NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ANALYSIS OF NEARSHORE CURRENTS NEAR A SUBMARINE CANYON

by

Matthew Stephan Cushanick

June 2005

Thesis Advisor: Thomas H.C Herbers
Second Reader: Edward B. Thornton

Approved for public release; distribution unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** June 2005	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: Analysis of Nearshore Currents Near a Submarine Canyon

5. FUNDING NUMBERS

6. AUTHOR(S) Matthew Stephan Cushanick

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 unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

Accurate prediction of nearshore waves and currents is of critical importance in littoral naval operations. This study examines the effects of complex bathymetry on nearshore currents. Data collected by an array of 12 pressure and velocity sensors in the Nearshore Canyon Experiment (NCEX), conducted near La Jolla, California in 2003, were analyzed to investigate the variability of nearshore currents near a submarine canyon. Time series of pressure, 3-component velocity, and wave heights along the 10 meter depth contour were analyzed to determine the relative importance of tides, waves, and winds in the forcing of nearshore currents outside the surf zone. Additionally, the spatial variability of the observed currents was investigated in relation to the nearby canyon head. Case studies are examined to determine how different wave and tide conditions affect the currents near the canyon.

In low-moderate wave conditions, tides dominate longshore currents, whereas cross-shore currents show the passage of irregular bore-like features. The currents are coherent away from the submarine canyon and decay towards the canyon head. Strong longshore currents were observed near the canyon head during a large wave event that were likely driven by an alongshore pressure gradient associated with wave set-up variations.

14. SUBJECT TERMS Nearshore Canyon Experiment, NCEX, Bathymetry, Scripps Canyon, La Jolla Canyon, Submarine Canyon, Nearshore Currents, Longshore Currents, Tides, Current Prediction

15. NUMBER OF PAGES 63

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

ANALYSIS OF NEARSHORE CURRENTS NEAR A SUBMARINE CANYON

Matthew S. Cushanick
Ensign, United States Navy
B.S., United States Naval Academy, 2004

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN APPLIED SCIENCE
(PHYSICAL OCEANOGRAPHY)

from the

NAVAL POSTGRADUATE SCHOOL
June 2005

Author: Matthew Stephan Cushanick

Approved by: Dr. Thomas H.C. Herbers
Thesis Advisor

Dr. Edward B. Thornton
Second Reader

Dr. Mary L. Batteen
Chair, Department of Oceanography

Dr. Donald P. Brutzman
Chair, Undersea Warfare Academic Committee

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Accurate prediction of nearshore waves and currents is of critical importance in littoral naval operations. This study examines the effects of complex bathymetry on nearshore currents. Data collected by an array of 12 pressure and velocity sensors in the Nearshore Canyon Experiment (NCEX), conducted near La Jolla, California in 2003, were analyzed to investigate the variability of nearshore currents near a submarine canyon. Time series of pressure, 3-component velocity, and wave heights along the 10 meter depth contour were analyzed to determine the relative importance of tides, waves, and winds in the forcing of nearshore currents outside the surf zone. Additionally, the spatial variability of the observed currents was investigated in relation to the nearby canyon head. Case studies are examined to determine how different wave and tide conditions affect the currents near the canyon.

In low-moderate wave conditions, tides dominate longshore currents, whereas cross-shore currents show the passage of irregular bore-like features. The currents are coherent away from the submarine canyon and decay towards the canyon head. Strong longshore currents were observed near the canyon head during a large wave event that were likely driven by an alongshore pressure gradient associated with wave set-up variations.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

This thesis would not have been possible without the enthusiasm, diligence, and insight of my thesis advisor Professor Tom Herbers. I would like to personally thank him for his motivation and guidance which kept me on course throughout my study at Naval Postgraduate School. Without his expertise I would not have learned how to practically apply my knowledge of the oceans in this analysis. I would also like to thank Mr. Paul Jessen for his patience and skill in the many tedious hours of data analysis done in my study. Without his willingness to help I would never have accomplished any of the work presented in this paper. My hope is they continue to do excellent work with the future students at NPS and I extend my most heartfelt thanks for their expert guidance and friendship during my year at NPS.

I. INTRODUCTION

A. MOTIVATION

The sheer power of an ocean wave breaking on a sandy beach is one of the most awesome scenes in nature. Despite its beauty, the surf zone possesses a singular power to radically alter beach morphology or devastate manmade coastal structures. As the global economy continues to expand into the coastal marine environment, it has become increasingly important to advance understanding and prediction of surface wave phenomena. Better understanding of the marine environment, specifically in the nearshore, is important to control beach erosion, determine hazards to vessels and recreation, carry out military operations, control pollution, and enhance marine economic productivity.

Prediction of wave and current regimes in regions of complex nearshore bathymetry is a tremendously difficult problem dating back to research conducted by Munk and Traylor at the Scripps Institution of Oceanography in 1947. Whereas much progress has been made in models of important physical processes including wave breaking, bottom friction, refraction, diffraction, longshore currents and undertow, field data remains scarce. This thesis focuses on nearshore waves and currents in areas with complex bathymetry using extensive observations from the recent Nearshore Canyon Experiment (NCEX). In particular, the effects of a submarine canyon on alongshore and cross-shore currents will be examined in relation to tides, waves, and wind forcing.

B. MILITARY APPLICATIONS

Superior understanding of the nearshore environment is imperative to future military applications. An increased awareness of wave interactions in regions of complex or shallow bathymetry is necessary now more than ever due to the ongoing transition by the United States Navy from a blue water (open-ocean) naval force to a brown water (littoral) naval force. The variability of nearshore processes makes the planning of precise littoral naval operations extremely difficult. Nearshore surface wave phenomena have great importance to operations such as amphibious landings, mine warfare, and special operations incursions. Improved nearshore understanding will facilitate superior prediction of sediment transport in the burial of mines and operational hazards for Autonomous Underwater Vehicles (AUVs) as well as environmental hazards to personnel in mine warfare operations, special operations incursions, and amphibious operations.

Waves and currents play an integral part in the coordination of operational timelines and the operating characteristics of equipment in littoral warfare. Prior forecasting of waves and currents provides the operator with the strategic ability to predict when conditions are optimal for essential missions or incursions. Mission success is greatly increased if the operator is better able to exploit environmental conditions in response to asymmetric enemy threats.

C. NEARSHORE PROCESSES

1. Wave Refraction and Diffraction

In the nearshore environment, the geometry of the coast, bathymetry, and shore protection structures affect the transformation of waves through diffraction and refraction. Diffraction is spreading of waves behind obstacles causing wave energy to be transferred toward sheltered areas (e.g. behind a breakwater) (Munk and Traylor, 1947). When a wave train encounters an obstacle, the crests bend, forming diffraction patterns similar to those of light in optics. Diffraction is important in harbors and around breakwaters, but usually weak on natural beaches, such as the site examined in this study (O’Reilly, 1989).

Of greater importance in most coastal environments is the process known as refraction by which waves are bent due to a gradient in their propagation velocity along the wave crest. As waves approach regions of decreasing depth their progress is slowed. Thus the portion of the crest over shallow depths is slowed more than portions in deeper water, causing the wave to bend towards shallower depths (Munk and Traylor, 1947). Progressing onshore the crest will become increasingly parallel to the depth contours as it comes onshore.

The complexity of the nearshore region is magnified by the fact that refraction can cause a multidirectional wave field with intersecting waves traveling at various angles incident to the coastline. The interaction of waves arriving from multiple directions creates regions of focusing, or convergence. Shoals and headlands are prime areas for wave focusing. As waves advance over a shoal or approach a headland, the wave crest is bent towards the shallower bottom features creating a region where the wave energy converges from multiple directions, often causing strongly amplified wave conditions.

2. Longshore and Rip Currents

Waves breaking on a beach can drive so-called longshore currents and rip currents. Longshore currents are formed where waves impact the coastline at an angle (Shepard and Inman, 1950). Momentum is transferred from the waves to a longshore current through a radiation stress (Longuet-Higgins, 1970). The current strength continues to increase until the associated bottom stress balances the wave radiation stress. Numerous studies have confirmed this dynamic balance in the surfzone (Thornton and Guza, 1986; Feddersen et al, 1998; Lentz et al, 1999).

Longshore currents can also be generated by alongshore pressure gradients due to variations in wave height. Large waves cause higher wave setup at the shoreline than small waves, resulting in alongshore pressure gradients that drive longshore currents flowing toward locations with small wave heights. This mechanism is important in regions where bathymetry affects wave height, specifically submarine canyons. Waves are refracted away from the canyon head, forming an area of low wave heights where longshore currents converge (Munk and Traylor, 1947).

A convergence of longshore currents may also occur on beaches where refraction causes waves to arrive from opposing directions. Where longshore currents converge, a jet may form shooting water away from the coast, commonly referred to as a rip current. Rip currents are common to areas with unprotected coastlines since waves can propagate freely onshore from a variety of large angles. Rip currents do not commonly extend beyond the surf zone since they are impacted by coastal currents, which deflect rip currents forming nearshore eddies (Shepard and Inman 1950).

D. RESEARCH FOCUS

Data analysis for this thesis focuses on the Nearshore Canyon Experiment (NCEX). Data were collected in the vicinity of Scripps Submarine Canyon off the San Diego, California coastline, which is a prime region for the study of the influences of bathymetry on the refraction of surface waves and the development of nearshore currents. In his thesis, entitled “Wave Refraction over Complex Nearshore Bathymetry,” Lieutenant Scott Peak of the Royal Australian Navy used the NCEX data to study specifically the effects of complex bathymetry on wave refraction. By examining the NCEX data, he validated the use of high-resolution spectral refraction models to forecast waves in regions of complex nearshore bathymetry. The observations showed slightly amplified wave heights to the north of the canyon and greatly reduced wave heights in the vicinity of the canyon head in good agreement with the refraction model predictions (Peak 2004).

Following on to the work of Lieutenant Peak, the objective of this study is to specifically examine the influence of the canyon bathymetry on mean currents in the nearshore. Both wave and tidal driven currents were observed with large variations around the head of Scripps Canyon.

Chapter II reviews the data collection in the Nearshore Canyon Experiment. Chapter III summarizes data analysis methods used in this study. Chapter IV covers the conditions throughout the experiment as well as the selection of case studies. Chapter V illustrates various case studies in an effort to analyze the effect of complex bathymetry on currents. Results are summarized in Chapter VI.

II. DATA COLLECTION METHODOLOGY

A. EXPERIMENT SITE

Data collection for this experiment took place off the coast of La Jolla, California in the same location as the classic experiment of Munk and Traylor in the late 1940s. This site, with two deep submarine canyons (Figure 1) extending seaward from the La Jolla coast, is ideal for studying the effects of complex bathymetry on waves and currents. The canyons, Scripps Canyon and La Jolla Canyon, extend from the fifteen meter depth contour and converge about one kilometer from shore. The northern canyon, Scripps Canyon, is the focus of this study.

The La Jolla coast is known for its beautiful beaches and wonderful surfing conditions. The coastline extends almost exactly from north to south until the head of Scripps Canyon where the shoreline turns gently to the south-southwest. On the coastline directly south of Scripps Canyon and between the heads of the two canyons, the Scripps Institution of Oceanography operates a pier where continuous wind measurements are collected.

