THE DYNAMIC RELATIONSHP BETWEEN FORAGING GRAY WHALES (*Eschrichtius robustus*) AND THEIR MYSID PREY (Mysidae), ALONG THE SOUTHWEST COAST OF VANCOUVER ISLAND, BRITISH COLUMBIA

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ABSTRACT

Gray whales (*Eschrichtius robustus* Lilljeborg) forage predominantly on hyper-benthic mysids (Mysidae) along the southwest coast of Vancouver Island, British Columbia. The role of mysids in the abundance and distribution of foraging gray whales prompted interest in this study. I relate the inter- and intra-annual foraging behaviour of gray whales to the number of mysid patches and biomass through boat based surveys of foraging whales, and the application of acoustic techniques for estimating mysid prey. I examine the spatial pattern of foraging gray whales and the 10 m isobath. The abundance and distribution of mysid patches are more common at a water depth of 10 m, and the likely mechanism driving the spatial pattern between foraging gray whales and the 10 m isobath. I examine whale abundance and distribution patterns during three consecutive foraging seasons. More whales forage in years when mysid prey are more abundant, and mysid patches are of larger size and higher in biomass. Whales have a considerable top-down effect on mysid populations. Years of heavy whale predation depletes mysid stocks. Mysid populations tend to increase in years of low whale activity. I examine whale abundance and distribution patterns of habitat use during a foraging season along the southwest coast of Flores Island and Nootka Sound. The abundance of mysid patches and biomass in Nootka Sound does not influence the whales' use of Flores Island; rather the whales exploited both areas concurrently. This study expands the understanding of gray whale habitat use along the southwest coast of Vancouver Island, British Columbia.

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May we all experience adventure within the arms of nature….

CHAPTER 1
GENERAL INTRODUCTION

1.0 Introduction

Predator-prey interactions are fundamental to understanding how organisms utilize their environments because predators generally occupy areas where their prey resources are distributed, and prey can have a considerable influence on the abundance and distribution of their predators (Dunham & Duffus 2001, Estes 1996, Estes *et al.* 2001). With prey resources being naturally patchy, a predator's response to this patchiness may affect its overall foraging success, which has implications for maintenance, growth, and reproduction (Kenney *et al.* 1986, Mursion & Gaskin 1989, Boyd 1996). To forage successfully, a predator in a terrestrial environment must respond to prey resources at various scales of the landscape and its features (Wiens 1976, Johnson *et al*. 2001 2002). However, in a marine environment, predators forage successfully by responding to various scales of prey resource abundance, distribution, and availability (Steele 1989, Fauchald *et al*. 2000, Fauchald & Erikstad 2002, Benoit-Bird & Au 2003).

Marine predators, such as foraging whales, demonstrate a variety of spatial and temporal responses to the abundance and distributions of their prey (Piatt *et al.* 1989, Dunham & Duffus 2001, Benoit-Bird & Au 2003). These studies provide a better understanding of how whales respond to the variability in the physical and biological drivers of their prey, and the role that whales have in the function of marine systems. However, because of their low densities and high mobility, an understanding of the effects of foraging whales on their prey populations, and how whales respond to these effects through space and time, is limited. This may explain why Katona and Whitehead

(1988) and Bowen (1997), suggest that the overall role of foraging cetaceans in marine ecosystems is not well understood, and thus requiring further study. Since resource abundance and availability define cetacean habitat quality (Dunham & Duffus 2001, Baumgartner & Mate 2003, Benoit-Bird & Au 2003, Hastie *et al.* 2004), quantifying how the abundance and distribution of prey resources fluctuates through space and time is critical to understanding cetacean habitat use.

1.1 Foraging ecology of large baleen whales

With their specialized feeding adaptations, baleen whales have two foraging strategies to ensure that they meet their daily metabolic demands while building their lipid cache for use during long periods of fasting (Brodie 1975, Brodie 1977). First, they locate areas where resources are far above average abundance, density, and biomass. Second, they consume large quantities of prey (Kenney *et al.* 1986, Mursion & Gaskin 1989, Piatt & Methven 1992, Dunham & Duffus 2001, Croll *et al*. 2005). Thus, whale abundance and distribution are spatial and temporal representations of the abundance, availability, and quality of their prey resources.

Previous research has demonstrated strong spatial and temporal correlations between foraging whales and high density and biomass prey items. For instance, blue whale (*Balaenoptea musculus*) distribution has been correlated with high concentrations of krill (*Euphausia* spp.) off the southern coast of California (Fiedler *et al*. 1998, Croll *et al*. 1998 2005). North Atlantic right whales (*Eubalaena glacialis*) have been correlated with high concentrations of copepods (*Calanus finmarchius*) in the Gulf of Maine (Kenney *et al.* 1986, Wishner *et al*. 1988, Kann & Wishner 1995) and in the Bay of

Fundy (Mursion & Gaskin 1989, Baumgartner & Mate 2003). Humpback whales (*Megaptera novaeangliae*) have been correlated with high concentrations of schools of sand eel (*Ammodytes americanus*) in the Gulf of Maine (Payne *et al*. 1986), and krill (*Euphausia* spp) off South Georgia Island, Antarctic (Reid *et al*. 2000). Furthermore, whales have been reported to shift their distribution in response to intra- and inter-annual variation in the abundance of prey patches, density, and biomass (Piatt *et al.* 1989, Weinrich *et al.* 1997, Dunham & Duffus 2001), and demonstrate non-linear responses to prey density such as threshold foraging (Piatt & Methven 1992, Olsen 2006).

The real time application of acoustic technology in sampling the water column reveals detailed structure and pattern of targeted organisms (Benoit-Bird & Au 2003). This allows researchers investigating the spatial and temporal interaction between whales and their prey to consider the effects of scale (Levin 1992, Reid *et al*. 2000, Croll *et al.* 1998 2005, Benoit-Bird & Au 2003). These studies, as well as others are conducted on pelagic species, and although they provide information about pelagic systems, multi-scale processes, and how whales utilize them, it limits our understanding of this relationship in a finer scale coastal system where gray whales (*Eschrichtius robustus* Lilljeborg) commonly forage.

Acoustic research has been utilized to investigate the relationship between foraging gray whales and their prey, with most of this research focused on benthic fauna (Nerini & Oliver 1983, Johnson & Nelson 1984, Kvitek & Oliver 1986). Recent research conducted by Olsen (2006) demonstrated that acoustic techniques can be utilized on other gray whale prey such as hyper-benthic mysids (Mysidae).

1.2 Foraging ecology of gray whales

Gray whales, the only species in the Family Eschrichtiidae, are unique among baleen whales in that they primarily forage on benthic prey and usually within coastal waters less than 50 m deep, which provides access to them to study their population and ecology. Currently, there are two populations: the Western North Pacific (WNP) or Korean-Okhotsk population, estimated at approximately 122 individuals (Cooke *et al.* 2006); and, the Eastern North Pacific (ENP) or California-Chukchi population, estimated at approximately 20,000 individuals (Rice & Wolman 1971, Rugh *et al.* 2005, Swartz *et al.* 2006). My research is specific to the ENP population of gray whales.

The ENP population of gray whales annually migrates north during the spring months, February to May, along the west coast of North America from their breeding lagoons in Baja California Sur, Mexico, as a response to the summer increase in their higher latitude prey resources (Rice & Wolman 1971, Kim & Oliver 1989). Along this migration route they forage opportunistically (Nerini 1984, Dunham & Duffus 2001), but are commonly associated with foraging in three regional habitats: the primary foraging grounds in the Bering, Chukchi and Beaufort Seas (Pike 1962, Rice & Wolman 1971, Nerini & Oliver 1983, Johnson & Nelson 1984, Oliver & Slattery 1985, Kim & Oliver 1989, Highsmith & Coyle 1992); the secondary foraging grounds along the coast of the Alaska Peninsula to southeast Alaska (Rice & Wolman 1971, Kim & Oliver 1989, Moore *et al.* 2003, Moore *et al.* 2007); and, the tertiary foraging grounds along the coast of California to Alaska (Pike 1962, Murison *et al.* 1984, Kvitek & Oliver 1986, Guerrero 1989, Kim & Oliver 1989, Duffus 1996, Dunham & Duffus 2001 2002, Newell & Cowles 2006).

Although gray whales do forage opportunistically, they are most commonly observed feeding on benthic amphipods (Gammaridae), which they locate in patches that are high in density and biomass (Nerini 1984, Oliver *et al*. 1984, Highsmith & Coyle 1992, Dunham & Duffus 2001). With the steady increase in the ENP population of gray whales, whales' use of these resources is increasing, particularly in their primary and secondary foraging grounds (Highsmith & Coyle 1992, Rugh *et al*. 2005, Moore *et al.* 2007, Swartz *et al.* 2006, Coyle *et al.* Accepted). With their low growth and fecundity rates, amphipod populations are not recovering under current levels of gray whale predation (Highsmith & Coyle 1992, Coyle *et al.* Accepted). Consequently, researchers have suggested that gray whales will eventually render these amphipod habitats devoid of profitable prey, and thus, seek alternative prey resources elsewhere (Moore *et al.* 2007, Coyle *et al*. Accepted). One such place is Clayoquot Sound, British Columbia, where whales have been consistently observed foraging on a variety of prey items since the late 1980s (Duffus 1996, Bass 2000, Dunham & Duffus 2001).

1.3 Gray whales in Clayoquot Sound

In Clayoquot Sound, prior to 1992, gray whales foraged almost exclusively on amphipods that were high in density and biomass (Kvitek & Oliver 1986, Duffus 1996, Bass 2000). Subsequently, gray whales forage on amphipods in late summer when amphipod body length has reached approximately 6 mm (Dunham & Duffus 2001). It is believed that through the top-down effects of foraging, they have rendered most of these habitats largely devoid of prey (Carruthers 2000). Observations made during this study confirm that the former foraging areas for amphipods attracts few if any whales.

The scale of this scenario is small, an area of about 10 km^2 and a dozen whales. However, the areas have "rested" from heavy foraging, but the prey stocks have not returned to historical levels (Carruthers 2000, Patterson 2006). If this situation provides insight about what is occurring in the primary and secondary foraging grounds, then it implies that further fine scale studies investigating the interaction between forging gray whales and their prey should be conducted, so as to better understand the mechanisms driving the abundance and distribution of gray whales and their prey at population levels. With the lack of amphipod stocks in this area, gray whales forage occasionally for benthic amphipods, pelagic porcelain crab larvae (Porcellanidae), benthic ghost shrimp (Thalassinidae), but more commonly on swarms of hyper-benthic mysids (Dunham & Duffus 2001 2002, Patterson 2004, Short 2005, Olsen 2006). Mysids are shrimp-like crustaceans that are distributed in all aquatic environs, and are characterized as being benthic, hyper-benthic, or pelagic (Mauchline 1980). In the coastal waters between Clayoquot and Nootka Sounds, British Columbia, ten to twelve species of hyper-benthic mysids have been identified, with *Holmesimysis sculpta* W. Tattersall usually the most common (Dunham & Duffus 2001 2002, Patterson 2004). Unlike other gray whale prey, mysids exhibit a strong fidelity for rocky substrates (Mauchline 1980, Murison *et al.* 1984, Hahn & Itzkowitz 1986, Kaartvedt 1989, Kim & Oliver 1989, Stelle 2001, Dunham & Duffus 2002), where they aggregate into swarms ten centimeters to several meters thick (Guerrero 1989, Kim & Oliver 1989, Stelle 2001, Olsen 2006).

1.4 Gray whales and mysids

Within a foraging season, gray whales locate areas where mysid patches are high in density and biomass (Stelle 2001, Dunham & Duffus 2001 2002, Olsen 2006). The within-season variation of mysid resources and their influence on the abundance and distribution of foraging whales is still not well understood. In addition, gray whales have a considerable top-down effect on the abundance and distribution of mysid patches and their biomass (Olsen 2006), but whether this affects the abundance of mysid patches and their biomass, and the response of gray whales over several foraging seasons is not known. Considering that recent research suggests that mysid patches high in density and biomass are composed of larger sized reproductive individuals (Stelle 2001, Patterson 2004), it is likely that gray whales control mysid population growth through foraging pressure. Therefore, the key to understanding this predator-prey dynamic is the linkage between fall and spring stock size of mysid populations, winter conditions, the spring pulse in productivity, and the interplay between prey-rich sites and early summer mysid growth rates. Given this, the purpose of this research is to focus on the implications of summer foraging, movement between foraging sites, and mysid fall stock size.

1.5 Objectives and questions

The current emphasis on mysids as the principal prey item for gray whales foraging within their tertiary range requires that I gain a better understanding of the influences that mysids have on the abundance and distribution of foraging whales, and the effects of foraging on mysid populations. Therefore, I set three objectives for this study. First, quantify mysid abundance and distribution by depth to examine the relationship between foraging gray whales and the 10 m isobath. Second, during three consecutive foraging seasons, quantify mysid patch abundance and biomass to determine the role mysids have in the abundance and distribution of foraging gray whales along the southwest coast of Flores Island. Third, within a foraging season, quantify mysid patch abundance, distribution, and biomass along Flores Island and Nootka Sound to compare with whale use of these discrete areas. To implement these objectives, I asked the following questions: 1) How are gray whales and the 10 m isobath related? I hypothesize that mysid patch abundance and distribution by depth will be at an average water depth of 10 metre. 2) How are foraging gray whales responding to the abundance of mysid patches and biomass over three consecutive foraging seasons, and what are the effects of foraging on mysid populations? I hypothesize that more whales will be observed foraging in years when mysid patches and biomass are abundant. 3) Is the whales' use of Flores Island influenced by mysid patch abundance and biomass documented in Nootka Sound? I hypothesize that whales will forage where mysid patches and biomass are abundant.

The research conducted for this thesis is presented in five chapters. In Chapter 2, I investigate the relationship between foraging gray whales and the 10 m isobath through the examination of mysid patch abundance and distribution by depth (m) along the southwest coast of Flores Island, British Columbia. In Chapter 3, I present a comparison of the foraging response of gray whales to the abundance of mysid patches and biomass along the southwest coast of Flores Island, British Columbia, during three foraging seasons (2004 to 2006). In Chapter 4, I investigate the response of foraging gray whales to the abundance and distribution of mysid patches and patch biomass between Flores

Island and Nootka Sound during the summer of 2006. Finally, Chapter 5 is a summary of my findings and their implications within the body of cetacean predator-prey research.

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CHAPTER 2
LIVING ON THE LINE: A RELATIONSHIP BETWEEN FORAGING GRAY WHALES AND THEIR PREY

2.0 Introduction

The large body size of baleen whales and their high metabolic demands necessitate that they forage efficiently by locating high density and biomass prey resources (Brodie 1977, Kenney *et al.* 1986, Piatt *et al.* 1989, Piatt & Methven 1992, Dunham & Duffus 2001, Baumgartner & Mate 2003, Croll *et al*. 2005). Prey resources generate spatial and temporal patterns that are reflected in the foraging behaviours of baleen whales (Piatt & Methven 1992, Dunham & Duffus 2001, Olsen 2006), and other foraging cetaceans (Benoit-Bird & Au 2003). A recent foraging pattern has been observed for gray whales (*Eschrichtius robustus* Lilljeborg) foraging in Clayoquot Sound, British Columbia (Short 2005), although this pattern has not been quantified and the mechanism driving the formation is poorly understood. Thus, in this chapter, I seek to explore one aspect of the pattern of foraging gray whales in a well-studied habitat along the southwest coast of Vancouver Island, British Columbia.

Gray whales in this area spend most of their time foraging on hyper-benthic mysids (Mysidae) (Dunham & Duffus 2001 2002). Previous research has identified ten to twelve species, with *Holmesimysis sculpta* W. Tattersall usually the most common (Dunham & Duffus 2002, Patterson 2004). Their abundance and distribution is similar to other coastal species of hyper-benthic mysids in that they occupy the littoral zone, where they aggregate in swarms, schools, and shoals (Clutter 1969, Mauchline 1971 1980, Ritz 1994, Patterson 2004).

Ten years (1997 – 2006) of fine spatial scale (1s to 10 km) coastal research have demonstrated a distinct linkage between foraging gray whales and the 10 m isobath, “The Line”, along the southwest coast of Flores Island, British Columbia (Figure 1). During this period, 53% of whales forage within 250 m of the 10 m isobath. This pattern has been recently observed further north along Hesquiat Peninsula and Nootka Island, in Nootka Sound (Short 2005, present study) (Figure 2). It is unclear whether the mechanism determining this pattern is inherent in the behaviour of the whales or a function of some attribute of their mysid prey. Therefore, the objective of this study is to investigate how foraging gray whales are related to the 10 m isobath by measuring the abundance and distribution of mysid patches by depth (m), relative to the 10 m isobath. I hypothesize that mysid patch abundance and distribution by depth (m) will be greatest at an average water depth of 10 m.

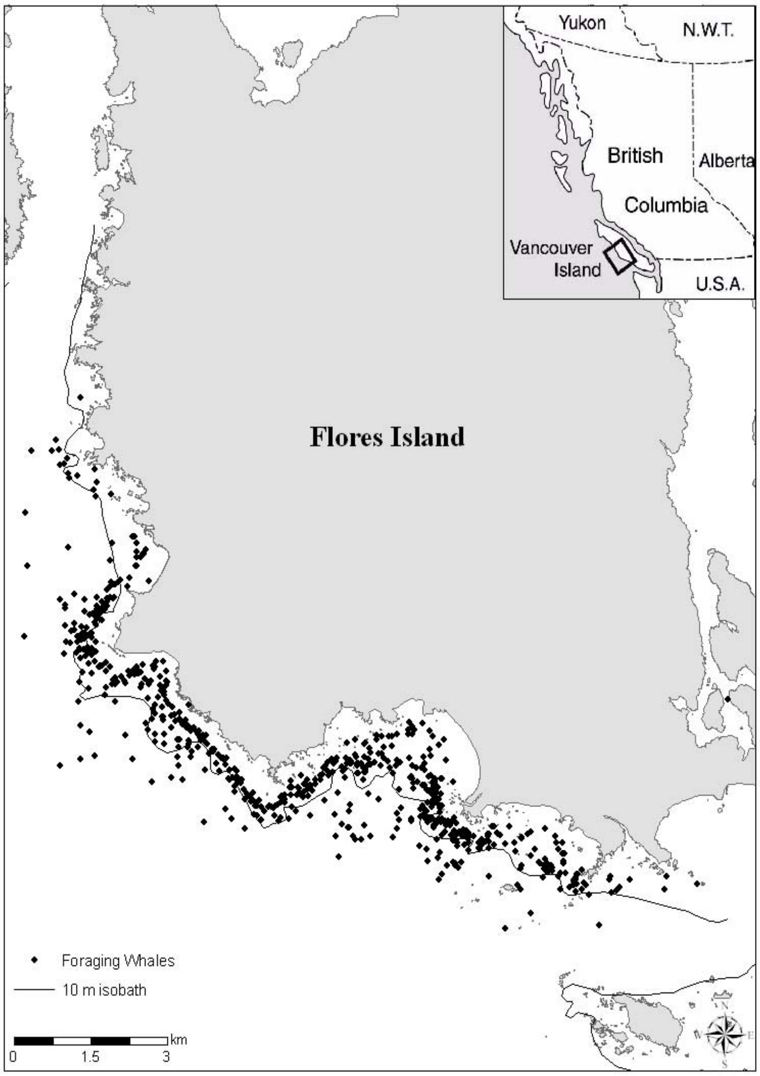

Figure 1. Gray whale foraging events (1997 - 2006) in relation to the 10 m isobath along the southwest coast of Flores Island, British Columbia.

