



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**FIELD OBSERVATIONS AND SWAN MODEL
PREDICTIONS OF WAVE EVOLUTION IN A MUDDY
COASTAL ENVIRONMENT**

by

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June 2009

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 2009	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE Field Observations and SWAN Model Predictions of Wave Evolution in a Muddy Coastal Environment			5. FUNDING NUMBERS	
6. AUTHOR(S) Lincoln Thomas Trainor				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) It is well known that the presence of mud deposits on the continental shelf can cause dramatic damping of ocean surface waves, but quantitative field observations are very scarce. Wave prediction models currently lack a physics-based representation of the mud-induced dissipation process, and hence the accuracy of wave predictions in muddy littoral environments is unknown. This thesis presents a comprehensive field data set for comparison with the operational wave model SWAN (Simulating Waves Nearshore). During February to March, 2008, an extensive array of 16 wave measuring instruments was deployed on the muddy shelf of Western Louisiana in depths ranging from 13 to 4 m. Box cores were collected at all instrument sites to characterize bottom sediment properties (Garcia-Garcia et al., 2008). Analysis of local wind sea events along two cross-shore transects shows a decay of waves from the deeper to the shallower instruments, with the strongest decay at the muddiest site. The wave spectra evolution shows strong decay of high-frequency wind sea spectral levels and weaker decay at the lower swell frequencies. The default bottom friction parameterization (the JONSWAP model with coefficient value $0.067 m^2/s^3$) in the SWAN model generally yields reasonable estimates of nearshore wave heights that are sufficiently accurate for most operational Navy applications. However, the predicted cross-shore wave decay is more gradual than is observed and the model does not capture the spectra decay at high frequencies.				
14. SUBJECT TERMS Ocean waves, Continental Shelf, Mud, Littoral, SWAN.			15. NUMBER OF PAGES 91	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

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**FIELD OBSERVATIONS AND SWAN MODEL PREDICTIONS OF WAVE
EVOLUTION IN A MUDDY COASTAL ENVIRONMENT**

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MASTER OF SCIENCE IN PHYSICAL OCEANOGRAPHY

from the

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ABSTRACT

It is well known that the presence of mud deposits on the continental shelf can cause dramatic damping of ocean surface waves, but quantitative field observations are very scarce. Wave prediction models currently lack a physics-based representation of the mud-induced dissipation process, and hence the accuracy of wave predictions in muddy littoral environments is unknown. This thesis presents a comprehensive field data set for comparison with the operational wave model SWAN (Simulating Waves Nearshore). During February to March 2008, an extensive array of 16 wave measuring instruments was deployed on the muddy shelf of Western Louisiana in depths ranging from 13 to 4 m. Box cores were collected at all instrument sites to characterize bottom sediment properties (Garcia-Garcia et al., 2008). Analysis of local wind sea events along two cross-shore transects shows a decay of waves from the deeper to the shallower instruments, with the strongest decay at the muddiest site. The wave spectra evolution shows strong decay of high-frequency wind sea spectral levels and weaker decay at the lower swell frequencies. The default bottom friction parameterization (the JONSWAP model with coefficient value $0.067 \text{ m}^2/\text{s}^3$) in the SWAN model generally yields reasonable estimates of nearshore wave heights that are sufficiently accurate for most operational Navy applications. However, the predicted cross-shore wave decay is more gradual than is observed and the model does not capture the spectra decay at high frequencies.

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TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	MOTIVATION AND OBJECTIVE.....	1
B.	BACKGROUND	2
C.	SCOPE	5
II.	EXPERIMENT	7
A.	INTRODUCTION.....	7
B.	FIELD SITE	7
C.	INSTRUMENTS AND DATA COLLECTION	8
1.	Bottom Pressure Sites	8
2.	Bottom Pressure and Velocity Sites.....	9
3.	Waverider Buoys.....	10
4.	Other Measurements	10
III.	WAVE DATA ANALYSIS.....	23
A.	INTRODUCTION.....	23
B.	DESCRIPTION OF THE WAVE FIELD	23
1.	Surface Elevation Spectrum.....	23
2.	Frequency-directional Spectrum.....	23
3.	Bulk Parameters.....	25
C.	SPECTRAL ANALYSIS.....	26
IV.	OBSERVATIONS.....	29
A.	INTRODUCTION.....	29
B.	WIND OBSERVATIONS	29
C.	WAVE OBSERVATIONS	31
1.	Cross-shore Transects	31
2.	Alongshore Transect.....	31
3.	Sea and Swell Contributions.....	32
V.	SWAN MODEL IMPLEMENTATION	41
A.	INTRODUCTION.....	41
B.	MODEL DESCRIPTION.....	41
C.	BOTTOM DISSIPATION.....	42
D.	MODEL IMPLEMENTATION	43
VI.	MODEL RESULTS	45
A.	INTRODUCTION.....	45
B.	CASE STUDIES.....	46
1.	Case I—Easterly Wind 0000Z February 17, 2008 (High Energy).....	46
2.	Case II—Northwesterly Wind 1200Z February 18, 2008 (Fetch Limited) single space vs. 1.5.....	48
3.	Case III—Easterly Wind 0400Z February 21, 2008 (Low Energy).....	48

4.	Case IV—No Wind 1200Z February 22, 2008 (Swell Only)	49
C.	OVERALL MODEL PERFORMANCE	49
VII.	SUMMARY AND CONCLUSIONS	65
	LIST OF REFERENCES	69
	INITIAL DISTRIBUTION LIST	73

LIST OF FIGURES

Figure 1.	Location of the MUDEX Experiment in the northern Gulf of Mexico.	12
Figure 2.	Bathymetry of the MUDEX area and location of instruments used in the experiment.....	13
Figure 3.	Image of mud plume taken during the recovery cruise of MUDEX.....	14
Figure 4.	Recovery of a pressure sensor (P A) tripod during the final recovery cruise of MUDEX. The pressure sensor is fitted to a fiberglass tripod equipped with lead feet to ensure stability on the ocean floor. The small cylinder to the right of the pressure sensor is an acoustic pinger that helps locate the instrument.	15
Figure 5.	Recovery of a pressure-velocity frame on the final cruise of MUDEX. The Nortek Vector pressure-velocity (PUV) instrument with a three-pronged acoustic receiver probe extends vertically upward from the tripod. The pressure sensor is located at the base of this probe. The Aquadopp current profiler is the horizontal cylinder mounted on the left side of the tripod. The acoustic release mechanism is located below the center of the tripod and attaches the tripod to a metallic frame equipped with weights to ensure stability on the ocean floor. The small cylinder above the right leg of the tripod is an acoustic pinger that helps locate the instrument.	16
Figure 6.	Datawell Waverider buoy (DW) after recovery on the final cruise of MUDEX. Both buoy's were fitted with an anti-spin triangular frame to reduce risk of damage from collisions.	17
Figure 7.	Box core taking a mud sample of the sea floor during the recovery cruise of MUDEX (Top panel). A close up of a sample, shown in the Bottom panel, indicates a few centimeters of very soft fluid mud overlying soft mud.	18
Figure 8.	Box cores characterizing sediment properties at all instrument sites along the Western Transect. A very thin film of soft fluid mud is observed at all sites. Sites are designated BC-x or P-x, where BC represents Box Core, P represents Ponar grab sampler and x is the site number. (From Garcia-Garcia et al., 2008).....	19
Figure 9.	Box cores characterizing sediment properties at all instrument sites along the Central Transect. The fluid mud is thicker than observed along the Western Transect, possibly because of the proximity of the Atchafalaya river. Site notation is same format as Figure 8. (From Garcia-Garcia et al., 2008)	20
Figure 10.	Meteorological buoy deployed by WHOI during MUDEX. The anemometer is 3m above sea level and is the tallest sensor attached to the buoy. (From Dr. Janet Fredericks at WHOI).....	21
Figure 11.	WHOI wind observations for the first leg of MUDEX. Cold fronts are marked by blue vertical lines. (Courtesy of Dr. John Trowbridge and Dr. Janet Fredericks at WHOI)	33

Figure 12.	Surface Analysis Weather Charts for February 17, 2008: 0600Z (Top panel) and 0900Z (Bottom panel). The experiment site is indicated with a black square. (From nomads.ncdc.noaa.gov).....	34
Figure 13.	Surface Analysis Weather Charts for February 22, 2008: 1200Z (Top panel) and 1500Z (Bottom panel). (Same format as Figure 12) (From nomads.ncdc.noaa.gov).....	35
Figure 14.	Surface Analysis Weather Charts for February 26, 2008: 0900Z (Top panel) and 1200Z (Bottom panel). (Same format as Figure 12) (From nomads.ncdc.noaa.gov).....	36
Figure 15.	Wave observations for the western transect. Significant wave height H_s (Top panel). Peak period T_p (Middle panel). Peak wave direction D_p (Bottom panel). Cold fronts are marked by blue vertical lines.	37
Figure 16.	Wave observations for the central transect. (Same format as Figure 15)	38
Figure 17.	Wave observations for the eastern transect. (Same format as Figure 15).....	39
Figure 18.	Wave observations for the central transect. Sea component of significant wave height H_s (sea) (Top panel). Swell component of significant wave height H_s (swell) (Bottom panel).	40
Figure 19.	SWAN model domain for MUDEX with instrument locations and depths in color (units m). Depth contours at 2m intervals.	44
Figure 20.	Wave and wind observations for the central transect displaying four case studies selected for analysis. Significant wave height H_s (Top panel). Wind speed (Middle panel). Peak wave direction D_p and wind direction (Bottom panel). Cold fronts are marked by blue vertical lines. Case studies are marked by black vertical lines. (Wind data courtesy of Dr. John Trowbridge and Dr. Janet Fredericks at WHOI).....	51
Figure 21.	SWAN Model output for Case Study I with instrument locations and significant wave height in color (units m). Depth contours at 2m intervals.	52
Figure 22.	Case I model-data comparisons for the western transect using the default JONSWAP bottom friction source term (wind-sea setting, $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). a. Observed wave energy spectra (Top panel) and mean direction vs. frequency (Bottom panel). b. Corresponding model predictions.....	53
Figure 23.	Case I model-data comparisons for the central transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). a. Observed. b. SWAN model prediction. (Same format as Figure 23)	54
Figure 24.	SWAN model predictions of wave energy spectra on the central transect for Case I using different values for the tuning parameter C_{bfr} in the JONSWAP bottom friction source term. a. $C_{bfr} = 0 \text{ m}^2/\text{s}^3$. b. $C_{bfr} = 0.038 \text{ m}^2/\text{s}^3$. c. $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$. d. $C_{bfr} = 0.09 \text{ m}^2/\text{s}^3$	55

Figure 25.	Comparison of observed significant wave heights and SWAN model predictions in Case I using different values of the bottom friction tuning parameter C_{bfr} : from top to bottom: $C_{bfr} = 0 \text{ m}^2/\text{s}^3$, $0.038 \text{ m}^2/\text{s}^3$, $0.067 \text{ m}^2/\text{s}^3$ and $0.09 \text{ m}^2/\text{s}^3$. a. Western transect (Sites from left to right are DW1, PV2, PA3, PV4 and PA6). b. Central transect (Sites from left to right are DW12, PV7, PA8, PV9 and PA10).....	56
Figure 26.	SWAN Model output for Case Study II with instrument locations and significant wave height in color (units m). Depth contours at 2m intervals....	57
Figure 27.	Case II model-data comparisons for the western transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). a. Observed. b. SWAN model. (Same format as Figure 23).....	58
Figure 28.	Case II model-data comparisons for the central transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). a. Observed. b. SWAN model. (Same format as Figure 23).....	59
Figure 29.	Case III model-data comparisons for the central transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). a. Observed. b. SWAN model. (Same format as Figure 23).....	60
Figure 30.	Case III comparison of observed significant wave height and SWAN model predictions on the central transect using different tuning parameter (C_{bfr}) values in the JONSWAP bottom friction source term (Sites from left to right are DW12, PV7, PA8, PV9, PA10). $C_{bfr} = 0 \text{ m}^2/\text{s}^3$ (Top panel). $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$ (default wind sea setting) (Bottom panel).....	61
Figure 31.	Case IV model-data comparisons for the central transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). a. Observed. b. SWAN model. (Same format as Figure 23).....	62
Figure 32.	Case IV comparison of observed significant wave height and SWAN model predictions on the central transect. Top panel: no friction, Bottom panel: default $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$. (Same format as Figure 30).....	63

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LIST OF TABLES

Table 1.	Instruments deployed during MUDEX. Depth for the PA and PV instruments are an estimated average from the pressure time series collected during the first leg. Depth for the DW buoys is estimated from the high resolution bathymetry.	11
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ACKNOWLEDGMENTS

The research conducted within this thesis was funded by the Office of Naval Research. Official thanks must go to the staff of the Scripps Institution of Oceanography (Doug, Richard and Spencer) and the crew of R/V PELICAN for their support during the experiment. Doug, I still owe you for the mud fight! Further, thanks to Dr. John Trowbridge and Dr. Janet Fredericks at Woods Hall Oceanographic Institute (WHOI) for supplying the wind data for the experiment. Thanks also to Dr. Ana Garcia-Garcia for her box cores and comprehensive analysis of the muddy seafloor. I really enjoyed making mud sculptures with you.

I would like to express my sincere gratitude and appreciation to my advisor, Professor Thomas Herbers, for his expert guidance, patience and support while I have been at NPS. Your dedication, enthusiasm and encouragement is the reason this thesis has become a reality. I must also acknowledge my second advisor, Dr. Tim Janssen at San Francisco State University, for his help setting up the SWAN wave model and being a sounding board on all aspects of the thesis and schooling. Your feedback and insights were valued highly and shaped my experience at NPS. I look forward to writing a paper with you both in the future.

I would especially like to recognize the tireless efforts of Paul Jessen. Your availability at short notice to provide technical assistance was absolutely invaluable in completing my thesis. Your skills in MATLAB coding are unmatched and I could not have graduated without your help.

Finally, I must thank my wife-to-be Dana Hudson, her daughter Rowan and the entire Hudson family (Darryl, Pat, Brian, Amber and Kari) for their tremendous support while I have been in the USA. You have made my stay in the USA truly unforgettable and I hope you all won't miss the apartment too much. I dedicate this thesis to you!

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I. INTRODUCTION

A. MOTIVATION AND OBJECTIVE

In September 1992, the U.S. Navy paper “From the Sea” signaled a shift in focus away from “operations on the sea toward power projection and the employment of naval forces from the sea to influence events in the littoral regions of the world”. This fundamental shift was a direct result of the changing strategic landscape of the world and moving away from dealing with a global maritime threat and toward projecting power and influence in regional areas. As a result many countries now focus their efforts on a greater understanding of the littoral environment.

On October 17, 2007, the Chief of Naval Operations presented, “A Cooperative Strategy for the 21st Century Seapower,” the first unified strategy for the maritime forces of the United States. This latest Maritime Strategic Concept reaffirmed its core capability of “Forward Presence” and listed one of its three strategic imperatives as the ability to “limit regional conflict with forward deployed, decisive maritime power”. The forecast of wave and surf conditions are critical to the success of maritime forces which are forward deployed in the littoral environment.

One example of a military operation that is significantly affected by wave conditions in the littoral environment is an amphibious landing. This was well highlighted in the delay of the D-Day invasion of Normandy in 1944 due to high winds and seas. Wave and surf conditions can also be crucial in many other military operations such as special force’s insertion, mine warfare and hydrographic survey operations. Any military operation in the littoral environment can be adversely affected by the coastal wave climate.

In addition to wave prediction in littoral military operations, there are many other applications including recreational, commercial and climate studies for which nearshore wave prediction is very important. A common operational model used for wave prediction in the coastal region is known as Simulation Waves Nearshore (SWAN) (Booij et al., 1999). SWAN is a third generation numerical wave model developed to predict

short-crested waves in shallow water in the presence of ambient currents. SWAN was designed to address the excessive computational demands of global wave models such as WAM (Komen et al., 1994) and Wavewatch III (Tolman and Chalikov, 1996) at high resolutions in coastal regions. SWAN incorporates many complex processes including refraction, shoaling, wind forcing, non-linear interactions and dissipation. Dissipation is further broken down into three mechanisms; bottom-induced dissipation, depth-induced breaking and whitecapping. The model treats bottom-induced dissipation as the drag induced by a rigid sandy sea floor (Booij et al., 1999) and employs the bottom friction model by Hasselmann et al. (1973). This use of a bottom friction model does not allow SWAN to account for dissipation of waves from a non-rigid muddy sea floor. The absence of mud-related dissipation has been reported as a major deficiency in SWAN (Dingemans, 1998). It has been shown in many modeling studies (Gade, 1958; Dalrymple and Liu, 1978; Ng, 2000) that surface gravity waves can be dramatically damped by viscous mud. Recent field studies (Sheremet and Stone, 2003; Winterwerp et al., 2007; Elgar and Raubenheimer, 2008; Cuchiaro et al., 2009; Rogers and Holland, 2009) also show that waves can be damped by soft mud layers. Muddy shorelines occupy an estimated area of some 170000km² or 75% of the world's coastline between the 25°N and 25°S Latitudes (Flemming et al., 2000). With this widespread presence of muddy shorelines in the world it is important that nearshore wave models properly account for the mud-induced dissipation process.

This project will examine observations from a recent field experiment, known as the Louisiana Mud Experiment (MUDEX), on the muddy continental shelf of Western Louisiana. An extensive array of instruments was deployed during the period of February to March 2008 to measure in detail the damping of waves by a muddy seabed and investigates its importance in the overall wave energy balance. Observational data from the experiment will be compared to SWAN model predictions.

