UNIVERSITY OF CALIFORNIA, SAN DIEGO

Blue and fin whale acoustics and ecology off Antarctic Peninsula

A dissertation submitted in partial satisfaction

of the requirements for the degree

Doctor of Philosophy

in

Oceanography

by

Ana Širović

Committee in charge:

Dr. John A. Hildebrand, Chair
Dr. Jay Barlow
Dr. Russel Lande
Dr. Dariusz Stramski
Dr. Maria Vernet
Dr. Clinton D. Winant

2006

The dissertation of Ana Širović is approved, and it is acceptable in quality and form for publication on microfilm:

Chair

University of California, San Diego

2006

“Nature, rightly questioned, never lies.”

A Manual of Scientific Enquiry, Third Edition, 1859

Table of contents

List of figures

I. Introduction

II. Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula

III. How far can blue and fin whales be heard in the Southern Ocean?

IV. Fall habitat of calling blue and fin whales off the Western Antarctic Peninsula

List of tables

Acknowledgements

During the many years it took me to ask the right questions of nature, I received help, in various forms, flavors, and liquid states, from a great number of people. I would like to thank my advisor, John Hildebrand, for providing me with numerous amazing opportunities and learning experiences during my tenure as a graduate student. My committee members have offered help, support, perspective, and advice when most needed, so thanks to Jay Barlow, Maria Vernet, Clint Winant, Dariusz Stramski, and Russell Lande. Also, thanks to Sue Moore, for being great support along the way in many different ways, including the offer to not be on my committee at the very end so that I could find a reasonable defense date.

There have been a number of scientific collaborators who have helped me grow as a scientist and a person. While the entire GLOBEC crew deserves a big thank you for their contributions to the overall project, there were a few who were particularly helpful in my quest for answers. Deborah Thiele taught me about Antarctic whales and their habitat, John Klinck and Eileen Hoffman taught be about the physical oceanography of the area, and Peter Wiebe and Gareth Lawson taught me about krill (and they all kindly provided their data for my analyses).

My life as a graduate student would not have been particularly fun without all the new and old friends who kept me entertained through this process. Thanks to Dave and Genna for always providing support and beer. My friend and officemate Erin offered not only many hours of scientific discussions, but also endless procrastination opportunities and excellently organized skiing and backpacking trips. I commiserated with Petra and Fiona through the years over the miserable aspects of the PhD-obtaining process. These past years would not have been the same without a number of other friends: Mumma, Bičko, Mika, Jason, Slaven, Ben, Jill, Julie, Yueng, and Steve G. And then there are those who kept me entertained (because sane was too high of a mark) during the long cruises. Erik of the Bird Box World Record fame, fellow polar swimmers Jim and Ryan, intrepid Antarctic explorer Dr. Alexi, and my roommates: Maggie, Deb G., and Bec. I also have to thank Chile and New Zealand for being green when I needed it the most. Finally, I want to thank The Ryan (aliases: Ed; Schmoopy) for providing much needed distraction and excuses for travel during the final stretches of the dissertation writing. I am looking forward to all the procrastination opportunities that lie in our future.

I want to thank my family for providing support through the years and, for better or worse, making me the person I am today. Had my dad not insisted I figure out what I wanted to be when I grow up since I was 10 years old, I probably never would have discovered that there was such a thing as ‘oceanography.’ My mom always kept me well fed and, surreptitiously, installed in me the disdain of frozen meals, which kept me eating proper food even in the middle of the dissertation writing. My sister Iva has been the best friend and travel partner for years. It is always nice to have someone along who can be convinced that triathlons, paragliding, or a trip to see the monument to Captain Cook an hour’s drive from Nuku’Alofa really were the greatest ideas since sliced bread. (Which, if you ask my mom, you will learn was not that great of an idea anyway.)

As a student, I participated in nine oceanographic cruises and I logged over 240 days at sea. (It is no wonder I received an official Certificate of Flipping). Those days would not have been anywhere nearly as successful (and fun) were it not for all the people who provided the logistic and scientific support. Masters and crews of the *L.M.Gould* and *N.B. Palmer* who participated in numerous GLOBEC cruises made the whole endeavor possible. Staff of Raytheon Polar Services, especially Alice Doyle, were always very helpful with any and all logistics issues. I want to thank the British Antarctic Survey and the crew of the *J.C. Ross* for taking me on one of their cruises and showing me South Georgia. Most of my sea time and research was funded by the National Science Foundation’s Office of Polar Programs. I also owe a special thanks to the SIO Graduate

Department for supporting my travel habit by funding trips to conferences worldwide. Thanks to all the people, current and past, who worked in the Hildebrand lab on building instruments, sorting out the logistics, solving computer problems, and generally keeping things going: Sean Wiggins, Allan Sauter, Chris Garsha, Kevin Hardy, Graydon Armsworthy, Harry Lam, Erin Oleson, Catherine Berchok, Lisa Munger, Melissa Soldevilla, Jessica Burtenshaw, Elizabeth Henderson, and Beve Kennedy.

Chapter II has been published and is reprinted with permission (Širović, A., J.A. Hildebrand, S.M. Wiggins, M.A. McDonald, S.E. Moore, and D. Thiele. 2004. Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. Deep-Sea Research II, 51: 2327–2344), and Chapter V has been accepted for publication (Širović, A., J.A. Hildebrand, and D. Thiele. 2006. Baleen whales in the Scotia Sea in January and February 2003. Journal of Cetacean Research and Management, in press). I was the primary researcher and the co-authors listed in this manuscript directed and supervised the research that forms the basis for those chapters. Chapter III is in preparation for submission (Širović, A., J.A. Hildebrand, S.M. Wiggins. How far can blue and fin whales be heard in the Southern Ocean? Journal of the Acoustical Society of America, in preparation).

Vita

1978	Born, Zagreb, Croatia
2000	B.A. University of California, Santa Barbara
2000-2006	Research Assistant, Scripps Institution of Oceanography, University of California, San Diego
2005	Teaching Assistant, Department of Biological Sciences, University of California, San Diego
2006	Ph.D., Scripps Institution of Oceanography, University of California, San Diego

Publications

Širović, A., J.A. Hildebrand, and D. Thiele. 2006. Baleen whales in the Scotia Sea in January and February 2003. Journal of Cetacean Research and Management, accepted.

Širović, A., J.A. Hildebrand, S.M. Wiggins, M.A. McDonald, S.E. Moore, and D. Thiele. 2004. Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. Deep-Sea Research II, 51: 2327–2344.

Thiele, D., E.T. Chester, S.E. Moore, A. Širović, J.A. Hildebrand, and A.S. Friedlaender. 2004. Seasonal variability in whale encounters in the Western Antarctic Peninsula. Deep-Sea Research II, 51: 2311–2325.

Selected abstracts

Sirovic, A., J.A. Hildebrand, D. Thiele, S.E. Moore, M.A. McDonald, and S.M. Wiggins. 2006. Ecological importance of whale population decimation off Antarctic Peninsula, Eos Transactions AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract OS36B-27.

Širović, A., J.A. Hildebrand, S.M. Wiggins, M.A. McDonald, S.E. Moore. 2005. How far can blue and fin whales be heard in the Southern Ocean? 16th Biennial Conference on the Biology of Marine Mammals, pp 260.

Širović, A., J.A. Hildebrand, M.A. McDonald, S.E. Moore, J. Barlow. 2005. Using blue and fin whale call detections for density estimation. 2nd International Workshop on Detection and Localization of Marine Mammals using Passive Acoustics, Monaco, pp 67.

Širović, A., J.A. Hildebrand, S.M. Wiggins, S.E. Moore, M.A. McDonald. 2004. Location and range of calling blue and fin whales off the Western Antarctic Peninsula. Journal of the Acoustical Society of America, 116: 2607.

Širovic, A., J.A. Hildebrand, S.M. Wiggins, S.E. Moore, M.A. McDonald, D. Thiele. 2004. Seasonality and density of blue and fin whale calls west of the Antarctic Peninsula. Eos Transactions of the AGU, 84(52), Ocean Sci. Meet. Suppl., Abstract OS12F-07.

Širovic, A., J.A. Hildebrand, S.M. Wiggins, S.E. Moore, M.A. McDonald, D. Thiele. 2003. Blue and fin whale calls west of the Antarctic Peninsula. 15th Biennial Conference on the Biology of Marine Mammals, pp 151.

Fields of study

Major Field: Oceanography

Studies in Acoustics.
Professors John A. Hildebrand and William Kuperman

Studies in Oceanography.
Professors Myrl C. Hendershott, Lynn D. Talley, Lisa A. Levin, David Checkley, Ralph F. Keeling, and Joris M. Gieskis

Studies in Biology.
Professors Robert R. Warner, John A. Endler, Armand M. Kuris, Sally J. Holbrook
University of California, Santa Barbara

Studies in Statistics.
Professor Jay Barlow
Professor Allan Stewart-Oaten, University of California, Santa Barbara

ABSTRACT OF THE DISSERTATION

Blue and fin whale acoustics and ecology
off Antarctic Peninsula

by

Ana Širović
Doctor of Philosophy in Oceanography
University of California, San Diego, 2006
Professor John A. Hildebrand, Chair

Blue (*Balaenoptera musculus*) and fin whales (*B. physalus*) in the Southern Ocean were subjects of extensive whaling industry during the twentieth century. Their current population numbers remain low, making population monitoring using traditional visual surveys difficult. Both blue and fin whales produce low frequency, regularly repeated calls and are suitable for acoustic monitoring. Eight, continuously recording acoustic recorders were deployed off the Western Antarctic Peninsula (WAP) between March 2001 and February 2003. Ranges to calling blue and fin whales were calculated using hyperbolic localization and multipath arrivals up to the distances of 200 and 56km, respectively. Calls of both species had high intensity, blue whales calls had the average source level 189±3dB re: 1µPa at 1m and the average fin whale call source level was

189±4dB re: 1μPa at 1m. Automatic call detection methods were used for analysis of calling blue and fin whale seasonal presence and habitat preferences. Blue whale calls were detected year round, on average 177 days/year, with peak calling in March and April, and a secondary peak in October and November. Fin whale calling rates were seasonal with calls detected between February and June (on average 51 days/year), and a peak in May. During the entire deployment period, detected calls from both species showed negative correlation with sea ice concentrations. Also, baleen whale sounds were recorded during multiple cruises off the Antarctic Peninsula using sonobuoys. Recordings from two fall cruises off the WAP were used for analyses of habitat preferences of calling blue and fin whales. The presence of calling blue whales was positively correlated with bottom depth and sea surface temperature, and negatively correlated with krill biomass in the top 100m and abundance of the rest of the zooplankton at depth (101–300m). Locations of fin whale calls were associated with a deep trough area and high Chl-*a* concentrations. Distribution of baleen whale calls recorded in the Scotia Sea (east of the Antarctic Peninsula) indicated that fin whales occur in open water, and blue, southern right (*Eubalaena australis*), minke (*B. bonaerensis*), and humpback whales (*Megaptera novaeangliae*) occur near islands or close to the ice edge.

I. Introduction

During the twentieth century, baleen whales were subjects of a vast commercial hunt that decimated their populations and affected the ecosystem structure of the Southern Ocean. Decades after the ban on commercial whaling, several baleen whale populations have remained at low levels (Branch and Butterworth, 2001a) and their recovery is uncertain. These low population numbers, along with the vastness and remoteness of the Southern Ocean, make studies of these animals using traditional visual survey techniques difficult and cost inefficient. Baleen whales, however, remain an integral part of the Southern Ocean, and understanding of their biology and ecology is crucial for successful management and conservation of the ecosystem. Passive acoustic monitoring has recently been used for providing long-term information on baleen whale presence in the Pacific, Atlantic, and Indian Oceans (e.g. Clark and Charif, 1998; Moore *et al.*, 1998; Watkins *et al.*, 2000; Stafford *et al.*, 2001; Burtenshaw *et al.*, 2004; Stafford *et al.*, 2004). This dissertation describes the results of the first long-term, passive acoustic, baleen whale monitoring project in the Southern Ocean, and presents findings on blue (*Balaenoptera musculus*) and fin whale (*B. physalus*) call characteristics, distribution and habitat preferences.

This chapter provides a background on the region and the history for the results presented in the dissertation. First, I describe the environment of the Antarctic Peninsula, with the review of the main physical and biological features, focusing on the importance of the seasonal variation that drives the Southern Ocean dynamics. Next, I present a short history of the whaling effort around the Antarctic Peninsula that had an enormous effect on the populations of their primary targets, blue and fin whales. In the end, I detail the goals and the contents of subsequent dissertation chapters.

A. Physical oceanography of the Antarctic Peninsula

Bathymetry

The continental shelf surrounding Antarctica, with its average depth of 500–600m, is deeper than most continental shelves in lower latitudes, typically <200m. The shelf is deeper due to the depression of the continent from the weight of its heavy ice burden. The West Antarctic Peninsula (WAP) continental shelf opens to the Bransfield Strait to the north and the Bellingshausen Sea to the south (Figure 1.1). The Bransfield Strait also serves as a connection to the Weddell Sea (Hofmann and Klinck, 1998a). The shelf extends as far as 200km from the continent. The bottom topography of the WAP continental shelf is rugged, with shallow plateaus and deep, cross-shelf trenches, which are over 1000m deep. The along-shore variability in bottom topography has a strong influence on water mass properties and circulation. Depressions on the shelf tend to become reservoirs of dense water and trenches serve as conduits for water exchange between the shelf and the ocean (Hofmann and Klinck, 1998b).

The Peninsula steers the Antarctic Circumpolar Current (ACC) system in this region, driving it further north than in other parts of the Southern Ocean. The Scotia Sea, to the east of the Peninsula and the Drake Passage, is bound by shallow island shelves to the south (the South Scotia Ridge), the north (the Falkland Plateau) and the east (the South Sandwich Island arc; Figure 1.1). The South Scotia Ridge is a connecting point between the Weddell and the Scotia Seas.