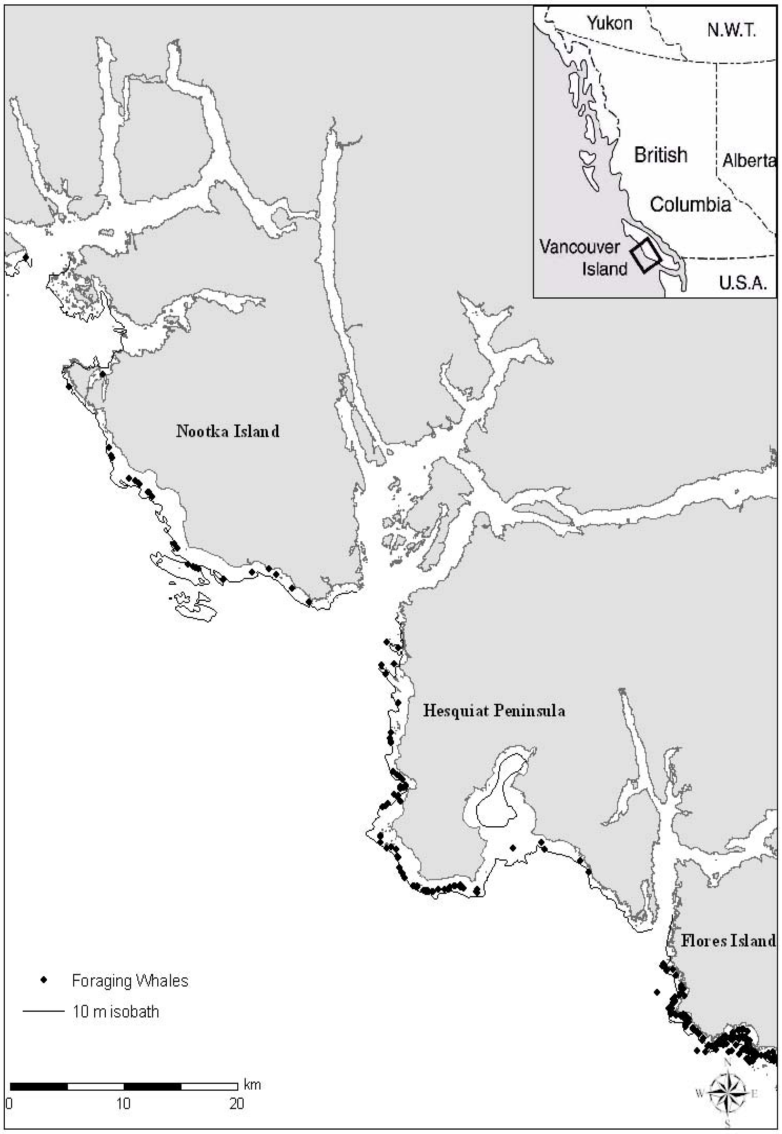

Figure 2. Gray whale foraging events (2003, 2006) in relation to the 10 m isobath along Hesquiat Peninsula and Nootka Island, British Columbia. Note: 2003 data provided by Short (2005).

2.1 Methods

2.1.1 Study area

I conducted this research in nearshore waters < 30 m deep along the southwest coast of Vancouver Island, British Columbia, between Catala Island (49° 50'N, 127° 02'W) in Nootka Sound, and Flores Island (49° 18'N, 126° 11'W) in Clayoquot Sound, from July 10 to October 2 2006 (Figure 3). The area is a coastal mosaic, consisting of sandy beaches, rocky shorelines, and shallow reefs that are dispersed amongst small islands and deep-water inlets. This diverse topography provides habitat for a variety of gray whale prey items: tube dwelling benthic amphipods (Gammaridae), pelagic porcelain crab larvae (Porcellanidae), hyper-benthic mysids (Mysidae) and benthic ghost shrimp (Thalassinidae) (Dunham & Duffus 2001 2002).

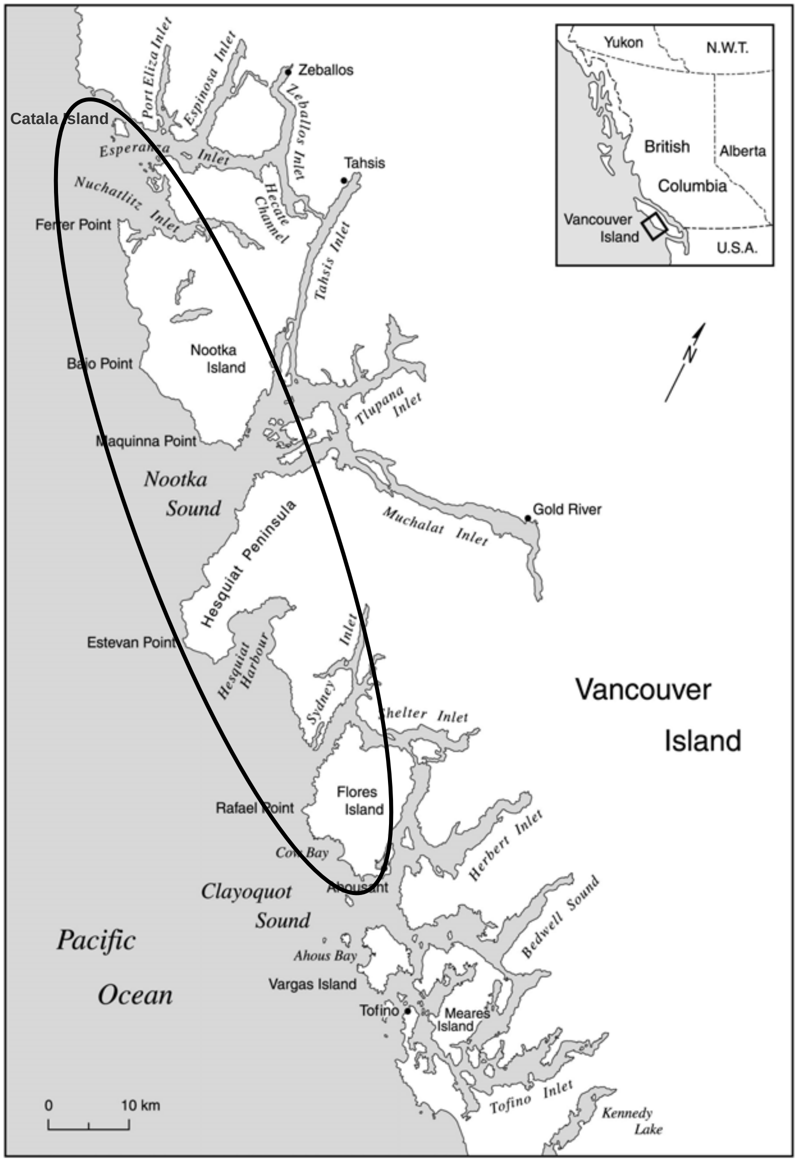

Figure 3. Eclipse represents the extent of the study area from Catala Island in Nootka Sound to Flores Island in Clayoquot Sound, British Columbia.

2.1.2 Survey design

Mysid patch abundance and distribution by depth (m) relative to the 10 m isobath was determined with acoustic surveys along 33 straight line transects positioned perpendicular to the coastline within the study area. Other studies have demonstrated that sampling along transects positioned perpendicular to the coastline reliably estimate mysid patch abundance and distribution by depth (Clutter 1967, Wooldridge 1981 1989). Also, utilizing acoustic surveys with net sampling techniques is a useful method for identifying the location, quantity, and depth of whale prey resources (Kenney & Wishner 1995, Croll *et al*. 2005, Olsen 2006).

Acoustic surveys were conducted in and around areas where gray whales were observed foraging on mysids, and where preliminary and previous year's surveys indicated the presence of mysid patches (Figure 4). Gray whales foraging on mysids are easily discerned by short ventilation intervals, dive times, and discrete circling behaviour over rocky substrates (Murison *et al*. 1984, Guerrero 1989, Mallonée 1991, Dunham & Duffus 2001, Stelle 2001). To prevent acoustic interference, surveys were conducted during sea states of low swell and Beaufort scale < 3.

Four sites were sampled during the study period in 2006. Within each site, a survey line was randomly located perpendicular to shore. The survey was navigated from a water depth of 4 to 24 m (±1 m) using a seven-metre vessel equipped with GPS. This survey was replicated in the opposite direction, keeping a 25 m (±1 m) interval between transects. The distance between transects minimizes the probability of counting the same mysid patch twice. Several replicates were conducted requiring each one hour to complete. I completed 9 transects off Flores Island on July 10, 10 off Hesquiat Peninsula on July 31, 10 off Catala Island on August 13, and 10 off Nootka Island on October 2.

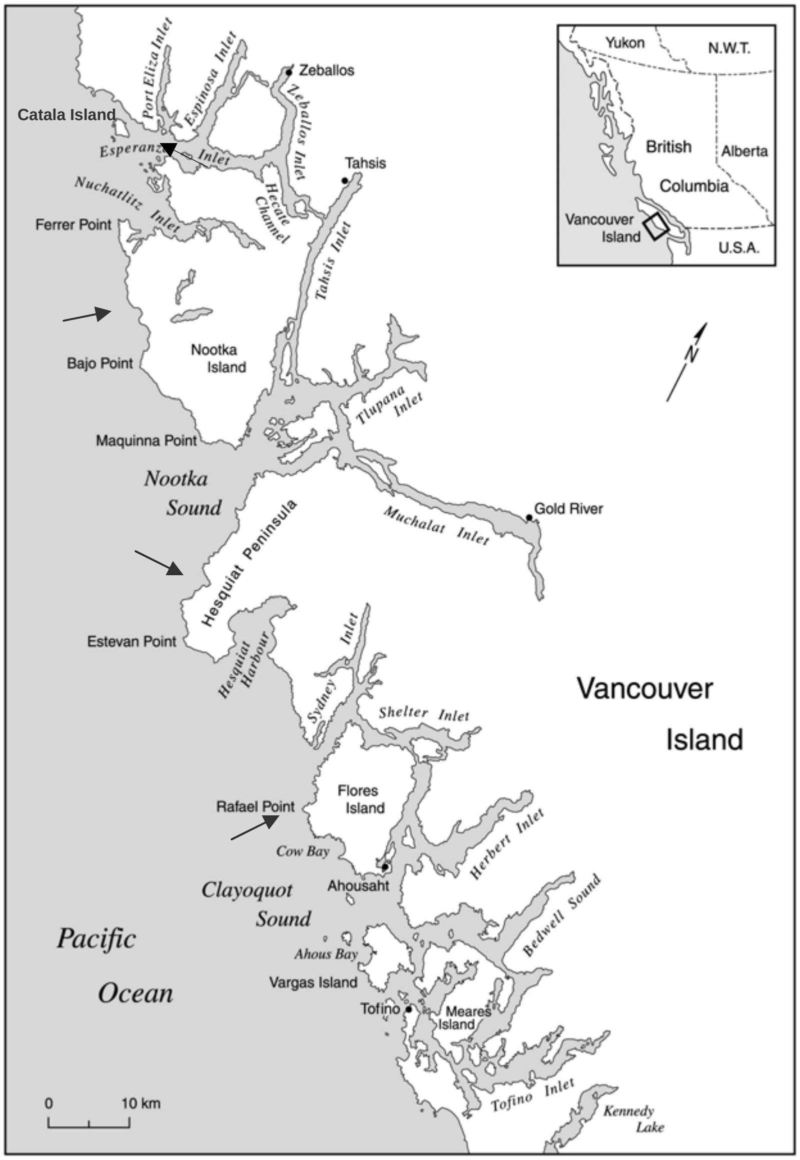

Figure 4. Arrows indicate location of acoustic surveys conducted along the southwest coast of Vancouver Island, British Columbia.

2.1.3 Patch acoustics

The echosounder used in this study was calibrated with multiple standard target spheres (Vagle *et al*. 1996). It uses two transducers operating at 110 kHz and 220 kHz to provide contrast between the patches and bottom materials. Transducers were mounted on a plate side by side 0.3 m apart and submerged 0.5 m below the surface of the water alongside the vessel. During surveys, the vessel maintained a constant speed of 5.0 knots. The echosounder emitted pings at a pulse length of 200 µs every 0.5 seconds. Return echoes of real time georeferenced (latitude-longitude) mysid patches were received through a customized acoustic software programme and recorded onto a laptop computer. Mysids, represented at target strength of -98 dB (decibels) (Olsen 2006), form carpet-like patches that vary in length and height above the substrate (Figure 5). For each survey, I sampled for mysid patches using an underwater camera and/or bongo-style (2 x 30 cm diameter) plankton net towed through the water column via the vessel.

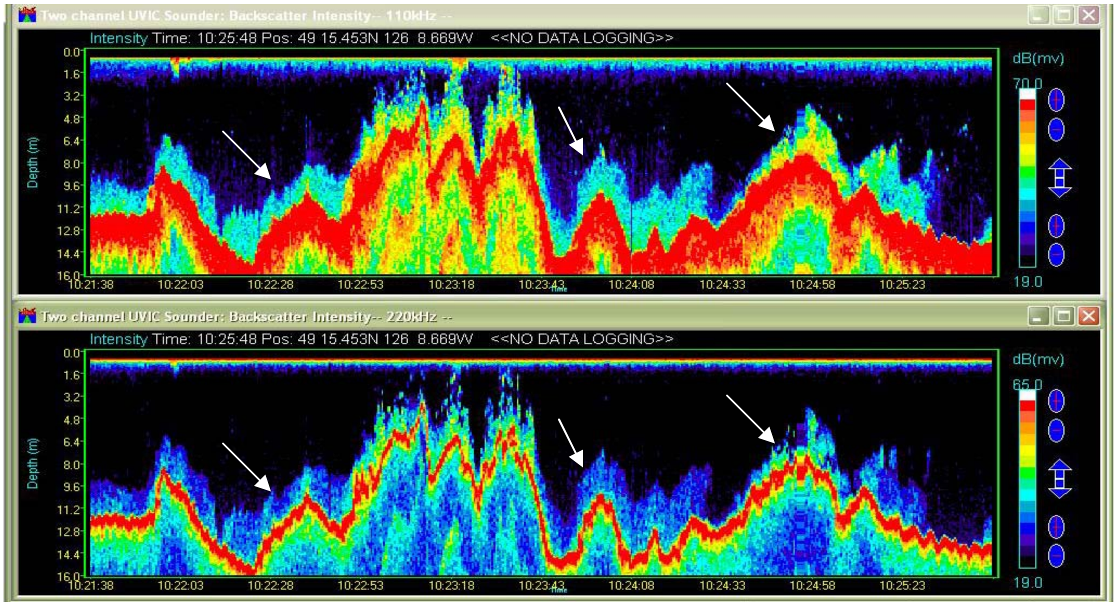

Figure 5. An echogram of mysid patches. Arrows indicate the location of several Patches above the substrate (red band) recorded at 110 kHz (upper tile) and 220 kHz (lower tile).

2.1.4 Patch analysis

To determine patch location (latitude-longitude), depth (m), length (m), and height (m), each mysid patch recorded is delineated through procedures incorporated into the acoustic analysis programme (see Olsen 2006 for patch delineation manual), and processed through Matlab® software (see Appendix I for Matlab® scripts). Considering that mysid patch depth varies with length, mysid patches reported here are mean depths. The mean depth of mysid patches are pooled, and from this I describe and compare mysid patch abundance and distribution by depth (m) relative to the 10 m isobath using descriptive statistics and a one sample t-test (test value = 10) at a significance level of $\alpha = 0.05$ using SPSS® 13.0.

2.2 Results

During the summer of 2006 a total of 149 mysid patches were detected: 28 along Flores Island; 35 along Hesquiat Peninsula; 37 along Nootka Sound; 49 along Catala Island. The abundance and distribution of pooled mysid patches by depth (m) was normal (Kolmogorov-Smirnov test = 1.089, n = 149, p = 0.186) (Figure 6). The mean depth of pooled mysid patches was 10.30 m and was not significantly different from a water depth of 10 m ($t_{149} = 1.326$, df = 148, p = 0.187).

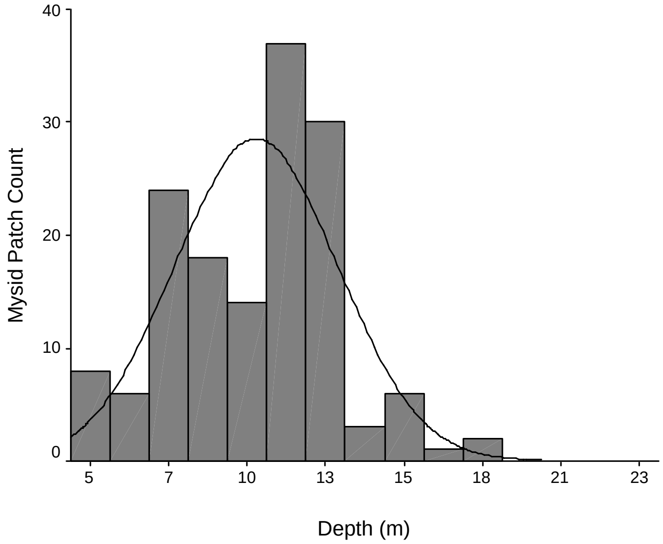

Figure 6. The distribution of mysid patches by depth (m) (n = 149, mean = 10.30, SD = 2.77).

2.3 Discussion

The results suggest that mysid patch abundance and distribution by depth is the likely mechanism for the observed foraging pattern between gray whales and the 10 m isobath along the southwest coast of Vancouver Island, British Columbia. Other whales have been reported to target areas where prey resources are concentrated along frontal and tidal features (Kann & Wishner 1995, Coté & Simard 2005). In these studies, as well as others, physical and biological drivers are responsible for resource abundance and availability.

The relationship between mysid abundance and bathymetry has not previously been documented along the southwest coast of Vancouver Island, but it is known in other areas, although explanations vary (Clutter 1967, Mauchline 1971 1980, Wooldridge 1981, Fosså & Brattegard 1990, Takahashi & Kawaguchi 1995). Generally, mysid patches are less abundant at shallower depths (4 to 7 m) (Figure 6). Shallow depths are closer to shore and exposed to breaking waves and turbulent conditions from ocean swell, which suggest that wave activity may limit patch formation and maintenance. Mysids conserve energy by locating areas where water is calmer and less turbulent (Wooldridge 1981, Buskey 1998). Other studies have reported few mysids in wave active-areas (Wooldridge 1981 1989, Takahashi & Kawaguchi 1995), and where water velocities exceed their swimming speeds (O'Brien 1988, Lawrie *et al.* 1999).