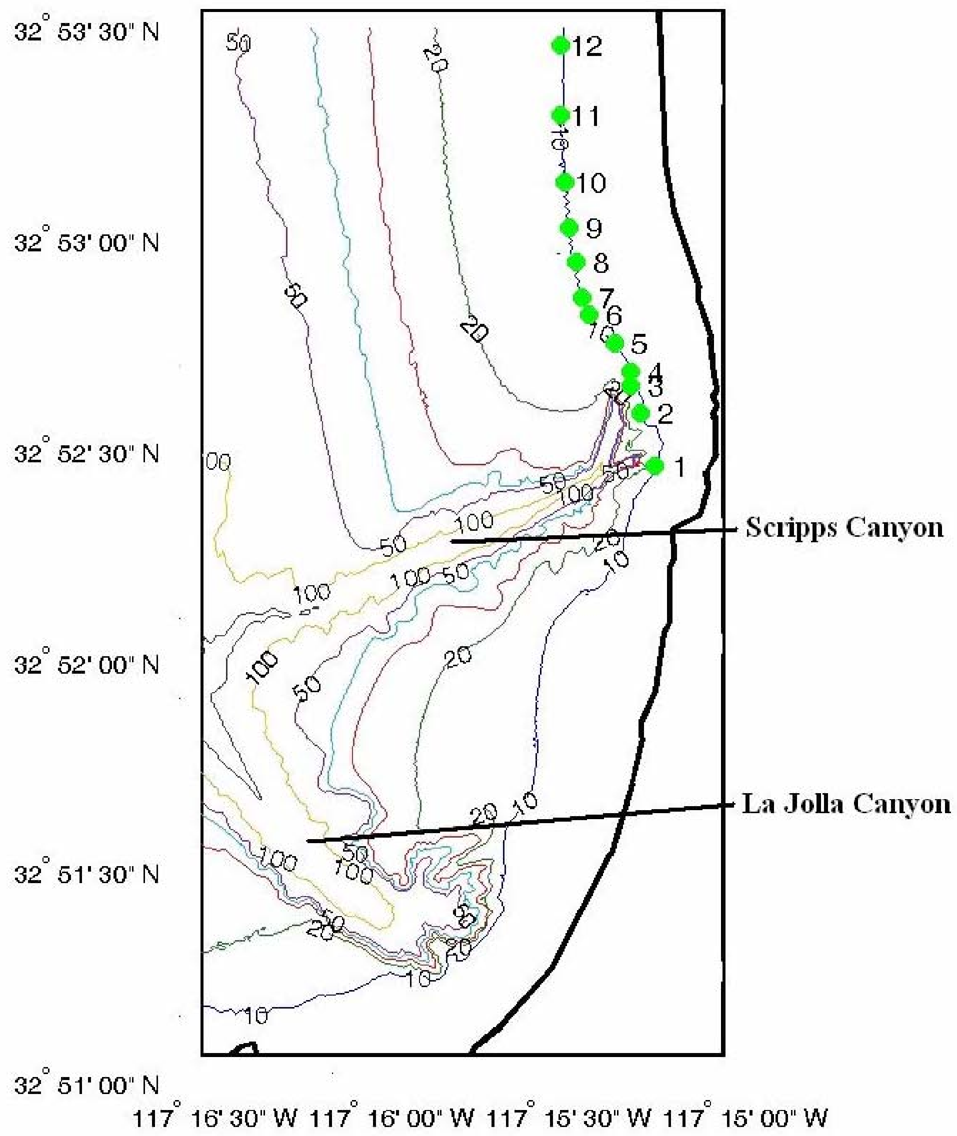

Figure 1. Bathymetry (depth contours in meters) and deployment sites of 12 Nortek Vector 3D Current and Pressure Meters along the 10 meter depth contour.

B. INSTRUMENTATION

For this analysis of the NCEX data, we will focus on an array of twelve Nortek Vector 3D Current Meters. The Nortek Vector is a combined pressure and current sensor which uses an acoustic Doppler technique to measure 3 component velocities. The Nortek Vector is capable of making measurements regardless of water quality, as long as enough particles are suspended in the water column to provide scatterers that facilitate Doppler shift measurements. An important advantage of this measurement technique is that it is non-intrusive. Data were collected at a sampling rate of 1 Hz in bursts of 137 minutes every three hours. The instruments were retrieved and redeployed at three week intervals to download the data.

Data collected consisted of pressure, horizontal (U and V) and vertical (W) velocity components, temperature, compass, and tilt measurements. The convention for collected data is that positive U velocity is to the east, positive V velocity is to the north, and positive W velocity is upwards. Of primary interest are the horizontal velocity components that will be used to define longshore and rip currents as well as mean wave directions. Additionally, the pressure data provides direct wave height measurements as well as tidal sea level data. As a consistency check on the level positioning of the sensors, vertical velocities should be small and fluctuating around a mean of 0 m/s. The instruments were attached to a fiberglass tripod with lead feet (Figure 2), which served as an anchor to the bottom and stable platform approximately half a meter off the sea floor.

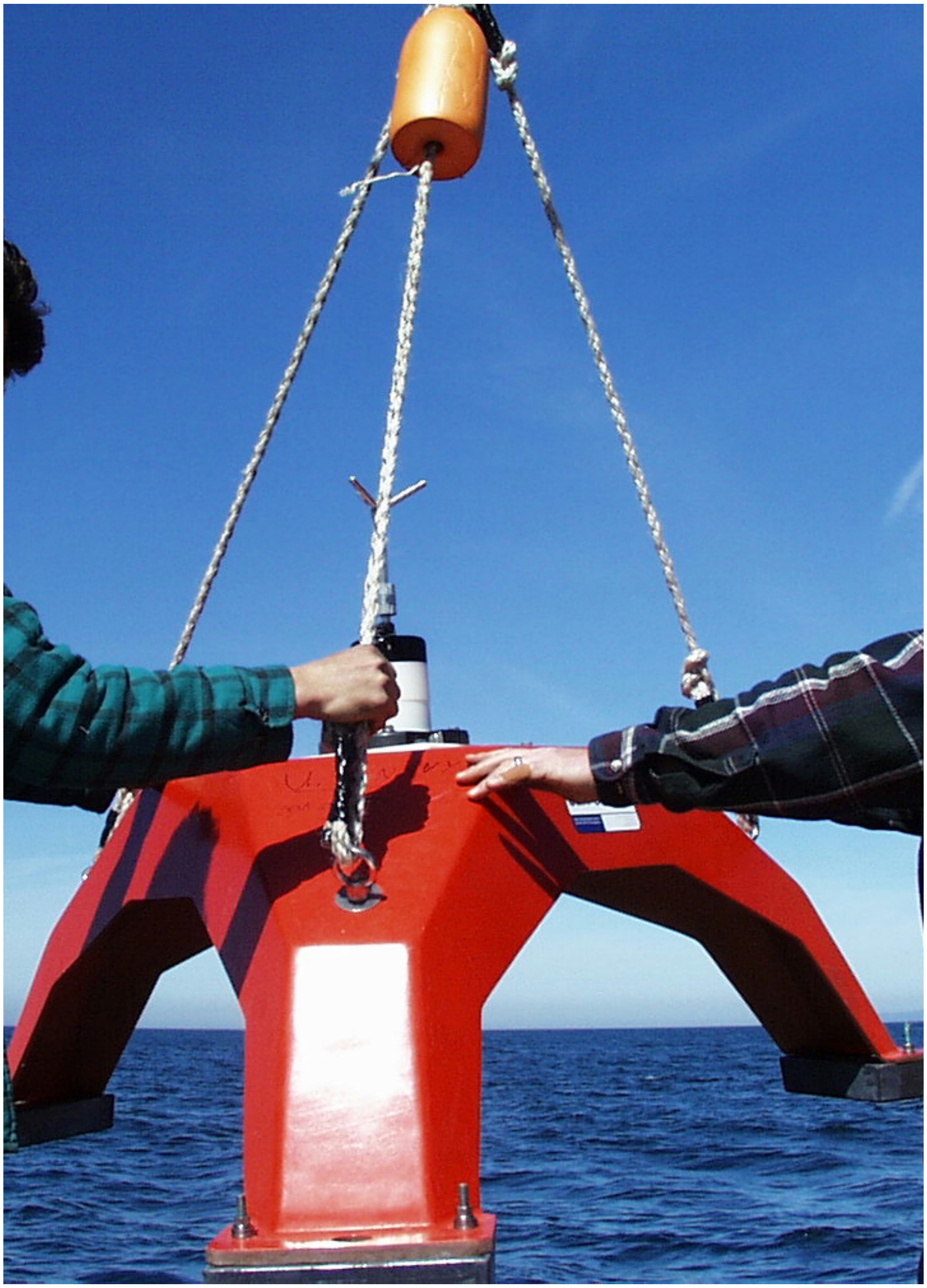

Figure 2. Nortek Vector 3D Current and Pressure Meter mounted on a fiberglass sea spider tripod.

C. DEPLOYMENT

The twelve instruments were deployed from the Research Vessel Gordon Sproul on 17 September 2003 and turned around at three week intervals until their ultimate retrieval on 15 December 2003. All Nortek Vector PUV sensors were deployed along the 10 meter depth contour at the locations listed in Table 1. PUV sensors 1 through 4 were deployed along the canyon head while sensors 5 through 12 were deployed directly north of the canyon (Figure 3).

Site	**Latitude**	**Longitude**
1	32^{o} 52.44′ N	117^{o} 15.26′ W
2	32^{o} 52.58′ N	117^{o} 15.30′ W
3	32^{o} 52.65′ N	117^{o} 15.33′ W
4	32^{o} 52.68′ N	117^{o} 15.33′ W
5	32^{o} 52.75′ N	117^{o} 15.37′ W
6	32^{o} 52.82′ N	117^{o} 15.45′ W
7	32^{o} 52.86′ N	117^{o} 15.47′ W
8	32^{o} 52.94′ N	117^{o} 15.48′ W
9	32^{o} 53.03′ N	117^{o} 15.50′ W
10	32^{o} 53.13′ N	117^{o} 15.51′ W
11	32^{o} 53.29′ N	117^{o} 15.53′ W
12	32^{o} 53.46′ N	117^{o} 15.53′ W

Table 1. Deployment positions of Nortek 3D Current and Pressure Meters.

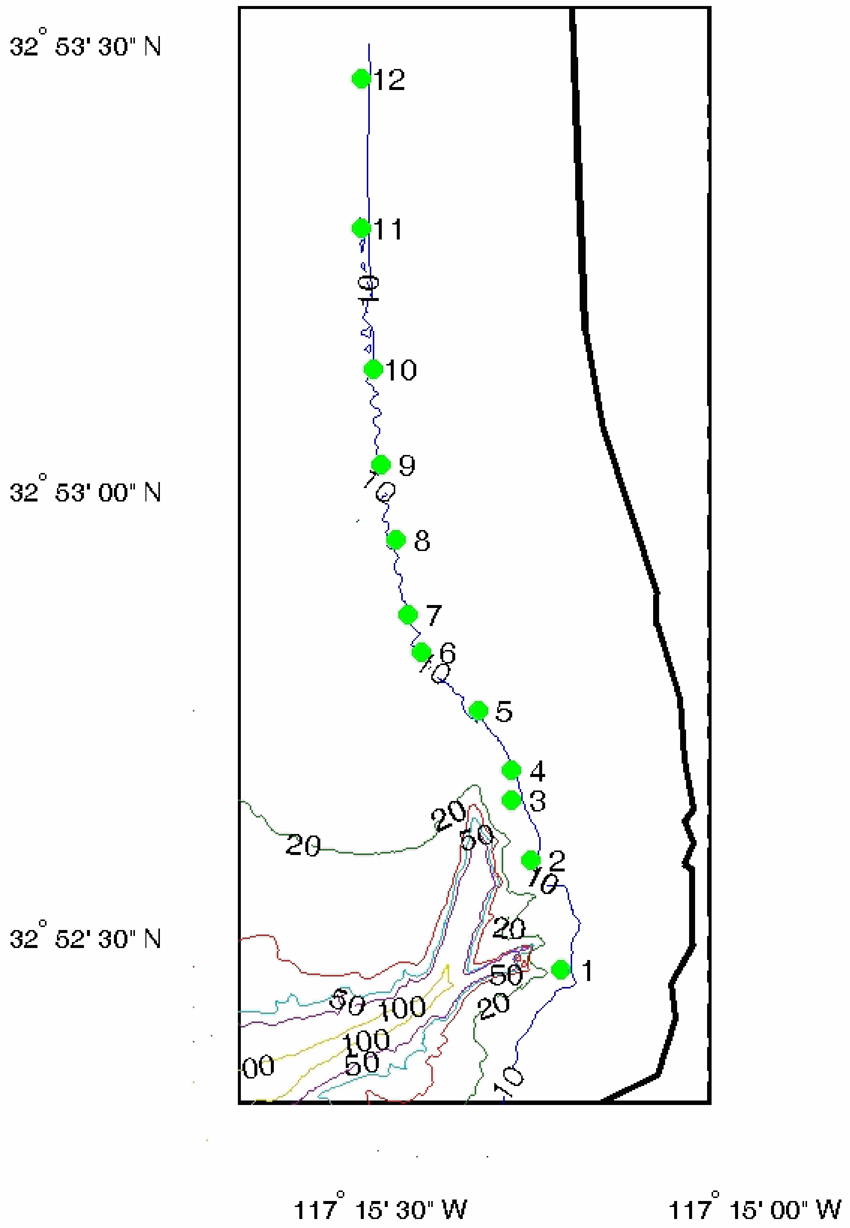

Figure 3. Enhanced view of deployment sites of 12 Nortek Vector 3D Current and Pressure Meters.