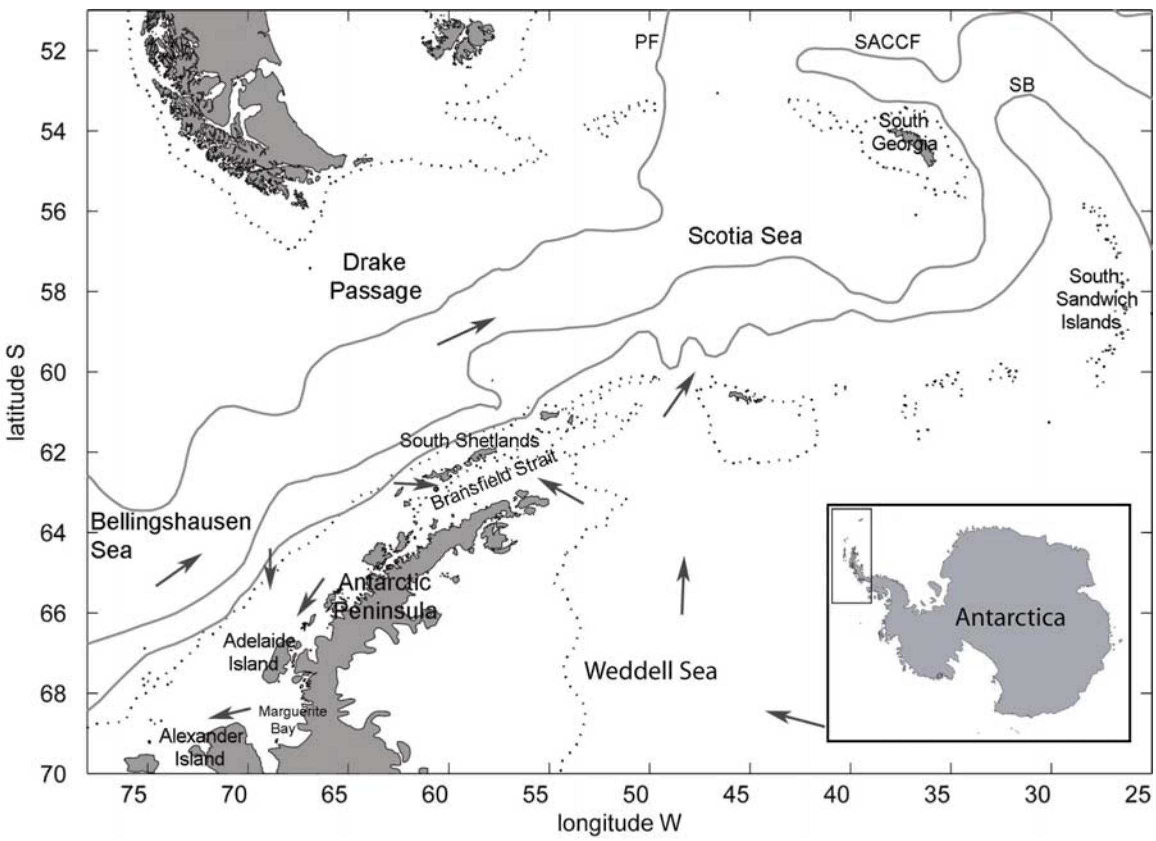

Figure 1.1. Map of the Antarctic Peninsula region with major currents and fronts. Dotted line is the 1000m bathymetry contour and solid lines are major oceanographic fronts: PF – the polar front, SACCF – southern Antarctic Circumpolar Current (ACC) front, SB – southern boundary of the ACC. The arrows represent major circulation patterns in the area, including the ACC, the Antarctic coastal current, and the Weddell gyre. Inset shows entire Antarctic continent, with the Peninsula region marked for reference.

Wind

The winds are the primary driving force behind Antarctic circulation, and they have a long, circumpolar fetch. There is a low-pressure trough at approximately 65°S latitude, which separates regions of opposing wind flow. The westerly winds that prevail north of this trough produce an eastward flow, with a strong northern component (due to the Coriolis effect). The winds south of the low-pressure trough blow from the east, producing a westward coastal flow. However, the wind patterns along the coast are complicated by the occurrence of katabatic winds.

The winds around the Antarctic Peninsula blow primarily from the north-northwest and produce downwelling circulation over the shelf and southward flow along the coast (Hofmann *et al.*, 1996; Hofmann and Klinck, 1998b; Beardsley *et al.*, 2004). There is evidence of cyclonic atmospheric circulation in the Weddell Sea (Hofmann and Klinck, 1998b).

Sea ice

Seasonal changes in the sea ice concentrations, which are driven by solar radiation availability, have a big influence on the seasonality of the Antarctic ecosystem. There is a five-fold fluctuation in the ice cover around Antarctica between the winter and the summer, with the lowest levels occurring in February and the annual retreat starting in September (Hofmann and Klinck, 1998b). The area around the Antarctic Peninsula shows a pattern that is somewhat different from the rest of the continent, with ice starting to form relatively late (into June) and the retreat starting earlier (August) than in other parts of the Antarctic. Ice concentration on the west and north coasts of the Peninsula reaches up to 60%, with thinner ice along the tip of the Peninsula (Stammerjohn and Smith, 1996). In the winter, the sea ice usually covers parts of the Scotia Sea south of the Antarctic convergence, while in the summer the Scotia Sea is free of ice.

Sea ice formation and melting have an important effect on the thermohaline properties of the continental shelf water. For example, brine rejection due to sea ice formation creates localized pockets of high salinity, while ice melt creates areas of lower salinity. Polynyas, clearings of open water inside the pack ice, allow large heat fluxes between the ocean and the atmosphere. They can form either by upwelling of the relatively warm ocean water or by constant removal of ice from an area by wind (Hofmann and Klinck, 1998b). Polynyas occur both in Marguerite Bay in the WAP and in the Weddell Sea. Increase in the salinity of deep waters in the regions of prevalent polynyas allows for formation of the Antarctic Bottom Water, an important hydrographic feature.

Circulation

The main feature of circulation around Antarctica is the Antarctic Circumpolar Current (ACC). The current circumnavigates the continent transporting 100Sv to the east in the water layer above 3000m depth (Orsi *et al.*, 1995) and causes complete isolation of the Antarctic continent from the waters of the sub-polar and temperate regions. The ACC gets steered by the ridges around Antarctica and in the WAP it comes to the continental shelf and follows it towards the northwest. The Drake Passage is the narrowest (and best-studied) region of the ACC. Transport across the Drake Passage is uniform (Reid and Nowlin Jr., 1971) but it is affected by seasonal cycles of the subtropical and the sub-polar regions (Peterson, 1988). As it continues east, the ACC separates from the shelf and flows in the deeper waters of the Scotia Sea, following the bathymetry towards the northeast and northwest, until it turns back east as it passes the South Sandwich Islands (Figure 1.1).

The Antarctic coastal current flows westward along most of the continent, but near the coast of the WAP, the flow is modified southward (Beardsley *et al.*, 2004; Klinck *et al.*, 2004). It is a wind and buoyancy driven current. There is evidence of a large, weak, cyclonic, baroclinic gyre circulation that is attached to the ACC on the shelf in the areas around Adelaide and Alexander Islands (Smith *et al.*, 1999; Klinck *et al.*, 2004). Sub-gyres can also occur at the northern and southern ends of the shelf, with the northern sub-gyre being more intense and the southern sub-gyre being on a larger scale. The total transport of the shelf gyre is small, 0.15Sv (Smith *et al.*, 1999). It remains uncertain whether there is just one, or if there are several stable mesoscale gyres in the area (Hofmann *et al.*, 1996; Hofmann and Klinck, 1998b; Beardsley *et al.*, 2004; Klinck *et al.*, 2004). The flow from the Weddell into the Scotia Sea occurs over the South Scotia Ridge (Gordon *et al.*, 1997), with part of the flow separating into the Bransfield Strait (Hofmann and Klinck, 1998b).

Hydrography

There are three major water masses in the Antarctic Peninsula region. The main surface water mass is the Antarctic Surface Water (AASW), a low temperature (-1.8–0°C), fresh (34.0–34.4) mass that is found in the top 200m of the water column (Hofmann and Klinck, 1998b; Smith *et al.*, 1999). This water mass is affected by a large number of mechanisms including atmospheric exchange, exchange across the permanent pycnocline, ice formation, and melting. It persists during the summer and fall around 100m depth as Winter Water (WW), but on the surface it is replaced by a warmer layer that has been heated by the sun. WW is very cold (<-1.5°C) and fresh (34.0–34.4). The erosion of WW and its mixing during the summer with the surface layer are influenced by the bathymetric features of the shelf.

The Circumpolar Deep Water (CDW) is the most prominent water mass in the region and it can be found at depths from 200–700m (Hofmann *et al.*, 1996). According to Hofmann and Klinck (1998b), in the Peninsula region the CDW is divided into the Upper Circumpolar Deep Water (UCDW), which is the signal of the ACC, and the Lower CDW. UCDW is warm (1.5–2°C) and salty (34.6–34.7) while the LCDW is a bit colder (1.3–1.5°C) and saltier. UCDW is found at the depth of 200m at the edge of the shelf, bringing oceanic water to the shelf in the form of ACC intrusions. CDW has been found as far as 130km inshore from the shelf break. These intrusions appear to be regular events steered by the bathymetry of the area, with shelf trenches serving as passages deeper onto the shelf (Klinck *et al.*, 2004). UCDW has thermohaline properties that are constant in time and influxes of this warm and nutrient rich water near the surface have important implications for biological productivity in general, and krill reproduction in particular (Hofmann *et al.*, 1992). The upwelled CDW provides a heat source that maintains the ice-melt and inhibits the formation of dense water. The depth of the shelf confines the mixing to the upper 150–200 m of the water column. It is this part of the column that undergoes seasonal changes due to wind forcing and heat and salt fluxes, while the deeper shelf waters remain unaffected by seasonal changes (Hofmann and Klinck, 1998b).

The major fronts that separate the polar, Antarctic waters from the sub-polar region have been described by Orsi *et al.* (1995) and they are: the Subantarctic Front (SAF), the Polar Front (PF), and the Southern Antarctic Circumpolar Current Front (SACCF). All of these fronts are deep-reaching (3000m) and their principal indicator is a large isopycnal tilt. The SAF is the northernmost border of the subantarctic waters and marks the transition between the Sub-Antarctic Surface Water and Sub-Tropical Surface Water. It is the only feature that is not entirely circumpolar, but gets broken up by South America. The position of the PF is indicated by a large horizontal temperature gradient where the AASW sinks. The southern boundary of the ACC, also the southern boundary of the UCDW, comes unusually close to the continent in the Drake Passage and can be found on the continental slope (Sievers and Nowlin, 1984; Pollard *et al.*, 1995).

Finally, an important water mass that forms in the Antarctic is Antarctic Bottom Water (AABW). This is a dense water mass that forms as a result of ice formation processes and sinks below the CDW to deep waters. AABW is not common in the WAP region, but it is a characteristic of the Weddell Sea (Hofmann and Klinck, 1998b).

Sound propagation characteristics

Sound propagation is affected by the sound speed characteristics and the boundary properties of the medium. Two most important factors affecting the sound speed in the ocean are water temperature and pressure (i.e. depth). The speed of sound has the same effects on sound propagation as the index of refraction has in optics. With its cold waters, the Southern Ocean is an upward refracting environment, suitable for long-range propagation (Urick, 1983). It is also characterized by a shallow (<200m) surface ducting layer. This surface ducting feature is more prominent in the summer due to the development of the Antarctic Surface Water (Figure 1.2a). In the winter, with the establishment of the Winter Water layer, the surface ducting gets weaker (Figure 1.2b). Sea ice also affects sound propagation and the combination of the surface duct with the sea ice cover creates best propagation conditions approximately for the 15 to 30Hz range (Urick, 1983).

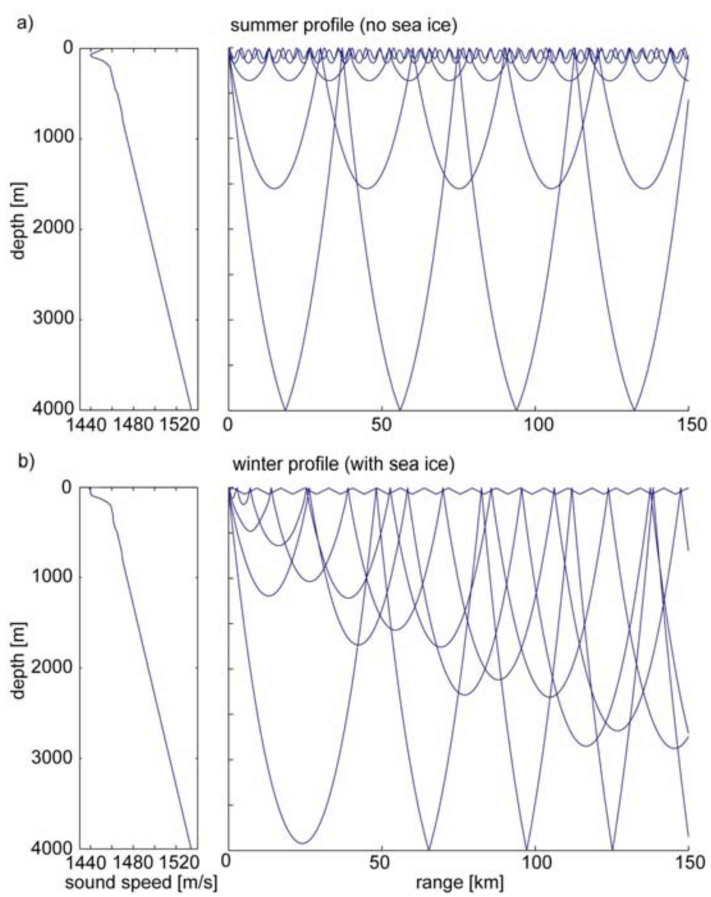

Figure 1.2. Sound propagation characteristics in the Southern Ocean during (a) summer and (b) winter conditions with associated sound speed profile characteristics.

B. Biological oceanography of the Antarctic Peninsula

Phytoplankton

Phytoplankton abundance in the Southern Ocean follows a strong seasonal cycle, imposed by large fluctuations in incident radiation. At the end of the winter, as the sea ice begins to melt, nutrients are released from the ice and become available for use by phytoplankton, which form blooms that follow the receding ice edge (Hart, 1934; Smith and Nelson, 1985). The blooms support high abundance of krill and large numbers of top predators such as penguins, seals, and baleen whales. The exact timing of the bloom is latitude dependent and it gets enhanced by the developing water column stability resulting from the ice melt (Hart, 1934). After the blooms occurring in the marginal ice zone dissipate, blooms can occur in the open ocean later in the season (Holm-Hansen *et al.*, 2004a).

There is a high degree of spatial variation in phytoplankton abundance in the Southern Ocean (El-Sayed and Weber, 1982). Waters of the Drake Passage generally have low phytoplankton abundance, the abundance is high in the Bransfield Strait, and it varies spatially across the Scotia Sea (Holm-Hansen *et al.*, 1997; Holm-Hansen *et al.*, 2004b). Shelf waters of the Antarctic Peninsula have high phytoplankton abundance in the spring and the summer, associated with episodic blooms, and very low in the winter (Smith *et al.*, 1996; Whitehouse *et al.*, 1996). Also, higher phytoplankton concentrations, mostly composed of large diatom cells, are usually found inshore from the shelf break, in the areas of topographically induced upwellings of the UCDW (Smith *et al.*, 1996; Prezelin *et al.*, 2000; Smith *et al.*, 2001). During non-bloom periods, and in the areas not fed by the UCDW intrusions, smaller diatoms and dinoflagellates dominate species composition (Holm-Hansen *et al.*, 1989; Prezelin *et al.*, 2000).

