2008

Internal waves over the continental shelf in south Monterey Bay

François Cazenave
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Cazenave, François, "Internal waves over the continental shelf in south Monterey Bay" (2008). *Master's Theses*. 3506.

DOI: <https://doi.org/10.31979/etd.kakk-26hs>

https://scholarworks.sjsu.edu/etd_theses/3506

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

INTERNAL WAVES OVER THE CONTINENTAL SHELF
IN SOUTH MONTEREY BAY

A Thesis
Presented to
The Faculty of Moss Landing Marine Laboratories
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
François Cazenave
May 2008

UMI Number: 1458174

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI[®]

UMI Microform 1458174

Copyright 2008 by ProQuest LLC.

All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 E. Eisenhower Parkway
PO Box 1346
Ann Arbor, MI 48106-1346

© 2008
François Cazenave
ALL RIGHTS RESERVED

APPROVED FOR MOSS LANDING MARINE LABORATORIES

Erika Shaw

Dr. Erika McPhee-Shaw

Kenneth W. Coale

Dr. Kenneth Coale

James Bellingham

Dr. James Bellingham, Monterey Bay Aquarium Research Institute

William Shaw

Dr. William Shaw, Naval Postgraduate School

APPROVED FOR THE UNIVERSITY

Thea L. Williamson 06/17/08

ABSTRACT

INTERNAL WAVES OVER THE CONTINENTAL SHELF IN SOUTH MONTEREY BAY

By François Cazenave

Temperature data from southern Monterey Bay reveal frequent solitons and semidiurnal internal tidal bores on the inner shelf. We undertook a field study to determine whether these features originate offshore and propagate shoreward over the continental shelf, and to characterize their evolution as they propagate. We sampled internal waves of various scales on the outer and mid-shelf during five surveys, using an autonomous underwater vehicle programmed for thermocline tracking and rapid, repeated CTD profiling. Internal tidal bores of amplitude greater than 20 meters propagating eastward from the outer bay were the dominant feature. Short period steep solitons appeared, propagated, and dissipated over the shelf without a definite pattern. Changes in stratification due to horizontal advection and atmospheric forcing appeared to affect internal wave generation and propagation on hourly to seasonal timescales. This may explain the high spatial and temporal variability of internal waves on the shelf.

ACKNOWLEDGEMENTS

Three leading oceanographic institutes were involved in this project. The Monterey Bay Aquarium Research Institute (MBARI) provided autonomous underwater vehicles (AUVs) and technical support for five surveys, as part of the Autonomous Ocean Sampling Network program (AOSN). The Naval Postgraduate School's (NPS) Ocean Turbulence group provided data from the Monterey Inner Shelf Observatory (MISO). Moss Landing Marine Laboratories (MLML) and the Physical Oceanography laboratory provided R/V Martin and R/V Point Sur and technical support for two surveys.

I thank:

- My advisor Dr. Erika McPhee-Shaw for her invaluable guidance all along this project.
- Dr. Jim Bellingham (MBARI) for initiating this project, for giving me the unique opportunity to work with AUVs, and for good advising.
- Dr. Bill Shaw (NPS) for his work planning the first shipboard survey on R/V Point Sur, for providing data from MISO, and for excellent discussions.
- Dr. Kenneth Coale (MLML) for very useful reviews and enthusiasm for the project.
- Dr. Tim Stanton (NPS) for generously sharing data from MISO, and for inspiring, passionate discussions.
- Thomas Hoover (MBARI) for his help planning AUV surveys and for technical support.

- Dr. Yanwu Zhang (MBARI) for his help planning the AUV surveys.
- Dr. John Ryan (MBARI) for providing satellite data and advice for analyzing AUV data.
- Dr. Larry Breaker for his very helpful advice on time series analysis.
- Friends of Moss Landing Marine Laboratories, and Drew Gashler's family for creating the 'Drew Gashler Internship', which allowed me to work at MBARI and learn about AUVs.
- Kim Fulton Bennett for his helpful comments on my paper.
- Luke Beatman for his technical help aboard R/V Martin and in the lab.
- Stephanie Flora for sharing her Matlab expertise.
- Dustin Carroll and Lauren Sassoubre for encouragement and support.
- Ashley Vizurraga and John Machado for their help with administrative matters.
- Jeff Arlt for pleasant commutes to Moss Landing.
- R/V Zephyr, R/V Point Sur and R/V John Martin crews for very professional work.
- My parents, brother, sisters, grand parents, and most of all, my wife Isabelle for their support and encouragement.

Table of Contents

LIST OF ACRONYMS	1
1 INTRODUCTION	2
1.1 PHYSICAL DESCRIPTION OF INTERNAL WAVES	2
1.2 THE IMPORTANCE OF INTERNAL WAVES	3
1.3 NONLINEAR INTERNAL WAVES ON CONTINENTAL SHELVES	5
1.4 PREVIOUS STUDIES OF INTERNAL WAVES IN MONTEREY BAY	8
1.5 PROJECT OVERVIEW AND HYPOTHESES	11
2 METHODS.....	14
2.1 OVERVIEW.....	14
2.2 MONTEREY INNER SHELF OBSERVATORY (MISO)	16
2.3 SHIPBOARD SURVEYS.....	17
2.3.1 <i>November 17, 2006 R/V Point Sur survey</i>	17
2.3.2 <i>November 16, 2007 survey on R/V Point Sur and R/V Martin</i>	19
2.4 AUV SURVEYS	21
2.4.1 <i>AUV capabilities</i>	21
2.4.2 <i>Sampling method</i>	23
2.4.3 <i>First AUV survey, May 14-15, 2007</i>	25
2.4.4 <i>Second AUV survey, August 27-28, 2007</i>	26
2.4.5 <i>Third AUV survey, November 26-27, 2007</i>	27

2.4.6	<i>AUV data processing</i>	28
3	RESULTS	31
3.1	MONTEREY INNER SHELF OBSERVATORY	31
3.2	SHIPBOARD SURVEYS.....	35
3.2.1	<i>R/V Point Sur Survey, November 17, 2006</i>	35
3.2.2	<i>R/V Point Sur and R/V Martin Survey, November 16, 2007</i>	42
3.3	AUV SURVEYS	48
3.3.1	<i>First AUV survey, May 14-15, 2007</i>	48
3.3.2	<i>Second AUV survey, August 27-28, 2007</i>	57
3.3.3	<i>Third AUV survey, November 26-27, 2007</i>	65
3.3	SUMMARY OF RESULTS	72
4	DISCUSSION	74
4.1	SOLITONS	74
4.2	INTERNAL TIDAL BORES	77
4.3	ARE AUVs EFFICIENT TOOLS FOR SAMPLING INTERNAL WAVES?	84
5	CONCLUSION	93
	REFERENCES	95

List of tables

Table 1: Temperature measured from MISO, R/V Point Sur, and R/V Martin stations at 10m depth (in °C).	47
Table 2: Characteristics of solitons and stratification for each survey.....	76
Table 3: Autocorrelation of temperature at MISO for five 30 day periods.....	81
Table 4: Cross correlation of tide and temperature at MISO for five 30 day periods.....	82
Table 5: Characteristics of AUV profiles. The temperature band width is the difference between the upper and the lower temperature bounds used for the AUV's profiling behavior. The average layer thickness, thermal gradient and profiling rate were averaged for entire surveys.	89

List of Figures

Figure 1: Nonlinear internal wave shape calculated using the KdV equations, for conditions typical in Monterey Bay in the fall.....	7
Figure 2: Map of Monterey Bay and the experiment site. The black arrows represent two likely generation sites for internal waves at the head of Monterey Canyon and at the outer bay shelf break.	13
Figure 3: Map of South Monterey Bay and locations of surveys and instruments.....	15
Figure 4: Timeline of project.	15
Figure 5: This figure shows the technique we used to plan our survey. The dotted lines show the predicted position of the internal wave. Two wave velocity estimates were used: 0.25m/s (blue dotted line) and 0.5m/s (red dotted line). At high tide, the internal wave is near the shore (distance along survey=0km). The gray line represents the predicted position of the ship. The most likely point of meeting with the internal wave is shown by the black arrow (figure by William Shaw).	19
Figure 6: Deployment of AUV from R/V Zephyr on November 26, 2007.....	22
Figure 7: AUV at the surface.	23
Figure 8: Temperatures and tide level at MISO. On the temperature plot, each line represents temperature at a different depth along the thermistor chain (from 0.5m to 8.5m above the seafloor). In the early part of the day, the	

water column became very homogeneous and relatively warm. Temperature decreased slightly until 316.5PST when the temperature dropped very sharply. Overturning occurred near the seafloor. This drop was followed by highly energetic short period internal waves. At the end of the day, the water column became more homogeneous and warmer again. This event happened during the high tide.32

Figure 9: Temperature and tide level measured at MISO in the summer (top) and in the winter (bottom). In the summer, temperatures oscillate dramatically because of internal waves. Oscillations are more pronounced near the bottom. In the winter, the water column is mixed and cannot support internal waves, therefore no internal waves are observed at MISO. Scales are the same for both plots.....33

Figure 10: Tide level and temperature measured at MISO in November 2006. Semi diurnal internal tidal bores arrived at MISO usually near the high tide. During these events, the temperature dropped up to 2.5°C within a few hours.....35

Figure 11: Locations of the CTD profiles taken from R/V Point Sur. We took profiles along a transect from near MISO to the shelf break. At station 32 to 42 we sampled a large soliton. We attempted to sample it again closer to the shore (station 46-54) but we did not succeed because of lack of time.38

Figure 12: Water temperature at all stations. Between stations 32 and 42, a 16m soliton was sampled.	39
Figure 13: Tide level, temperature at MISO and temperature measured offshore from R/V Point Sur. The two vertical black lines in the center plot show the arrival time of the internal wave sampled offshore (arrow), calculated using two velocity estimates.	42
Figure 14: Tide level and temperature measured at three different stations. No correlation appears between the stations. Several solitons appeared at the North station (R/V Point Sur) whereas none appeared at the West station (R/V Martin).	46
Figure 15: Temperature at three stations, at 10m depth.	47
Figure 16: May 14-15 AUV survey, transects 1 to 5.	52
Figure 17: May 14-15 AUV survey, transects 6 to 10.	53
Figure 18: May 14-15 AUV survey, transects 11 to 15.	54
Figure 19: May 14-15 AUV survey, transects 16 to 20.	55
Figure 20: Tide level, temperature measured at MISO and temperature measured by the AUV on the mid-shelf.	57
Figure 21: August 27-28 AUV survey, transects 1 to 5.	60
Figure 22: August 27-28 AUV survey, transects 6 to 10.	61
Figure 23: August 27-28 AUV survey, transects 11 to 15.	62

Figure 24: August 27-28 AUV survey, transects 16 to 19.	63
Figure 25: Tide level and temperature measured with the AUV on the mid-shelf on august 27-28 2007.....	64
Figure 26: November 26-27 AUV survey, transects 1 to 5.....	67
Figure 27: November 26-27 AUV survey, transects 5 to 10.....	68
Figure 28: November 26-27 AUV survey, transects 11 to 15.....	69
Figure 29: November 26-27 AUV survey, transects 16 to 17.....	70
Figure 30: Tide level, temperature at MISO and temperature measured with AUV on mid-shelf during November 16-27 survey.	71
Figure 31: Temperature at MISO at 12m depth and temperature at MLML's seawater intake, near the Monterey Canyon head. The mean was removed from both signals.....	80
Figure 32: The upper plot shows a KdV model of a nonlinear internal wave for conditions typical of Monterey Bay in late summer. The lower plot shows the slope of the same wave.	87
Figure 33: Actual AUV path and temperature bounds during the first survey. The black line shows the actual path of the AUV during the first transect of the first AUV survey. The blue line and the red line represent the lower and the upper temperature bounds. The AUV followed the isotherms very accurately, even during a steep soliton (between 1000m and	

1500m).89

Figure 34 Actual AUV path and temperature bounds during the second survey. The black line shows the actual path of the AUV during the second transect of the second AUV survey (August). The blue line and the red line represent the lower and the upper temperature bounds.90

Figure 35: Actual AUV path and temperature bounds during the third survey. The black line shows the actual path of the AUV during the fourth transect of the third AUV survey (November). The blue line and the red line represent the lower and the upper temperature bounds. The thermal gradient was low so the AUV sampled a thick layer of the water column.90

List of acronyms

AUV: Autonomous Underwater Vehicle.

CTD: Conductivity, Temperature, and Depth sensor.

INL: Intermediate Nepheloid Layer.

ITB: Internal Tidal Bore.

MBARI: Monterey Bay Aquarium Research Institute.

MISO: Monterey Inner Shelf Observatory.

MLML: Moss Landing Marine Laboratories.

NLIW: Nonlinear internal waves.

NPS: Naval Postgraduate School.