B. BACKGROUND

Extensive mud banks have been observed on continental shelves around the world. Well known examples are the south-west Indian coast, north-east coast of South

America and the Gulf of Mexico. The soft bed has a pronounced effect on surface wave propagation in such areas and spectacular damping rates are observed and reported, sometimes exhibiting nearly full attenuation of the surface wave field over just a few wavelengths (Gade, 1958; MacPherson, 1980). For instance, the damping characteristics of the Louisiana ‘Mud-Hole’ (92 °30’W) are used by local fishermen as a shelter in case of an emergency in high seas.

This remarkable natural phenomenon led Gade (1958) to present a first theoretical analysis of wave damping characteristics of surface gravity waves over mud, based on a two-layer representation of the medium. He considered long-wave propagation on the surface of an inviscid upper fluid superposed on a ‘mud’ layer represented as a viscous fluid. Later extensions include the propagation of shorter waves over a sub-layer modeled as a viscous fluid (Dalrymple & Liu, 1978; Ng, 2000), visco-elastic fluid or linear Voigt body sub-layers (MacPherson, 1980; Piedra-Cueva, 1993), or long waves over a Bingham-plastic (Mei & Liu, 1987). In effect, for these two-layer models, wave damping occurs through the work done by the pressure gradient acting on the interface. Viscosity (rather than elasticity) plays a crucial role here since it pushes the forcing relation away from exact quadrature, in absence of which no attenuation would occur (MacPherson, 1980).

In recent years, observational studies (Sheremet and Stone, 2003; Elgar and Raubenheimer, 2008; Cuchiara et al., 2009) suggest the wave damping problem may be more complex than a simple two layer fluid system. It has been generally thought that mud-induced dissipation only affects waves in the low frequency band of the wave spectrum because these waves are the only waves that interact efficiently with the bottom. Results from these recent studies suggest otherwise and show strong dissipation at both high and low frequencies. Sheremet and Stone (2003) propose that significant sediment resuspension and deposition processes may be the cause of high frequency wave damping and this is further supported in Jaramillo et al. (2009). The latter study shows that the mud layer is much more dynamic than first thought and is triggered by weather features such as frontal passages causing near-bed sediment transport processes.

Such processes can include bed liquefaction, resuspension and advection. Such evidence suggests that mud resuspension and fluidization of the entire water column may also play a role in dissipation of waves in muddy coastal environments.

Although modeling studies have been ongoing since Gade (1958), comprehensive field observations remain scarce and the most notable observational studies have only taken place in the past decade. This has made it difficult to verify model results. Hsiao and Shemin (1980) used two observations 3.5 km apart in Eastbay, Louisiana, from Tubman and Suhayda (1976) in 19.2 and 5.3 m water depths. They showed that the proposed viscoelastic model predicts wave energy decay much more effectively than a bottom friction model. It was noted that a high friction constant above 0.01 could not be justified in the study because of the very fine bottom sediment found in that area. This study was limited in observations and did not sufficiently capture the cross-shore evolution of the wave field. Sheremet and Stone (2003) also conducted an experiment in the coastal waters of Louisiana. In this study, two observations were made at two sites, one located in a muddy environment, and the other in a sandy environment. They were located 150 km apart in a water depth of 5 m. The sites were considered to be subjected to similar wave generation and propagation conditions. Comparison of observations to the standard SWAN model showed severe over-prediction of wave energy at the muddy site but found agreement at the sandy site. The results from Sheremet and Stone (2003) are somewhat inconclusive because of the large distance between the two observation sites (i.e., differences in wind conditions, wave climate).

A more detailed study of the cross-shore evolution of the wave field in shallow water (5 m to 2 m water depths) was recently conducted by Elgar and Raubenheimer (2008). Detailed observations across 1.8 km of the Louisiana inner continental shelf were used to calibrate a new dissipation function in a non-linear wave propagation model. While the model accurately reproduces the observed wave energy spectra transformation, these results were obtained in very shallow water, and may not apply to greater depths across the continental shelf where waves are dispersive and non-linear interactions are weak.

Another recent field data set examining cross-shore wave evolution in a muddy environment was collected at Cassino Beach, Brazil, in 2005. A collection of papers were published recently that compare this dataset to predictions of various two-layer boundary models (Cuchiara et al., 2009; Rogers and Holland, 2009; Soltanpour et al., 2009). The array spanning 35km consisted of four instruments: a directional waverider buoy in 25m water depth, an acoustic doppler profiler in 8m, and two pressure gauges in 6m and 2m depths (Rogers and Holland, 2009). A mud layer of 40cm was observed between 9 to 15m water depths, placing all sensors either offshore or inshore of the observed mud deposits. Using these field observations, Rogers and Holland (2009) investigated dissipation by viscous mud with two formulations in SWAN: (1) De Wit (1995) with a mud parameterization by Winterwerp et al. (2007) and (2) Ng (2000). Without mud-induced dissipation SWAN over-predicted wave energy at all sensors inshore of the mud deposit zone. It only showed comparable results during one high energy wave event. When the mud formulations were included, simulations modestly under-predicted wave energy, suggesting dissipation in these formulations is too strong. Uncertainty in the rheology, distribution and depth of mud are cited as possible reasons for this difference. An inversion methodology was used to infer the mud distribution from the model that produces the observed wave heights. This methodology suggests the mud layer was up to 50% thinner than observed and more dynamic than expected with the distribution extending further inshore.

C. SCOPE

Field observations of mud-induced wave dissipation are scarce and hence the performance of operational wave prediction models in muddy environments is poorly understood. This thesis presents a comprehensive field dataset to study the transformation of ocean surface waves across a muddy continental shelf, in particular the expected strong wave damping. Observations from an extensive array of instruments deployed on the shelf of Western Louisiana, during the ONR funded MUDEX Experiment, are compared to predictions from the operational SWAN model to evaluate

the overall performance of SWAN in its standard configuration in a muddy environment. The bottom friction source term of Hasselmann et al. (1973) will be examined to see if there is an optimal tuning coefficient that can match field observations.

The two-dimensional array includes two cross-shore transects and one alongshore transect spanning a 40 x 25km area in depths ranging from 13m to 4m. Instruments were deployed at 16 sites, including two directional waverider buoys, six bottom tripods equipped with a pressure and velocity sensor and a current profiler, and eight bottom tripods equipped with a pressure sensor.

The thesis is organized in eight chapters. Chapter II describes the MUDEX Experiment including the location of the experiment, instruments used and data collection. Chapter III reviews methods used to analyze the field data. Chapter IV contains analysis of the observations. The implementation of the SWAN model is described in Chapter V. Results of model-data comparisons are examined in Chapter VI, focusing on four case studies, including local wind-sea and mixed swell-sea events with a range of wave directions and heights. This chapter also investigates model performance for different settings of the bottom friction parameter. Finally, Chapter VII contains a summary and conclusions.

II. EXPERIMENT

A. INTRODUCTION

The Louisiana Mud Experiment (MUDEX) was conducted in the northern Gulf of Mexico on the shelf of the western Louisiana coast, between Chenier Plain and Trinity Shoal, in the late winter/early spring of 2008 (Figure 1). Wave measurements were collected at 16 sites in 4-13m depth from February 09 to March 27. The instruments were deployed at specifically chosen sites to create two cross-shore transects and one alongshore transect (Figure 2). Data were collected in two separate legs from February 09 to February 25 and March 04 to March 27, to allow for the retrieval of records from instruments midway through the experiment. Initial deployment, redeployment and recovery of instruments were conducted from the Universities National Oceanographic Laboratory System (UNOLS) Research Vessel (R/V) PELICAN which was home ported in Cocodrie, Louisiana. The study was part of a larger field experiment, funded by the Office of Naval Research, to investigate the mechanisms of water wave damping over mud. Scientists from several universities and institutions participated in the research effort including John Hopkins University, Massachusetts Institute of Technology (MIT), Woods Hole Oceanographic Institution (WHOI), Boston College, Louisiana State University (LSU), National Cheng Kung University, AOA Geophysics, the Scripps Institution of Oceanography (SIO) and the Naval Postgraduate School (NPS). This thesis is focused on the data collected by the NPS group in collaboration with the SIO and AOA groups.

B. FIELD SITE

The west Louisiana coast is a very active segment of coastline at the confluence of the Mississippi River outflow and the Gulf of Mexico. The area is under the influence of the Atchafalaya River (Figure 1), the largest tributary of the Mississippi River, which captures about 30% of its discharge, with an average sediment load of 84 million metric tons per year (Sheremet and Stone, 2003). Mud plumes, which are normally confined shoreward of the 10m isobaths, vary in size and extent based on the severity of

the weather conditions. Peak mud plume activity occurs in late winter and early spring months, coinciding with high river discharge levels and intense cold fronts (Mossa and Roberts, 1990). Figure 3 illustrates a mud plume observed during the experiment. The image was taken during the recovery cruise on the second leg of the experiment and illustrates how much the water column can change from mud fluidization. A significant cold front had passed through the area a week prior to the recovery cruise and may have contributed to the mud suspension. A nearby waverider buoy, in a water depth of 13m, recorded waves reaching nearly three meters during the peak of the storm.

The MUDEX study area, shown in Figure 2, displays a coastline that is predominantly NW/SE. The bathymetry contours parallel the coastline along the Chenier Plain until the Trinity Shoal. At the Trinity Shoal, the contours curve south to approximately 40km offshore and then turn east. The Trinity Shoal has a minimum depth of approximately 5m.

C. INSTRUMENTS AND DATA COLLECTION

The array consisted of two cross-shore transects and one alongshore transect. The cross-shore transects named, “Western” and “Central” respectively, relative to their position in the array, were approximately 18km long and span water depths ranging from 4m to 13m. The alongshore transect, named “Eastern”, was approximately 25km long and extends from Trinity Shoal (5m depth) westward to about 12m depth. In total, eight bottom tripods with a pressure sensor (designated as PA-x where x is the site number), six bottom mounted frames each containing a pressure-velocity sensor and a current profiler (designated PV-x), and two surface-following waverider buoys (designated DW-x) were deployed (Table 1 and Figure 2). The array was designed to provide a comprehensive field dataset on the evolution of surface waves across a muddy shelf. The instruments were recovered and redeployed in the same positions during a turnaround cruise in late February 2008 to retrieve data records from the first leg.

1. Bottom Pressure Sites

The eight bottom pressure sensors were each mounted on a fiberglass tripod fitted to a recovery line with a surface float (Figure 4). A small acoustic pinger was also fitted

to the tripod to locate it underwater during recovery. They were deployed from the R/V PELICAN using differential GPS for precise positioning with accuracy to within 5m. The instrument is a self contained, battery powered and internally recording package with a Setra 270 capacitance-type pressure gauge (developed and built at SIO). The pressure (PA) tripods were deployed at various sites to measure wave-induced near-bottom pressure fluctuations in water depths of 4 to 10m. Three pressure sensors were located on the western transect (sites 3, 5 and 6), three on the central transect (sites 8, 10 and 11), and two on the eastern transect (sites 14 and 15). Two pressure sensors, at sites 6 and 11, were not recovered during the turnaround cruise as they were possibly dragged by the high volume of fishing vessels in the area. Also a third sensor, at site 10, was not recovered during the final recovery cruise for the same reason. The pressure records were recorded internally at a continuous sampling rate of 2 Hz.

2. Bottom Pressure and Velocity Sites

The six Nortek Vector pressure-velocity instruments were each mounted on a fiberglass tripod in a similar way to the pressure sensors. The instrument contains an Acoustic doppler velocimeter that measures three-component velocity fluctuations at a single point above the instrument and a pressure gauge. The fiberglass tripod was also equipped with a Nortek Aquadopp current profiler, to provide redundant pressure and velocity measurements in case the Vector instrument fails. The tripod was mounted on a 1.1m tall metallic frame to keep the instruments from sinking into the mud (Figure 5). To aid recovery, all tripods were fitted with an acoustic release mechanism, a small acoustic pinger, and a recovery line with surface float. The near-bottom pressure and horizontal velocity measurements collected at six sites, in depths of 6 to 12m, were used to estimate wave-height and directional spectra through the techniques described in Chapter III. Two pressure-velocity tripods were located on the western transect (sites 2 and 4), two on the central transect (sites 7 and 9), and two on the eastern transect (sites 13 and 16). The Vector pressure and velocity data were recorded internally in bursts of 68 minutes, every 4 hours, at a sampling rate of 2 Hz. The Aquadopp wave data were recorded internally in bursts of 34 minutes, every 1 hour, at a sampling rate of 1 Hz.

3. Waverider Buoys

Two 0.9m diameter surface-following Dataswell Directional Waverider buoys were deployed in water depths of 11m and 13.5m (Figure 6). Each buoy is equipped with a three-component accelerometer, a compass, and a tilt sensor to measure vertical and horizontal sea surface displacements in an absolute (north, west, vertical) coordinate frame. Waverider buoys are capable of producing wave-height and direction spectra in real-time using their onboard microprocessor, however, this feature was not used and instead this information was carefully computed from the post-processed displacement data. The vertical displacement data were used to estimate wave-height spectra and both the horizontal and vertical displacements were used to estimate directional spectra through techniques discussed in Chapter III. One buoy was located at the most offshore site of the western transect (site 1) and the other buoy at the deep end of both the central and eastern transects (site 12) (Figure 2). The displacement data was recorded internally in 30 minute segments continuously at a sampling rate of 1.28 Hz.

4. Other Measurements

Box core observations of bottom sediments were taken at each site during the deployment and recovery cruises by Geologist, Dr Anna Garcia-Garcia, to characterize the rheology of mud in the area (Figure 7, 8 and 9). These samples were also analyzed using a Rheometer in the Department of Civil Engineering at John Hopkins University by Khatoon Sabouri-Shargh to estimate viscosity in the mud layer.

Wind observations were taken by an anemometer on a meteorological buoy (Figure 10) that was deployed by Dr. John Trowbridge from WHOI during MUDEX. The meteorological buoy was located between sites 5 and 6 on the western transect (Figure 2). Mean wind speed and direction observations were recorded at 3m above sea level at five minute intervals from February 14 to the end of MUDEX. These wind measurements (provided by Dr. Janet Fredericks from WHOI) were corrected to 10m elevation (U_{10}) using a standard logarithmic wind profile and Charnocks's (1955) estimate of the sea surface roughness (using a coefficient value of 0.0144).

A bathymetry grid with a resolution of 0.001 degrees was assembled for the Louisiana coastal region by Paul Jessen (Figure 2) at NPS from the NOAA National Ocean Survey (NOS) Hydrographic database. Bathymetric data was extracted using the NDGC GEODAS tool.

Site Number	Instrument Type	Latitude (Deg North)	Longitude (Deg West)	Depth (m)
1 D	W	29.444	92.632	13.0
2 PV		29.477	92.625	12.39
3 PA		29.504	92.603	10.80
4 PV		29.523	92.599	9.39
5 PA		29.539	92.595	Not recovered
6 PA		29.553	92.592	6.00
7 PV		29.424	92.5	11.37
8 PA		29.453	92.494	10.85
9 PV		29.491	92.475	8.40
10 PA		29.518	92.463	5.28
11 PA		29.529	92.459	Not recovered
12 D	W	29.33	92.489	11.5
13 PV		29.327	92.432	9.83
14 PA		29.308	92.39	8.75
15 PA		29.308	92.317	7.38
16 PV		29.294	92.265	6.91

Table 1. Instruments deployed during MUDEX. Depth for the PA and PV instruments are an estimated average from the pressure time series collected during the first leg. Depth for the DW buoys is estimated from the high resolution bathymetry.



Figure 1. Location of the MUDEX Experiment in the northern Gulf of Mexico.

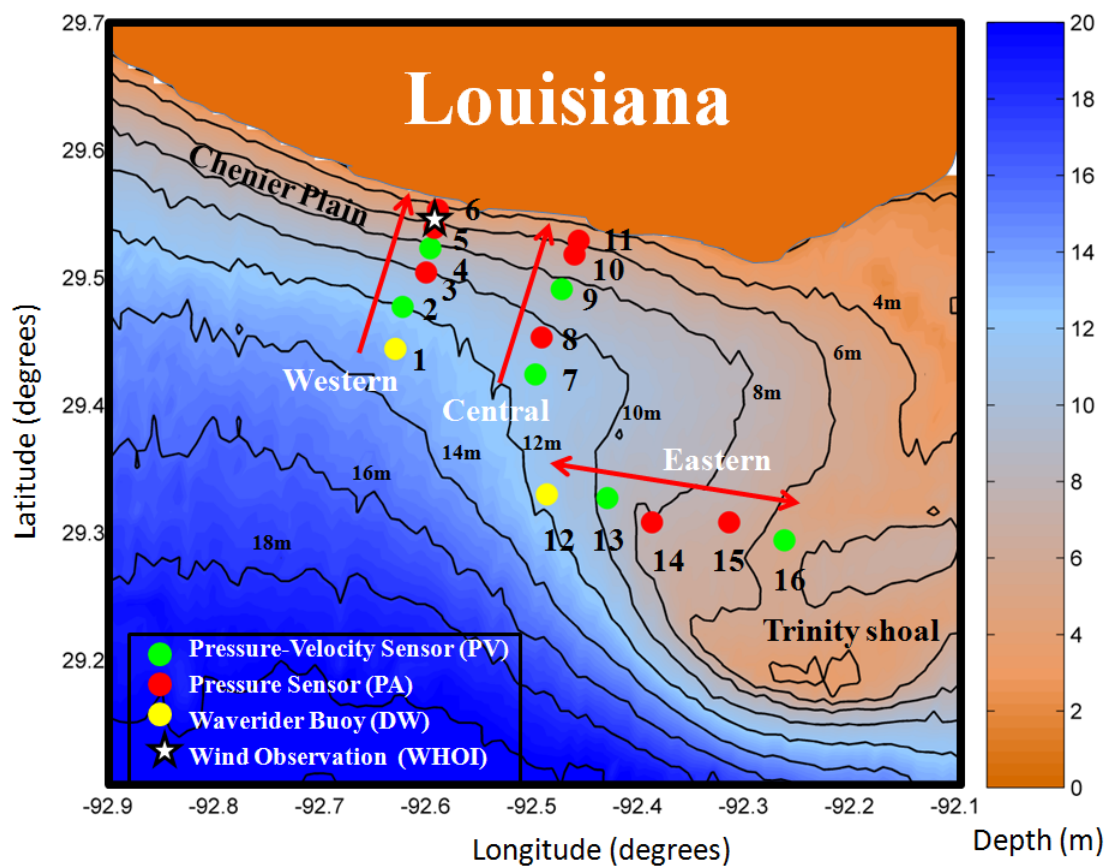


Figure 2. Bathymetry of the MUDEX area and location of instruments used in the experiment.