Krill

Antarctic krill, *Euphausia superba*, as the main prey of fishes, birds, seals, and whales, is a key species of the Southern Ocean ecosystem (Laws, 1985; Kawamura, 1994). Siegel (2000) provided an overview of *E. superba* life history. They can live up to seven years and grow over 50mm in length. While *E. superba* generally spawn during the summer, the onset of the spawning season is determined by the winter sea ice extent. Their eggs sink after spawning and over-winter at depth, avoiding predation. The krill larvae undergo ‘developmental ascent’ back to the euphotic zone the following summer. Adult *E. superba* also undergo vertical migrations. The migrations show seasonal and annual changes, and they are affected by the size and developmental stage of the individuals (Godlewska, 1996).

There are large interannual changes in the standing krill stocks (Priddle *et al.*, 1988). Main factors affecting krill abundance and distribution are: production, survival, retention, and export (Siegel, 1988; Daly and Macaulay, 1991). High krill abundances are found usually in the marginal ice zone and just south of the ice edge (Murray *et al.*, 1995; Brierley *et al.*, 2002), because under-ice environment serves as a source of food and protection (Daly and Macaulay, 1991). Historically, WAP and the Scotia Sea appear to be areas with the highest krill densities in the Southern Ocean (Marr, 1962; Atkinson *et al.*, 2004). WAP is also a region of high concentration of larval krill (Pakhomov *et al.*, 2004), which are transported to other regions (Siegel *et al.*, 1990; Ichii *et al.*, 1998; Hofmann and Murphy, 2004; Murphy *et al.*, 2004). Krill exhibit seasonal differences in their offshore and inshore distribution on the west Antarctic Peninsula shelf (Ross *et al.*, 1996; Lascara *et al.*, 1999) based on their maturity. Gravid females are found in the offshore, frontal waters, which could facilitate transport of larvae to other regions (Ichii *et al.*, 1998).

In recent years, the harvest of *E. superba* in the Scotia Sea accounted for a large percentage of the world krill fishery (Nicol and Endo, 1999). With this expanding fishery, successful management of the resource will require better knowledge of the total abundance and the effects of migration and predation on the krill (Hewitt *et al.*, 2004).

C. Whaling history of the Antarctic Peninsula

The Southern Ocean was the main commercial whaling region in the twentieth century. The whaling started in 1913 with the establishment of the first land whaling stations. Until 1928, most whaling activities were limited to areas close to the land stations. In 1929, the advent of the whaling factory ship made vast areas of the open Southern Ocean available for whale exploitation for the first time. Land stations continued their operations for several decades after the beginning of the pelagic whaling, the last station closed on South Georgia in 1965. The International Whaling Commission (IWC) was established in 1946 with the goal of effective development and management of the whaling industry. The IWC distinguishes six regions around the Antarctic (south of 60°S) for management purposes, and Areas I and II (between 60 and 120°W and 0 and 60°W, respectively) cover the region around the Antarctic Peninsula.

When whaling started in 1913, the primary target species was the blue whale. As the largest baleen whale, it offered the greatest profit yield. (The blubber was used for margarine and oil, bones for glue, and meat for consumption.) Through the 1930's, most of the industry was focused on this species. During the period of World War II (1939-1945) whaling operations diminished, but they resumed at pre-war levels as soon as the War ended. However, the depletion of blue whales was evident by that point and fin whales became the new targets, as the second largest species. Blue whales continued to be taken opportunistically throughout this period, thus enabling their exploitation past the point of economic extinction and bringing them to the brink of biological extinction. By

1960's fin whale populations were also severely depleted and the whaling moved on to the next largest species, the sei whale (*B. borealis*). Sei whales, however, prefer temperate waters and the pelagic whaling industry moved further north for a while. In 1965, blue whales, extremely depleted at this point, became protected and could no longer be hunted. Fin whales continued to be taken until 1976, when they became protected as well. A total of 102,354 blue and 269,578 fin whales were taken from IWC Areas I and II during the whaling period. Current population estimates in the Antarctic for these species, 1,100 blue and 5,500 fin whales (Branch and Butterworth, 2001a), indicate that the populations are still at small fractions of the pre-exploitation levels.

The IWC collected data on the numbers and locations of all commercial whale catches. Often the location data are accurate only to 1° latitude and longitude. In case of land stations, many locations reported before the 1940's were those of the landing stations, not the actual catch locations. Also, there has been evidence of falsification of some number data after the enactment of the quota system in the 1940's, especially by the whalers from the former Soviet Union (Yablokov, 1994). While there is no information on effort, thus making it difficult to consider the data quantitatively, we can assume that number of whales caught in one area can serve as a proxy for relative whale density in the region. Therefore, it is informative to look at the locations of whale catches during this period.

The data from the pre-pelagic whaling period (1913-1928) show large catches from land stations located on South Georgia and South Shetland Islands (Figure 1.3). This indicates that large numbers of blue whales could be found very close to shore and were common on the continental shelf (Hardy and Gunther, 1935). No blue whales were caught on the shelf after that period however. Also, blue whale catches greatly diminished in the vicinity of South Georgia over time and, over the years, whalers had to venture further

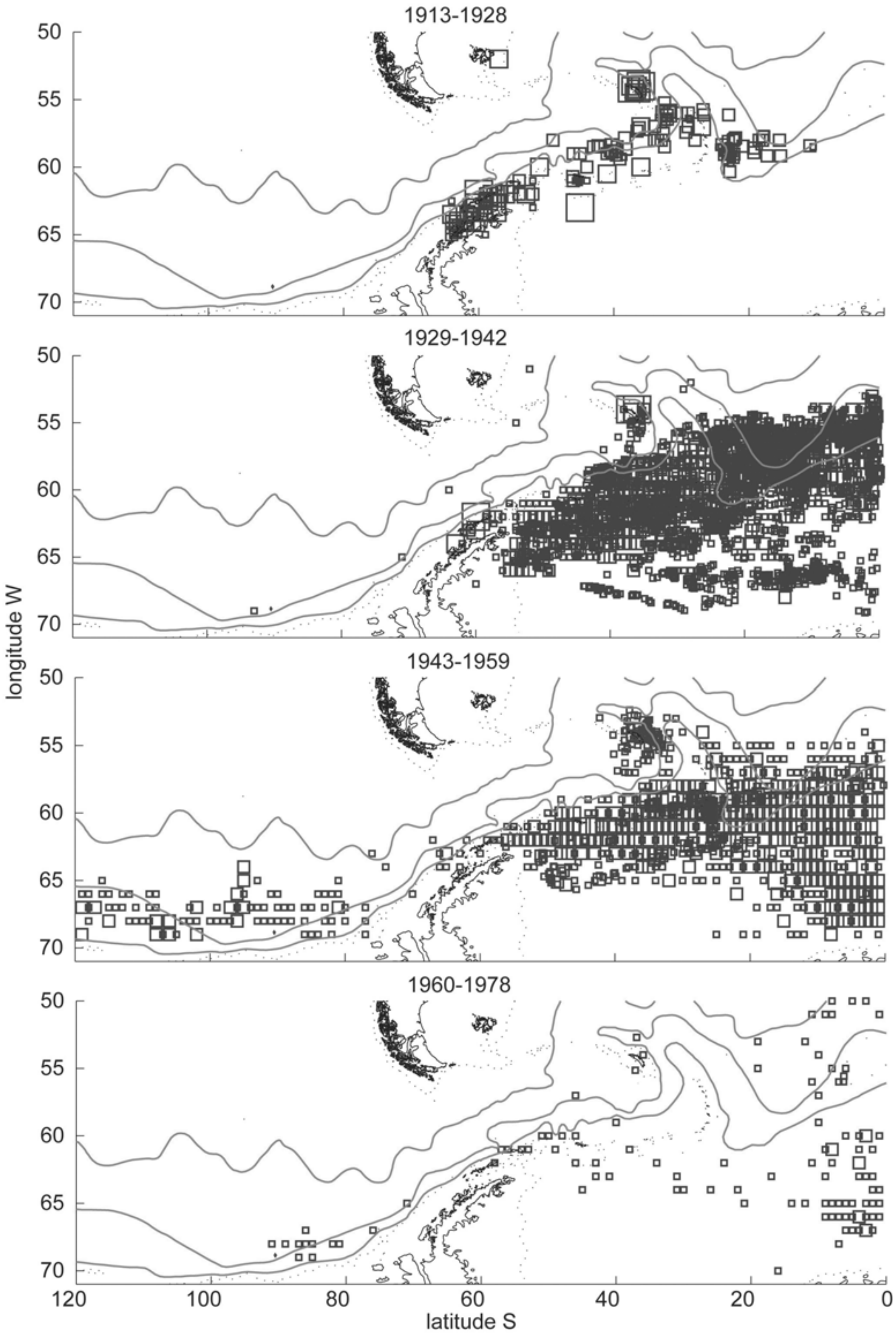

Figure 1.3. Locations of blue whale historic catches in IWC Areas I and II. The size of the square corresponds to the number of blue whales caught at that location during the given period. Starting from the smallest and going to the largest square, the size groupings are: 1-10, 11-100, 101-1,000, 1,001-10,000, and >10,000.

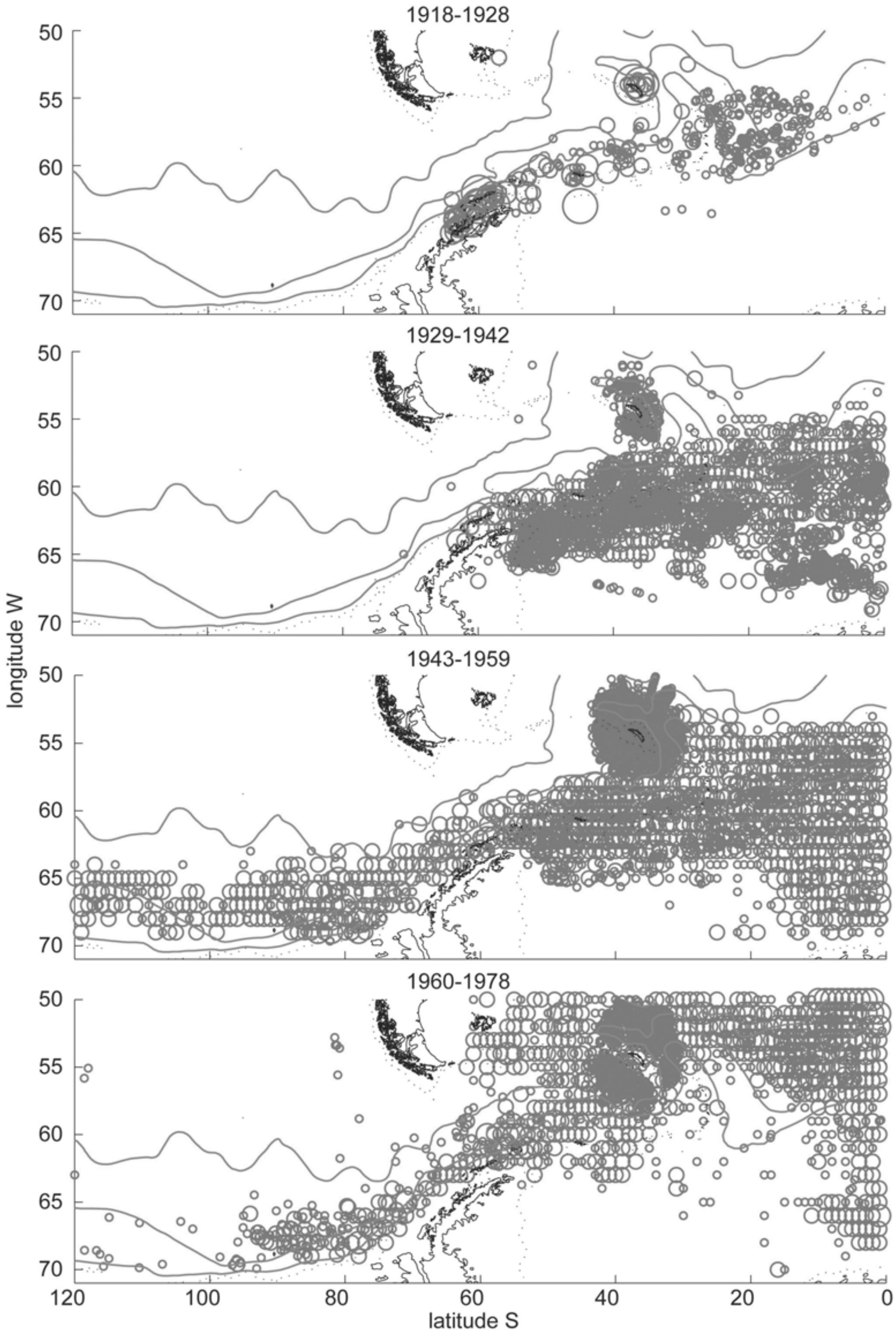

Figure 1.4. Locations of fin whale historic catches in IWC Areas I and II. The size of the circle corresponds to the number of fin whales caught at that location during the given period. Starting from the smallest and going to the largest circle, the size groupings are: 1-10, 11-100, 101-1,000, 1,001-10,000, and >10,000.

and further away from the island to catch fin whales (Figure 1.4). Both factors could imply a degree of site fidelity in these two species. Even though most of these animals migrate to this region seasonally (Mackintosh, 1965), it is possible that they return to the same, small area. There is also some evidence of possible site fidelity from the *Discovery* tags, showing recovery of tags in longitudinal locations very close to the original deployment locations (Brown, 1962b).

The second implication from the whaling records is that blue and fin whales were somewhat spatially segregated and were not uniformly distributed circumpolarly. Early pelagic whaling records show that initially, large concentrations of blue whales occurred east of the South Sandwich Islands. Largest fin whale concentrations, on the other hand, occurred at the southwestern edge of the Scotia Sea. Region west of the Antarctic Peninsula and the Bellingshausen Sea were not originally a popular pelagic whaling destination and their exploitation started after WWII. It is probable that this area was not exploited at first because of its remoteness, but once whaling started there, the catches were not as large as in the eastern regions. Therefore it seems reasonable to assume that the Bellingshausen Sea never sustained large blue and fin whale populations.

D. Dissertation goals

The overarching goals of my dissertation were to investigate: 1) seasonal presence and absence, and 2) distribution and habitat preferences of blue and fin whales around the Antarctic Peninsula using a novel, passive acoustic technology. Acoustics can provide a cost-effective way to monitor whale populations in remote regions. I investigated the time, frequency, and amplitude properties of the calls made by blue and fin whales and determined their potential for intraspecific communication, as well as for research using passive acoustics. These results have a potential for providing a baseline estimate of relative population densities and serve for future comparisons and investigations into population recovery or decline. In the light of the possibility of opening up of the Southern Ocean for further commercial resource exploitations, both of krill and possibly whales, having such a baseline would be crucial for future attempts at sustainable management. I also investigated the relationships that affect blue and fin whale distributions in the Antarctic. I wanted to determine whether their current distributions can be linked to the current environmental parameters (e.g. water characteristics, sea ice cover, the distribution of whale prey), or if they could be predominately the result of the past exploitation history.

