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The Internal Wave Dynamics of Barkley Submarine Canyon

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THE INTERNAL WAVE DYNAMICS OF BARKLEY SUBMARINE CANYON

A Thesis

Presented to

The Faculty of the Department of Marine Science

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Drew Arlen Burrier

December 2019

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The Designated Thesis Committee Approves the Thesis Titled

THE INTERNAL WAVE DYNAMICS OF BARKLEY SUBMARINE CANYON

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ABSTRACT

THE INTERNAL WAVE DYNAMICS OF BARKLEY SUBMARINE CANYON

by Drew Arlen Burrier

Submarine canyons are prominent bathymetric features in the ocean and in addition to being interesting geological regions, submarine canyons are associated with important physical processes in the ocean. Internal wave reflection from sloping boundaries can cause strong mixing in the turbulent boundary layers near sloping topography. Boundary mixing driven by internal waves may account for a significant portion of the overall oceanic vertical mixing. By observing internal waves using three cabled ADCPs at three sites in and around Barkley Submarine Canyon in spring pre-upwelling, and summer upwelling periods, this thesis has established a strong canyon effect on the internal wave field. We have also found a seasonal effect in the internal wave field, with all sites showing a reduction of energy at the M2 period from spring to summer. Finally, this thesis found that internal waves affect the vertical structure of the water columns via bottom intensification. This is likely attributed to the downward propagation of energy associated with the upward phase propagation shown in the M2 harmonics.

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1. Introduction

1.1 Background

Submarine canyons are prominent bathymetric features in the ocean and are commonly found along both coasts of the United States. Submarine canyons incise 20% or more of the Pacific North American shelf between the equator and Alaska, and 50% north of 45° (Hickey 1995). In addition to being interesting geological features, submarine canyons are associated with important physical processes in the ocean. For example, canyon regions are known to be locations for enhanced upwelling (Hickey 1997), increased mixing (Ledwell et al. 2000), and are important for cross-shelf exchange (Hickey and Banas 2008). Submarine canyons have also long been identified as centers for biological productivity in the ocean (De Leo et al. 2014; Huvanee and Davies 2014). The relationship between the ecosystem dynamics and the underlying physical processes in canyon regions is complex and dynamic, and has long been considered an important field of study for all branches of oceanographic research.

One possible explanation for elevated productivity near submarine canyons is that biological productivity could be responding to enhanced upwelling in narrow canyons, in which shelf currents produce unbalanced up-canyon pressure gradients that drive up-canyon flow (Freeland and Denman 1982). Theoretical and numerical studies show that strong upwelling occurs on the downstream side of canyons that are narrower than half the Rossby radius (Klink 1996; Allen 1996; Chen and Allen 1996). Upwelling is enhanced on the southern sides of these canyons forced by the cross-shelf pressure

gradient associated with the equatorward flowing coastal jet. Hickey and Banas (2008) have also estimated that in spring, nitrate supplied to the shelf bottom due to upwelling enhancement by canyons is roughly the same as (or more than) the amount that local coastal upwelling supplies to the southern Vancouver Island/Washington shelf. The canyon enhancement is also comparable to the nutrient supply by the Strait of Juan de Fuca. Another possible mechanism for the vertical transport of nutrients near canyons is elevated turbulent mixing. Much of this transfer of energy has yet to be thoroughly understood; however, the theory suggests that diapycnal mixing in the oceans is driven by intermittent patches of small-scale turbulence produced by breaking internal gravity waves (Müller and Liu 2000).

Diapycnal mixing, or the mixing of fluids across density interfaces, is critical not only to our understanding of ecosystem processes, but is a component of the large-scale meridional overturning circulation. The upwelling transport of dense oceanic bottom water back to the surface requires mechanical energy, and the source of that energy is still a topic of investigation in oceanography. The conventional thinking is that intermittent patches of small-scale turbulence drive diapycnal mixing. These patches of turbulent mixing are only a few meters in the vertical dimension and are caused by breaking internal gravity waves (Müller and Briscoe 2000). It has been hypothesized that submarine canyons are regions of elevated mixing in the ocean due to their effects on internal wave propagation.

Internal waves are gravity waves that occur when fluid bodies with different densities overlie, and can be generated either by wind at the sea surface, or by tidally driven flow

over topography on the seafloor. They break by either shear or convective instabilities that are caused by random superpositions or encounters with critical layers, instances when mean background flow is equal to horizontal phase speed (Muller and Natarov 2003). Free internal gravity waves occupy a frequency range bounded on the low end by the local inertial frequency (f) and at the higher end by the buoyancy frequency:

$$N = \sqrt{\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}} \quad (1)$$

in which g is the acceleration due to gravity, ρ_0 is a constant background density, ρ is the local density and z is depth. The two most energetic parts of the global internal wave spectrum are near-inertial waves and the M2 lunar semidiurnal frequency (Hopkins et al. 2014). Spectral signatures of these two contrasting mechanics are very different, with the former being distributed widely spatially and spectrally broad as a result of the episodic nature of storms, and the latter concentrating its energy narrowly spatially and in a sharp frequency range owing to the predictable nature of the tide (Van Haren 2004).

The dispersion relation for internal waves is quite different from the dispersion relation for surface waves. The frequency of surface waves depends only on the magnitude of the wavenumber, and not on its direction, whereas the frequency of internal waves is independent of the magnitude of the wavenumber and depends only on the orientation of the wave vector, i.e. on the angle of the wavenumber with the horizontal. When the wave vector is horizontal the particle motion is purely vertical and displacement along the phase line gives a vertical displacement. The buoyancy force in the vertical corresponding to that displacement is perpendicular to the wave vector, i.e. is along the crests of the waves, meaning that the wave motion is transverse. As a result,

when the group velocity has an upward component, the phase speed has a downward component. Waves propagating their phase upwards will be propagating their energy downwards and vice versa.

It has been established in the laboratory that internal wave reflection from sloping boundaries can cause strong mixing in the turbulent boundary layers near sloping topography (Cacchione and Wunsch 1974). In the ocean this process is more difficult to observe, but it is well documented that there is enhanced boundary mixing, and it is likely attributable to internal wave reflection (Eriksen 1982, 1998; Ledwell et al. 1995). Nonlinear interaction and scattering processes transfer energy out of the large-scale waves into ever smaller-scale waves that eventually break and cause turbulence and mixing. In a breaking event, the wave energy is partly dissipated into heat and partly converted to potential energy, since the mixing of a stably stratified fluid increases its potential energy (Müller, 1998). Boundary mixing driven by internal waves may account for a significant portion of the overall oceanic vertical mixing (Wunsch and Hendry 1972; Gordon 1980; Petruncio et al. 1997). This mixing is likely caused by the breaking of internal gravity waves as they interact with the continental shelf or other sloping boundaries near islands or seamounts. The most effective conditions for boundary mixing occur when an oncoming wave reflects from a bottom slope α that nearly matches the angle of wave propagation θ . When this happens, internal wave theory suggests that a small amplitude oncoming wave may be reflected with large amplitude, causing wave breakdown and turbulence. The flux of reflected energy from the slope changes in two ways: wave energy is transferred to shorter wavelength, and the group velocity decreases.

At the critical condition $\theta=\alpha$, the theory predicts a reflected wave of infinite amplitude, tiny wave length, and zero group velocity, trapping the oncoming wave energy in the boundary region (Slinn and Riley 2001). The term critical frequency is applied to the frequency of propagating internal waves relative to a critical slope that meets the critical condition $\theta=\alpha$. The relationship between the critical slope and critical frequency can be calculated using the equation:

$$\tan\alpha = \left[\frac{\sigma^2 - f^2}{N^2 - \sigma^2} \right]^{\frac{1}{2}} \quad (2)$$

where σ is the characteristic internal wave frequency. Eriksen (1998) observed enhancement in the internal wave spectrum at the critical frequency predicted for the slope and buoyancy frequency of the Fieberling Guyot.