III. DATA ANALYSIS METHODOLOGY

The analysis of data from the Nortek Vector 3D Current Sensors and the Coastal Data Information Program (CDIP) Wind Sensors was formed using Matrix Laboratory (MATLAB) software. Time series of the three-component current velocities and pressure were sampled at 1 Hz over a 137 minute record length. Significant wave height and mean wave direction were estimated for each record using standard techniques (e.g. Lentz et al, 1999). The CDIP wind data consisted of hourly averages of wind velocity and direction.

As part of the initial quality control, the average pressures and currents over the length of each record were examined for trends or shifts over the entire experiment. Particular attention was paid to pressures and vertical velocities in order to determine the continuity of positioning with regard to the data collected. The lack of large mean pressure shifts over the length of the experiment showed that the sensors were redeployed following instrument turnarounds at a near consistent depth. Diurnal and semi-diurnal fluctuations in the mean pressures were attributed to the tidal cycle of the region. In order to determine if the sensors were deployed on a near-horizontal bottom, the vertical velocities were carefully examined. Small vertical velocities (< 1 cm/s) compared with the horizontal components confirm the proper current meter alignment (Figure 4c).

After determining the fidelity of positioning and data collection, the horizontal current velocities in the east-west and north-south directions were examined. Averaging of horizontal currents was done over the entire record length (137 minutes) and over a much shorter two minute interval. The use of two minute averaging was done to take a closer look at velocity fluctuations with periods longer than wind waves and swell. Average 137 minute currents, computed at 3 hour intervals, were used to identify strong current events (Figures 4a, 4b). Once these events were identified, averaging over the two minute period was utilized to analyze velocity fluctuations in greater detail over a period of typically four to five days.

Offshore wave height data from CDIP Buoy 100, the Outer Torrey Pines Buoy, was used to initialize a spectral refraction model for predicting wave heights and directions at each of the PUV stations (Peak, 2004). Wind, current, pressure, and wave time series were examined to identify correlations between winds, currents, waves, and tides in relation to surrounding bathymetry.

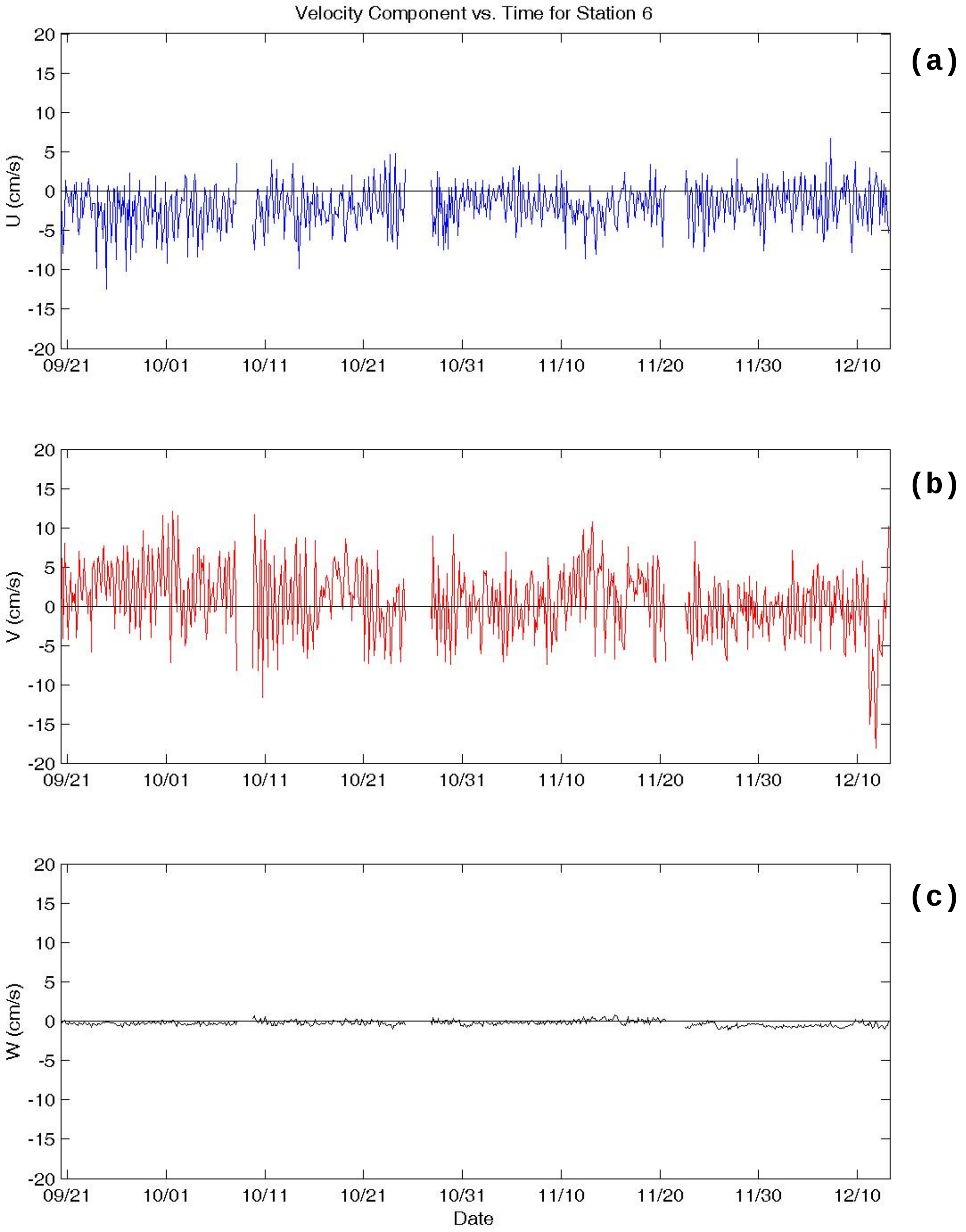

Figure 4. a) Cross-shore, b) alongshore, and c) vertical current velocities at Station 6 during the 3 month long NCEX Experiment.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. OVERVIEW OF OVERALL CONDITIONS DURING NCEX

A. WINDS, WAVES, AND CURRENTS

Throughout most of the NCEX Experiment wave and wind conditions were benign (Figures 5, 6). Winds were predominantly weak and variable. Wind data collected at the Scripps Institution of Oceanography Pier show wind speeds were typically less than 4 m/s, and exceeded 6 m/s only twice during the experiment (Figures 5a,6a). Peak wind speeds of 6.5 m/s and 8.5 m/s were recorded on October 31st and December 12th respectively. During both events the wind direction was from the west and the unlimited fetch was favorable for wind-sea generation (Figures 5b, 6b).

Similar to the winds, wave heights were typically small (Figures 5c, 6c). Significant wave heights rarely exceeded 1 meter and peak wave events occurred infrequently. A major storm related wave event occurred on December 12th. At all stations the dominant wave arrival direction was from the west over the entire NCEX data collection period with very little fluctuation (Figures 5b, 6b). Swell conditions dominated over the experiment with wave periods of 12 to 16 seconds.

Mean currents measured along the 10 meter depth contour rarely exceeded 20 centimeters per second in either the cross-shore or alongshore directions (Figures 5d, 6d). Typical cross-shore current velocities were directed offshore at less than 5 cm/s. Longshore current velocities tended to vary more in both speed and direction. Longshore currents to the north were more common and slightly stronger than to the south, with typical currents to the north of 5 cm/s vice 3 cm/s to the south. Notably stronger

(15-40 cm/s) southward flow was observed during the December storm (Figures 5d, 6d).

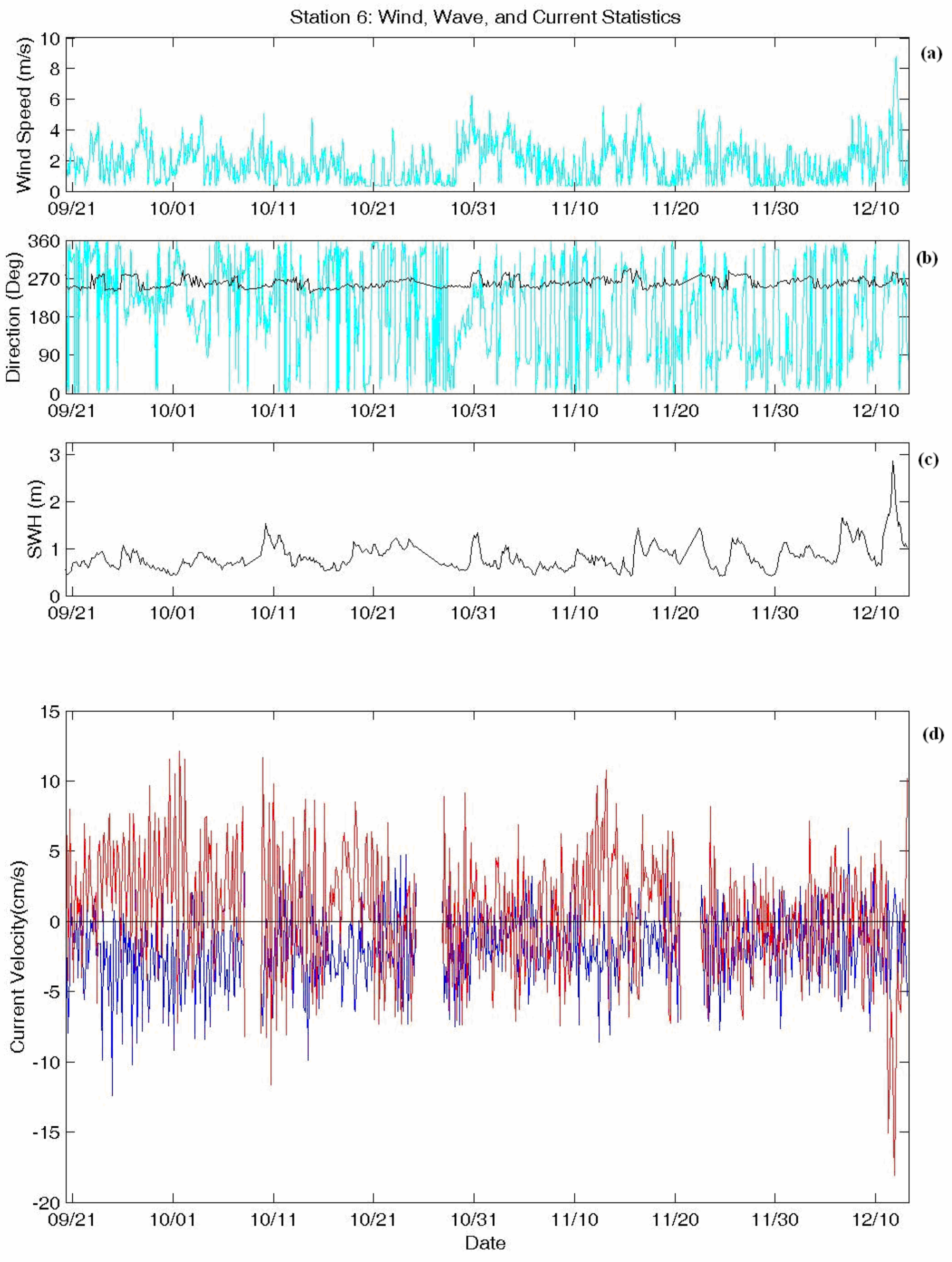

Figure 5. Conditions at Station 6 during the Nearshore Canyon Experiment. a) Wind speed (at Scripps Pier). b) Wind (cyan) and wave (black) directions. c) Significant wave heights. d) Cross-shore (blue) and alongshore (red) current velocities.