Most goals of the dissertation are addressed throughout each of the chapters. Chapters II and III are based on data collected using long-term moored recorders, and the data on whale presence used in chapters IV and V were collected using sonobuoys. Chapter II presents results on long-term seasonal patterns of blue and fin whale calls off the Western Antarctic Peninsula between March 2001 and February 2003. It also provides detailed descriptions of the temporal and frequency characteristics of blue and fin whale calls in the Southern Ocean, and relates the whale distributions to sea ice cover. Chapter III describes the process of determining source levels of calling animals. Chapter IV discusses habitat preferences of the calling blue and fin whales, especially relative to bottom depth, sea ice, sea temperature, chlorophyll *a* concentrations, and krill and other zooplankton distributions, from the data collected during survey cruises in the austral falls of 2001 and 2002. Chapter V compares the distributions of multiple baleen whale species in the Scotia Sea during the austral summer of 2003. Chapter VI provides a synthesis of the dissertation, and presents areas in need of further research, and possible design improvements for those future studies. Chapters II through V are intended to be self-sufficient, publishable units, therefore, there may be some redundancy in their introduction and methods sections.

II. Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula

A. Abstract

The calling seasonality of blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales was assessed using acoustic data recorded on seven autonomous acoustic recording packages (ARPs) deployed from March 2001 to February 2003 in the Western Antarctic Peninsula. Automatic detection and acoustic power analysis methods were used for determining presence and absence of whale calls. Blue whale calls were detected year round, on average 177 days per year, with peak calling in March and April, and a secondary peak in October and November. Lowest calling rates occurred between June and September, and in December. Fin whale calling rates were seasonal with calls detected between February and June (on average 51 days/year), and peak calling in May. Sea ice formed a month later and retreated a month earlier in 2001 than in 2002 over all recording sites. During the entire deployment period, detected calls of both species of whales showed negative correlation with sea ice concentrations at all sites, suggesting an absence of blue and fin whales in areas covered with sea ice. A conservative density estimate of calling whales from the acoustic data yields 0.43 calling blue whales per 1000 n mi^2 and 1.30 calling fin whales per 1000 n mi^2, which is about one third higher than the density of blue whales and approximately equal to the density of fin whales estimated from the visual surveys.

B. Introduction

Baleen whales were severely depleted throughout Antarctic waters by intense commercial whaling in the first half of the 20th century. Large species such as blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales were the most sought after. It has been estimated that over 360,000 blue whales and 725,000 fin whales were removed from the southern hemisphere by whaling during the 20th century (Clapham and Baker, 2001). Efforts to document the status of whale populations in the Western Antarctic Peninsula region have been limited to three cruises simultaneously conducted by up to four vessels under the auspices of the International Whaling Commission during 1982/83, 1989/90, and 1993/94 in Area I (longitude 60º – 120ºW). These cruises yielded only 9 blue whale sightings and 14 fin whale sightings (Branch and Butterworth, 2001a). Such alarmingly low sightings suggest either a population in jeopardy, inadequate population assessment methods, or both (Horwood, 1986; IWC, 2001). The need to develop alternative methods of assessing whale populations, such as passive acoustics, has already been established (Clark and Ellison, 1988; 1989; Clark and Fristrup, 1997), but this need is even more important for the Southern Ocean given the considerable expense and logistical constraints of working there (Costa and Crocker, 1996).

Seasonal migrations have been documented, both visually and acoustically, for several baleen whale species (Mackintosh and Wheeler, 1929; Dawbin, 1966; Mackintosh, 1966; Clapham and Mattila, 1990; Katona and Beard, 1990; Mate *et al.*, 1999; Norris *et al.*, 1999; Stafford *et al.*, 1999b). In general, many baleen whales spend summers feeding in productive waters at high latitudes and over-winter in warmer waters at lower latitudes (Mackintosh and Wheeler, 1929; Mackintosh, 1965; Bowen and Siniff, 1999). Whaling records suggest that blue and fin whales migrate seasonally to and from the Southern Ocean (Kellogg, 1929; Brown, 1962a; Mackintosh, 1966). Although blue whales have been found close to the ice edge in the austral summer (Kasamatsu *et al.*, 1988), there is little information on their wintering areas (Mackintosh, 1965; Mizroch *et al.*, 1984) and some high-latitude areas, such as South Georgia and the North Pacific, may be continuously occupied by blue whales (Kellogg, 1929; Hart, 1935; Curtis *et al.*, 1999; Watkins *et al.*, 2000; Stafford *et al.*, 2001). Fin whales are rarely sighted at the ice edge during the summer and in the winter they appear to calf and breed at low latitudes (Laws, 1961; Brown, 1962a).

Aggregations of blue and fin whales have been observed in association with dense patches of euphausiids during the summer and fall in regions with high biological productivity (Croll *et al.*, 1998; Fiedler *et al.*, 1998; Reid *et al.*, 2000; Murase *et al.*, 2002). These regions often have distinguishing characteristics such as complex bathymetry, presence of sharp oceanographic fronts, eddies, and upwelling that can support high phytoplankton and zooplankton biomass (Beklemishev, 1960; Whitehead and Glass, 1985; Reilly and Thayer, 1990; Fiedler *et al.*, 1998; Tynan, 1998). In the highly productive Southern Ocean, sea ice is an additional factor that affects the ecosystem, generally increasing krill productivity in areas of large sea ice fluctuation, thereby also affecting higher trophic predators (Smith and Nelson, 1985; Fraser *et al.*, 1992; Loeb *et al.*, 1997; Nicol *et al.*, 2000b; Croxall *et al.*, 2002). The Western Antarctic Peninsula has a distinct, fluctuating sea ice pattern (Stammerjohn and Smith, 1996) which could support high primary productivity, concentrations of Antarctic krill and higher predators.

Blue and fin whales produce low frequency (<1kHz), high intensity (above 180dB re: 1μPa at 1m) calls and are good subjects for acoustic monitoring (Clark, 1990). Whale call detections have been applied to studies of seasonal occurrence and migration since the 1980's (e.g., Clark and Ellison, 1988; 1989; Stafford *et al.*, 1999a; Watkins *et al.*, 2000). Blue whale calls can be distinguished by their relatively long duration (10-20s) and very low frequency (20-100Hz) (Cummings and Thompson, 1971; Edds, 1982; McDonald *et al.*, 1995; Stafford *et al.*, 1998). Typically, the calls consist of two to four units that can be either pulsed or tonal in character. Blue whales produce a single call-type with uniform acoustic characteristics around the Antarctic (Ljungblad *et al.*, 1998; Matsuoka *et al.*, 2000; Clark and Fowler, 2001). Fin whale calls have been well documented in the northern hemisphere (Watkins, 1981; Edds, 1988; McDonald *et al.*, 1995). They typically consist of short (1s duration), repetitive downsweeps, but they show some variation among different geographic locations in the frequency range of the sweep and the intercall interval (Thompson *et al.*, 1992). We are not aware of any previous reports of fin whale call recordings from the Antarctic.

Recent advances in computer technologies have enabled the development of instruments capable of long-term autonomous acoustic sampling (McDonald *et al.*, 1995; Stafford *et al.*, 1999a; Fox *et al.*, 2001; Wiggins, 2003). We took advantage of this developing technology and deployed seven acoustic recording packages (ARPs) near the SO GLOBEC study site in the Western Antarctic Peninsula from March 2001 until February 2003 to monitor for baleen whale calls (Wiggins, 2003). They provided a record of seasonal occurrence of these large euphausiid predators that can be integrated further with the studies of other biotic and abiotic parameters within the SO GLOBEC framework. In this paper we report the first results on the seasonality of blue and fin whale calls from this acoustic monitoring effort.

C. Methods

Seven ARPs were deployed in the Western Antarctic Peninsula from March 2001 to February 2003 (Figure 2.1). ARPs are bottom-moored instruments that consist of a data logging system with a 16-bit A/D converter and 36GB of storage capacity, a hydrophone tethered 10m above the seafloor-mounted package (sensitivity –198dB re: 1Vrms/μPa and a –3dB low-end roll-off at around 5Hz), an acoustic release, two ballast weights, batteries, and flotation (Wiggins, 2003). The acoustic data were collected at 500 samples/s with a –6dB roll-off at 250Hz, so the effective bandwidth sampled was 5 – 250Hz. At this sampling rate, the instruments were capable of recording data for 400 days. The instruments were retrieved in February 2002 for data recovery and battery replacement, then redeployed with final recovery in February 2003. In this paper we refer to the period between March 2001 and February 2002 as the ‘first year of deployment’, while the ‘second year of deployment’ refers to February 2002 – February 2003.

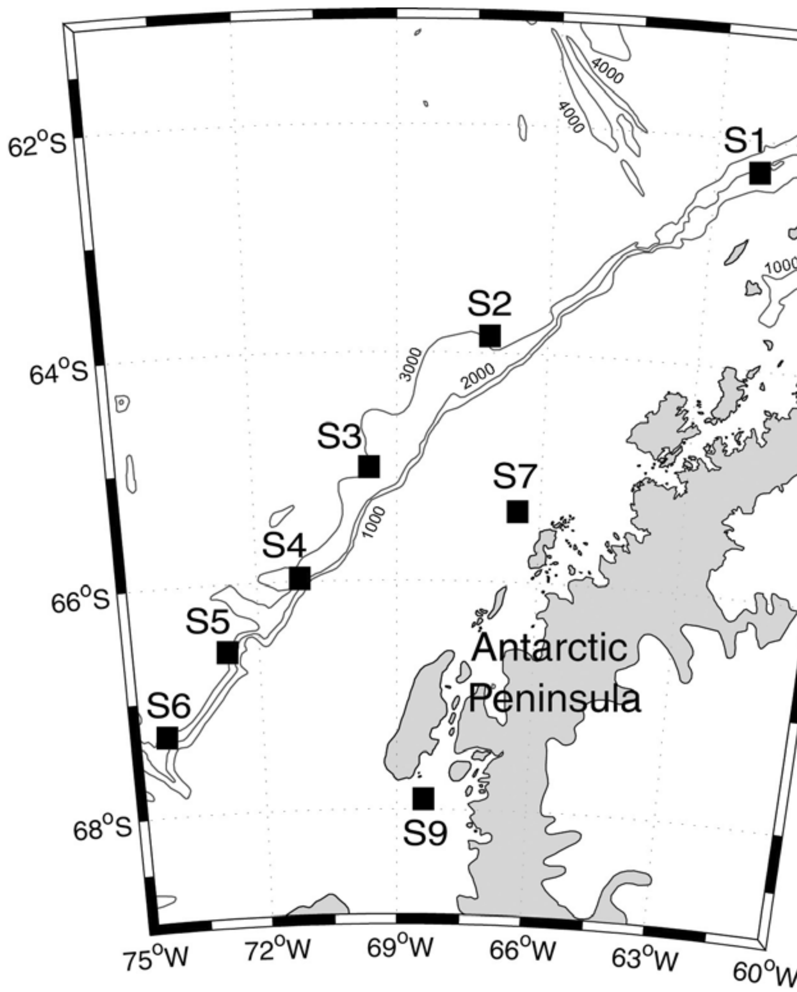

Figure 2.1. ARP deployment locations west of the Antarctic Peninsula. The actual locations for ARPs were as follows: S1 - 62˚ 16.44’ S 62˚ 10.02’ W; S2 - 63˚ 50.63’ S 67˚ 08.33’ W; S3 - 64˚ 59.41 S 69˚ 28.79 W; S4 - 65˚ 58.40’ S 71˚ 04.10’ W; S5 – 66˚ 34.99 S 72˚ 41.43 W; S6 - 67˚ 18.25’ S 74˚ 10.15’ W; S7 - 65˚ 22.62 S 66˚ 28.21’ W; S9 - 67˚ 54.50’ S 68˚ 23.00’ W.

Two ARPs were located on the continental shelf (sites 7 and 9) at depths of 450 and 870m. Six ARPs were located on the shelf break; the northernmost (site 1) was at a depth of approximately 1600m, while the depths of the remaining five ARPs ranged between

2500 and 3500m. In this paper, we refer to sites 1 and 2 as 'northern sites', sites 3 and 4 are 'central sites', 5 and 6 are 'southern sites', and 7 and 9 are 'shelf sites.' Distances between neighboring ARPs ranged from 110 to 260km. Acoustic data for the two northern sites were available for the entire deployment period, data for site 3 were available from July 2001 to February 2002, data for site 4 were available only for the first year of deployment and those for sites 5, 6, 7, and 9 were available only for the second year of deployment.

In order to describe the acoustic characteristics of blue and fin whale calls, we measured beginning and ending frequencies, durations, intercall and intersequence intervals (time between successive call sequences that is shorter than 100s and is presumably too short to be a surfacing event; only applicable for fin whales), and long intervals (time between successive call series longer than 100s, when the calling animal is presumably at the surface) of calls of both species. We used spectrograms of calls with high signal-to-noise ratios from several different times and various sites. We reported the mean and the standard deviation of each property.

We used these measurements to conduct automatic detection of blue and fin whale calls from this large dataset using spectrogram correlation (Mellinger and Clark, 2000; Mellinger, 2001). This method cross-correlates the dataset spectrogram with an artificial kernel that represents a whale call. The values for two kernels that represented blue and fin whale calls were obtained from the ARP dataset as described above. For blue whales, we used a kernel that started with a 9s flat tone at 27.7Hz, followed by a 1s downsweep to 19.5Hz and another 7s downsweep to 18.8Hz. The fin whale call kernel was made to last 1s and sweep down in frequency from 28 to 15Hz.

When analyzing data by automatic spectrogram correlation, a detection threshold must be set. Exceeding this threshold for a set period of time (6s for blues and 0.5s for fins) triggered a detection event. We initially chose high thresholds to minimize false detections. The detection threshold was iteratively adjusted until the false detection rate was less than 1%. The consequence of a high detection threshold, however, is the omission of calls with low signal-to-noise ratios, which results in an underestimate of the total number of calls. Detected calls were saved as individual WAV files, along with the information on the day and time when the call occurred. Files from days with low call counts (<50) were additionally screened to verify the detections. Of the remaining files, we randomly chose for verification approximately 1000 files for each species' calls to confirm that the false detection rate was <1%. Calling statistics and seasonality were reported for the automatic detection results. We define seasonality (or seasonal calling) as a pattern by which whale calls were present during one part of the year and absent during another continuous period longer than one month. Intermittent calling is used to describe a pattern of calling in which there are no periods longer than one month during which there are no detected calls. Detection totals for each species and site were combined into 8-day bins for qualitative comparison with sea ice concentrations.

Sound velocity profiles were calculated from XBTs (expendable bathythermographs) deployed in the region. They indicated that the Western Antarctic Peninsula was an upward refracting environment for sound propagation with a relatively shallow (50 – 150m) sound channel axis in the summer. Most of the ARPs were in deep water, therefore minimizing reception of very distant (>1000km) calls. The manual detection range for blue whale calls was determined to be up to 250km by observing calling sequences produced by the same animal and recorded on multiple instruments. It was then possible to localize on the animal using differences in arrival times of the same call to multiple instruments. Comparison of those calls to automatic detections yielded an automatic detection range of up to 60km for blue whales, and somewhat less for fin whale calls. It should be noted, however, that the spectrogram correlation method is signal-to-noise dependent and the automatic detection range changes depending on ambient acoustic conditions. During times of high ambient noise the detection range will be diminished. Since the instruments were fairly deep, sea ice formation and melting did not increase the ambient noise in the detected bands and the noise was generally lowered during the periods of ice cover. Therefore the presence of sea ice did not decrease our capability to detect calling whales.

