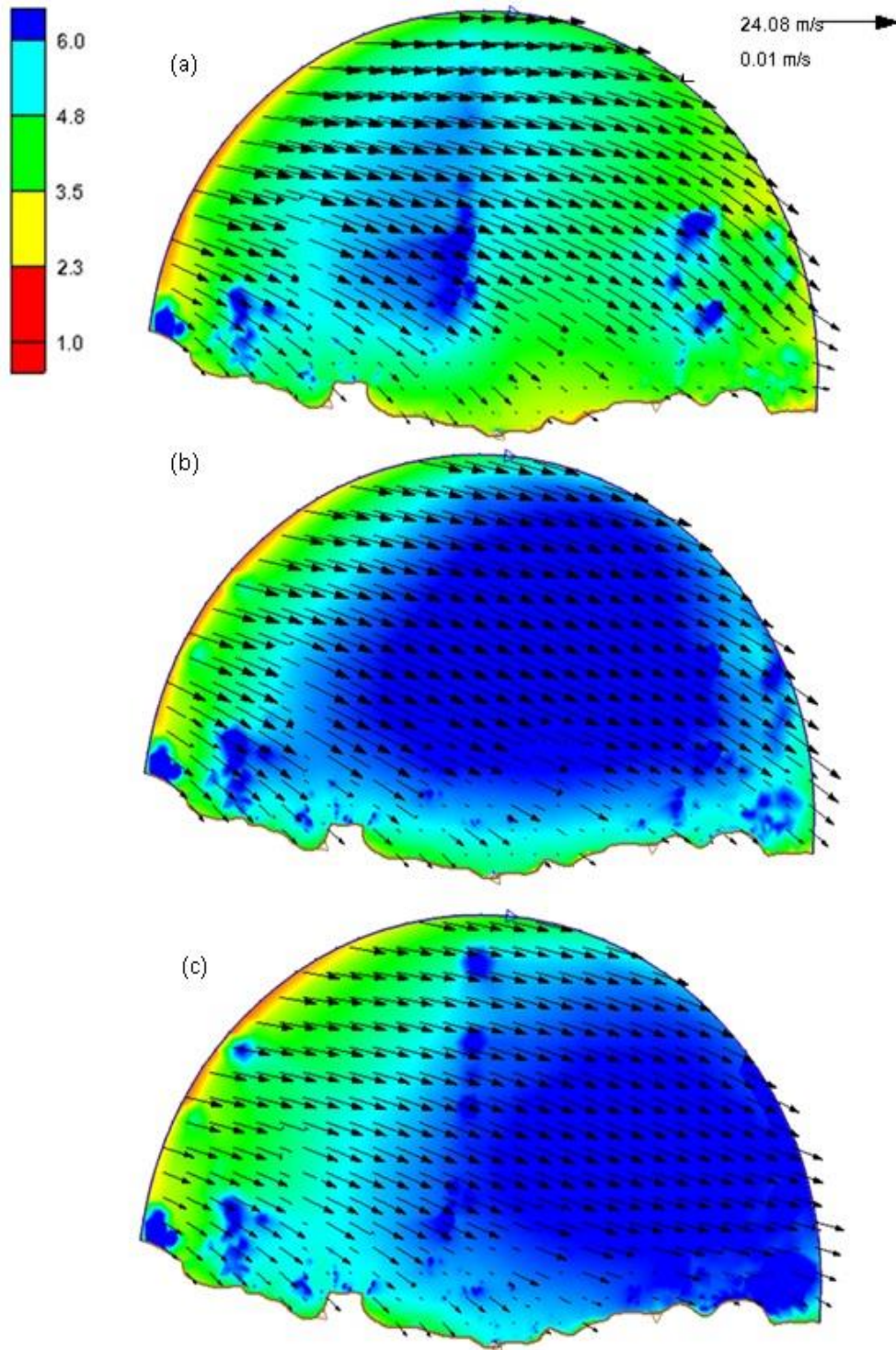


Figure 5.1: Maximum significant wave heights with contours in meters and wind velocity vectors for a) September 24,2014 00:15am b) September 24,2014 02:45am c) September 24,2014 06:30am

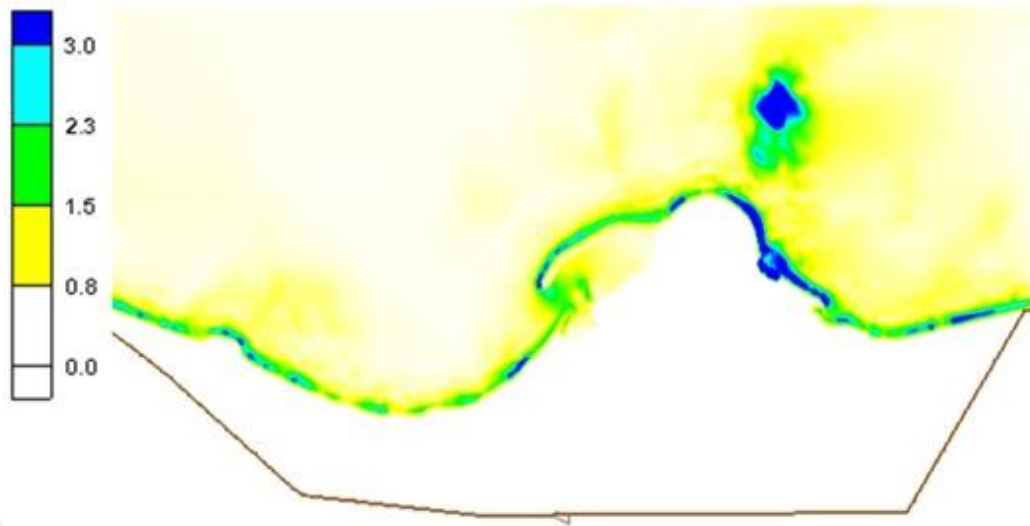


Figure 5.2: Maximum current velocities for Case 1 with contours in meters per second

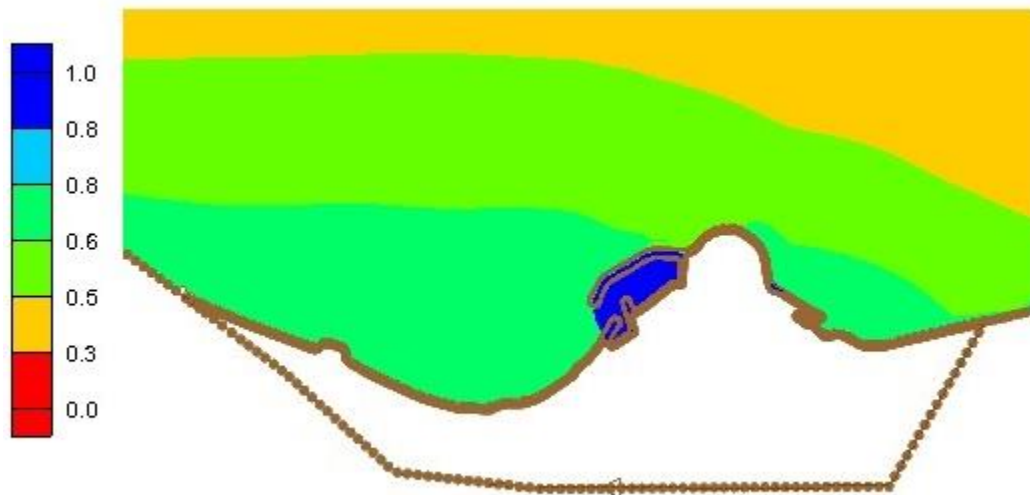


Figure 5.3: Maximum water elevations for Case 1 with contours in meters

Maximum wave height and peak period distributions for Case 1 are presented in Figure 5.4 and Figure 5.5 respectively. As it can be seen in Figure 5.4 maximum

wave heights above 7.0m are observed on northeast side of the cape. The location where sudden decrease in water depth is also occurs in this area. Minimum wave heights are observed to be located behind the breakwater whereas wave heights along the shoreline on the west side of the cape ranges from 3.0m-4.0m. On the east side of the cape, wave heights range from 5.0m up to 7.0m for some points along the shoreline.

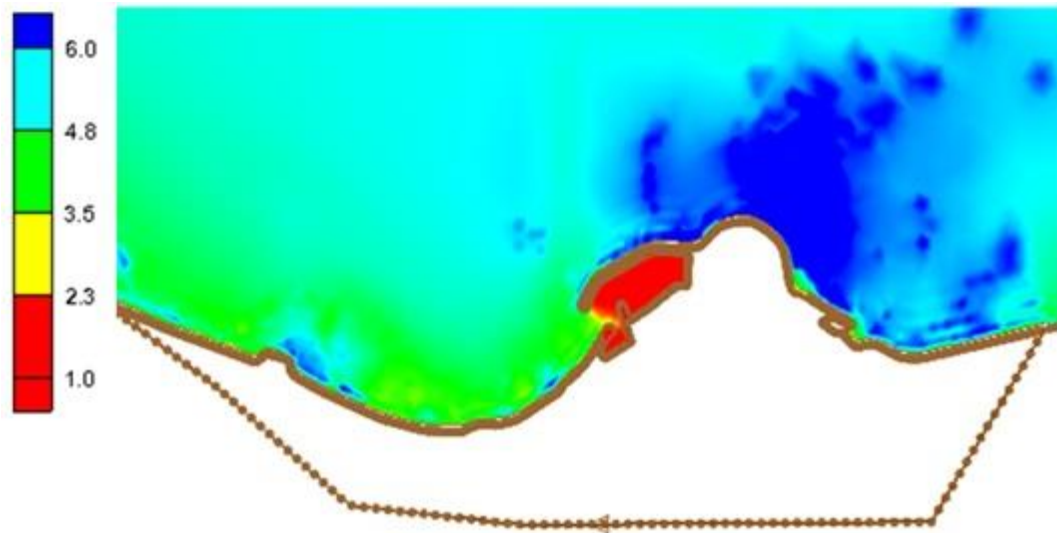


Figure 5.4: Maximum significant wave height distribution for Case 1 with contours in meters

Maximum peak periods computed along the shoreline change from 10s to 12s. Values for maximum peak periods on the northeast of the cape are observed to be greater than 20s and along the east of the cape peak periods are between 8s-11s.