1 Introduction

1.1 Physical description of internal waves

Internal waves are gravity waves that travel within the ocean, supported by density gradients. They arise from perturbations of the hydrostatic equilibrium, where balance is maintained between the force of gravity and the buoyant force. They are a widespread phenomenon in the world's oceans. Depending on the nature of the ocean's stratification, these waves can travel horizontally or with some vertical component. In a two-layer ocean, internal waves travel horizontally at the pycnocline. In the abyssal ocean, they can propagate at an angle with the horizontal, depending on the stratification. Their amplitude can vary from a few centimeters to hundreds of meters. Periods can vary from a few minutes to a few hours (Garret and Kunze 2006, Gill 1982), which corresponds to frequencies between f (Coriolis frequency) and N (buoyancy frequency).

Internal waves can be generated by atmospheric forcing (Hosegood and Van Haren, 2004) but most of the internal wave energy comes from tidal current flow over topographic features. The change of slope at the shelf break is an ideal location for barotropic to baroclinic energy conversion (Baines et al. 1974, Carter et al. 2005). Energy from the tide is transformed to displacement of density surfaces and radiates away as internal waves.

A characteristic slope of the seafloor, α , is optimal for internal wave generation. This slope is given by the following equation:

$$\alpha = \sqrt{\frac{\omega^2 - f^2}{N^2 - \omega^2}} \quad (1)$$

where f is the Coriolis frequency, ω is the wave frequency, N^2 is the buoyancy frequency and α is expressed in radians (Wunsch, 1969).

Most observations show internal waves travel shoreward on the shelf, but internal waves traveling down slope have also been observed (Carter 2005). Phase speeds of internal waves over the continental shelf usually range from 0.2m/s to 1.5m/s (Klymak and Moum, 2003, Petruncio, 1998, Ramp, 2004).

Strong currents may be associated with internal waves. These currents can be stronger than those generated by the barotropic tide. Values of 40cm/s have been measured in Monterey Canyon and the Northern California margin (Petruncio et al., 1998, McPhee-Shaw, 2004) and values exceeding 1.2m/s have been observed in the South China Sea (Ramp, 2004).

1.2 The importance of internal waves

Internal waves play an important role in ocean physics, sediment transport and biology.

Internal waves can transport large amounts of energy. The nonlinear nature of internal waves makes this very difficult to study and quantify. Because they can have a vertical

component of group velocity, internal waves may transport energy up or down the water column. On a global scale, internal tides play an important role enhancing mixing in the deep ocean, which in turn controls the meridional overturning (Garret and Kunze, 2006). They also account for the dissipation of 30% of the tidal energy (Munk and Wunsch, 1998). Observations have shown high turbulence levels near internal waves. This implies that part of the internal wave energy is dissipated as it propagates (Gill 1986, Moum et al., 2003). However, quantifying the energy loss is difficult, especially when the water depth and the stratification are not constant.

As they pass, internal waves may transport phytoplankton in and out of the euphotic zone where photosynthesis can occur. Thus, the magnitude and frequency of these waves can have important consequences in phytoplankton growth and cell division, and may explain the cell cycle periodicity of certain members of the phytoplankton community (Lennert-Cody et al., 2002). Coupled with upwelling, internal waves may help bring essential micronutrients or resting spores into the euphotic zone where they can be utilized by phytoplankton (Leichter 2003, McPhee-Shaw, 2003). This may influence the rates of shelf production in the coastal zone.

The turbulent breaking of internal waves plays a role in generating detaching boundary layers called intermediate nepheloid layers (INLs). These INLs enhance spreading and offshore transport of suspended sediment (Cacchione and Drake, 1986, Gardner, 1989, Azetsu-Scott et al., 1995, McPhee-Shaw et al, 2004). Turbulence created by the interaction of internal waves with the seafloor may also be critical to the transport of sediments to the ocean's interior. Intensification of near-bottom water velocities and

bottom shear stresses caused by reflection of internal tide affects sedimentation patterns and bottom gradients (Cacchione et al., 2002).

1.3 Nonlinear internal waves on continental shelves

Packets of nonlinear internal waves (NLIWs) have been observed on continental shelves throughout the world. Sites of such observations include the Saint Lawrence Estuary (Bourgault 2007), the South China Sea (Duda 2004, Ramp 2004, Lui 1998), the shelf of Northern Oregon (Stanton 1998, Klymak 2003, Moum 2003), the Gulf of Oman (Small, 2002), the shelf of Portugal (Sherwin, 2002) and the Malin Shelf (Small 1999, Small 2003).

NLIWs have an important effect on coastal dynamics. They enhance mixing and transport (Leichter, 2003, Moum, 2003). They affect biology by redistributing plankton (Pineda 1999, Scotti and Pineda 2007). They resuspend and transport sediment (Bogucki 1997, Butman 2006). In spite of their importance, the generation of NLIWs is poorly understood. Observed NLIWs may be phase locked with the tide, as is the case in the Luzon Strait in the South China Sea (Ramp, 2004). This suggests they are the result of the interaction of the barotropic tide with the shelf break.

In this study, I compared field observations with predictions made using a non-rotating, two-layer fluid. Several studies have used this approach and obtained satisfactory results (Liu et al, 1998). This model is described below.

NLIWs can depress the thermocline by a distance that is comparable to the equivalent

depth, defined by:

$$h_e = \left(1 - \frac{h}{D}\right) h \quad (2)$$

With h = depth of the thermocline

D = total depth

(Michallet and Barthelemy, 1998).

A balance between nonlinearity and dispersion controls the evolution of NLIWs. The Korteweg de-Vries (KdV) equations are used to describe NLIWs for a simplified two-layer ocean model as follows:

$$\frac{\delta\eta}{\delta t} + (c + \alpha\eta) \frac{\partial\eta}{\partial x} + \beta \frac{\delta^3\eta}{\delta x^3} = 0 \quad (3)$$

where η is the vertical displacement of an isopycnal surface,

c is the phase velocity,

h_1 is the thickness of the upper layer with density ρ_1 ,

h_2 is the thickness of the lower layer with density ρ_2 ,

With $\rho_2 > \rho_1$

The parameters of the equation are:

$$c = \sqrt{\frac{g(\rho_2 - \rho_1)}{\rho} \frac{h_1 h_2}{h_1 + h_2}}, \quad \alpha = \frac{3c(h_2 - h_1)}{2h_1 h_2}, \quad \beta = \frac{c h_1 h_2}{6} \quad (4)$$

This equation has a family of well known solutions. This model works well in some cases but other models such as the CombKdV model must be used to account for higher degrees of nonlinearity (Lee and Beardsley 1974, Stanton 1998). Figure 1 shows an

example of a NLIW form calculated with the KdV equations, for condition similar to those in Monterey Bay in the fall.

Figure 1: Nonlinear internal wave shape calculated using the KdV equations, for conditions typical in Monterey Bay in the fall.

Waves of depression are usually observed in regions where the layer of water above the pycnocline is thinner than the layer below it. The shape changes to a wave of elevation when the pycnocline is in the lower half of the water column (Liu et al., 1998, Orr 2003, Ramp, 2004). As a NLIW approaches sufficiently shallow water, breaking occurs as the trailing edge overtakes the wave trough (Vlasenko and Hutter 2002, Kao 1985). An interesting feature of NLIWs is that despite the regularity of the barotropic tide, their characteristics vary greatly. Two days with similar tides could have very

different NLIWs.

In this paper I use the following terminology to describe nonlinear internal waves:

- **Internal Tidal Bore** (ITB) refers to tide-induced, semidiurnal-period disturbance of the isopycnals.
- **Soliton** refers to short period (15 minutes to 1 hour), highly nonlinear, steep disturbances of the isopycnals (Stanton and Ostrovsky 1998).
- **Solibore** refers to ITBs and solitons propagating together (Hosegood and Van Haren 2004).

1.4 Previous studies of internal waves in Monterey Bay

In Monterey Bay, many observations of internal waves have been made. Several studies have focused on Monterey Canyon. Broenkow and McKain (1972) recorded density oscillations in Monterey Canyon of up to 115m. Based on these observations, they concluded that the internal tide was propagating at 20-30cm/s, with horizontal wavelength approximately 10km.

Observations made in 1994 by Petruncio (Petruncio 1998) reveal semidiurnal currents of about 20cm/s, ten times larger than the estimated barotropic tidal currents. They are caused by a highly energetic internal tide propagating up the canyon. Smooth ridge (45 km offshore) and Steep Ridge (30km offshore), were identified as possible regions of generation of internal waves for the Monterey Canyon.

Observations made in 1997 by Rosenfeld (Rosenfeld 1999) reveal strong internal tides along the axis of the canyon near the canyon head. Using bottom mounted and shipboard ADCP, and CTD profiling, internal tidal bores were sampled. They were sharp drops in temperature occurring at 11-13h interval. They were more prominent between the spring and the neap tide.

A 2002 study by Kunze (Kunze 2002) showed that internal waves in the outer Monterey Canyon are ten times more energetic than in typical open ocean fields. It also showed that significant energy is dissipated as they propagate.

A 2005 study by Carter (Carter, 2005) focused on internal waves on the outer shelf, near the canyon edge. Most observations showed upward energy propagation. Carter explains that as the barotropic tide passes over the shelf break or canyon rim, a second internal tide is generated. He also notes that on the shelf, the internal wave field is dominated by the locally generated internal tide but appears to contain energy from the surface reflection of the more distantly generated internal tide. Elevated levels of turbulent kinetic energy dissipation rates were observed. Considerable temporal and spatial variability was observed. An important and unexpected finding of this study was the existence of down slope propagating nonlinear internal waves which transformed to waves of depression as they went into water deeper than about 120m, at the rim of Monterey Canyon.

A 2001 study by Storlazzi in south Monterey Bay showed the regular arrival of internal waves on the inner shelf. These bore-like features were followed by packets of short period internal waves. These features lagged the surface tide by about 3 hours and

were stronger when stratification in the Bay was high. Internal waves were stronger between the spring and neap tides, which is similar to observations made by Rosenfeld in Monterey Canyon but opposite to observations made in other regions of the world (Ramp, 2004 for example). Storlazzi suggested that during the neap tide, low shear was unfavorable to internal wave generation, whereas during the spring tide, enhanced mixing lowered stratification, which limited internal wave propagation. As a result, conditions were generally more favorable for propagation between neap and spring tide (Storlazzi et al. 2003).

NPS student Kendra Crabbe analyzed 6 months of ADCP and thermistor data from the Monterey Inner Shelf Observatory (MISO, see section 2.2 for more details) as part of her master's thesis. She focused her research on directional characteristics of inner shelf internal tidal bores. Her main findings were the following:

- Currents induced by internal tidal bores were not directly affected by wind forcing or tide amplitude.
- Internal tidal bores created net offshore flow in the lower water column.
- Internal tidal bores approached MISO from Marina and moved towards Monterey.

The conclusion of her study was that internal tidal bores at MISO are most likely being generated at the Monterey Bay Submarine Canyon or are cross-shore events that reach the coastline, refract and propagate southward as internal edge waves (Crabbe, 2007).

1.5 Project overview and hypotheses

The studies described in paragraph 1.4 focused on single regions of Monterey Bay (i.e., the Monterey Canyon, the mid to outer shelf, or the inner shelf), and did not specifically address the evolution of internal waves between the shelf break and the shore. Some important questions remain: what is the fate of internal waves as they travel shoreward over the continental shelf, what are the main energy paths, how do the shape, amplitude and phase speed of internal waves evolve as they propagate up the shelf? These are questions I address in this study.

This study was first motivated by striking features recorded by a thermistor chain at the Monterey Inner Shelf Observatory (MISO, see section 2.2 for more details), 600m north of Del Monte beach, in 12m depth. Semi diurnal internal tidal bores (ITB) have been recorded there. They appear as rapid drops of the temperature (up to 4°C) usually followed by rapid oscillations. These highly energetic features occur daily from early spring to late fall, with varying intensity. In the winter they occur only occasionally. To understand the origin of these internal waves, we undertook a field study of internal waves over the South Monterey Bay continental shelf. During two shipboard surveys and three AUV surveys, we attempted to sample internal waves on the outer and mid-shelf, before they reach MISO. I analyzed data sets from the five surveys and identified specific events. I compared internal wave events to predictions made using the two-layer non-rotating ocean models. I compared data from different locations to help understand the relationship between tide, internal waves on the inner shelf and the outer shelf. In addition to these scientific considerations, an important goal of this project was to

evaluate a new way to use AUVs to sample internal waves.

The hypotheses I tested in this study are the following:

- The semi diurnal temperature oscillations observed at MISO are internal tidal bores that propagate onshore from the outer shelf.
- These internal tidal bores are generated by the interaction of the barotropic tide with the steep topography of Monterey Bay. The main generation regions are the outer Bay shelf break and the Monterey Canyon (Figure 2).
- Internal tidal bores travel shoreward over the continental shelf until they reach shallow water, where they break. Their shape and phase speed depend on stratification and can be predicted using the non-rotating two-layer ocean model.
- Internal waves start as linear features at the shelf break and then become nonlinear as they travel up the shelf.