Canyons, being regions of rough topography, are most commonly associated with the narrow band tidally driven internal wave energy. Several studies have identified canyons as potential internal wave “hotspots.” For example, internal wave fluctuations are dramatically larger in canyons compared to the open ocean, such that available potential energy increases by a factor of 10 toward the bottom, and 100 toward the head of Hudson Canyon (Hotchkiss and Wunch 1982). Furthermore, estimates have shown canyon internal wave fields to be an order of magnitude above those seen in the open ocean as demonstrated by Kunze et al. (2002) in Monterey Canyon. In this study, near-inertial motions were absent, and semidiurnal internal tides and their harmonics dominated. Kunze et al. (2002) speculate that canyons are effective at funneling remotely generated internal wave energy, but also that flow interaction with bottom topography is responsible for locally generated internal waves. Focusing of internal waves towards the

bottom of canyons, as well as toward the head has also been reported in: Baltimore Canyon (Gardner 1989) where it is likely responsible for resuspension events at certain times of year, La Jolla Canyon, where only downward propagating internal waves are apparent (Gordon and Marshall 1976), and Sable Gully, where intensified bottom tidal flows are non-linear due to interactions of the various tidal constituents (Greenan et al. 2013).

It is important to state, however, that these data come from a small number of submarine canyons, and there are no comparative studies to suggest that this enhancement of internal wave energy is the case in canyons in general. The complex and unique morphology of canyons makes generalization difficult, as the orientation, depth, and angle of the canyon floor and walls are all variable. In addition, most previous studies on this topic have been limited to short durations, owing to being conducted from research vessels, or temporarily deployed instrumentation platforms as opposed to cabled moored arrays. It was therefore an interest in the design of this project to focus on a study region with a fairly typical v-shaped canyon, and a cabled-ocean observing system collecting long-term velocity data at a sampling interval useful for the examination of internal waves, with instruments located at several representative positions within the canyon. These conditions were met in Barkley Canyon off Vancouver Island with instrumentation deployed by Ocean Networks Canada.

1.2 Barkley Canyon Region

Barkley Canyon is located at the edge of the continental shelf off Vancouver Island (Figure 1) British Columbia, in the northern portion of the California Current System (CCS). The CCS includes the southward-flowing coastal jet, the wintertime northward Davidson Current, and the northward California Undercurrent, which flows over the continental slope beneath the southward flowing upper layers.

Figure 1. Offshore bathymetry of the Pacific Northwest. Highlighted region seen in Figure 2. Open source data from: (<https://www.arcgis.com/home/item.html?id=5ae9e138a17842688b0b79283a4353f6>)

The dominant scales and dynamics of the circulation over much of the CCS are set by strong alongshore winds and a relatively narrow and deep continental shelf. Because of these characteristics, coastally trapped waves are efficiently generated and propagate long distances along the continental margins of much of western North America. Coastally trapped waves are non-dispersive waves, which become trapped against the coastal boundary. As a result, much of the variability in the northern California Current System is caused by processes originating south of the region, that is to say, remotely forced (Hickey and Banas 2003). Due to the generally southward alongshore wind stress in spring and summer, coastal upwelling is an important process controlling water property variability.

Currents and water properties of the CCS, both over the shelf and offshore of the shelf undergo large seasonal fluctuations. The equatorward coastal jet and poleward California Undercurrent are strongest in summer to early fall and weakest in winter. The poleward and surface-intensified Davidson Current is strongest in winter. Seasonal mean shelf currents are generally southward in the upper water column from early spring to summer and northward the rest of the year. Over the shelf, the seasonal duration of spring-summer southward flow usually increases with distance offshore and with proximity to the sea surface (Strub et al. 1987 for the entire CCS; Hickey 1989 for Washington shelf). A northward undercurrent is commonly observed over the slope during the summer and early fall. Off the coast of Vancouver Island a northward flowing buoyancy driven current, the Vancouver Island Coastal Current, exists year-round from the coast to at least mid shelf (Thomson 1981; Hickey et al. 1991). This current opposes

the southward shelf break jet current that connects to southward flow off the outer Washington shelf. While there is strong seasonal variability in the Pacific Northwest, the dominant source of variability occurs at the storm timescales (i.e., several days). Fluctuations in currents, water properties, and sea level over the shelf at most locations are dominated by wind forcing, with typical scales of 3–10 d (Hickey and Banas 2003).

Submarine canyons are common features of the shelf break in the northern CCS and upwelling has been associated with the presence of such canyons (Allen 1996; Hickey 1989). This can be so pronounced that macronutrient supplies to the Washington coast are similar to Oregon despite weaker upwelling winds off Washington. It has been speculated that the upwelling contribution from submarine canyons may compensate for those weaker winds (Hickey and Banas 2008; Connolly and Hickey 2014). It has also been documented that canyons alter regional circulation patterns in a manner that increases the possibility of local retention (Hickey 1995, 1997). Cyclonic circulation patterns are generally observed both within and over submarine canyons, although not necessarily extending to the sea surface. Allen et al. (2001) showed however that Barkley Canyon can exert an influence very close to the surface (at the thermocline depth of 10 m) and that near the rim, stretching vorticity generated over the canyon is strong enough to produce a closed cyclonic eddy. The velocity measurements found at Barkley Canyon are well positioned to examine the canyon's effect on background flow.

1.3 Objectives and Scope of Project

It is the goal of this study to investigate the deep tidal-band kinetic energy in a submarine canyon, on a temporal scale that far exceeds spring-neap cycling. This study is conducted using data from multiple bottom mounted acoustic Doppler current profilers (ADCPs) operated by Ocean Networks Canada in and around Barkley Canyon. This is a novel approach to studying internal wave fields in canyons, primarily because of the temporal scale that a cabled-moored array affords. It is also an opportunistic approach to use a long-term velocity dataset for purposes of investigating internal waves. This project represents a new approach to addressing complex oceanographic questions with the use of publicly available data. However, the opportunistic nature of this data set presents some challenges. Because the moorings in this array do not capture the entire water column in deep water, it is not possible to separate the internal tide from the barotropic tide. This study is limited to studying the tidal kinetic energy in the canyon, but captures variability over longer periods than the spring-neap cycling. This cross-seasonal dataset affords the opportunity to determine whether or not internal wave energy in this canyon is dominated by spring-neap cycling, or if there is an irregular pattern. It also allows for an examination of the effects of seasonality on these patterns. This analysis examines the characteristic features of the tidal band internal wave energy, in particular, the dominant frequency. This was accomplished by utilizing spectral and time series analysis on the current data taken from the Ocean Networks Canada Ocean Observatory.

2. Methods

2.1 Study Area

Located roughly at latitude: $48^{\circ}19' \text{ N}$, longitude: $126^{\circ}03' \text{ W}$, Barkley Canyon incises the continental shelf edge from a depth of roughly 400 m and extends down to 985 m along its thalweg. The NEPTUNE Canada Barkley Canyon node installed and operated by Ocean Networks Canada supports four instrument groupings: an upper slope site outside of the canyon at a depth of 396 m; a pair of instrument platforms near the base of the north wall of the canyon at 890 m; a canyon axis site at 985 m (Figure 2).

Figure 2. Bathymetry of Barkley Canyon and instrument locations.

Open source data from:

(<https://www.arccgis.com/home/item.html?id=5ae9e138a17842688b0b79283a4353f6>)

Each of these platforms contains an array of biological, physical and chemical sensors. This thesis utilizes data acquired from Pod 1 (canyon axis), Pod 3 (canyon slope) and Pod 2 (canyon rim) installed in 2010. Instruments are maintained once a year by Ocean Networks Canada. During this study Pods 1 and 3 were lifted to the surface, cleaned, failed instruments swapped, and redeployed at the same location.

2.2 Data Collection

Data from all instruments are archived and available online in near real-time using the Oceans 2.0 software interface (dmas.uvic.ca). Pods 1 and 3 are separated by about 0.6 km along the canyon, while Pod 2 is around 15 km NW of pod 3. Both Pods 1 and 3 were surfaced during the study period in May of 2014 and the ADCP on Pod 1 was replaced. Pod 2 was not moved for the duration of the study period. See Table 1 for Pod information.