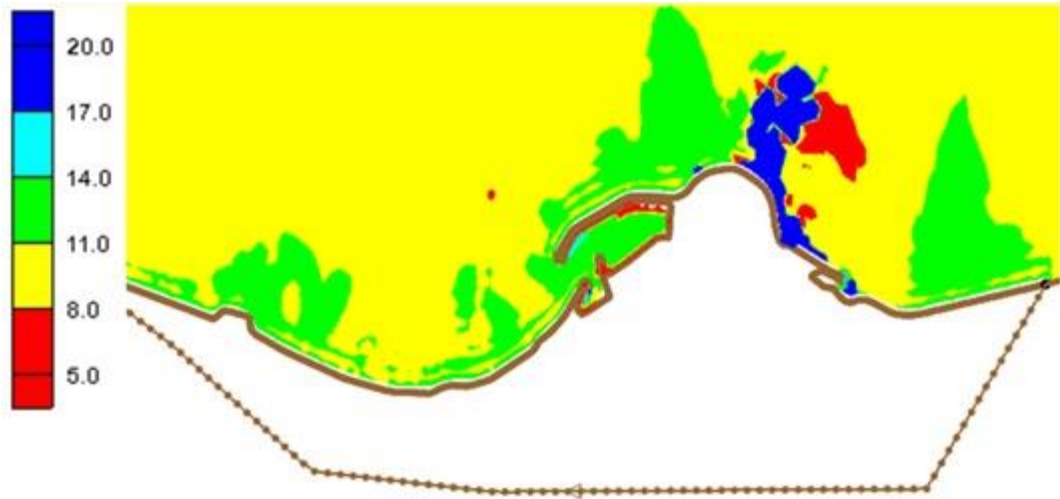


Figure 5.5: Maximum peak period distribution for Case 1 with contours in seconds

5.1.2 Case 2 Results

Maximum wave height and peak period distributions for Case 2 are presented in Figure 5.6 and Figure 5.7 respectively. As it can be seen in Figure 5.6 maximum wave heights above 7.0m are observed like Case 1 on northeast side of the cape but this time they cover a much limited area. Minimum wave heights are again occurred behind the breakwater. On the west side of the cape maximum significant wave heights along the coast are around 2.6m and reaches up to 4.0m for some locations. On the east side of the cape maximum wave heights are computed around 3.5m.

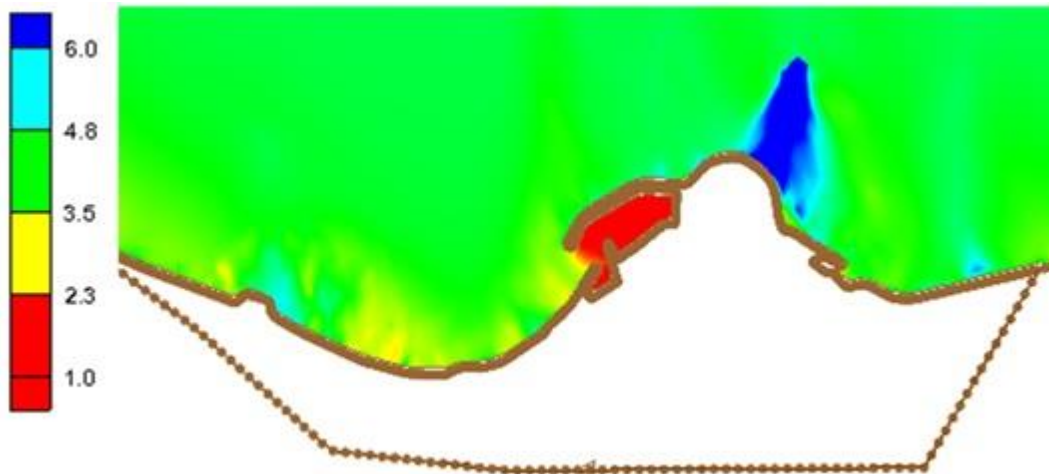


Figure 5.6: Maximum significant wave height distribution for Case 2 with contours in meters

When Figure 5.7 is compared with the results of Case 1, it can be said that there is an overall increase in the maximum peak period values.

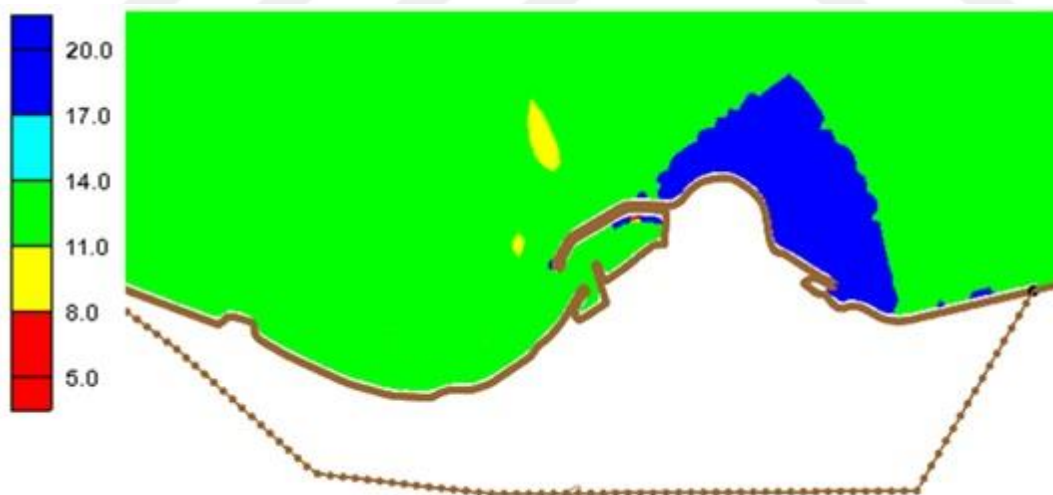


Figure 5.7: Maximum peak period distribution for Case 2 with contours in seconds

5.1.3 Case 3 Results

Maximum wave height and peak period distributions for Case 3 are presented in Figure 5.8 and Figure 5.9 respectively. Maximum wave heights above 7.0m are observed just like Case 1 on northeast side of the cape. On the west side of the cape maximum significant wave heights along the coast are slightly increased when compared to Case 1 results with heights ranging from 3.3m to 4.5m. On the east side of the cape maximum wave heights are above 5.0m. It is observed that since relaxation due to wetting drying process is disabled in ADCIRC calculations, some flooding is computed by SWAN in the southeast of the cape due to increased water heights.

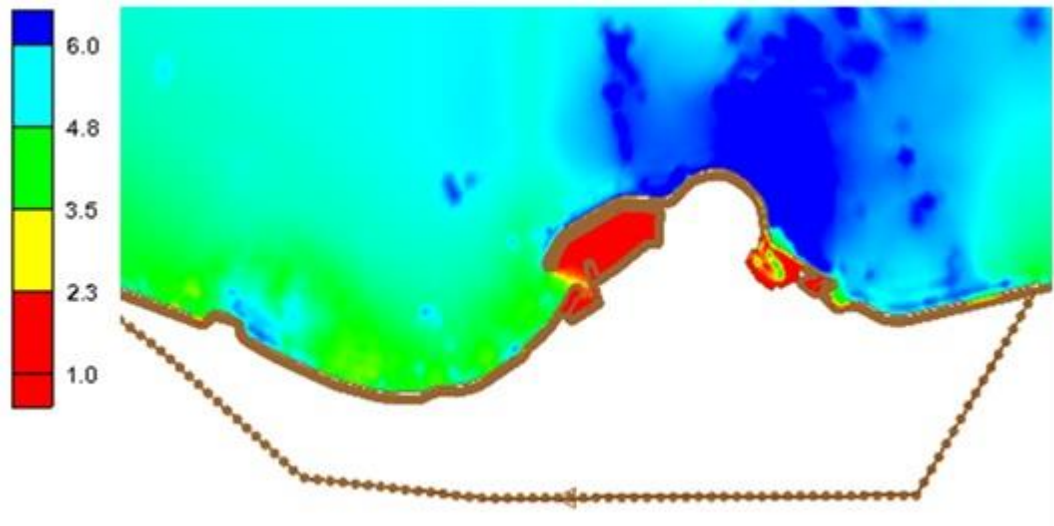


Figure 5.8: Maximum significant wave height distribution for Case 3 with contours in meters

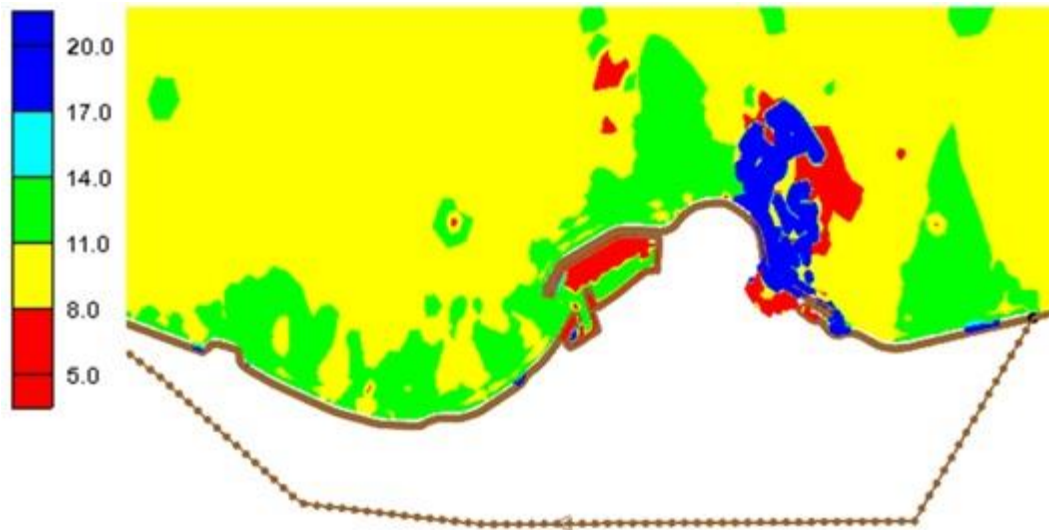


Figure 5.9: Maximum peak period distribution for Case 3 with contours in seconds

5.1.4 Case 4 Results

Distribution of maximum water elevations computed for Case 4 where wave effects are disregarded by not coupling ADCIRC model with SWAN wave model is presented in Figure 5.10. When compared to Case 1 results, there is not any significant change observed