Figure 2: Map of Monterey Bay and the experiment site. The black arrows represent two likely generation sites for internal waves at the head of Monterey Canyon and at the outer bay shelf break.

2 Methods

2.1 Overview

Internal waves are difficult and costly to sample because they are difficult to predict, they usually cannot be detected at the surface and their motion is usually complex. Several techniques have been used by scientists to sample internal waves. The currents associated with internal waves alter the roughness of the sea surface and create rough and smooth bands. Photographs from aircraft or satellites and other remote sensing techniques such as radar can be used to detect these “slicks” (Gasparovic, 1988, Thompson, 1994, Ramp, 2004). ADCPs can be used to measure currents associated with internal waves. CTD profilers or moored sensors can detect oscillations of temperature, density and salinity, which are caused by the passage of internal waves. For this project, internal waves were sampled using traditional methods (CTD profilers deployed from R/V Point Sur and R/V Martin, and a thermistor chain at MISO) and a new method we developed using MBARI's AUV. Because our goal was to understand the evolution of internal waves as they travel shoreward on the shelf, we combined these methods and made simultaneous measurements at different locations. Using results from the analysis of MISO data, we predicted position and timing of internal waves over the shelf and planned the shipboard and AUV surveys accordingly. Figure 3 shows the locations of the different surveys. The data collection and processing methods are described in the paragraphs below.

Figure 3: Map of South Monterey Bay and locations of surveys and instruments.

Figure 4: Timeline of project.

2.2 Monterey Inner Shelf Observatory (MISO)

MISO is an underwater cabled observatory, located in South Monterey Bay, 600m north of Del Monte beach, near Monterey (Latitude: 36.607°N, Longitude: 121.874°W). The water depth there is 12m. It is connected via a cable to a station on land, thus providing power to the instruments and allowing immediate access to the data. It was designed and deployed in 2000 by Tim Stanton and the Ocean Turbulence Research group at the Naval Postgraduate School in Monterey. The station is equipped with numerous instruments but for this study, we only used data from a thermistor chain and a pressure sensor.

The thermistor chain runs from 0.5m to 8.6m above the seafloor. It is composed of 16 sensors, which measure water temperature at 1 minute intervals. The thermistor chain was deployed in June 2006 and is still in use.

A high precision digital pressure sensor (Paro Scientific) recorded pressure every second but a running average was used to filter out surface gravity waves. This instrument yields a precise record of the tide level.

These data sets are exceptional because they are long, nearly continuous, very accurate and have very high sampling frequencies. The data can be accessed almost in real time, which was helpful for planning surveys.

The temperature data from MISO were used to predict internal waves and plan shipboard and AUV cruises. They were also used to compare with data from AUV and shipboard cruises.

2.3 Shipboard surveys

A common and simple way to sample internal waves is by using a CTD profiler from a ship at a fixed location. Rapid, repetitive profiles are taken to measure the evolution of the stratification, thereby detecting internal waves passing under the ship. The downside of this technique is that it does not give the direction of the internal wave; it only gives the period, the amplitude and the shape. By using several ships at different locations, direction and velocity can be calculated.

Using this technique, we attempted to sample internal waves traveling across the continental shelf before they reach MISO. The paragraphs below describe these surveys.

2.3.1 November 17, 2006 R/V Point Sur survey

On November 17, 2006, we went out on R/V Point Sur with the physical oceanography class to attempt to sample an internal wave at several locations before it reached MISO. To plan our survey, we made three assumptions:

- Large internal waves arrive at MISO near the high tide. This assumption was based on observations made at MISO in the weeks preceding the survey (see results section).
- These internal waves travel over the continental shelf from the outer Monterey Bay shelf break to the inner shelf.
- The velocity of these internal waves can be calculated given stratification, assuming a two-layer ocean. We calculated this velocity using stratification data

from Monterey Bay in November 2005 (see results sections). We used two velocity estimates: 0.25m/s and 0.5m/s.

Based on these assumptions, we calculated the likely position of the internal wave as it propagates over the shelf, with respect to time. We planned our survey according to this information (Figure 5). We planned to make CTD profile measurements at regular intervals starting at the inner shelf, near MISO, and going out towards the shelf break. If we sampled an internal wave, we would turn around and steam back towards shore and attempt to sample the internal wave again. Most of the planning for this cruise was done by our physical oceanography professor, Dr. William Shaw.

We started sampling in shallow water near MISO around 10:45PST, and then made CTD profiles measurement at regular intervals along the transect. A MATLAB® program written by Dr. Shaw allowed us to immediately view the density structure. Around 13:40PST, we sampled a large soliton-like internal wave near the shelf break (see Figure 12 in results section). This matched our predictions. We attempted to track it by sampling it again closer to shore but we were not successful because of lack of time.

Figure 5: This figure shows the technique we used to plan our survey. The dotted lines show the predicted position of the internal wave. Two wave velocity estimates were used: 0.25m/s (blue dotted line) and 0.5m/s (red dotted line). At high tide, the internal wave is near the shore (distance along survey=0km). The gray line represents the predicted position of the ship. The most likely point of meeting with the internal wave is shown by the black arrow (figure by William Shaw).

2.3.2 November 16, 2007 survey on R/V Point Sur and R/V Martin

As for our previous cruise on R/V Point Sur, our goal was to sample an internal wave on the mid-shelf before it reaches MISO. That time, we used two ships, R/V Martin and R/V Point Sur. Using two ships at fixed location, coupled with MISO, we expected to sample the internal wave at three different locations, which would allow us to calculate

its direction and phase speed.

As for the previous survey on R/V Point Sur, we used results from our analysis of MISO data to plan this survey (see results section). Using stratification data from November 2006, and the non-rotating two-layer ocean model, I calculated the likely travel speed of internal waves at this time of the year. Based on this information, I calculated the most likely position of the internal tidal bore for a given time and selected the positions for the ships accordingly. We decided to have R/V Martin offshore from MISO (West North West) and R/V Point Sur in the direction of the head of the Monterey Canyon (North). With this technique, we expected to determine the direction of internal waves and to verify whether or not it comes as an edge wave, from the head of the Monterey canyon, as it has been suggested (Crabbe 2007).

The stations are described below and can be seen on the map (Figure 3).

R/V Martin Position:

36.635°N, 121.889°W

Depth at this position: 63m.

R/V Point Sur Position:

36.655°N, 121.857°W

Depth at this position: 50m.

R/V Martin collected data from 09:10PST to 16:26PST, with only a 5-minute break around 14:00PST. In total, 136 profiles were taken. Over 7.25 hours of data collection, this comes to one profile every 3.2 minutes.

R/V Point Sur started collecting data at 09:27PST. At 12:40PST, the pulley block broke and the CTD was damaged. The instrument was replaced and measurements resumed at 13:52PST, until 15:33PST. In total, 86 profiles were taken. Over 4.9 hours of data collection, this comes to one profile every 3.5 minute. The mean buoyancy frequency on that day was approximately $N=0.015\text{Hz}$ so the theoretical shortest period of internal waves was $2\pi/N = 421\text{s}=7\text{min}$. Therefore the sampling frequency was barely high enough.

This survey was part of the fall 2007 physical oceanography class. Doctor Erika Shaw and her class participated in cruise planning and onboard operation.

2.4 AUV surveys

2.4.1 AUV capabilities

AUVs are self-propelled autonomous underwater vehicles that can carry scientific equipment to full ocean depths (Sibenac et al, 2002). They travel at speeds ranging from 0.3m/s to 2m/s. Because AUVs are battery powered, they are limited to relatively short duration missions, on the order of a few hours to a few days. A variety of AUVs are currently being used for scientific purposes, ranging in length from less than a meter to over 6 meters. Large AUVs such as those of MBARI need a shipboard crane or lifting device to be deployed from a boat. AUVs are used for a wide variety of purposes: water

quality monitoring, surveillance, mapping and scientific research (Bellingham and Rajan, 2007). MBARI's AUVs are deployed in Monterey Bay on a regular basis from R/V Zephyr. They can be equipped with chemical, biological and or physical sensors. For this study, only CTD data were used. Temperature was used as a tracer for density because thermistors are very reliable sensors and density is mostly driven by temperature in this region. The data are recorded by the AUV's onboard computer and can be downloaded by radio once the AUV is at the surface or by cable when the AUV is recovered.

Figure 6: Deployment of AUV from R/V Zephyr on November 26, 2007.

Figure 7: AUV at the surface.

2.4.2 Sampling method

Typically, AUVs are programmed to run in a sawtooth pattern, within a predetermined depth envelope. The data can be viewed as a multitude of CTD profiles taken along a transect except the profiles are at an angle near 20° with the surface.

An algorithm was written by MBARI's research engineer Dr. Yanwu Zhang to allow the AUV to stay within temperature bounds instead of depth bounds. These temperature bounds can be adjusted so that the AUV follows the thermocline. If the thermocline depth rises or drops because of an internal wave, the AUV will follow it. If the temperature envelope is narrow, the thermocline will be followed very accurately, but only a narrow band of the water column will be sampled. If the temperature envelope is wide, a wide band of the water column will be sampled, but with a lower sampling rate. A good compromise must be found. Navigation and control issues must also be taken into account. A narrow temperature envelope means more vertical profiles, which can

lead to problems.

To increase our chances of sampling internal waves, we decided to run 18 hour overnight surveys. The large internal waves recorded at MISO have periods in the 12 hour range, so an 18 hour survey is very likely to sample an entire internal wave. For each cruise, the AUV was first deployed in the morning for a short survey and then recovered to recharge the batteries. The data of the morning survey were analyzed onboard to find the thermocline depth and adjust the temperature bounds in the AUV program. The AUV was then deployed again, and recovered the next day, after the overnight survey.

The survey consisted of a 4.5 km transect running perpendicular to the isobaths. Over 18 hours, the AUV was able to cover this transect approximately 18 times. Each pass can be viewed as a snapshot of the thermocline. However, because the AUV's velocity is only two to three times the estimated velocity of internal waves, the data are not quite synoptic. If an internal wave travels in the same direction as the transect, it can be recorded up to three times at different locations.

At the end of each transect, the AUV came up to the surface to get a GPS fix and make corrections to its heading and make up for dead reckoning errors. AUV surveys were carried out during spring tides, which are more favorable to internal wave generation (Petruncio, 1998, Stanton 1998).

An important part of this study was to evaluate the performance of this new sampling method with the AUV. To our knowledge, this type of measurements (repetitive transect with a temperature following behavior) had not been done before. A note about the

advantages and drawbacks of this kind of measurements is included in the discussion part of this paper.

2.4.3 First AUV survey, May 14-15, 2007

The first survey was originally planned earlier in the year but was postponed several times because of bad weather and technical problems. AUVs can only be deployed in fairly calm weather. The location of this survey can be seen on Figure 3. This location was selected because it is just inshore of a very steep part of the shelf break where internal waves are likely to appear. Also, during a previous cruise on R/V Point Sur, a large internal wave had been sampled nearby. The seafloor slopes gently along the transect, with no sharp topographic features.

The stations are described below and can be seen on the map (Figure 3).

Offshore point:

36.702°N, 121.935°W Depth at this position: 97m.

Inshore point:

36.685°N, 121.890°W Depth at this position: 81m.

On May 14, R/V Zephyr deployed the AUV around 09:00 PDT at the inshore point. A first short survey with a regular depth-bound sawtooth pattern was carried out to measure the stratification of the water column. The data were then downloaded by radio and analyzed immediately to define the temperature bounds. We selected the temperature

bounds so that the vehicle remained near the thermocline, where the temperature gradient is highest. The lower temperature bound was set to 10.1°C and the upper temperature bound was set to 10.3°C. A second survey was carried out in the morning to test the temperature following behavior. The AUV was recovered around 12:00 PDT for a fast charge of the batteries. The data from the morning survey were analyzed to verify that the temperature following behavior was working properly. At 15:00 PDT, the AUV was deployed for the overnight survey. The next day, the AUV was recovered around 08:00PDT after 17 full transects and two half transects.

2.4.4 Second AUV survey, August 27-28, 2007

The location of this survey can be seen on Figure 3. We decided to move the transect closer to MISO to make the comparison of AUV data and MISO data easier. For safety reasons, the AUV cannot be left unattended by a vessel if it is operating closer than 2km from the coast, so the inshore point for this survey is as close to the coast as it could be, about 2km. Again, the transect is perpendicular to the isobaths, a likely direction of propagation of internal waves. The seafloor slopes gently along the transect, with no sharp topographic features.

The stations are described below and can be seen on the map (Figure 3).

Offshore point:

36.667°N, 121.922°W. Depth at this position: 85m.

Inshore point:

36.638°N, 121.889°W. Depth at this position: 64m.