Figure 3. Image of mud plume taken during the recovery cruise of MUDEX.



Figure 4. Recovery of a pressure sensor (PA) tripod during the final recovery cruise of MUDEX. The pressure sensor is fitted to a fiberglass tripod equipped with lead feet to ensure stability on the ocean floor. The small cylinder to the right of the pressure sensor is an acoustic pinger that helps locate the instrument.



Figure 5. Recovery of a pressure-velocity frame on the final cruise of MUDEX. The Nortek Vector pressure-velocity (PUV) instrument with a three-pronged acoustic receiver probe extends vertically upward from the tripod. The pressure sensor is located at the base of this probe. The Aquadopp current profiler is the horizontal cylinder mounted on the left side of the tripod. The acoustic release mechanism is located below the center of the tripod and attaches the tripod to a metallic frame equipped with weights to ensure stability on the ocean floor. The small cylinder above the right leg of the tripod is an acoustic pinger that helps locate the instrument.



Figure 6. Datawell Waverider buoy (DW) after recovery on the final cruise of MUDEX. Both buoy's were fitted with an anti-spin triangular frame to reduce risk of damage from collisions.



Figure 7. Box core taking a mud sample of the sea floor during the recovery cruise of MUDEX (Top panel). A close up of a sample, shown in the Bottom panel, indicates a few centimeters of very soft fluid mud overlying soft mud.

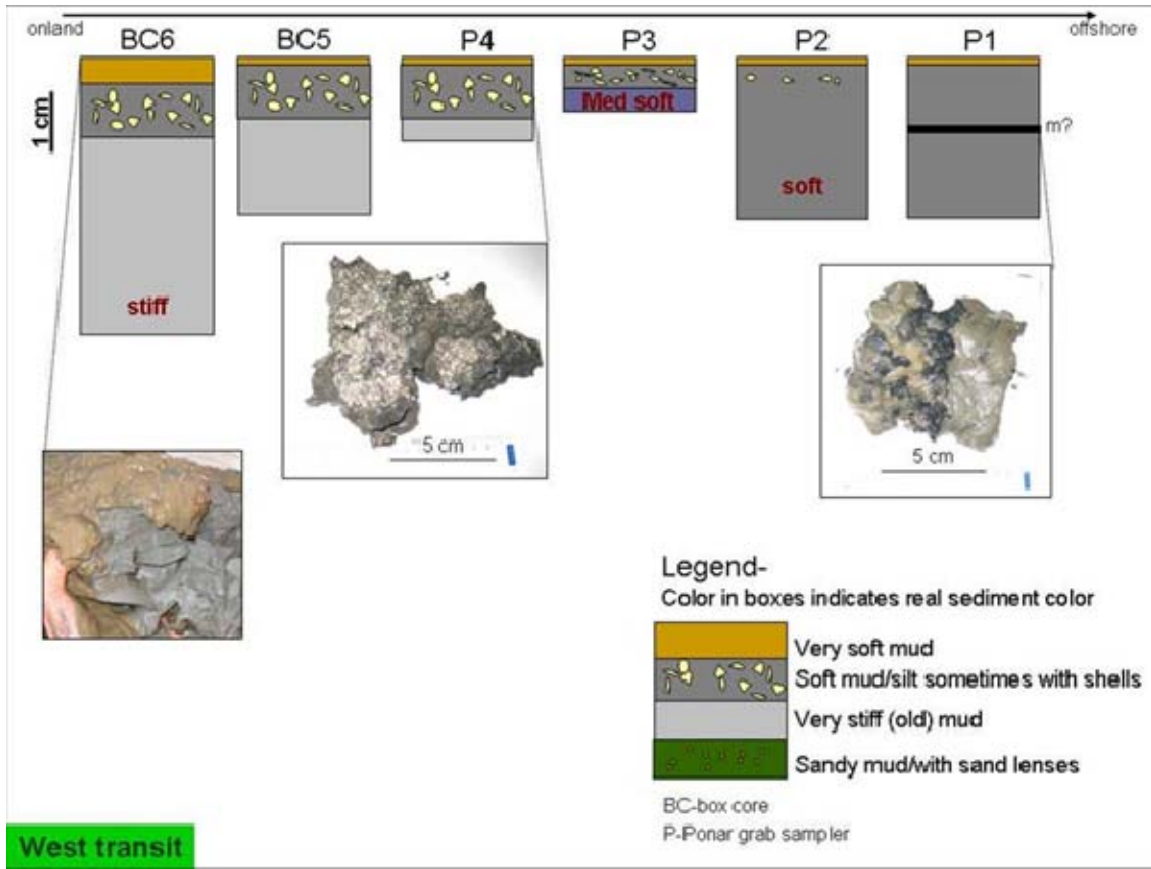


Figure 8. Box cores characterizing sediment properties at all instrument sites along the Western Transect. A very thin film of soft fluid mud is observed at all sites. Sites are designated BC-x or P-x, where BC represents Box Core, P represents Ponar grab sampler and x is the site number. (From Garcia-Garcia et al., 2008)

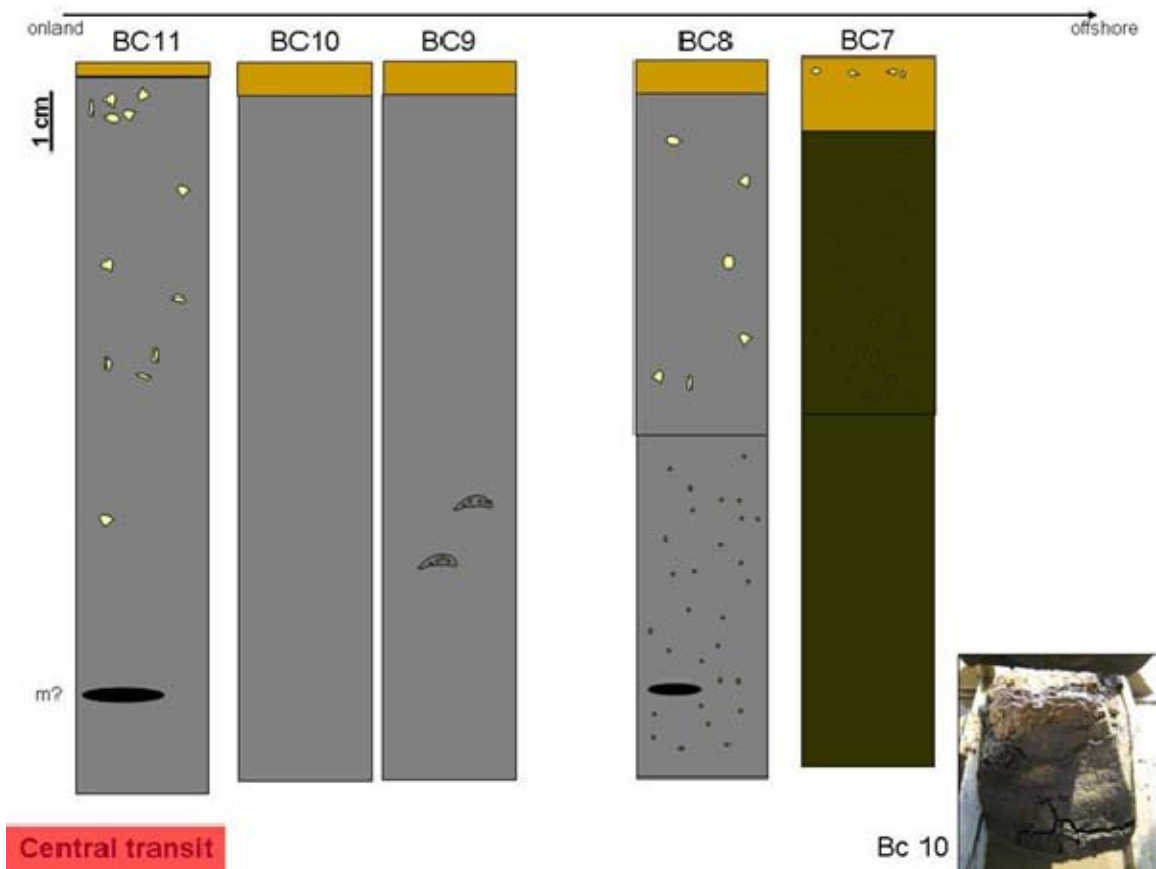


Figure 9. Box cores characterizing sediment properties at all instrument sites along the Central Transect. The fluid mud is thicker than observed along the Western Transect, possibly because of the proximity of the Atchafalaya river. Site notation is same format as Figure 8. (From Garcia-Garcia et al., 2008)



Figure 10. Meteorological buoy deployed by WHOI during MUDEX. The anemometer is 3m above sea level and is the tallest sensor attached to the buoy. (From Dr. Janet Fredericks at WHOI)

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III. WAVE DATA ANALYSIS

A. INTRODUCTION

This chapter outlines the methods used to obtain surface elevation frequency and directional wave spectra from the various instruments deployed during MUDEX. It also details techniques used to calculate common parameters such as significant wave height, wave peak period and mean wave direction.

B. DESCRIPTION OF THE WAVE FIELD

1. Surface Elevation Spectrum

To estimate the surface elevation spectrum $E(f)$ from the near-bottom pressure measurements at the PA and PV sites, linear wave theory was used to account for vertical attenuation of the wave motion. The linear transfer function between sub-surface pressure (in units of equivalent water column height) and surface elevation is given by:

$$H(f) = \frac{\cosh kh}{\cosh kd} \quad (1)$$

where h is the total water depth, and d is the height of the pressure sensor above the sea floor. The wavenumber k is given by the dispersion relation $(2\pi f)^2 = gk \tanh kh$. An estimate of the sea surface spectrum is obtained by multiplying the subsurface pressure spectrum $E_p(f)$ by the squared transfer function:

$$E(f) = |H(f)|^2 E_p(f) \quad (2)$$

A simpler procedure applies to the Wave rider Buoy DW sites. The spectrum of the vertical buoy displacement data yields a direct estimate of $E(f)$.

2. Frequency-directional Spectrum

The directionality of waves is often described by the mean direction $\theta_{mean}(f)$ as a function of frequency, that can be estimated with a high degree of accuracy from

directional wave buoys (e.g., O'Reilly et al., 1996) and pressure-velocity sensors (e.g. Herbers et al., 1999). It is commonly defined in terms of the first order directional moments a_1 and b_1 of the frequency-directional wave spectrum $E(f, \theta)$ (Longuet-Higgins et al., 1963):

$$\theta_{mean}(f) = \tan^{-1} \left(\frac{b_1(f)}{a_1(f)} \right) \quad (3)$$

with

$$a_1(f) \equiv \int \frac{\cos \theta E(f, \theta) d\theta}{E(f)} \quad (4)$$

$$b_1(f) \equiv \int \frac{\sin \theta E(f, \theta) d\theta}{E(f)} \quad (5)$$

In this definition, $\theta_{mean}(f)$ represents the direction of the wave energy flux as a function of frequency, and thus has a simple physical interpretation. The moments a_1 and b_1 are readily determined from either surface x,y,z displacements or sub-surface p,u,v measurements. For the waverider (DW) buoys a_1 and b_1 are related to the spectra and cross spectra of the horizontal and vertical displacements by Longuet-Higgins et al., (1963):

$$a_1(f) = \frac{iQ_{xz}(f)}{\left\{ C_{zz}(f) [C_{xx}(f) + C_{yy}(f)] \right\}^{\frac{1}{2}}} \quad (6)$$

$$b_1(f) = \frac{iQ_{yz}(f)}{\left\{ C_{zz}(f) [C_{xx}(f) + C_{yy}(f)] \right\}^{\frac{1}{2}}} \quad (7)$$

Where C_{ij} and Q_{ij} indicate the co- and quadrature spectrum between measurements i and j . Similar relations exist for pressure and velocity (PV) measurements in terms of the normalized co-spectra of the horizontal velocity components u and v and pressure p (e.g., Herbers et al., 1999):

$$a_1(f) \equiv \frac{C_{pu}(f)}{\{C_{pp}(f)[C_{uu}(f) + C_{vv}(f)]\}^{\frac{1}{2}}} \quad (8)$$

$$b_1(f) \equiv \frac{C_{pv}(f)}{\{C_{pp}(f)[C_{uu}(f) + C_{vv}(f)]\}^{\frac{1}{2}}} \quad (9)$$

Finally, to initialize the SWAN model with an offshore boundary condition, a full frequency-directional wave spectrum $E(f, \theta)$ is required. This spectrum was estimated from the buoy measurements at site DW 12 using the Maximum Entropy Method (MEM) of Lygre and Krogstad (1963). This method uses the full cross spectral matrix of the buoy measurements.

3. Bulk Parameters

In addition to the surface elevation frequency and directional spectra, the peak wave period T_p , peak wave direction D_p and significant wave height H_s were calculated. The peak wave period, T_p , and wave direction D_p , were taken as the period and mean direction corresponding to the frequency band with the maximum spectral density. The significant wave height was calculated using the standard definition:

$$H_s = 4 \sqrt{\int_{0.05 \text{ Hz}}^{0.25 \text{ Hz}} E(f) df} \quad (10)$$

where the spectral density, $E(f)$, is integrated across a wide frequency band from 0.05 Hz to 0.25 Hz. Higher frequency components are not included to avoid errors associated with the strong attenuation of the pressure signals at the deeper PV and PA sites.

The significant wave height was also calculated for the sea and swell components separately to investigate differences in the transformation of longer wavelength swell that feel the bottom across the shelf and shorter wavelength sea that are less affected by the seafloor. These computations use the same definition as (8) but with restricted frequency bands of 0.05 Hz to 0.15 Hz for the swell component and 0.15 Hz to 0.25 Hz for the sea component:

$$H_s(\text{swell}) = 4 \sqrt{\int_{0.05 \text{ Hz}}^{0.15 \text{ Hz}} E(f) df} \quad (11)$$

$$H_s(\text{sea}) = 4 \sqrt{\int_{0.15 \text{ Hz}}^{0.25 \text{ Hz}} E(f) df} \quad (12)$$

C. SPECTRAL ANALYSIS

To facilitate comparisons of different instruments, the data from each instrument was processed for a common 68 minute time interval that is long compared with the propagation time of swell to cross the instrumented transects, while wind-sea conditions usually are reasonably stationary over an hour. The PV sensors collected data in 68.2 minute bursts every 4 hours while the DW buoys and PA sensors collected data continuously. To yield a common time interval, the DW buoy data (with a different sample rate, see below) was processed in 70 minute bursts every 4 hours and the PA sensor was processed in 68.2 minute bursts every 4 hours to match the PV sensor.

Spectra (and cross-spectra) were computed for the PA and PV sensors from 68.2 minute records (8192 points with a sample interval of 0.5 seconds) using a segment length of 128 points and a 50% overlap, resulting in 128 degrees of freedom for a frequency resolution of 0.015625 Hz. The DW buoy data analysis was performed on 70

minute records (5376 points) with a sample interval of 0.78 seconds, using a segment length of 128 points and a 50% overlap, yielding 84 degrees of freedom and a frequency resolution of 0.01 Hz.

The mean wave direction $\theta_{mean}(f)$ as computed from ensemble averages of the directional moments (a_1, b_1) in (3) are weighted by the energy density $E(f)$ using the relations from equations 4 and 5 for the DW sensors and equations 6 and 7 for the PV sensors. For each instrument site this process yielded average wave spectra and mean wave directions (as a function of frequency) at 4 hour intervals starting at 00:00, 04:00, 08:00, 12:00, 16:00, 20:00 GMT over the entire experiment period.

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IV. OBSERVATIONS

A. INTRODUCTION

In this chapter, wind and wave observations are presented for the first leg of MUDEX. The second leg is not included in the observational analysis because the inshore sensor at site 10 was not recovered during the final recovery cruise. Site 10 is considered rather special, as it represents the most inshore operational sensor on the muddier central transect where the strongest wave damping is observed.

B. WIND OBSERVATIONS

A time series for wind observations during the first leg of MUDEX is presented in Figure 11. Surface analysis weather charts for the northern Gulf of Mexico are also presented in Figures 12, 13, and 14 to provide a greater insight into the wind field. As specified in Chapter II, wind observations were taken by a single meteorological buoy, from WHOI, located between sites 5 and 6 on the western transect. A second meteorological station operated by Louisiana State University (LSU) was located 50km east of the WHOI buoy. However, since the MUDEX area is relatively small, and similarity between wind observations at the two stations (not shown) suggest fairly homogeneous wind conditions, only data from the WHOI buoy was used in this study.