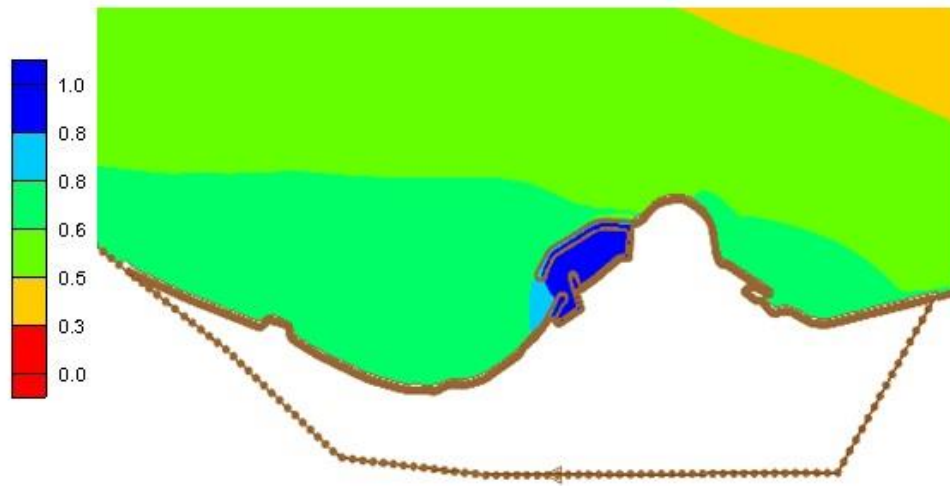


Figure 5.10: Maximum water elevations for Case 4 with contours in meters

5.1.5 Case 5 Results

Maximum wave height and peak period distributions for Case 5 are presented in Figure 5.11 and Figure 5.12 respectively. Results are observed to be similar to Case 1 results. As it can be seen in Figure 5.11 maximum wave heights above 7.0m are observed on northeast side of the cape. Wave heights along the shoreline on the west side of the cape ranges from 3.0m-4.0m. On the east side of the cape, wave heights range from 5.0m up to 7.0m for some points along the shoreline.

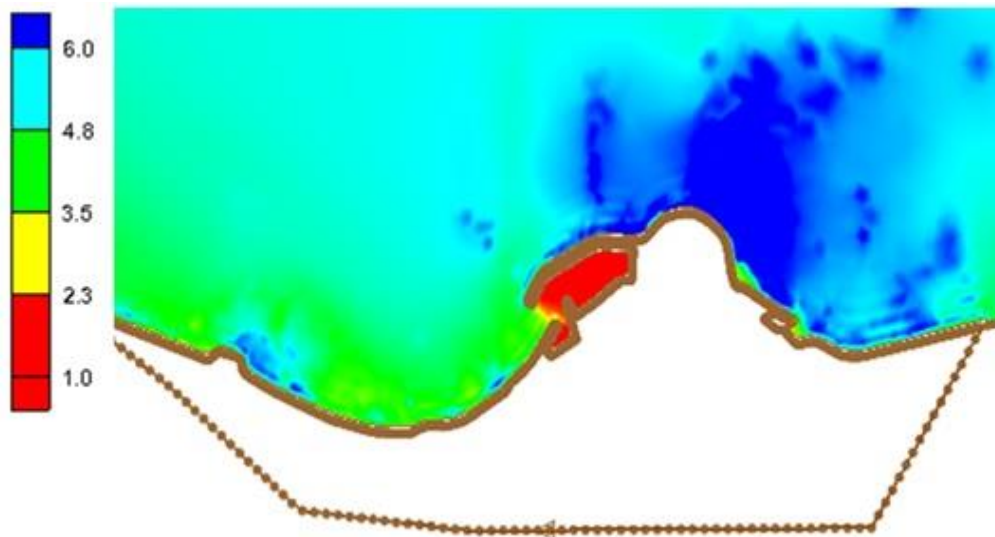


Figure 5.11: Maximum significant wave height distribution for Case 5 with contours in meters

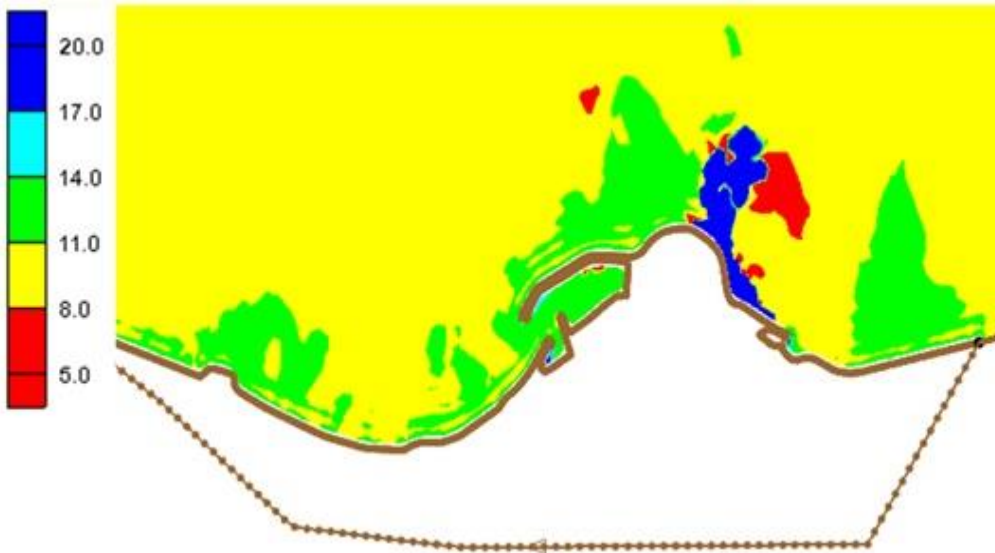


Figure 5.12: Maximum peak period distribution for Case 5 with contours in seconds

5.1.6 Case 6 Results

Maximum wave height and peak period distributions for Case 6 are presented in Figure 5.13 and Figure 5.14 respectively. It is observed that wave heights are much less than Case 1 and Case 5.

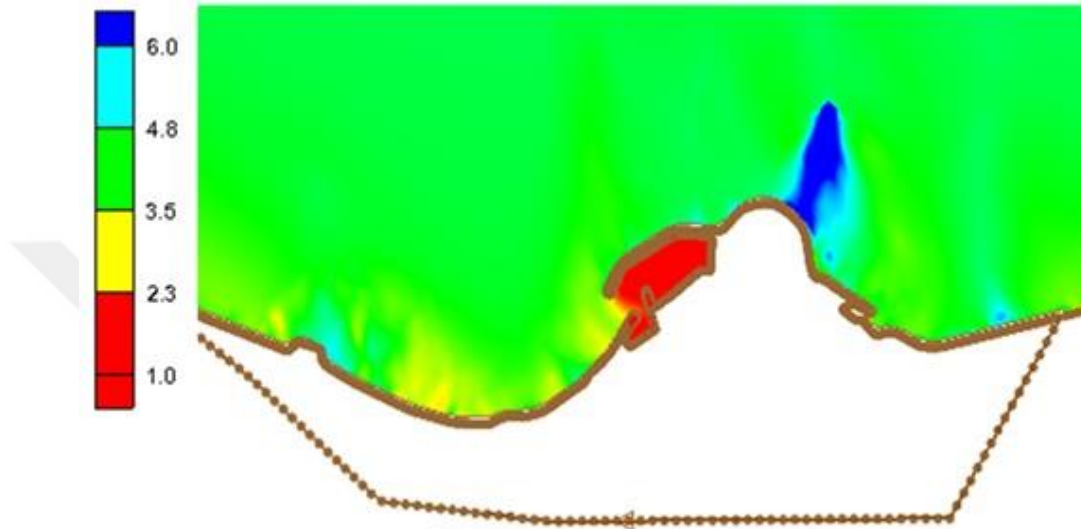


Figure 5.13: Maximum significant wave height distribution for Case 6 with contours in meters

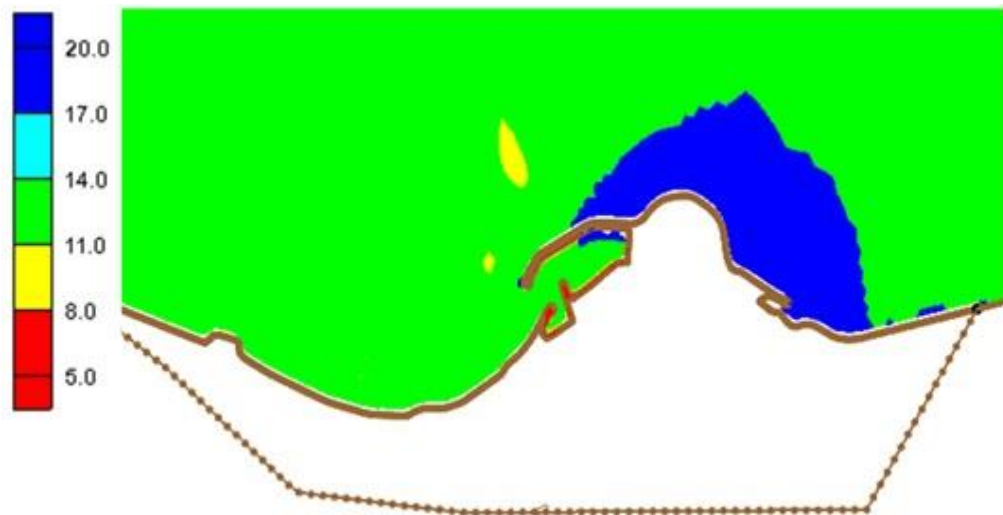


Figure 5.14: Maximum peak period distribution for Case 6 with contours in seconds

5.2 Discussion of the Storm Study Results

Comparing Case 1 to and Case 2 results shows that disabling current and water elevation information passing from ADCIRC to SWAN does not lead to significant changes in the wave heights in deep water however difference between the results observed to be increasing with decreasing water depth, Case 1 results providing higher maximum wave heights. Around the shoreline the differences were around 40% and inside the breakwater the results are decreased again. Parallel to the shoreline maximum differences in wave heights coincide with the maximum difference of computed radiation stresses. Figure 5.15 percent differences in maximum significant wave heights are presented.