Following a similar plan as for the May 14-15 survey, we deployed the AUV for a short mission in the morning and set the temperature boundaries for the overnight survey. During this survey, the water column was more stratified, which is typical for this time of the year. The lower temperature bound was set to 12.0°C and the upper temperature bound was set to 12.4°C. We used a wider temperature envelope (0.4°C instead of 0.2°C for the May 14-15 survey) for two reasons: firstly, the temperature gradient was higher in August so 0.2°C would only have covered a very small portion of the water column, and secondly, very rapid profiling during the first survey caused the AUV to stall out and lose control several times.

At 14:20PDT, the AUV was deployed for the overnight survey. The next day, it was recovered around 08:00PDT, after 19 full transects between offshore and onshore points.

2.4.5 Third AUV survey, November 26-27, 2007

The location of this survey was the same as for the previous survey (Figure 3). Because of a technical problem with the crane, we were only able to deploy the AUV late in the morning. We ran a short survey to measure the stratification. As expected for that time of the year, the temperature gradient was low and there was not a well defined thermocline, but rather two weak thermoclines. The lower temperature bound was set to 11.2°C and the upper temperature bound was set to 11.6°C. Using the same temperature band width as for the previous cruise turned out to be a mistake. Because the thermal

gradient was low, the AUV was not constrained to a narrow portion of the water column and did not follow the isotherm accurately. A 0.2°C or even smaller temperature band width would have been more appropriate. Unfortunately, we did not have time to test the temperature following behavior with these temperature bounds before the overnight survey.

At 15:20PST, the AUV was deployed for the overnight survey. The next day, it was recovered around 06:00PST after 16 full transects. The mission stopped earlier than expected because of low batteries.

A fourth survey was planned for December 16, 2007, but was canceled because of bad weather.

2.4.6 AUV data processing

Processing the AUV data was a rather complex, time consuming task. MBARI's software engineers have designed programs that generate plots from AUV data. However, these plots are not suitable for repetitive transects because the data are plotted versus distance from the beginning of the survey. Also, these plots do not have a very high resolution and the interpolation of the data hides a lot of the small scale features.

I developed several programs in MATLAB® to process raw AUV data and generate specific plots. The main program used to process the data goes through the following steps:

- Interpolate data from the AUV's different instruments to the same sampling frequency.
- Correct depth depending on AUV pitch (the pressure sensor and the CTD intake are about 2.9m apart in the vehicle, so the measured depth does not reflect the CTD's intake depth when the vehicle is tilted).
- Correct CTD data for plumbing lag. I estimated this lag to one second by comparing temperatures measured at the same depth during the upcast and the downcast. On average, they were closest when a one second lag was removed from the CTD data.
- Calculate the distance from the inshore point for each point.
- Apply a zero-phase digital filter to the depth and the temperature to remove unwanted noise (frequencies above 0.3Hz).
- Detect peaks and valleys in the sawtooth pattern and identify upcasts and downcasts.
- Separate casts and place them in a matrix.
- Detect times of diving, using the GPS data, to identify each transect.

This program yielded a set of matrices which I then used in other programs to calculate and plot various parameters.

I developed a program to generate 3-D plots to show the temperature versus distance from the inshore point, and depth. Another program calculated the average depth of the upper and lower temperature bounds for each up or downcast. I used it to generate plots showing two isotherms, one for the upper bound temperature, and one for the lower bound temperature. I used these plots to measure internal wave amplitude, wavelength and velocity.

Finally I created a program to calculate the average temperature over 500m sections of the transect. For each section the program calculated the average layer thickness, the temperature gradient, the strain, and the strain rate. I used these values to characterize the evolution of the water column with respect to time. I used 500m sections so that the averages could be calculated using about 10 or more discreet values. These values are not accurate for the extremities of the transects because the vehicle sometimes surfaced or dove hundreds of meters away from the way points so fewer values were recorded there.

3 Results

3.1 Monterey Inner Shelf observatory

Semi-diurnal internal tidal bores appear at MISO on a daily basis. They appear as rapid drops of the temperature (up to 4°C) usually followed by rapid oscillations. These events usually last from 4 to 12 hours. The oscillations are usually strongest near the seafloor. Figure 8 shows an example of an ITB on November 12, 2006. Within less than 2 hours, the temperature near the seafloor dropped by approximately 2.5°C. The period of this internal tidal bore was approximately 12 hours while the rapid solitons following the leading edge had periods in the 15 to 20 minute range.

These highly energetic features occur from early spring to late fall, with varying intensity. In the winter they occur only on occasions. Because an unstratified water column cannot support internal waves, these ITBs do not appear in the winter, when the Monterey Bay inner shelf is well-mixed. Figure 9 shows the huge difference between winter (February 2007), when the water is not stratified, and summer (August 2007), when the water is highly stratified.

Figure 8: Temperatures and tide level at MISO. On the temperature plot, each line represents temperature at a different depth along the thermistor chain (from 0.5m to 8.5m above the seafloor). In the early part of the day, the water column became very homogeneous and relatively warm. Temperature decreased slightly until 316.5PST when the temperature dropped very sharply. Overturning occurred near the seafloor. This drop was followed by highly energetic short period internal waves. At the end of the day, the water column became more homogeneous and warmer again. This event happened during the high tide.

Figure 9: Temperature and tide level measured at MISO in the summer (top) and in the winter (bottom). In the summer, temperatures oscillate dramatically because of internal waves. Oscillations are more pronounced near the bottom. In the winter, the water column is mixed and cannot support internal waves, therefore no internal waves are observed at MISO. Scales are the same for both plots.

ITBs appear to be phase locked with the tide. However the phase shift varies significantly with time. NPS student Kendra Crabbe analyzed six months of temperature and found there was not a dominant phase shift between high tide and ITB events (Crabbe 2007). However, over shorter periods of time (5-10 days), the phase shift can be relatively steady. To plan the shipboard surveys, we needed to predict the arrival of ITBs at MISO (see methods section), so we estimated the phase shift by analyzing data from the weeks preceding the survey or data from the previous year at the same period. To plan the November 17, 2006 survey, we visually analyzed plots of tide and temperature from the weeks preceding the survey. We found that, on average, ITBs arrived at MISO near the high tide. To plan the November 16, 2007 survey, I used data from November 2006 (Figure 10). I visually analyzed temperature plots for 30 events and I calculated the time lag between the high tide and the arrival of ITBs. On average, ITBs appeared at MISO 2.03 hours after the high tide. So, for that time of the year, I assumed that internal tidal bores appeared at MISO approximately 2 hours after the high tide. This value was for the peak of the internal tidal bore. The leading edge of the internal tidal bore usually arrived 1 to 2 hours earlier depending on how steep the edge was. The standard deviation was 1.91 hours, which shows there was much day-to-day variability.

Figure 10: Tide level and temperature measured at MISO in November 2006. Semi diurnal internal tidal bores arrived at MISO usually near the high tide. During these events, the temperature dropped up to 2.5°C within a few hours.

MISO data were also analyzed for the days of the shipboard and AUV surveys. This analysis is described in the chapters below, for each survey.

3.2 Shipboard surveys

3.2.1 R/V Point Sur Survey, November 17, 2006

Figure 11 shows the location of the CTD profiles for the November 17, 2006 survey, aboard R/V Point Sur. Figure 12 shows the temperature measured at each station. The first section of the plot shows the data collected from station 1 to 13. For these stations

the ship stayed near the shore, in less than 30m of water. Oscillations of the thermocline of up to 4m were observed. These oscillations were probably not related to the steep solitons observed at MISO. They were more likely background noise, which was also observed at MISO at the same period (Figure 13).

Between stations 13 and 14, there was a significant drop of the thermocline depth (8 meters). Station 14 was much farther offshore than station 13, so a drop of temperature was expected. However this drop was not entirely due to the increase distance from the coast because for other stations farther offshore, the thermocline rose again (station 15 to 20). This drop may have been due to an internal tidal bore. The leading edge of the ITB may have been between station 13 and 14 while the ship was steaming to station 14, so it was not sampled. This ITB arrived at MISO approximately 0.04 days (1 hour) later (Figure 12). The velocity of the ITB cannot be calculated because the position of its leading edge is unknown.

From station 15 to 23 the thermocline became shallower. This may have been the tail end of the ITB. There were small variations that can be attributed to background noise. Only at station 23 did the thermocline drop significantly (4m). At this point, R/V Point Sur was near the outer bay and might have entered a different water mass, with generally lower temperatures.

From station 32 to 42 while holding position, a large internal wave was sampled. Its characteristics are described below:

Position (beginning of wave)

36.679°N, -121.946°W

Time (beginning of wave)

321.5611 PST

Observed period (crest to crest): 21 minutes

Full water depth: 95m

Observed amplitude: Approximately 16m. 13°C isotherm drops from 14m down to 30m.

While the internal wave was being sampled, the boat drifted approximately 250m. There was no wind at that time so we can assume that the drift was solely due to the surface current. The surface current can be estimated to $250m/(21min \times 60s) = 0.2m/s$ with a direction of approximately 250 degrees. This current may have been partly due to the internal wave, but it is impossible to distinguish it from barotropic currents. The wave direction is assumed to be shoreward but this cannot be validated. The shape of this internal wave is characteristic of a soliton. After the main wave, the thermocline dropped again. The soliton was probably followed by other lower amplitude waves.

After sampling this internal wave, we attempted to sample it again closer to shore. We steamed towards shore and took a few more profiles at stations 46 to 54. But the thermocline was fairly flat and no internal waves were sampled. Unfortunately, around 15:30PST, we had to leave. Had we stayed longer, we might have sampled the soliton again.

Figure 11: Locations of the CTD profiles taken from R/V Point Sur. We took profiles along a transect from near MISO to the shelf break. At station 32 to 42 we sampled a large soliton. We attempted to sample it again closer to the shore (station 46-54) but we did not succeed because of lack of time.

Figure 12: Water temperature at all stations. Between stations 32 and 42, a 16m soliton was sampled.

Correlation with MISO

Using the non-rotating two-layer ocean model, the travel speed C of the soliton observed at station 32 to 42 was estimated.

$$C = g'h \quad (5)$$

With the thickness of the upper layer $h = 20 \text{ m}$,

the reduced gravity acceleration $g' = g \times \frac{\rho_2 - \rho_1}{\rho}$ ($g = 9.8 \text{ m/s}^2$),

the density of the upper layer $\rho_1 = 1025 \text{ kg/m}^3$,

the density of the lower layer $\rho_2 = 1025.6 \text{ kg/m}^3$,

$$C = 0.3 \text{ m/s}$$

The distance from MISO was 10.5km. Assuming that the internal wave was traveling at 0.3m/s and was going straight towards MISO, the travel time was: $10500\text{m} \times 0.3\text{m/s} = 31500\text{s} = 8\text{h}45\text{min}$. But the internal probably slowed down when it arrived in shallower water so we can also use a slow velocity estimate of 0.2m/s: $10500\text{m} \times 0.2\text{m/s} = 21000\text{s} = 5\text{h}50\text{min}$.

So the predicted wave arrival at MISO would be between:

$$321.5611\text{PST} + 35000\text{s}/(24\text{h} \times 3600\text{s}) = 321.966\text{PST} \text{ for the high speed estimate}$$

and

$$321.5611\text{PST} + 21000\text{s}/(24\text{h} \times 3600\text{s}) = 321.168\text{PST} \text{ for the low speed estimate}$$

On Figure 13, the two vertical black lines on the MISO temperature plot show the arrival time calculated above. For high wave speed estimate, the calculated time of arrival at MISO matched a period of low energy, whereas with the low speed estimate, it matched the peak an internal tidal bore.

It is possible that the internal wave observed at MISO around 322.2PST was related to the soliton observed offshore, however we don't have enough evidence to verify it. The internal wave velocity can change very much on the inner shelf, in ways that are hard to predict and the direction of the soliton is unknown. Even if it was traveling onshore, it is unlikely that it was heading straight towards MISO.

Finally, as can easily be seen on Figure 13, the time scales of the soliton offshore, and the internal tidal bore at MISO are very different (21 minute period offshore, versus 12 hour period at MISO). It is almost certain that the soliton we sampled was only a component (possibly the leading edge) of a much longer ITB, which later appeared at MISO.

The temperature at MISO and the tide level appear to be phase-locked (Figure 13). Using the cross correlation function, I calculated the phase shift over two days around November 17, 2006.

The phase shift or lag between tide and temperature measured at MISO at 0.6m (8.5m) above the sea floor is 3.7 hours (1.7 hours). The standardized cross correlation coefficient is -0.66 (-0.8). It is negative because a rise in sea level corresponds to a decrease in temperature.

Figure 13: Tide level, temperature at MISO and temperature measured offshore from R/V Point Sur. The two vertical black lines in the center plot show the arrival time of the internal wave sampled offshore (arrow), calculated using two velocity estimates.

3.2.2 R/V Point Sur and R/V Martin Survey, November 16, 2007

Figure 14 shows the tide, the temperature measured at MISO, the temperature measured from R/V Martin, and the temperature measured from R/V Point Sur during the November 16, 2007 survey (see Figure 3 for location).