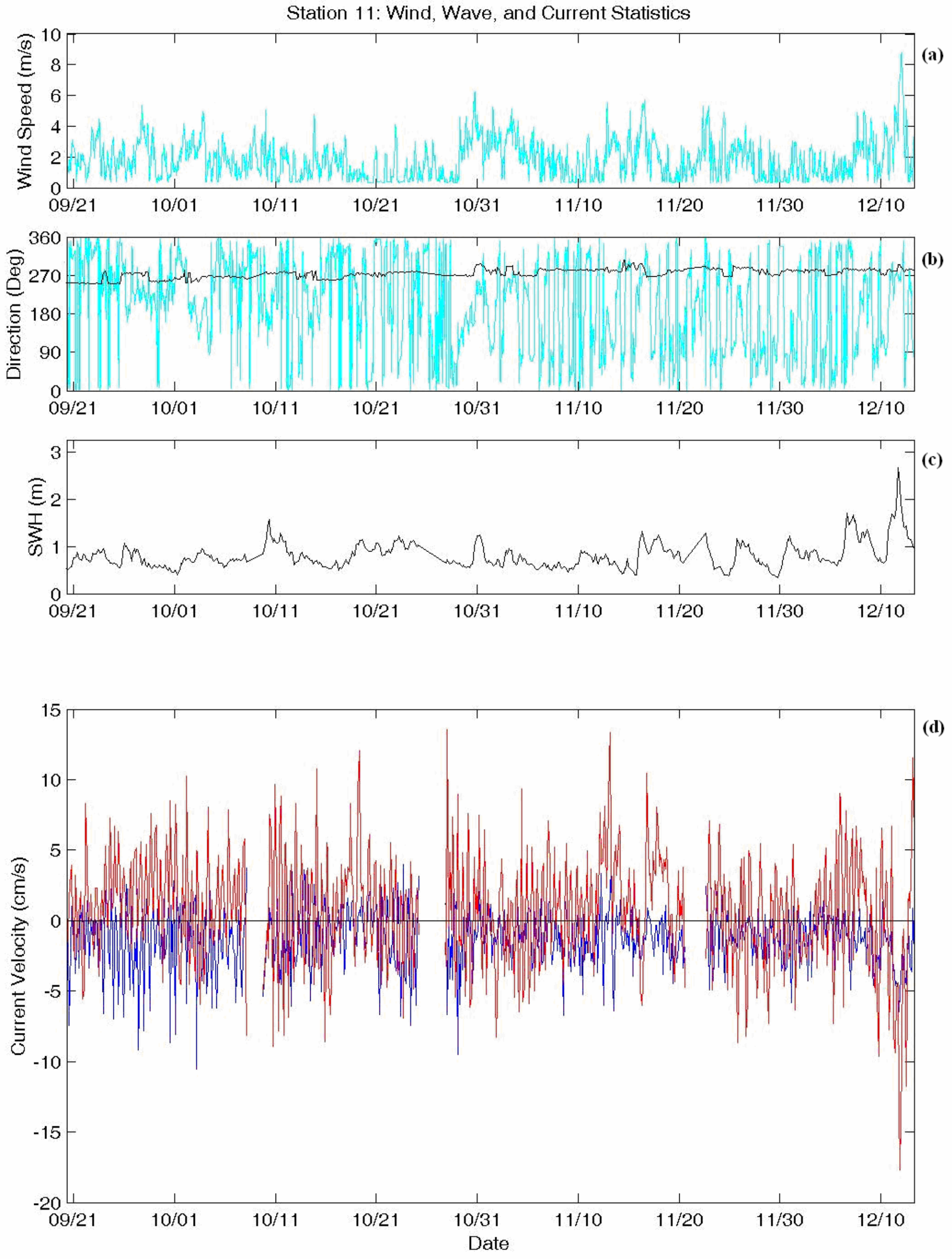

Figure 6. Conditions at Station 11 during the Nearshore Canyon Experiment. a) Wind speed (at Scripps Pier). b) Wind (cyan) and wave (black) directions. c) Significant wave heights. d) Cross-shore (blue) and alongshore (red) current velocities.

B. CASE STUDY SELECTION

Case studies were selected to examine the mean currents in relation to wave, wind, and tidal forcing. The overall weakness of currents and forcing conditions (wind and wave) made the selection of events difficult. The presence of a detectable mean current event (i.e. well above instrument noise levels) was the predominant factor in the selection of a case study. Beyond this criterion, the selection of case studies was based on the appearance of prominent features in the data, such as the presence of a strong tidal signature in the currents or unusually large spatial variations in currents or wave heights.

The case study analyses focus not only on spatial structure of mean circulation around complex bathymetry but also on the relatively strong tidal influence observed in the data. Case study I demonstrates the tidal influences on longshore currents in benign conditions and the influence of the nearby submarine canyon. Case study II emphasizes the differences between cross-shore and longshore velocities following a small wave event. Case study III illustrates large alongshore variations in wave-driven longshore currents during a winter storm.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CASE STUDY ANALYSIS

A. CASE STUDY I: OCTOBER 10 – OCTOBER 14

Over the extent of case study I winds were weak (about 2 m/s) and variable (Figures 7a, 7b, 8a, 8b). Maximum significant wave heights of 1.5 meters were observed on October 10th and declined to 0.8 meters by October 14th, which matched wave model predictions (Figures 7c, 8c). The relatively weak winds, and the decline in wave height that is not accompanied by a similar decay in currents (Figures 7d,8d), suggest that the nearshore currents in this case may be due to some other forcing mechanisms.

Further examination of the longshore velocities suggests strong tidal influence. Pressure time series indicate the presence of a semidiurnal tide with a range of 1.25m. When these semidiurnal tidal oscillations are compared to the time series of alongshore velocity, it is clear that a strong tidal component exists in the longshore current at stations 6-12 away from the canyon (Figure 9). In sharp contrast, this correlation is not apparent for longshore currents at stations 1-4 closest to the canyon.

In this case, tides are clearly the principal driving force for longshore currents. Pressure and longshore velocity exhibit a clear 90 degree phase difference with pressure fluctuations leading longshore current fluctuations (Figure 9).

Longshore velocity fluctuations are much larger at stations away from the canyon than those near the canyon. Peak longshore currents away from the canyon reach upwards of 25 cm/s whereas near the canyon the peak longshore velocity component reaches only 10 cm/s (Figure 9). This result suggests that the submarine canyon strongly reduces the tidal flow.

The cross-shore velocities, unlike the alongshore velocities, exhibit no clear tidal influence. Like the alongshore velocity component, cross-shore velocities display different behavior for stations near the canyon than those extending further to the north (Figure 10). Steep bore-like features do appear in the cross-shore velocities possibly indicating the propagation of internal waves up the continental shelf (Figure 10). These features are coherent north of the canyon at stations 6-10, more irregular near the canyon at stations 2-4, and largely have disappeared at station 1.

To summarize, this case study illustrates three distinct points. First, a clear tidal dominance of the longshore current is observed. Second, cross-shore flows exhibit no clear tidal influence, but show coherent bore-like features that are possibly internal waves. Third, both alongshore and cross-shore flows are weak near the canyon head.

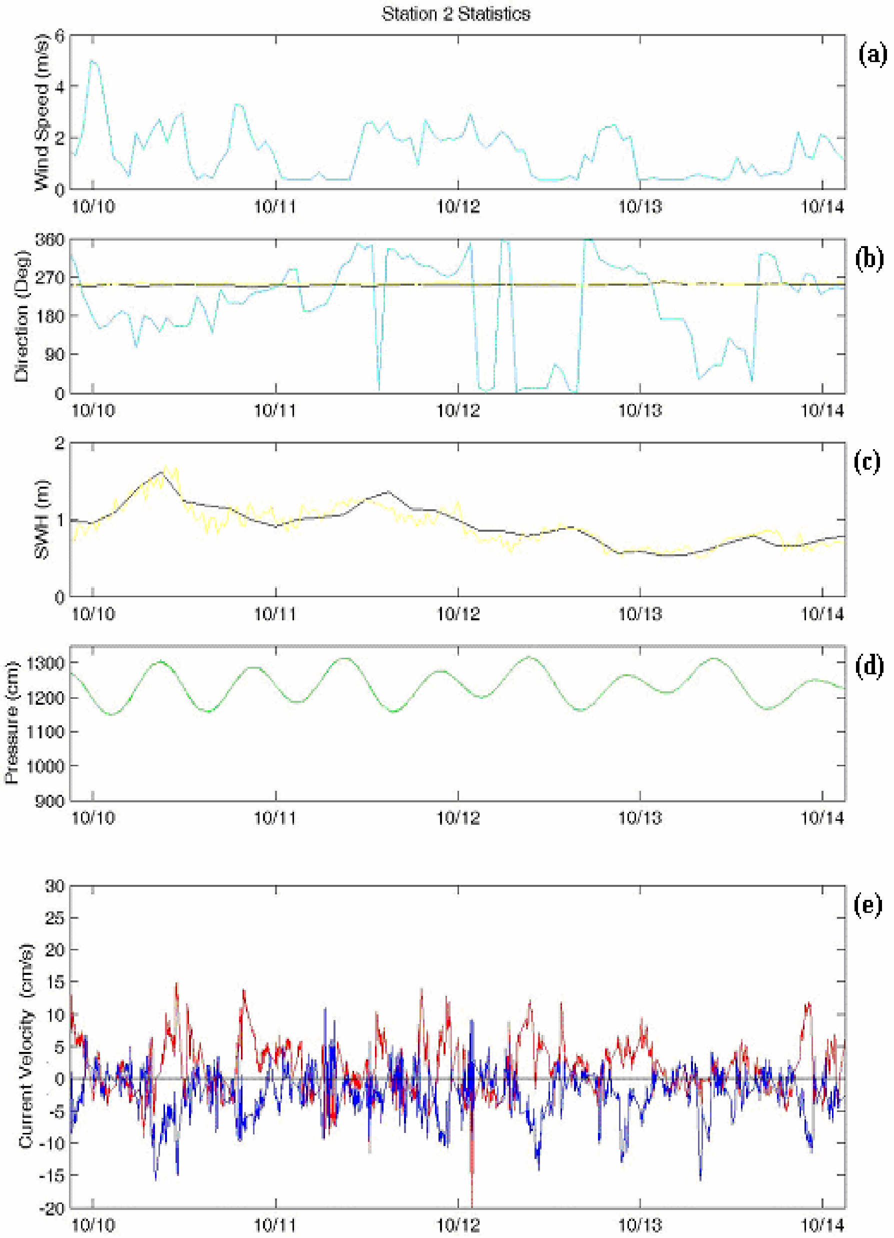

Figure 7. Station 2 statistics for Case Study I. a) Wind speed (at Scripps Pier). b) Wind direction (cyan), observed wave direction (black), and predicted wave direction (yellow). c) Significant wave heights observed (black) and predicted (yellow). d) Pressure. e) Cross-shore U (blue) and alongshore V (red) current velocities.