Table 1. Deployment Locations, Depths, Instruments, and Characteristics of Moorings

Site	Depth	Location	Instruments	Type	Range	Name
Pod 1	985 m	48°19.0046' N 126°03.0075' W	ADCP 75 kHz	RDI Workhorse Long Ranger	648 m	Canyon Axis
Pod 2	396 m	48°25.6215' N 126°10.4787' W	ADCP 75 kHz	RDI Workhorse Long Ranger	648 m	Canyon Rim
Pod 3	888 m	48°18.9004' N 126°03.5375' W	ADCP 150 kHz	RDI Workhorse Quartermaster	254 m	Canyon Slope

The 75 kHz instruments had bin sizes of 8 m, and the 150 kHz had bin sizes of 5 m.

ADCP data were downloaded in one-minute ensemble periods, this option relied on ONC data portal search to perform the standard box-car average resampling on the data.

'Boxes' of time are defined based on the ensemble period, e.g., starting every minute on the 15s, with the time stamp given as the center of the 'box.' Acoustic pings that occur within that box are averaged and the summary statistics are updated. This process is often called 'ping averaging.' The process uses log scale averaging on the intensity data, which involves backing out the logarithmic scale, compute the weighted average, and then compute the logarithmic scale again. The data also incorporated velocity bin-mapping (a built in algorithm by RDI used to correct for vertical differences between bins when the pitch or roll are non-zero), which was to the nearest vertical bin. CTD data from the line P program was also used for estimation of oceanographic parameters (<http://www.dfo-mpo.gc.ca/science/data-donnees/line-p/index-eng.html>)

2.3 Analysis

2.3.1 Harmonic Analysis

In a typical oceanic time series, tidal variability is often the dominant signal. The tides are a consequence of the gravitational attraction of the Moon and Sun on the Earth and Ocean. Since the period of the orbits of the Moon and Sun, and their relative positions over the surface of the Earth are known from astronomical observations, the “tidal harmonics” (frequencies) are predictable and known. A complete tidal analysis may include more than 60 harmonic constituents. The results of such an analysis are the

amplitudes and phases of the known tidal constituents. It is therefore necessary to be able to identify those components of oceanographic time series and remove, or characterize their components for further analysis. Given that this time series is below surface layers, and the dominant generation mechanisms of internal waves in the ocean are related to tides, it is of particular importance to this project. To accomplish this, the MATLAB package T_Tide was utilized to perform a classical harmonic analysis (Pawlowicz et al. 2002). This package allows for the analysis of series up to a year in duration and computes confidence intervals for the considered constituents. Harmonic analysis identifies periodic motions with a consistent amplitude and phase. This study examines the phase and amplitude of the M2 constituent, at each bin of the three pods.

2.3.2 Principal Axis

The goal of principal axis analysis of a vector time series is to find the axis along which the variance in the observed velocity measurements is maximized. This type of analysis can be used to find the main orientation of fluid flow at a current meter or profiler, and in this case, each depth bin of an ADCP. This analysis was accomplished using the *princax* function in the RPSstuff package produced by Rich Signell (<https://woodshole.er.usgs.gov/operations/sea-mat/RPSstuff-html/princax.html>). It was run on each bin of each pod for both two-month study periods.

Figure 3. Illustration of the shifted coordinate system. The angle θ represents the 30° shifted from true east to align the system with the canyon's axis. See Github link (Appendix 6.1) for MATLAB code used.

2.3.3 Rotated Spectrum

It is customary for current meters and profilers to record velocity measurements as their individual components of eastward (u) and northward (v) time series. In the coastal ocean and near prominent topographical barriers, it is preferable to resolve the vector components into cross-shore (u') and along-shore (v') components through the rotation:

$$u' = u \cos\theta + v \sin\theta \quad (3)$$

$$v' = -u \sin\theta + v \cos\theta \quad (4)$$

where the angle θ is the orientation of the coastline (or the local bottom contours). This coordinate system is applied to all instruments and all depths, and was set to 30° , to align with the physical geometry (Figure 3). Since the mean and low frequency currents in relatively shallow waters are generally "steered" parallel to the coastline or local bottom contours. When applied to velocity measurements taken inside a canyon these directions become "up-canyon," and "across-canyon." Once the rotation was imposed on each bin, the power spectral density for the rotated velocity vectors was determined using the *pwelch* function in MATLAB, which uses the Welch's overlapped segment averaging estimator as well as a Hamming window (Emery and Thomson 2004). The default parameters were applied for number of segments (8); overlap (50%) and number of fast Fourier transform (nfft) points (the maximum of 256 or the next power of two greater than the length of the segment). This operation was performed for the bins closest to the bottom (≈ 16 MAB), and nearest to 100 MAB.

Calculations were made to estimate a critical frequency (Crit) for the region using CTD data from the Line P P1 survey site outside of the canyon region, and a simple rise over run calculation using bathymetry data for the canyon. The angle of the topography was determined to be 9.648° , and the buoyancy frequency was 0.0226 s^{-1} . This critical frequency was a rough calculation made for the entire region and should only serve as a reference point, and not taken to be the actual critical frequency for each location.

2.3.4 Wavelet Analysis

A common feature of time series in oceanography is that they exhibit statistical non-stationarity. Stationarity is the attribute that statistical properties in a time series like the mean, variance, autocorrelation, etc. are all constant over time. Series might contain dominant periodic signals as seen in the previous methodologies, but those signals may also vary in amplitude and frequency over time in ways that are not captured by the harmonics, or spectral analysis. By decomposing a time series into time–frequency space, wavelet analysis allows users to determine both the dominant modes of variability and how those modes vary in time (Torrence and Compo 1998).

Wavelet software was provided by C. Torrence and G. Compo, and is available at URL: <http://atoc.colorado.edu/research/wavelets/>.

2.3.5 Rotary Spectrum (Appendix)

For studies of circular motions and elliptical, such as inertial waves and tidal currents, decomposition into clockwise and counterclockwise rotary components is often more useful than examining the cross-shore/alongshore motions. Rotary analysis of a current field involves the separation of the velocity vector for a specified frequency ω , into clockwise and counterclockwise rotating circular components with defined amplitude and phase (Emery and Thomson 2004). Therefore, instead of dealing with the raw Cartesian components of the velocity signal (u , v) we have two circular components (A^- , φ^- ; A^+ , φ^+) in which A is the amplitude and φ is the phase. There are several advantages to this

type of analysis: the first is that breaking up a velocity vector into oppositely rotating components can elucidate important characteristics of the wave field at specified frequencies. This is been proven especially useful in the analysis of time series near rough topography (like canyons), diurnal frequency continental shelf waves (like those seen in canyons) among others. Secondly, many of the rotary properties, namely spectral energy and rotary coefficient, do not vary under coordinate rotation. This means that local steering effects by bottom topography are not a factor in the analysis. Although there are several packages in MATLAB to perform rotary spectral analysis, a new routine was written incorporating the *pwelch* and *cpsd* functions in MATLAB. This was done following Emery and Thomson (2004), specifically equations 5.8.50 a, b (shown below) that show that when u , v are orthogonal Cartesian components of the velocity vector, $w = (u, v)$, then the clockwise S^+ (5) and counter-clockwise S^- (6) rotary spectra can be expressed as:

$$\begin{aligned}
 S^+(\omega) &= [A^+(\omega)]^2, \omega \geq 0 \\
 &= \frac{1}{2} [S_{uu} + S_{vv} + 2Q_{uv}] \\
 (5)
 \end{aligned}$$

$$\begin{aligned}
 S^-(\omega) &= [A^-(\omega)]^2, \omega \leq 0 \\
 &= \frac{1}{2} [S_{uu} + S_{vv} - 2Q_{uv}] \\
 (6)
 \end{aligned}$$

where S_{uu} and S_{vv} are the autospectra of the u and v Cartesian components of velocity, and Q_{uv} is the quadrature spectrum between the two components.