At MISO, for November 16 and 17, the average temperature difference between 0.6m

above the seafloor (deepest sensor) and 8.5m above the seafloor (shallowest sensor) was 1.50°C. This is slightly higher than it was during the November 16, 2006 cruise (1.24°C) but much lower than in late summer, when the water column was strongly stratified (3.45°C for September 2007). Indeed, in the weeks before the cruise, the weather had been cold and stormy which appeared to lower stratification considerably. This has two direct consequences on internal waves:

- the density gradient is weaker so internal waves are not guided by the thermocline as much as in the summer.
- less energy is required to displace the isotherms so internal wave may be generated more easily.

The result of this appears to be that internal waves at MISO are of smaller amplitude and are less regular than in times of strong stratification. On Figure 14, the plot of temperature at MISO shows isotherm oscillations of more than 8m. Soliton like features appeared early and late in the day (around 320.05PST and around 320.9PST) with steep waves of depression followed by smaller undulations. There does not appear to be a relationship between the tide and the temperature at MISO.

The tide for November 16 was as follows:

High tide: 04:30PST (1.16m)

Low tide: 08:04PST (1.07m)

High tide: 13:26PST (1.41m)

The tidal range was therefore very low: 0.34m.

No large nonlinear internal waves were observed at the West-North-West station (R/V Martin). There were no sharp changes in isotherm depth; however there were gradual displacements of isotherms throughout the survey. From 320.45 to 320.55, the 12°C isotherm dropped approximately 8m. After 320.55, there was a homogenization of the water column at mid depth. The isotherms in the lower part of the water column dropped approximately 5m while isotherms near the surface rose approximately 5m.

Overall, the water column remained relatively still during the survey. The rapid isotherm displacements observed at MISO did not appear at that station. The homogenization of the water column at mid depth could be due to the advection of a different water mass.

At the North Station (R/V Point Sur), things were very different. In the first part of the survey, a soliton-like event was measured. There was a sharp drop of the isotherms, throughout the water column. From 320.423 PST to 320.443 PST, the isotherms at mid depth dropped nearly 10m. They returned to their original position by 320.441 PST so the period of this event was 0.43 hours. A smaller oscillation followed with 5m amplitude at 320.447 PST and yet another smaller one at 320.456 PST. This is typical of solitons which are usually rank-ordered (Sandstrom and Oakey 1995, Moum 2003). Later in the survey, around 320.477 PST, there was another small drop of the isotherms (6m) followed by smaller oscillations.

No data were collected between 320.578PST and 320.649PST (13:52PM and 15:33PM) because of technical issues and a different CTD profiler was used for the second part of the survey.

In the second part of the survey, more changes were observed in the water column. First of all, temperature throughout the water column was generally higher than in the first part of the survey. The mean temperature calculated between 10 and 40m depth was 0.34°C higher in the second part of the survey. This could be due to the advection of a colder water mass or, more simply to a bad calibration of the thermistor used in the second part of the survey.

Three internal waves were observed in the second part of the survey. The first one, the largest, started around 320.590 and ended at 320.611 (period: 0.48 hours). The amplitude was over 8m. Two other internal waves followed at 320.622 and 320.642, with amplitudes near 5m and periods in the 0.5 hours range. Again they were rank ordered. The amplitudes of the solitons observed on November 16, 2007 were about half the amplitude of the soliton observed of the outer shelf on November 17, 2006. The water was also about half as deep. However the periods were in the same range (0.4 hour). The most surprising finding of this survey is the big difference between the two stations. At the South West station, no solitons were observed, whereas at the North East station several solitons were observed throughout the survey. Figure 15 shows the temperature at 10m depth measured at the three stations and Table 1 shows the mean, the standard deviation, the minimum, the maximum and the range (all in °C) for the same data. The difference between the three stations is striking. At MISO, the temperature range was close to 2°C and the temperature changed gradually in a long period wave (over 5 hours). At the R/V Martin station, the temperature hardly changed during the survey. Most of the temperature variation is inherent to the sampling technique and background variability.

No clear oscillations were observed. For the Point Sur station, the standard deviation was much higher and significant oscillations were observed. But the period of these oscillations was much shorter than at MISO (near 30 minutes). There does not appear to be any relationship between the three data sets. Similar plots were made for other depths but no correlation was found.

Figure 14: Tide level and temperature measured at three different stations. No correlation appears between the stations. Several solitons appeared at the North station (R/V Point Sur) whereas none appeared at the West station (R/V Martin).

Table 1: Temperature measured from MISO, R/V Point Sur, and R/V Martin stations at 10m depth (in °C).

	Mean temperature	Standard deviation	Minimum temperature	Maximum temperature	Temperature range
MISO	12.97	0.63	12.25	14.12	1.87
R/V Martin	12.95	0.12	12.60	13.30	0.7
R/V Point Sur	12.93	0.40	12.15	13.79	1.64

Figure 15: Temperature at three stations, at 10m depth.

3.3 AUV surveys

3.3.1 First AUV survey, May 14-15, 2007

Figure 16 to 18 show the depth of the 10.1°C and 10.3°C isotherms along the AUV transect, over approximately 17 hours, during the May 14-15 overnight survey (see Figure 3 for location). The main features of these data are described below. Using a MATLAB® program, I divided the transects in 500m sections. For each section, the program calculated the isotherm depth, the layer thickness, the temperature gradient, the strain and the strain rate. Values calculated by this program are used in the description below.

Displacement of isotherms

Throughout the entire survey, isotherms were displaced up and down. The most rapid change occurred between transect 1 and transect 2. The isotherms at 1400mfip (meters from the inshore point) dropped 22m in approximately one hour. In transects 1 to 4, isotherms descended a lot (20m), especially is the inshore part of the transect. In transect 6 to 12, isotherms rose about 20m, starting from the offshore region. In the last few transects the isotherms dropped a little and stabilized as a whole. This long period oscillation appears very clearly on Figure 20 (third subplot), which shows the depth of the isotherms, averaged for each transect. This low frequency oscillation of the isotherms was likely due to an internal tidal bore propagating over the shelf. The sharp drop observed from transect 1 to transect 2 may have been the leading edge of the ITB. The wavelength of the tidal bore was longer than the transect so it is not possible to determine

it. It seems it propagated shoreward across the shelf because the rise of the isotherms in the offshore part of the transect was followed by their rise in the inshore part. However it is not possible to tell whether it comes from the West (outer bay shelf break) or the North (Monterey Bay canyon).

Change of layer thickness (thermal gradient)

The thickness of the layer between the two isotherms also changed rapidly during the survey. For example, the layer thickness at 2750mfip (meters from inshore point) in transect 4 was 20m. Six hours later, it was reduced to 4m, and 11hours later, it was less than 1m. These changes were probably due to the advection of water masses with different density structures. They could also have been due to mixing caused by high-mode internal waves.

The lowest thermal gradient averaged over 500m was $0.01^{\circ}\text{C}/\text{m}$, between 2500 and 3000mfip in transect 4. The highest was $0.33^{\circ}\text{C}/\text{m}$, between 4000 and 4500mfip in transect 17. The average thermal gradient for the entire survey was: $0.053^{\circ}\text{C}/\text{m}$.

Solitons

Against our expectations, no large solitons were observed during the survey. However, many small internal oscillations were observed. It is interesting to note that when the isotherms were closer (higher temperature gradient, higher buoyancy frequency), more high frequency solitons were observed (transect 2 to 6, between 0 and 2000mfip, transect 12 to 13, near 700mfip, transect 16 to 18 near 3500mfip). In transect

2, a packet of small solitons (amplitude > 5m, wavelength 100m) was observed near 700mfip (meters from inshore point). In transect 4 and 5, a soliton (amplitude 6m, wavelength 200m) was observed near 700mfip.

Only one soliton was clearly seen propagating through the transect. It first appeared at 2750fip in transect 11, then in transect 12 (at 2200mfip), 13 (at 1600mfip) and 14 (at 1000mfip). Its amplitude was near 6m. Further proof that it was propagating shoreward, its wavelength appeared shorter when the AUV was going towards the offshore point, because of the Doppler shift effect. This is particularly clear on transects 12 to 13. The phase speed of this soliton, assuming it was traveling exactly in the direction of the transect is: $(2750m - 1000m)/(12.4h - 9.5h) \times 3600s = 0.17m/s$.

On transects 15 to 20, a packet of solitons appeared near the offshore point. The amplitudes were 5-10m. It also appeared to be propagating shoreward.

Fronts

Relatively sharp boundaries between water masses with different properties appear in the data. In transects 1 to 7 a front appeared near the middle of the transect. In transect one, it was near 2500mfip (meters from inshore point). It slowly moved inshore to 2000mfip (transect 4) then moved offshore to 2500mfip. It moved onshore again in transect 7, and then disappeared. It moved shoreward, then seaward, so it probably wasn't an internal wave. The density structure was very different on either side of the front.

For example, on transect 4, offshore of this front, the average thermal gradient was

low ($0.01^{\circ}\text{C}/\text{m}$) and onshore of the front, it was much higher ($0.08^{\circ}\text{C}/\text{m}$). Also the isotherm depth was very different. The 10.1°C isotherms onshore of the front was on average 10m (and up to 25m) deeper than offshore of the front. These were clearly different water masses. This front may have been associated with an eddy.

Figure 16: May 14-15 AUV survey, transects 1 to 5.

Figure 17: May 14-15 AUV survey, transects 6 to 10.

Figure 18: May 14-15 AUV survey, transects 11 to 15.

Figure 19: May 14-15 AUV survey, transects 16 to 20.

Comparison with MISO data

Figure 20 shows the tide level, the temperature at MISO and the isotherm depth measured by the AUV, averaged over each transect. A strong correlation appears between the three data sets. I compared the data sets using the cross-correlation function. I interpolated the data sets to the same sampling frequency and standardized them by removing the mean and dividing by the standard deviation. I then calculated the cross correlation.

The time lag between tide and temperature measured at MISO at 0.6m (8.5m) above the sea floor is 3.7 hours (3.1 hours). The standardized cross correlation coefficient is -0.24 (-0.21). It is negative because a rise in sea level corresponds to the decrease in temperature.

The time lag between the 10.4°C isotherm depth measured by the AUV and the temperature measured at MISO at 0.6m (8.5m) above the sea floor is 1.9 hours (0.1 hours). The standardized cross correlation coefficient was -0.36 (-0.68). It is negative because a rise of the isotherms corresponds to the decrease in temperature.

The time lag between tide and the 10.4°C isotherm depth measured by the AUV is 3.4 hours. The standardized cross correlation coefficient is 0.57. It is positive because a rise in sea level corresponds to a rise of the isotherms.

Figure 20: Tide level, temperature measured at MISO and temperature measured by the AUV on the mid-shelf.

3.3.2 Second AUV survey, August 27-28, 2007

Figure 21 to 23 show the depth of the 12.0°C and 12.4°C isotherms along the AUV transect, over approximately 17.5 hours, during the august 27-28, 2007 overnight survey (see figure 3 for location). The main features of these data are described below.

Displacement of isotherms

Vertical isotherm displacements were more gradual than for the first AUV survey.

There were no sharp changes. In the first 6 transects, the isotherms gradually dropped approximately 6m but remained fairly level along the transect. From transect 7 to 11, isotherms remained in the same depth range. From Transect 12 to the last transect, isotherms were displaced up nearly 20m (25m in one region) but still remained fairly flat. This general rise of the isotherms can be seen in Figure 25, which shows the depth of the isotherms averaged for each transect. This rise was probably due to the end of an ITB. The leading edge of the ITBs had probably gone through the transect just before the survey started. It seems that the rise of the isotherms started at the offshore point and propagated inshore, but this is not very clear. Near the end of the survey, it occurred over the entire transect simultaneously. This is likely because the wavelength of the ITB was much longer than the transect. It could also be because the ITW came from the north (Monterey Bay Canyon) and propagated nearly perpendicularly to the transect.

Changes of layer thickness (thermal gradient)

Changes of the layer thickness were lower and more gradual in this survey. In the first six hours of the survey, the thermal gradient increased slowly and was fairly homogeneous along the transect. In the following transects, there were more variations. A region of low thermal gradient appeared near 2250mfip (meters from inshore point) and slowly moved onshore from transect 10 to transect 15. A region of high thermal gradient appeared near 2500mfip and remained there for the rest of the survey.

The lowest thermal gradient averaged over 500m is $0.04^{\circ}\text{C}/\text{m}$, between 1500 and 2000mfip in transect 12. The highest is $1.14^{\circ}\text{C}/\text{m}$, between 2000 and 2500mfip in

transect 14. The average thermal gradient for the entire survey was: $0.11^{\circ}\text{C}/\text{m}$. This is much higher than for the May 14 survey.