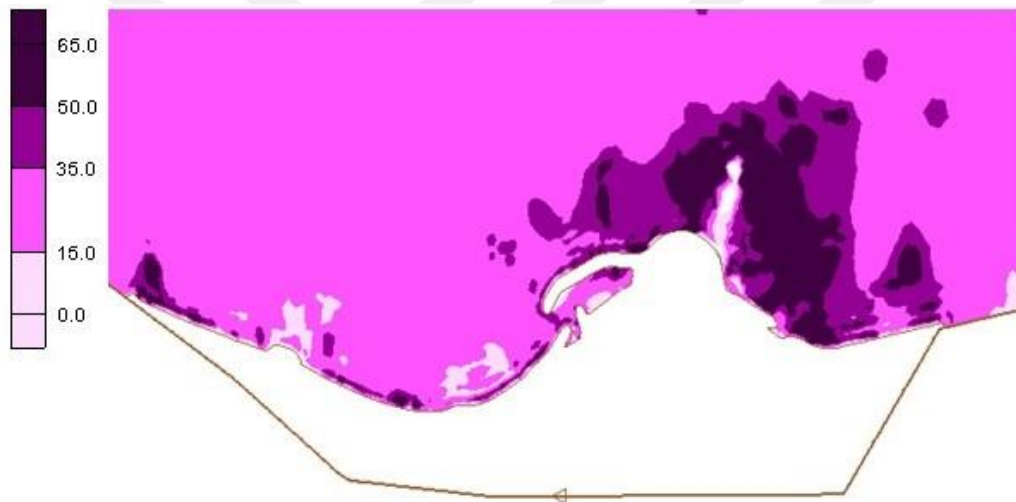


Figure 5.15: % Differences in maximum significant wave heights between Case 1 and Case 2, dark purple areas indicate where Case 1 results are higher

Maximum still water elevations are compared for two cases; one for the fully coupled simulation -Case 1- and the other one is the only ADCIRC simulation where the wave effects are disregarded - Case 4-. The effect of radiation stress terms from SWAN on maximum water elevations are found to be negligible. Differences between the water elevations range within $\pm 1\%$. This result can be expected due to low wind speeds accounted in the simulations and the

corresponding low radiation stresses. However during Hurricane Katrina simulations incorporating radiation stresses leads to up to 40% rise in maximum water levels (Dietrich,2010).

Maximum significant wave heights computed for Case 5 results are compared with Case 1 results and the differences are observed to very low. Generally the change in wave heights are observed to be between $\pm 1\%$ compared to Case 1 results for all over the domain. Near the shoreline there are higher differences occurred, yet limited around $\pm 10\%$. In Figure 5.16 change in maximum significant wave heights obtained during Case 5 simulations compared to Case 1 results is presented.

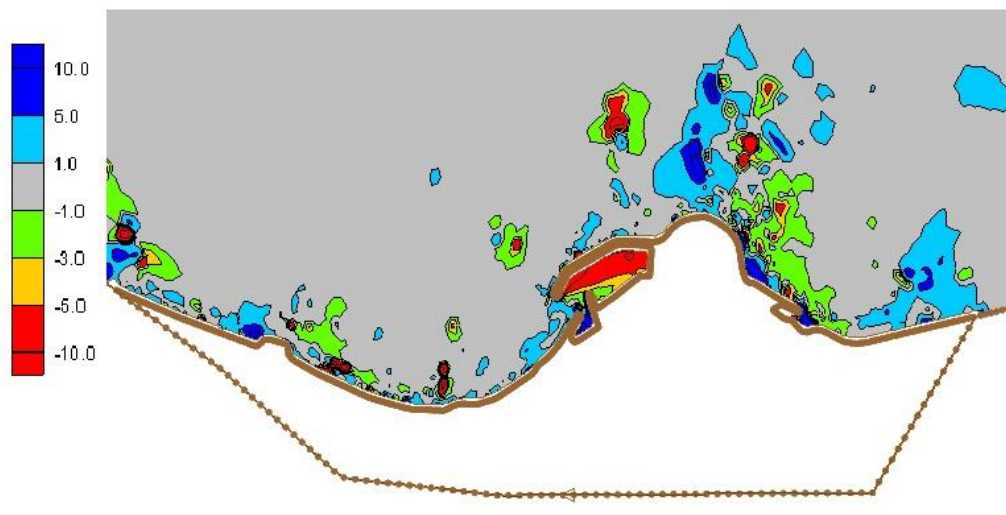


Figure 5.16: % Differences in maximum significant wave heights between Case 1 and Case 5, blue areas indicate where Case 1 results are higher

Examining Case 6 results shows that disabling current velocities to be passed to SWAN resulted decreased wave heights for almost whole domain compared to Case 1 results. Differences in maximum significant wave heights are observed to be less than 5% in deep water whereas a gradual increase is seen towards the

shore. Differences are more than 20% in west of the cape and reaches 40% on the eastern side. SWAN part of the fully coupled model obtains both current information and water elevations information from ADCIRC. When Case 6 and Case 5 results are compared, it is seen that resulted wave heights are more sensitive to current information. Figure 5.17 percent differences in maximum significant wave heights are presented.

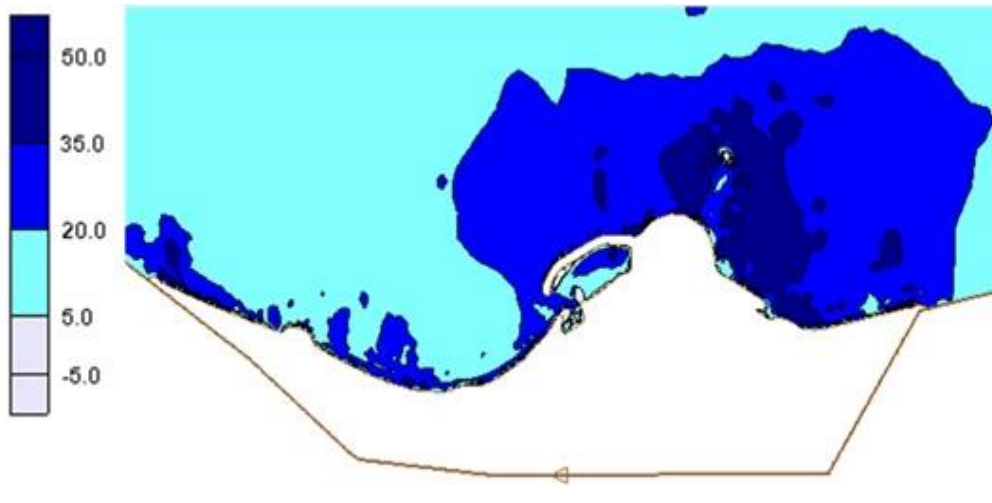


Figure 5.17: % Differences in maximum significant wave heights between Case 1 and Case 6, darker blue areas indicate where Case 1 results are higher

Closing finite amplitude term and wetting/drying option in ADCIRC resulted in slightly increased wave heights when Case 3 and Case 1 results are compared. For most of the domain the increase is less than 1% however near the shoreline differences increased. Closing wetting drying process disables the relaxation of water columns along the water-land boundary, therefore leads to more piling up of the water in this area. During analysis of the simulation results, between 20-40% increase in maximum wave heights are observed along the coastline. In

Figure 5.18 percent differences in maximum significant wave heights are presented.

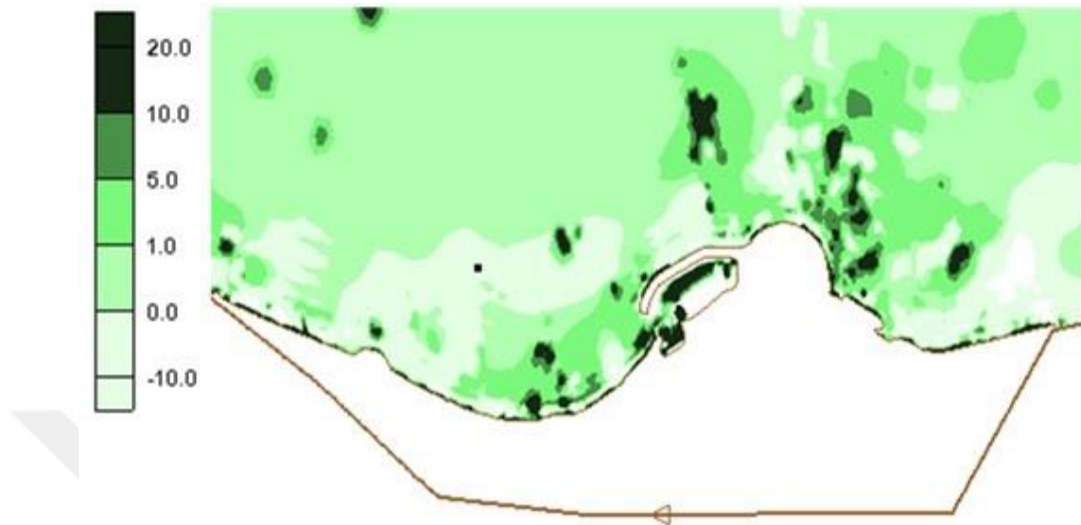


Figure 5.18: % Differences in maximum significant wave heights between Case 3 and Case 1, darker green areas indicate where Case 3 results are higher

5.3 Inundation Study Results

Inundation studies are performed for different cases. Wave parameters in front of the cape obtained from ADCIRC+SWAN simulation for Case 1 are used to create input data for Case A simulation performed by NAMI-DANCE. Significant wave height and period values are used to create water surface elevations which are then given as boundary conditions by MATLAB using JONSWAP spectrum approach with peak enhancement factor of 3.3 for 15 minutes. Other cases represents the theoretical possible scenarios.

Interpretations of the video records provided that the wave period is about 11s at the time of one of the video recording (Figure 5.19). The results of ADCIRC-SWAN simulations showed that the peak and mean periods in the storm are

11.25 sec and 9 sec respectively. The computed significant wave height in the storm from ADCIRC and SWAN simulations ranges between 4.5m and 7.5 m. Therefore three different irregular wave data (CASE A and CASE B) is used as input wave in the simulations to compute the inundation at Giresun using NAMI DANCE software. They are tabulated in Table 5.2 . The simulation results are given in the following sections separately.