3. Results

The data presented in this section are organized by seasonal period March/April, or spring period, starting at 03/01/13 and ending on 5/01/13, followed by June/July, or summer, starting at 06/01/13 and ending on 8/01/13. Data are displayed in an “across-canyon” sequence starting with the canyon axis, followed by the canyon slope and canyon rim. The results appear in the following order: Section 3.1 will discuss seasonal flow patterns, section 3.2 will present the harmonics analysis, section 3.3 the principal axis analysis, section 3.4 the rotated spectrum and concluding with 3.5 the wavelet analysis. The rotary spectrum analysis are found in the Appendix. All code used to process and analyze data for this thesis can be found at:

<https://github.com/druzzzy811/Thesis.git>

3.1 Seasonal Flow Patterns

Currents and water properties of the CCS both over the shelf and offshore of the shelf undergo large seasonal fluctuations (Hickey and Banas 2003). One of the main objectives of this study was to determine the seasonal patterns of internal wave energy in Barkley Canyon. Like the rest of the analysis, this section will be arranged by location within the canyon. In this section, both seasons will be presented together at each location to illustrate the differences between seasons.

Initial examination of the raw velocity measurements from the ADCPs shows that tidal motions are a very important component of the variability, as will be discussed in detail in later sections. The first goal is to examine seasonal differences at the different

canyon locations, and specifically, between upwelling and non-upwelling seasons and the changes in regional oceanography that accompany those shifts. To make observations about the seasonal differences, it was then necessary to low pass filter the data in order to remove tidal and inertial motions. This was done using a PL64 filter with half-amplitude period of 33 hours (Rosenfield 1983). Data are displayed above 100 m depth at the canyon rim site for orientation purposes but due to signal reflection off the surface, it is not considered in the analysis.

3.1.1 Pod 1: Canyon Axis

In both seasons, weaker de-tided velocities were observed at the canyon axis than at the other locations. There is a persistent offshore and equatorward flow visible at the top of the ADCPs range in the spring period (Figure 4) that is absent in the summer data (Figure 5). This highlights increased water column variability in the spring, particularly in the up-canyon axis. More energetic upward-propagating oscillations are observed in the across-canyon axis over the full range of depths, most pronounced in the late summer months (Figure 5). These stronger late summer oscillations are shorter in duration than the more commonly observed event scale variability seen early in the summer and throughout the spring.

Figure 4. De-tided and rotated u and v velocity measurements from the canyon Axis site in the spring. A) Up-canyon velocity (u). B) Across-canyon velocity (v). Color bar is narrowed compared to other sites to enhance view-ability.

Figure 5. De-tided and rotated u and v velocity measurements from the canyon axis site in the summer. A) Up-canyon velocity (u). B) Across-canyon velocity (v). Color bar is narrowed compared to other sites to enhance viewability.

3.1.2 Pod 3 Canyon Slope

The canyon slope data show dramatically different flow patterns than what was shown at the canyon axis (Figure 4 and Figure 5). The spring data (Figure 6) show a largely offshore, and poleward flow in the upper range of the ADCP, and largely shoreward, and equatorward flow in the lower portion of the water column. The periods of variability also change dramatically between seasons with longer periods in the spring where the up-canyon axis data show weekly shifts, and the across-canyon axis data

exhibit monthly periods and longer. The summer months' data show fairly consistent periods of variability between axes, at the several-day event scale.

There is a distinct horizontal banding pattern in the data seen at the canyon slope site in the spring up-canyon (Figure 6), and summer-across-canyon (Figure 7). There was no explanation for this artifact in the instrument documentation provided by ONC, and we cannot explain its origin.

Figure 6. De-tided and rotated u and v velocity measurements from the canyon Slope site in the spring. A) Up-canyon velocity (u). B) Across-canyon velocity (v).

Figure 7. De-tided and rotated u and v velocity measurements from the canyon Slope site in the summer. A) Up-canyon velocity (u). B) Across-canyon velocity (v).

3.1.3 Pod 2 Canyon Rim

The canyon rim is the nearest to the surface and therefore the physical forcings observed in this part of the ocean are dominated by the wind and surface currents. While this site did not require de-tiding to see shifts in seasonal patterns, it was done to remain consistent with the previous sites. As with the slope, there is a strong shift in the periods of variability, but the direction of flow is consistent between seasons (Figure 8). The canyon slope data show that strong offshore and poleward flow alternates with onshore and equatorward flow. The period of variability is much shorter in the spring with weekly shifts, and switches to monthly shifts in the summer.

Figure 8. De-tided and rotated u and v velocity measurements from the canyon rim site in the spring. A) Up-canyon velocity (u). B) Across-canyon velocity (v).

At all sites, the up-canyon velocities are stronger in the summer than they are in the spring (Figure 9). There is also a dramatic switch from a poleward, to equatorward flow seen in the upper portions of the slope data, and at the rim. The canyon axis data show the lowest velocities of any of the sites, as we would expect of the deeper location. This site has more consistency in patterns through its vertical range than do the other two sites.

Figure 9. De-tided and rotated u and v velocity measurements from the canyon rim site in the summer. A) Up-canyon velocity (u). B) Across-canyon velocity (v).

3.2 Harmonic Analysis

During the spring season the amplitude of the M2 harmonic varies considerably between locations. In the canyon axis, there is an amplitude minimum at approximately 800 m with an increase in amplitude above and below that depth (Figure 10). At the slope, the amplitude stays more consistent throughout the water column, with a local minimum near 730 m and an increase towards the bottom. At the canyon rim, the amplitude decreases away from the surface until about 180 m before shifting to increase towards the seafloor. The magnitude of the amplitude is much greater above the canyon

rim, that is to say, in the higher reaches of the slope instrument range (above 400 m), and at the rim site. The amplitude is highest among all sites and depths at around 400 m.

The phase propagation also varies by location during spring. Upward phase propagation is observed in the canyon axis above and below approximately 750 m. At the canyon slope location, upward propagation is observed below 700 m, with a slight reversal to downward at approximately 850 m. At the canyon rim location, relatively stable phase is observed below 200 m, above which phase propagates upward. The observed phase propagation and variation of amplitude with depth, is characteristic of internal wave propagation. These results show that internal waves interact with the topography differently at each individual site. As mentioned in the introduction, phase propagation is the opposite direction of energy propagation, and these results (with the exception of the slope, which is the opposite) indicate downward propagation of energy, which is also expected in canyons (Jachec et al. 2006). It is also noteworthy that this downward phase propagation occurs at similar depth ranges at the canyon axis and canyon slope sites. It is also worth noting, that there is a seasonal component to the phase and energy propagation, and these patterns shift during the summer.

Figure 10. Plots for the harmonics at all three canyon locations for the spring. A) M2 major axis amplitude of velocity signal vs. depth at canyon axis. B) M2 phase in degrees relative to Greenwich vs. depth at canyon axis. C) M2 major axis amplitude of velocity signal vs. depth at canyon slope. D) M2 phase in degrees relative to Greenwich vs. depth at canyon slope. E) M2 major axis amplitude of the velocity signal vs. depth at canyon rim. F) M2 phase in degrees relative to Greenwich vs. depth at canyon rim.

There are noticeable differences in the M2 harmonics between seasons. Perhaps the most striking of these is the change in amplitude at the canyon axis site (Figure 10a and Figure 11a). There is higher amplitude below 400 m with a maximum at 600 m, followed by a decline to around 750 m below which the amplitude is larger towards the bottom. At the canyon slope site, there is a similar pattern to what was found at this location in the spring. There is an oscillatory pattern with a minimum below 700 m and a maximum around 800 m. The canyon rim is the most similar between seasons of the three locations,

showing an almost identical pattern to that seen in the spring: a decrease in amplitude away from the surface to around 180 m followed by an increase towards the bottom. This is an interesting observation that the shallowest site shows the least change with season, as one would expect shallower water to be more dynamic, and deeper waters to be less seasonally variable.