Solitons

Only a few small solitons were observed during this survey. On transects 12 to 14, a packet of solitons appeared near the center of the transect but it quickly disappeared. In transect, 15, the isotherms were essentially flat. The amplitude of the solitons did not exceed 4m.

Fronts

A front started to develop in transect 8, near 3500mfip (meters from inshore point). It slowly moved inshore and became steeper. In transect 11, the front was at 1500mfip. In transect 14, the thermal gradient inshore of the front was $0.04^{\circ}\text{C}/\text{m}$, and $1.1^{\circ}\text{C}/\text{m}$ offshore of the front. These were clearly two different water masses. Strangely, the 12.4°C isotherm was 10m lower onshore, whereas the 12.0°C isotherm was at the same depth as on the offshore side of the front.

From transect 15 to 17 the front moved offshore a little and dissipated. The front was not caused by internal waves because it propagated in both directions and even stayed in the same location for a while.

Figure 21: August 27-28 AUV survey, transects 1 to 5.

Figure 22: August 27-28 AUV survey, transects 6 to 10.

Figure 23: August 27-28 AUV survey, transects 11 to 15.

Figure 24: August 27-28 AUV survey, transects 16 to 19.

Comparison with MISO data

MISO was out of service during this survey, so no comparison is possible. However, the AUV data are compared with the tide level measured by the Monterey harbor tide station in Figure 25. The lower plot represents the isotherm depth averaged for each transect. There did not appear to be strong relationship between the two signals. Around 240.0 PDT, the tide level dropped nearly 1.5m. Shortly after the tide level started dropping, the isotherms were rapidly (6 hours) displaced up nearly 20m.

Figure 25: Tide level and temperature measured with the AUV on the mid-shelf on august 27-28 2007.

3.3.3 Third AUV survey, November 26-27, 2007

Figure 26 to 28 show the depth of the 11.2°C and 11.6°C isotherms along the AUV transect, over approximately 14.5 hours, during the November 26-27 overnight survey. Technically speaking, this survey was not as successful as the previous ones. Because the stratification was much lower, the AUV did not follow the thermocline as precisely, and the sampling rate (number of times the AUV crosses the thermocline during one transect) was much lower. The temperature band should have been lowered to 0.2°C instead of 0.4°C. Twice during the survey, the thermistor produced bad data, which caused the AUV to go deeper than the temperature bound. Finally, the extremities of the transect were sometimes cut off, for unknown reasons.

The main features of the data are described below.

Displacement of isotherms

Once again, there were large isotherm displacements throughout the entire survey. The displacements were more localized than in the previous surveys. The 11.2°C isotherm rose up to 22m over the first nine hours of the survey, mostly in the inshore half of the transect. It then dropped nearly 15m in the inshore half of the survey while it rose rapidly in the offshore half. Between transect 13 and 15, the 11.2°C isotherm rose over 20m at 3000mfip (meters from inshore point). This rise of the isotherms observed in the last three transects might be due to an ITB propagating perpendicular to the transect. The maximum amplitude of the displacement was observed at 3700mfip. Between transect 7 and 15, the 11.2°C isotherm rose 35m.

Change of layer thickness (thermal gradient)

The thickness of the layer between the two isotherms also changed rapidly throughout the survey. For example, the layer thickness at 500mfip (meters from inshore point) in transect 4 was 32m. Eight hours later, it was reduced to 6m. These changes were probably due to the advection of water masses with different density structures. In the offshore part of the transect, near 3000mfip, the 25 meter layer observed in transect 8 was essentially gone in transect 15. This rapid change of the density structure can be explained by the arrival of a large ITB or the advection of a water mass with a different density structure. It could also be due to mixing caused by internal waves.

The lowest thermal gradient averaged over 500m was $0.01^{\circ}\text{C}/\text{m}$, between 500 and 1000mfip in transect 3. The highest was $0.0542^{\circ}\text{C}/\text{m}$, between 0 and 500mfip in transect 12. The average thermal gradient for the entire survey was: $0.02^{\circ}\text{C}/\text{m}$. This was much lower than for the May 14 and August 27 surveys.

Solitons

No solitons were observed during this survey. It is possible that solitons with small wavelengths were not sampled because the sampling rate was low in this survey.

Fronts

No fronts were observed during this survey.

Figure 26: November 26-27 AUV survey, transects 1 to 5.

Figure 27: November 26-27 AUV survey, transects 5 to 10.

Figure 28: November 26-27 AUV survey, transects 11 to 15.

Figure 29: November 26-27 AUV survey, transects 16 to 17.

Comparison with MISO data

Figure 30 shows the tide, the temperature at MISO and the isotherm depth measured by the AUV, averaged over each transect. The low tide at 330.67PST is followed by an ITB as MISO, peaking approximately 2 hours later. There does not appear to be a strong relationship between MISO data and the AUV data.

Figure 30: Tide level, temperature at MISO and temperature measured with AUV on mid-shelf during November 16-27 survey.

3.3 *Summary of results*

The main objective of this study was to show that internal waves observed at MISO are generated at the shelf break and propagate up the shelf. We attempted to sample internal waves at different locations as they propagate up the shelf. We partly succeeded in doing so.

During our first shipboard survey on R/V Point on November 17, 2006, we sampled a large soliton (16m amplitude, 21min period) near the shelf break. Its location matched the prediction we had made using data from MISO and from a 2005 shipboard survey. This may have been accidental. There did not appear to be a strong relationship between that soliton and internal waves at MISO. Also during this survey, signs of an internal tidal bore were observed on the mid-shelf, matching an internal tidal bore at MISO. This internal tidal bore lagged the tide by approximately 2 hours.

During the second shipboard survey, on R/V Point Sur and R/V Martin on November 16, 2007, no relationship was found between internal waves at MISO, internal waves at both stations on the mid-shelf and the tide. Several solitons (period near 30min, amplitude up to 8m) were observed at the north station (R/V Point Sur), probably coming from the head of Monterey Canyon. These solitons did not appear at the West station (R/V Martin). Meanwhile, a long period internal wave was observed at MISO. It did not appear offshore, which suggests it was generated locally. The low tide amplitude and low stratification that day may explain why no internal tidal bore propagated across the shelf.

On May 14-15, 2007 a large internal tidal bore (25m amplitude, 13 hour period) was sampled both at MISO and on the mid-shelf by the AUV (see figure 3 for location). This internal tidal bore lagged the barotropic tide by about 3 hours and appeared on the inner shelf shortly after it appeared on the mid-shelf. A few small solitons were also observed. One soliton was observed propagating along the transect at 0.17m/s. A sharp front was observed, possibly due to an eddy. The density structure changed dramatically throughout the survey, probably because of the advection of different water masses. Mixing caused by internal waves may also have been a factor.

During the second AUV survey, on August 27-28 (see figure 3 for location), a large internal tidal bore (amplitude over 20m) was observed over the mid-shelf. It did not appear to be directly correlated with the tide. Very few solitons were observed. As in the first AUV survey, a front was observed, separating water masses with very different density structures.

During the last AUV survey, on November 26-27, 2007 (see Figure 3 for location), isotherm displacements of up to 35m were observed along the transect. There was no apparent relationship between tide, internal waves at MISO, and internal waves on the mid-shelf. No solitons or fronts were observed.

4 Discussion

4.1 Solitons

Short period solitons are a common feature on the continental shelf from spring to fall. At MISO they appear on a regular basis, usually as components of solibores. On the mid and outer shelf, they were observed during most surveys. Waves of depression are usually observed in regions where the layer of water above the pycnocline (h_1) is thinner than the layer below it (h_2) (see section 1.3 for more details). The shape changes to a wave of elevation when the pycnocline is in the lower half of the water column (Liu et al., 1998, Orr 2003, Ramp, 2004). The continental shelf can therefore be divided in three regions. In the first region, the farthest offshore, h_1 is thinner than h_2 . Waves of depression are expected there. All the shipboard and AUV surveys were carried out in that region. All the solitons we sampled in that region were waves of depression (Table 2). In the second region, h_1 is thicker than h_2 , and waves of elevation are expected. We did not make any measurements in that region, except for a few CTD profiles in the early part of the first survey on R/V Point Sur. In the third region, near the coast, the water depth is less than h_1 . MISO is in that region, and waves of elevation are observed there. The fact that most of our observations agree with this aspect of nonlinear internal wave theory is encouraging. It supports the idea that models can be used to predict the evolution of internal waves over the shelf. The solitons we sampled offshore were more linear than solitons at MISO. Some small solitons measured by the AUV during the first two surveys even had nearly sinusoidal shapes (Table 2). As they approach shallower water they become more nonlinear. It would be interesting to make measurements with

the AUV in the region where $h_1 > h_2$, to observe internal waves evolving from waves of depression to waves of elevation. This is difficult because the AUV cannot operate in shallow water without supervision of a ship, for safety reasons, so long overnight surveys are not possible. Also, the AUV cannot sample the lowest 5 meters of the water column, where most of the energy is transferred as can be seen in the data from MISO.

Solitons packets evolve to be rank-ordered, as the tallest waves propagate fastest (Sandstrom and Oakey, 1995). This was the case for the soliton packets observed from R/V Martin on November 16 2007. This suggests that the waves were observed some distance from their generation sites since rank-ordering requires some time for dispersion to take effect. These solitons were probably generated at the shelf break or farther offshore. The solitons packets observed by the AUV on May 15 2007 were not rank-ordered, their shape was more sinusoidal and their amplitude smaller. Furthermore, in at least one case, the soliton packet seemed to appear inside the transect, propagate for about 3 km and dissipate (figure 17). This may suggest that solitons are generated on the shelf but also evolve and dissipate rapidly. Solitons may be formed as part of the dissipation of internal tidal bores, as suggested by Carter (2005). In some cases, the soliton packets appeared and disappeared rapidly inside the transect, probably because they were propagating perpendicularly to the transect.

Several times during the AUV surveys, solitons were observed propagating along the transect. One soliton was observed propagating along the transect at 0.17m/s (Figure 18).

This matches observations made by Carter (2005), who measured solitons velocities near 0.15-0.22m/s on the shelf.

During our first shipboard survey, we attempted to detect an internal wave and track it to sample it a different locations along its path. Then on the second shipboard survey, we attempted to sample an internal wave at two locations, by using two ships. However, we did not succeed in sampling a recognizably similar feature at different stations. This technique is probably suitable for large scale oscillations of isopycnal caused by internal tidal bores but does not work for short period solitons because they evolve and dissipate too rapidly.

Table 2: Characteristics of solitons and stratification for each survey.

	H1	H2	Type of soliton	Rank ordered	Amplitude
11/17/06 R/V Point Sur	18m	77m	Nonlinear waves of depression, Amplitude	Yes	16m
11/16/07 R/V Point Sur	12m	38m	Nonlinear waves of depression	Yes	8m
11/16/07 R/V Martin	12m	51m	No solitons	N/A	N/A
05/14/07 AUV 1	19m	62m	Nearly sinusoidal solitons	No	4m to 10m
08/27/07 AUV 2	22m	63m	Few solitons. Nearly sinusoidal	No	4m
11/26/07 AUV cruise 3	18m	67m	No solitons	N/A	N/A

4.2 Internal tidal bores

Internal tidal bores are the dominant features observed at MISO and during the AUV and shipboard surveys. They appear at MISO from spring to fall, with varying intensity. During the first shipboard survey, and during all the AUV surveys, ITBs were sampled. The main hypothesis tested in this study was that the semi-diurnal temperature oscillations observed at MISO are internal tidal bores that propagate onshore from the outer shelf. Data collected with the AUV show that it was the case on May 14-15. On that day, a strong ITB occurred at MISO (figure 19). Meanwhile, isopycnals oscillated at the same frequency on the mid-shelf (figure 19), leading the ITBs at MISO by approximately 1 hour. The correlation with the barotropic tide was also strong (see results), the tide led the isopycnal oscillation by approximately 3 hours. Also, during the first shipboard survey on R/V Point Sur (November 2006), we sampled part of an internal tidal bore on the mid-shelf. It appeared at MISO less than an hour later, following a similar pattern as during the AUV survey. The ITB was also highly correlated with the barotropic tide, with a 2 to 4 hour phase lag. One explanation is that the barotropic tide generated an internal tide offshore (at the shelf break or even farther offshore) which propagated shoreward. It was first sampled by the AUV on the mid-shelf, and shortly after at MISO. The rise of the isopycnals in the offshore part of the AUV transect was followed by their rise in the inshore part, another piece of evidence that the ITB was traveling shoreward.