Figure 5.19: Snapshots from video recording taken during the storm, two consecutive waves are marked with red ellipse (Öztürk, 2014)

During visualization of the results Golden Software programs, Surfer (Surfer® 13,2016) and Grapher (Grapher™ 12,2016) are used.

Table 5.2: Input wave parameters

Case	Hs (m)	Ts (s)
A	6	11
B	5.5	12
C	4.5	10

5.3.1 Case A Results

Irregular time series of wave fluctuations satisfying computed offshore wave characteristics (Hs and Ts) in regard to JONSWAP spectrum are computed and inputted to numerical model NAMI DANCE from the offshore border and nearshore wave motion and hence the inundation are computed.

The input time series for Hs=6m Ts=11s that is used as input from offshore boundary for Case A is presented in Figure 5.19

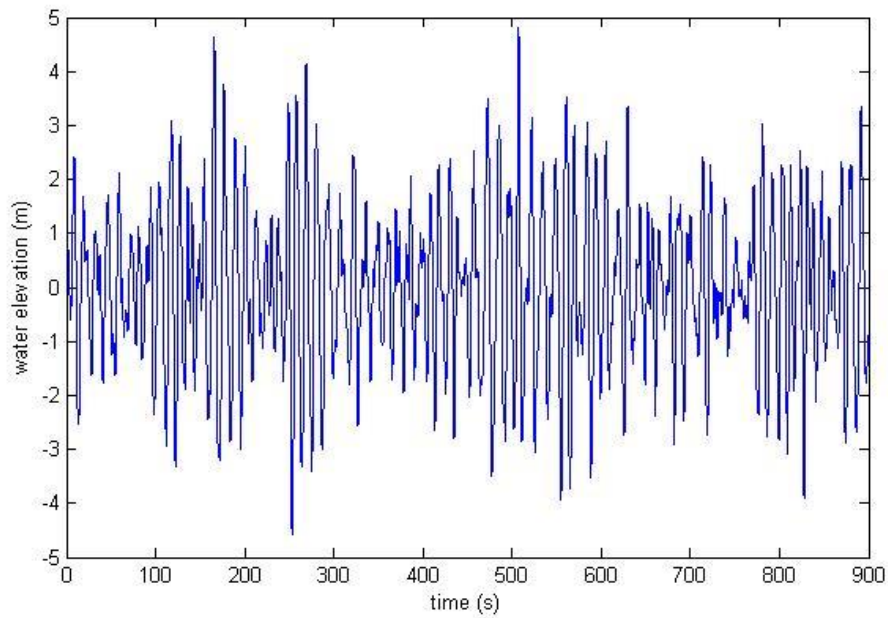


Figure 5.20: The input of irregular wave fluctuations for CASE A as $H_s=6\text{m}$ $T_s=11\text{s}$

The distribution of maximum water elevations near the coastline (at land or in the sea) are shown as bar graph in the upper picture and inundated areas are shown in the lower picture of Figure 5.21. Maximum water depths around 3.3m are observed in front of the cape. This region is also the location where maximum water heights with 5.5m height are observed near the coast. Over the tip of the breakwater flow depths reach 2.8m while along the coastline flow depths are computed to be approximately 1.0m over the flooded areas.

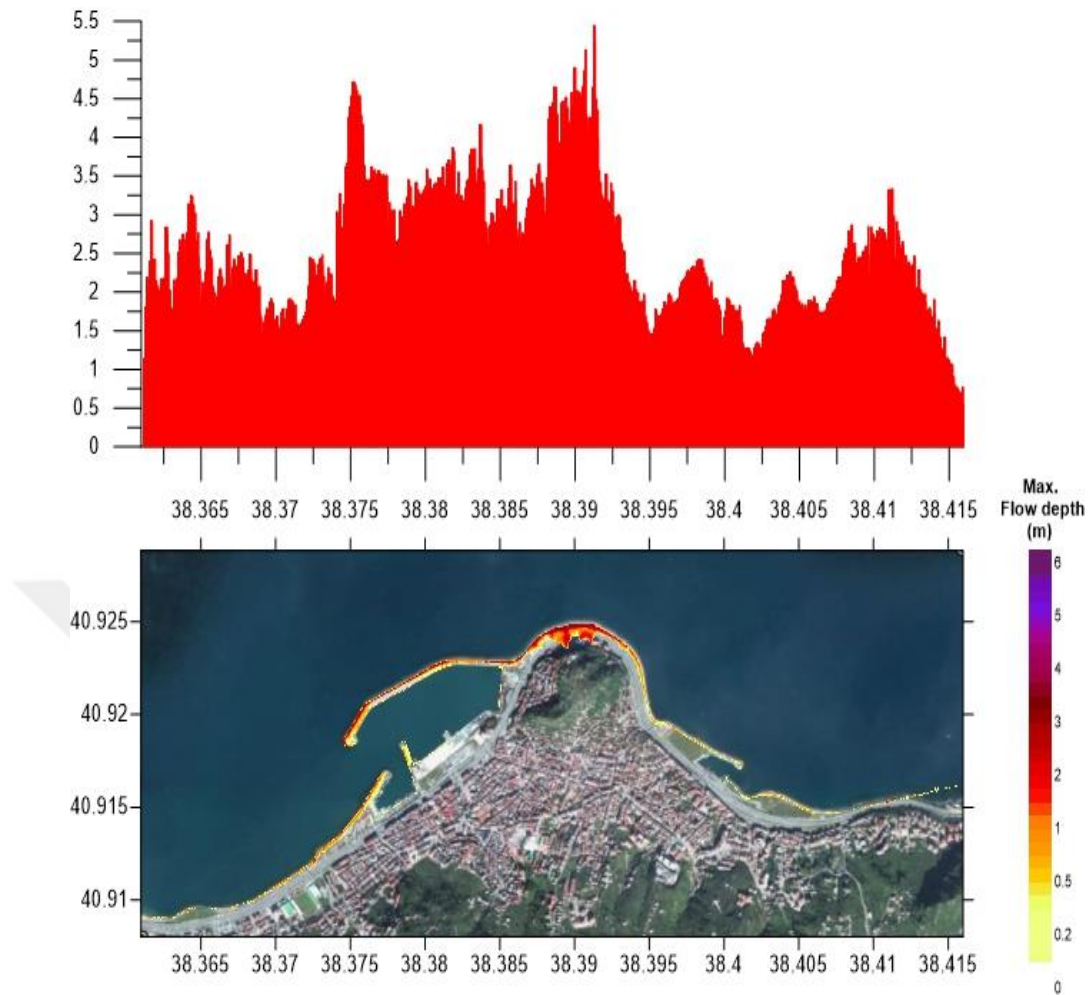


Figure 5.21: The distribution of maximum water elevations near the coast computed during the simulations (upper plot) and computed inundated areas (lower plot).

5.3.2 Case B Results

Irregular time series of wave fluctuations satisfying computed offshore wave characteristics (H_s and T_s) in regard to JONSWAP spectrum are computed and inputted to numerical model NAMI DANCE from the offshore border and nearshore wave motion and hence the inundation are computed.

The input time series for $H_s=5.5\text{m}$ $T_s=12\text{s}$ that is used as input from offshore boundary for Case B is presented in Figure 5.22.

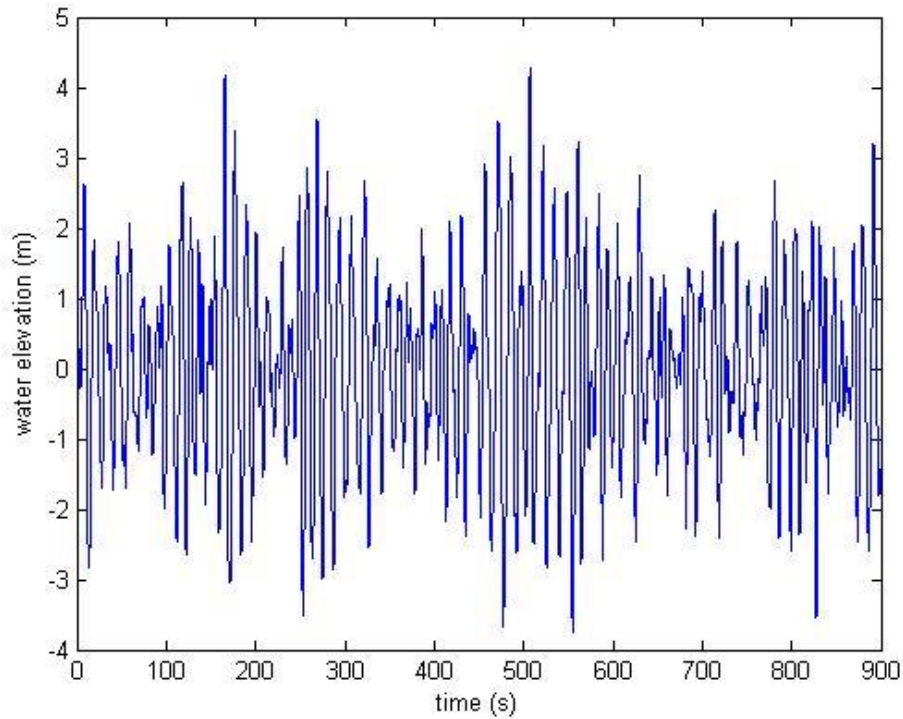


Figure 5.22: The input of irregular wave fluctuations for CASE B as $H_s=5.5\text{m}$ $T_s=12\text{s}$

The maximum water elevation computed during the simulations (upper plot) and computed inundated areas (lower plot) are shown in Figure 5.23. Maximum flow depths over the land area are observed in front of the cape with depths between 2.5m-3.0m. Flow depths over the inundated areas on the tip of the breakwater and along the shoreline are very similar to Case A results.