Phase propagation is demonstrably different between seasons and the largest differences are observed at the Pod 3 canyon slope site (Figure 10b and Figure 11d) in which phase propagation shifts from downward to upward. The canyon axis harmonics, while overall showing higher phase, exhibit a similar decrease below 400 m to around 700 m. As in the spring, there is a shift to higher phases towards the seafloor, and this shift is consistent with that observed at the canyon slope site (Figure 11). The slope shows the most pronounced and consistent upward phase propagation of any analyzed period, increasing steadily from the bottom to just above 700 m. Finally, the phase propagation at the canyon axis is very similar to what was observed at this location in the spring: a fairly consistent phase to about 180 m depth, followed by upward phase propagation towards the surface.

It has been shown at the Mid-Atlantic Ridge (van Haren 2006) that 80% of incoherent semidiurnal tidal phase propagates downward, 90% of near-inertial phase propagates upward. While only the M2 harmonic was analyzed for this thesis, there is some evidence of an asymmetric phase propagation (at the canyon slope in Mar-Apr and the canyon axis in Jun-Jul) the general trend is an upward phase propagation which means a general trend for the downward propagation of internal wave energy. This trend is seasonally

dependent (although there is some degree of variability), being more pronounced in the summer when the amplitudes are also higher. This is especially true at the slope (Figure 11d).

Figure 11. Plots for the harmonics at all three canyon locations for the summer. A) M2 major axis amplitude of velocity signal vs. depth at canyon axis. B) M2 phase in degrees relative to Greenwich vs. depth at canyon axis. C) M2 major axis amplitude of velocity signal vs. depth at canyon slope. D) M2 phase in degrees relative to Greenwich vs. depth at canyon slope. E) M2 major axis amplitude of velocity signal vs. depth at canyon rim. F) M2 phase in degrees relative to Greenwich vs. depth at canyon rim.

3.3 Principal Axis Analysis

As mentioned in the introduction, the usefulness of principal axis analysis is that it can be used to find the main orientation of fluid flow, this is particularly useful in the canyon setting because it can reveal the steering effect of the canyon's complex

topography on the flow throughout the portion of the water column that the ADCPs can measure.

3.3.1 March/April

The principal axis analysis (Figure 12) shows that while the general profile of the major axis magnitude consistently decreases with depth across the three sites, the overall magnitude changes considerably between the canyon sites and the rim site. At the Pod 1 canyon axis site the major axis of the principal ellipse is fairly consistent in the bottom 300 m of the water column, after which it increases towards the surface. The angle of maximum variance, which is measured counterclockwise from east, decreases away from the bottom before leveling off at around 375 MAB. The Pod 3 canyon slope site shows a more stable major axis up to around 180 MAB before increasing toward the surface. The angle of maximum variance decreases away from the bottom before leveling off around 100 MAB and staying between 60 and 70 degrees towards the surface. Finally, the Pod 2 canyon rim site data demonstrate a stable major axis across the entire water column below the surface where the data is unreliable. The angle of maximum variance increases away from the bottom up to around 100 MAB before stabilizing for the rest of the water column. We therefore expect to see the least change in amplitude and orientation at the canyon rim site because it is located outside of the canyon, and away from the associated effects on flow. This does in fact appear to be the case. The horizontal banding pattern seen in Section 3.1 is also apparent in the principle axis data, which rules out filtering

error, as the princax data are not filtered. Further analysis will focus on the bottom 100 m of the water column at all locations.

Figure 12. Principal axis analysis at all three canyon locations for spring and summer. A) Major axis of the principle ellipse vs. depth at canyon axis. B) Angle of maximum variance (AOMV) for canyon axis. C) Major axis of principle ellipse vs. depth at canyon axis. D) Angle of maximum variance (AOMV) for canyon slope. E) Major axis of principle ellipse vs. depth at canyon rim. F) Angle of maximum variance for canyon rim. Note the x-axis on the AOMV plots has been narrowed in order to show patterns in the lower water column.

3.3.2 June/July

There are remarkably few differences between seasons in the principal axis analysis. However given the restricting nature of the physical bounds of the canyon on flow this is

not surprising. The canyon axis (Figure 12) data exhibit some of the biggest differences between seasons, the principle ellipse in the summer shows a decrease away from the bottom to a depth of around 250 MAB followed by a similar increase towards the surface as was found in the spring. The angle of maximum variance, on the other hand decreases away from the bottom to a depth of about 300 MAB, before increasing towards the surface. The canyon slope site data show an almost identical major axis of the principal ellipse profile. The angle of maximum variance shows an increase away from the bottom to around 200 m before decreasing towards the edge of the instruments range. The aforementioned-banded structure is again visible at this site during summer as well. Finally, the canyon rim site data show a stable major axis across the entire water column below the surface where the data is unreliable. The angle of maximum variance decreases away from the bottom slightly before leveling off at around 150 MAB at 60° before surface processes take over. One major change between the seasons is that the overall magnitude at the Pod 1: canyon axis site is much reduced in summer. This seems to be consistent with the harmonic analysis.

3.4 Rotated Spectrum

The goal of spectral analysis is to separate the relevant periodic oscillations from the random and aperiodic fluctuations common in oceanographic time series. This “noise” can be due to background geophysical variability, or instrument error. Spectral analysis (both rotated and rotary, shown in Appendix 6.2) provides the capacity to focus on the fluctuations associated with physical forcings of interest.

3.4.1 March/April

There are four frequencies of particular interest that will be marked on all ensuing spectral plots: the K1 lunar diurnal tidal constituent (period 23.93 hours) the Coriolis frequency (period 16.068 hours at latitude 48.3165°), the M2 semi-diurnal lunar tidal constituent (period 12.42 hours), and the critical frequency. The critical frequency was estimated from stratification and topography data (Equation 2) to have a period of 3.53 hours.

The canyon axis spectra show dramatic differences between depths in the power spectrum in the up-canyon direction (Figure 13) with significantly higher power in the spectra of the velocity series near the bottom (16 MAB) than higher in the water column (100 MAB). This is clearly visible at all frequencies between the diurnal and the critical frequency but is most pronounced at the diurnal and semi-diurnal frequencies. The difference in power between the depths is clearly significant relative to the error bar showing 95% confidence interval. The across-canyon power spectrum exhibits little difference between depths. There are nominal differences at the diurnal and semidiurnal peaks but neither is statistically significant. What is clear is that the tidal ($1/d$, and $2/d$) frequencies dominate the energy spectra both near the bottom and further up in the water column.

Figure 13. Power spectral density (PSD) from rotated velocity signal for canyon axis for the spring. A) u measurements rotated to an up-canyon orientation, or along-slope. B) v measurements rotated to an across-canyon orientation or on-slope. In both panels, the blue plot is 16 m above the bottom, and the red plot is 100 m above the bottom.

The canyon slope (Figure 14) data show a very similar power spectrum profile in the up-canyon axis, with there being significantly higher power in the spectra of the velocity series 16 MAB versus 100 MAB. This elevated energy near the bottom is clearly visible at all frequencies between the diurnal ($1/d$) and the critical frequency (Crit), but is most pronounced at the diurnal and semi-diurnal frequencies ($2/d$). The difference in power between the depths at these tidal frequencies is clearly significant relative to the error bar showing 95% confidence interval.

There is little difference in the across-canyon power spectrum between depths; this appears to be a consistent feature of the across-canyon spectra in the spring. The slope and axis sites are very similar in the across-canyon spectra, there are nominal differences at the diurnal and semidiurnal peaks but neither is significant and these frequencies dominate the energy spectra both near the bottom and further up in the water column.

Figure 14. PSD from rotated velocity signal for canyon slope for spring. A) u measurements rotated to an up-canyon orientation, or along-slope B) v measurements rotated to an across-canyon orientation or on-slope. In both panels, the blue plot is 16 m above the bottom, and the red plot is 100 m above the bottom.

The most distinct power spectrum of the three locations is from the canyon rim (Figure 15). There is no evidence of a peak at the diurnal frequency in the up canyon axis at this location. While there is enhancement 100 MAB around the Coriolis frequency (f)

and at 16 MAB between the semi-diurnal and critical frequencies, there are no significant differences in power between depths. The across-canyon axis data show the highest power at the semi-diurnal frequency of any of the locations, both at 16 MAB and 100 MAB. There is a slight enhancement at 100 MAB around the Coriolis frequency (f) and at 16 MAB between the semi-diurnal and critical frequencies; there are no significant differences in power between depths.