Crabbe (2007) suggests that ITBs at MISO originate at the head of the Monterey Canyon. Figure 31 shows temperature at 12m depth at MISO, and temperature measured

at the Moss Landing Marine Laboratories' seawater intake, near the head of the Canyon at 20m depth. These data show that ITBs also appeared at the head of the Canyon and the correlation between the two signals was strong. If the ITBs originated near the head of the Monterey Canyon, they would appear at the seawater intake before they appear at MISO. But this is not the case. In fact, the oscillations appeared at MISO a little bit earlier than at MLML's seawater intake. This shows that the ITB propagated from West to East and not from North to South. This suggests that the effect of the Canyon may be less important for the generation of ITBs than previously thought. It is possible that much of the internal tidal bore energy comes from the outer Bay. The ITB signal at MLML's water intake is more regular than the one at MISO and amplitudes are also greater (this is a trend observed for the entire record). This is probably because the water intake is at 20m depth, whereas MISO's deepest sensor is at 12m depth, usually shallower than the thermocline where the energy is strongest.

Data from the August 27-28 and the November 26-27 AUV surveys are more difficult to interpret. The ITB sampled on the mid-shelf by the AUV on August 27-28 had a period longer than the entire survey (18 hours) and the relationship with the tide did not appear as clearly as for the first AUV survey (Figure 25). Furthermore, MISO was out of service at that time, so I am unable to compare this event with events on the inner shelf. During the November 26, 2007 AUV surveys, isotherm displacements of up to 35 meters were observed but they did not appear to be directly related to the tide (Figure 30). Because of cold, stormy weather in November, the stratification was weak, and internal

wave propagation was altered.

Results from the November 16, 2007 survey do not show a clear propagation pattern either. A bore (5 hour period) was observed at MISO, but it did not appear offshore, suggesting that it was generated on the inner shelf (Figure 15), or that small, linear oscillations observed on the midshelf from R/V Martin were amplified and became nonlinear as they propagated up the shelf. Several solitons were sampled. Soliton packet observed at the North station did not appear at the West station, so it is possible that they were travelling southward, along the coast. Results from this survey and the May 14-15 AUV survey are very different because of weaker stratification and the very small tidal range during the November 16 survey.

Broenkow and McKain (1972) calculated that the wavelength of the internal tide in Monterey Canyon was between 8.9 and 13.4 km and the phase velocity between 0.2 and 0.3 m/s. Rosenfeld calculated the wavelength was near 30km (Rosenfeld 1999) and the phase velocity near 0.5m/s. I calculated it took approximately 2 hours or less (see results section) for the ITB to propagate from the AUV transect to the shore. Given that the distance from the transect to the shore was about 5 km, and that the period was approximately 12 hours, this implies a phase speed near 0.7m/s and wavelength near 30km. These estimates are very coarse, as it is difficult to accurately calculate the phase lag between AUV data and MISO data with only an 18 hour record.

Given the long period and wavelength, and given that it propagates from West to East, it is possible that the internal tide is generated far offshore. The generation mechanism

and region are probably the same for ITBs observed at MISO and MLML's water intake.

Figure 31: Temperature at MISO at 12m depth and temperature at MLML's seawater intake, near the Monterey Canyon head. The mean was removed from both signals.

To investigate the relationship between the tide and ITBs at MISO, I calculated the correlation between the temperature and the tide level measured at MISO. I did this for a 20 day period of 2006, and four 30 day periods of 2007. I also calculated the autocorrelation of the temperature signal. The results of this analysis are summarized in Table 3 and Table 4. The temperature's autocorrelation is fairly strong and consistent during the year (Table 3). The average autocorrelation lag for the five data sets is 24h54min (with standard deviation about 30 minutes), which is very close to the mixed tide's 24h50min cycle. This is because the ITBs follow the barotropic tide's cycle.

Table 3: Autocorrelation of temperature at MISO for five 30 day periods.

	0.6m above bed		4.3m above bed		8.6m above bed	
	Lag (h)	Coefficient	Lag (h)	Coefficient	Lag (h)	Coefficient
May-07	24.2	0.28	23.7	0.32	23.9	0.36
July-07	25.2	0.32	24.6	0.21	24.5	0.15
September-07	24.25	0.33	24.4	0.35	25.5	0.2
November-06	24.7	0.11	25.4	0.13	24	0.17
November-07	24.5	0.21	25	0.32	24.3	0.34

ITBs are generated by the tides, so one would expect a strong correlation between the temperature and the tide. It does not appear to be the case (Table 4). Correlation coefficients are generally low, and there is no dominant lag. Even at different depths for the same period, the lags show a high discrepancy, especially for May and July. This is probably because the lag varies so much over 30 days. For November 2006, September and November 2007 the lags are more consistent, with the tide leading the temperature by approximately one hour. The correlation coefficients are still low.

Table 4: Cross correlation of tide and temperature at MISO for five 30 day periods.

	0.6m above bed		4.3m above bed		8.6m above bed	
	Lag (h)	Coefficient	Lag (h)	Coefficient	Lag (h)	Coefficient
May-07	-7	-0.3	-2	0.33	-3.3	0.47
July-07	-0.56	-0.22	-2	-0.13	-11	0.3
September-07	0	-0.27	-0.5	-0.24	-0.1	-0.2
November-06	2	-0.2	1	-0.19	0.6	-0.3
November-07	1.95	-0.4	0.8	-0.41	0.5	-0.47

This weak correlation between the barotropic tide and the internal tide has been observed many times before. Studies show that internal tides in Monterey Bay and along the California coast are highly variable and not locked consistently with the surface tide (Broenkow 1972, Pineda 1994, Carter 2005, Crabbe 2007). The authors of these studies all suggest that the changes of stratification on seasonal scales are responsible for this weak correlation, because conditions for generation and propagation of internal tides depend directly on stratification. The data from the AUV surveys show that the stratification varies not only on seasonal scales (see thermal gradients in Table 5), but also on hourly scales. During the three AUV overnight surveys, the density structure of the water column changed dramatically over just a few hours (see AUV surveys result section for details). For example, during the first AUV survey, the thickness of the layer between the 12.0°C and 12.4°C isotherms changed from 20m to 4 m in 6 hours in one region of the transect. Similarly, during the third AUV survey, the thickness of the layer

between the 11.2°C and 11.6°C isotherms changed from 32m to 6m in 8 hours. These changes were probably due to the advection of different water masses. Fronts were also associated with these rapid changes (see AUV results section for description of these fronts). These density changes and fronts may have been the result of mesoscale and submesoscale eddies. The fronts observed in the AUV data may have been edges of eddies. No satellite data were available to compare with AUV data to verify this hypothesis. Eddies can be generated at the inshore side of the California along-shore current and advect cold water into the Bay (Warn-Varnas et al., 2007). Submesoscale eddies can also be generated within Monterey Bay. They have life times of 4 to 12 hours and scales near 10km (Ivanov, 2004). They induce flows which play a significant role in the exchange of water properties on the shelf (Ivanov, 2004). This may explain the rapid changes in density structure, and the high variability of ITBs: mesoscale eddies affect generation of ITBs at the shelf break or farther offshore, and submesoscale eddies affect the propagation of ITBs on the shelf.

In addition, ITBs generated at different sites could occur simultaneously in a single location as suggested by Pineda (1994), further increasing the variability of observations. Some of the stratification changes could also be caused by turbulent mixing associated with breaking internal waves. This is difficult to quantify and beyond the scope of this study.

4.3 Are AUVs efficient tools for sampling internal waves?

Oceanographers and ocean technologists are always looking for more effective ways to make measurements in the ocean. Sampling internal waves is particularly challenging, because of the generally unpredictable and complex nature of these features. Existing techniques either yield very detailed information at a single location (bottom mounted sensors or moorings) or limited information for several locations (shipboard measurements, images from airplanes and satellites). Sampling from a moving ship as we did on our first cruise (November 17, 2006) is not efficient because much time is wasted while going from one station to the other, and it is difficult to link the events observed at the different stations. Also, very little time is spent at each station. Observations from space and from airplanes only give indications on the wave's surface expression. AUVs can be a solution to make detailed measurement over large areas.

One of the main goals of this study was to develop and test a new technique for sampling internal waves, using MBARI's CTD AUV. It was programmed to sample repetitively along a transect between two way points. Instead of the usual sawtooth pattern between depth bounds, the AUV was programmed to stay within temperature bounds, thereby following a given isotherm. This technique had several advantages over shipboard surveys. The AUV surveys lasted up to 18 hours, whereas shipboard surveys only lasted a few hours. This is important because ITBs had periods near 12 hours. During the first survey, we were able to capture an entire ITB (Figure 20). A longer survey would be even better, ideally covering several tide cycles. This would be especially helpful for later comparison of the data with longer time series such as MISO.

The AUV transect length was approximately 4.5km. This was chosen for several reasons. Firstly, 4.5km was long enough for capturing an entire packet of solitons and a significant distance before and after it, allowing some ability to determine propagation along the transect (the soliton we sampled from R/V Point Sur had a wavelength near 400m, so for a possible packet of five solitons, the length would be approximately 2 km). Secondly, 4.5km was a reasonable distance for the AUV to navigate without coming to the surface for a GPS fix. Finally, 4.5km was the distance the AUV could cover in approximately one hour, a convenient figure. It proved to be an appropriate length. Even though it was not long enough to cover the entire wavelength of ITBs, it was enough to see its progression along the transect. The isopycnals in the offshore part of the transect were displaced shortly before they were displaced in the inshore part. This would not have been observed with a shorter transect. A longer transect, going as far as the shelf break, or even farther offshore could yield some interesting information about the evolution of ITB over the shelf, but the resolution would be very low. In some cases, isopycnals were displaced so rapidly that the difference between one transect and the next was difficult to interpret. With a longer transect, the resolution would be even lower. This problem could be solved by using faster vehicles or by using several vehicles, each covering portions of a long transect.

For the AUV to sample internal waves efficiently, it must stay near the thermocline. The AUV's ability to do so depends on two factors: proper pitch angle and reactivity to temperature changes.

The AUV's pitch angle must be greater than the steepest possible slope of the

thermocline, to avoid intersection of internal waves. According to a model based on KdV equations, for conditions typical of Monterey Bay when stratification is high (summer and early fall), the slope can reach 13° (Figure 32). Therefore the AUV's pitch angle should not be lower than 13° . We set the pitch angle to 20° for the first survey, and it appears to have worked very well. Figure 33 shows the AUV path and the isotherms corresponding to the AUV's temperature bounds. Between 1000m and 1500m, the AUV sampled a steep soliton. The pitch was still much higher than the slope of the soliton, so it was properly sampled. Lowering the AUV's pitch angle would increase the horizontal velocity of the AUV, thereby covering more distance during a survey. But from a 20° pitch angle to a 15° pitch angle, the vertical velocity is increased by only 2%, so it is probably better to use a 20° pitch. Another factor to take into account when selecting the pitch angle is the AUV's steering capability. During the first survey, with a 20° pitch angle, the AUV sometimes stalled out and lost steerage, so we reduced it to 15° for the upcasts for the last survey.

Figure 32: The upper plot shows a KdV model of a nonlinear internal wave for conditions typical of Monterey Bay in late summer. The lower plot shows the slope of the same wave.

The AUV must react quickly to temperature changes to stay within its temperature bounds. In that respect, the AUV performed very well. On average it went over or below the temperature bounds by approximately 2m (Figure 33, Figure 34 and Figure 35). At one point of the last survey, the CTD produced bad data, so the AUV went far below the lower temperature bound, until it reached the altitude limit.

I calculated that the CTD had a 1 second lag (see methods part). Reducing this lag would improve the AUV's reactivity to temperature changes only slightly. In 1 second, the AUV's vertical displacement is only 0.5m/s (with pitch=20°C and velocity=1.5m/s). The overshoot is probably mostly due to the AUV's inertia and the limited steerage capability.

To select the temperature bounds, we ran short surveys with a depth bound sawtooth behavior, we analyzed the data to determine the thermocline depth, and we selected the depth bounds accordingly. It is important to adjust the temperature band width depending on the thermal gradient. In the second survey, although the band width was half of what it was for the first survey, the sampled layer of water was thinner (Table 5). For the third survey, the band width was much too high for the stratification conditions, so the AUV did not stay near the thermocline. The thermal gradient for the third survey shown in Table 5 is very low because of the lower stratification, and also because it was calculated over 15.68m, instead of near the thermocline, like the first two surveys.

The profiling rate depends directly on the temperature band and the AUV's pitch angle. With a narrow temperature band, the profiling rate is higher. For the May and August surveys, the sampling rate was much higher than for the November survey (Table 5, Figure 33, Figure 34, and Figure 35). A high sampling rate is necessary to get a precise image of the isotherms and to capture small and steep features. To increase the sampling rate, the temperature band width could be lowered.

Table 5: Characteristics of AUV profiles. The temperature band width is the difference between the upper and the lower temperature bounds used for the AUV's profiling behavior. The average layer thickness, thermal gradient and profiling rate were averaged for entire surveys.

	Temperature band width ($^{\circ}\text{C}$)	Average layer thickness (m)	Average thermal gradient ($^{\circ}\text{C}/\text{m}$)	Profiling rate (profiles/km)
AUV survey 1	0.2	7.87	0.05	35
AUV survey 2	0.4	5.70	0.11	30
AUV survey 3	0.4	15.68	0.02	10

Figure 33: Actual AUV path and temperature bounds during the first survey. The black line shows the actual path of the AUV during the first transect of the first AUV survey. The blue line and the red line represent the lower and the upper temperature bounds. The AUV followed the isotherms very accurately, even during a steep soliton (between 1000m and 1500m).