Food availability facilitates mysid patch formation (Mauchline 1980, Ritz 1994, Ritz *et al.* 1997, Folt & Burns 1999). Mysid food resources, such as detritus and plankton are not capable of directed movement and are entirely transported through the water column via water currents (Mauchline 1980). In wave active areas, rip currents transport mysid food resources seaward (Wooldridge 1989). Over sandy substrates these food resources flow relatively easily concentrating at particular depths, which influences mysid abundance and distribution. For instance, Clutter (1967) reported that mysids were more abundant in areas where lateral shore rip currents concentrated detrital and plankton material along the coast of California. Similar, Wooldridge (1981 1989) demonstrated that the increase in abundance of a beach mysid *Gastrosaccus psammodytes* W. Tattersall, was in association with plankton material that was concentrated by lateral shore rip currents along a high-energy surf zone off the southern coast of Africa. In this study, mysids are located over rocky substrates. Thus, it is likely that rip currents produced by local wave activity are dissipated seaward; the substrate restricts current flow. As a result, mysid food resources are suspended and concentrated over topographically complex bottoms (see Figure 5). These bottoms may provide an area where resources are easily accessible to mysids, and/or provide refuge at times when current velocities exceed their swimming speeds (Clutter 1969, Buskey 1998).

According to the results, this may occur at approximately 7 meters and seaward when mysid patch abundance increases. Beyond the depth of 14 m, however, mysid patches are least abundant, indicating that food resources may be limited. It is likely that mysids do occur at deeper and more seaward sites, but those are likely tied to rocks and reefs, which in our site are isolated and sparsely distributed in a matrix of the flat, sandy seafloor.

2.4 Conclusion

The purpose of the chapter was to investigate the relationship between foraging gray whales and the 10 m isobath through the examination of their prey. Mysid patch abundance and distribution is a strong contender for the driving force of the relationship between foraging gray whales and the 10 m isobath along the southwest coast of Vancouver Island. Clearly, the prey concentrate along this depth and the whales follow suit. The attempt to conceptualize mechanisms involved in controlling the abundance and distribution of mysid patches in relation to 10 m isobath should stimulate interest and generate hypotheses about the abundance and behaviour of mysids and the role that food resources, nearshore currents, and substrate features have in their distribution, which is pertinent in understanding gray whale habitat use. A fruitful area of future research for investigating and understanding the distributions of cetacean foraging should be directed at the level of their prey, its spatial behavior and relative productivity in space.

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CHAPTER 3
INTER-ANNUAL FORAGING BY GRAY WHALES

3.0 Introduction

Foraging whales require large amounts of prey to meet their high metabolic demands (Brodie 1977, Kenny *et al.* 1986, Williams *et al*. 2004). Since prey resources are patchy, whales will target patches (swarms, schools) that are high in density and biomass (Piatt *et al.* 1989, Dunham & Duffus 2001, Baumgartner & Mate 2003, Croll *et al*. 2005). If the majority of the prey's population is contained within these patches, baleen whales will exert top-down pressure, and may control prey population growth, community structure (Oliver & Slattery 1985), and ecosystem dynamics (Laws 1985). When foraging events are focused over small areas, these effects are magnified to a point where prey populations become severely depressed, energy flows may become decoupled and sites become devoid of profitable prey (Carruthers 2000). While there is a growing body of literature on the effects of top-down forcing by marine mammals such as walruses (*Odobenus rosmarus*) (Feder *et al.* 1994), killer whales (*Orcinus orca*) (Springer *et al.* 2003, Williams *et al*. 2004) and sea otters (*Enhydra lutris*) (Estes 1996), the general inaccessibility of larger, highly mobile whales has limited research. However, an opportunity exists to investigate this issue with gray whales (*Eschrichtius robustus* Lilljeborg), due to their inshore coastal distribution and reliance on largely sedentary prey.

Gray whales are usually benthic foragers, and have a significant influence on the structure of their prey communities and population size through top-down pressure and habitat disturbance through perturbation (Oliver & Slattery 1985, Highsmith & Coyle

1992, Coyle *et al*. Accepted). With gray whale population estimates at pre-whaling numbers, top-down pressures have increased on their primary and secondary foraging grounds (Coyle *et al*. Accepted). Researchers have suggested that they will eventually consume most of their benthic fauna, consequently forcing them to forage on other prey items outside this range (Highsmith & Coyle 1992, Moore *et al*. 2003, Moore *et al.* 2007, Coyle *et al*. Accepted).

For the past ten years, gray whales have been commonly observed foraging on dense patches of hyper-benthic mysids (Mysidae) along the southwest coast of Vancouver Island. It is now accepted that they constitute the principal prey resource for gray whales in this part of their tertiary range (Nerini 1984, Mursion *et al*. 1984, Kim & Oliver 1989, Stelle 2001, Duham & Duffus 2001). In Clayoquot Sound, ten to twelve species of hyper-benthic mysids have been identified, but unlike their traditional benthic amphipod (Gammaridae) prey, there is little known about the overall effects of top-down pressures exerted by gray whales on these mysid populations. What is known is that within a foraging season, May to September, gray whales have a strong top-down influence by removing mysid patches to levels below foraging thresholds (Olsen 2006). Whether this affects mysid populations during the winter months and is carried over to the next spring is unknown. With the lack of primary productivity during the winter months, and their limited reproductive capacity during this time (Mauchline 1980), mysid populations may have difficulty sustaining enough individuals to survive past the next spring after a summer of heavy gray whale predation. The purpose of the research reported in this chapter is to investigate the response of whales to the abundance of mysid patches and biomass throughout three foraging seasons so as to assess the cumulative effect of top-down foraging by gray whales on mysid populations. In the present study I examine the temporal aspects of the dynamic relationship between foraging gray whales and mysids over three seasons (2004 – 2006) along the southwest coast of Flores Island, British Columbia. I use the estimated abundance of mysid patches and biomass within a foraging season as measures of mysid populations. The response of gray whales to these indices is measured as the number of individuals per survey day within a foraging season. I hypothesize that gray whales' level of use will have a strong association with the number of mysid patches and biomass over three foraging seasons. I expect that in years where there is an abundance of mysid patches and biomass there should be an abundance of whales. The pattern of use within each season will also indicate the nature of within-season patterns of predation in three consecutive years, which will reveal at least part of the relationship between the end of summer season conditions and the state of prey in the following spring.

3.1 Methods

*3.1.1 Study a*rea

This study was conducted in nearshore waters < 30 m deep along the southwest coast of Flores Island (49° 18'N, 126° 11'W), Clayoquot Sound, British Columbia (Figure 1). The study area, approximately 40 km^2, is dominated by rocky shores with sandy bays and beaches, and is constrained by deep-water (> 50 m) glaciated inlets. Gray whales do not forage in the deep-water inlets, thus creating discrete foraging areas (Dunham & Duffus 2001 2002).

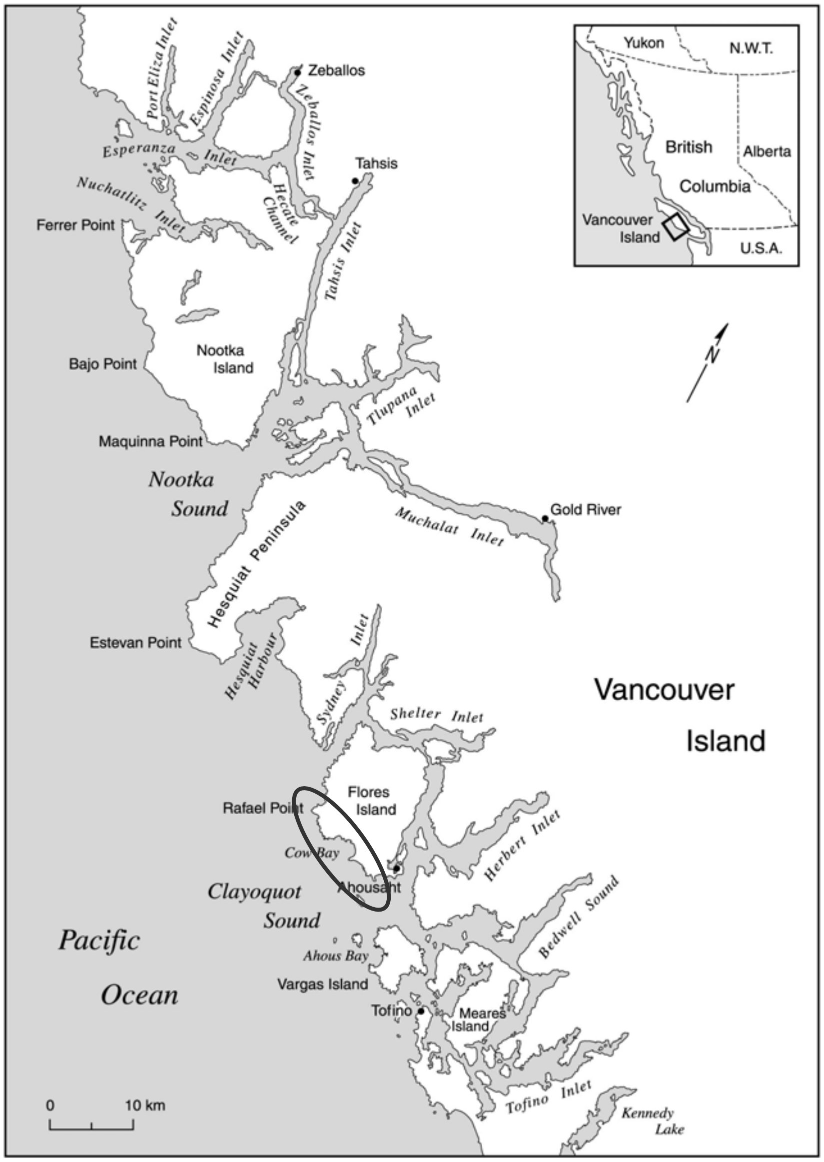

Figure 1. Eclipse represents study area along the southwest coast of Flores Island, British Columbia.

3.1.2 Survey design

To determine the effects of gray whales and their inter-annual foraging response on the abundance of mysid patches and biomass, between year comparisons were made from observations of the number of gray whales and mysid patches along the southwest coast of Flores Island, British Columbia, from May 15 to September 15, 2004, May 13 to September 15, 2005, and May 13 to October 2, 2006.

3.1.3 Whale surveys

Gray whale abundance was measured bi-weekly via boat-based census surveys. For each survey, a seven-metre vessel navigated a pre-defined route within 1 km of shore along the southwest coast of Flores Island (Figure 2). Four observers covered a 360° view for whale ventilations. Upon locating a blow, the vessel approached the whale and determined its behaviour, i.e., traveling, foraging, etc, and recorded its location using GPS. Only gray whales foraging on mysids were used for this study. Mysid foraging is classified by ventilation intervals, dive times, and discrete circling behaviour over rocky substrates (Murison *et al*. 1984, Guerrero 1989, Mallonée 1991, Dunham & Duffus 2001, Stelle 2001). To ensure all whales were counted, surveys were conducted during sea states of low swell and Beaufort scale < 3. Also, close attention was given to the unique identifiable markings on gray whales to prevent counting the same individual twice.

3.1.4 Patch surveys

Mysid patch abundance surveys were conducted weekly along the same route used for recording gray whales, within a day of gray whale surveys, weather permitting (Figure 2). Patch abundance was estimated using an echosounder with two transducers operating at 110 kHz and 220 kHz calibrated with multiple standard target spheres (Vagle *et al*. 1996). Transducers were mounted on a plate side by side 0.3 m apart and submerged 0.5 m below the surface of the water along side the vessel. The echosounder emitted pings at a pulse length of 200 μs every 0.5 seconds. Return echoes of georeferenced (latitude-longitude) mysid patches were received through an acoustic analysis software programme and recorded onto a laptop computer. During surveys the vessel maintained a constant speed of 5.0 knots.

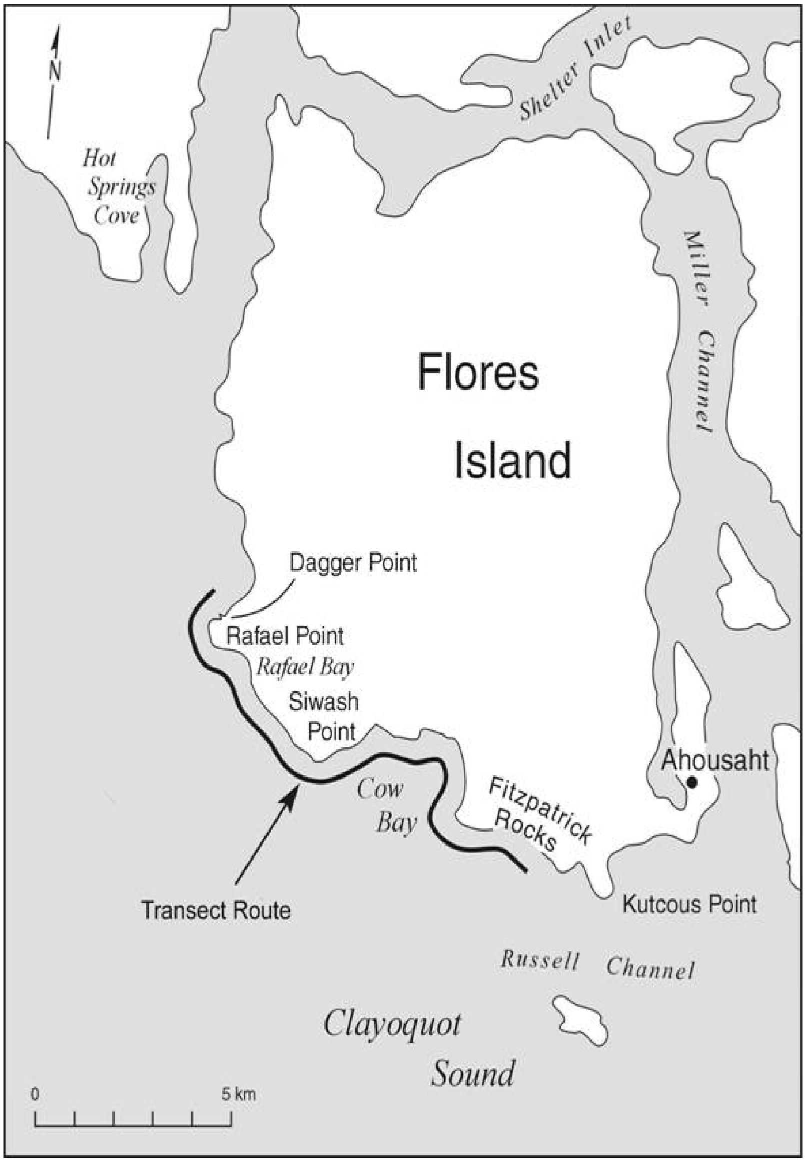

Figure 2. Repeated survey route for gray whale and mysid patch abundance along the southwest coast of Flores Island, British Columbia.

Mysids, represented at target strength of -98 dB (decibels) (Olsen 2006), form carpet-like patches that vary in length and height above the substrate (Figure 3). Groundtruthing of mysid patches was conducted on every other survey in 2004, every survey in 2005, and opportunistically in 2006 using a bongo-style (2 x 30 cm diameter) plankton net towed through the water column via the vessel.

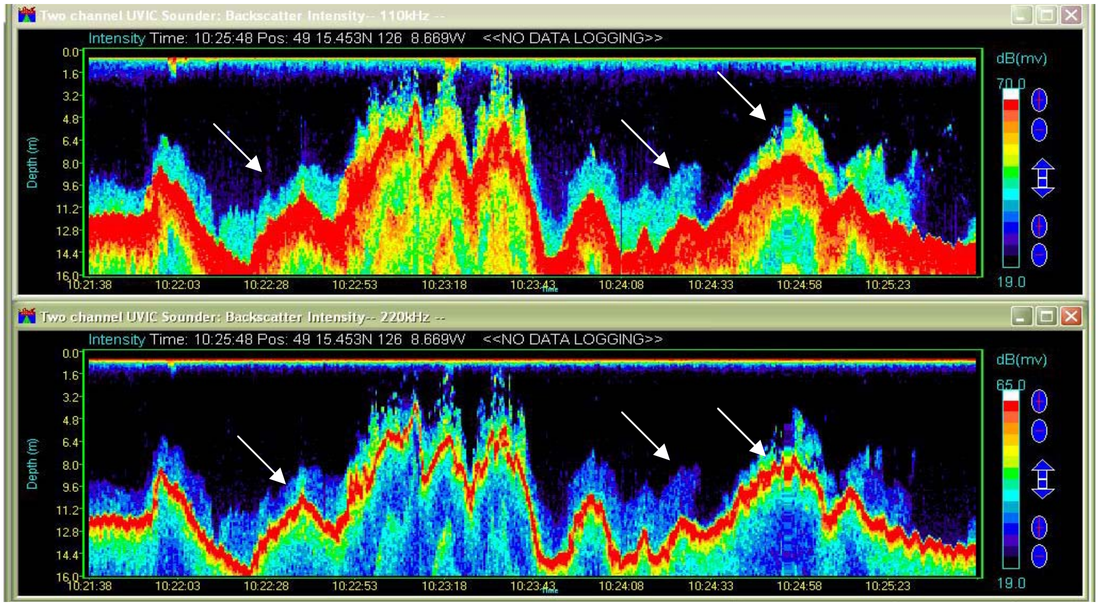

Figure 3. An echogram of mysid patches. Arrows indicate the location of patches above the substrate (red band) recorded at 110 kHz (upper tile) and 220 kHz (lower tile).

3.1.5 Patch analysis

Echograms for each survey for all years were processed through the Matlab® software to determine the number of mysid patches and their attributes: location (latitude - longitude), depth (m), length (m), height (m), patch volume (m^3), and number of mysids · m^{3-1} (see Appendix II for Matlab® script). Patches from each survey were mapped and queried to remove doubtful targets in ARC GIS® 9.0 by using conditional statements that select patches based on *in situ* observations of mysid patches using SCUBA (Stelle

2001). These statements were: 1) mysid patch height must be ≥ 0.5 m and ≤ 12 m; 2) mysid patch length must be ≤ 1 km; and 3) the difference between the number of mysids · m^{3-1} at 110 kHz and number of mysids · m^{3-1} at 220 kHz must be $\leq 10{,}000$. The filtered patches were then sorted by selecting those represented at 110 kHz, as previous work conducted by Olsen (2006) demonstrated that the target strength (-98 dB) of an averaged length (11 mm) *Holmesimysis sculpta* W. Tattersall was best represented at this frequency. From this, mysid patch biomass was determined using procedures reported by Olsen (2006). For interpretation, the number of mysid patches in the study area is a relative measure, not absolute, and biomass is represented in kilograms (kg). To compare whale abundance to estimates of mysid patch abundance and biomass during the study period, I used the means, total counts, ANOVA and Kruskal-Wallis multiple comparisons test statistics. Post-hoc comparisons were employed using Dunnett's C-test and Nemenyi test for parametric and non-parametric data (Zar 1996). Statistical analysis was performed using SPSS® 13.0 at a significance level of $\alpha = 0.05$.

3.2 Results

3.2.1 Whale abundance

Thirty-one gray whale census surveys were conducted in each year of the study. There was a significant difference in the number foraging whales observations in 2004 ($n = 276$) compared to 2005 ($n = 59$) and 2006 ($n =186$) (Chi-square test $\chi^2 = 136.88$, df = 2, $p = 0.003$) (Table 1). The mean number of whales foraging in 2004 was significantly higher than in 2005, but similar to the number in 2006 (Kruskal-Wallis test, $\chi^2 = 6.83$, df = 2, $p = 0.033$, post-hoc Nemenyi test). In 2004, a maximum of 30 whales were observed on July 15, and no whales were observed after August 3 (Figure 4). In contrast, during 2005, a maximum of 5 whales were observed on July 9, with none observed on May 24, June 3, July 16 and 19, and September 5 (Figure 4). In 2006, a maximum of 17 whales were observed on July 10, with none observed on August 8, 17, 19, and 28, September 8 and 11 (Figure 4). Whale foraging efforts during June and July appear to be similar in 2004 (93 %) and 2006 (85 %), but different in 2005 (44 %). In 2005, more whales were observed foraging during July and August (69 %) (Figure 4). Differences in the observations of foraging gray whales during the study period are discussed below with reference to mysid patches and biomass.