Figure 15. PSD from rotated velocity signal for canyon rim for spring. A) u measurements rotated to an up-canyon orientation, or along-slope B) v measurements rotated to an across-canyon orientation or on-slope. In both panels, the blue plot is 16 m above the bottom, and the red plot is 100 m above the bottom

3.4.2 June/July

The across-canyon axis data shows the same general profile near the bottom, as in the spring, with a slight shift in power from the f to the $2/d$ peak (Figure 16). At 100 MAB, however, the energy spectra show more pronounced peaks at the $1/d$, $2/d$, and f frequencies. The across-canyon axis shows a very similar profile to the spring, with the exception of a more defined peak at the f frequency at both depths.

Figure 16. PSD from rotated velocity signal for canyon axis, summer. A) u measurements rotated to an up-canyon orientation, or along-slope B) v measurements rotated to an across-canyon orientation or on-slope. In both panels, the blue plot is 16 m above the bottom, and the red plot is 100 m above the bottom.

The slope data (Figure 17) show more dramatic differences between seasons, in both axes. The up-canyon spectra show more power at the $1/d$ frequency near the bottom, as

well as a unique split peak near the diurnal frequency higher up in the water column (Figure 17a). In the across-canyon axis, there is more energy at the diurnal frequency in the summer season than the spring at both depths, as well as a more clearly defined peak at the Coriolis frequency and the same increase in energy higher in the water column as the semi-diurnal frequency seen in the spring season.

Figure 17. PSD from the rotated velocity signal for canyon slope, summer. A) U measurements rotated to an up-canyon orientation, or along-slope B) V measurements rotated to an across-canyon orientation or on-slope. In both panels, the blue plot is 16 m above the bottom, and the red plot is 100 m above the bottom.

In addition to having the most unique spectra amongst the three locations, the canyon rim site data also reveal the biggest difference between seasons (Figure 18). In the up-

canyon axis, the spectra show increased energy in the summer at the diurnal frequency 100 MAB, and a significant difference between seasons as well. There is also less energy around the Coriolis frequency near the bottom in the summer season. Finally, there is a slight enhancement at the semi-diurnal frequency, 100 MAB, as well. The across-canyon axis diurnal energy is similar between seasons and depths, while the spectra around the Coriolis frequency have different profiles between seasons. The diurnal frequency data show the highest energy at any location at both depths in the spring season, but there is a decrease in energy near the bottom in the summer. Finally, there is also a significant difference between seasons at frequencies shorter than semi-diurnal, 100 MAB.

Figure 18. PSD from rotated velocity signal for canyon rim, summer. A) U measurements rotated to an up-canyon orientation, or along-slope B) V measurements rotated to an across-canyon orientation or on-slope. In both panels, the blue plot is 16 m above the bottom, and the red plot is 100 m above the bottom.

The spectral analysis shows significant bottom enhancement in the up-canyon axis in both seasons, consistent with downward propagation of energy shown in previous sections. There is also bottom enhancement at the rim in the summer that is not present in the spring, potentially due to increased local generation in that season. Finally it is important to note here that there is significant and elevated energy at the diurnal frequency at all locations and depths. This will be discussed further in depth in later sections but is likely indicative of coastally trapped waves.

3.5 Wavelet Analysis

The results of the wavelet analysis confirm a lot of the findings stated above, namely that the dominant signals in the energy spectra are at the M2 (semidiurnal or two per day) and K1 (diurnal or one per day) tidal frequencies. There are, however, some interesting elements that emerge from looking at the intraseasonal variability of the energy spectra that will be summarized by season and location below.

3.5.1 March/April

At canyon axis site (Figure 19) the most energy occurs around the M2 frequency at both depths. Interestingly, elevated energy at the K1 frequency occurs at times when the M2 was weaker. There is a very clear spring-neap pattern to the M2 at both depths, and a more subtle fortnightly signal in the K1 frequency at 16 MAB. The fortnightly signal is even less visible at 100 MAB. There is slightly more energy near the bottom of the water

column throughout this period, but it is especially pronounced around 3/27.

Figure 19. Wavelet power spectrum for the canyon Axis site during March and April at 16 meters above bottom (A) and 100 meters above bottom (B). The thick black line denotes the cone of influence (COI) above which is significant (95% confidence interval).

The canyon slope site (Figure 20) is very similar to the canyon axis at the M2 frequency near the bottom of the water column, where the most energy is present and there is apparent fortnightly period of variability. However, there is much less energy at the K1 frequency at both depths. This pattern is more apparent near the bottom where the signal was stronger in the canyon axis. In addition, there is a great deal of energy at longer periods above two days higher up in the water column just above the cone of

influence (COI), marking the region (in the lower corners) where the results are affected by the edges of the time series. This is consistent with the low frequency variability seen in section 3.1.

Figure 20. Wavelet power spectrum for canyon slope site during March and April at 16 m above bottom (A) and 100 m above bottom (B). The thick black line denotes the cone of influence (COI) marks the region (in the lower corners) where the results are affected by the edges of the time series.

As in all previous analyses the canyon rim site (Figure 21) is the least like the others, likely due to its proximity to the surface and location outside of the canyon. The M2 signal is much less powerful at both depths, while almost not existent 100 MAB. There is also more of a monthly period of variability in the M2 as opposed to the fortnightly signal seen at the other sites. The K1 harmonic is much more important near the bottom than at

the surface and is more powerful when the M2 is weaker. Finally, there is elevated power at longer periods, which is most clear in the middle of this window.

Figure 21. Wavelet power spectrum for canyon rim site during March and April at 16 m above bottom (A) and 100 m above bottom (B). The thick black line denotes the cone of influence (COI) marks the region (in the lower corners) where the results are affected by the edges of the time series.

3.5.2 June/July

There is quite a dramatic shift in the wavelet power spectrum between seasons. The canyon axis site (Figure 22) data demonstrate a significant reduction of energy at the M2 period, at both depths, although this is more dramatic near the bottom (where it was a stronger signal in the spring). There is also a less noticeable fortnightly signal. The K1

takes over as the dominant signal at both depths with a much less clear period for its variability. The 100 MAB also shows more energy at the two-day period towards the end of the window. Finally, there is an interesting multi-day signal starting around 7/13 that shows peaks in energy at the M2, K1 at both depths, and the two-day periods 100 MAB.

Figure 22. Wavelet power spectrum for canyon axis site during June and July at 16 m above bottom (A) and 100 m above bottom (B). The thick black line denotes the cone of influence (COI) marking the region (in the lower corners) where the results are affected by the edges of the time series.

The canyon slope (Figure 23) data also suggest a shift in energy from the M2 to the K1 at both depths. The M2 maintains its fortnightly period of variability while the K1 shows very little discernable patterns at either depth. The 7/13 peaks are still visible in the M2, and K1 periods, while less so at the two-day frequency.

Figure 23. Wavelet power spectrum for the canyon slope site during June and July at 16 m above bottom (A) and 100 m above bottom (B). The thick black line denotes the cone of influence (COI) marking the region (in the lower corners) where the results are affected by the edges of the time series.

The canyon rim site (Figure 24) shows even less energy at the M2 period in the summer than it did in the spring at 16 MAB. The K1 signal is pretty similar to the previous season at that depth, and the variability of both signals is difficult to discern. There is very little energy at 100 MAB at any of the frequencies under consideration. There is a slightly elevated energy at longer periods, but that signal is very close to the COI.

Figure 24. Wavelet power spectrum for canyon rim site during June and July at 16 m above bottom (A) and 100 m above bottom (B). The thick black line denotes the cone of influence (COI) marking the region (in the lower corners) where the results are affected by the edges of the time series.