It is evident in the WHOI buoy wind observations (Figure 11) that there were three distinct frontal passages during the first leg, each accompanied by a sudden change in wind direction observed on February 18, 22, and 26 (Figure 11 Bottom Panel). There is also another less pronounced frontal system that passed the area during February 17. It is represented by a brief wind change and significant increase in wind speed (Figure 11). Other fronts crossed the area early on February 13 and March 4 (not shown) and the effects of these can be seen in the wave observations (Figure 15, 16, and 17). It appears that fronts generally cross the area every four to five days. Examining wind speed for the frontal events shown in Figure 11, it is evident that the first, second and fourth fronts are

much stronger than the third front with wind speeds greater than 12 m/s (>23kts). Interestingly, the first front has the strongest winds before the frontal passage, whereas the second and fourth front have stronger winds after the frontal passage.

Figure 12 shows surface weather charts for the first front at 0600Z and 0900Z on February 17 (Figure 12). The chart at 0600Z shows initial strong to gale force wind conditions offshore of the MUDEX area, before the front, from wind barbs displaying 25-35kts. Then as the front crosses the area at 0900Z the winds moderate briefly across the area. The wind freshens again on February 18 as a second front (surface weather chart not shown) quickly moves into the area tightening the pressure gradient and reflecting the increase in wind speed shown in the time series (Figure 11 Top Panel).

The third frontal passage is displayed in weather charts at 1200Z and 1500Z on February 22 (Figure 13). The chart at 1200Z shows initial weak wind conditions throughout the area before the front. The winds then remain relatively light as the front crosses the area, shown in the chart at 1500Z. However, this is only short lived as a ridge of high pressure moves into the area behind the front causing winds to freshen by late on February 22.

The fourth front is shown in weather charts at 0900Z and 1200Z on February 25/26 (Figure 14). The chart at 0900Z shows strong wind conditions of 20-25kts offshore before the front. However, these conditions are not as strong as the wind conditions before the first front. This can be explained by the fact that the low pressure system passing north of the area is much weaker in the fourth frontal case. Winds become strong to gale force during the frontal passage shown in chart 1200Z with a 40kt wind barb offshore of the MUDEX area. Winds remain quite strong and offshore until the middle of February 27 (Figure 11 Top Panel) as the intense high pressure system behind the front combines with the low pressure system north of the area (not shown).

C. WAVE OBSERVATIONS

1. Cross-shore Transects

Time series of wave observations for the western and central transects are displayed in Figures 15 and 16. Wave observations include significant wave height H_s , peak wave period T_p and peak wave direction D_p .

Wave height observations along the western transect (Figure 15 Top Panel) show a general decay as waves propagate from the deepest sensor DW1 to the shallowest sensor PA6. However, a much stronger decay is observed along the central transect (Figure 16 Top Panel) between sites DW12 and PA10 with reductions in wave height by as much as 45%. This may be a result of the closer proximity to the outflow of the Atchafalaya river producing a thicker layer of soft mud on the central transect (Figure 9). The frontal passages are reflected in the wave heights of both transects with strong to gale force wind conditions before the first front creating the largest wave heights during February 17. The passage of the third weaker front and associated low pressure system is responsible for the slight rise in wave heights during February 21 and 22. The fourth front caused the rise in wave heights during February 26.

Peak wave period observations, in Figures 15 and 16 (Middle Panel), are very similar for the two transects and show a range in period between 4 and 10 seconds. The peak period generally remains below 8 seconds as severe storms that produce longer swells in the Gulf of Mexico are uncommon during the winter months.

The peak wave directions in Figures 15 and 16 (Bottom Panel) show a general southerly direction except after strong fronts when the wind turns offshore causing northerly (i.e. fetch-limited) wave directions for up to 24 hours.

2. Alongshore Transect

Time series for wave observations on the eastern transect are shown in Figure 17 (Top Panel). As this transect runs alongshore into Trinity Shoal, it does not display the

same decay in wave heights as the cross shore transects. Wave heights are relatively similar at all sites and reflect the frontal activity. Peak period and direction are very similar to the cross shore transects.

3. Sea and Swell Contributions

As discussed in Chapter III, the bulk parameter of significant wave height was also separated into sea and swell components. These components were calculated to better understand the cross-shore decay in different parts of the wave spectrum when waves moved inshore along the cross-shore transects. Time series of the sea and swell components of wave height for the central transect are presented in Figure 18. Whereas the longer wavelength swell component may be expected to be affected more by the seafloor boundary layer processes, surprisingly the sea component of the wave height experiences significantly greater decay than the swell component. It is also evident that the frontal activity has more of an effect on the sea component with the wave heights more closely aligned to the wind observations.

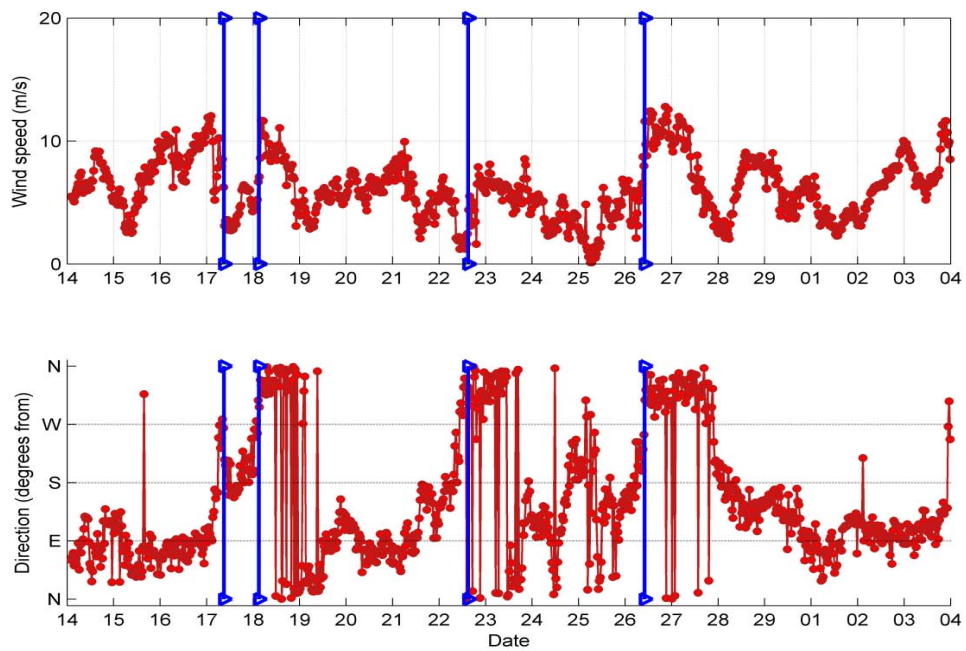


Figure 11. WHOI wind observations for the first leg of MUDEX. Cold fronts are marked by blue vertical lines. (Courtesy of Dr. John Trowbridge and Dr. Janet Fredericks at WHOI)

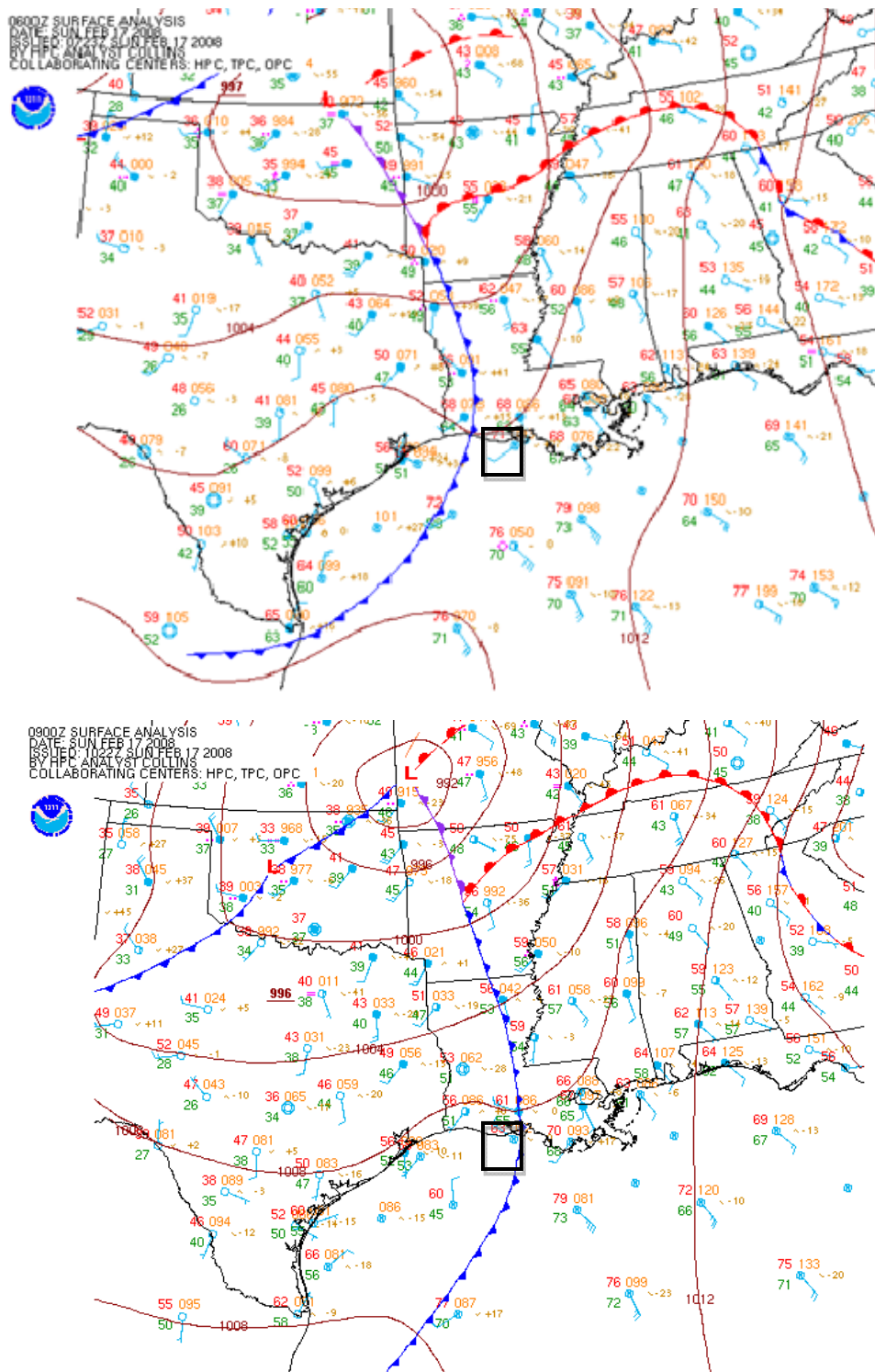


Figure 12. Surface Analysis Weather Charts for February 17, 2008: 0600Z (Top panel) and 0900Z (Bottom panel). The experiment site is indicated with a black square. (From nomads.ncdc.noaa.gov)

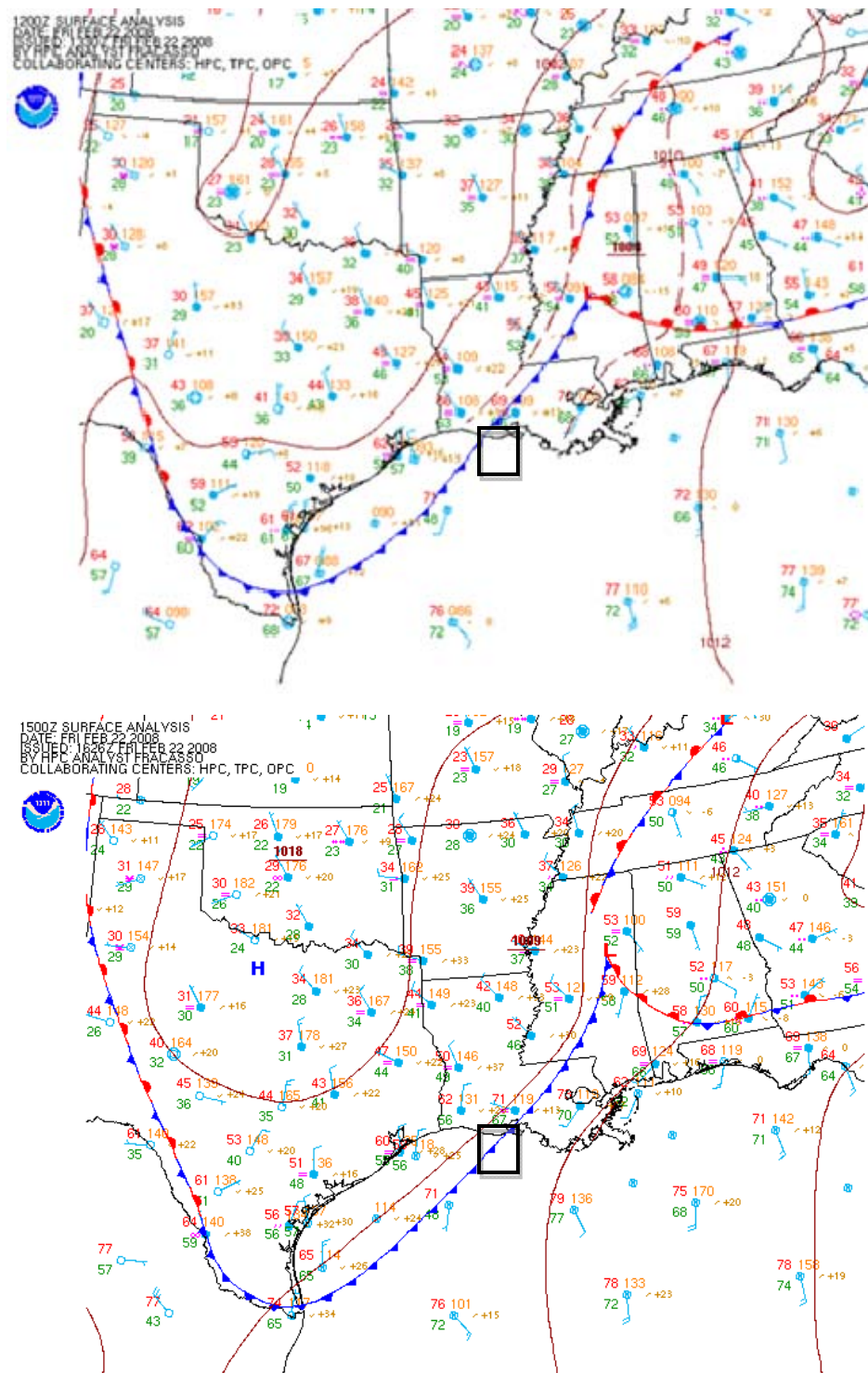


Figure 13. Surface Analysis Weather Charts for February 22, 2008: 1200Z (Top panel) and 1500Z (Bottom panel). (Same format as Figure 12) (From nomads.ncdc.noaa.gov)

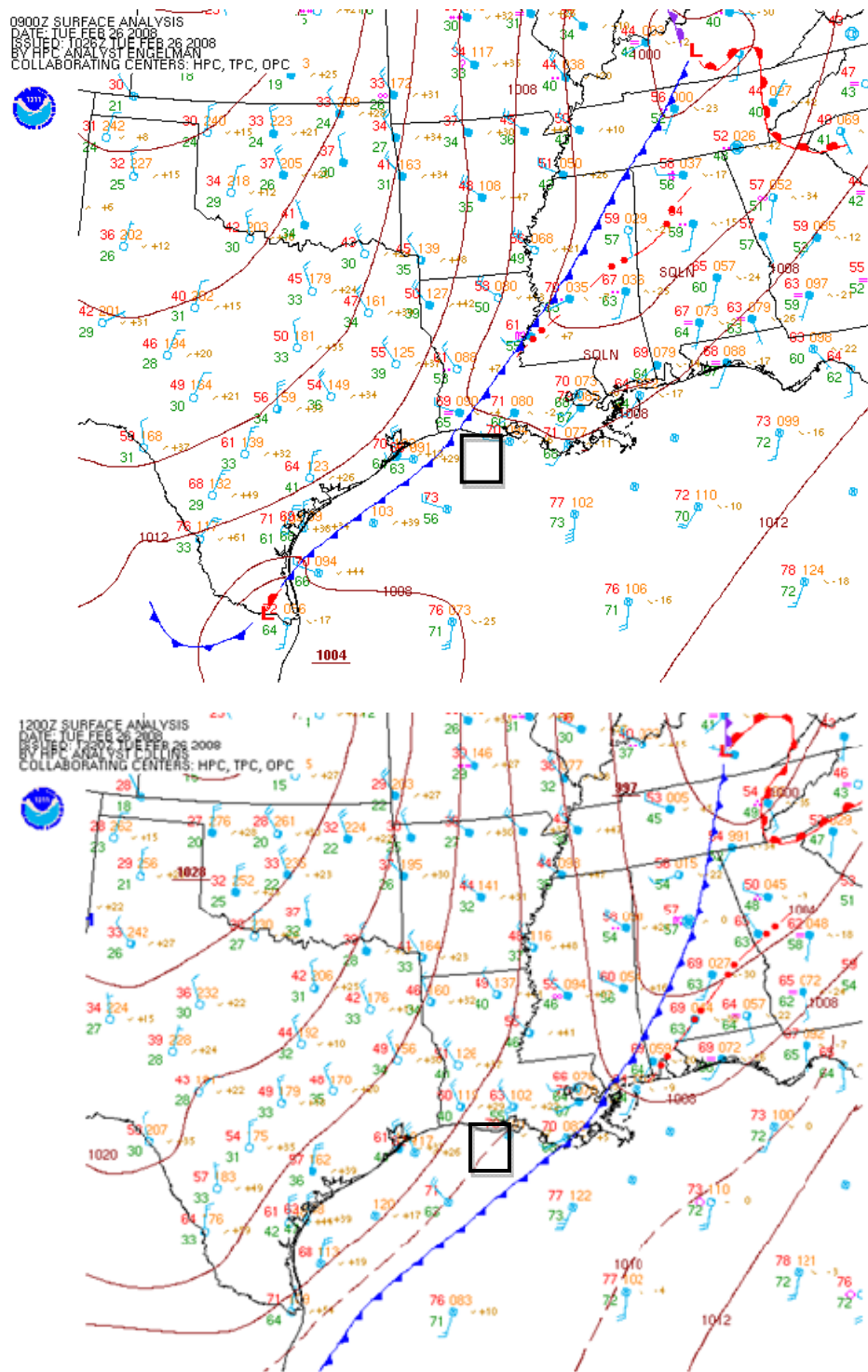


Figure 14. Surface Analysis Weather Charts for February 26, 2008: 0900Z (Top panel) and 1200Z (Bottom panel). (Same format as Figure 12) (From nomads.ncdc.noaa.gov)