Table 1. The number of gray whales observed foraging during the study period. No. Observedis the total count. Mean ± SD is number of animals per survey.

	2004	2005	2006
No. Observed	276	59	186
Mean	8.9 ± 9.2	1.8 ± 1.4	6.0 ± 5.7

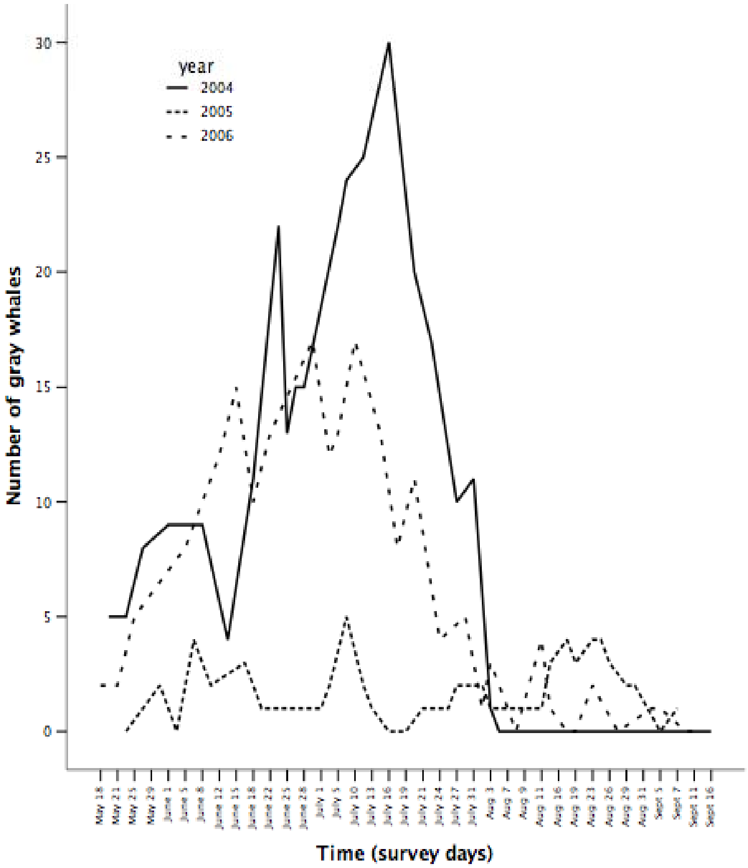

Figure 4. Inter-annual observations of gray whales foraging along the southwest coast of Flores Island, British Columbia.

3.2.2 Whales, patches and biomass

During the study period, 14 mysid surveys were conducted in 2004, 8 in 2005, and 15 in 2006. Technical difficulties in 2005 limited acoustic surveys to July and August. As a result, samples sizes are unequal; thus caution should be used when interpreting these results. In 2004, the variability in the estimated number of patches was less than the variability in the estimated biomass (Table 2). For this period, there was a significant and strong positive correlation between the total number of whale observations and the total estimated number of mysid patches ($r = 0.732$, $n = 14$, $p = 0.003$), but not the total estimated biomass ($r = 0.502$, $n = 14$, $p = 0.067$) (Figure 5 & 6).

In 2005, the variability in the estimated number of patches was less than the variability in the estimated biomass (Table 2). In 2005, no correlation existed between the total number of whale observations and the total estimated number of patches (r = -0.328, n = 8, p = 0.427), and the total estimated biomass (r = -0.171, n = 8, p = 0.685) (Figure 5 & 6). In 2006, the variability in the estimated number of mysid patches was less than the variability in the estimated biomass (Table 2). In 2006, there was a strong negative correlation between the total number of whale observations and total estimated number of patches (r = -0.745, n = 15, p = 0.000), but not total estimated biomass (r = 0.149, n = 15, p = 0.597) (Figure 5 & 6).

Table 2. Inter-annual estimated number of mysid patches and biomass (kg) by survey. Data are means ± SD. CV: Coefficient of variation.

Year	Patches	CV	Biomass	CV
2004	64 ± 54 (n = 14)	0.84	169752 ± 188517 (n = 14)	1.11
2005	33 ± 18 (n = 8)	0.54	43689 ± 59159 (n = 8)	1.35
2006	117 ± 45 (n =15)	0.38	160203 ± 118579 (n =15)	0.74

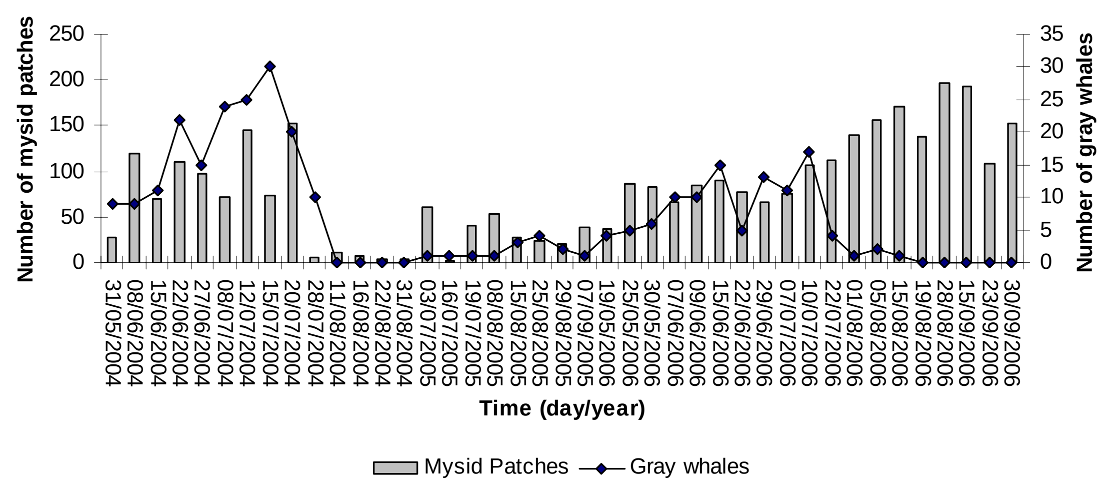

Figure 5. The total number of foraging whales and mysid patches per survey day during the 2004 to 2006 field season. Note: The whale survey conducted nearest to the weekly mysid survey date was used.

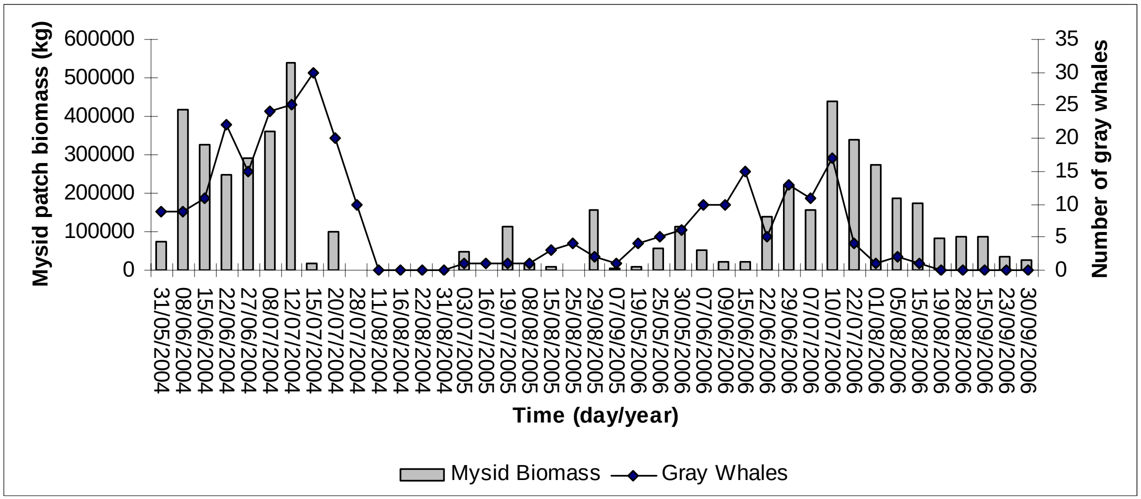

Figure 6. The total number of foraging whales and mysid patches per survey day during the 2004 to 2006 field season. Note: The whale survey conducted nearest to the weekly mysid survey date was used.

The mean number of foraging whale observations was significantly greater in 2004 than in 2005 (Kruskal-Wallis test, $\chi^2 = 6.83$, df = 2, p = 0.03, post-hoc Nemenyi test) (Table 3). During this period, the mean number of patches decreased significantly by 48 % (Kruskal-Wallis test, $\chi^2 = 14.26$, df = 2, $p \leq 0.05$, post-hoc Nemenyi test) (Table

3), and mean biomass decreased significantly by 74 % (Kruskal-Wallis test, χ^2 = 4. 926, df = 2, p = 0.04, post-hoc Nemenyi test) (Table 3). Mean patch biomass significantly decreased 50 % during this period (ANOVA test, F = 25.81, $p \leq 0.05$, post-hoc Dunnett C-test, log transformed data) (Table 3). These data suggests that larger size patches accounted for most of the decrease in estimated biomass during this period. The data also suggest that the number of foraging gray whales in 2004 had a significant top-down influence on mysid populations that may have been realized in 2005 (Figure 5& 6).

In 2005, whales were significantly less abundant than 2006 (Kruskal-Wallis test, χ^2 = 6.83, df = 2, p = 0.03, post-hoc Nemenyi test) (Table 3). During this period, the mean number of patches significantly increased by 72 % (Kruskal-Wallis test, χ^2 = 14.26, df = 2, p = 0.00, post-hoc Nemenyi test) (Table 3), and mean estimated biomass increased significantly by 73 % (Kruskal-Wallis test, χ^2 = 4. 926, df = 2, p = 0.04, post-hoc Nemenyi test) (Table 3). There were no significant changes in mean estimates of patch biomass during this period (ANOVA test, F = 25.81, $p > 0.05$, post-hoc Dunnett C-test, log transformed data) (Table 3). This suggests that patch size does not account for the increase in biomass, but rather that the number of smaller-sized patches accounts for the higher biomass during that period.

Table 3. Inter-annual observations of foraging gray whales, estimated patches and biomass . Whales: number of whales observed foraging per survey. Patches: estimated number of mysid patches per survey. Biomass: estimated biomass (kg) per survey. Patch Biomass: estimated biomass (kg) per patch. Data are means ± SD.

Year	Foraging Whales	Patches	Biomass	Patch Biomass
2004	8.9 ± 9.2 (n = 276)	64 ± 54 (n = 14)	169752 ± 188517 (n = 14)	2649 ± 13002 (n = 897)
2005	1.8 ± 1.4 (n = 59)	33 ± 18 (n = 8)	43689 ± 59159 (n = 8)	1313 ± 7849 (n = 266)
2006	6.0 ± 5.7 (n = 186)	117 ± 45 (n =15)	160203 ± 118579 (n =15)	1367 ± 7846 (n = 1757)

Mean whale observations in 2004 were higher than 2006 (post-hoc Nemenyi test) (Table 3). Mean estimates of biomass were similar in 2004 and 2006 (post-hoc Nemenyi test) (Table 3). Mean number of patches was significantly lower in 2004 than 2006 (Kruskal-Wallis test, $\chi^2 = 14.26$, df = 2, $p \leq 0.05$, post-hoc Nemenyi test) (Table 3), but mean estimates of patch biomass were significantly higher in 2004 than 2006 (ANOVA test, F = 25.81, $p \leq 0.05$, post-hoc Dunnett C-test, log transformed data) (Table 3).

3.3 Discussion

Generally, whale numbers increased and decreased concurrently with the number of patches and biomass during the study period. If more acoustic surveys had been conducted in 2005, perhaps the result of this study would have been more informative. Nonetheless, it appears that when there is an abundance of foraging gray whales along Flores Island, there is an abundance of mysid prey, which supports the hypothesis that the inter-annual abundance and distribution of foraging whales is driven by the abundance and distribution of their primary prey resource (Piatt *et al*. 1989, Dunham & Duffus 2001).

It is unclear which variable has more of an influence on the inter-annual foraging response of gray whales along Flores Island. Since biomass estimates were similar in 2004 and 2006, and fewer patches were estimated in 2004 than 2006, larger sized patches may explain the greater number of whales observed foraging in 2004. Patch biomass estimates in 2004 were the highest during the study period. Gray whales have been reported to be more abundant in years when mysid biomass estimates were higher (Dunham & Duffus 2001, Stelle 2001).

Threshold foraging has been reported for humpback whales (*Megaptera novaeanglia*) (Piatt & Methven 1992) and recently for gray whales (Olsen 2006). In those studies, patch density set limits for the threshold. In this study, there was a negative correlation between the number of foraging whales and the total number of patches in 2006. Mysid patches in 2006 were smaller in biomass than 2004, and similar in 2005; fewer whales were observed foraging that year. It is likely that through foraging gray whales decreased the biomass of patches to a point where it was no longer efficient to forage. This behaviour is predicted by the marginal value theorem, where predators foraging in patchy environments exploit patches until the mean value of that patch is equal to its surroundings, at which time predators leave the area to exploit resources elsewhere and thus reveal thresholds (Charnov 1976).

Gray whales appear to have had a top-down control on mysid populations during the study period. Few studies have reported such findings for other large cetaceans, but Laws (1985) suggested that whales of the southern ocean controlled krill (*Euphausia* *superba*) population growth because when industrial whaling removed these whales, krill populations increased dramatically, consequently increasing other krill eating marine mammal populations. Gray whales appear to be controlling amphipod populations in the Chirikov Basin (Highsmith & Coyle 1992, Coyle *et al.* Accepted). In these studies, slow growth and low fecundity rates prevent amphipod populations from rebounding under intense gray whale foraging. Comparatively, mysids have faster generation times and growth rates, which may be advantageous in the face of intense gray whale foraging. Generally, mysid populations occupying littoral zones in latitudes between 25° and 50° produce three to four generations per year (Mauchline 1980, Meese *et al.* 1994, Stelle 2001). The mysid, *Holmesimysis sculpta* is the main prey item for gray whales in this study, and may produce three generations during the summer (Stelle 2001). With this life history, most of the breeding occurs during the spring, with another generation in the summer, and little during the winter (Mauchline 1980, Wooldridge 1986, Meese *et al.* 1994). Individuals from the final summer generation make up the majority of the winter population, which may breed and contribute to a spring generation. If a significant disturbance occurs, causing high mortality to the summer generation, then the results of that disturbance should be reflected in the size of the populations in the spring of the following year. Given this, intense foraging by gray whales reducing mysid patches and biomass to minimal levels by August 2004, most likely had a major effect on mysid abundance in the spring of 2005. Although no acoustic surveys were conducted at that time, net tows demonstrated few mysids in the area. It has been suggested that increased water temperature and food limitations are factors responsible for reduced mysid abundance in the spring of 2005 along the Oregon coast, which was implicated in low gray whale observations in that area (Newell & Cowles 2006). The results of this study indicated that reduced levels of mysid abundance in the spring 2005 by intense whale foraging in 2004 may have caused mysid populations to become more sensitive to environmental factors, which further delayed or reduced mysid population growth during the summer months (Mauchline 1980, Turpen *et al.* 1994).

The lack of whales in 2005 released predation pressure on mysid populations, which allowed them to grow during the summer. In late August of 2005, the number of patches and biomass was higher than the same period in 2004. With more individuals in August of 2005, there was a larger contribution to the winter and spring generations, which created a higher number of mysid patches and biomass during spring surveys in 2006 than 2005. The higher abundance of mysids at this time increased the capacity for the population to grow during the summer, which would explain the increased response of the number of whales in 2006. A similar response has been reported for the timing of rock fish recruitment and the summer increase in the abundance of *Holmesimysis costata* along the coast of California (Turpen *et al.* 1994).

By August 2006, gray whale foraging decreased mysid biomass, but the number of mysid patches increased, suggesting a shift to smaller sized patches. As a result, whales departed the area and foraged further north. This was confirmed during whale abundance and distribution surveys further north in Nootka Sound. The smaller sized patches may contribute to the winter and spring generations or serve as a valuable food sources for other marine predators (Guerrero 1989, Turpen *et al*. 1994). Nevertheless, further investigation in the summer of 2007 will reveal the implications of top-down forcing by gray whales on mysid populations along Flore Island in 2006.

3.4 Conclusion

This chapter focuses on investigations of the inter-annual foraging response of gray whales to mysid patches and biomass and the potential effects of top-down forcing by gray whales on mysid populations along the southwest coast of Flores Island, British Columbia. During the study period, whale abundance varied concurrently at times with the abundance of mysid patches and biomass. However, mysid patch size may be a more important factor than total number of patches and biomass in dictating the abundance and distribution of foraging gray whales along Flores Island.

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CHAPTER 4
INTRA-ANNUAL FORAGING BY GRAY WHALES

4.0 Introduction

Prey patchiness affects the overall foraging success of predators, which has implications for growth, maintenance, and reproduction (Kenney *et al*. 1986, Murison & Gaskin 1989, Boyd 1996). As a response, predators will adjust their behaviour, abundance, and distribution to forage efficiently (Krebs & Davies 1993, Dunham & Duffus 2001, Benoit-Bird & Au 2003). Baleen whales forage efficiently by locating patches of prey high in density and biomass, and where these patches are more abundant over various scales of space and time (Piatt *et al.* 1989, Weinrich *et al*. 1997, Dunham & Duffus 2001). Most research investigating the response of foraging cetaceans to variations in the abundance of prey patches, density, and biomass has been conducted at coarse spatial scales (100s km) on large pelagic species (e.g., Kenney & Wishner 1995, Croll *et al.* 1998 2005). Within a foraging season, these animals exploit profitable resources by moving over large areas of space (10s to 100s of km) over short periods of time. There have been few studies that document cetacean foraging where animals utilize resource patches at finer spatial scales (1s to 10s of km), and fewer studies where whales exploit resources at the scale of the patch (1s to 10s of m).

Fine spatial scale research documenting the foraging behaviour of gray whales (*Eschrichtius robustus* Lilljeborg) along the southwest coast of Flores Island, British Columbia, has demonstrated that whales commonly forage on patches of hyper-benthic mysids (Mysidae) (Dunham & Duffus 2001, Patterson 2004, Olsen 2006). Within a foraging season, May to September, whales locate areas where mysids are high in density and biomass (Dunham & Duffus 2001), and in certain years, foraging whales can have a strong top-down influence on mysid populations by decreasing the number of mysid patches below a foraging threshold (Olsen 2006). When this occurs, whales abandon this site and search for other profitable areas.