Recordings were also analyzed by comparing the acoustic power in frequency bands characteristic for whale calls, to the power levels of adjacent frequencies. We calculated power spectral density (500-point FFT, 50% overlap, Hanning window) of the entire dataset and averaged it over 15 minute samples. We determined the ratio of the power in the whale call frequency band to the average power in two adjacent bands where no whale sounds were expected. We assumed linear noise at frequencies around the whale call. For blue whales, we used power at 28Hz as the calling band and compared it to powers at 15 and 41Hz as the noise bands. For fin whales, we compared the power at 89Hz (see Figure 2.2b) as the calling band to powers at 80 and 98Hz as the noise bands. We used the higher frequency component of fin whale call to avoid overlap with blue whale calls and because of lower ambient noise at higher frequencies. The range of detection using this method is probably larger than for automatic detections, but it is also a signal-to-noise dependant method. We calculated one-day averages of the signal-to-noise ratios and cross-correlated the results to one-day total automatic detections, and we used a t-test to determine whether the two methods yielded significantly different results.

The nature of the acoustic data enables us to determine only when calling animals are present in the detection area. During periods when no calls are detected, whales may be absent or silent (Stafford *et al.*, 1999b). In this paper, we use call abundance as a proxy for whale abundance. The relationship between the number of calls detected and the number of animals present is not currently understood. We assume that higher calling rates in automatic detection and higher signal-to-noise ratios in acoustic power analysis reflect a greater number of animals present, although seasonal variation in the tendency to call may also be reflected in these data.

In calculations of the average number of days/site that whales were detected during the year, we did not include site 3 (because it did not have a full deployment year of data) nor site 9 (because no blue or fin whale calls were detected). We reported the average number of calls at all sites, normalized by the number of sites recording that month and the number of days with recordings per month for each site, as well as the total number of blue and fin whale call detections for each deployment year. We compared the differences between the two years as well as the differences among sites. Also, we cross-correlated in time daily detections at different sites, for indication of blue and fin whale movement between the sites. These time lag analyses were conducted for periods when data were available at all sites (Apr 2, 2001 – Feb 9, 2002 during the first deployment year and Mar 1, 2002 – Feb 17, 2003 during the second) and we report the ones that showed clear trends. We did not perform time lag calculations for site 7 because of the low call detection numbers at that site.

Sea ice concentration estimates were made using Special Sensor Microwave / Imager (SSM/I) passive microwave data obtained from the National Snow and Ice Data Center. Derived daily gridded sea ice concentration datasets were generated using the Bootstrap algorithm (Comiso, 1991, updated 2002) and are archived from 1995. Ice concentrations are binned to 25km square cells in a polar stereographic projection. We extracted daily mean values for 75km x 75km areas centered around each ARP using the imaging software *WIM* (Kahru, 2000). Since sites 7 and 9 were less than 75km from coastline that has snow and ice cover year round, it is likely that the sea ice coverage on these sites is overestimated. We calculated 8-day averages for qualitative comparison to whale call detections. Since daily or weekly samples are not necessarily independent, to determine the number of independent sea ice and whale call samples at each site we calculated the integral time scales from autocorrelations of the sea ice and whale call detection data. We calculated Pearson's coefficient of correlation between blue and fin whale call detections and sea ice concentrations binned in periods corresponding to the integral time scale. The number of deployment days was divided with the calculated integral time scale to determine the number of independent samples, N, at each site. We used a t-test for testing a null hypothesis that sea ice concentration and the number of blue and fin whale call detections are not related, using significance level $\alpha = 0.05$.

We made minimum density estimates of calling whales. We assumed detection radius of 60km (32.4 n mi) for both species. Since we know blue whales make calls at regular 62s intervals, we assumed there were two calling whales present when two calls were detected in less than a minute and we inspected the automatic detection results at each of the sites for sequences of calls with the intercall interval shorter than one minute. For fin whales, we estimated the number of calls that occurred in a 13s interval. We report the values in number of calling animals / n mi^2 so that they are comparable to the results of visual surveys.

D. Results

The call of the Antarctic blue whale (Ljungblad *et al.*, 1998; Clark and Fowler, 2001) consists of three components and lasts about 18.6s (Figure 2.2a). For our data, on average, the call starts with a tone at 27.7 ± 0.4Hz that lasts 9.5 ± 1.4s. The second component is a short, 1.1 ± 0.5s duration downsweep in frequency from 27.7 ± 0.4Hz to 19.5 ± 0.4Hz, and the third component is a slightly downswept 18.9 ± 0.5Hz tone lasting 8.0 ± 3.0s (for all measurements, n = 241). The calls are produced in sequences and repeated with intercall intervals of 62.3 ± 5.2s (n = 316) and long intervals of 172 ± 48s (n = 44), presumably for breathing.

Fin whales in the Antarctic produce short, 0.7 ± 0.3s average duration pulsed calls (Figure 2.2b). They sweep down from 27.6 ± 2.2Hz to 14.9 ± 1.3Hz (n = 277). There is an additional, simultaneous pulse centered at 89.2 ± 0.7Hz with an average bandwidth of 4.5 ± 0.9Hz (n = 90). The calls are repeated at 12.9 ± 0.5s intercall intervals (n = 238) and 29.7 ± 6.5s intersequence intervals (n = 32) over long periods, with long intervals of 140 ± 64s (n = 8), again presumably for breathing.

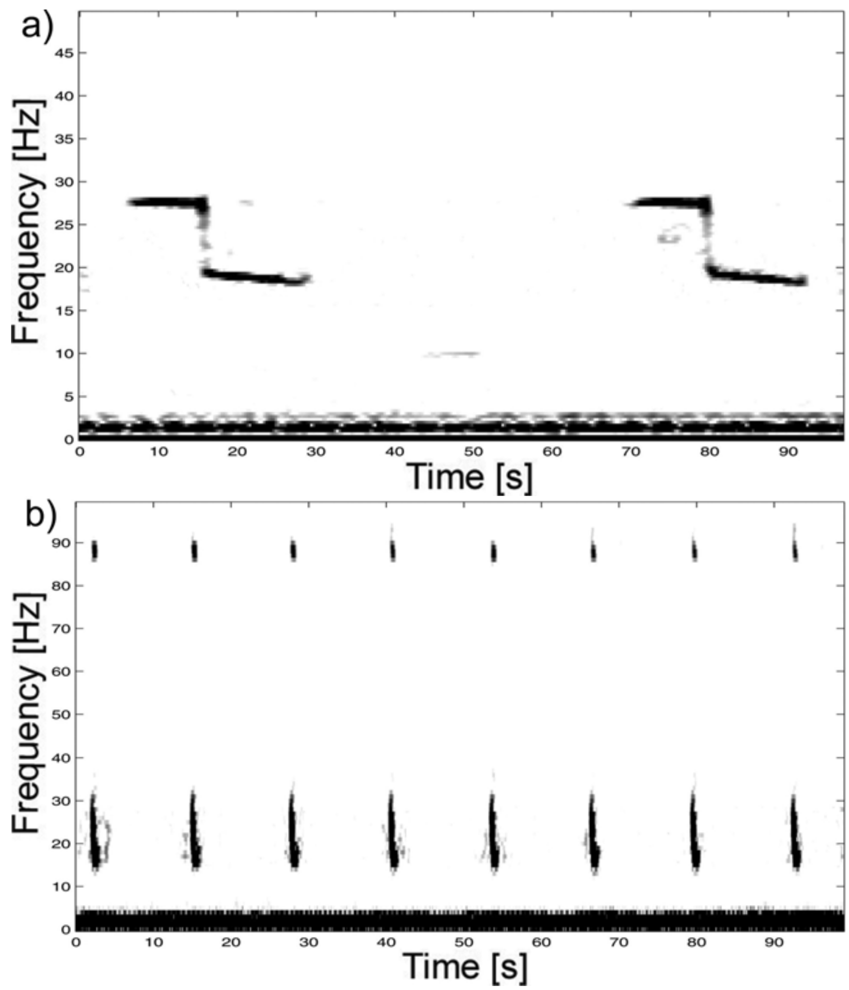

Figure 2.2. Spectrograms of (a) Antarctic blue (1500-point FFT, 90% overlap, Hanning window) and (b) fin whale (500-point FFT, 90% overlap, Hanning window) calls recorded west of the Antarctic Peninsula.

Calls attributed to blue and fin whales were recorded at seven out of eight sites in the Western Antarctic Peninsula, with no calls from either blue or fin whales detected at site

9 in Marguerite Bay. A total of 258,706 blue whale calls were automatically detected from March 2001 to February 2003 by use of spectrogram correlation. Likewise, 72,194 fin whale calls were detected by spectrogram correlation during this period, although poor performance of the automatic call detection method during periods of intense calling suggests that the total number of fin whale calls in our data was actually higher. On average, blue whale calls were detected on 177 days during a year and fin whale calls were detected on 51 days. There was a significant increase in the number of blue whale call detections at the northern sites (1 and 2) from the first deployment year to the second ($\chi^2 = 432$, df = 2, $p<0.001$; $\chi^2 = 1128$, df = 2, $p<0.001$, respectively). There was also a significant increase in fin whale call detections at the same sites during that period ($\chi^2 = 88$, df = 2, $p<0.001$ at site 1; $\chi^2 = 1295$, df = 2, $p<0.001$ at site 2).

On average for all sites and both years, blue whale calls were detected intermittently year round in the Western Antarctic Peninsula (Figure 2.3a). The highest blue whale calling rates were in March and April. Calling decreased in May and was minimal between June and August. There was a secondary peak in calling in October and November. Typically, few calls were detected in December. Fin whale calls showed a strong seasonal presence (Figure 2.3b). They were detected from February until June, with the peak in call detections in May. No calls were detected between July and January.

Blue whale calling varied among sites and between deployment years (Figure 2.4). Northern sites had intermittent calling during the austral winter of the first deployment year and seasonal calling during the second year. Other sites had a seasonal pattern of blue whale calls throughout their deployment periods. Fewer calls were detected on the shelf sites than on the shelf break sites. The detections at the two northern sites occurred simultaneously during the second year of deployment (Figure 2.5). Calls on the two southern sites occurred simultaneously as well, but they lagged the northern sites by 3-4 weeks during the summer, and preceded them by about a month in the spring. The first big increase in the number of detections during austral summer (February – March) 2002 was at the northern sites. Detections increased on the southern sites in April, but in May they were higher at northern sites. In October 2002, the first high detections occurred at the southern sites. In early November the detection peak shifted north, and in late November and early December it returned to the southern sites.

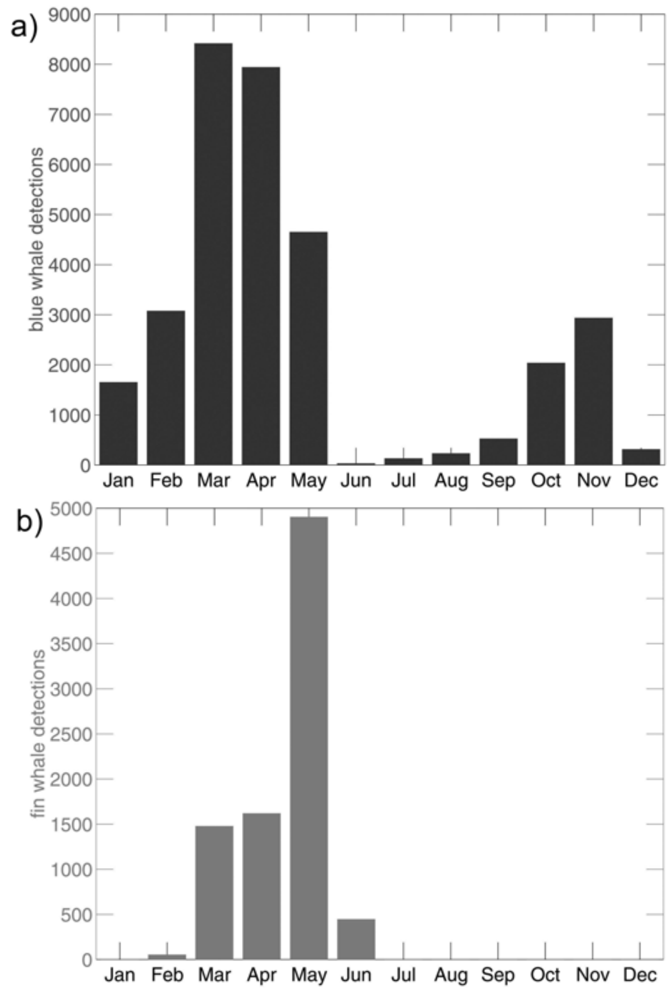

Figure 2.3. Monthly averages of the number of blue (a) and fin (b) whale call automatic detections over the whole deployment period, normalized by the number of sites with recordings in a month and the number of days with recordings at each site.