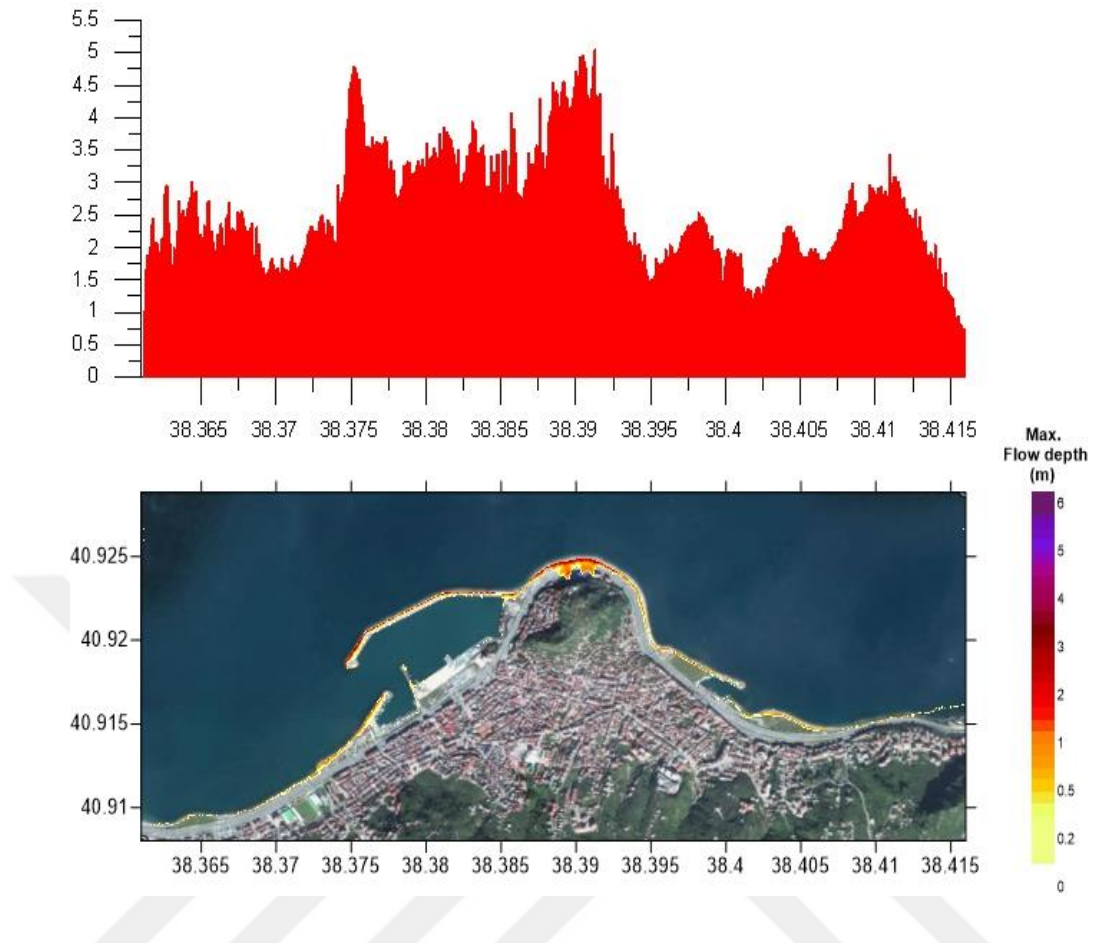


Figure 5.23: The distribution of maximum water elevations near the coast computed during the simulations (upper plot) and computed inundated areas (lower plot).

5.3.3 Case C Results

The input time series for $H_s=4.5\text{m}$ $T_s=10\text{s}$ that is used as input from offshore boundary for Case C simulation is presented in Figure 5.24.

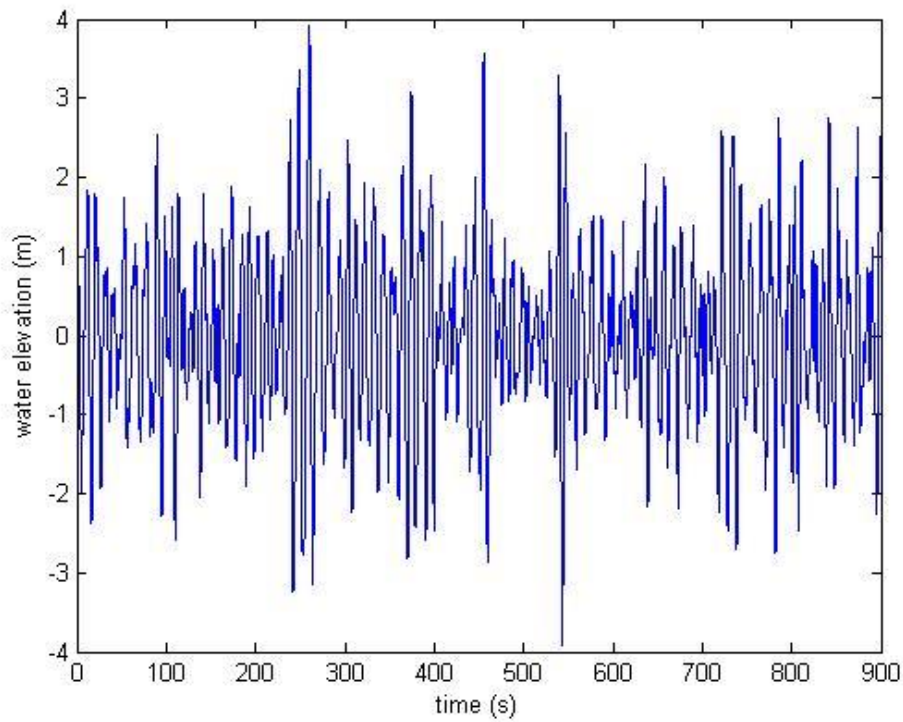


Figure 5.24: The input of irregular wave fluctuations for CASE B as $H_s=4.5\text{m}$ $T_s=10\text{s}$

Maximum water elevations near the coastline (sea or land) are shown as bar graph in the upper picture and inundated areas are shown in the lower picture in Figure 5.25. Maximum flow depths over the inundated area in front of the cape are computed to be around 2.5m. Area covered with water over the breakwater is much decreased and flow depths reach up to 1.0m depths at some points. Along the coastline inundated areas are also decreased and maximum water depths reach up to 1.0m.

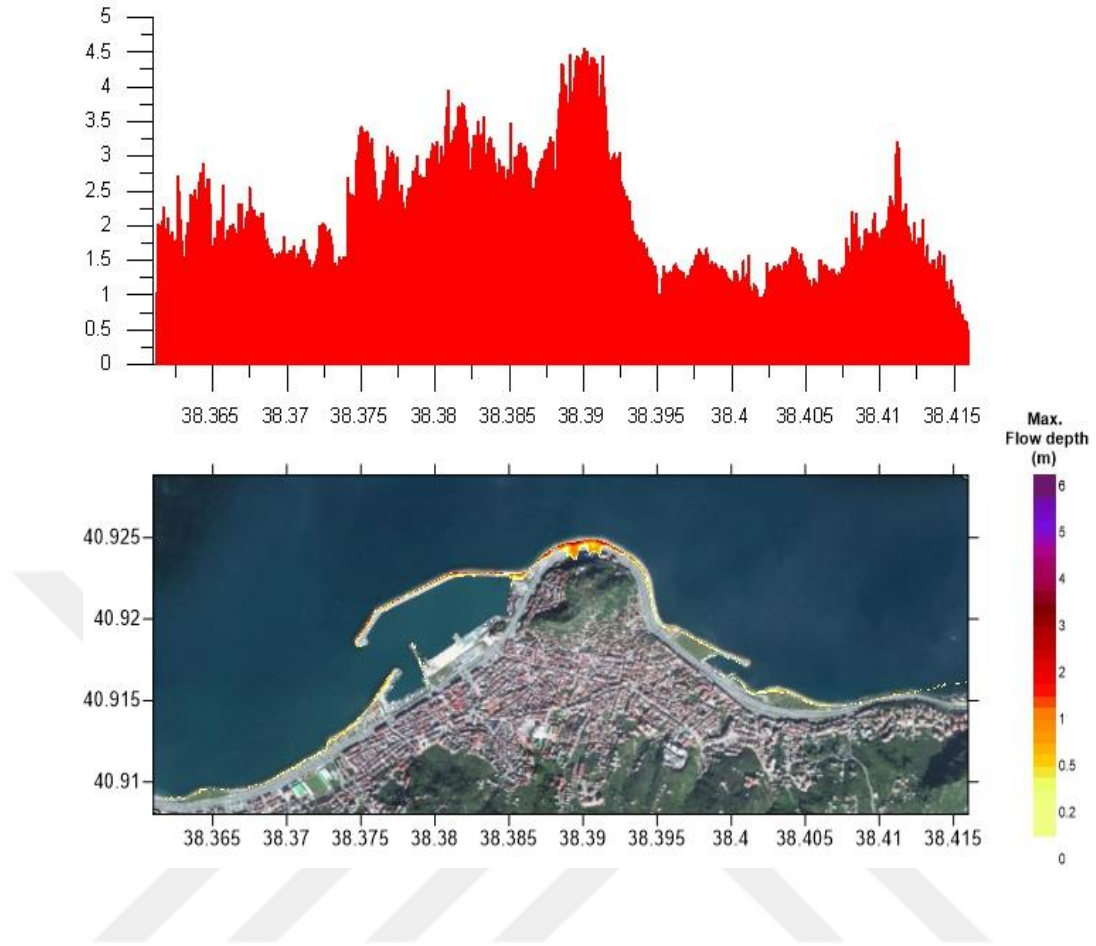


Figure 5.25: The distribution of maximum water elevations near the coast computed during the simulations (upper plot) and computed inundated areas (lower plot).

5.4 Discussion of the Inundation Study Results

When field observations are collected from news and interviews of eye witnesses, it is observed that the Black Sea Coast Highway was flooded due to storm and left severely damaged. Numerical model studies performed by NAMI-DANCE results in coastal flooding for all three cases which agrees with the observations. It is seen that the tip of the cape is the most vulnerable to flooding where maximum flow depths are observed. It has also been confirmed with eye witness and news reports. Furthermore inundated areas are also

calculated for each case and presented in Table 5.3. It is seen from Table 5.3 that more inundation occurred in case A where the wave height is largest.

Table 5.3: Inundated areas for each case

	Inundated area (km ²)	Hs	Ts
Case A	0.094815	6	11
Case B	0.092927	5.5	12
Case C	0.070782	4.5	10

Actually it is difficult to perform quantitative comparison with the observation because of absence of measure inundation data. But it can be said that qualitatively the results of simulations using the input as Hs= 6m Ts=11s show fairly well agreement with the observations. Therefore the procedure followed in this study provided qualitatively satisfactory results. As a recommendation for quantitative comparisons accurate topographical data including structural elevations should be used and compared with the on site measured data.