Nootka Sound, British Columbia, approximately 50 km north of Flores Island is an area where whales have been observed foraging on mysids (Patterson 2004, Short 2005). Short (2005) documented the interchange of whales between this site and the Flores Island site, although the driving mechanisms was not quantified and thus poorly understood. The proximity of Nootka Sound to Flores Island adds an interesting component to the dynamic relationship between foraging gray whales and mysids, and the use of these two areas during a summer foraging season. Although Flores Island is a well documented foraging habitat, its use may be influenced by the abundance and availability of mysid patches and biomass in Nootka Sound. Whales can exploit mysid prey in Nootka Sound within about 4 to 7 hrs of Flores Island, given that whales travel at an average speed between 3 to 5 knots. Here I test the hypothesis that the presence of foraging gray whales along Flores Island is influenced by fluctuations in mysid patches and biomass in Nootka Sound. I focus on the spatial aspects of the dynamic relationship between foraging gray whales and mysids over a foraging season using the estimated abundance of mysid patches and biomass within a season as measures of prey availability. The response of gray whales to these prey levels is measured as the number of individuals per survey day within a foraging season. I expect that gray whales' level of use will have a strong association with areas where mysid patches and biomass are greatest.

4.1 Methods

4.1.1 Study area

I conducted this research in nearshore waters (< 30 m) along the southwest coast of Vancouver Island, British Columbia, between Ferrer Point (49° 35’N, 126° 02’W) on Nootka Island, and Entrance Rocks on Flores Island (49° 18’N, 126° 12’W) from May 19 to October 2 2006 (Figure 1). The study area, approximately 240 km^2, is a coastal mosaic, consisting of sandy beaches, rocky shorelines, and shallow water reefs that are dispersed amongst small islands and deep-water (> 50 m) glaciated inlets. Gray whales do not forage in deep-water inlets, but prefer discrete foraging areas along coastal shores, headlands, and sand bays (Dunham & Duffus 2001 2002).

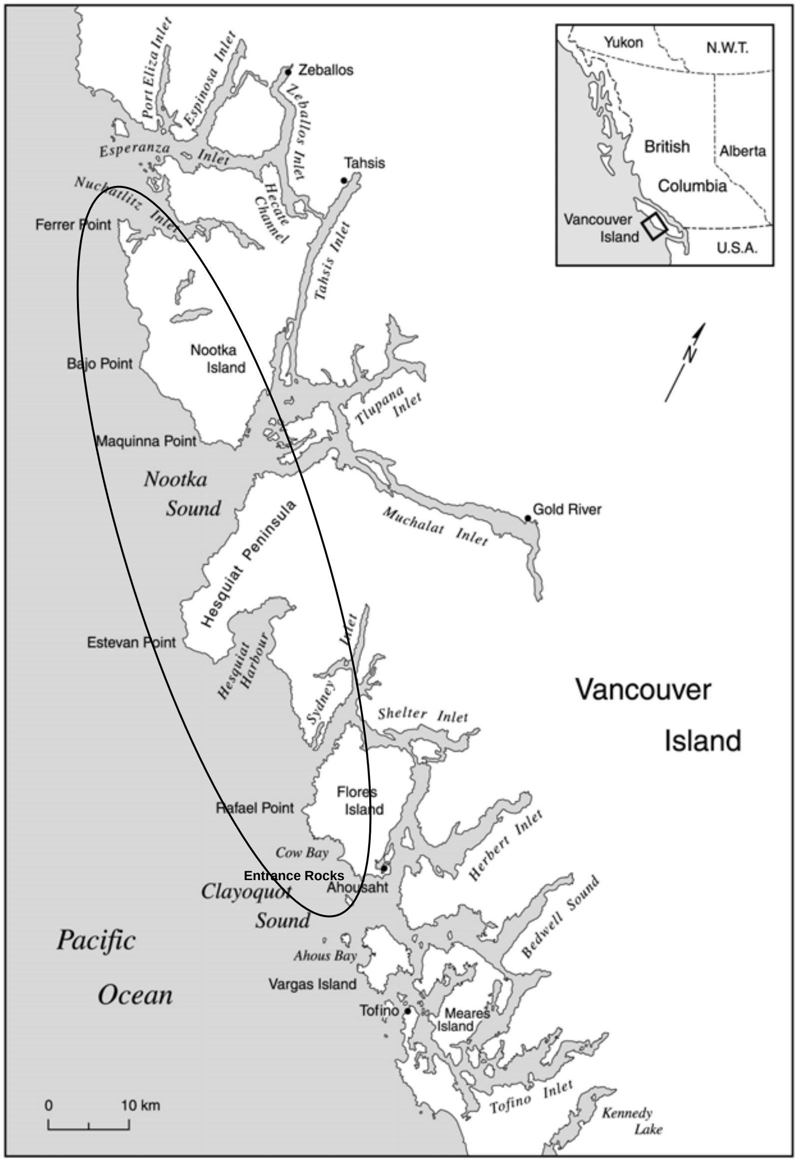

Figure 1. Eclipse represents study area between Nootka Island, Nootka Sound and Flores Island, Clayoquot Sound, along the southwest coast of Vancouver Island, British Columbia.

4.1.2 Survey design

To test the hypothesis that gray whales' use of Flores Island is influenced by the abundance and availability of mysid patches and biomass in Nootka Sound, I compared observations of the number of gray whales, mysid patches, and biomass along the southwest coast of Flores Island and Nootka Sound, British Columbia, from May 19 to October 2 2006.

4.1.3 Patch surveys

Mysid patch abundance and distribution was estimated through boat-based acoustic surveys along a fixed route positioned parallel to shore navigating the 10 m isobath between Nootka and Flores Islands (Figure 2). Several days were needed to survey the study area, weather permitting. During this time, it was assumed that the abundance and distribution of whales did not fluctuate. For instance, whales observed along Flores Island one day would not be observed along Nootka Island the next or following day. This was confirmed through photo-identification of whales taken during several surveys of this research. The partial surveys of the study area were pooled and thus represented a full survey. Approximately fourteen days separated full surveys. For logistical reasons, the starting point and direction navigated for each survey varied. To prevent acoustic interference, surveys were conducted in low swell and Beaufort scale < 3.

Patch abundance was estimated using an echosounder with two transducers operating at 110 kHz and 220 kHz calibrated with multiple standard target spheres (Vagle *et al*. 1996). Transducers were mounted on a plate side by side 0.3 m apart and submerged 0.5 m below the surface of the water along side the vessel. The echosounder emitted pings at a pulse length of 200 µs every 0.5 seconds. Return echoes of georeferenced (latitude-longitude) mysid patches were received through a customized acoustic software programme and recorded onto a laptop computer. During surveys the vessel maintained a constant speed of 5.0 knots.

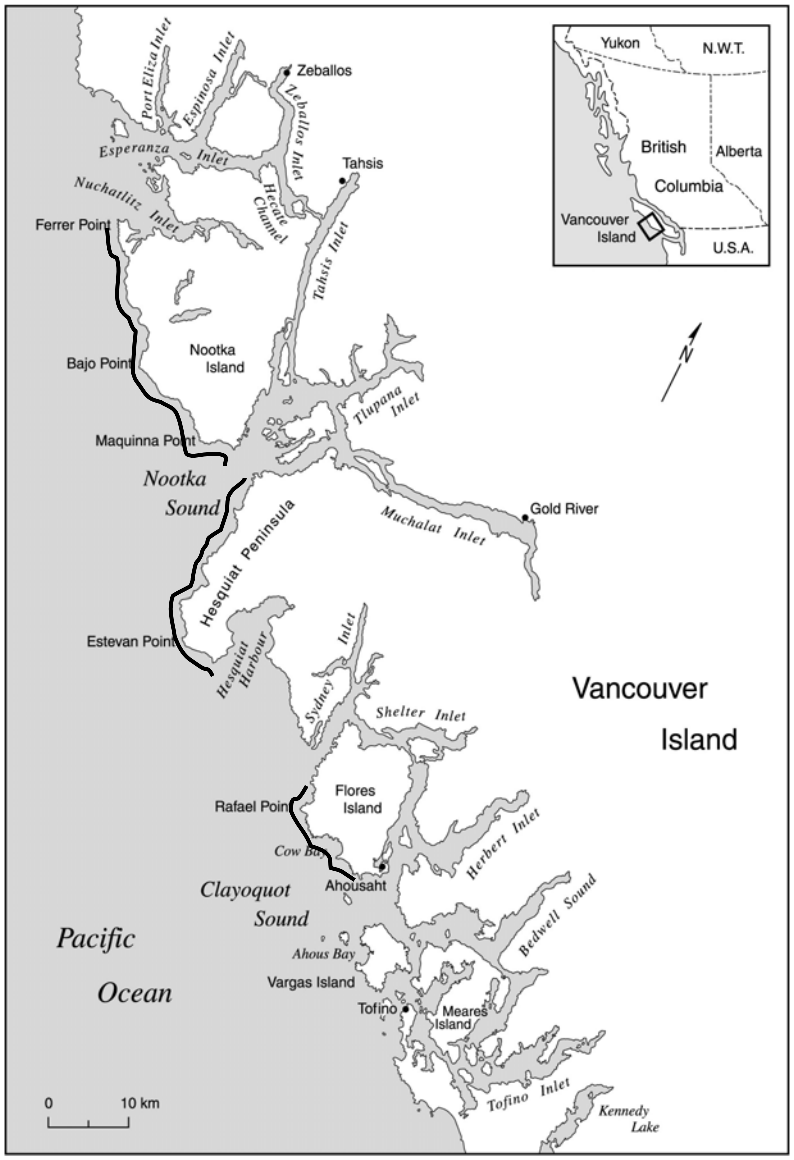

Figure 2. Lines indicate survey routes along Nootka Island, Hesquiat Peninsula, and Flores Island, southwest coast Vancouver Island, British Columbia.

Mysids, represented at target strength of -98 dB (decibels) (Olsen 2006), form carpet-like patches that varying in length and height above the substrate (Figure 3). These patches were groundtruthed using a bongo-style (2 x 30 cm diameter) plankton net pulled through the water column via the vessel.

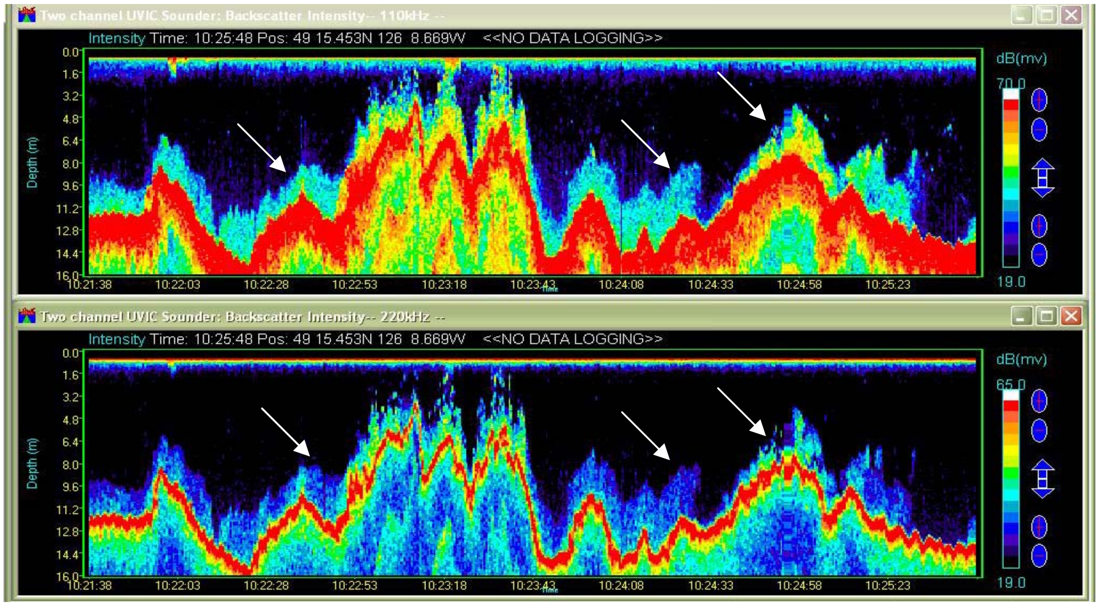

Figure 3. An echogram of mysid patches. Arrows indicate the location of patches above the substrate (red band) recorded at 110 kHz (upper tile) and 220 kHz (lower tile).

4.1.4 Whale surveys

The abundance and distribution of foraging whales was determined while conducting mysid acoustic surveys. As the vessel was moving, four observers scanned 300 m on both sides of the vessel. Only whales foraging on mysids were recorded. This is defined through the observations of gray whales exhibiting short ventilation intervals, dive times, and performing a discrete circling behaviour over rocky substrates (Murison *et al*. 1984, Guerrero 1989, Mallonée 1991, Dunham & Duffus 2001, Stelle 2001). To ensure all whales were counted, surveys were conducted during sea states of low swell and Beaufort scale < 3. Also, close attention was given to the unique identifiable markings on gray whales to prevent counting the same individual twice.

4.1.5 Data analysis

Echograms for each survey were processed through the Matlab® software to determine the number of mysid patches and their attributes: location (latitude-longitude), depth (m), length (m), height (m), patch volume (m^3), and number of mysids · m^{3-1} (see Appendix II for Matlab® script). Patches from each survey were mapped and queried to remove doubtful targets in ARC GIS® 9.0 by using conditional statements that select patches based on *in situ* studies of mysid patches using SCUBA (Stelle 2001). These statements were: 1) mysid patch height must be ≥ 0.5 m and ≤ 12 m; 2) mysid patch length must be ≤ 1 km; and 3) the difference between the number of mysids · m^{3-1} at 110 kHz and number of mysids · m^{3-1} at 220 kHz must be $\leq 10{,}000$. The filtered patches were then sorted by selecting those represented at 110 kHz, as previous work conducted by Olsen (2006) demonstrated that the target strength (-98 dB) of an averaged length (11 mm) *Holmesimysis sculpta* W. Tatterall was best represented at this frequency. From this, patch biomass was determined using procedures reported by Olsen (2006). For interpretation, the number of mysid patches in the study area is a relative measure, not absolute, and biomass is represented in kilograms (kg). I compared foraging whale abundance to estimates of mysid patch abundance and biomass between both areas during the study period using total counts, means, proportions, and Mann-Whitney U test statistics. Statistical analysis was performed using SPSS® 13.0 at a significance level of $\alpha = 0.05$.

4.2 Results

During the summer of 2006 from May 15 to October 2, I conducted seven full surveys of the study area (Table 1). Late in the study period, after July 16, I observed significantly fewer whales foraging along Flores Island (n = 38) than in Nootka Sound (n = 108) ($\chi^2 = 32.38$, df = 1, $p \leq 0.05$) (Figure 4). The overall mean number of whales observed foraging along Flores Island was less than in Nootka Sound (Z = - 2.05, n = 14, p = 0.038) (Table 2).

Table 1. Dates of acoustic and gray whale surveys conducted during the study period in 2006.

Survey ID	Date
1	May 25
2	June 22
3	July 5
4	July 16
5	August 1
6	August 15
7	September 30

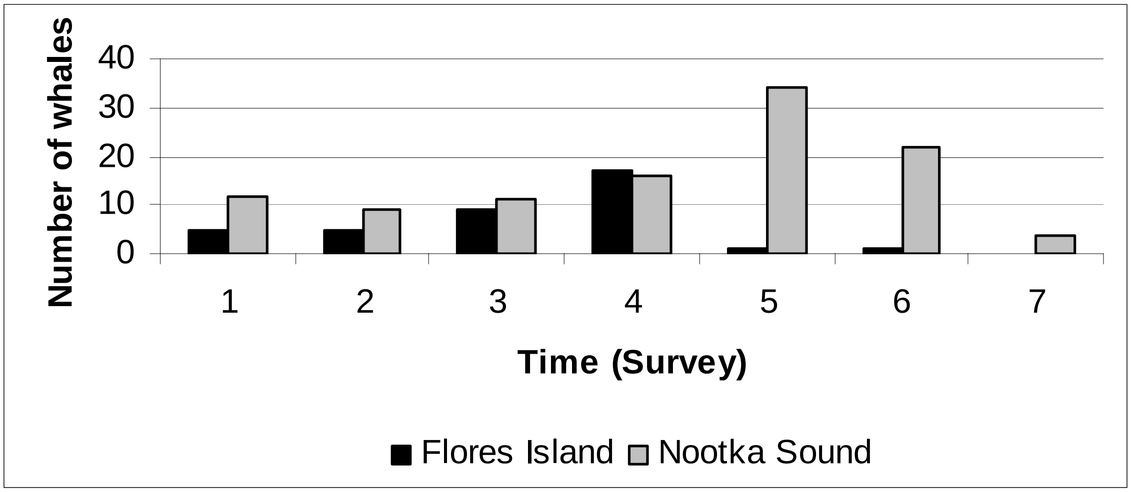

Figure 4: Total number of whales observed foraging per survey period along Flores Island and Nootka Sound during the study period in 2006.

Table 2. Observations of foraging gray whales, mysid patches, and biomass (kg) during the summer foraging season along Flores Island and Nootka Sound in 2006. Whales: number of whales observed foraging per survey. Patches: estimated number of mysid patches per survey. Biomass: estimated biomass (kg) per survey. Data are means ± SD.

Location	Whales	Patches	Biomass
Flores Island (n = 7)	5.43 ± 5.8	108 ± 33	41514 ± 21941
Nootka Sound (n = 7)	15.43 ± 9.9	133 ± 23	173784 ± 29862

The estimated total number of patches was smaller along Flores Island (n = 756) than in Nootka Sound (n = 931) (χ^2 = 18. 15, df = 1, p ≤ 0.05) (Figure 5), but the mean number of patches was similar (Z = -1.46, n = 14, p = 0.165) (Table 2). The mean estimated biomass was significantly less along Flores Island than in Nootka Sound (Z = -2.747, n = 14, p = 0.004) (Table 2; Figure 6). This may explain why I observed fewer whales foraging along Flores Island than in Nootka Sound during the 2006 foraging season.

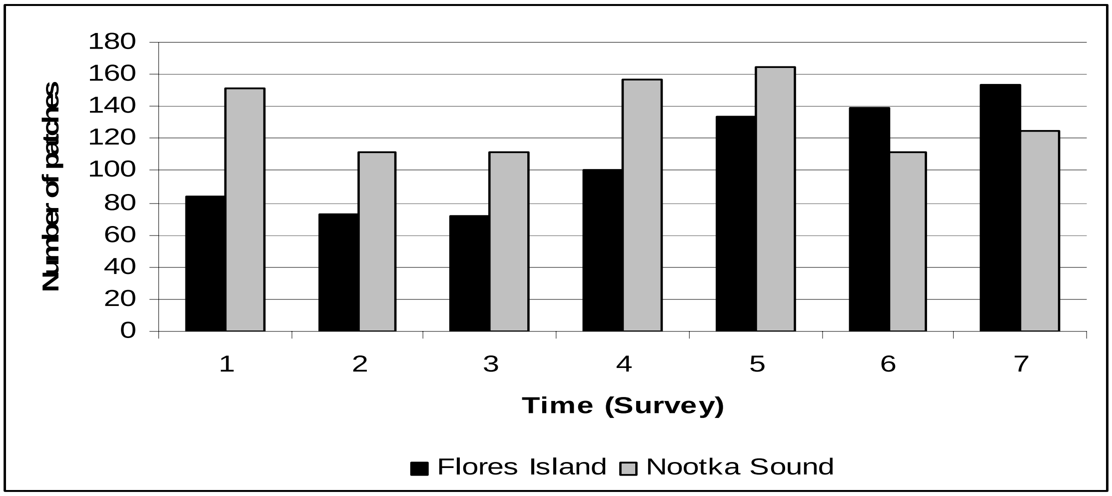

Figure 5: Total estimated number of mysid patches per survey period along Flores Island and Nootka Sound during the study period in 2006.