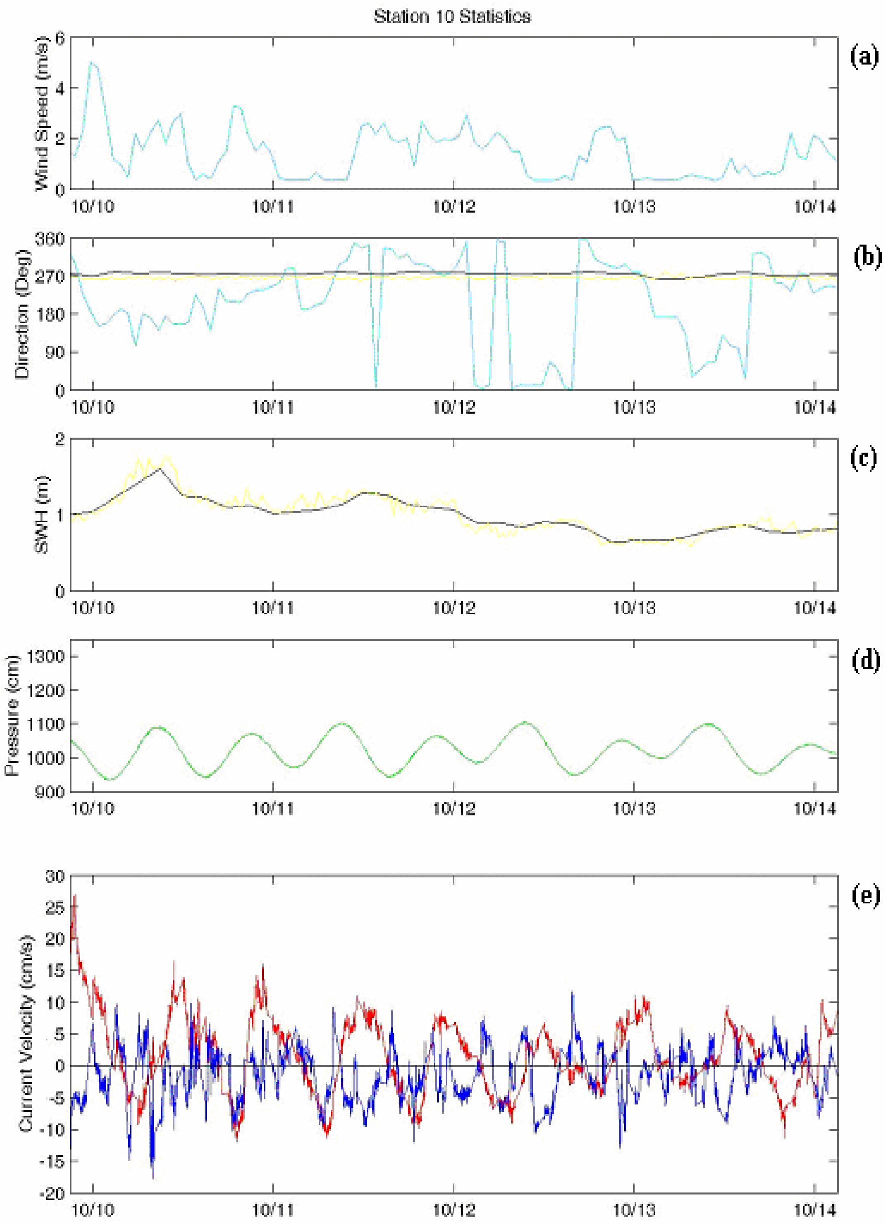

Figure 8. Station 10 statistics for Case Study I. a) Wind speed (at Scripps Pier). b) Wind direction (cyan), observed wave direction (black), and predicted wave direction (yellow). c) Significant wave heights observed (black) and predicted (yellow). d) Pressure. e) Cross-shore U (blue) and alongshore V (red) current velocities.

Figure 9. Northward (positive) and southward (negative) alongshore velocities with pressure overlaid at all stations for Case Study I.

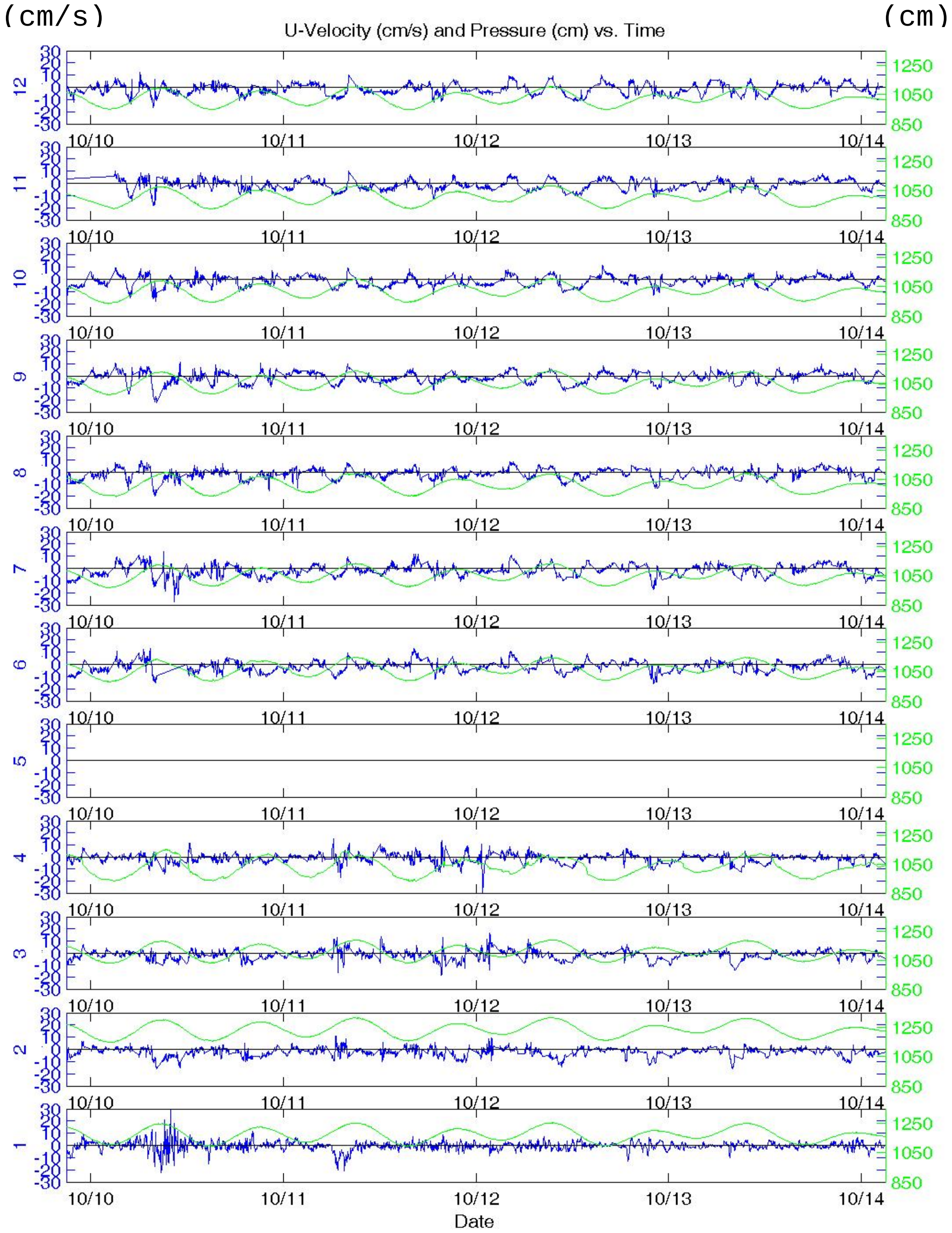

Figure 10. Eastward (positive) and westward (negative) cross-shore velocities with pressure overlaid at all stations for Case Study I.

B. CASE STUDY II: OCTOBER 29 – NOVEMBER 3

The events of early November were selected to expand on the structure of nearshore currents during the passage of a moderate swell event. Once again winds were light and variable, although slightly stronger than in case I with speeds of 2 to 4 m/s (Figures 11b, 12b). Significant wave heights varied considerably during this time period and are in good agreement with model predictions. Waves increased from 0.5 meters to 1.25 meters by October 31st and steadily declined until the end of the case study (Figures 11c, 12c). The tidal signature differs significantly from case study I, as observed in the pressure fluctuations, with a clear mixed tide that contains both diurnal and semidiurnal components (Figures 11d, 12d). As in case I, the tide appears to be the dominant forcing mechanism.

The correlation of longshore currents with tidal pressure variations is less clear than in case study I, possibly because of the mixed tide regime or owing to other forcing mechanisms (e.g. winds). Stations away from the canyon once again display a high degree of coherence in the longshore velocities whereas the current strength is greatly reduced near the canyon (Figure 13).

Once again the crosshore flow displays no clear tidal variation, but there are interesting temporal changes. In the few days leading up to the wave event of October 31st, the cross-shore currents at all stations feature moderate fluctuations between +5 m/s (onshore) and -15 m/s (offshore) that decay towards the canyon head. Once wave heights begin to increase, the cross-shore flow decays rapidly (Figure 14). When wave heights have reached their peak on October 31st (Figures 11c, 12c), the cross-shore velocities have decayed to less than 5 cm/s across the instrument array for the remainder of this case study (Figure 14). The cause of this flow decay is unknown.

To summarize, the main observations in this case are: First, the presence of a mixed tidal regime and possibly increased winds made longshore currents more variable. Second, stations exposed to the open ocean again experience a high degree of coherency in the cross-shore and alongshore velocity components and both components decay towards the canyon head. Lastly, the cross-shore current oddly decayed during a moderate swell event.

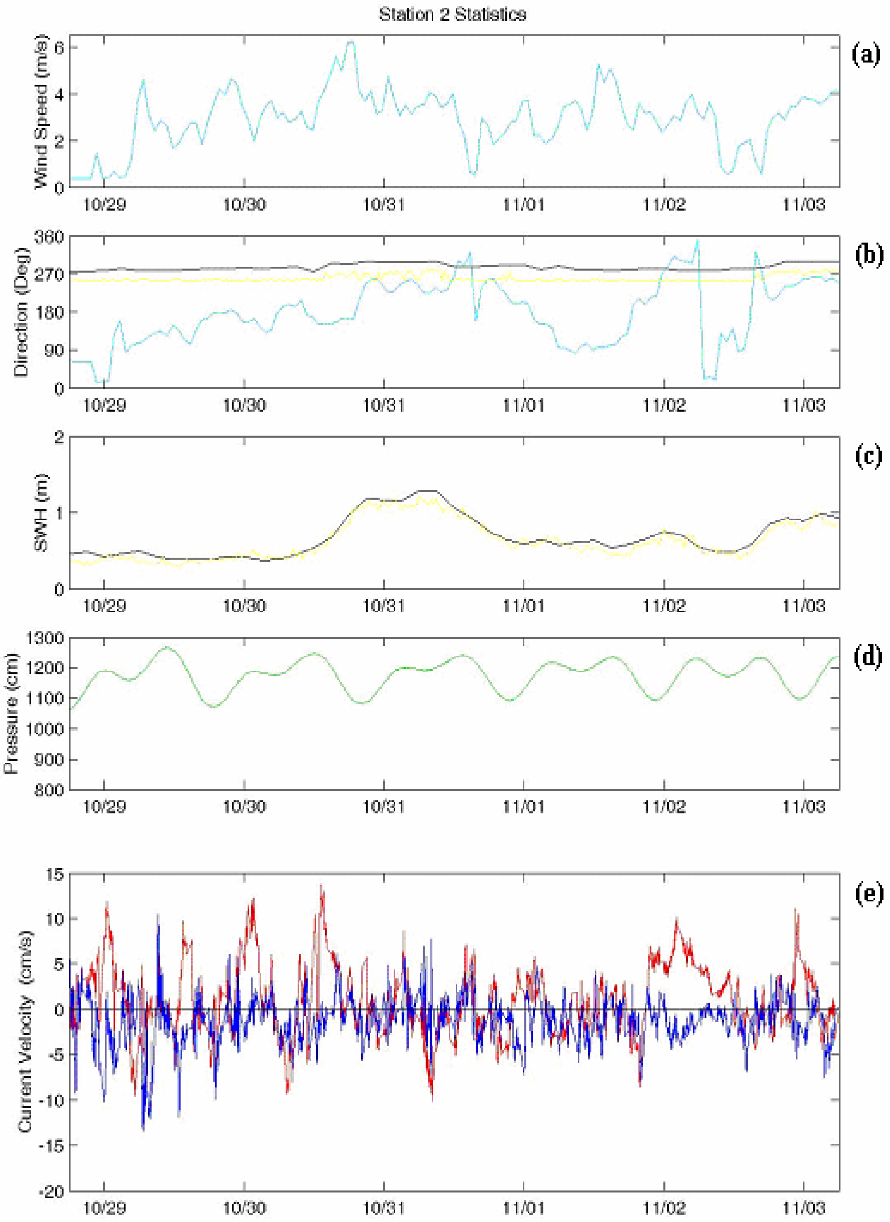

Figure 11. Station 2 statistics for Case Study II. a) Wind speed (at Scripps Pier). b) Wind direction (cyan), observed wave direction (black), and predicted wave direction (yellow). c) Significant wave heights observed (black) and predicted (yellow). d) Pressure. e) Cross-shore U (blue) and alongshore V (red) current velocities.