The wavelet analysis shows how the power spectra vary through time. In general the M2 and K1 are the dominant signals at all locations, in both seasons, as we would expect. The strength of these signals and the amount of time they are in either mode is both seasonally, and spatially variant, however. A prime example of this is the K1 frequency, which is much stronger at all locations in the summer, and it does not have a discernible fortnightly pattern. This seems to be indicative of coastally trapped waves, as discussed in the following section. The M2 frequency on the other hand tends to be stronger in the

summer, and closer to the bottom. This is indicative of bottom intensification of internal wave beams.

4. Discussion

There are two main goals for this thesis: first, to characterize the internal wave energy in a submarine canyon with a typical “V” shape, and second, to determine the effects of seasonality on that internal wave climate. The construction of this thesis was opportunistic, and designed around publicly available data, made possible by the cabled observatory operated by Ocean Networks Canada and the moorings they operate in and around Barkley Canyon. The study period for this thesis was selected for periods of time with few or no gaps in data collection, and to capture periods of both upwelling and non-upwelling under the assumption that this is the dominant seasonal oceanographic feature in this region.

The analysis conducted for this thesis will be separated in to four categories for further discussion. The first will focus on characterizing each site. The second will focus on the vertical structure of the water column, with a particular focus on the phase propagation and the associated interpretations for the internal wave field. Third we will discuss the seasonal effects seen in our analysis and relate that to the physical oceanography of the region. Finally, this thesis will conclude with remarks on some of the limitations of this work, avenues for improvement, as well as directions for future research.

4.1 Site Characteristics

Both the rotated frequency spectra, and the rotary spectra (Sections 3.4 and 3.5) are dominated by the semi-diurnal frequency. The diurnal frequency is the next most

powerful signal at locations except the canyon rim (in some cases it is the highest peak). They appear as wide bands around the key frequencies, as opposed to clearly defined lines, likely due to the presence of incoherent constituents. The presence of peaks at frequencies above the semi diurnal are common and are likely complex tides, generally known as mixed tides, having large components of both diurnal and semidiurnal frequencies, indicating a degree of nonlinearity to the internal tide field (Kunze et al. 2002). Barkley Canyon lies poleward of the turning latitude of the diurnal internal tide, which means that diurnal tidal constituents are lower than the local inertial frequency. Therefore, progressive diurnal internal tides are not allowed. Nonetheless, trapped diurnal internal tides may exist (Dale et al. 2001; Swart et al. 2011) and could explain the elevated energy seen at those frequencies. Additionally, coastally trapped waves can exist at subinertial frequencies, and several studies have demonstrated that the region is one of anomalously large diurnal tidal currents due to the generation of coastally trapped waves at the entrance of the Juan de Fuca Strait (Cummins et al. 2000). As there seems to be similar diurnal peak across depths, this explanation makes the most sense. Hotchkiss and Wunsch (1982) showed that V-shaped submarine canyons focus the energy of internal waves that enter the canyon from the offshore boundary toward the canyon head if the internal wave frequencies are greater than a critical value. The canyon sites clearly show elevated energy at frequencies higher than the critical frequency, but without more detailed information about the hydrography of the area during the study period that is all that can be said.

Over the canyon rim, little can be made of a comparison between the canyon sites, because the critical frequency is estimated for the whole region, and not the specific sites due to low resolution bathymetry data as well as a lack of hydrographic data for the study period.

By and large the results are as expected; the two canyon sites show the most similarity and the rim site is the least like the others. These results are echoed in the wavelet analysis (Section 3.5), in which the M2 period dominates in the canyon, but is much less powerful on the shelf. Even the periods of variability seem to be different in the canyon versus at the rim. A very clear fortnightly signal is present in both canyon sites at both depths, while that same trend does not hold on the rim. The canyon sites generally vary together, while the rim is out of phase, as shown for the M2 frequency in Figure 25. This suggests that the canyon sites receive primarily locally generated energy. This is highly indicative of internal wave beams while the rim receives both locally and remotely generated waves.

Figure 25. Wavelet power at the M2 frequency during the Mar-Apr period for all locations 16 m above bottom.

4.2 Vertical Structure

The M2 harmonic (Section 3.2) showed evidence of an asymmetric phase propagation (at the canyon slope in Mar-Apr and the canyon axis in Jun-Jul) the general trend appears to be an upward phase propagation, which translates to downward propagation of internal wave energy. This trend is seemingly seasonally dependent, being more pronounced in the summer when the amplitudes are also higher. This is especially true at the slope (Figure 11d) For the sites inside the canyon, the harmonic amplitude is in general smaller at the bottom and increases towards the surface, but it is important to note this is not a linear or smooth trend.

Both the rotated frequency spectra and the rotary spectra (Sections 3.4 and 6.2) show elevated energy closer to the sea floor at frequencies higher than the semi-diurnal internal tide. The amplitude of the M2 velocities vary with depth and position within the canyon as shown in Figure 26.

Figure 26. M2 Power at all locations for the Jun-Jul period at all depths. The red line shows the 95% confidence interval.

The phase of the M2 tidal velocity showed a general tendency for upward phase propagation inside the canyon, while outside the canyon it was relatively stable below 200 MAB (Section 3.2). Assuming these motions are due to linear internal waves, this upward phase propagation is associated with downward energy propagation as has been shown in canyon modeling studies (Vlasenko et al. 2016). The group and phase velocity

vectors of internal waves are perpendicular to one another such that the horizontal components are in the same direction, while the vertical components are opposite (Gordon and Marshall 1976).

The wavelet analysis (Section 3.5) generally shows that there is more energy near the bottom than at 100 MAB at all locations, and this is confirmed to be true throughout the water column in Figure 35. This is most pronounced at the axis site, and is a little more subtle at the slope site, but interestingly there also appears to be an element of seasonality to the vertical structure. The difference in energy between depths is greater in the spring than in the summer.

4.3 Seasonality

As highlighted in Hickey and Banas (2003) the currents of the northern portion of the California Current System display a high degree of seasonal variability, both over the shelf as well as offshore of it. Off the coast of Vancouver Island a northward flowing buoyancy driven current, the Vancouver Island Coastal Current, exists year-round from the coast to at least mid shelf (Thomson 1981; Hickey et al. 1991). Both the coastline and topography serve as barriers for flow. There is an element of seasonality present in the M2 harmonics at the canyon sites in both phase and amplitude.

Figure 27. Spring and summer rotated spectra at the canyon slope site, 16 m above the bottom. The black line shows the 95% confidence interval.

The canyon axis showed a trend of upward phase propagation in both seasons as well as greater amplitude at in the middle of the water column (where the signal is better) in the summer than in the spring. The canyon slope on the other hand showed significantly higher energy in the summer at the K1, and the reverse for the M2 (Figure 27). In other analyses, it also showed opposing phase propagation, with a downward phase shift in the spring and an upward phase shift in the summer (Section 3.2). This indicates that the direction of energy propagation flips at the slope seasonally; this is likely due to the seasonal development of the poleward undercurrent in the late summer persisting to the early spring. There is no apparent seasonality at the canyon rim in the M2 harmonics.

The spectral results show a high degree of seasonality in the internal wave field. This is clear in the rotary spectra (see Appendix) as well as in the rotated spectra, however, in that analysis the slope site shows increases in energy in the at the diurnal frequency near the bottom, as well as a greater separation of depth profiles in the summer than in the spring.

The wavelet analysis perhaps best highlights the differences between seasons. At all sites there is a significant reduction of energy at the M2 period from spring to summer, which is very interesting as this is one of the few similarities seen at all sites and the M2 is the most dominant signal in the spectra results. Inside the canyon, there is an increase (perhaps shift) of energy at the K1 frequency at both depths, as well as a shift in the periods of variability.

4.4 Summary

This thesis establishes that there is an apparent canyon effect to the internal wave field in and above Barkley Canyon. Of all analyses conducted, the sites in the canyon for the most part closely resemble one another, and the rim site looks completely different.

Figure 28. Depicts a schematic of an internal wave beam (gray region) over supercritical canyon rim. The red arrows indicate phase speed, while the black lines indicate group velocity.