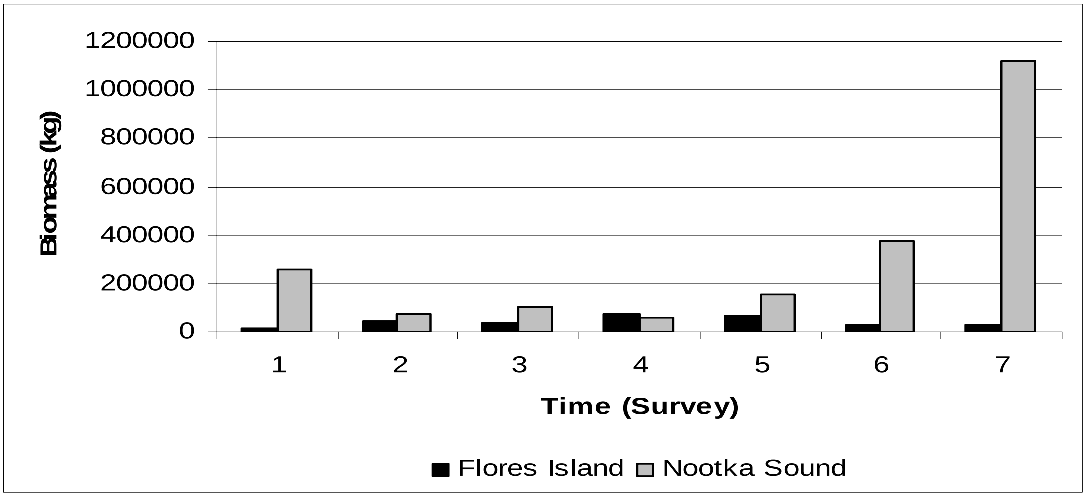

Figure 6: Total estimated mysid biomass per survey period along Flores Island and Nootka Sound during the study period in 2006.

On May 25, I observed fewer whales foraging along Flores Island (n = 5) than in Nootka Sound (n =12) (Table 3) (Figure 1). During this survey, the proportion of total mysid patches along Flores Island (36 %) was smaller than in Nootka Sound (64 %) (χ^2 = 15. 92, df = 1, $p \leq 0.05$) (Table 3), and the proportion of total mysid biomass was less along Flores Island (5 %) than in Nootka Sound (95 %) (χ^2 = 183.39, df = 1, $p \leq 0.05$) (Table 3). Mean patch biomass was also less along Flores Island than in Nootka Sound (Z = -2.11, n = 235, p = 0.035) (Table 4).

Table 3. Comparisons of the total number of whales observed foraging, total estimated number of mysid patches and total estimated mysid biomass (kg) along Flores Island and Nootka Sound during each survey period in 2006. Parentheses represent proportions expressed as percentages of the total estimated number of mysid patches and biomass.

Survey	Flores Island			Nootka Sound		
	Total Foraging Whales	Total Patches (%)	Total Biomass (%)	Total Foraging Whales	Total Patches (%)	Total Biomass (%)
1	5	84 (36)	14069 (5)	12	151 (64)	258921 (95)
2	5	73 (40)	45535 (39)	9	111 (60)	72020 (61)
3	9	72 (39)	57756 (35)	11	111 (61)	105693 (65)
4	17	101 (42)	74719 (45)	16	137 (58)	90598 (55)
5	1	135 (45)	65701 (30)	34	165 (55)	153797 (70)
6	1	139 (56)	26903 (7)	22	111 (44)	373786 (93)
7	0	153 (55)	27918 (2)	4	125 (45)	1121470 (98)

During the next survey, June 22, I observed fewer whales foraging along Flores Island (n = 5) than in Nootka Sound (n = 9), but the number of whales remained the same along Flores Island while decreasing in Nootka Sound since that last survey period (Table 3) (Figure 1). At this time, the proportion of total mysid patches was smaller along Flores Island (39 %) than in Nootka Sound (61 %) ($\chi^2 = 6.28$, df = 1, p = 0.012) and the proportion of total mysid biomass was less along Flores Island (39 %) than in Nootka Sound (61 %) ($\chi^2 = 7.68$, df = 1, p = 0.005) (Table 3). Mean patch biomass was similar in both areas (Z = - 2.558, n = 184, p = 096) during this survey (Table 4).

Table 4. Comparisons of the total number of whales observed foraging and mean estimated mysid patch biomass (kg) along Flores Island and Nootka Sound during each survey period in 2006. Whale data are counts. Patch biomass are mean ± SD.

Survey	Flores Island		Nootka Sound	
	Total Foraging Whales	Mean Patch Biomass	Total Foraging Whales	Mean Patch Biomass
1	5	167 ± 466 (n = 84)	12	1714 ± 5563 (n = 151)
2	5	623 ± 1830 (n = 73)	9	648 ± 5345 (n = 111)
3	9	796 ± 1404 (n = 72)	11	952 ± 5534 (n = 111)
4	17	739 ± 1982 (n = 101)	16	661 ± 1343 (n = 137)
5	1	486 ± 1628 (n = 135)	34	932 ± 4957 (n = 165)
6	1	193 ± 538 (n = 139)	22	3367 ± 21148 (n = 111)
7	0	182 ± 718 (n = 153)	4	8971 ± 36135 (n = 125)

During the July 5 survey #3, I observed fewer whales foraging along Flores Island (n = 9) than in Nootka Sound (n = 11) (Table 3). The proportion of total mysid patches was smaller along Flores Island (39 %) than in Nootka Sound (61 %) (χ^2 = 7.61, df = 1, p = 0.005) (Table 3), and the proportion of total mysid biomass was smaller along Flores Island (35 %) than in Nootka Sound (65 %) (χ^2 = 42.17, df = 1, p = 0.001) (Table 4). Mean patch biomass was similar along Flores Island and Nootka Sound (Z = -1.111, n = 183, p = 0.266). Since May 25, the number of whales observed foraging along Flores Island increased from 5 to 9, while in Nootka Sound, the number of whales remained relatively the same (Table 3).

A similar number of whales were observed foraging along Flores Island (n = 17) and in Nootka Sound (n = 16) during the fourth survey of July 16 (Table 3). At this time, the proportion of total mysid patches was less along Flores Island (42 %) than in Nootka Sound (58%) (χ^2 = 11.06, df = 1, p = 0.005) (Table 3), but the proportion of total mysid biomass was similar along Flores Island (45 %) and Nootka Sound (55 %) (χ^2 = 42.17, df = 1, p = 0.056) (Table 3). Mean patch biomass was also similar along Flores Island and Nootka Sound (Z = - 0.692, n = 258, p = 0.489) (Table 4). The number of whales observed in both areas had increased from the last survey period, and it appeared that gray whales were distributing themselves between Flores Island and Nootka Sound in proportion to mysid biomass.

During the August 1 survey #5, the number of whales observed foraging along Flores Island (n = 1) was considerably less than in Nootka Sound (n = 34) (Table 3). This difference can be explained by the movement of most whales from Flores Island to Nootka Sound (Table 3). During this survey, the proportion of total mysid patches was similar along Flores Island (45 %) and Nootka Sound (55 %) (χ^2 = 2.58, df = 1, p = 0.108) (Table 3), but the proportion of total mysid biomass was not similar along Flores Island (30 %) than in Nootka Sound (70 %) (χ^2 = 53. 28, df = 1, p = 0.000) (Table 3). Mean patch biomass was less along Flores Island than in Nootka Sound (Z = - 1.181, n = 300, p = 0.023) (Table 4). Whales appeared to respond to the decrease in the mysid biomass along Flores Island by moving to Nootka Island where mysid biomass was greater.

On August 15, I observed fewer whales foraging along Flores Island (n = 1) than in Nootka Sound (n = 22) (Table 3). From the last survey period, the number of whales along Flores Island remained the same, while there was a decrease from 34 to 22 in Nootka Sound (Table 3). This indicates that whales did not return to Flores Island but moved out of the study area. During this survey, the proportion of total mysid patches was similar along Flores Island (56 %) and Nootka Sound (44 %) (χ^2 = 3.09, df = 1, p = 0.078) (Table 3), but the proportion of total mysid biomass was less along Flores Island (7 %) than in Nootka Sound (93 %) (χ^2 = 180. 83, df = 1, p = 0.000) (Table 3). Mean patch biomass was less along Flores Island than in Nootka Sound (Z = - 1.834, n = 250, p = 0.067) (Table 4).

I did not observe whales foraging along Flores Island, and few in Nootka Sound (n = 4) during the last survey #7 of the study period (Table 3) (Figure 1). The proportion of total mysid patches during this survey was similar along Flores Island (55 %) and Nootka Sound (45 %) (χ^2 = 2.36, df = 1, p = 0.124) (Table 3). The proportion of total mysid biomass was less along Flores Island (2 %) than in Nootka Sound (98 %) (χ^2 = 252.13, df = 1, p = 0.001) (Table 3), and mean patch biomass was less along Flores Island than in Nootka Sound (Z = - 4. 17, n = 278, p = 0.000) (Table 4). The decrease in the number of whales observed along Flores Island and in Nootka Sound from the last survey period cannot be explained by differences in the data recorded during this survey. Perhaps whales switched to benthic prey during this survey period (Dunham & Duffus 2001).

4.3 Discussion

More gray whales were observed foraging in Nootka Sound than along Flores Island during the study period. At this time, mysid resources were generally more abundant in Nootka Sound than along Flores Island. However, whales continued to forage along Flores Island even though mysid resources were more abundant in Nootka Sound. Therefore, mysid resource abundance and availability in Nootka Sound does not completely determine the abundance and distribution of whales foraging along Flores Island. Thus, this study does not support the hypothesis that gray whale foraging along Flores Island is determined solely by mysid resource abundance and availability in Nootka Sound; rather whales exploit both sites within a foraging season.

Even though mean patch biomass was similar in both areas during two surveys, I expected that most, if not all the whales to forage in Nootka Sound where the abundance of mysid patches and biomass was greatest. My results suggest that the abundance of mysid patches distributed between Flores Island and Nootka Sound and the ability of gray whales to locate them may influence their foraging strategies. For example, Woodby (1984) suggested that when prey patches are superabundant early in the foraging season, thick-billed murres (*Uria lomvia*) would not track prey over larger spatial scales, preferring an ambush method of foraging. This strategy required the least energy expenditure, and was the most efficient method of foraging given resource abundance and availability (Woodby 1984). Like marine birds, gray whales actively seek out mysids, and although mysids are somewhat sedentary, they are very patchy, which requires a certain expenditure of energy to locate them. Since mysids are superabundant throughout the study area early in the foraging season, taking advantage of opportunistic mysid patches along Flores Island may be a more efficient strategy for whales instead of traveling to Nootka Sound where mysid resources are greater in abundance.

As mysid resources are depleted in the study area, the whales ability to locate and forage on them may be more difficult. Whales likely adjust their behaviour to increase or maintain their rate of resource intake (Krebs & Davies 1993, Dunham & Duffus 2001). On July 16, a similar number of whales were observed foraging along Flores Island and in Nootka Sound. At this time, mean patch biomass and the proportion of total mysid biomass were similar in both areas, but the proportion of total mysid patches was not. This result suggests that whales were distributing themselves in proportion to the amount of mysid biomass. This strategy is similar to the ideal free distribution concept, where foragers can minimize within-patch competition by distributing themselves in proportion to resource availability so each individual has a similar rate of intake (Fretwell 1970, Krebs & Davies 1993). A similar pattern has been previously reported for gray whales foraging concurrently on mysids patches and porcelain crab larvae (*Porcellanidae*) along Flores Island (Dunham & Duffus 2001).

Between July 16 and August 1, whales moved north from Flores Island to Nootka Sound. At this time, the proportion of total mysid patches was similar along Flores Island and in Nootka Sound, but mean patch biomass and the proportion of total mysid biomass was greater in Nootka Sound than along Flores Island, suggesting that mysid biomass most likely was the driving mechanism behind the whale's movement. This movement is probably a consequence of whales foraging down mysid stocks along Flores Island to a threshold level where the prey resources cannot support the number of whales in the given area. The ability of whales to find profitable patches along Flores Island may be confounded by the exclusion of individuals by other conspecifics (Krebs &

Davies 1993). Although I did not observe such behaviour, perhaps further studies investigating group foraging dynamics may reveal such constraints.

In the latter part of the study period it is unclear why few whales foraged in Nootka Sound when mysid resources were very abundant. This result may be explained by benthic prey size and the lack of profitable predictable mysid prey sites. For instance, in late August and September when gray whale benthic prey (e.g., amphipods) has reached the minimal size that can be filtered by baleen, whales prey-switch from hyper-benthic to benthic prey (Dunham & Duffus 2001). This was confirmed when gray whales were observed foraging on benthic prey in Cow Bay and Ahous Bay in Clayoquot Sound, about the same time the last mysid surveys were conducted of the study area. In addition to benthic prey size, Dunham & Duffus (2001) suggested that pelagic prey is less predictable than benthic prey, and as a response, gray whales will target less predictable prey first, then forage on benthic prey when pelagic prey is no longer abundant. Hyper-benthic mysids may fit this hypothesis, but they are somewhat predictable as they are tied to rocky substrates features, convergence zones, and creek mouths that whales target from year to year (Nelson *et al.* Accepted).

Other whale species benefit energetically by targeting more predictable sites such as upwelling areas and tidal fronts from year to year (Croll *et al*. 2005, Coté & Simard 2005). Given this, it is likely that profitable, predictable mysid sites were targeted during the foraging season and then exhausted by the time the latter mysid/whale surveys were conducted of the study area. Whales were observed foraging on mysids in specific locations in Nootka Sound, e.g., Barcaster Bay, but not in other areas where on several occasions, sonar echograms indicated abundant mysid prey. Perhaps gray whales do not always forage where mysids are, but only where they are more predictable.

4.4 Conclusion

The purpose of this chapter was to investigate the hypothesis that the presence of foraging gray whales along Flores Island may be driven by fluctuations in mysid patches and biomass in Nootka Sound. It appears that this is not the case. Relative prey abundance may be one factor, but there are other factor at work here. Individual whale experience or preference, chance, competition, or perhaps disturbance may contribute to different habitat use patterns.

When a large number of whales are observed foraging in Nootka Sound, it is likely that they have foraged down mysid stocks along Flores Island and have moved to Nootka Sound making use of available mysid resources. What this study has demonstrated is that the proximity of mysid prey sites along Flores Island and in Nootka Sound can be easily exploited by gray whales within a foraging season. The dynamics between these sites may have an important role in providing habitat for gray whales when resources in either area are subject to disturbances through top-down foraging or bottom-up forcing. Furthermore, with the Eastern North Pacific population of gray whales increasing, fine scale habitat sites such as these within a large tertiary foraging area, may be of greater significance to the whales that utilize them in the near future (Highsmith *et al.* 2006).

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CHAPTER 5
GENERAL DISCUSSION AND CONCLUSION

During foraging events the spatial and temporal distribution of baleen whales is intrinsically associated with areas where prey resources are high in abundance, density, and biomass. For the past ten years, gray whales (*Eschrichtius robustus* Lilljeborg) have been observed primarily foraging on dense patches of hyper-benthic mysids (Mysidae) along the southwest coast of Vancouver Island (Dunham & Duffus 2001). Considering the current importance of mysids to gray whales utilizing these coastal waters, and that there is a limited understanding of this interaction, the purpose of this research is to focus on the implications of summer foraging, movement between foraging sites, and mysid fall stock size. In doing so, I set three objectives: 1) investigate the observed pattern between foraging gray whales and the 10 m isobath; 2) investigate and determine the foraging response of gray whales to the abundance of mysid patches and biomass, and the effects of foraging on mysid populations during three consecutive foraging seasons, and; 3) determine the foraging response of gray whales to the abundance and distribution of mysid patches and biomass between Flores Island and Nootka Sound during the 2006 summer foraging season.

In chapter 2, I determined that a water depth of 10 m is an important attribute of the abundance and distribution of mysids, and the likely mechanism behind the association between foraging gray whales and the 10 m isobath. Mysid distribution is probably driven by a combination of physical and biological drivers working in concert. Observations of echograms during the analysis stage of this study suggest that complex topographical bottoms (see Figure 5 Chapter 2) where mysids were observed play an additional role by either concentrating mysids or their food resources by influencing currents, and/or providing refuge at times when current velocities exceed their swimming speeds (Clutter 1969, Buskey 1998). Given the difficulties associated with investigating the influence of currents on mysids in natural settings, and that mysids have a high degree of site fidelity for rocky substrates, substrate features may be the most important indicator when determining mysid habitat. This, along with acoustic techniques used in this study that can determine micro scale (1s to 10s m) substrate features, may prove to be a valuable area of research when understanding the spatial and temporal variations of mysids and ultimately gray whale habitat use.

In Chapter 3, during three consecutive foraging seasons, I determined that more whales were observed foraging on mysids in 2004 and 2006 than in 2005. The number of mysid patches and mysid biomass were more abundant during those years. Technical difficulties in 2005 limited acoustic surveys that may have contributed more information about mysid abundance in that year and to the overall study. Therefore, the general pattern observed in this study suggests that when whales are abundant along Flores Island, so is their mysid prey.

It was also determined that patch size may be an important aspect of gray whale foraging decisions, rather than the number of patches during the three year study period. For instance, more whales were observed foraging in 2004 when mysid patches were larger and patch biomass estimates were higher. Fewer whales were observed foraging in 2006 when patch size and patch biomass estimates were smaller, although estimates of the number of mysid patches were the highest during the three year study. If diving is the greatest cost to foraging whales, then it is likely that whales expend more energy locating and foraging on more abundant smaller sized patches, rather than foraging on few larger sized patches. Thus, patch biomass or perhaps size may set foraging threshold limits, rather than the number of patches previously reported by Olsen (2006). Furthermore, smaller sized patches may be difficult to locate if mysids take refuge in areas where rocky substrates are more topographically complex. Understanding these components is an important aspect of gray whale foraging that should be further investigated.

Gray whales exerted top-down pressure on local mysid populations during the three year study period. Generally, in 2004 whales reduced mysid stocks, but in 2005, few whales were observed foraging on mysids, and consequently, mysid stocks were released from predation and recovered, becoming more abundant the following spring of 2006. In that year, more whales where observed foraging on mysids, which reduced those stocks. Observations in 2007 report even fewer whales foraging (Feyrer pers. comm.). This pattern suggests that mysids may need a year of low whale activity to ensure that the population size in the fall months contributes to the spring generation of the following year. However, if predation pressure becomes consistent, which is a likely probability considering the annual increase in the Eastern North Pacific gray whale population, whales may control mysid population growth. Furthermore, if mysid populations are held at low levels by gray whale predation, they may be more susceptible to the influence of other disturbances such as changes in coastal upwelling and fluctuating primary productivity that further limit population growth (Mauchline 1980, Turpen *et al.* 1994, Newell & Cowles 2006). This outcome would eventually render this gray whale habitat devoid of profitable mysid prey, similar to the heavily preyed upon amphipod beds located in these same waters. Additional monitoring of mysid habitat sites documenting the interaction between whales and mysids may prove to be beneficial in understanding whale habitat use and effects of foraging on mysid populations in the near future.