Figure 34 Actual AUV path and temperature bounds during the second survey. The black line shows the actual path of the AUV during the second transect of the second AUV survey (August). The blue line and the red line represent the lower and the upper temperature bounds.

Figure 35: Actual AUV path and temperature bounds during the third survey. The black line shows the actual path of the AUV during the fourth transect of the third AUV survey (November). The blue line and the red line represent the lower and the upper temperature bounds. The thermal gradient was low so the AUV sampled a thick layer of the water column.

Some improvements could be made to the AUV's software to increase the sampling efficiency. One fairly simple improvement could be to automatically detect the thermocline and set the temperature bounds, at the beginning of the survey. This would save time and allow a deployment from a distance (from a docking station for instance). The AUV would first navigate to the survey region. It would then make a few depth bound profiles, and calculate the thermal gradient and the thermocline depth. Depending on the thermal gradient and other preset parameters, it would then calculate the optimal temperature bounds, and start the survey.

Ultimately, an AUV could detect an internal wave, and adapt its course to track it and make biological and chemical measurements about it. This is probably too difficult to achieve in Monterey Bay, because internal waves are unpredictable, and their shape evolves as they propagate. Features such as fronts could easily be mistaken for internal waves. Also, tracking an internal wave would require knowing its direction of propagation. Tracking an internal wave may be possible in places like the Luzon Strait in the South China Sea, where internal waves are highly predictable and steep (Ramp, 2004).

The main drawback of our sampling technique is that it does not yield the direction of propagation of internal waves. This problem could be solved by using two or more vehicles running, along different transects. Finding the ideal configuration is a study topic in itself. One vehicle running on a triangle, rectangle and V shaped transect, could also do the job, but its speed should be at least doubled to avoid undersampling.

One can only imagine what internal wave surveys will be like a few years from now: a

flock of mini AUVs, running at 3m/s for one week surveys, assisted by satellites or unmanned aircraft that detect internal wave slicks and send the information to the AUVs when they come to the surface for GPS fixes. Scientists could also supervise these tireless workers from the comfort of their office, by using satellite communication.

Overall, the sampling method was very effective. It gave very detailed information about isotherm displacements, and changes of the density structure near the thermocline. I was able to identify internal waves and calculate their amplitudes, phase velocities, and wavelengths. After processing of the data, I was able to calculate the thermal gradient, the strain, and strain rate along isotherms. I am not aware of other techniques that could yield such data. AUVs have the potential to reveal much more information about internal waves, by using ADCP, chemical and biological sensors, and by making improvements to the sampling method, as recommended in this section.

5 Conclusion

Internal tidal bores and solitons were the dominant feature observed during this study. We observed ITBs during all five surveys. On the mid-shelf, their amplitudes ranged from 20m to 35m and periods ranged from 5 hours to over 18 hours. In at least one case (May 14-15, 2007), we observed an ITB clearly propagating eastward, originating at the shelf break or farther offshore and becoming increasingly nonlinear as it propagated up the shelf. In that case, phase locking with the tide was strong. In other surveys, propagation direction and phase locking with the tide were not as clear.

Solitons were also observed during all surveys. Their amplitudes ranged from 4 meters to 16 meters and periods were usually near 30 minutes. No definite propagation pattern was recognized. Some solitons appeared to be generated on the shelf, possibly as part of the dissipation of ITBs.

During AUV surveys, the density structure changed dramatically. The thermal gradient at the thermocline sometimes increased or decreased more than ten fold within less than a tide cycle. Fronts separating water masses with very different density structures were present intermittently during the surveys. These fronts may have been the results of eddies generated inside and outside of Monterey Bay. These rapid changes in stratification affect internal wave generation and propagation. This explains, at least partly, the high spatial and temporal variability of internal waves on the shelf.

This study showed the complexity of the internal wave field in Monterey Bay. There is still much to be learned. For future research, I suggest a thorough analysis and comparison of long temperature and current time series from Stillwater Cove, MISO and

MLML's seawater intake, which all show similar ITBs. Longer AUV surveys would yield very useful data for understanding the evolution of ITBs on the shelf. AUV surveys should also be carried out in other regions of the shelf: on the inner shelf, near the shelf break and in North Monterey Bay. Analysis of internal wave slicks, using images from satellites or aircraft, would help to better understand the propagation patterns in Monterey Bay. Ultimately, remote sensing from aircraft, satellite or sonar could be coupled with in-situ AUV measurements. Finally, the biological and geological impacts of internal waves on the Monterey Bay shelf should be investigated.

References

Azetsu-Scott K., Johnson B.D., Petrie B., 1995. An intermittent, intermediate nepheloid layer in Emerald Basin, Scotian Shelf. *Oceanographic Literature Review*, 1995. Elsevier Science.

Baines P. G., 1974. The Generation of Internal Tides over Steep Continental Slopes. Philosophical Transactions of the Royal Society of London. Series A, *Mathematical and Physical Sciences*, Vol. 277, No. 1263 (Jul. 18, 1974), pp. 27-58.

Bellingham J., Rajan K., 2007. Robotics in Remote and Hostile Environments. *Science magazine*. November 16, 2007 issue.

Bogucki D., Dickey T., Redekopp L.G., 1997. Sediment Resuspension and Mixing by Resonantly Generated Internal Solitary Waves. *Journal of Physical Oceanography*.

Bourgault D., Blokhina M.D., Mirshak R., Kelley D.E., 2007. Evolution of a shoaling internal solitary wavetrain. *Geophysical Research Letters*, Volume 34, Issue 3.

Broenkow W., McKain S., 1972. Tidal oscillations at the head of Monterey Submarine Canyon and their relation to oceanographic sampling and the circulation of water in Monterey Bay. *Moss Landing Marine Laboratories Technical publications*.

Butman, B., Alexander, P. S., Scotti, A., Beardsley, R. C., Anderson, S., 2006. Large internal waves in Massachusetts Bay transport sediments offshore. *Continental Shelf Research*, Volume 26.

Cacchione D.A., Drake D.E., 1986. Nepheloid layers and internal waves over continental shelves and slopes. *Geo-Marine Letters* (1986).

Cacchione D. A., Pratson L. F., Ogston A. S., 2002. The Shaping of Continental Slopes by Internal Tides. *Science*, 26 April 2002, Vol. 296. no. 5568, pp. 724 – 727.

Carter G.S., Gregg M.C., Lien R.C., 2005. Internal waves, solitary waves, and mixing on the Monterey Bay shelf. *Continental Shelf Research*, 2005.

Crabbe K., 2007. Directional characteristic of inner shelf internal tide. Naval Postgraduate School oceanography master's thesis.

Duda T.F., Lynch J.F., Irish J.D., Beardsley R.C., Ramp S.R., Ching-Sang Chiu, Tswen Yung, 2004. Internal tide and nonlinear internal wave behavior at the continental slope in the northern south China Sea. *IEEE Journal of Oceanic Engineering*, Volume: 29, Issue: 4.

Garrett C., Munk W., 1979. Internal waves in the ocean. *Annual Review of Fluid*

Mechanics, January 1979, Vol. 11, Pages 339-369.

Garrett C., Kunze E., 2007. Internal Tide Generation in the Deep Ocean. *Annual Review of Fluid Mechanics*, January 2007, Vol. 39, Pages 57-87.

Gasparovic, R. F.; Apel, J. R.; Kasischke, E. S., 1988. An overview of the SAR Internal Wave Signature Experiment. *Journal of Geophysical Research*, Volume 93, Issue C10.

Gill, A.E., 1982. *Atmosphere-Ocean Dynamics*. Academic press.

Hosegood P., Bonnin J., Haren H., 2004. Solibore-induced sediment resuspension in the Faeroe-Shetland Channel. *Geophysical Research Letters*, 2004.

Ivanov L.M., Melnichenko O.V., 2004. Mesoscale and submesoscale zoo observed with HF radar in Monterey Bay. *Geoscience and Remote Sensing Symposium*, 2004. IEEE International

Klymak J.M., Moum J.N., 2003. Internal solitary waves of elevation advancing on a shoaling shelf. *Geophysical Research Letters*, 2003.

Lee CY, Beardsley RC, 1974. The generation of long nonlinear internal waves in a weakly stratified shear flow. *Journal of Geophysical Research*, 1974.

Leichter J., Stewart H., Miller S., 2003. Episodic Nutrient Transport to Florida Coral Reefs. *Limnology and Oceanography*, Vol. 48, No. 4 (Jul., 2003), pp. 1394-1407.

Lennert-Cody C., Franks Peter S., 2002. Fluorescence patches in high-frequency internal waves. *Marine ecology. Progress series* 2002, vol. 235, pp. 29-42.

Liu A.K., Chang Y.S., Hsu M.K., Liang N.K., 1998. Evolution of nonlinear internal waves in the East and South China Seas. *Journal of Geophysical Research*, 1998.

McPhee-Shaw E., Kunze E., 2002. Boundary layer intrusions from a sloping bottom: A mechanism for generating intermediate nepheloid. *Journal of Geophysical Research*.

McPhee-Shaw E., Sternberg R.W., Mullenbach B., 2004. Observations of intermediate nepheloid layers on the northern California continental margin. *Continental Shelf Research*, 2004.

Michallet H., Barthélemy E., 1998. Experimental study of interfacial solitary waves. *Journal of Fluid Mechanics* (1998), 366: 159-177

Moum, J. N., D. M. Farmerb, W. D. Smythc, L. Armid, and S. Vagle, 2003. Structure and Generation of Turbulence at Interfaces Strained by Internal Solitary Waves Propagating

Shoreward over the Continental Shelf. *Journal of Physical Oceanography*, Volume 33, Issue 10.

Orr, M., Mignerey P., 2003. Nonlinear internal waves in the South China Sea: Observation of the conversion of depression internal waves to elevation internal waves. *Journal of Geophysical Research*, Volume 108.

Petruncio E., Rosenfeld L., Paduan J., 1998. Observations of the Internal Tide in Monterey Canyon. *Journal of Physical Oceanography* Article: pp. 1873–1903.

Pineda J., 1994. An internal tidal bore regime at nearshore stations along western U.S.A.: Predictable upwelling within the lunar cycle. *Continental Shelf Research*, Volume 15, Number 8.

Ramp, S.R., Tswen Yung Tang, Duda T.F., Lynch J.F., Liu A.K., Ching-Sang Chiu, Bahr F.L., Hyoung-Rok Kim, Yang Y.J., 2004. Internal solitons in the northeastern south China Sea. Part I: sources and deep water propagation. *IEEE Journal of Oceanic Engineering*. Volume: 29, Issue: 4.

Rosenfeld L., JD Paduan J.D., Petruncio E.T., 1999. Numerical simulations and observations of the internal tide in a submarine canyon.

Sandstrom, H., Oakey, N.S., 1995. Dissipation in internal tides and solitary waves. *Journal of Physical Oceanography*, volume 25.

Scotti, A., Pineda, J., 2007. Plankton accumulation and transport in propagating nonlinear internal fronts. *Journal of Marine Research*, Volume 65, Number 1.

Sherwin T.J., Vlasenko V.I., Stashchuk N., Jeans D.R.G., Jones B., 2002. Along-slope generation as an explanation for some unusually large internal tides. *Deep Sea Research Part I: Oceanographic Research Papers*, Volume 49, Number 10.

Sibenac M., Kirkwood W.J., McEwen R., Shane F., Henthorn R., Gashler, D., Thomas H., 2002. Modular AUV for routine deep water science operations. *Oceans '02 MTS/IEEE*, Volume: 1.

Small J.; Hallock Z.; Pavay G.; Scott J., 1999. Observations of large amplitude internal waves at the Malin Shelf edge during SESAME 1995. *Continental Shelf Research*, Volume 19, Number 11.

Small J., Martin J., 2002. The generation of nonlinear internal waves in the Gulf of Oman. *Continental Shelf Research*, Volume 22, Number 8.

Stanton, T. P.; Ostrovsky, L. A., 1998. Observations of highly nonlinear internal solitons

over the Continental Shelf. *Geophysical Research Letters*, Volume 25, Issue 14.

Storlazzi C.D., McManus M.A., Figurski J.D., 2003. Long-term, high-frequency current and temperature measurements along central California: insights into upwelling/relaxation and internal waves on the inner shelf. *Continental Shelf Research*, Volume 23.

Vlasenko V.I., Hutter K., 2002. Transformation and disintegration of strongly nonlinear internal waves by topography in stratified. *Annales Geophysicae*, 2002.

Warn-Varnasa A., Gangopadhyay A., Hawkins J.A., 2007. Water masses in the Monterey Bay during the summer of 2000. *Continental Shelf Research*, Volume 27.