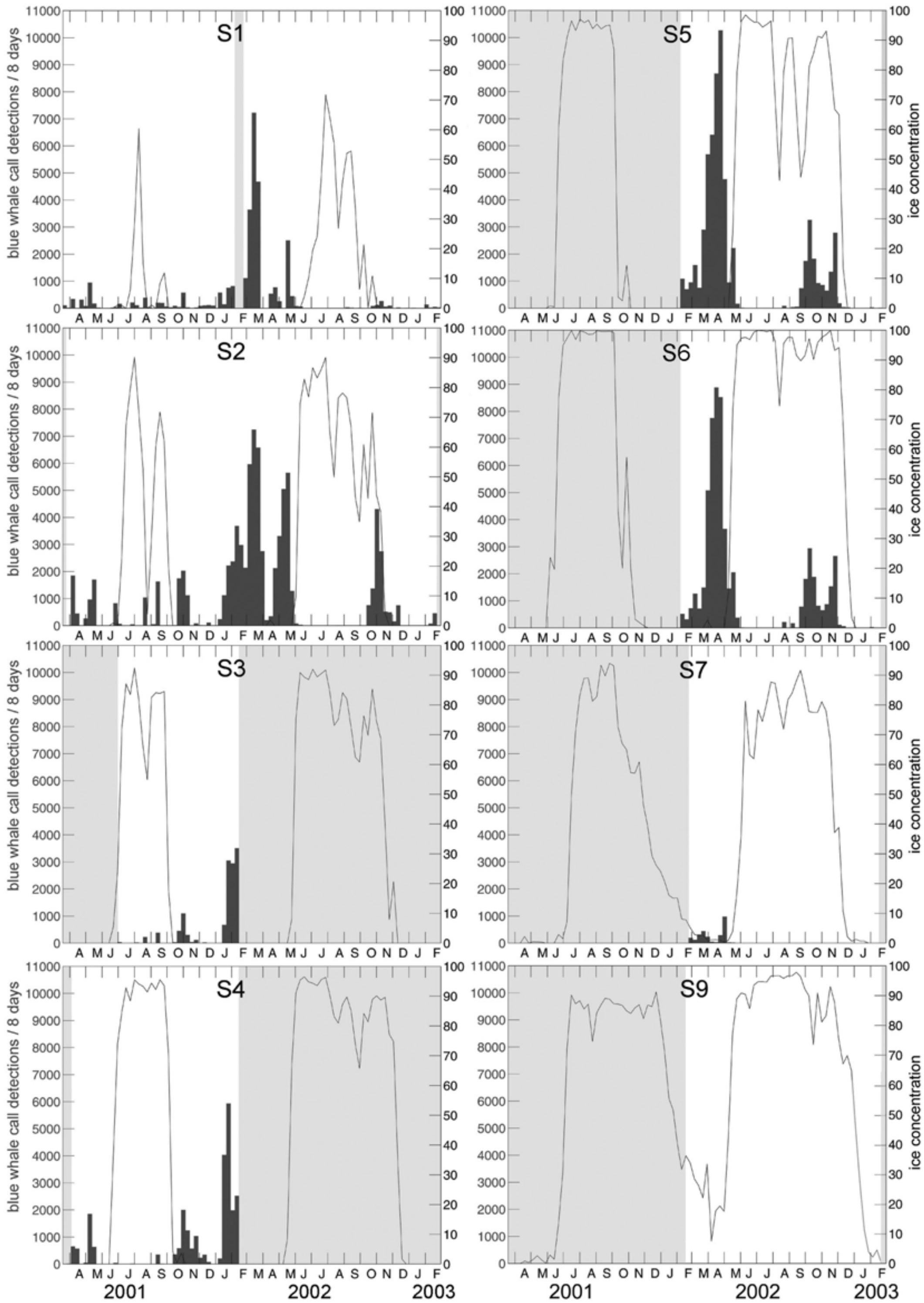

Figure 2.4. Blue whale call automatic detections (bars) and sea ice concentration data (line) in 8-day bins for all sites. Gray rectangles represent periods during which there were no acoustic data.

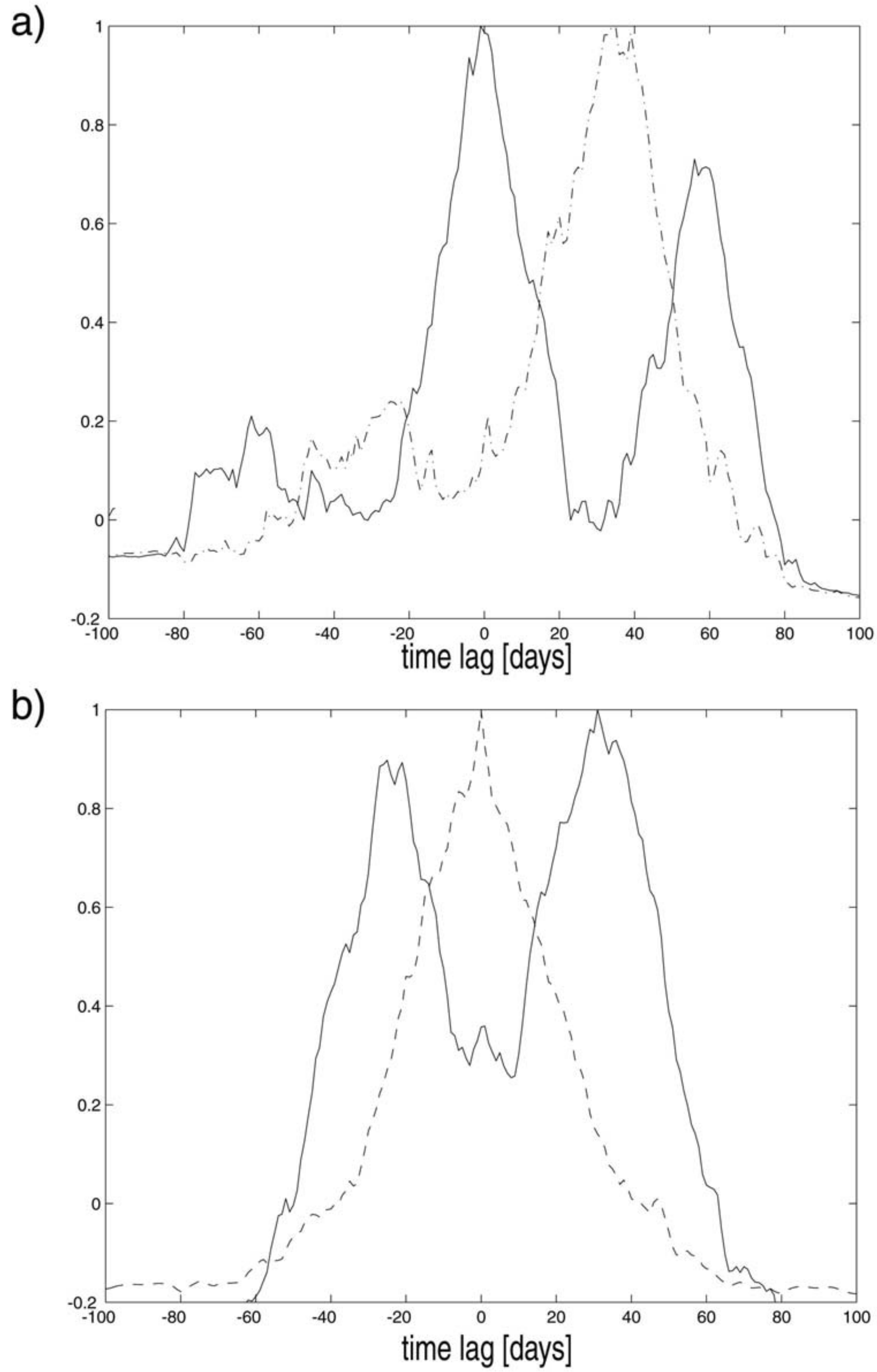

Figure 2.5. Time-delayed correlations between blue whale call detections at different sites. a) Solid: sites 1 and 2 (1 Mar 02–17 Feb 03); dash-dotted: sites 1 and 5 (1 Mar 02–17 Feb 03). b) Solid: sites 2 and 5; dashed: sites 5 and 6 (both 1 Mar 02–17 Feb 03).

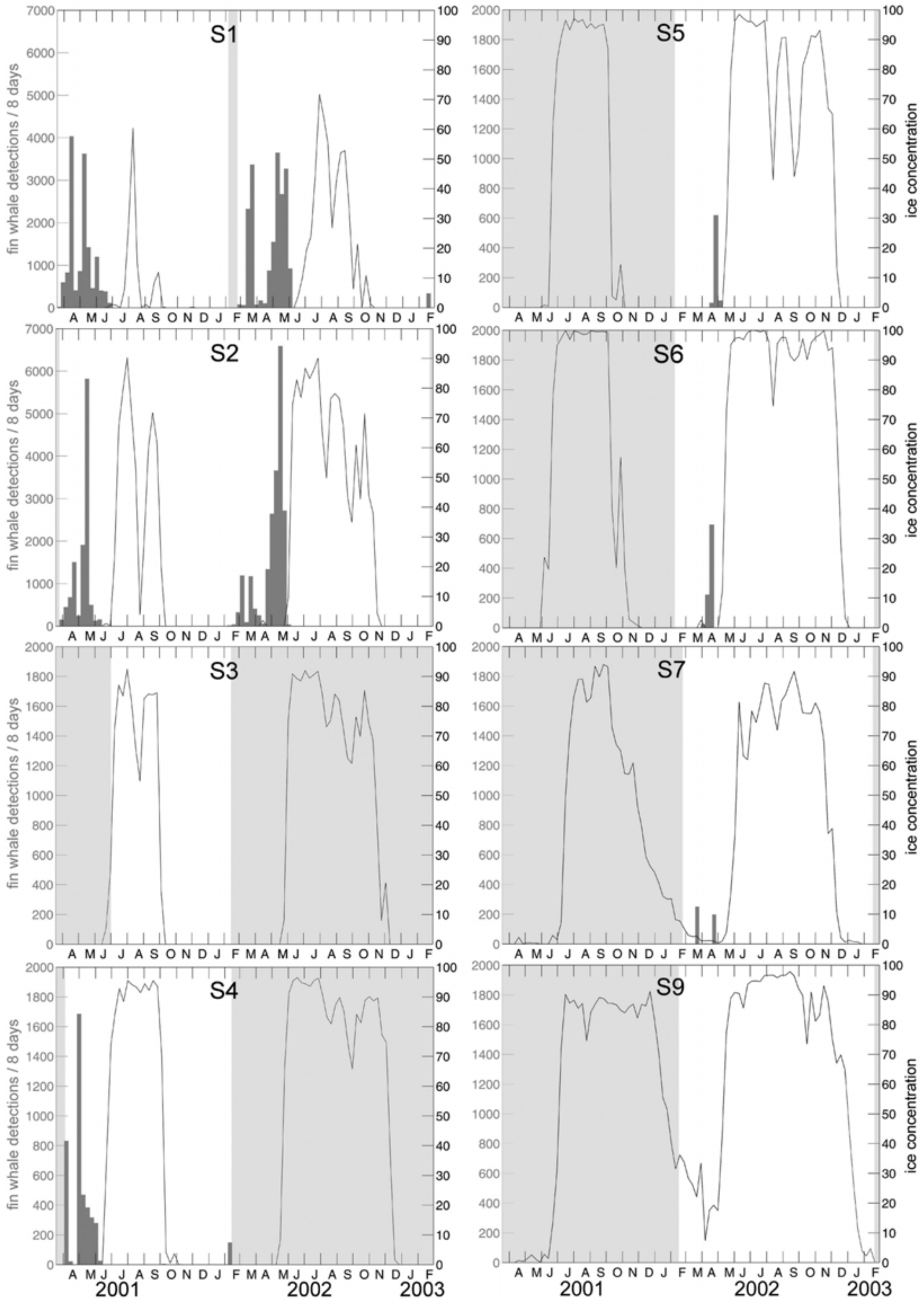

Figure 2.6. Fin whale call automatic detections (bars) and sea ice concentration data (line) in 8-day bins for all sites. Gray rectangles represent periods during which there were no acoustic data. Note different scales for automatic detections between northern and all other sites.

Fin whale calls showed a strong seasonal presence on all sites where calls were detected (Figure 2.6). A few calls were detected on site 4 in October and November 2001 (5 and 2 detections, respectively). The highest call counts were at the northern sites. Low detection numbers or no call detections were characteristic of the shelf sites. Peaks in calls were delayed between the two northern sites by about 10 days. In 2002, peaks in calling at northern sites were preceded by calling at southern sites by approximately a month. Fin whale calls were detected on site 6 four days earlier than on site 5. The detections of fin whale calls typically stopped as the sea ice began to form.

The results obtained by the acoustic power analysis were not significantly different from the automatic detection results, except on the shelf site. Results on seasonality of blue whale calls were very consistent between the two methods (Figure 2.7). However, there was a slight difference in fin whale presence patterns between the two methods (Figure 2.8). Acoustic power method inferred a more continuous presence of fin whales and in some cases about a month longer presence than the automatic detection method. Manual inspection of data during fin whale presence revealed frequent fin whale calling, resulting in a persistent fin whale “noise” band, especially at northern sites, ranging in frequency between 15 and 30Hz (and around 90Hz). This band of calling “noise” decreased the signal-to-noise ratio of individual calls, therefore decreasing the number of automatic detections. The acoustic power method was better at detecting the continuous, fin whale calling band signal. This was quite pronounced at the two northern sites. The fin whale calling band (and acoustic power) was stronger at site 1, and fewer fin whale calls were detected there than at site 2, which had a weaker calling band. There were few calls detected at site 7 on the shelf, and these low calling rates caused the acoustic power method to be less robust relative to the automatic call detection method. Even though both methods yielded similar results, it is clear that each method has its advantages and disadvantages and the choice of method should vary depending on the species and their

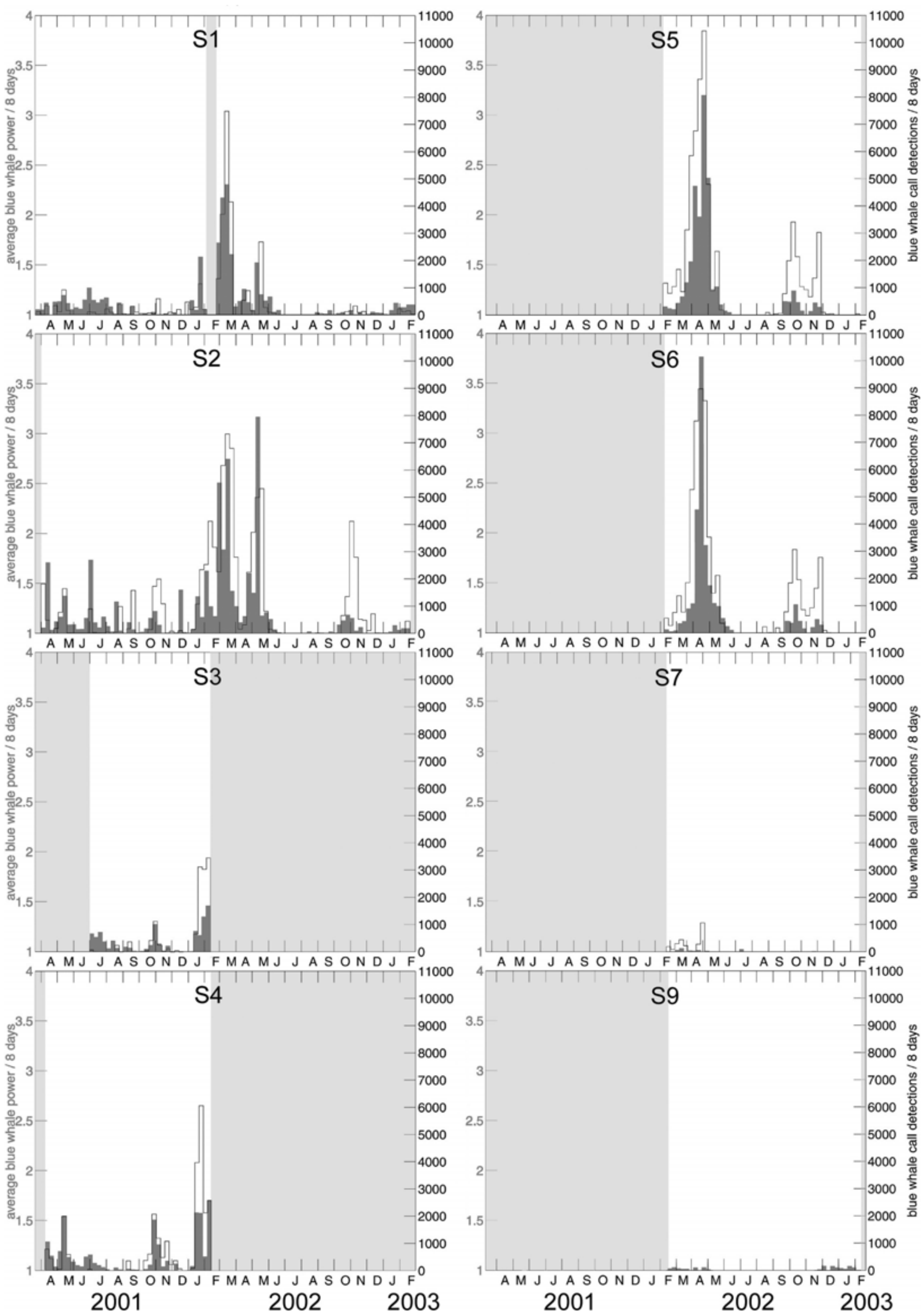

Figure 2.7. Comparison of blue whale seasonality obtained by acoustic power (shaded bars) and automatic detection (clear bars) methods for all sites. Gray rectangles represent periods during which there were no acoustic data.