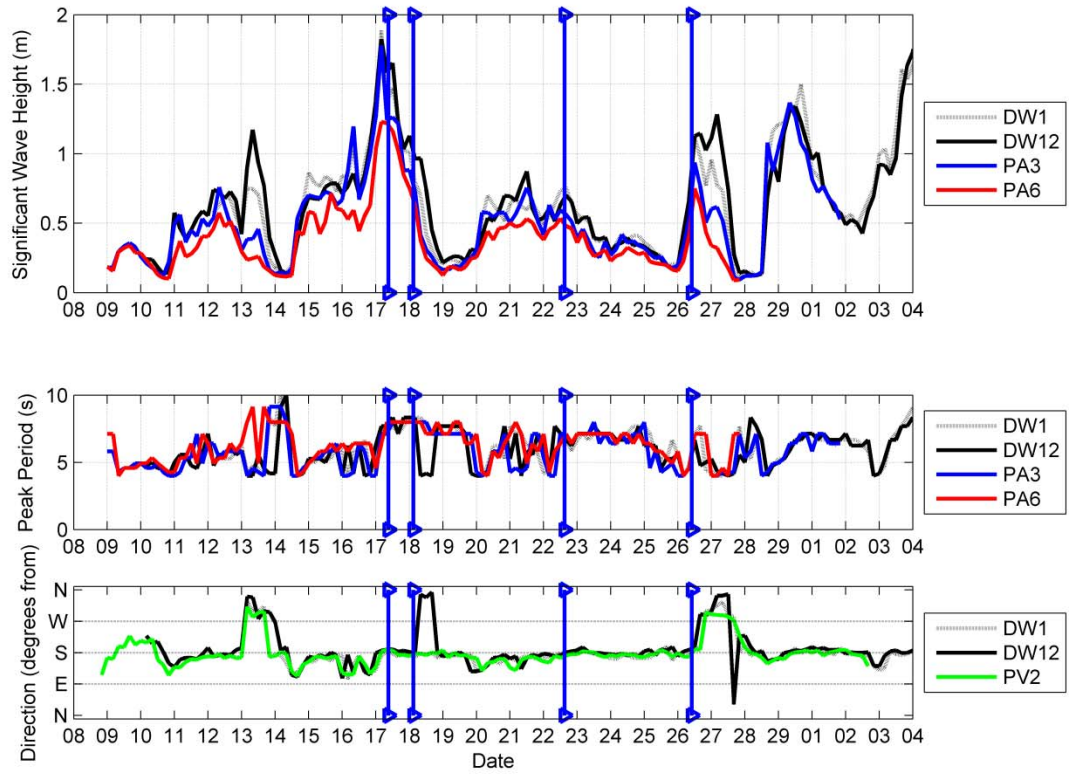


Figure 15. Wave observations for the western transect. Significant wave height H_s (Top panel). Peak period T_p (Middle panel). Peak wave direction D_p (Bottom panel). Cold fronts are marked by blue vertical lines.

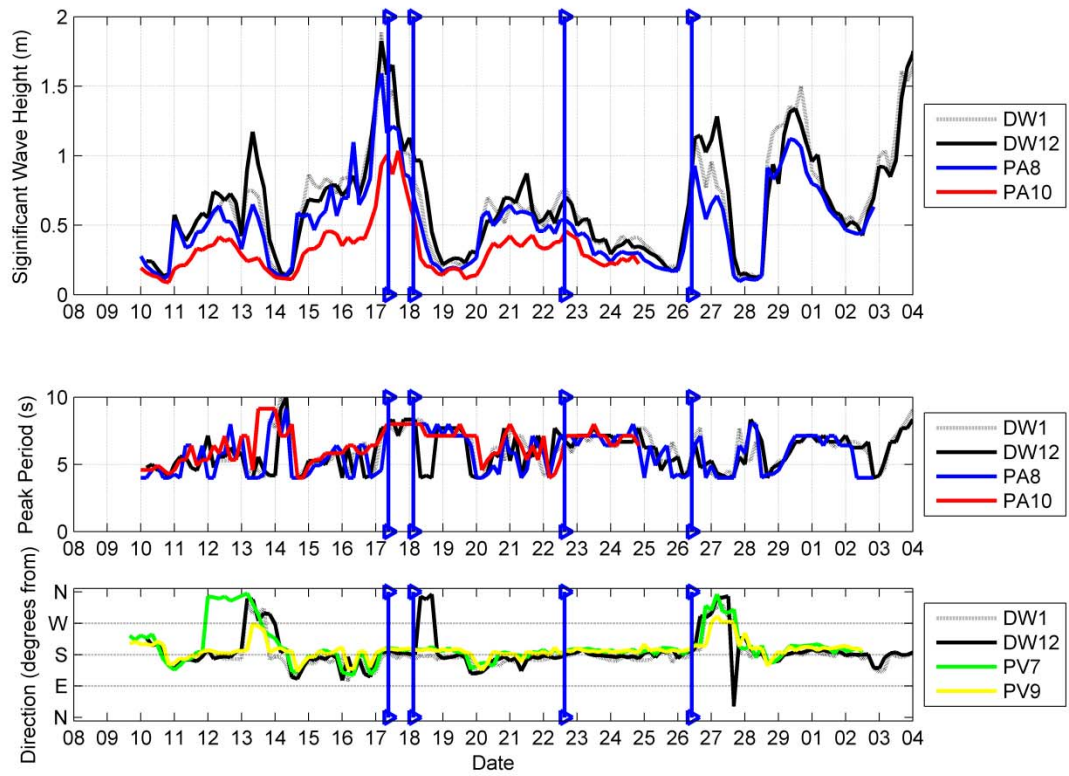


Figure 16. Wave observations for the central transect. (Same format as Figure 15)

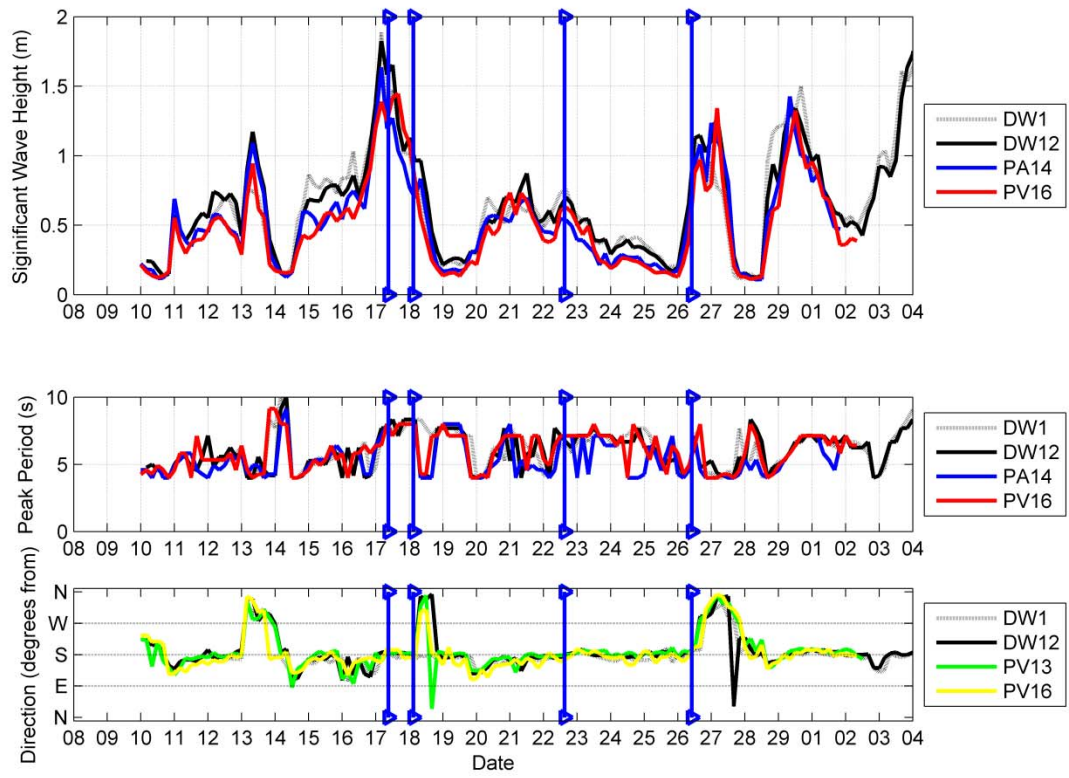


Figure 17. Wave observations for the eastern transect. (Same format as Figure 15)

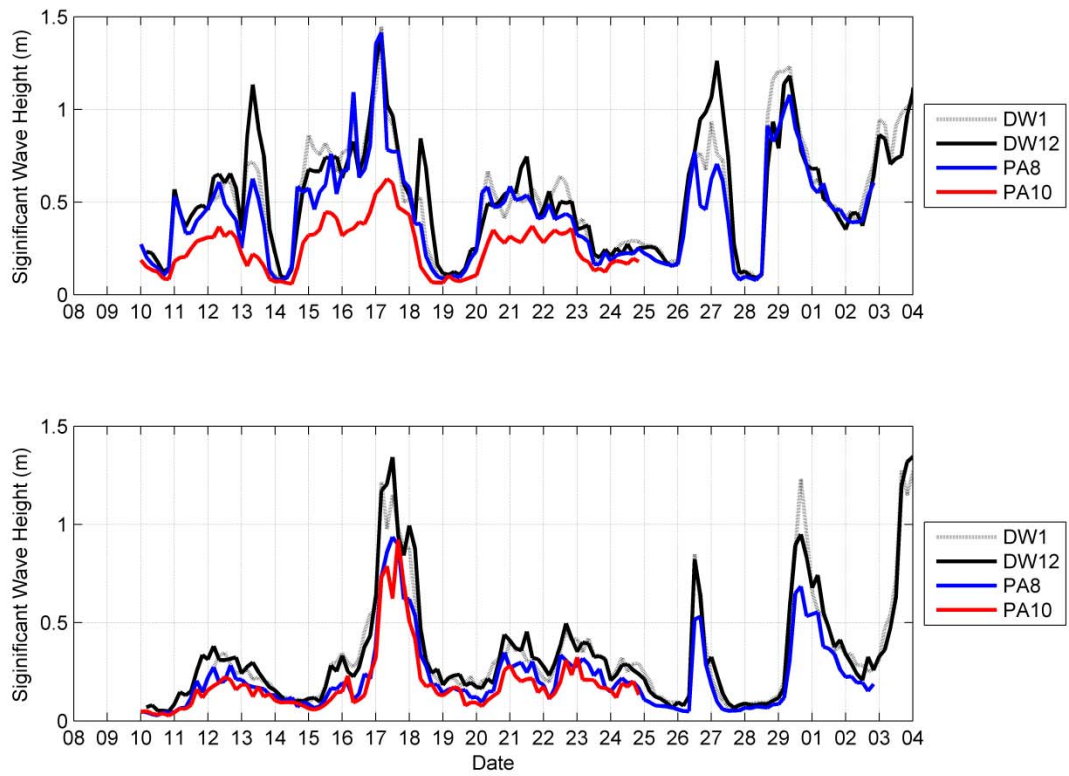


Figure 18. Wave observations for the central transect. Sea component of significant wave height H_s (sea) (Top panel). Swell component of significant wave height H_s (swell) (Bottom panel).

V. SWAN MODEL IMPLEMENTATION

A. INTRODUCTION

Simulating WAVes Nearshore (SWAN) is a two-dimensional, third-generation, spectral wave model developed by Delft University of Technology (Booij et al., 1999). A third-generation model predicts wave spectral evolution without any prior assumption of spectral shape. The standard SWAN model is an open source community model that is widely used by scientists and engineers to obtain estimates of wave parameters in coastal areas, lakes and estuaries from a specified wind field, bottom topography and input ambient currents (Holthuijsen et al., 2007). It is also commonly used around the world in military forecasting centers to obtain predicted wave heights before a military operation in the littoral environment. This chapter will provide a brief description of the SWAN model and detail its implementation for MUDEX.

B. MODEL DESCRIPTION

The governing equation of the SWAN model used for MUDEX is the steady state energy balance equation in spherical coordinates described in Holthuijsen (2007):

$$\begin{aligned} \frac{\partial c_{g,\lambda} E(f, \theta; \lambda, \varphi)}{\partial \lambda} + (\cos \varphi)^{-1} \frac{\partial c_{g,\varphi} E(f, \theta; \lambda, \varphi)}{\partial \varphi} \\ + \frac{\partial c_{\theta} E(f, \theta; \lambda, \varphi)}{\partial \theta} = S(f, \theta; \lambda, \varphi) \end{aligned} \quad (13)$$

where $E(f, \theta)$ is the energy density spectrum in terms of wave frequency f and wave direction θ . The first and second term on the left hand side of (13) represent the wave energy flux gradients associated with advection in latitude (φ) and longitude (λ) geographic space. The third term represents depth-induced refraction. The right hand side of (13) represents the total source/sink term for the energy density. It accounts for the effects of generation, nonlinear wave-wave interactions and dissipation. It is generally written as the sum of a number of separate source terms, each representing a different type of process:

$$S(f, \theta) = S_{in}(f, \theta) + S_{ds}(f, \theta) + S_{nl}(f, \theta) \quad (14)$$

where S_{in} represents wave generation by wind, S_{nl} is the wave energy transfer between spectral components due to nonlinear wave-wave interactions (including both quadruplet and triad interactions), and S_{ds} is the dissipation of wave energy due to whitecapping, wave-bottom interactions and depth induced breaking.

C. BOTTOM DISSIPATION

The standard version of SWAN does not explicitly account for mud-induced wave-damping but instead contains various formulations of bottom friction over a rigid sandy seabed that is considered the dominant bottom dissipation mechanism for continental shelf seas with sandy bottoms. The default bottom dissipation parameterization in SWAN is the widely used empirical JONSWAP bottom friction model of Hasselmann et al. (1973) that takes the form of a simple linear source term (see Holthuijsen, 2007 for a review):

$$S_{bfr}(f, \theta) = -\frac{C_{bfr}}{g^2} \left[\frac{2\pi f}{\sinh(kh)} \right]^2 E(f, \theta) \quad (15)$$

where C_{bfr} is a (dimensional) tuning parameter. Hasselmann et al., (1973) suggested $C_{bfr} = 0.038 \text{ m}^2/\text{s}^3$ for swell conditions and Bouws and Kommen (1983) suggested $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$ for wind-sea conditions, the latter value was implemented as the default setting in SWAN.

There are two other bottom friction models available in SWAN: the drag law model of Collins (1972) and the eddy-viscosity model of Madsen et al. (1988). In this study we use the simpler JONSWAP formulation because the physics of mud-induced wave damping are not captured by any of these models, and thus a simple linear damping term with a tunable coefficient provides a sensible starting point to investigate the observed damping rates over a muddy seafloor.

D. MODEL IMPLEMENTATION

SWAN Cycle III version 40.51AB was implemented in this study. The model was run in a two-dimensional stationary mode on a spatial grid and formulated in spherical coordinates. A small model domain of 34km (longitude) by 66km (latitude) was selected with a uniform rectangular grid to cover the western and central transects (Figure 19). Default settings were used for the source term parameterizations of wind forcing, quadruplet wave-wave interactions, whitecapping dissipation and depth induced breaking (Holthuijsen et al., 2007). However, different values of the tuning parameter C_{bfr} in the linear JONSWAP bottom friction source term were used to investigate optimal model settings that match the wave dissipation observed at the field site.

As discussed in Chapter IV, the wind field can be considered homogeneous for this relatively small model domain. The wind speed and direction were averaged for a 60 minute period centered on the model run start time. The averaged value for the wind speed was then corrected to U_{10} (10m elevation) using a logarithmic profile and Charnock's (1955) parameterization of sea surface roughness. A high resolution bathymetry data set was interpolated onto the model domain (Figure 19). Frequency directional spectra were estimated from buoy DW12, using the MEM method by Lygre and Krogstad (1986) (see Chapter III), and applied as the offshore boundary condition on the southern side of the model domain.

The model was run with 60 frequency bands spaced logarithmically over a frequency range of 0.04 Hz to 1.0 Hz. The direction resolution of the model was set at 5 degrees (72 bins). The cross shore spatial resolution was set at 131m (250 meshes) and the along shore spatial resolution was set at 137m (500 meshes).