Top-down predation pressure by gray whales on mysid populations observed during the study period is unlikely to lead to a trophic cascade, as the food chain between phytoplankton to mysids to gray whales is short. It is likely that gray whales are structuring mysid species diversity in these waters through years of varying predation pressure. For instance, in the absence of gray whale predation, the dominant mysid *Holmesimysis sculpta* W. Tattersall may competitively exclude other mysid species. Thus, under years of varying predation intensities, mysid species diversity is increased, which may explain why ten to twelve species of mysids have been identified in this relatively small, but well used gray whale foraging habitat (Dunham & Duffus 2001, Patterson 2004). Consistent annual net sampling of mysids at this site may be beneficial to test this hypothesis.

In Chapter 4 I did not find any influence of the number of patches and biomass recorded in Nootka Sound on the presence of foraging gray whales along Flores Island, rather whales exploit both areas during the foraging season. The pattern indicates, however, that whales will distribute themselves in proportion to mysid biomass between both areas, and forage on mysid stocks along Flores Island before moving to Nootka Sound in response to more abundant mysid prey. Since the whales approach the study area from a south to north pathway along their migration route, Flores Island may be “first in line” when searching and foraging on mysid prey as the whales move north to Nootka Sound. This strategy may be more efficient in patchy environments in that whales may benefit by foraging on mysid resources that they first encounter along their migration route, rather than expend energy to search for areas where resources are of higher abundance, such as Nootka Sound. It is likely the whales do not function at the scale of “Sounds”, but rather move between them, exploiting smaller scale areas within them that produce profitable mysid prey.

As the Eastern North Pacific population of gray whales increases and subsequent use of their primary and secondary foraging grounds, smaller scale habitat sites such as those described in this study may have greater importance in the maintenance and conservation of the population. That being said, it is recommended that future research investigating the interactions between foraging gray whales and their prey should consider the finer spatial and temporal scale dynamics of this relationship, how it is linked, and how its affects their populations.

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APPENDIX I
MANUAL VERSION OF MATLAB® CODE FOR MYSID PATCH DETECTION AND ATTRIBUTE DESCRIPTION

```
% Svein Vagle, May 2005
% modified Aug 2005  to accept format of mnf files using Matlab V5 release,
chandlerp@pac.dfo-mpo.gc.ca
function ReadPatches
clear
StartDepth=3;
Psi=[0.0634 0.0160];
B=[-85.86 -82.42];  % log10(B)
alpha=[0.04 0.06];  % dB/m
% Choose file
[filename, pathname] = uigetfile('*.dat', 'Choose Sounder file to process:');
datafile=[pathname filename];
patchfile=[pathname filename];
h=find(patchfile=='.');
patchfile(h+1:h+3)='mnf';
patchoutfile=[pathname filename];
h=find(patchoutfile=='.');
patchoutfile(h+1:h+3)='ptc';
% Open files
fid=fopen(datafile);
fim=fopen(patchfile);
fo=fopen(patchoutfile,'wt');
if fid<=0 | fim<=0 | fo<=0
   fprintf('One or the other of the files (%s or %s %s) do not
exist...\n',datafile,patchfile,patchoutfile);
else
   %Determine the size of the sonar file
   fseek(fid,0,1);    % Go to the end of the file
   fsize=ftell(fid);  % Get size of file
   fseek(fid,0,-1);   % Go back to the beginning of the file
   header_mysid=fgetl(fim);
   % Read in sonar file header
   Active=fread(fid, 4, 'char');
   Ch1_Beamwidth=fread(fid, 1, 'float');
   Ch2_Beamwidth=fread(fid, 1, 'float');
   Ch1_ReceiveResponse=fread(fid, 1, 'float');
   Ch2_ReceiveResponse=fread(fid, 1, 'float');
   Ch1_TransmitResponse=fread(fid, 1, 'float');
   Ch2_TransmitResponse=fread(fid, 1, 'float');
   Ch1_Depth=fread(fid, 1, 'float');
   Ch2_Depth=fread(fid, 1, 'float');
   SoftwareVersion=fread(fid, 100, 'char');
```

```
s=sprintf('%s',SoftwareVersion)
USBSerialNo=fread(fid, 16, 'char');
USBDescription=fread(fid, 64, 'char');
if isempty(findstr(s,'Sounder1.0'))
   FirmwareVersion=fread(fid, 100, 'char');
end
Dummies=fread(fid,6,'float');
   PL1=fread(fid, 1, 'int');
PL2=fread(fid, 1, 'int');
BinSize=fread(fid, 1, 'int');
Bins=fread(fid, 1, 'int');
Pingratems=fread(fid, 1, 'int');
Frequency1=fread(fid, 1, 'int');
Frequency2=fread(fid, 1, 'int');
Soundspeed=fread(fid, 1, 'int');
TVGdelay=fread(fid, 1, 'int');
TVGrisetime=fread(fid, 1, 'int');
TVGstartlevel=fread(fid, 1, 'int');
   headersize=ftell(fid);  % Determine the size of the header in bytes
   MaxTime = Bins*(BinSize/Frequency1)*1000;  % In milliseconds
SampleRate=1/((1/Frequency1)*BinSize);
DataLengthPerCh=Bins;
   Pingsize=4+4+12+24+Bins*2+Bins*2;
Number_of_pings=(fsize-headersize)/Pingsize;
   % Make space for the vectors and matrices used to store the data
% This is not required but will speed up things
   PingNumber=zeros(1,Number_of_pings);
Day=zeros(1,Number_of_pings);              % Monthday
GPSTime=zeros(1,Number_of_pings);
Latitude=zeros(1,Number_of_pings);
Longitude=zeros(1,Number_of_pings);
DataCh1=zeros(Number_of_pings,Bins);
DataCh2=zeros(Number_of_pings,Bins);
   range=(Soundspeed/2)*[0:Bins-1]/SampleRate+Ch1_Depth;
L(1)=PL1/110000;
L(2)=PL2/110000;
Volume(1,:)=(Psi(1)/3)*((range+L(1)/4).^3-(range-L(1)/4).^3);
Volume(2,:)=(Psi(2)/3)*((range+L(2)/4).^3-(range-L(2)/4).^3);
TL(1,:)=20*log10(range)+alpha(1)*range;
TL(2,:)=20*log10(range)+alpha(2)*range;
%Coeff(1,:)=B(1)+2*TL(1,:)-10*log10(Volume(1,:))-TVGstartlevel;
%Coeff(2,:)=B(2)+2*TL(2,:)-10*log10(Volume(2,:))-TVGstartlevel;
Coeff(1,:)=B(1)-10*log10(Volume(1,:))-TVGstartlevel;
Coeff(2,:)=B(2)-10*log10(Volume(2,:))-TVGstartlevel;
% Read in patch data
   patchnum=1;
```

```
while 1
   p1=fgetl(fim);
   p2=fgetl(fim);
   if feof(fim)==1,break,end
   p1=words(p1); % the p1 string broken up into discrete words
   dayMon=[p1(1,4:5),'/', p1(1,1:2),'/', p1(1,7:10)];
   hourMinSec=[p1(2,:) p1(3,:)];
   dtg=datenum(dayMon,0)+datenum(hourMinSec,0);
   dateTime=datestr(dtg);
   DD=str2num(p1(1,1:2));
   MM=str2num(p1(1,4:5));
   hh=str2num(dateTime(13:14));
   mm=str2num(dateTime(16:17));
   ss=str2num(dateTime(19:20));
   fpos=str2num(p1(4,:));
   pn=str2num(p1(5,:));
   lat=str2num(p1(6,:));
   lon=str2num(p1(7,:));
   de=str2num(p1(8,:));
   Patch(patchnum).DD=DD;
   Patch(patchnum).MM=MM;
   Patch(patchnum).Day(1)=DD+hh/24+mm/1440+ss/86400;
   Patch(patchnum).Lat(1)=lat;
   Patch(patchnum).Lon(1)=lon;
   Patch(patchnum).Depth(1)=de;
   Patch(patchnum).fpos(1)=fpos;
   Patch(patchnum).pn(1)=pn;
         p2=words(p2); % the p1 string broken up into discrete words
   dayMon=[p2(1,4:5),'/', p2(1,1:2),'/', p2(1,7:10)];
   hourMinSec=[p2(2,:) p2(3,:)];
   dtg=datenum(dayMon,0)+datenum(hourMinSec,0);
   dateTime=datestr(dtg);
   DD=str2num(p1(1,1:2));
   MM=str2num(p1(1,4:5));
   hh=str2num(dateTime(13:14));
   mm=str2num(dateTime(16:17));
   ss=str2num(dateTime(19:20));
   fpos=str2num(p2(4,:));
   pn=str2num(p2(5,:));
   lat=str2num(p2(6,:));
   lon=str2num(p2(7,:));
   de=str2num(p2(8,:));
   Patch(patchnum).DD=DD;
   Patch(patchnum).MM=MM;
   Patch(patchnum).Day(2)=DD+hh/24+mm/1440+ss/86400;
   Patch(patchnum).Lat(2)=lat;
```

```
    Patch(patchnum).Lon(2)=lon;
    Patch(patchnum).Depth(2)=de;
    Patch(patchnum).fpos(2)=fpos;
    Patch(patchnum).pn(2)=pn;
        patchnum=patchnum+1;
  end
  fclose(fim);
  patchnum=patchnum-1;
    % Process all patch data one patch at a time
    firsttime=1;
  outpatcnum=1;
  for n=1:patchnum
    fseek(fid,Patch(n).fpos(1)-Pingsize*10,'bof');
    m=1;
    n
    while 1
      Fpos(m)=ftell(fid);
      PingsAveraged=fread(fid, 1, 'int');
      if feof(fid)==1,break,end
      PingNumber(m)=fread(fid, 1, 'int');
      TimeStr=fread(fid, 12, 'char');  % Time string
      s=sprintf('%s\n',char(TimeStr));
      %fprintf('Time: %s',s);
      cHour(m)=str2num(s(1:2));
      cMinute(m)=str2num(s(4:5));
      cSecond(m)=str2num(s(7:12));

Day(m)=fix(Patch(n).Day(1))+str2num(s(1:2))/24+str2num(s(4:5))/1440+str2num(s(7:12
))/86400;
      GPStime=fread(fid,8,'char');
      s=sprintf('%s\n',char(GPStime));
      GPSLat_deg=fread(fid,1,'int');
      GPSLat_min=fread(fid,1,'float');
      GPSLon_deg=fread(fid,1,'int');
      GPSLon_min=fread(fid,1,'float');
      Latitude(m)=GPSLat_deg+GPSLat_min/60;
      Longitude(m)=GPSLon_deg+GPSLon_min/60;
      DataCh1(m,:)=fread(fid,Bins,'unsigned short')';  % Data from channel 1
      DataCh2(m,:)=fread(fid,Bins,'unsigned short')';  % Data from channel 2
      if PingNumber(m)>=Patch(n).pn(1) & PingNumber(m)<=Patch(n).pn(2)
        Patchdef(m)=1;
      else
        Patchdef(m)=0;
      end
      if PingNumber(m)>=Patch(n).pn(2)+10
        break;
```

```
   end
   m=m+1;
end
Day=Day(1:m);
Latitude=Latitude(1:m);
Longitude=Longitude(1:m);
Patchdef=Patchdef(1:m);
DataCh1=DataCh1(1:m,:);
DataCh2=DataCh2(1:m,:);
h=find(DataCh1<1);
if ~isempty(h)
   DataCh1(h)=1;
end
h=find(DataCh2<1);
if ~isempty(h)
   DataCh2(h)=1;
end
y1=20.*log10(DataCh1)+ones(size(DataCh1,1),1)*Coeff(1,:);
y2=20.*log10(DataCh2)+ones(size(DataCh2,1),1)*Coeff(2,:);
Depth=(Soundspeed/2)*[0:Bins-1]/SampleRate+Ch1_Depth;
      Hour=(Day-fix(Day(1)))*24;
Minute=(Hour-fix(Hour(1)))*60;
h=find(Patchdef>0);
Patchstart(n)=Minute(h(1));
Patchend(n)=Minute(h(length(h)));
Long_m=(Longitude-Longitude(1)).*60.*1852.*sin(Latitude*pi/180);
Lat_m=(Latitude-Latitude(1))*60*1852;
figure(1)
clf
plot(Long_m,Lat_m)
set(gca,'xdir','reverse')
xlabel('Longitude [m]')
ylabel('Latitude [m]')
s=sprintf('File: %s  Boat track',filename);
title(s)
      xb(1,1)=Patchstart(n);
xb(1,2)=Patchstart(n);
xb(2,1)=Patchend(n);
xb(2,2)=Patchend(n);
xb(3,1)=Patchstart(n);
xb(3,2)=Patchend(n);
xb(4,1)=Patchstart(n);
xb(4,2)=Patchend(n);
      yb(1,1)=StartDepth;
yb(1,2)=Patch(patchnum).Depth(1);
yb(2,1)=StartDepth;
```

```
    yb(2,2)=Patch(patchnum).Depth(2);
    yb(3,1)=Patch(patchnum).Depth(1);
    yb(3,2)=Patch(patchnum).Depth(2);
    yb(4,1)=StartDepth;
    yb(4,2)=StartDepth;
        figure(2)
    clf
    subplot(2,1,1)
    imagesc(Minute,Depth,y1')
    caxis([-20 10])
    set(gca,'ylim',[0 20]);
    ylabel('Depth [m]')
    s=sprintf('File: %s   110 kHz',filename);
    title(s)
    colorbar;
    hold on
    xa=axis;
    plot([Patchstart(n) Patchstart(n)],[StartDepth Patch(patchnum).Depth(1)],'w');
    plot([Patchend(n) Patchend(n)],[StartDepth Patch(patchnum).Depth(2)],'w');
    plot([Patchstart(n) Patchend(n)],[Patch(patchnum).Depth(1)
Patch(patchnum).Depth(2)],'w');
    plot([Patchstart(n) Patchend(n)],[StartDepth StartDepth],'w');
    plot([xa(1) xa(2)],[(yb(3,1)+yb(4,1))/2 (yb(3,1)+yb(4,1))/2],'r');
    plot([(xb(1,1)+xb(2,1))/2 (xb(1,1)+xb(2,1))/2],[xa(3) xa(4)],'r');
    subplot(2,1,2)
    imagesc(Minute,Depth,y2')
    caxis([-20 10])
    set(gca,'ylim',[0 20]);
    ylabel('Depth [m]')
    title('220 kHz')
    colorbar;
    hold on
    plot([Patchstart(n) Patchstart(n)],[StartDepth Patch(patchnum).Depth(1)],'w');
    plot([Patchend(n) Patchend(n)],[StartDepth Patch(patchnum).Depth(2)],'w');
    plot([Patchstart(n) Patchend(n)],[Patch(patchnum).Depth(1)
Patch(patchnum).Depth(2)],'w');
    plot([Patchstart(n) Patchend(n)],[StartDepth StartDepth],'w');
    plot([xa(1) xa(2)],[(yb(3,1)+yb(4,1))/2 (yb(3,1)+yb(4,1))/2],'r');
    plot([(xb(1,1)+xb(2,1))/2 (xb(1,1)+xb(2,1))/2],[xa(3) xa(4)],'r');
    s=sprintf('Minutes since %2.2d:00:00 on day %d',fix(Hour(1)),fix(Day(1)));
    xlabel(s)
    ans=input('Is this okay? y/n [n] (Remove patch=r, Quit=q): ','s');
    if isempty(ans)
      ans='n';
    end
        if ans=='n'
```

```
         disp('Use mouse to choose new box limits. (Left click=change, Right
click=done)');
         while(1)
            figure(2)
            [xp,yp,button]=ginput(1);
            if button>1
               break;
            end
            if (xp<xb(1,1) & xp>xa(1)) | (xp>xb(1,1) &
xp<(xb(1,1)+(xb(1,1)+xb(2,1))/2)/2)
               xb(1,1)=xp;
               xb(1,2)=xp;
               xb(3,1)=xp;
               xb(4,1)=xp;
            elseif (xp>xb(2,1) & xp<xa(2)) | (xp<xb(2,1) &
xp>(xb(2,1)+(xb(1,1)+xb(2,1))/2)/2)
               xb(2,1)=xp;
               xb(2,2)=xp;
               xb(3,2)=xp;
               xb(4,2)=xp;
            elseif (yp<yb(4,1) & yp>xa(3)) | (yp>yb(4,1) & yp<(yb(4,1)+yb(3,1))/2 &
xp>(xb(1,1)+(xb(1,1)+xb(2,1))/2)/2)
               yb(4,1)=yp;
               yb(4,2)=yp;
               yb(1,1)=yp;
               yb(2,1)=yp;
            elseif xp>(xb(1,1)+(xb(1,1)+xb(2,1))/2)/2 & xp<(xb(1,1)+xb(2,1))/2
               if (yp>yb(3,1) & yp<xa(4)) | yp<yb(3,1)
                  yb(3,1)=yp;
                  yb(1,2)=yp;
               end
            elseif xp<(xb(2,1)+(xb(1,1)+xb(2,1))/2)/2 & xp>(xb(1,1)+xb(2,1))/2
               if (yp>yb(3,2) & yp<xa(4)) | yp<yb(3,2)
                  yb(3,2)=yp;
                  yb(2,2)=yp;
               end
            end
            figure(2)
            clf
            subplot(2,1,1)
            imagesc(Minute,Depth,y1')
            caxis([-20 10])
            set(gca,'ylim',[0 20]);
            ylabel('Depth [m]')
            s=sprintf('File: %s   110 kHz',filename);
            title(s)
```

```
          colorbar;
          hold on
          xa=axis;
          for ll=1:4
             plot(xb(ll,:),yb(ll,:),'w');
          end
          plot([xa(1) xa(2)],[(yb(3,1)+yb(4,1))/2 (yb(3,1)+yb(4,1))/2],'r');
          plot([(xb(1,1)+xb(2,1))/2 (xb(1,1)+xb(2,1))/2],[xa(3) xa(4)],'r');
          subplot(2,1,2)
          imagesc(Minute,Depth,y2')
          caxis([-20 10])
          set(gca,'ylim',[0 20]);
          ylabel('Depth [m]')
          title('220 kHz')
          colorbar;
          hold on
          for ll=1:4
             plot(xb(ll,:),yb(ll,:),'w');
          end
          plot([xa(1) xa(2)],[(yb(3,1)+yb(4,1))/2 (yb(3,1)+yb(4,1))/2],'r');
          plot([(xb(1,1)+xb(2,1))/2 (xb(1,1)+xb(2,1))/2],[xa(3) xa(4)],'r');
          s=sprintf('Minutes since %2.2d:00:00 on day %d',fix(Hour(1)),fix(Day(1)));
          xlabel(s)
       end
    end
    if ans~='q' & ans~='r'
       % Vertically integrate TS and average over patch to get TS per sq m of
       % patch. Also calculate length of patch and mean thickness of patch
             patch_t0=xb(1,1);
       patch_t1=xb(2,1);
       patch_d0=yb(1,1);
       patch_d1a=yb(1,2);
       patch_d1b=yb(2,2);
       h=find(Minute>=patch_t0&Minute<=patch_t1);
       figure(1)
       hold on
       plot(Long_m(h),Lat_m(h),'r');
       Lo1=Long_m(h(1));
       Lo2=Long_m(h(length(h)));
       La1=Lat_m(h(1));
       La2=Lat_m(h(length(h)));
       patchsize=sqrt((Lo2-Lo1)^2+(La2-La1)^2);
       patchdepth=(patch_d1a+patch_d1b)/2-patch_d0;
             z=y1(h,:);
       slope=(patch_d1b-patch_d1a)/(length(h)-1);
       dthres=slope*([1:length(h)]-1)+patch_d1a;
```

```
    for mm=1:length(h)
      xs=10.^(z(mm,:)/10);
      hd=find(Depth>=patch_d0&Depth<=dthres(mm));
      TS(mm)=trapz(Depth(hd),xs(hd));
    end
    TSmean1=10*log10(mean(TS));
    TS1=10*log10(TS);
          z=y2(h,:);
    for mm=1:length(h)
      xs=10.^(z(mm,:)/10);
      hd=find(Depth>=patch_d0&Depth<=dthres(mm));
      TS(mm)=trapz(Depth(hd),xs(hd));
    end
    TSmean2=10*log10(mean(TS));
    TS2=10*log10(TS);
    if firsttime==1
      fprintf(fo,'Day/Month   Time     Filepos  Pingnumber  Latitude Longitude
Waterdepth[m] Patchlength[m] Patchthickness[m] Sa_110kHz Sa_220kHz\n');
      firsttime=0;
    end
    k=h(1);
    fprintf(fo,'%2.2d/%2.2d  %2.2d:%2.2d:%6.3f %9.9d %6.6d      %8.5f  %9.5f
%6.2f  %6.1f  %5.1f  %5.2f  %5.2f\n',...

Patch(n).DD,Patch(n).MM,cHour(k),cMinute(k),cSecond(k),Fpos(k),PingNumber(k),...
      Latitude(k),Longitude(k),patch_d1a,patchsize,patchdepth,TSmean1,TSmean2);
    k=h(length(h));
    fprintf(fo,'%2.2d/%2.2d  %2.2d:%2.2d:%6.3f %9.9d %6.6d      %8.5f  %9.5f
%6.2f  %6.1f  %5.1f  %5.2f  %5.2f\n',...

Patch(n).DD,Patch(n).MM,cHour(k),cMinute(k),cSecond(k),Fpos(k),PingNumber(k),...
      Latitude(k),Longitude(k),patch_d1b,patchsize,patchdepth,TSmean1,TSmean2);
          P(outpatcnum).La=Latitude(k);
    P(outpatcnum).Lo=Longitude(k);
    P(outpatcnum).Size=patchsize;
    P(outpatcnum).z=patchdepth;
    P(outpatcnum).d=(patch_d1b+patch_d1a)/2;
    P(outpatcnum).TS1=TSmean1;
    P(outpatcnum).TS2=TSmean2;
          theta=[0:pi/360:2*pi];
    figure(3)
    clf
    calib=0.0001;
    for o=1:outpatcnum
      xo=P(o).Size*calib*cos(theta);
      yo=P(o).Size*calib*sin(theta);
```

```
            plot(P(o).Lo+xo,P(o).La+yo)
            hold on
         end
         outpatcnum=outpatcnum+1;
      end
      if ans=='q'
         break;
      end
   end
   fclose('all');
end
function all_words = words(input_string)
remainder = input_string;
all_words = '';
while (any(remainder))
   [chopped,remainder] = strtok(remainder);
   all_words = strvcat(all_words,chopped);
end
```