CHAPTER 6

CONCLUSION AND FUTURE RECOMMENDATIONS

In this study coastal inundation in Giresun due to the storm event between 23-25 September, 2014 is investigated. Storm generated wave parameters are obtained by fully coupled ADCIRC+SWAN model and obtained parameters are used to generate input data for inundation study by NAMI-DANCE. Moreover during storm study, sensitivity of the model to the shared information passes from either ADCIRC to SWAN or from SWAN to ADCIRC are analyzed. The concluding remarks are summarized as follows.

1. For the condition where maximum wind speeds having 24m/s magnitude, incorporation of wave effects by SWAN has a negligible effect on maximum water elevations.
2. Coupled (ADCIRC-SWAN) model is more sensitive to current information than water elevation information.
3. Disabling circulation effects (without ADCIRC) leads to much less wave heights especially near the coastline.
4. Due to the considerable effects of circulation observed during the study, ADCIRC+SWAN coupling is recommended for storm induced wave field studies.
5. Nonlinear shallow water equations is capable of solving long period storm waves and compute inundation and flow depths.
6. The irregular time series satisfying computed offshore wave characteristics (H_s and T_s) can be used as input to numerical model from

the offshore border and nearshore wave motion and hence the inundation can be computed.

7. The offshore wave characteristics of September 2104 storm in Giresun are around $H_s = 6\text{m}$ and $T_s = 11\text{s}$.
8. The inundation area in Giresun town during the storm is about 0.095 km^2
9. The flow depth at Giresun cape reached to 4.2m .

The followings are recommended for future studies.

1. The detailed field survey is necessary for determination of accurate inundation.
2. Accurate bathymetry and topography including structures will help to obtain accurate results and comparisons.
3. Further studies might include nonlinear shallow water equations considering breaking and/or dispersion for inundation analysis.

REFERENCES

- Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER), Global Digital Elevation Model Version 2 (GDEM V2) (2011). Retrieved 20 January 2015, from <http://gdex.cr.usgs.gov/gdex/>.
- Andrey Zaytsev, Irina Kostenko, Andrey Kurkin, Efim Pelinovsky and Ahmet Yalciner, (2016), Simulation scenarios of the tsunami in the Okhotsk Sea (due to the earthquake of 05/24/2013), *Turkish J Earth Sci* (2016)25:©TÜBİTAK doi:10.3906/yer-1509-6
- Aquaveo (n.d.). *SMS Introduction* | *Aquaveo.com*. Retrieved 1 January 2016, from <http://www.aquaveo.com/software/sms-surface-water-modeling-system-introduction>
- Aytöre, B. (2015). Assessment of tsunami resilience of ports by high resolution numerical modeling: a case study for Haydarpasa port in the sea of Marmara, 93 p., M.Sc. thesis, *METU Department of Civil Engineering*, Ankara, Turkey.
- Bender, C., Miller, W., Naimaster, A., & Mahoney, T. (2012). WAVE MODELING WITH SWAN+ADCIRC FOR THE SOUTH CAROLINA COASTAL STORM SURGE STUDY. *Int. Conf. Coastal. Eng.*, 1(33). <http://dx.doi.org/10.9753/icce.v33.waves.48>
- Black, P. G., D'Asaro, E. A., Drennan, W. M., & French, J. R. (2007). AIR-SEA EXCHANGE IN HURRICANESL: Synthesis of Observations from the Coupled Boundary Layer Air-Sea Transfer Experiment. *Bulletin of the American Meteorological Society*, 88(3), 357. doi:10.1175/BAMS-88-3-357
- Blumberg, A. F. and Mellor, G. L. (1987) A Description of a Three-Dimensional Coastal Ocean Circulation Model, In *Three-Dimensional*

Coastal Ocean Models (ed N. S. Heaps), American Geophysical Union, Washington, D.C.. doi: 10.1029/CO004p0001

Çankaya, Z.C. (2015). High Resolution Tsunami Vulnerability Assessment by GIS-Based Multi-Criteria Decision Making Analysis at Yenikapı, İstanbul. M.Sc. Thesis, 94p, METU, Department of Geological Engineering, Ankara, Turkey

Cavaleri, L., Malanotte-Rizzoli, P. (1981). Wind wave prediction in shallow water: theory and applications. *J. Geophys. Res.* 86 (C11), 10961–10973.

Cicin-Sain, B., Knecht, R. W., & Foster, N. (1999). Trends and future challenges for US national ocean and coastal policy. *National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA*. Retrieved from http://oceanservice.noaa.gov/websites/retiredsites/natdia_pdf/ctrends_proceed.pdf

Collet, I., & Engelbert, A. (2013). Coastal regions: people living along the coastline, integration of NUTS 2010 and latest population grid. *Statistics in focus*, 30, 2013.

Deadliest World Tropical Cyclones | Weather Underground. (2016). *Wunderground.com*. Retrieved 27 January 2016, from <https://www.wunderground.com/hurricane/deadlyworld.asp?MR=1>

Dietrich, J. C. (2011). *Development and application of coupled hurricane wave and surge models for southern Louisiana*. University of Notre Dame.

Dietrich, C. (n.d.1) *Definition of storm sectors from Black et al. (2007)*. Retrieved 01 January 2016 from <https://ccht.ccee.ncsu.edu/wind-drag-based-on-storm-sectors/>

Dietrich, C. (n.d.2) *Variation of wind drag coefficient in storm sectors after Powell (2006)*. Retrieved 01 January 2016 from <https://ccht.ccee.ncsu.edu/wind-drag-based-on-storm-sectors/>

EMU Park Online,(n.d.). *Storm surge and storm tide*. Retrieved 20 January 2016 from http://www.emuparkonline.com.au/ses/get_ready_queensland.html

Fallis, A. (2013). SCIENTIFIC AND TECHNICAL DOCUMENTATION. *Journal of Chemical Information and Modeling*, 53(9), 1689–1699. doi:10.1017/CBO9781107415324.004

Garratt, J. R. (1977). Review of Drag Coefficients over Oceans and Continents. *Monthly Weather Review*. doi:10.1175/1520-0493(1977)105<0915:RODCOO>2.0.CO;2

General Bathymetric Chart of the Oceans, GEBCO_08 Grid (Version 20100927) (2010). Retrieved 20 January 2015, from <http://www.gebco.net>

Giresun'da dev dalgalar sahil yolunu sular altında bıraktı. (2014). *Habername.com*. Retrieved 2 October 2015, from <http://www.habername.com/haber-giresunda-dev-dalgalar-sahil-yolunu-sular-altinda-birakti-izle-102799.htm>

Grapher™ 12 (2016). Retrieved 1 January 2016, from <http://www.goldensoftware.com/products/grapher>

GRID-Arendal,. (2006). *Coastal population and altered land cover in coastal zones (100 km of coastline)*. Retrieved 20 January 2016, from <http://www.grida.no/graphicslib>

GRID-Arendal,. (2016). *Population of Coastal Cities*. Retrieved 20 January 2016, from <http://www.grida.no/graphicslib>

Hinrichsen, D. (1998). The Coastal Population Explosion. *The Next 25 Years: Global Issues*, 27–29.

Holthuijsen, L. H. (2015). *Waves in Oceanic and Coastal Waters. Cambridge University Press* (Vol. 1). doi:10.1017/CBO9781107415324.004

Hurricanes in History. (2016). Retrieved 27 January 2016, from <http://www.nhc.noaa.gov/outreach/history>

Jelesnianski, C., Chen, J., & Shaffer, W. (1992). SLOSH: Sea, lake, and overland surges from hurricanes. *NOAA Tech. Rep. NWS 48, NOAA AOML Library, Miami, Fla.* (Vol. 48). Retrieved from http://slosh.nws.noaa.gov/sloshPub/pubs/SLOSH_TR48.pdf

Kamphuis, J. W. (2000). Introduction to Coastal Engineering and Management. *Advanced Series on Ocean Engineering* (Vol. 16). doi:10.1007/s13398-014-0173-7.2

Kennedy, A. B., Westerink, J. J., Smith, J. M., Hope, M. E., Hartman, M., Taflanidis, A. a., ... Dawson, C. (2012). Tropical cyclone inundation potential on the Hawaiian Islands of Oahu and Kauai. *Ocean Modelling*. doi:10.1016/j.ocemod.2012.04.009

Kerr, P., Martyr, R., Donahue, A., Hope, M., Westerink, J., & Luetlich, R. et al. (2013). U.S. IOOS coastal and ocean modeling testbed: Evaluation of tide, wave, and hurricane surge response sensitivities to mesh resolution and friction in the Gulf of Mexico. *J. Geophys. Res. Oceans*, 118(9), 4633-4661. <http://dx.doi.org/10.1002/jgrc.20305>

Kerr, P. C., Martyr, R. C., Donahue, A. S., Hope, M. E., Westerink, J. J., Jr, R. A. L., ... Westerink, H. J. (2013). U . S . IOOS coastal and ocean modeling testbed: Evaluation of tide , wave , and hurricane surge response sensitivities to mesh resolution and friction in the Gulf of Mexico, 118, 4633–4661. doi:10.1002/jgrc.20305

Kian,R. (2015). *TSUNAMI INDUCED WAVE AND CURRENT AMPLIFICATION AND SEDIMENTATION IN CLOSED BASINS*. (Doctoral dissertation, MIDDLE EAST TECHNICAL UNIVERSITY).

Kian, R., Velioglu, D., Yalciner, A. C., & Zaytsev, A. (2016). Effects of Harbor Shape on the Induced Sedimentation; L-Type Basin. *Journal of Marine Science and Engineering*, 4(3), 55.