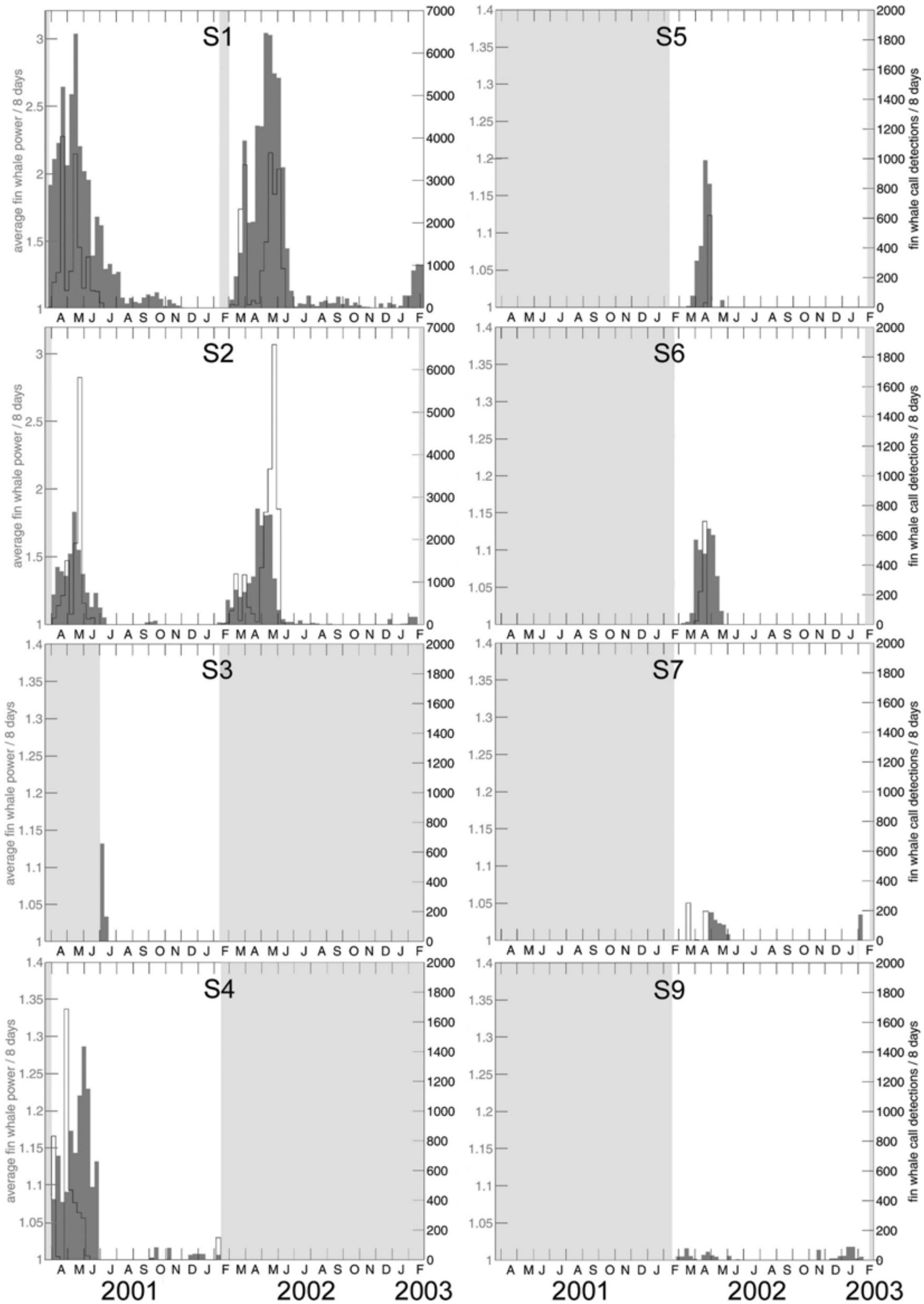

Figure 2.8. Comparison of fin whale seasonality obtained by acoustic power (shaded bars) and automatic detection (clear bars) methods for all sites. Gray rectangles represent periods during which there were no acoustic data. Note different scales between northern and all other sites.

Table 2.1. Correlations between the number of blue and fin whale call detections and sea ice concentrations binned in N-day bins by year (a) and overall (b, when applicable). Data for site 9 were not included since there were no whale call detections at that site.

a)

	2001/02					2002/03				
	Blues		Fins			Blues		Fins		
Site	r	p	r	p	N	r	p	r	p	N
1	-0.052	> 0.2	-0.163	> 0.2	36	-0.225	> 0.1	-0.295	> 0.05	37
2	-0.321	> 0.2	-0.297	> 0.2	13	-0.469	> 0.1	-0.346	> 0.2	11
3	-0.640	> 0.1	-	-	7	-	-	-	-	-
4	-0.488	> 0.1	-0.379	> 0.2	10	-	-	-	-	-
5	-	-	-	-	-	-0.300	> 0.2	-0.283	> 0.2	8
6	-	-	-	-	-	-0.120	> 0.2	-0.207	> 0.2	7
7	-	-	-	-	-	-0.461	> 0.2	-0.462	> 0.2	5

b)

	Overall				
	Blues		Fins		
Site	r	p	r	p	N
1	-0.253	> 0.2	-0.327	> 0.1	21
2	-0.394	> 0.05	-0.285	> 0.2	19

calling intensities. In general, the acoustic power method may be sensitive to more distant calls and provides better results during periods of intense calling, whereas the call detection method is superior for periods of sparse calling and nearby animals.

At some point during the year, sea ice extended over all the instruments during both deployment years (Figures 2.4 and 2.6). On average, sea ice started to form a month earlier and retreated a month later in 2002 than in 2001. As expected, sea ice started forming first on the central and southern sites in May and June, and it fully retreated from these sites in November and December. During at least half of the time, the sea ice cover was over 90% at the southern sites, and over 80% at the central sites. Sea ice at the shelf sites formed approximately at the same time as on the central and southern sites, but the coverage was less than 80% during half of the time. Also, the sea ice never completely melted at those sites between the two years. At northern sites the sea ice formed in June and July and retreated by October or November. The average sea ice concentration during the time of coverage for sites 1 and 2 was 32% and 61%, respectively.

Sea ice concentration had a longer integral time scale for independence of estimates at all sites than call detections from either species, ranging from 8 to 53 days. There was a negative correlation between blue and fin whale calls and sea ice concentration at all sites on these weekly to monthly scales during the entire deployment period, although none of the p-values were statistically significant (Table 2.1; Figures 2.4 and 2.6). On the annual scale, however, the year with longer ice coverage had more whale calls of both species.

While making minimum density estimates, we found one-minute intervals with more than one blue whale call on all shelf break sites in a given day. Therefore we assumed two blue whales calling at each site on the shelf break, and no blue whales calling at the shelf sites, and obtained a blue whale density of 0.43 calling whales per 1000 n mi^2. To obtain the fin whale calling intensity that we observed on the northern sites, there had to be at least one fin whale calling for every second of the intercall interval, which is 13 seconds. So we assumed 15 simultaneously calling whales at each of the two northern sites, and no calls at other sites, and obtained a fin whale density of 1.30 calling whales per 1000 n mi^2 over the whole area, or 4.55 calling whales per 1000 n mi^2 at the northern sites.

E. Discussion

Blue whale calls were recorded intermittently year round, while fin whale calls were recorded only seasonally in continental slope and shelf waters west of the Antarctic Peninsula. There was a clear temporal overlap in occurrence, as indicated by simultaneous reception of calls from the two species. More calls of each species were detected in the second year of deployment, which was also a year with longer sea ice coverage. On weekly to monthly time scales, however, whale calls from both species were negatively correlated with sea ice concentrations. Whales may have left the area or stopped calling as the sea ice began to form. The peak in calling for both species occurred about a month later during both years (March – May) than predicted from whaling data (February – March) (Mackintosh and Brown, 1956; Laws, 1961).

It is possible that the differences in the detections of the two species are due to the fact that the area we sampled is not an equally preferred habitat by blue and fin whales (Mackintosh, 1965). The sites on the continental shelf break (1-6) were located along the flowpath of the Antarctic Circumpolar Current (Hofmann *et al.*, 1996). Those were the sites with high call detection rates for both species and they all had periods of open ocean as well as times with sea ice coverage. While blue whales are known to associate with sea ice (Mackintosh, 1965; Kasamatsu *et al.*, 1988), fin whales are not (Mackintosh and Wheeler, 1929) and could be staying farther north. Notably, there were fewer fin whale calls on the southern sites, while blue whale call detections were highest at those sites.

Sites 7 and 9, which were both on the continental shelf, had few or no calls from either species. It appears that blue and fin whales did not come onto the continental shelf for long periods of time and probably did not go into Marguerite Bay even at times when the sites were free from sea ice.

While it has been reported in both the northern and the southern hemispheres that blue whales can overwinter at high latitudes (Kellogg, 1929; Clark and Charif, 1998; Watkins *et al.*, 2000; Stafford *et al.*, 2001), Antarctic-type blue whale calls have been detected in the Eastern Tropical Pacific in July (see Figures 3a and 3b in Stafford *et al.*, 1999a). The blue whale calling rate decreased at our instruments between June and August, suggesting that some northward migration may have taken place during the winter. Blue whale calls were detected at northern sites intermittently throughout the winter (June – October) 2001, indicating presence of at least some calling whales. This intermittent calling could be an implication of a time-lagged migration, or that some individuals skip migration. Our data are consistent with the IWC sightings data indicating that blue whale population in the Antarctic does not increase dramatically between November and February (Kasamatsu *et al.*, 1996) and the whaling data showing blue whale presence in September and October (Horwood, 1986).

The cessation of fin whale calls in May is most likely an indication of fin whale migration out of the area, as it coincided with the sea ice formation across all sites. Fin whales did not start calling again before the middle of February. There have been suggestions that fin whales use repetitive calls as reproductive displays (Watkins *et al.*, 1987; Croll *et al.*, 2002) so in spring they could be present west of the Antarctic Peninsula feeding (Mackintosh and Wheeler, 1929; Gaskin, 1982), but producing few or no calls. Autumn is the onset of their mating season (Laws, 1961) at which time they could start to engage in more frequent calling. Whaling records, however, show a higher proportion of fin whale catches after January (Kellogg, 1929; Mackintosh, 1965), just as the more recent IWC sightings data show increased sightings in January (Kasamatsu *et al.*, 1996) indicating that a late-summer arrival to the Antarctic is a likely explanation for the February start of calling.

While more calls were detected during the year with longer sea ice cover, on shorter time scales sea ice concentration and whale calls were negatively correlated. This negative correlation on a shorter time scale is consistent with previous observations (Mackintosh, 1965), but the lack of significance in most cases could be due to the small independent sample sizes. The big increase in the number of calls between the two deployment years was not expected. It cannot be attributed to population growth because it would imply an increase of more than 30% in one year, which is an unrealistic growth rate. This increase in relative abundance could have resulted from the movement of animals from other areas of the Antarctic. However, the whaling and sightings data suggest limited meridional movement (Brown, 1954; Kasamatsu *et al.*, 1996). Or it might be possible the differences between the years were related to the observed differences in sea ice conditions (Fraser *et al.*, 1992; Nicol *et al.*, 2000b). Longer acoustic time series with year-round coverage could shed more light on this observation. Also, further comparisons of whale calls with other biological parameters (e.g. krill abundance) could reveal the causes of this increase in relative abundance.

Such comparisons could also further understanding of the apparent movements of these two species of whales. Both blue and fin whale calls were detected sequentially on instruments distributed along the continental shelf break, moving in the southwest-northeast direction. Since blue and fin whales feed in Antarctic waters (Mackintosh and Wheeler, 1929; Kawamura, 1980; Gaskin, 1982; Kawamura, 1994), their movement along the shelf could reflect the seasonality of their prey (Kellogg, 1929; Nemoto, 1957; Springer *et al.*, 1999) and sea ice conditions. For example, the notable decline in blue whale call detections in late December and early January, which would not be predicted from the catch data (Mackintosh and Wheeler, 1929), could indicate that blue whales use a larger area for foraging than the area covered by our acoustic array and they could be further south during this period of low detections. A northeast-southwest movement pattern along the shelf break was especially noticeable from both blue and fin whale calls during the second year of deployment. During the austral summer this movement for both species was from the northern sites towards the southwest, and it reversed towards the northeast in the fall. In spring, blue whale calling occurred first at the southern sites and moved northeast again, but it reversed in late October and returned to the southern sites. There is clearly a bias in this interpretation due to the locations of instruments. However, this movement may be explained by productivity and sea ice patterns in the area (Siegel, 1988; Holm-Hansen and Mitchell, 1991; Ross *et al.*, 1996; Stammerjohn and Smith, 1996). During autumn, the whales may be moving north as the sea ice begins to form. In the spring, on the other hand, the first high blue whale call detections occurred at the southern sites, during a period when the sea ice cover was still substantial. At this time the whales could be following productivity blooms to the retreating ice edge.

We can make a comparison of whale densities between the acoustic data and visual census. Data from the circumpolar visual surveys conducted by the International Whaling Commission indicate an average density in the Antarctic of 0.32 blue whales per 1000 n mi^2 and 1.59 fin whales per 1000 n mi^2 (Branch and Butterworth, 2001a). Minimum density estimates from the acoustic data can be considered conservative because we based them on the automatic detections, which are an underestimate of the total number of calls due to the omission of calls with a low signal-to-noise ratio. Also, we did not take into account gender (McDonald *et al.*, 2001; Croll *et al.*, 2002) or other factors that could affect calling. Still, our blue whale estimate is about a third higher than the density estimate from visual surveys. Fin whale density values are equal to or several times greater than predicted from the visual surveys. In both the blue and fin whale cases presented here, the assumptions were very conservative given the real acoustic data, which indicates that, locally, both species are more abundant than the Antarctic-wide visual estimates predict. The calling ecology of blue and fin whales, however, is not well understood and needs to be explored further before we can interpret acoustic data in terms of blue and fin whale absolute abundance.