APPENDIX II
AUTOMATED VERSION OF MATLAB® CODE FOR MYSID PATCH DETECTION AND ATTRIBUTE DESCRIPTION

```
% Script used to read in UVIC sounder raw files, calibrate the data,
% detect the bottom and mysid patches and write out patch information to ascii files
%
% December 13, 2006, SV
clear
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% System parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Psi=[0.0634 0.0160];
B=[-166.07 -157.79];    % Calibration coefficients log10(B)
alpha=[0.04 0.06];      % Attenuation in dB/m
MysidTS= -98;           %Estimated TS of mysid in dB
defaultyear=2006;        % Default data set year
defaultdir='d:\software\UVICsounder\Nov06\'; % Start directory to use for looking for
data files
thres1= -40;  %Threshold level for detecting the sea floor in 110kHz channel (dB)
thres2= -40;  %Threshold level for detecting the sea floor in 220kHz channel (dB)
PatchThreshold1 = -80;
DynamicThreshold=1;
PatchThreshold2 = -70;
PatchBin1 = 5;
PatchBin2 = 5;
NumberThreshold = 50;
Maximum_depth=30;  %Maximum water depth in meter, used for plotting of data
Display_intermediates=1;        %Yes=1. Set to 0 (No) if not interested in seeing
intermediate plots during processing
Display_Bottom_referenced_Sv=1; %Yes=1. Set to 0 (No) if not interested in seeing
these data
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
yt=sprintf('Field work year? 04, 05, 06 or ? [default=%d]:',defaultyear);
%Remove comments on the next line
%pathname = uigetdir(defaultdir,'Choose Directory where raw sounder files are
located:');
while 1
   year=input(yt,'s');
   year=str2num(year);
   if isempty(year)
      year=defaultyear;
   end
   if year<2000
```

```
      year=year+2000;

   end
   if year>2003
      break;
   end
 end
 pathname=sprintf('C:\\DATA\\%2.2d',year-2000);  % Comment out this line
 FileList = get_files_of_type('.dat',pathname);
pathname=[pathname '\']
 if year==2004
   B(1)=B(1)-8;
end
patchnum=1;
clear Patch
if ~isempty(FileList)                    % Files exist, continue processing
   fprintf('Found %d sounder files\n',size(FileList,1))
   for filenum=1:size(FileList,1)
      filename_in=FileList(filenum,:);
      fprintf('Processing %s%s  (File %d of %d)\n',pathname,filename_in, filenum,
size(FileList,1));
      [Header,fi]=ReadFileHeader(Psi, B, alpha, year, pathname,filename_in);
      PingNumber=zeros(1,Header.Number_of_pings);
      Day=zeros(1,Header.Number_of_pings);                % Monthday
      Mattime=zeros(1,Header.Number_of_pings);
      GPSTime=zeros(1,Header.Number_of_pings);
      Latitude=zeros(1,Header.Number_of_pings);
      Longitude=zeros(1,Header.Number_of_pings);
      Sv1=zeros(Header.Number_of_pings,Header.Bins);
      Sv2=zeros(Header.Number_of_pings,Header.Bins);
      n=1;
      while 1
         Data=ReadRecord(Header,fi);
         if isempty(Data)
            break;
         end
         Day(n)=Data.Day;
         Mattime(n)=Data.Mattime;
         Latitude(n)=Data.Latitude;
         Longitude(n)=Data.Longitude;
         Sv1(n,:)=Data.Sv1;
         Sv2(n,:)=Data.Sv2;
         n=n+1;
      end
      fclose(fi);
      n=n-1;
```

```
 Sv1(:,1:15)=NaN;
 Sv2(:,1:15)=NaN;
 % Detect bottom
Bottom=zeros(1,n);
 for m=1:n
    h=find(Sv2(m,:)>=thres2 & Header.range>2);
    if ~isempty(h)
       h=h(1);
       Bottom(m)=h;
    else
       h=find(Sv1(m,:)>=thres1 & Header.range>2);
       if ~isempty(h)
          h=h(1);
          Bottom(m)=h;
       else
          Bottom(m)=Bottom(m-1);
       end
    end
 end
 Bottom=clean(Bottom);
 Bottom=Bottom-4;
 figurenum=1;
 s=sprintf('110 kHz Sv. File: %s',filename_in);
 if Display_intermediates==1
    figure(figurenum)
    clf
    subplot(2,1,1);
    imagesc(Mattime,Header.range,Sv1');
    set(gca,'ylim',[0 Maximum_depth]);
    caxis([-90 -20])
    colorbar
    ylabel('Depth [m]');
    title(s);
    hold on
    plot(Mattime,Header.range(Bottom),'k');
    datetick
    subplot(2,1,2);
    imagesc(Mattime,Header.range,Sv2');
    set(gca,'ylim',[0 Maximum_depth]);
    caxis([-90 -20])
    colorbar
    ylabel('Depth [m]');
    title('220 kHz Sv')
    hold on
    plot(Mattime,Header.range(Bottom),'k');
    datetick
```

```
   figurenum=figurenum+1;
end
Range=Header.range-Header.Ch1_Depth;
Svs1=ones(size(Sv1))*NaN;
Svs2=ones(size(Sv2))*NaN;
i2=size(Sv1,2);
for m=1:n
   i1=Bottom(m);
   if i1<1
      i1=1;
   end
   Sv1(m,i1:i2)=NaN;
   Sv2(m,i1:i2)=NaN;
   y=fliplr(Sv1(m,1:i1-1));
   Svs1(m,1:length(y))=y;
   y=fliplr(Sv2(m,1:i1-1));
   Svs2(m,1:length(y))=y;
end
clear Sv1 Sv2
dt=(Day(2)-Day(1))*86400;
cutoff=10;
Wn=dt*2/cutoff;
[Bf,Af]=butter(3,Wn,'low');
for n=1:size(Svs1,2)
   y=Svs1(:,n);
   h=find(isnan(y));
   if ~isempty(h)
      y(h)= -900;
   end
   Svs1(:,n)=filtfilt(Bf,Af,y);
   y=Svs2(:,n);
   h=find(isnan(y));
   if ~isempty(h)
      y(h)= -90;
   end
   Svs2(:,n)=filtfilt(Bf,Af,y);
end
Mysid1Num=10.^((Svs1-ones(size(Svs1))*MysidTS)/10);
Mysid2Num=10.^((Svs2-ones(size(Svs1))*MysidTS)/10);
% Detect patches using threshold values "PatchThreshold1" and
% "PatchThreshold2"
if DynamicThreshold==1
   x=sort(Svs1(:,PatchBin1));
   h=find(x> -90);
   x=x(h);
   nx=fix(length(x)/10);
```

```
    PatchThreshold1=mean(x(1:nx))+5;
  end
  Mysid1NumThres=((PatchThreshold1-MysidTS)/10);
  Mysid2NumThres=((PatchThreshold2-MysidTS)/10);
  n=1;
  nmax=size(Svs1,1);
  while 1
    % Find beginning of patch m
    while (Svs1(n,PatchBin1)<PatchThreshold1)
      n=n+1;
      if n>=nmax; break; end
    end
    if n>=nmax; break; end
    Patch.StartTime(patchnum)=Day(n);
    Patch.StartMattime(patchnum)=Mattime(n);
    Patch.StartLatitude(patchnum)=Latitude(n);
    Patch.StartLongitude(patchnum)=Longitude(n);
    Patch.StartDepth(patchnum)=Header.range(Bottom(n));
    [x1,y1,utmzone] = deg2utm(Latitude(n),-Longitude(n));
    % Find end of patch m
    n1=n+1;
    while (Svs1(n1,PatchBin1)>=PatchThreshold1)
      n1=n1+1;
      if n1>=nmax; break; end
    end
    n1=n1-1;
    Patch.EndTime(patchnum)=Day(n1);
    Patch.EndMattime(patchnum)=Mattime(n1);
    Patch.EndLatitude(patchnum)=Latitude(n1);
    Patch.EndLongitude(patchnum)=Longitude(n1);
    [x2,y2,utmzone] = deg2utm(Latitude(n1),-Longitude(n1));
    Patch.Width(patchnum)=sqrt((x2-x1).^2+(y2-y1).^2);
    Patch.EndDepth(patchnum)=Header.range(Bottom(n1));
    Patch.MysidMeanNumber1(patchnum)=0;
    Patch.MysidStdNumber1(patchnum)=0;
    Patch.MysidMeanNumber2(patchnum)=0;
    Patch.MysidStdNumber2(patchnum)=0;
    num=0;
    for n2=n:n1
      h=find(Mysid1Num(n2,:)>NumberThreshold & Mysid1Num(n2,:)<1e6);
      if ~isempty(h)
Patch.MysidMeanNumber1(patchnum)=Patch.MysidMeanNumber1(patchnum)+mean(M
ysid1Num(n2,h));
Patch.MysidStdNumber1(patchnum)=Patch.MysidStdNumber1(patchnum)+std(Mysid1N
um(n2,h));
```

```
Patch.MysidMeanNumber2(patchnum)=Patch.MysidMeanNumber2(patchnum)+mean(M
ysid2Num(n2,h));
Patch.MysidStdNumber2(patchnum)=Patch.MysidStdNumber2(patchnum)+std(Mysid2N
um(n2,h));
                num=num+1;
              end
          end
          if num>0
     Patch.MysidMeanNumber1(patchnum)=Patch.MysidMeanNumber1(patchnum)/num;
           Patch.MysidStdNumber1(patchnum)=Patch.MysidStdNumber1(patchnum)/num;
     Patch.MysidMeanNumber2(patchnum)=Patch.MysidMeanNumber2(patchnum)/num;
           Patch.MysidStdNumber2(patchnum)=Patch.MysidStdNumber2(patchnum)/num;
          end
          clear Patchdepth
          for n2=n:n1
              h=find(Mysid1Num(n2,:)<NumberThreshold);
              if ~isempty(h)
                  Patchdepth(n2-n+1)=Range(h(1));
              else
                  Patchdepth(n2-n+1)=Patchdepth(n2-n);
              end
          end
          Patch.Thickness(patchnum)=mean(Patchdepth);
          if Patch.Width(patchnum)>0 & Patch.Thickness(patchnum)>0
Patch.Volume(patchnum)=pi*(Patch.Width(patchnum)/2).^2*Patch.Thickness(patchnum
);
              patchnum=patchnum+1;
          end
          n=n1+1;
      end
      if Display_Bottom_referenced_Sv==1
          figure(figurenum)
          clf
          subplot(3,1,1)
          imagesc(Mattime,Range,Svs1')
          set(gca,'ydir','normal')
          set(gca,'ylim',[0 10])
          caxis([-80 -10]);
          ylabel('Range [m]')
          title(s)
          colorbar;
          hold on
          ax=axis;
          h=find(Patch.StartMattime>=ax(1) & Patch.EndMattime<=ax(2));
          for n=1:length(h)
```

```
            plot([Patch.StartMattime(h(n)) Patch.EndMattime(h(n))],[Range(PatchBin1)
Range(PatchBin1)],'r','linewidth',2);
        end
        datetick
        subplot(3,1,2)
        imagesc(Mattime,Range,Svs2')
        set(gca,'ydir','normal')
        set(gca,'ylim',[0 10])
        caxis([-90 -20]);
        ylabel('Range [m]')
        title('220 kHz Sv (Bottom referenced)')
        ax=axis;
        colorbar
        hold on
          for n=1:length(h)
            plot([Patch.StartMattime(h(n)) Patch.EndMattime(h(n))],[Range(PatchBin1)
Range(PatchBin1)],'r','linewidth',2);
        end
        datetick
        subplot(3,1,3)
        plot(Mattime,Svs1(:,PatchBin1))
        hold on
        plot(Mattime,Svs2(:,PatchBin2),'r')
        datetick
        ylabel('Sv [dB]')
        set(gca,'ylim',[-90 -20])
        set(gca,'xlim',[ax(1) ax(2)])
        plot([ax(1) ax(2)],[PatchThreshold1 PatchThreshold1],'b');
        plot([ax(1) ax(2)],[PatchThreshold2 PatchThreshold2],'r');
        s1=sprintf('110 kHz. log10(Mysids/m^3). File: %s',filename_in);
        figurenum=figurenum+1;
        figure(figurenum)
        clf
        subplot(3,1,1)
        imagesc(Mattime,Range,log10(Mysid1Num)')
        set(gca,'ydir','normal')
        set(gca,'ylim',[0 10])
        caxis([0 6]);
        colorbar
          hold on
        ax=axis;
        h=find(Patch.StartMattime>=ax(1) & Patch.EndMattime<=ax(2));
        for n=1:length(h)
            plot([Patch.StartMattime(h(n)) Patch.EndMattime(h(n))],[Range(PatchBin1)
Range(PatchBin1)],'r','linewidth',2);
        end
```

```
          ylabel('Range [m]')
          title(s1)
          datetick
          subplot(3,1,2)
          imagesc(Mattime,Range,log10(Mysid2Num)')
          set(gca,'ydir','normal')
          set(gca,'ylim',[0 10])
          caxis([0 6]);
          colorbar
          hold on
          for n=1:length(h)
             plot([Patch.StartMattime(h(n)) Patch.EndMattime(h(n))],[Range(PatchBin1)
Range(PatchBin1)],'r','linewidth',2);
          end
          ylabel('Range [m]')
          title('220 kHz. log10(Mysids/m^3)')
          ax=axis;
          datetick
          subplot(3,1,3)
          plot(Mattime,log10(Mysid1Num(:,PatchBin1)))
          hold on
          plot(Mattime,log10(Mysid2Num(:,PatchBin2)),'r')
          plot([ax(1) ax(2)],[Mysid1NumThres Mysid1NumThres],'b');
          plot([ax(1) ax(2)],[Mysid2NumThres Mysid2NumThres],'r');
          ylabel('log10(Mysids/m^3)')
          set(gca,'ylim',[0 7])
          set(gca,'xlim',[ax(1) ax(2)])
          datetick
          figurenum=figurenum+1;
          pause(1)
       end
    end
end
Patch.Year=year;
% Write out matlab file
x=datevec(Patch.StartMattime(1));
s=sprintf('save patch%2.2d%2.2d%2.2d%2.2d.mat Patch',Header.Year-
2000,Header.Month,Header.Day,x(4));
eval(s);
% Write out ascii file
s=sprintf('%2.2d%2.2d%2.2d%2.2d.ptc',Header.Year-
2000,Header.Month,Header.Day,x(4));
fo=fopen(s,'wt');
if fo>0
    fprintf(fo,'Patch Day/Month/Year Time(hh:mm:ss) Latitude Longitude Waterdepth[m]
Patchwidth[m] Patchthickness[m] (MysidNumber/m^3)_110kHz
```

```
(MysidNumber/m^3)_220kHz Patch Volume [m^3] Mysids_in_Patch_110kHz
Mysids_in_Patch_220kHz\n');

   for n=1:patchnum-1
      x=datevec(Patch.StartMattime(n));
      fprintf(fo,'%3d %2.2d/%2.2d/%2.2d  %2.2d:%2.2d:%6.3f %7.4f %8.4f %6.2f %6.1f
%6.2f %7.0f %7.0f %6.4e %6.4e %6.4e\n',...
         n,x(3),x(2),x(1)-
2000,x(4),x(5),x(6),Patch.StartLatitude(n),Patch.StartLongitude(n),Patch.StartDepth(n),P
atch.Width(n),...
       Patch.Thickness(n),Patch.MysidMeanNumber1(n),Patch.MysidMeanNumber2(n),...
Patch.Volume(n),Patch.Volume(n)*Patch.MysidStdNumber1(n),Patch.Volume(n)*Patch.
MysidStdNumber2(n));
      x=datevec(Patch.EndMattime(n));
      fprintf(fo,'%3d %2.2d/%2.2d/%2.2d  %2.2d:%2.2d:%6.3f %7.4f %8.4f %6.2f %6.1f
%6.2f %7.0f %7.0f %6.4e %6.4e %6.4e\n',...
         n,x(3),x(2),x(1)-
2000,x(4),x(5),x(6),Patch.EndLatitude(n),Patch.EndLongitude(n),Patch.EndDepth(n),Pat
ch.Width(n),...
       Patch.Thickness(n),Patch.MysidMeanNumber1(n),Patch.MysidMeanNumber2(n),...
Patch.Volume(n),Patch.Volume(n)*Patch.MysidStdNumber1(n),Patch.Volume(n)*Patch.
MysidStdNumber2(n));
   end
   fclose(fo);
end
```