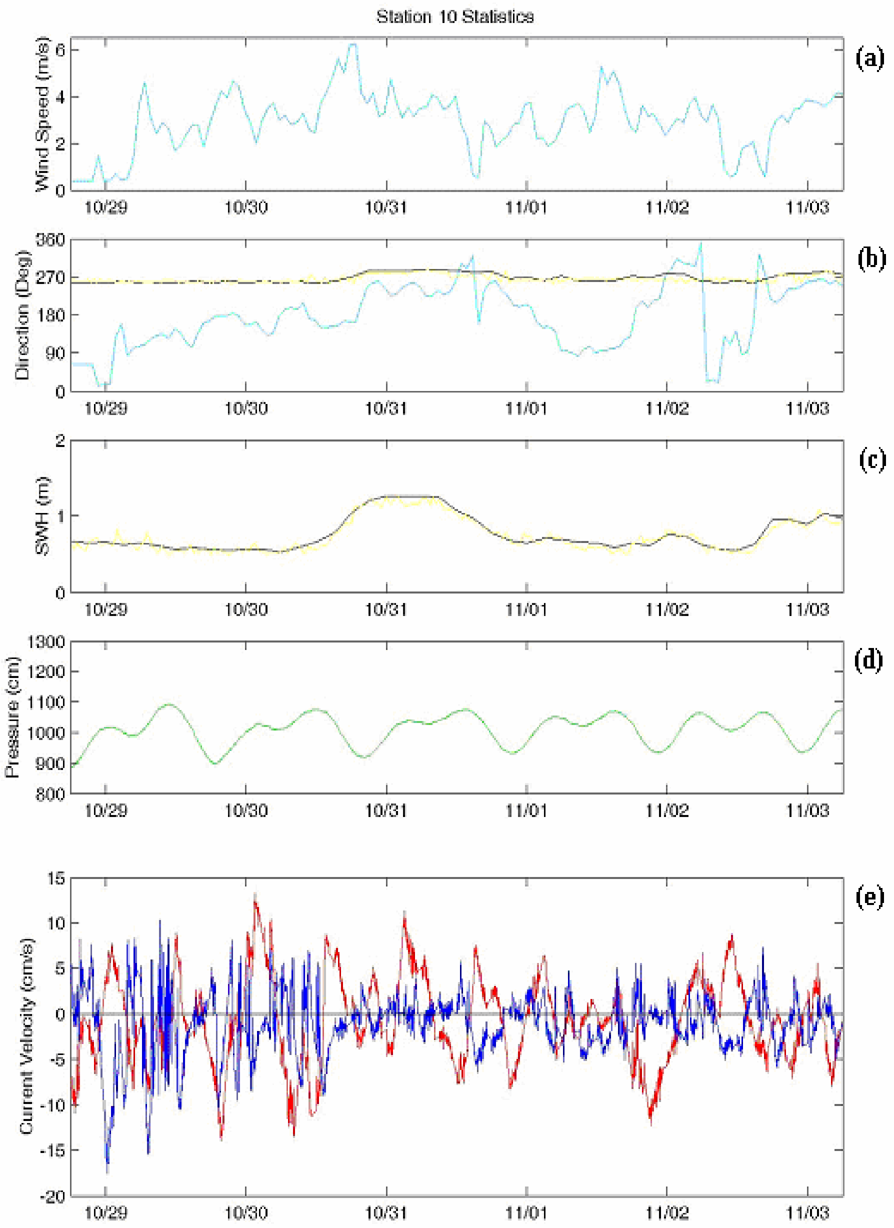

Figure 12. Station 10 statistics for Case Study II. a) Wind speed (at Scripps Pier). b) Wind direction (cyan), observed wave direction (black), and predicted wave direction (yellow). c) Significant wave heights observed (black) and predicted (yellow). d) Pressure. e) Cross-shore U (blue) and alongshore V (red) current velocities.

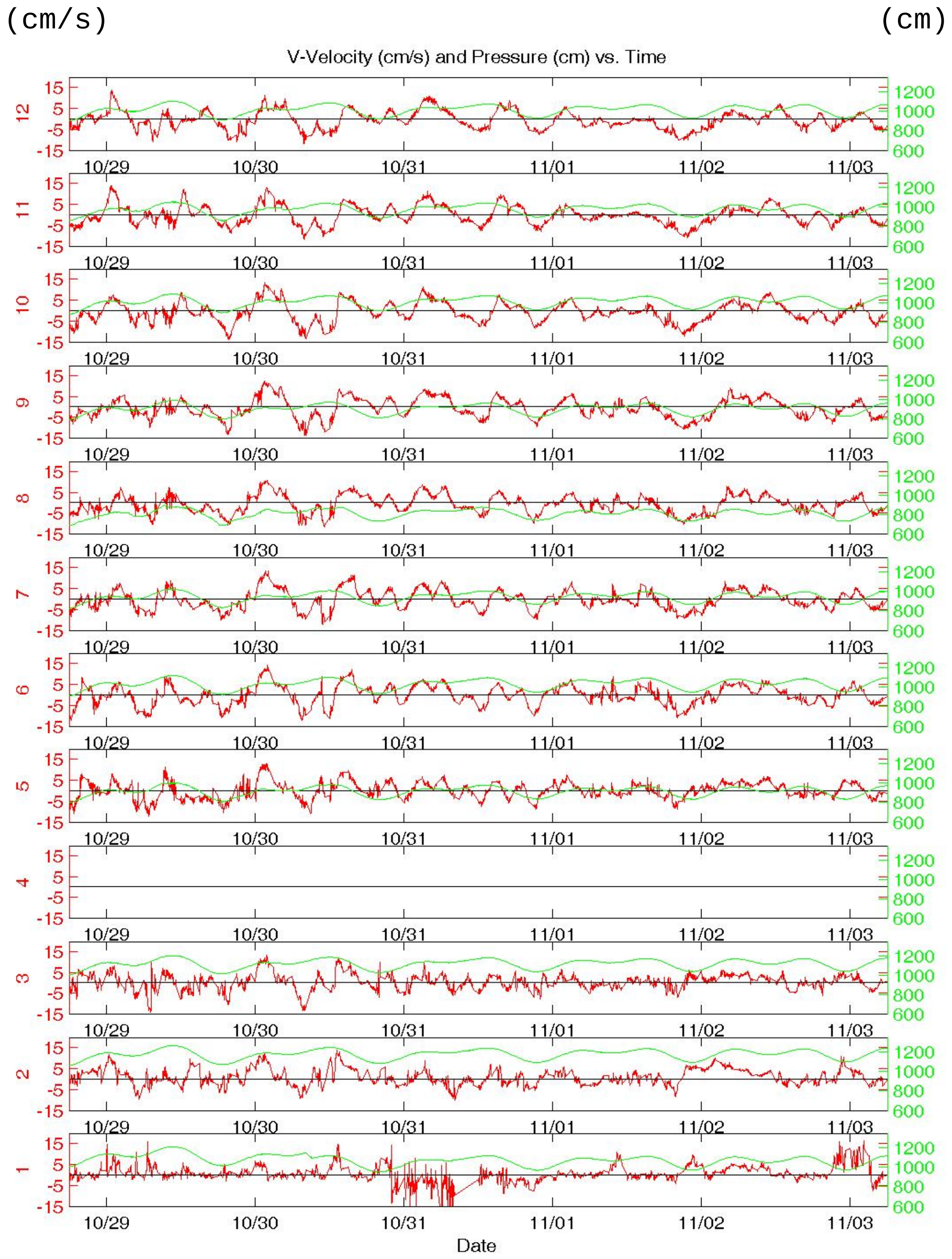

Figure 13. Northward (positive) and southward (negative) alongshore velocities with pressure overlaid at all stations for Case Study II.

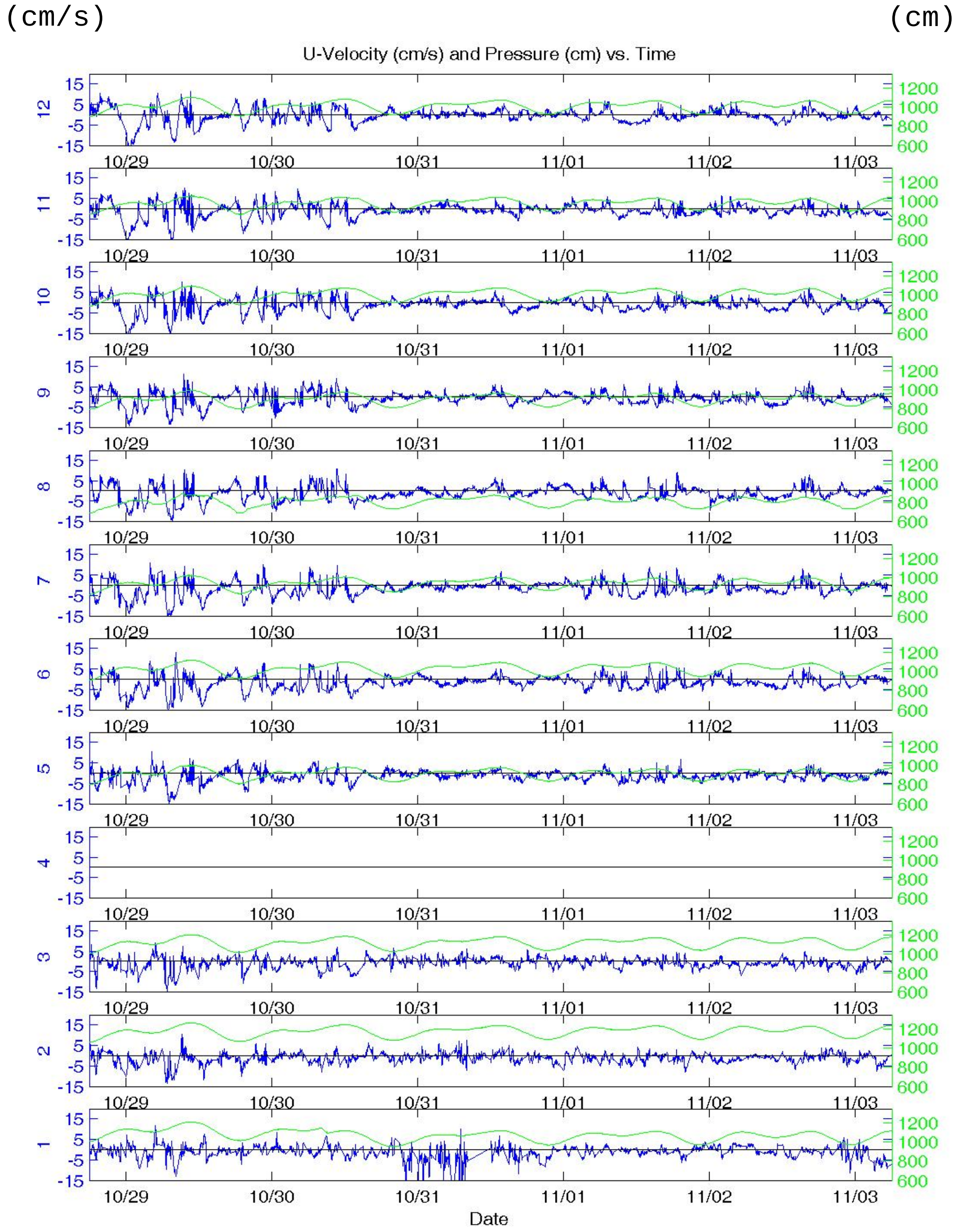

Figure 14. Eastward (positive) and westward (negative) crosshore velocities with pressure overlaid at all stations in Case Study II.

C. CASE STUDY III: DECEMBER 9 – DECEMBER 14

During this case study, a winter storm directly impacted the Southern California coast. The high wind and large waves are unusual for the typically placid conditions of the region. Except in the hours leading up to the peak wave event, winds were light and variable (1 to 5 m/s) while wave heights increased to 3m, and winds increased to a maximum speed of 8.5 m/s about 6 hours after the peak wave heights were observed (Figures 15a,15c,16a,16c). The peaks in wave heights and currents occurred concurrently (Figures 15c, 15e, 16c, 16e) leading to the hypothesis that longshore currents are driven by the sharp increase in wave heights rather than winds in this case.