- Kuznetsov, S. Y., Saprykina, Y. V., Kos'yan, R. D., & Pushkarev, O. V. (2006, May). Formation mechanism of extreme storm waves in the Black sea. *Doklady Earth Sciences* (Vol. 408, No. 1, pp. 570-574). MAIK Nauka/Interperiodica.
- Liu, H., Xie, L., Pietrafesa, L. J., & Peng, M. (2006). Effect of ocean surface waves on storm surge and coastal flooding. *27th Conference on Hurricanes and Tropical Meteorology*, 24–28.
- Longuet-Higgins, M. S., & Stewart, R. w. (1964). Radiation stresses in water waves; a physical discussion, with applications. *Deep Sea Research and Oceanographic Abstracts*, 11(4), 529–562. doi:10.1016/0011-7471(64)90001-4
- Luettich, R.A., Westerink, J.J. & Scheffner, N.W. (1992). ADCIRC: an advanced three-dimensional circulation model for shelves coasts and estuaries, report 1: theory and methodology of ADCIRC-2DDI and ADCIRC-3DL, *Dredging Research Program Technical Report DRP-92-6*, U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS, 137p.
- Luettich, R.A. and Westerink, J.J. (2004). Formulation and numerical implementation of the 2D/3D ADCIRC finite element model, version 44.XX, 74 pp. Available at http://adcirc.org/adcirc_theory_2004_12_08.pdf.
- Moon, I. J., Oh, I. S., Murty, T., & Youn, Y. H. (2003). Causes of the unusual coastal flooding generated by Typhoon Winnie on the West Coast of Korea. *Natural Hazards*, 29(3), 485–500. doi:10.1023/A:1024798718572
- NAMI DANCE (2016). Manual of Numerical Code NAMI DANCE. Retrieved 15 October 2015, from <http://namidance.ce.metu.edu.tr>.
- Niedoroda, A. W., Resio, D. T., Toro, G. R., Divoky, D., Das, H. S., & Reed, C. W. (2010). Analysis of the coastal Mississippi storm surge hazard. *Ocean Engineering*, 37(1), 82–90. doi:10.1016/j.oceaneng.2009.08.019

NOAA. (2013). National Coastal Population Report. *NOAA's State of the Coast*.

Öztürk, C. (2014). *Giresun'da Fırtına Etkili Oldu*. [Video file]. Retrieved 01 January 2016 from <https://www.youtube.com/watch?v=LxEpuTRoNC0>

Peng, M., Xie, L., & Pietrafesa, L. J. (2004). A numerical study of storm surge and inundation in the Croatan–Albemarle–Pamlico Estuary System. *Estuarine, Coastal and Shelf Science*, 59(1), 121–137. doi:10.1016/j.ecss.2003.07.010

Peng, M., Xie, L. & Pietrafesa, L. J. (2006), A numerical study on hurricane-induced storm surge and inundation in Charleston Harbor, South Carolina, *Journal of Geophysical Research*, 111, C08017, doi:10.1029/2004JC002755.

Pierson, W. J. and L. Moskowitz, 1964, A proposed spectral form for fully developed wind seas based on the similarity theory of S. A. Kitaigorodskii, *J. Geophys. Res.*, 69, 24, 5181–5190

Powell, M. D., & Ginis, I. (2006). Drag coefficient distribution and wind speed dependence in tropical cyclones. *Final Report to the National Oceanic and Atmospheric Administration (NOAA) Joint Hurricane Testbed (JHT) Program*.

Rusu, Liliana, and Dorin Butunoiu. "Numerical modelling of the wave propagation close to the Sacalin island in the Black Sea." *Journal of Marine Science and Technology* 23.5 (2015): 669-677.

Salmon, J. (2011). Re-scaling the Battjes-Janssen model for depth- induced wave-breaking, (November). doi:10.13140/2.1.2525.9842

Schwartz, M. L. (Ed.). (2005). *ENCYCLOPEDIA of COASTAL SCIENCE*. Springer.

- Sebastian, A., Proft, J., Dietrich, J. C., Du, W., Bedient, P. B., & Dawson, C. N. (2014). Characterizing hurricane storm surge behavior in Galveston Bay using the SWAN+ADCIRC model. *Coastal Engineering*, 88, 171–181. doi:10.1016/j.coastaleng.2014.03.002
- Sheng, Y. P., (1986). A Three-Dimensional Mathematical Model of Coastal, Estuarine and Lake Currents Using Boundary-Fitted Grid. *Technical Report No. 585*, Aeronautical Research Associates of Princeton, Princeton, New Jersey.
- Sheng, Y. P., (1989). Evolution of a three-dimensional curvilinear-grid hydrodynamic model for estuaries, lakes and coastal waters: CH3D. *Estuarine and Coastal Modeling*, pp. 40-49.
- Sheng, Y. P., Zhang, Y., Alymov, V. & Lee, J. (2002). Implementation of wetting-and-drying algorithm to CH3D. Technical Report, Department of Civil and Coastal Engineering, University of Florida, Gainesville
- Sheng, Y. P., Zhang, Y., & Paramygin, V. a. (2010). Simulation of storm surge, wave, and coastal inundation in the Northeastern Gulf of Mexico region during Hurricane Ivan in 2004. *Ocean Modelling*, 35(4), 314–331. doi:10.1016/j.ocemod.2010.09.004
- Shuto, N., Imamura, F., Yalciner, A. C., & Ozyurt, G. (2006). *TUNAMI N2: Tsunami Modeling Manual*. Iwate Prefectural University.
- Sun, Y., Chen, C., Beardsley, R. C., Xu, Q., Qi, J., & Lin, H. (2013). Impact of current-wave interaction on storm surge simulation: A case study for Hurricane Bob. *Journal of Geophysical Research: Oceans*, 118(5), 2685–2701. doi:10.1002/jgrc.20207
- Surfer® 13 (2016). Retrieved 1 January 2016, from <http://www.goldensoftware.com/products/surfer>
- Tarakcioglu, G. O., Yalciner, A. C., Kirezci, C., Guler, G., Baykal, C., Erol, O., ..., Kurkin, A. (2015). Recent Extreme Marine Events at Southern Coast of

Black Sea. Poster session presented at European Geosciences Union General Assembly 2015, Vienna, Austria.

Tolman, H. L. (1992). Effects of numerics on the physics in a third-generation wind-wave model, *J. Phys. Oceanogr.*, 22, 10, 1095–1111

Van Vledder, G., & Akpınar, A. (2015). Wave model predictions in the Black Sea: Sensitivity to wind fields. *Physics Procedia*, 53, 161–178. doi:10.1016/j.apor.2015.08.006

WACOP (n.d.). *Diagram of the parameters measured*. Retrieved 13 April 2016 from http://wacop.gsd.spc.int/STC_Winston_inundation.html

Walton, T. L., & Dean, R. G. (2009). Landward limit of wind setup on beaches. *Ocean Engineering*, 36(9), 763–766

Weisberg, R. H., & Zheng, L. (2005). A simulation of the Hurricane Charley storm surge and its breach of North Captiva Island. *Florida Scientist*, (January), 1–26.

Weisberg, R., & Zheng, L. (2006). Hurricane Storm Surge Simulations for Tampa Bay. *Estuaries and Coasts*, 29(6), 899–913. doi:10.1007/BF02798649

Wu, J. (1982), Wind-stress coefficients over sea surface from breeze to hurricane, *J. Geophys. Res.*, 87(C12), 9704–9706, doi:10.1029/JC087iC12p09704

Xie et al. (2004). Incorporation of a Mass-Conserving Inundation Scheme into a Three Dimensional Storm Surge Model.pdf.

YALCINER, A.C., SYNOLAKIS, C.E., ALPAR, B., BORRERO, J., ALTINOK, Y., IMAMURA, F., TINTI, S., ERSOY, S., KURAN, U., PAMUKCU, S., KANOGLU, U. (2001). Field Surveys and Modeling 1999 Izmit Tsunami, International Tsunami Symposium ITS 2001, Paper 4–6, Seattle, Washington, pp. 557–563.

- YALCINER, A.C., ALPAR,B., ALTINOK,Y., OZBAY,I., IMAMURA,F (2002). Tsunamis in the Sea of Marmara: Historical Documents for the Past, Models for Future, *Marine Geology*, 2002, 190, pp. 445–463.
- YALCINER, A.C., PELINOVSKY, E., SYNOLAKIS C., OKAL, E (2003). NATO SCIENCE SERIES, Submarine Landslides and Tsunamis, Publisher: Kluwer Academic Publishers, Netherlands (Editors; Yalciner, A.C., Pelinovsky, E., Synolakis, C., Okal, E.), 329 Pages, ISBN: 1-4020-1348-5 (HB), ISBN: 1-4020-1349-3 (PB).
- YALCINER, A., PELINOVSKY, E., TALIPOVA, T., KURKIN, A., KOZELKOV,A. and ZAITSEV, A (2004). Tsunamis in the Black Sea: Comparison of the Historical, Instrumental, and Numerical Data, *J. Geophys.Res.*, AGU,V109,C12023, doi:10.1029/2003JC002113.
- YALCINER, A.C. and PELINOVSKY, E. (2007). A Short Cut Numerical Method for Determination of Resonance Periods of Free Oscillations in Irregular Shaped Basins, *Ocean Engineering*, Vol. 34, Issues 5–6, April 2007, pp. 747–757.
- YALCINER, A.C., OZER, C., KARAKUS, H., ZAYTSEV, A., GULER, I. (2010). Evaluation of Coastal Risk at Selected Sites against Eastern Mediterranean Tsunamis, *Proceedings of 32nd International Conference on Coastal Engineering (ICCE 2010)*, Shanghai, China, June 30–July 5, 2010.
- Yalciner, A.C., A. Zaytsev, B. Aytore, I. Insel, M. Heidarzadeh, R. Kian, and F. Imamura. (2014). A possible submarine landslide and associated tsunami at the Northwest Nile Delta, Mediterranean Sea. *Oceanography* 27(2):68–75, <http://dx.doi.org/10.5670/oceanog.2014.41>.
- ZAHIBO, N., PELINOVSKY, E.,YALCINER, A.C., KURKIN, A., KOZELKOV, A., ZAITSEV, A. (2003). Modeling the 1867 Virgin Island Tsunami, *Journal of Natural Hazards and Earth System Sciences*, European Geosciences Union, 3, June-2003, pp. 367–376.

ZAITSSEV, A., YALCINER, A.C., PELINOVSKY, E., KURKIN, A., OZER, C., INSEL, I., KARAKUS, H., OZYURT, G. (2008). Tsunamis in Eastern Mediterranean, Histories, Possibilities and Realities, *Proceedings of 7th International Conference on Coastal and Port Engineering in Developing Countries*, Dubai, UAE, February 24–28, 2008.

Zijlema, M., Van Vledder, G. P., & Holthuijsen, L. H. (2012). Bottom friction and wind drag for wave models. *Coastal Engineering*, 65, 19–26. doi:10.1016/j.coastaleng.2012.03.002