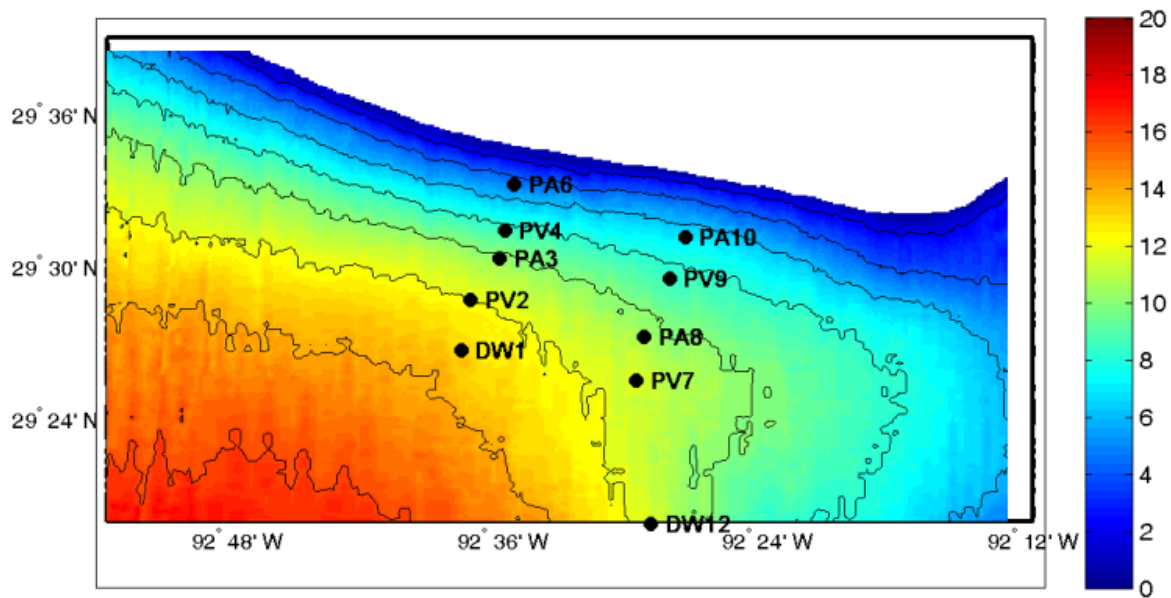


Figure 19. SWAN model domain for MUDEX with instrument locations and depths in color (units m). Depth contours at 2m intervals.

VI. MODEL RESULTS

A. INTRODUCTION

In this chapter, the observational results from MUDEX in Chapter IV will be compared to SWAN model predictions (described in Chapter V). Specifically, this chapter will evaluate the standard SWAN model's performance in a muddy environment. It will also examine an optimal value for the tuning coefficient (C_{bfr}), in the bottom friction model of Hasselmann et al. (1973), to match wave damping at the field site.

Four case studies were carefully selected to represent different wind conditions (Cases I and III - easterly, Case II - northwesterly and Case IV - no wind) (Figure 20). A steady southerly swell was also present in Cases I, III and IV. Case II was a fetch limited case with a building northwesterly wind sea. Wind conditions were relatively steady for each case with Case I chosen nine hours before the first front, Case II nine hours after the second front, Case III during a stationary ridge of high pressure and Case IV three hours before the third front (Figure 20 Top panel). Input wind conditions for the model used average wind speed and direction observations over a one hour period, centered on the start of the wave observation records. Wind speeds observed during the preceding and following one-hour periods did not deviate more than 2.8 m/s from the input conditions for all case studies.

The offshore frequency-directional spectrum was estimated from the waverider buoy at site 12 (described in Chapter III) and implemented as the boundary condition on the southern side of the model domain for all cases. This was considered to be a reasonable assumption as the alongshore wave height variations observed on the eastern transect are much smaller than the cross-shore variations along the western and central transect (compare Figure 17 with Figures 15 and 16). This is further supported by wave energy spectra for the eastern transect (not shown) which are similar at all sites.

Wave conditions display some temporal variation in wave height for each case study. This is particularly evident with Cases I and II during the passage of the first two fronts as shown in Figure 20 (Top Panel). However, a closer analysis of the transects, shows that the observed wave heights do not vary more than 0.2 m for all case studies within a one hour period before or after model start time. Therefore, wave heights are considered reasonably steady to conduct model predictions at the selected times.

B. CASE STUDIES

1. Case I—Easterly Wind 0000Z February 17, 2008 (High Energy)

Case I represents a high energy southerly swell with strong easterly winds nine hours before a frontal passage (Figure 20 Top Panel). An average wind direction of 102 degrees and wind speed of 12.4 m/s was computed from wind observations between 1630Z and 1730Z on February 17, 2009. Figure 21 shows the predicted significant wave height and peak direction across the model domain. The dominant south-easterly wave direction is fairly uniform across the domain, indicating refraction effects are weak, and differs by about 30 degrees from the wind direction. The predicted wave heights decay with decreasing depth primarily owing to the bottom friction source term. Numerical errors in wave height and direction are apparent on the eastern side of the model domain where the lateral boundary creates a shadow zone. These boundary effects occur in subsequent case studies but do not affect predicted wave parameters at the instrument sites as the domain is sufficiently large. This was further confirmed when the model was run on a much larger domain (not shown) with comparable results.

Observed energy spectra and mean directions (θ_{mean}) as a function of frequency are compared to model predictions for the western transect in Figure 22. The model prediction, using the default JONSWAP wind sea setting of $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$, matches the observed spectral evolution fairly well. Figure 23 displays the same spectral information for the central transect. The mean direction (θ_{mean}) is well represented by the model, and the model captures the low frequency swell decay quite well. However, the considerable decay for high frequency wind waves at the inshore sensors, PV09 and

PA10, is not predicted by the model. The observed difference in high-frequency wave decay between the eastern and central transects may be related to the greater extent of mud deposits found on the central transect that is in closer proximity to the outflow of the Atchafalaya river. The strong to gale force wind forcing observed offshore of the MUDEX area for three hours prior to the frontal passage (Figure 12 Top Panel) may have also played a role in stirring up the water column and thus increasing the fluidized mud content (see Sheremet and Stone, 2003; Jaramillo et al., 2009).

Predicted energy spectra are presented in Figure 24 for different values of the tuning parameter C_{bfr} in the JONSWAP bottom friction model. Increasing C_{bfr} enhances the damping of the low frequency swell peak but has no effect on the high-frequency wind-waves. This result illustrates a limitation of the standard bottom damping term in SWAN that is based on the near-bed orbital wave motion (the $\sinh^2(kh)$ term in equation 13) and thus does not predict the decay of high frequency waves that are attenuated at the seafloor. These relatively short wavelength waves may be damped by high sediment concentrations in the water column, a process that is currently not represented in wave prediction models.

Figure 25 displays the comparison of observed wave heights to predicted wave heights for different bottom friction factors along both transects. The western transect shows little variation between the observations and model predictions with $C_{bfr} = 0.038 \text{ m}^2/\text{s}^3$ (swell setting) providing the best agreement with the observations. At the central transect the model cannot capture the observed evolution with the zero friction ($C_{bfr} = 0 \text{ m}^2/\text{s}^3$) run matching only offshore observations (PV07 and PA08) and the $C_{bfr} = 0.09 \text{ m}^2/\text{s}^3$ run matching only inshore observations (PV09 and PA10). The model does not reproduce the sharp reduction in wave height at the inshore sites, but instead predicts a more gradual decay that starts further offshore.

2. Case II—Northwesterly Wind 1200Z February 18, 2008 (Fetch Limited) single space vs. 1.5

Case II depicts fetch limited conditions with north westerly winds nine hours after a frontal passage (Figure 20 Top Panel). An average wind direction of 347 degrees and wind speed of 10.3 m/s was computed from wind observations between 1130Z and 1230Z on February 18, 2009. Model predictions (Figure 26) show north-westerly wave propagation with wave heights increasing offshore as expected for fetch limited development. Similar boundary effects, discussed in Case I, cause errors in wave direction along the western boundary.

Figure 27 displays observations and model predictions of energy spectra and mean directions vs. frequency for the western transect. Model predictions are based on the default bottom friction setting ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). Similar to Case I, the model captures low frequency swell decay with nearly constant mean directions fairly well. However, observations at the inshore sites show much lower energy levels at high frequencies than is predicted. This apparent suppression of high frequency energy levels inshore is even more pronounced on the muddier central transect (Figure 28). It appears that the muddy environment causes a dramatic slowing of the fetch limited wave development on the inner shelf that is very different from the predicted wave growth.

3. Case III—Easterly Wind 0400Z February 21, 2008 (Low Energy)

Case III represents a low energy southerly swell with easterly winds (Figure 20 Top Panel) directed by a firm ridge of high pressure. An average wind direction of 64 degrees and wind speed of 8.8 m/s was computed from wind observations between 0330Z and 0430Z on February 21, 2009.

This case features a similar mix of southerly swell and easterly wind seas as Case I, but the energy levels are much lower. Model-data comparisons for the central transect (Figure 29) show that the model, with default friction, captures the observed spectra and mean wave directions fairly well. The observed energy spectra show slightly more damping of high frequencies at the inshore sensor, PA10, than is predicted but the

difference is not as significant as in Case I. This result supports the hypothesis by Sheremet and Stone (2003) that frontal passages may play a pivotal role in stirring up the sediment in the water column and damping high frequency waves.

The comparison of observed and predicted wave height variations (Figure 30) yields a similar result as Case I. The model run with zero friction ($C_{bfr} = 0 \text{ m}^2/\text{s}^3$) matches only offshore observations (PV07 and PA08) while the default friction ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$) run matches the inshore observation of PA10 but shows a more gradual cross-shore decay than is observed.

4. Case IV—No Wind 1200Z February 22, 2008 (Swell Only)

Case IV depicts a southerly swell with little to no winds (Figure 20 Top Panel) associated with a high pressure system over the area. An average wind direction of 295 degrees and wind speed of 1.5 m/s was computed from wind observations between 1130Z and 1230Z on February 22, 2009.

In these relatively simple swell conditions with nearly uni-directional onshore wave propagation, the model (using the default bottom friction setting of $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$) predicts a nearly uniform decay of the spectrum and constant directions across the central transect that agrees well with the observations (Figure 31). The observed and predicted wave heights along the central transect are compared in Figure 32. As in previous cases, the model run with zero friction ($C_{bfr} = 0 \text{ m}^2/\text{s}^3$) over-predicts the wave height. However, when the default bottom friction ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$) is used the predicted wave heights closely match the observations at all sites.

C. OVERALL MODEL PERFORMANCE

Overall, the present results show that the default wind sea setting ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$) for the JONSWAP bottom friction parameterization used in the standard

SWAN model, gives reasonable estimates of significant wave heights that are satisfactory for most operational military purposes. The largest error in wave height prediction was 25 centimeters, at the shallowest site PA10 on the central transect, during Case I.

The comparison between observed and predicted energy spectra showed that the model (with default setting $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$) generally captures the low frequency swell decay and matches the mean direction for each of the four case studies. However, the model failed to reproduce the appropriate level of high frequency wind wave damping for the central transect in Case I, both western and central transects in Case II and the central transect in Case III. Observations show wave damping was strongest on the central transect and in particular during Case I which involved the strongest winds. The model did not show the same variation between the transects.

The simple linear bottom friction model does not reflect a mud dissipation process and since it is driven by near-bottom orbital wave motion it is effective only at damping low frequency swell peaks. When the system becomes bimodal with strong wind and swell conditions, the model fails to predict damping of high frequency waves.

Although only four case studies were examined, the different damping rates suggest that mud-induced damping of high frequency waves is enhanced when there is a strong frontal event. Frontal activity may stir up the water column fluidizing the mud and cause dissipation of high frequency waves with short wave lengths that are de-coupled from seafloor processes. This may provide an additional dissipation mechanism that is different from the traditional direct wave-bottom interaction processes. A better understanding of the physics of the mud suspension process and the associated increase in viscosity is needed to parameterize this effect in a coastal wave prediction model. Until this process is properly accounted for, the default wind sea setting of the JONSWAP bottom friction model is recommended for operational purposes.

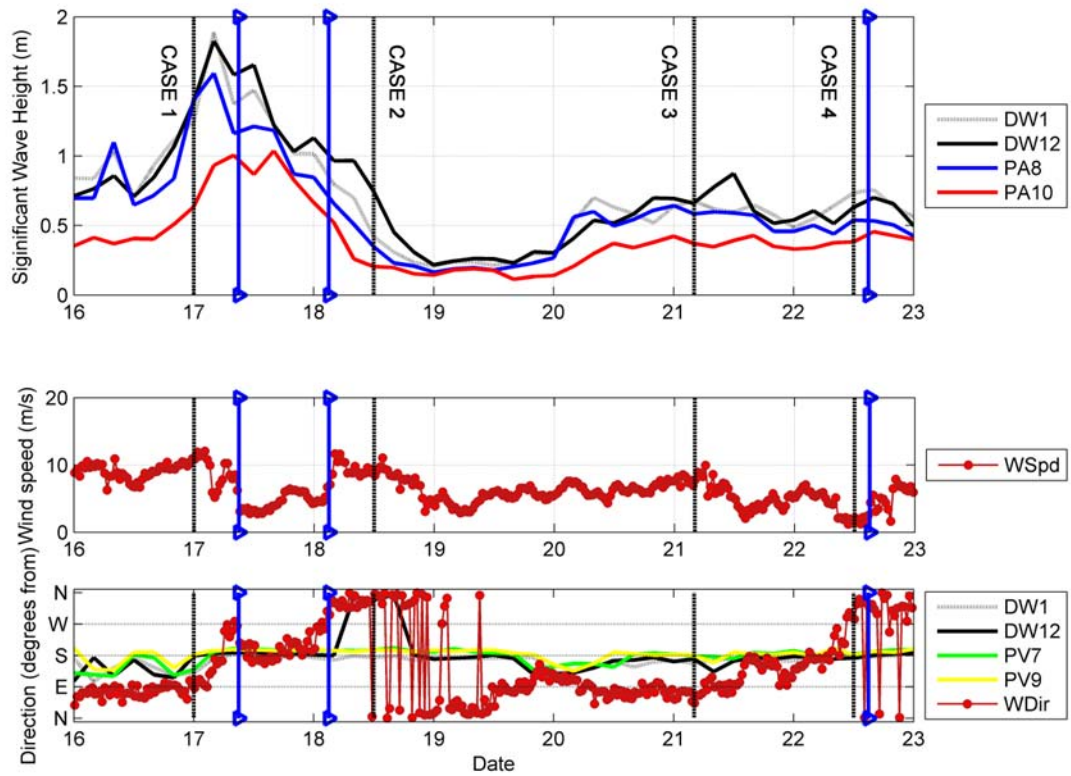


Figure 20. Wave and wind observations for the central transect displaying four case studies selected for analysis. Significant wave height H_s (Top panel). Wind speed (Middle panel). Peak wave direction D_p and wind direction (Bottom panel). Cold fronts are marked by blue vertical lines. Case studies are marked by black vertical lines. (Wind data courtesy of Dr. John Trowbridge and Dr. Janet Fredericks at WHOI)

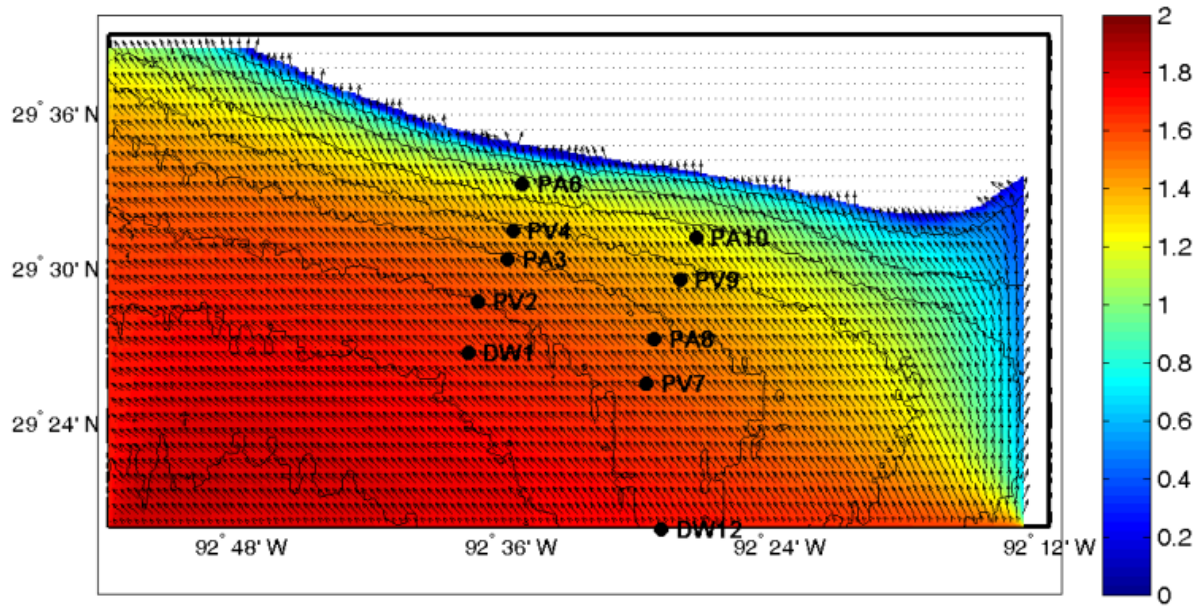


Figure 21. SWAN Model output for Case Study I with instrument locations and significant wave height in color (units m). Depth contours at 2m intervals.