Observed and predicted swell heights (waves in the frequency range 0.04-0.10 Hz) are compared in figure 17. Over the first two days of the case study swell heights steadily declined below 1 meter but rose sharply to nearly 2 meters at noon on December 10th. All wave predictions for stations 2-12 are in good agreement with the collected data, but due to a malfunctioning instrument the prediction for station 1 could not be confirmed (Figure 17). From the observed and predicted swell heights, a clear wave height gradient in the direction of the canyon is noted creating a large setup for the formation of a longshore current toward the canyon head.

Once again the longshore currents display a tidal component which diminishes near the canyon (Figure 18). The currents show the concurrent semidiurnal nature of the region in their twice daily fluctuation around a mean value. The most striking observation of this period is the appearance of a strong southward longshore flow at the time of peak wave heights. This flow is not observed at the northern stations, which show only tidal fluctuations in the alongshore component (Figure 18). In both the alongshore and cross-shore flows, the major current increase at the peak wave event is only registered in close proximity to the canyon (Figures 18, 19). This observation is consistent with variations associated with the large wave height variations between sites 1 and 3 (Figure 17) that are expected to drive a strong southward longshore flow.

To illustrate the sharp contrast between the currents near and away from the canyon, station 2 and station 12 are compared in figures 15 and 16. When wave heights begin to increase, station 2 displays small cross-shore velocities and rapidly increasing longshore velocities, which are not apparent at station 12 (Figures 15e, 16e). After 6 hours of increasing waves, peak longshore currents switch from northward at 15 cm/s to southward at 70 cm/s. Cross-shore velocity peaks simultaneously with 20 cm/s offshore flow. Away from the canyon the currents were much weaker. During the wave event, peak velocities at station 12 reach only 5 cm/s offshore and 15 cm/s to the south (Figure 16e). These large spatial variations in currents illustrate the important influence of the submarine canyon on the nearshore environment.

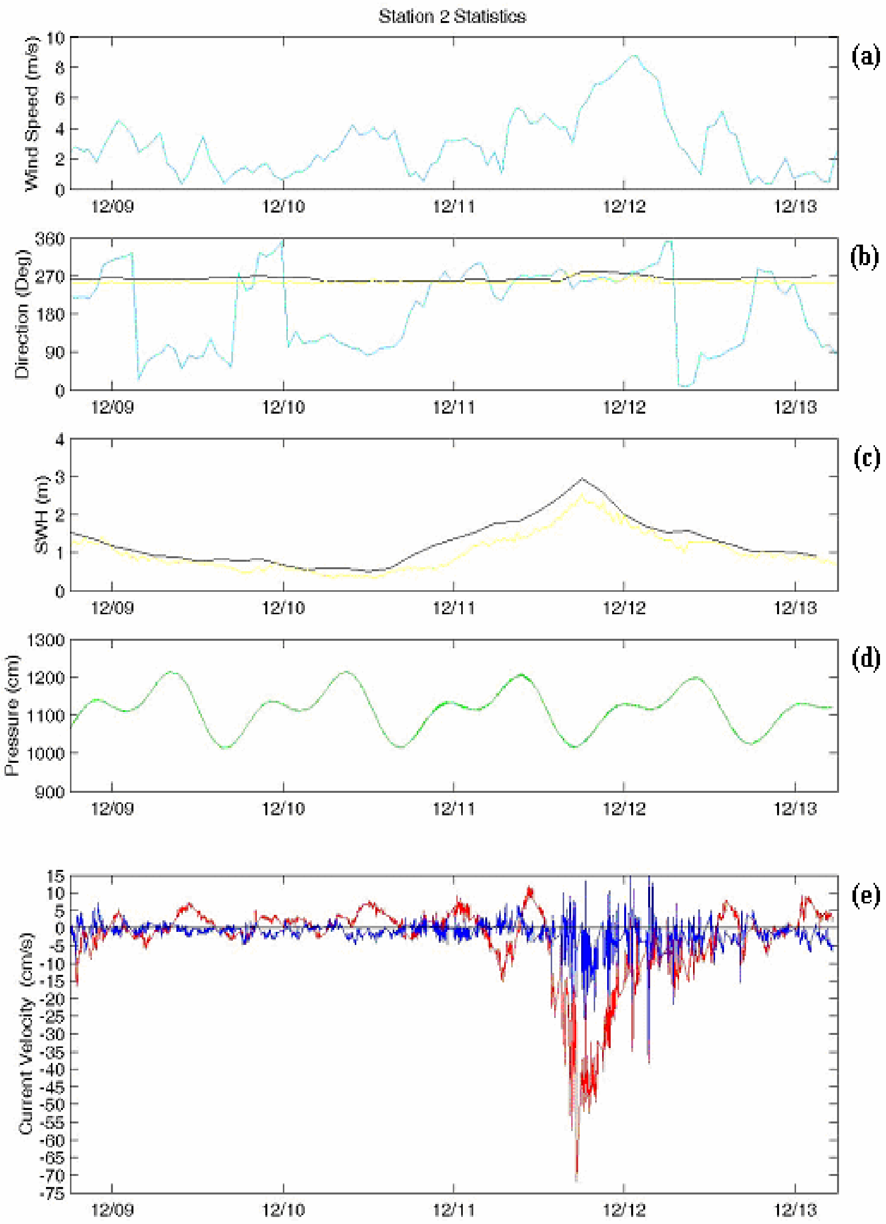

Figure 15. Station 2 statistics for Case Study III. a) Wind speed (at Scripps Pier). b) Wind direction (cyan), observed wave direction (black), and predicted wave direction (yellow). c) Significant wave heights observed (black) and predicted (yellow). d) Pressure. e) Cross-shore U (blue) and alongshore V (red) current velocities.

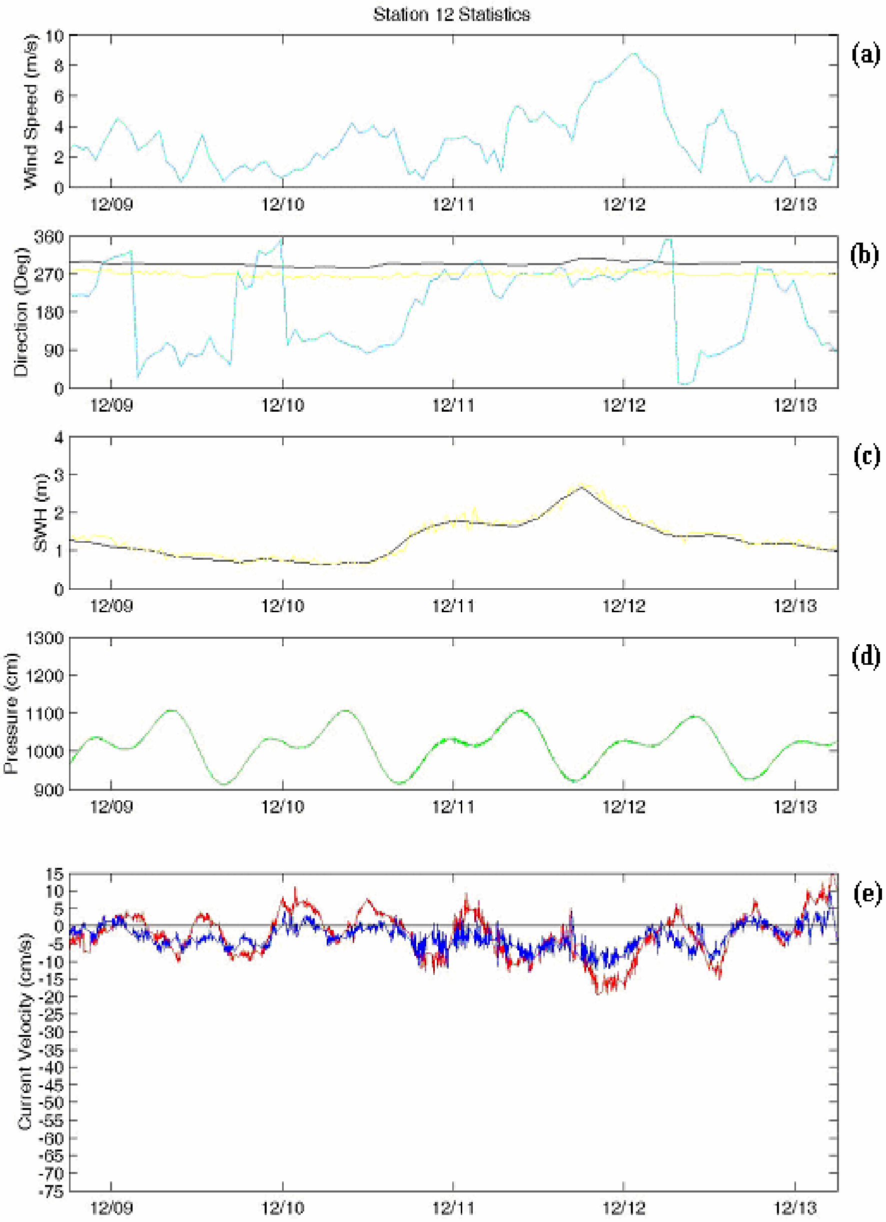

Figure 16. Station 12 statistics for Case Study III. a) Wind speed (at Scripps Pier). b) Wind direction (cyan), observed wave direction (black), and predicted wave direction (yellow). c) Significant wave heights observed (black) and predicted (yellow). d) Pressure. e) Cross-shore U (blue) and alongshore V (red) current velocities.

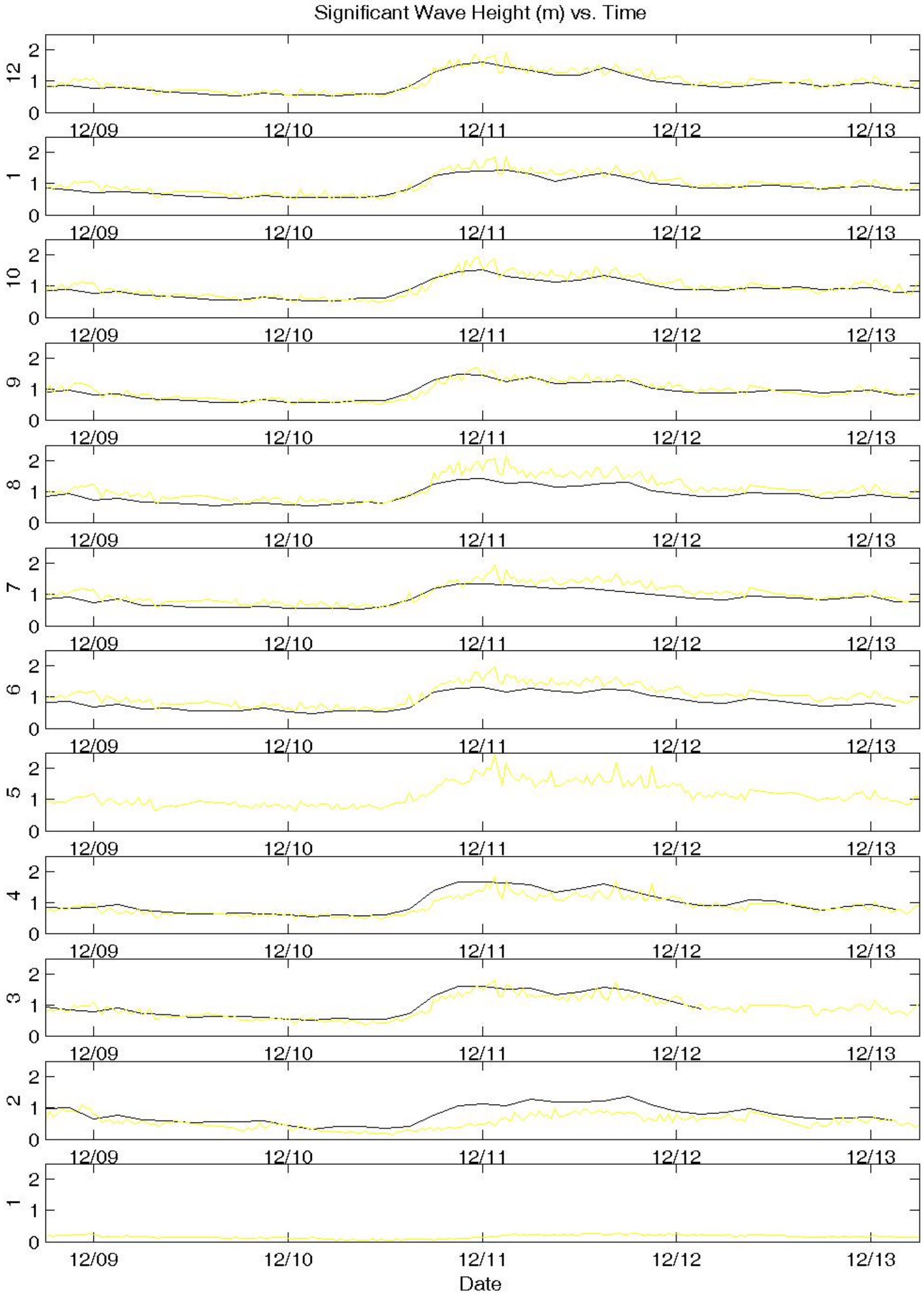

Figure 17. Significant wave heights observed (black) and predicted (yellow) at all stations for Case Study III.