Secondly there is bottom intensification at almost every site in almost every type of analysis. This is likely attributed to the downward propagation of energy associated with the upward phase propagation shown in the M2 harmonics, as well as the possibility for critical frequency internal waves dispersing energy at the slopes (although that is speculation given the lack of fine scale bathymetry and hydrography data to examine this in depth). This concept is illustrated in Figure 28.

Finally there is an evident seasonality to the internal wave field demonstrated in almost every type of analysis done. This is in line with the seasonal shifts that occur in the oceanography in this region with the onset of an upwelling regime between the spring

and summer seasons. This process likely affects the degree of stratification of the water column, thus affecting the manner in which internal waves are able to propagate.

4.5 Future Work

It has been well documented that in the summer, coastally trapped waves are usually important in the Pacific Northwest, particularly at more northern latitudes such as the British Columbia coast (Hickey et al. 1991). It is possible that with better spatial coverage, this would have emerged from the data, particularly with more sites outside of the canyon. It would be interesting to compare the canyon site with a nearby shelf site to determine whether the results seen here are unique to canyons or these are features of the continental shelf break at large.

The results of this thesis show that there is a definite seasonal variability to the internal wave energy in Barkley Canyon, it would be interesting to further this work by taking velocity measurements for the entire water column during periods of interest via LADCP measurements, or a chain of ADCPs, as well as full water column hydrographic data during the study period and within the canyon. This would allow for a discussion of the available potential energy within the canyon as a result of propagating internal waves, as well as a specific discussion of the criticality of slope relative to those internal wave trends. The instrumentation deployed combined with the timescales available for analysis are unique and merit more dedicated internal wave focused study. This discussion would be able to include where and how internal waves are implicated in the mixing of water properties within the canyon. There is still a great deal to be learned about the internal

wave climate of Barkley Canyon, and hopefully this study has provided some insight into the scale that these fascinating oceanographic features operate in submarine canyons in general as well as how they may vary with seasons and local oceanography. This study shows that there are interesting changes to internal waves around the critical frequency, that are most associated with driving mixing in submarine canyons, related to season and merit further, more detailed examination. In addition to showing a bottom intensification of energy consistent with downward propagating internal waves, thesis has established that there is seasonality to the internal wave field in a canyon region in the northern CCS. Better understanding the variability of internal wave energy in the is critical to many large scale questions in oceanography, and this study site, will prove to be useful in further addressing them.

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Appendix

Code

All code to process and analyze data for this thesis can be found at:

<https://github.com/druzzzy811/Thesis.git>

A.1 Rotary Spectrum

A.1.1 March/April

The rotary spectra (Figures 29-34) echo some of the results of the rotated spectra, namely that the diurnal and semi-diurnal frequencies dominate the energy spectra. This is clearly seen in the spring data at the canyon axis as well (Figure 29). Very similar energy is observed between these dominant frequencies at both depths. Interestingly there does not appear to be a strong inertial wave signal in the canyon axis in the spring as evidenced by the similar profiles between the diurnal and semidiurnal frequencies in the clockwise (CW) and counter-clockwise (CCW) rotary spectra. The diurnal period does exhibit increased energy higher up the water column during the spring months in both rotary components. There is also a peak in the energy spectra between the semi-diurnal frequency and the critical frequency in both rotary components but there is a similar peak in the 16 MAB spectra only in the CW component that is accompanied by a general enhancement near the bottom at higher frequencies in the CW spectra.

Figure 29. Rotary power spectra from rotated velocity signal for canyon axis in the spring. A) Shows the negatively rotating power spectrum, or the Counter Clockwise (CCW). B) Shows the positive rotating power spectrum, or Clockwise (CW). In both panels, the blue plot is 16 meters above the bottom, and the red plot is 100 meters above the bottom.

The canyon slope site (Figure 30) shows significantly less energy at the diurnal period in the spring than was displayed in the canyon axis in both rotary components and at both depths. There appears to be slightly more energy at the semi-diurnal frequency on the slope than in the axis, but it does not appear to be a significant difference. There is however a notable difference between depths at this $2/d$ frequency with the CCW showing more energy at 16 MAB, and the CW rotation showing more energy higher in the water column (Figure 30). There is also significant enhancement between the semi-diurnal frequency and the critical frequency near the seafloor.

Figure 30. Rotary power spectra from rotated velocity signal for the canyon slope in the spring. A) shows the negatively rotating power spectrum, or the Counter Clockwise (CCW). B) Shows the positive rotating power spectrum, or Clockwise(CW). In both panels, the blue plot is 16 meters above the bottom, and the red plot is 100 meters above the bottom.

As expected the canyon rim (Figure 31) once again shows the most unique energy profile of the three locations in the rotary spectra. There is very little difference between depths in the CCW rotation at the lower frequencies of interest, with the exception of the semi-diurnal frequency where there is more energy 16 MAB than at 100 MAB but it does not appear to be significant. There is notable enhancement near the bottom above the semi-diurnal frequency. The same is true for the CW rotation, except that the semi-diurnal depth difference in energy does appear to be significant and is the highest energy

for this period at the three locations. The depth enhancement is not as prevalent above the semi-diurnal frequency as well.

Figure 31. Rotary power spectra from rotated velocity signal for canyon axis in the spring. A) Shows the negatively rotating power spectrum, or the Counter Clockwise (CCW). B) Shows the positive rotating power spectrum, or Clockwise (CW). In both panels, the blue plot is 16 meters above the bottom, and the red plot is 100 meters above the bottom.

A.1.2 June/July

The summer season data show several significant differences in the rotary spectra in the canyon axis (Figure 32). There is a near order of magnitude increase in energy at the diurnal frequency at both depths in both the CCW and CW rotation. There is also a decrease in energy between the diurnal and semi-diurnal frequency in the summer season at both depths and in both rotary components. The energy at the semi-diurnal frequency

and there is an increase in energy in the frequencies between the semi-diurnal frequency and the critical frequency at 16 MAB, and in the CCW rotation.

Figure 32. Rotary power spectra from rotated velocity signal for canyon axis in the summer. A) Shows the negatively rotating power spectrum, or the Counter Clockwise (CCW). B) Shows the positive rotating power spectrum, or Clockwise (CW). In both panels, the blue plot is 16 meters above the bottom, and the red plot is 100 meters above the bottom.

The canyon slope data show a similar increase in energy at the semi-diurnal frequency at both depths and in both rotary components, however the increase is larger in the CCW direction (Figure 33). The semi-diurnal frequency shows a drop in energy at both depths in the CCW rotary component, however, there is a dramatic drop in the 16 MAB signal accompanied by an increase in the 100 MAB signal. Finally above the semi-

diurnal frequency there is significant enhancement near the bottom in the CCW rotary component that is not present in the CW.

Figure 33. Rotary power spectra from rotated velocity signal for canyon slope in the summer. A) Shows the negatively rotating power spectrum, or the Counter Clockwise (CCW). B) Shows the positive rotating power spectrum, or Clockwise (CW). In both panels, the blue plot is 16 meters above the bottom, and the red plot is 100 meters above the bottom.

The canyon rim (Figure 34) shows several key differences between seasons as well, starting with an increase in energy at the diurnal frequency at all depths and rotations, but it is more pronounced near the bottom than further up in the water column. There is also a significant difference at the Coriolis frequency between the summer CCW and CW rotations, with a much higher signal in the CW rotary component at both depths, this is consistent with near inertial motions. There is little difference between the higher

frequency signals save the decrease in energy observed in the CW from the spring season. Finally, there is a dramatic increase in semi-diurnal energy at both depths but it is an order of magnitude larger near the bottom. The elevated internal tidal activity in the deep part of the canyon can be explained in terms of the downward propagation and focusing of multiple internal tidal beams generated at the shelf break.

Figure 34. Rotary power spectra from rotated velocity signal for canyon rim in the summer. A) Shows the negatively rotating power spectrum, or the Counter Clockwise (CCW). B) Shows the positive rotating power spectrum, or Clockwise (CW). In both panels, the blue plot is 16 meters above the bottom, and the red plot is 100 meters above the bottom.