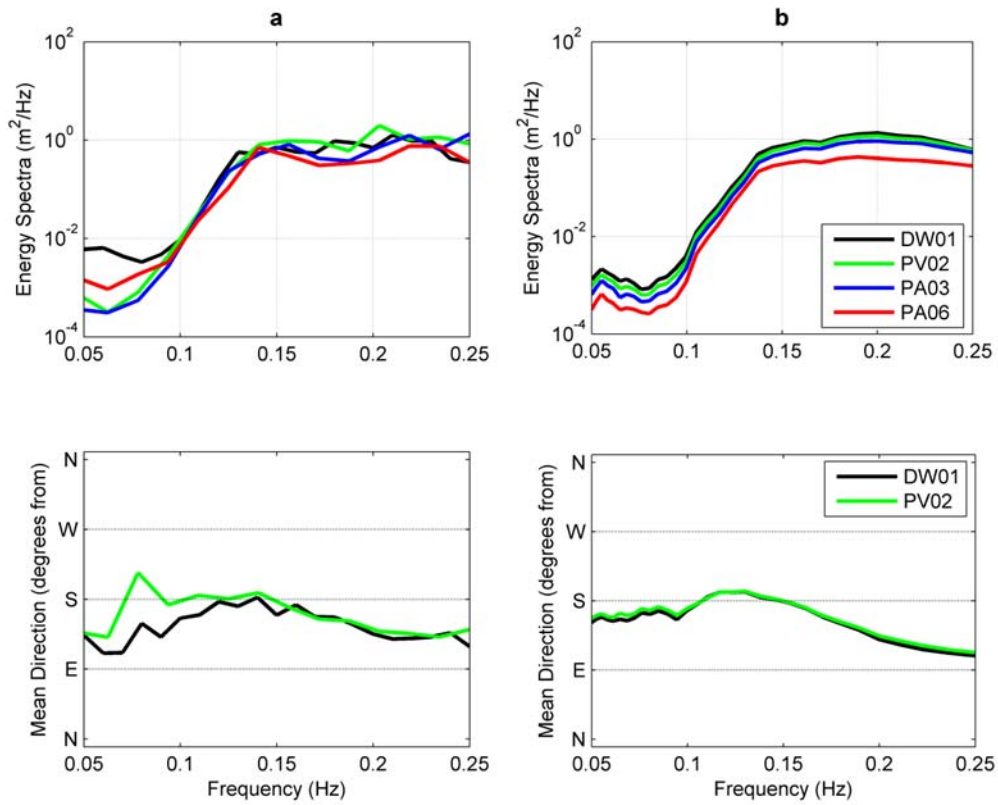


Figure 22. Case I model-data comparisons for the western transect using the default JONSWAP bottom friction source term (wind-sea setting, $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). **a.** Observed wave energy spectra (Top panel) and mean direction vs. frequency (Bottom panel). **b.** Corresponding model predictions.

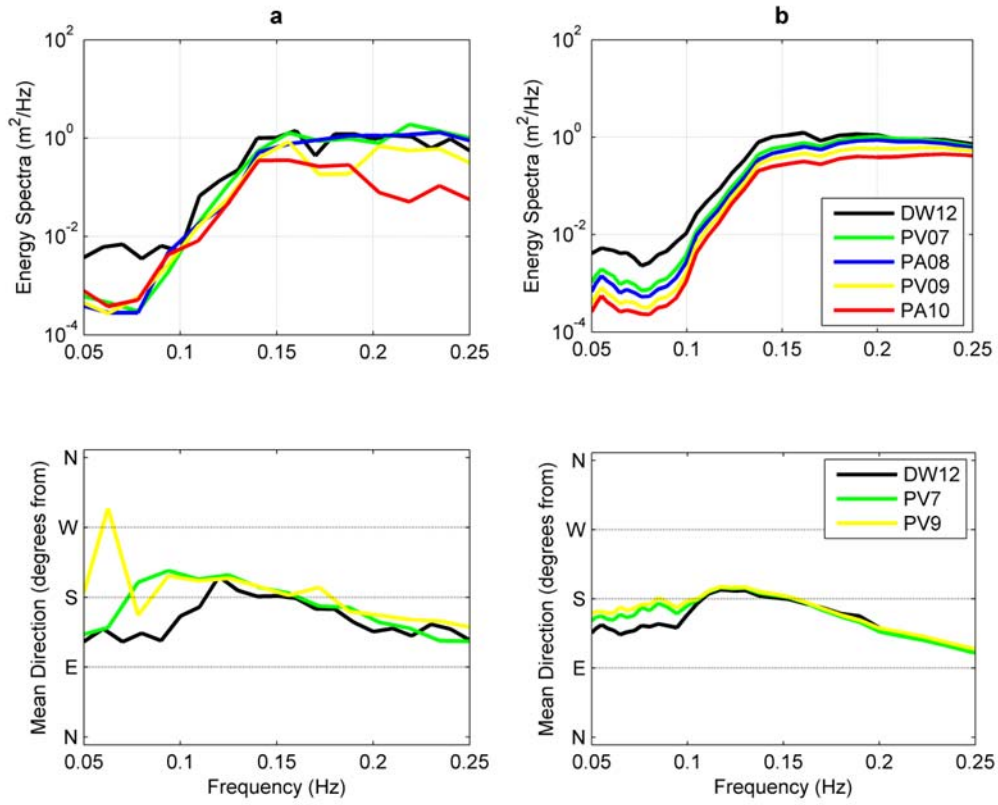


Figure 23. Case I model-data comparisons for the central transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$).
a. Observed. **b.** SWAN model prediction. (Same format as Figure 23)

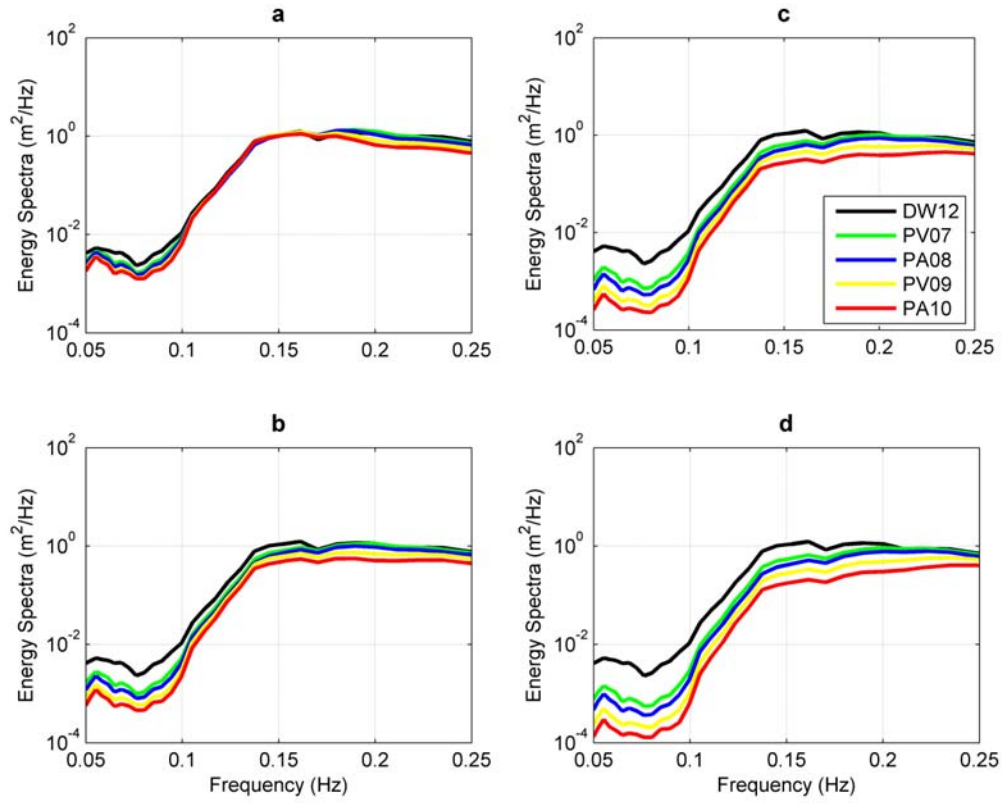


Figure 24. SWAN model predictions of wave energy spectra on the central transect for Case I using different values for the tuning parameter C_{bfr} in the JONSWAP bottom friction source term. **a.** $C_{bfr} = 0 \text{ m}^2/\text{s}^3$. **b.** $C_{bfr} = 0.038 \text{ m}^2/\text{s}^3$. **c.** $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$. **d.** $C_{bfr} = 0.09 \text{ m}^2/\text{s}^3$.

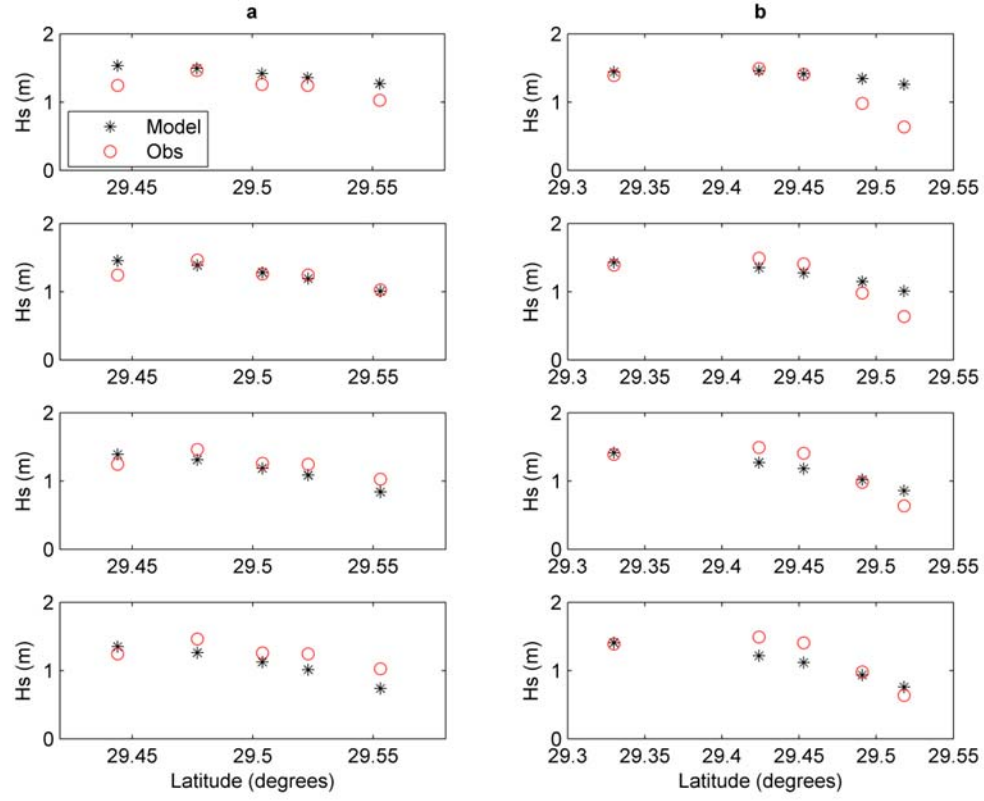


Figure 25. Comparison of observed significant wave heights and SWAN model predictions in Case I using different values of the bottom friction tuning parameter C_{bfr} : from top to bottom: $C_{bfr} = 0 \text{ m}^2/\text{s}^3$, $0.038 \text{ m}^2/\text{s}^3$, $0.067 \text{ m}^2/\text{s}^3$ and $0.09 \text{ m}^2/\text{s}^3$. **a.** Western transect (Sites from left to right are DW1, PV2, PA3, PV4 and PA6). **b.** Central transect (Sites from left to right are DW12, PV7, PA8, PV9 and PA10).

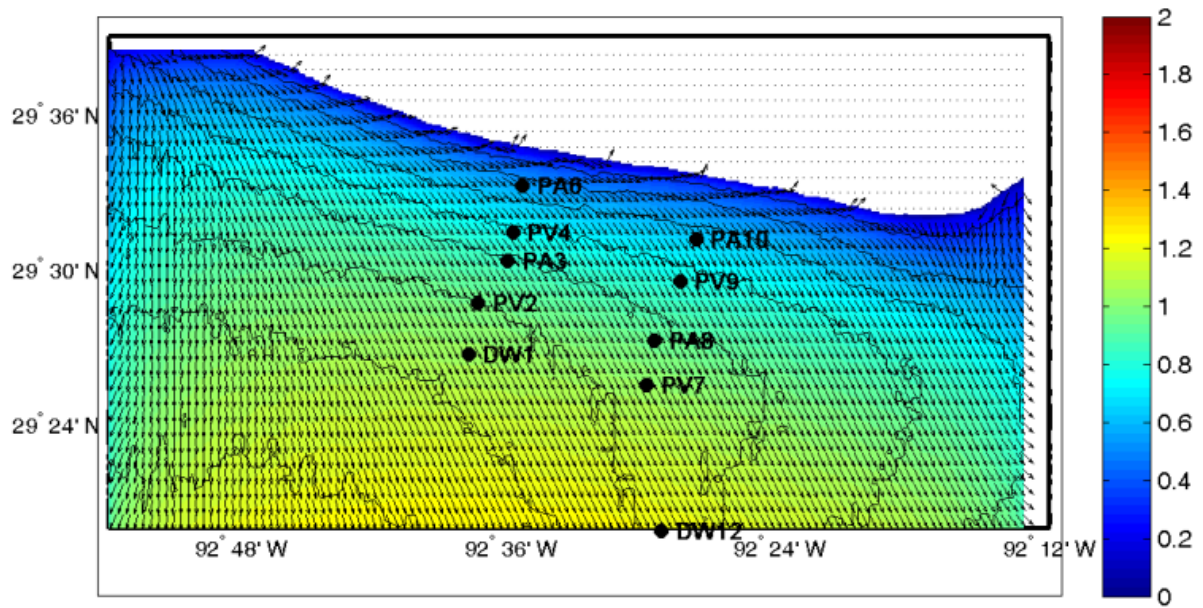


Figure 26. SWAN Model output for Case Study II with instrument locations and significant wave height in color (units m). Depth contours at 2m intervals.

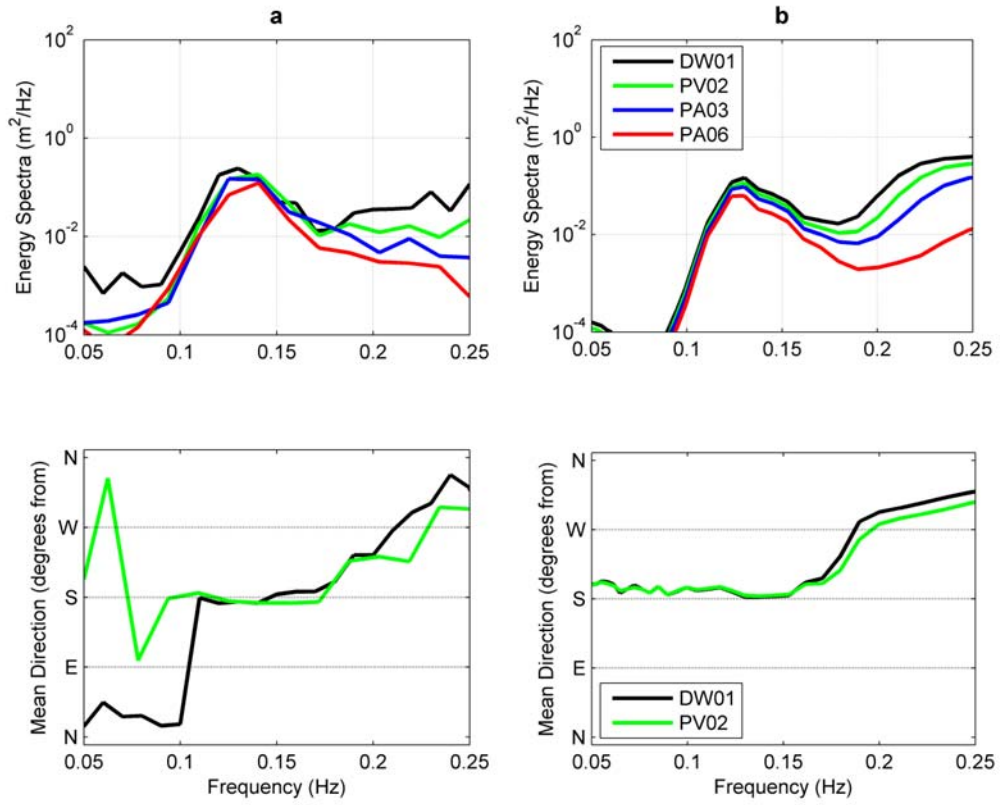


Figure 27. Case II model-data comparisons for the western transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$).
a. Observed. **b.** SWAN model. (Same format as Figure 23)