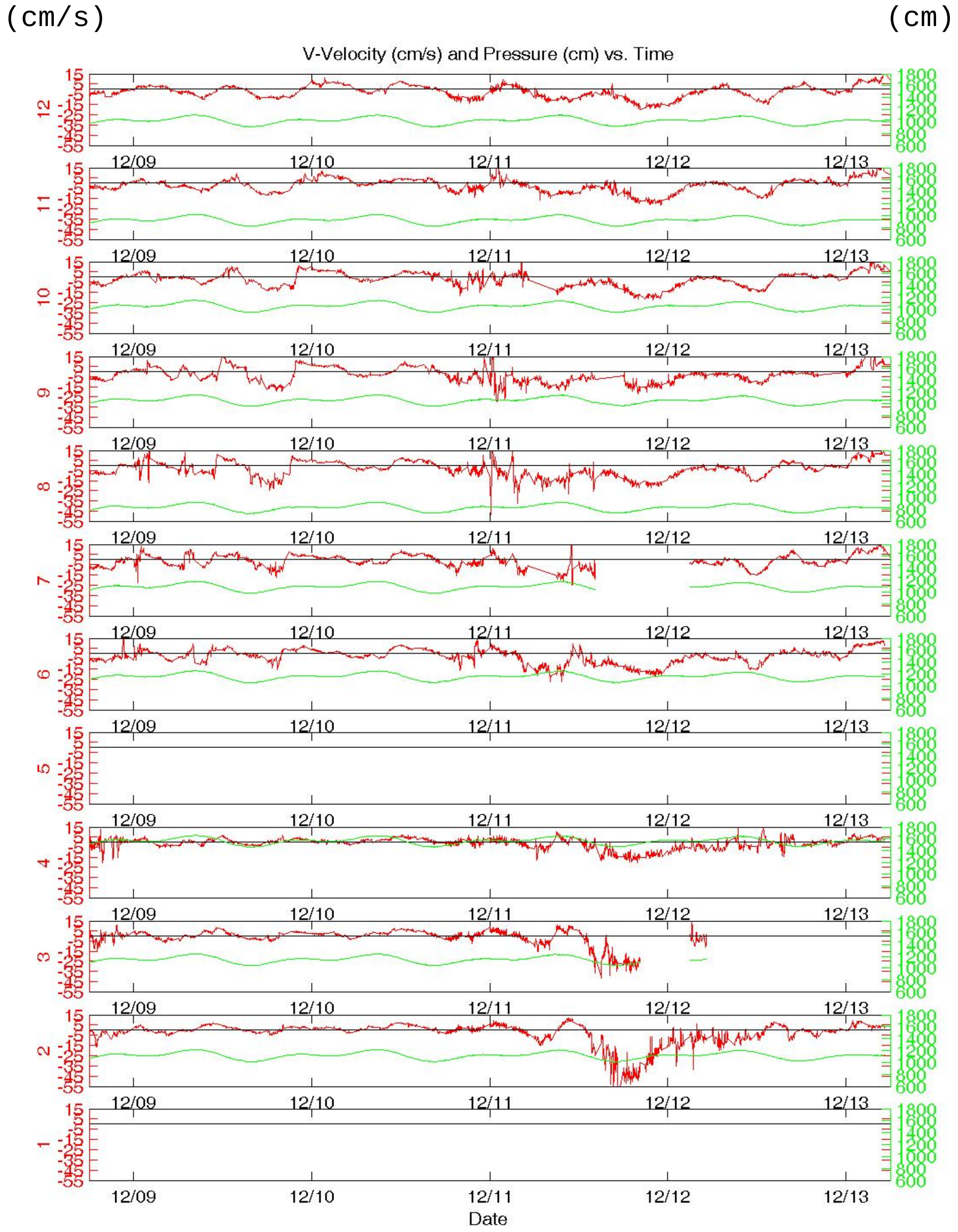

Figure 18. Northward (positive) and southward (negative) alongshore velocities with pressure overlaid at all stations for Case Study III.

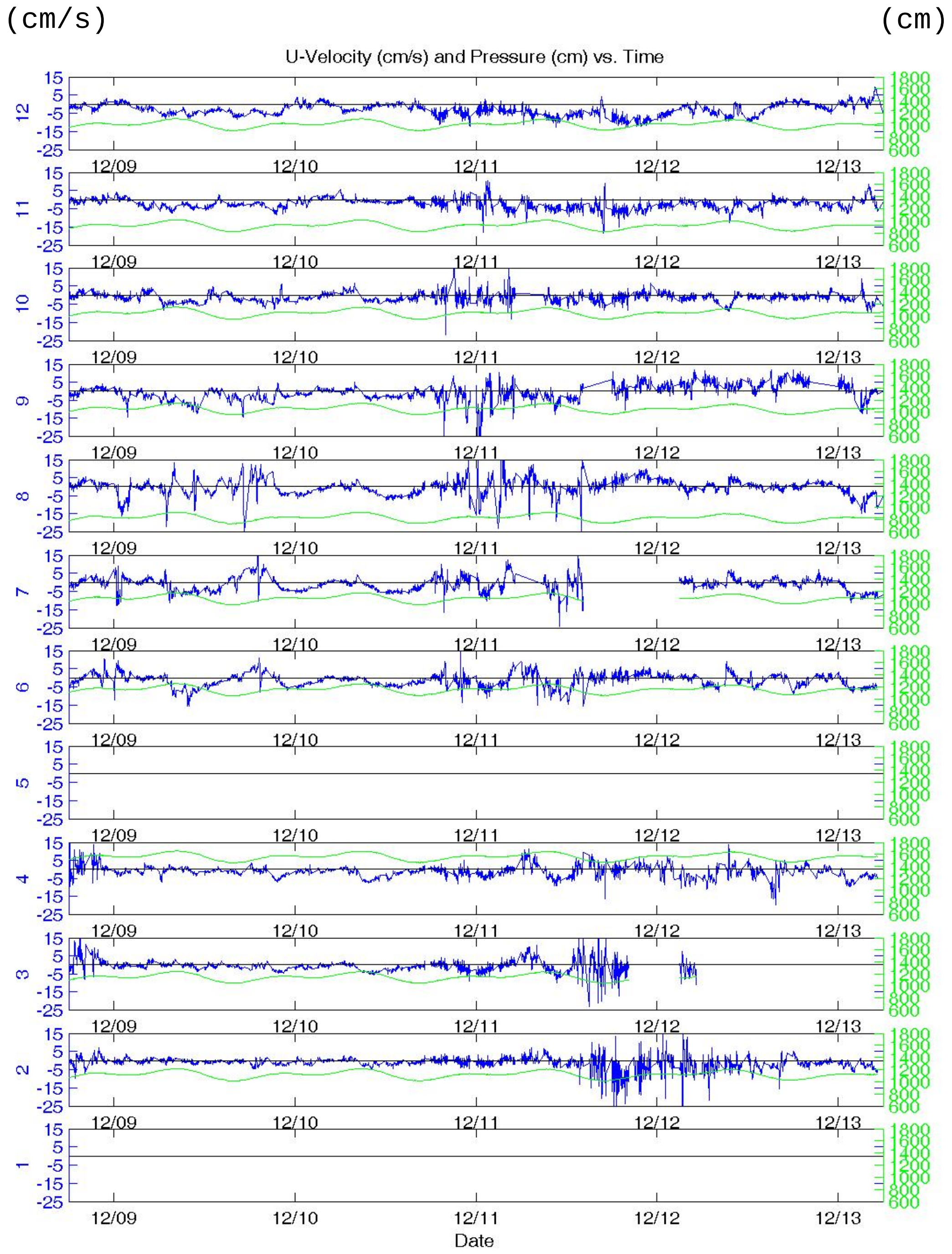

Figure 19. Eastward (positive) and westward (negative) crosshore velocities with pressure overlaid at all stations for Case Study III.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. SUMMARY AND CONCLUSIONS

The Nearshore Canyon Experiment (NCEX) was carried out off the coast of La Jolla, California, in the fall of 2003. An array of instruments was deployed extending northward and behind Scripps submarine canyon to determine the effect of the canyon on nearshore waves and currents. In this study, time series of pressure, 3-component velocity, wave heights, and winds were analyzed to better understand the behavior of longshore and cross-shore currents near complex bathymetry. Selected case studies during peak wave events were analyzed to explore the different conditions that arise around the canyon in relation to local winds, waves, and tides.

Over the entire NCEX experiment local winds were typically weak and variable. No clear correlation was observed between local winds and currents, suggesting local winds are not a dominant driving force for nearshore currents in this region. Rather, tides and waves were much more important in the formation of longshore currents.

At the canyon head wave heights were strongly reduced by refraction that focuses the wave energy to the north of the canyon. The setup associated with this wave height variation creates a pressure gradient that is likely the driving force for the strong longshore currents the head of the canyon observed in a winter storm.

The interactions between tides and the submarine canyon were the most apparent aspect of this study. At stations away from the canyon a significant tidal signal is unmistakably evident in the longshore current. Tides clearly lead longshore velocity by a 90 degree phase shift.

In low-moderate wave conditions, tides dominate longshore currents whereas cross-shore currents show the passage of irregular bore-like features. The currents are coherent away from the submarine canyon and decay towards the canyon head. Strong longshore currents were observed near the canyon head during a large wave event that were likely driven by an alongshore pressure gradient associated with wave set-up variations.

LIST OF REFERENCES

Feddersen, F., Guza, R.T., Elgar, S., and Herbers, T.H.C., “Alongshore momentum balances in the nearshore,” *Journal of Geophysical Research*, v.103, no.C8, pp.15667-15676, 1998.

Lentz, S., Guza, R.T., Elgar, S., Feddersen, F., and Herbers, T.H.C., “Momentum balances on the North Carolina inner shelf,” *Journal of Geophysical Research*, v.104, no.C8, pp.18250-18226, 1999.

Longuet-Higgins, M.S., “Longshore Currents Generated by Obliquely Incident Sea Waves,” Journal of Geophysical Research, v.75. no.33, pp.6778-6789, 1970.

Munk, W.H. and Traylor, M.A., “Refraction of ocean waves: a process linking underwater topography to beach erosion,” *The Journal of Geology*, v.55, no.1, pp.1-26, 1947.

O’Reilly, W.C., “Modeling the Storm Waves of January 17-18, 1988,” *Center for Coastal Studies*, A-009, pp.32-36, 1989.

Peak, S.D., Wave Refraction Over Complex Nearshore Bathymetry, Master’s Thesis, Naval Postgraduate School, Monterey, California, 2004.

Shepard, F.P. and Inman, D.L., “Nearshore water circulation related to bottom topography and wave refraction,” *Transactions*, American Geophysical Union, v.31, no.2, pp.196-212, 1950.

Thornton, E.B. and Guza, R.T., “Surf Zone Longshore Currents and Random Waves: Field Data and Models,” Journal of Physical Oceanography, v.16, pp.1165-1178, 1986.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Professor Thomas H.C. Herbers
   Naval Postgraduate School
   Monterey, California

4. Professor Edward B. Thornton
   Naval Postgraduate School
   Monterey, California

5. Professor Mary L. Batteen
   Naval Postgraduate School
   Monterey, California

6. Professor Donald P. Brutzman
   Naval Postgraduate School
   Monterey, California