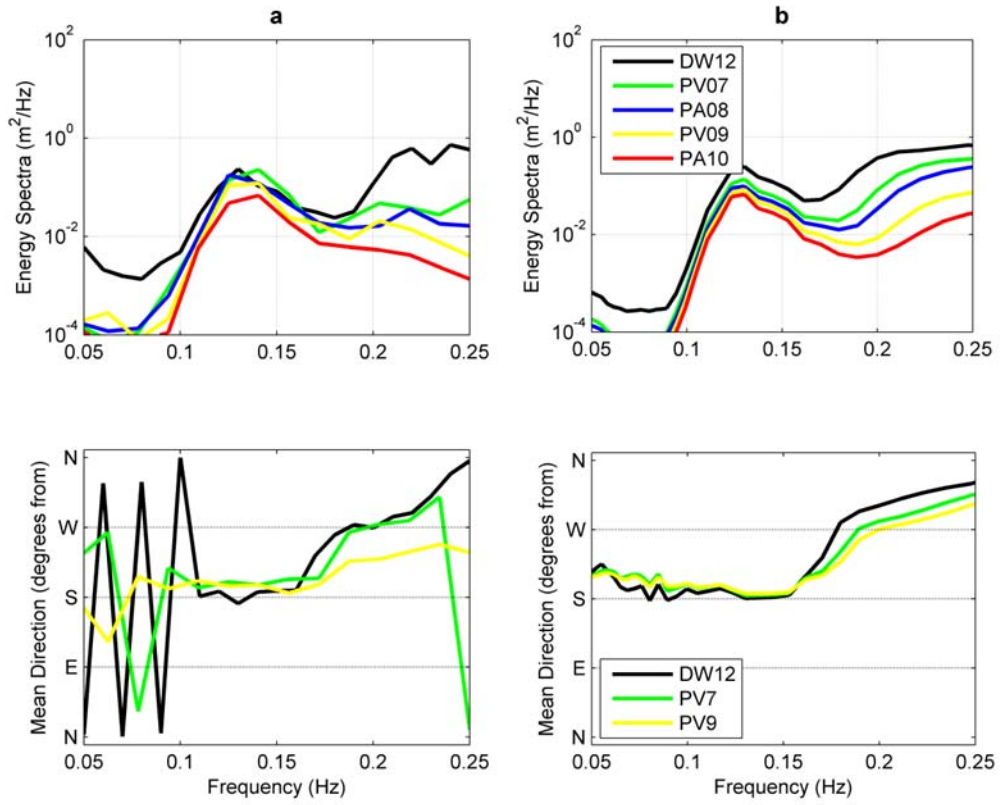


Figure 28. Case II model-data comparisons for the central transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$).
a. Observed. **b.** SWAN model. (Same format as Figure 23)

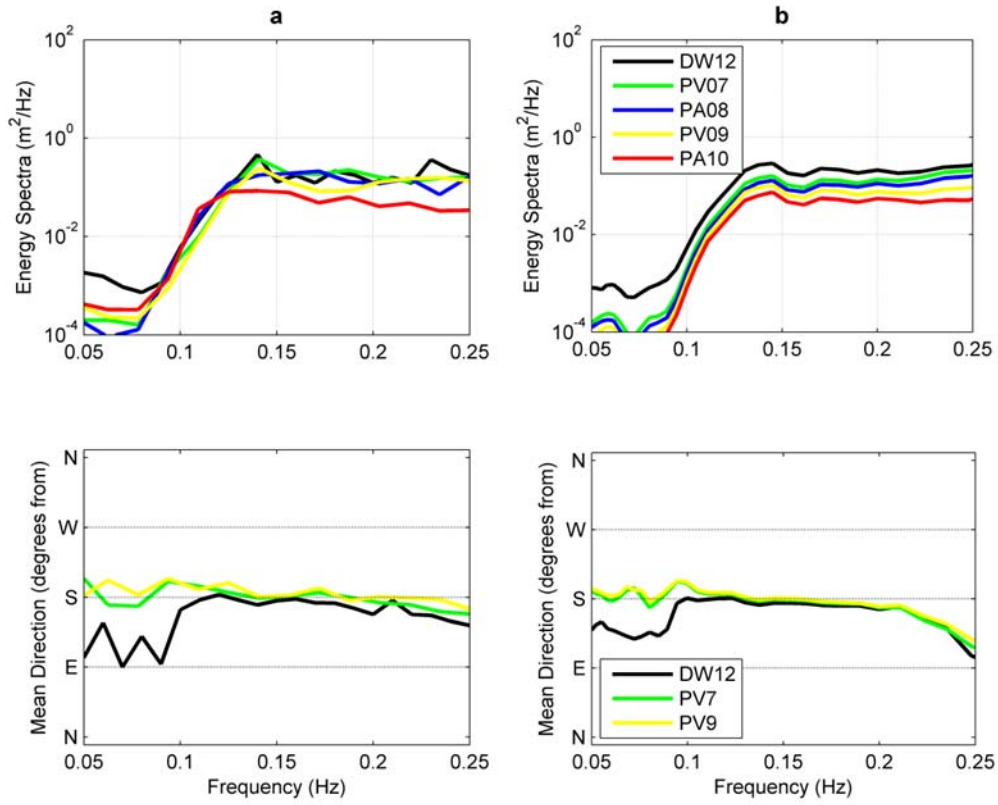


Figure 29. Case III model-data comparisons for the central transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$).
a. Observed. **b.** SWAN model. (Same format as Figure 23)

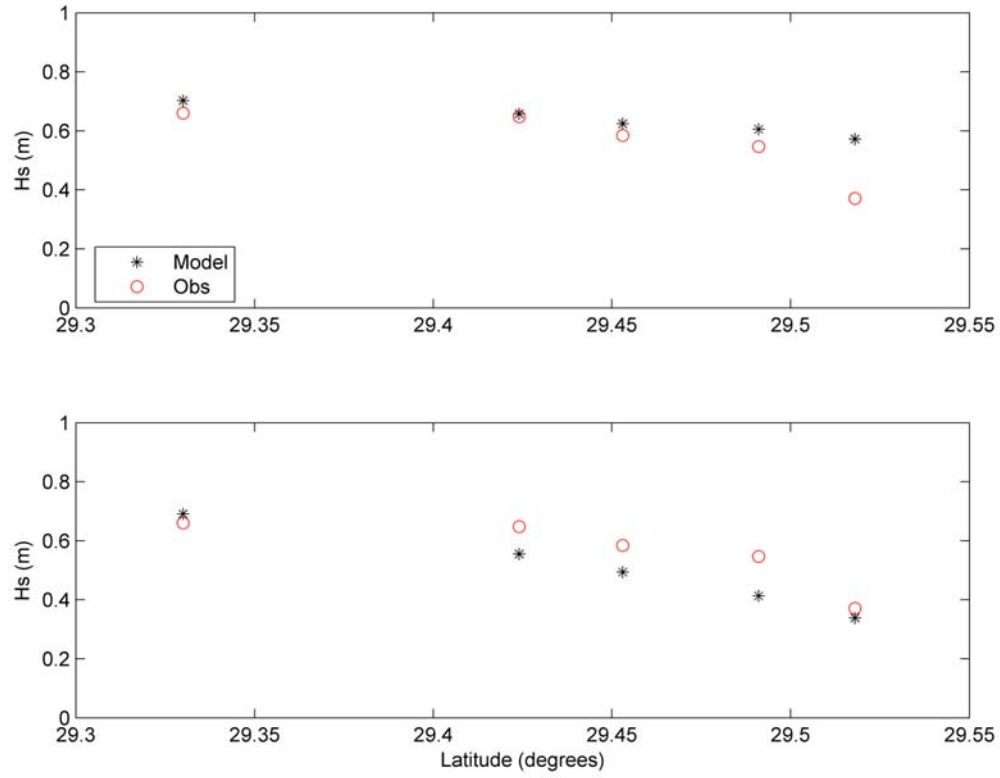


Figure 30. Case III comparison of observed significant wave height and SWAN model predictions on the central transect using different tuning parameter (C_{bfr}) values in the JONSWAP bottom friction source term (Sites from left to right are DW12, PV7, PA8, PV9, PA10). $C_{bfr} = 0 \text{ m}^2/\text{s}^3$ (Top panel). $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$ (default wind sea setting) (Bottom panel).

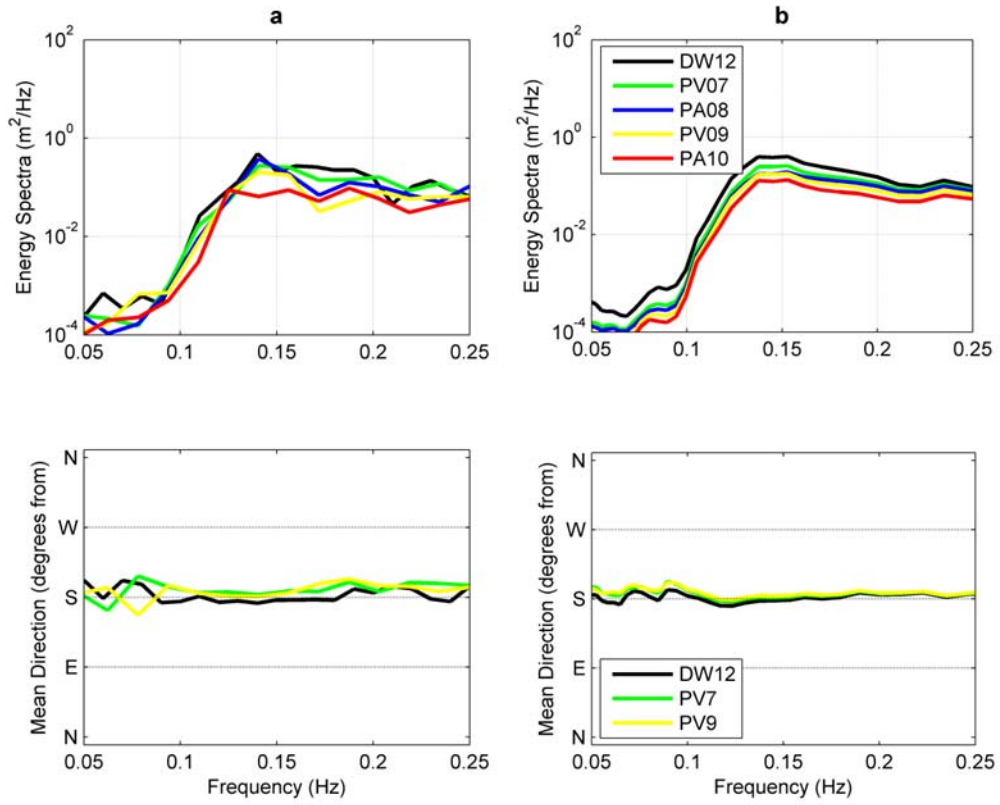


Figure 31. Case IV model-data comparisons for the central transect ($C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$).
a. Observed. **b.** SWAN model. (Same format as Figure 23)

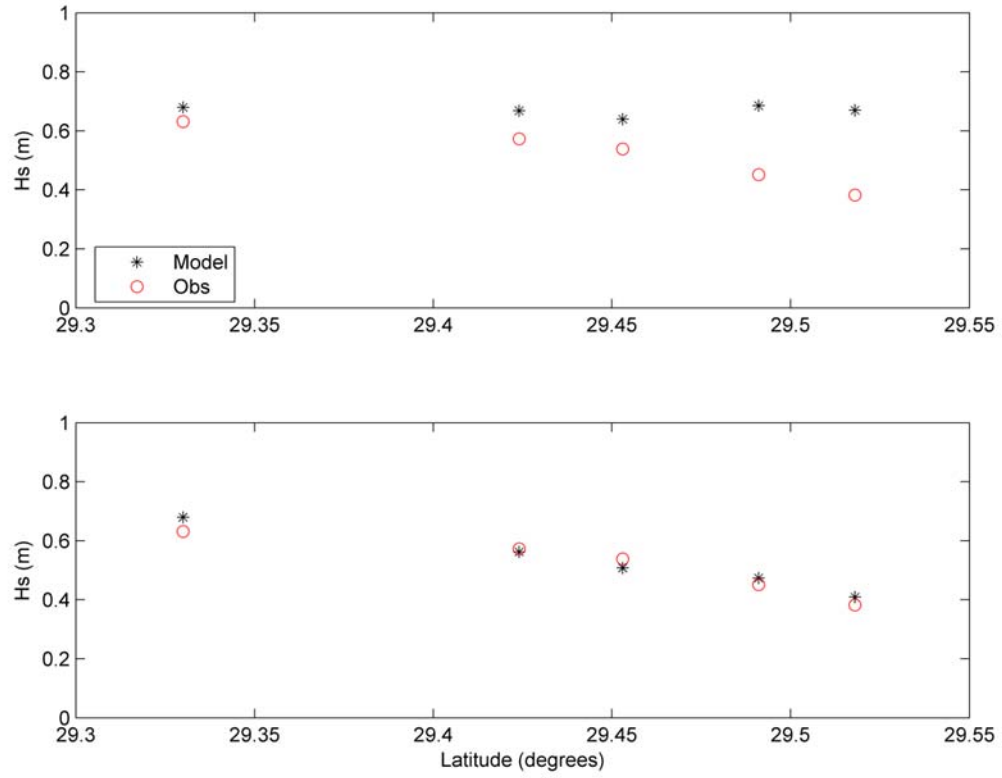


Figure 32. Case IV comparison of observed significant wave height and SWAN model predictions on the central transect. Top panel: no friction, Bottom panel: default $C_{bfr}=0.067\text{ m}^2/\text{s}^3$. (Same format as Figure 30)

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VII. SUMMARY AND CONCLUSIONS

The transformation of ocean surface waves across the muddy continental shelf of Western Louisiana was examined with two months of extensive wave data collected during the ONR-funded Louisiana MUD EXperiment (MUDEX) held in the late winter/early spring of 2008. The experiment was designed to provide a comprehensive field data set for analysis of mud-induced wave damping and validation for an operational wave prediction model such as SWAN (Simulating WAVes Nearshore). This thesis presents the initial analysis of the MUDEX observations and a comparison of observed and predicted wave parameters and spectra with SWAN predictions. Specifically, the overall performance of the SWAN model in its standard configuration is evaluated and a recommendation for the optimal value of the tuning coefficient in the bottom friction parameterization (based on the model of Hasselmann et al., 1973) is given.

The MUDEX Experiment included the deployment of 16 wave measuring instruments between February-March, 2008, in depths ranging from 13 to 4m. The instruments included two directional waverider buoys, six bottom tripods equipped with a pressure-velocity sensor and a current profiler, and eight bottom tripods equipped with a pressure sensor. The two-dimensional 40 by 25 km array consisted of two cross-shore transects, named 'Western' and 'Central' and an alongshore transect named 'Eastern'.

Analysis of box core samples collected on the two cross-shore transects showed there was a greater extent of soft mud (5-10 cm) and very soft fluid mud (1-2 cm) on the central transect when compared to the western transect (soft mud <5 cm and very soft fluid mud <1 cm). This was probably a direct result of the central transect being closer in proximity to the muddy outflow of the Atchafalaya River. Wind observations and surface weather chart analysis showed that fronts regularly cross the area every four to five days and cause increased wave heights due to increased wind forcing. Analysis of general wave observations along the cross-shore transects showed a gradual decay along the western transect and a much sharper decay at the shallowest instruments along the central transect. This sharper decay along the central transect may be attributed

to the thicker layer of mud measured on that transect. The alongshore eastern transect observations showed much smaller variations in wave heights than the cross-shore transects.

Four wind sea events were examined in detail along the cross-shore transects and compared to SWAN model predictions (default bottom friction setting of $C_{bfr} = 0.067 \text{ m}^2/\text{s}^3$). The comparison between observed and predicted energy spectra for each event showed that the model generally captures the low frequency swell decay fairly well. The model also approximately reproduced the observed mean wave direction as a function of frequency. However, the observed considerable decay of high frequency wind-waves at the inshore sensors was not captured by the model. This high frequency decay was especially strong (as much as an order of magnitude) on the central transect, when the wave field was bimodal with a strong alongshore easterly wind in the presence of a high energy southerly swell. When the alongshore wind-sea and swell subsided, the high energy frequency decay was less pronounced. Similar to the easterly winds case, the model also under-predicts energy levels at high frequencies during periods of offshore north-westerly winds. In this fetch limited regime the observations show strong suppression (up to two orders of magnitude) of high frequency energy levels inshore on both the western and central transect, although this is slightly more prominent on the muddier central transect. It is apparent that the muddy environment causes a dramatic slowing of the fetch limited sea development in shallow water.

Analysis of different values of the tuning parameter (C_{bfr}) in the bottom friction parameterization showed that increasing the value of C_{bfr} enhances the damping of the lower frequency swell component of the wave spectrum, but has no effect on the high-frequency waves. In relatively simple swell conditions with no wind-sea, the model spectra closely matched the observed spectra for the default value of $0.067 \text{ m}^2/\text{s}^3$. However, tuning the value of C_{bfr} to the observed wave height decay in bimodal sea states yielded excessive damping of the swell component and not enough damping of the high-

frequency wind-sea. Clearly, the bottom friction model based on the drag exerted by the near-bed wave orbital motion cannot describe the observed dissipation of high-frequency wind-seas that are attenuated at the sea floor.

Overall, the comparison of observed and predicted significant wave heights for each event showed that the standard SWAN model, with the default bottom friction setting, gives reasonable results for most Navy littoral operations that require only wave height predictions. However, when there are alongshore winds, the model does not quite match the observed sharp reduction in wave height near the shore at the inshore sites, but instead predicts a more gradual decay that starts further offshore.

Although only four case studies were analyzed, results suggest that wave damping in shallow water is enhanced when there is a strong frontal event (strong easterly winds and high energy southerly swell). In shallow water the strong wind forcing before and during a frontal passage may fluidize the mud over the entire water column and the increased viscosity may cause high frequency wave dissipation, as suggested by Sheremet and Stone (2003) and Jaramillo et al., (2009). This may provide an additional dissipation mechanism that is different from the traditional bottom-induced mud dissipation process. While improvements of wave models requires new physics-based mud-induced dissipation mechanisms, at present the default settings for SWAN appear to provide a reasonable approximation of wave heights inshore of a muddy environment, and is recommended for use in military operations.

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