F. Conclusions

We have found passive acoustic detections to be a powerful tool for studying blue and fin whale seasonal occurrence in the Western Antarctic Peninsula. Acoustic data can be collected year-round despite the harsh environmental conditions present in the Southern Ocean. Periods of whale presence were revealed over the 24-month deployment period, showing different degrees of seasonality in the presence of both blue and fin whales. These results suggest that acoustic monitoring may be an efficient method of studying these animals in the Southern Ocean.

Our initial analysis has considered only the relationship between the sea ice and blue and fin whale calls. However, sea ice alone is not enough to provide a full explanation of the changes in whale calling and future analyses will include data on other biological and physical factors, which are available from the SO GLOBEC data sets. Knowledge of the behavioral context of calling is limited, despite some suggestions that calling sequences such as those reported here are primarily breeding displays by males (Watkins *et al.*, 1987; McDonald *et al.*, 2001; Croll *et al.*, 2002). Knowledge of the ecology of calling, however, is necessary for understanding the role of calling in the life histories of these species. In addition, to census populations acoustically, data are needed to quantify the number of calling animals at any one time and the proportion of animals present that are calling. A combination of acoustic and behavioral data would enhance our ability to monitor calling whales over large regions and long time periods.

G. Acknowledgements

This work was supported by NSF Office of Polar Programs grant OPP 99-10007 as part of the SO GLOBEC program, with program guidance by Polly Penhale. We are grateful for the assistance of Raytheon Polar Services marine and science support personnel, the Masters, Officers and crew of ASRV L.M. Gould during cruises LMG01-03, LMG02-01A, and LMG03-02. We also acknowledge National Snow and Ice Data Center for the processing and distribution of sea ice concentration data. We thank Dr. Allan Sauter for assistance with ARP preparation and deployment, Jessica Burtenshaw for her help with sea ice data acquisition, and editor Dr. Daniel Costa and anonymous reviewers for helpful advice on this manuscript. This is U.S. GLOBEC contribution number 468.

The text of Chapter II, in full, is a reprint of the material as it appears in Deep-Sea Research II (Širović, A., J.A. Hildebrand, S.M. Wiggins, M.A. McDonald, S.E. Moore, and D. Thiele. 2004. Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. Deep-Sea Research II, 51: 2327–2344). The dissertation author was the primary researcher and author and the co-authors listed in this publication supervised the research which forms the basis for this chapter.

III. How far can blue and fin whales be heard in the Southern Ocean?

A. Abstract

Blue (*Balaenoptera musculus*) and fin whale (*B. physalus*) populations in the Southern Ocean have remained at very low numbers more than three decades since they became protected. Both species produce high intensity, low frequency calls, which probably serve as communication signals during mating and feeding. The source levels of blue and fin whale calls off the Western Antarctic Peninsula were calculated from the recordings made using calibrated, bottom-moored hydrophones. Blue whales were located to a range of 200km using hyperbolic localization and time difference of arrival. The distance to fin whales was estimated using multipath arrivals of their calls up to a range of 56km. The standard error in range measurements was 2.2km using hyperbolic localization, and 3.4km using multipath arrivals. When the range to the same blue whale calls was determined using both methods, the average difference in the ranges was 4.9km, but the results were not significantly different. Both species produced high intensity calls, the average blue whale call source level was 189±3dB re: 1μPa at 1m over the 25–29Hz band, and the average fin whale call source level was 189±4dB re: 1μPa at 1m over the 15–28Hz band. The range over which blue and fin whales were detected in this study was limited by the methods used, but the calls of these two species could be detectable up to the distance of 1300km. Source level and detection range data are helpful in calculating the relative density of calling whales from passive acoustic recordings.

B. Introduction

Several methods have been developed for acoustic localization and source level estimation in the marine environment (Frazer and Pecholcs, 1990; Cato, 1998; Jensen *et* *al.*, 2000; Spiesberger, 2001). The theory was developed predominately for naval and seismic purposes, but similar methods can be used to determine locations and source levels of calling cetaceans in the wild (Watkins and Schevill, 1972; McDonald *et al.*, 1995; Stafford *et al.*, 1998; McDonald and Fox, 1999; Clark and Ellison, 2000; Thode *et al.*, 2000; Charif *et al.*, 2002). It has been established that certain baleen whale calls can be detected at ranges of hundreds of kilometers (Cummings and Thompson, 1971; Payne and Webb, 1971; Clark, 1995; Stafford *et al.*, 1998).

Blue (*Balaenoptera musculus*) and fin whales (*B. physalus*) make distinctive low frequency, high intensity calls that vary geographically (Cummings and Thompson, 1971; Watkins, 1981; Edds, 1982; 1988; Clark, 1995; McDonald *et al.*, 1995; Ljungblad *et al.*, 1998; Stafford *et al.*, 1999a; McDonald *et al.*, 2006), and their source levels have been measured at several worldwide locations. Cummings and Thompson (1971) measured source level of blue whale moans off Chile in the 14 to 222Hz band to be 188dB re: 1μPa at 1m. Calls of blue whales from the eastern North Pacific Ocean had maximum intensity 180–186dB re: 1μPa at 1m over the 10–110Hz band (Thode *et al.*, 2000; McDonald *et al.*, 2001). Fin whale downswept call source levels have been reported at 160–186dB re: 1μPa at 1m in the western North Atlantic and between 159 and 184dB re: 1μPa at 1m in the eastern North Pacific Ocean (Watkins, 1981; Watkins *et al.*, 1987; Charif *et al.*, 2002). Northrop *et al.* (1968) reported fin whale downsweeps of even higher intensity in the Central Pacific Ocean, ranging between 165 and 200dB re: 1μPa at 1yd.

Frequency and temporal characteristics of the calls blue and fin whales make in the Southern Ocean have been described previously (Ljungblad *et al.*, 1998; Širović *et al.*, 2004; Rankin *et al.*, 2005). Blue whale calls last up to 18s and generally consist of three segments: a 9s long, 27Hz tone, followed by a 1s downsweep to 19Hz and another, longer-lasting downsweep to 18Hz (Širović *et al.*, 2004; Rankin *et al.*, 2005). Fin whales produce short (<1s) downsweeps from 28 to 15 Hz (Širović *et al.*, 2004; Širović *et al.*, 2006). Calls of both species are usually repeated at regular intervals. No call source levels from either species have been reported for the Southern Ocean.

Blue and fin whales were the primary targets of the commercial whaling industry that developed in the Southern Ocean during the twentieth century. Populations of both species were brought to near extinction before their hunt was banned in the 1960's and 70's (Clapham and Baker, 2001), and their population recovery has been slow (Best, 1993; Branch and Butterworth, 2001a; Branch *et al.*, 2004). It has been hypothesized that calls are an important part of the mating and feeding behaviors (Watkins *et al.*, 1987; McDonald *et al.*, 2001; Croll *et al.*, 2002; Oleson *et al.*, 2006), so the low population densities caused by the commercial whaling might make it more important for the whales to be able to communicate over longer distances.

Call intensity is important for successful intraspecific communication, as well as our understanding of the potential impacts of anthropogenic noise on these animals. Monitoring long-term changes in the overall calling levels, also, can aid in determining population trends of these two species that are still at small fractions of their pre-exploitation levels in the Southern Ocean. In this paper, we report the average source levels for blue and fin whale calls recorded off the Antarctic Peninsula and investigate the variation in the source levels within the population. Also, we calculate the ranges over which these calls can be expected to propagate.

C. Methods

Acoustic data were recorded using Acoustic Recording Packages (ARPs) deployed off the Western Antarctic Peninsula between March 2001 and February 2003. Detailed information on ARPs, these deployments, and temporal characteristics of blue and fin whale calls used in the analyses is given in Wiggins (2003) and Širović *et al.* (2004). The

ARPs were not navigated after deployment for precise locations, so the maximum error in the deployment locations, given the average ARP sinking speed (40m/min) and assuming maximum speed of the Antarctic Circumpolar Current (15cm/s, Pickard and Emery, 1990), is less than 1km.

Multipath arrivals

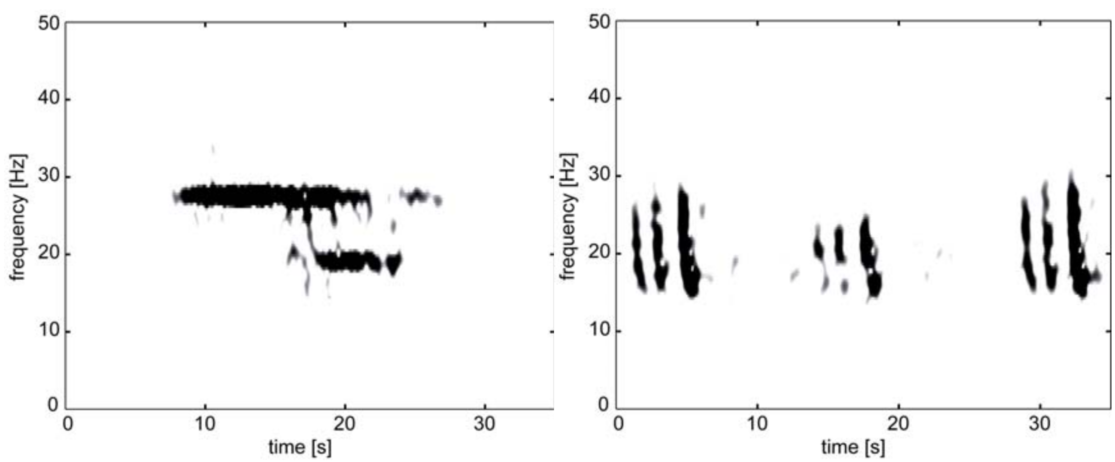

Figure 3.1. Blue (left) and fin whale (right) calls recorded off the Western Antarctic Peninsula, showing multipath arrivals.

As the sound travels through the water column from the source to the receiver, it can follow a direct path, or it can be reflected off the surface and the bottom. The arrival time differences of those multipaths to a single receiver can be used to determine the distance between the source and the receiver. Both blue and fin whale calls were suitable for this analysis because the downswept parts of their calls made it possible to distinguish exact multipath arrival times (Figure 3.1). Arrival time for the downsweep was measured in the time-frequency domain at the time of the highest frequency for all multipaths, and the differences between the multipath arrival times were calculated. Only calls with three or more multipath arrival times were used in the analysis. The error in the calculation of the arrival time differences was determined by taking repeated measurements of the multipath arrival times of an individual whale call. The range to the calling whale was calculated separately for each measurement and the standard deviation of those ranges was reported as the standard error in range determination.

The following assumptions were made in the multipath arrival model: whale calling occurred at the surface, instruments were located on the bottom, sound speed profile was homogeneous (c=1480m/s), and the bottom was flat. Blue whales are known to make calls at depths less than 50m (Thode *et al.*, 2000; Oleson *et al.*, 2006), and the calling depth for fin whales is reported to be around 50m (Watkins *et al.*, 1987). The hydrophone was suspended 10m above the ocean floor. Given the water column depth of around 3000m, differences in water column depth <100m could reasonably be approximated as calling at the surface and receiver on the bottom. All the ARPs used in these analyses were deployed in locations close to the shelf break, but the regions away from the shelf break had a relatively flat or slightly sloping bottom. This region is an upward refracting environment (Urick, 1983), so the calls produced in the relatively shallow water on the shelf and shelf-break could not be recorded by the ARPs located in deep water (see Figure 3.2 and section "Sound propagation modeling" below). Therefore, whales that were recorded on the ARPs had to be located in the region away from the shelf break, and flat bottom was a good assumption.

Determining the range to calling animals using multipath arrivals was possible only at times when there were no overlapping calls. This method estimated only the distance to the calling whale from the ARP, not the location of the calling whale. The range information, however, was sufficient for source level calculations.

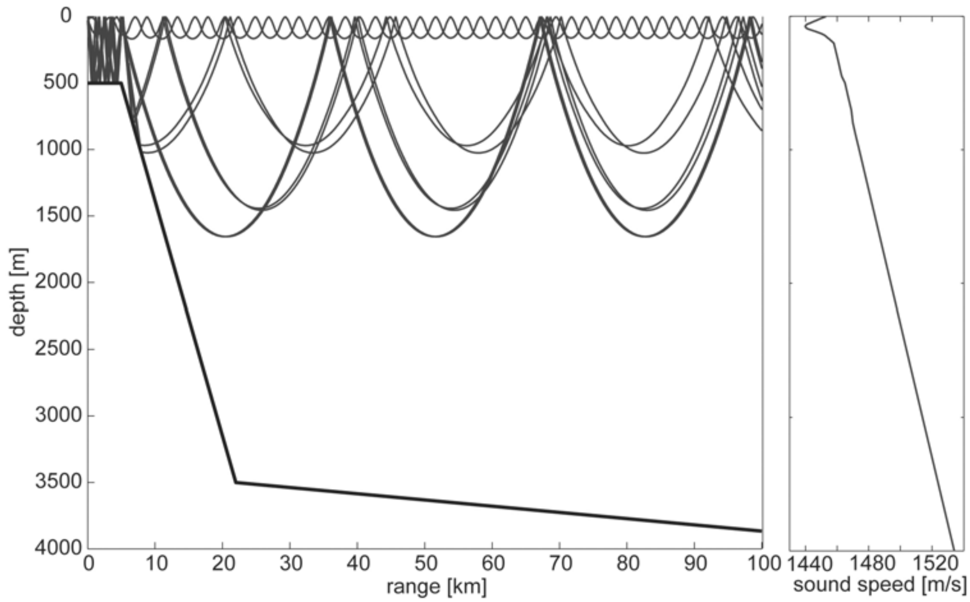

Figure 3.2. Ray trace diagram from Bellhop model of a 27Hz sound originating on the shelf and propagating in the deep water off the shelf. Sound speed profile used for this study, with typical spring conditions, is shown on the right.

<u>Time difference of arrival and hyperbolic localization</u>

To use time difference of arrival (TDOA) for determining range and location, a minimum of three instruments need to receive the same call (Spiesberger, 2001). Periods when the same calls were recorded on multiple instruments were identified by finding sections that had blue whale call sequences with matching intercall intervals. This was possible because the noise at this frequency range is low in the Antarctic, there were not many other calling animals present, and blue whale calls are produced in long, repetitive sequences. Search times were limited by the maximum possible travel time difference between the instruments. Once a matching sequence was identified on three instruments, arrival times of blue whale calls to each instrument were measured manually in the time-frequency domain (i.e. using spectrograms). The point used as the arrival time was the beginning of the first downswept segment of the blue whale call (Figure 3.1), since multipath arrivals made it impossible to determine the timing of different arrivals of the tonal segment. After correcting for the drift in the instrument clocks, the TDOA was calculated for each instrument pair.

The TDOA between pairs of instruments confine possible locations of the calling animal in 2D to a hyperbola. When multiple pairs of instruments are used, the intersections of these hyperbolae give the location of the caller. Hyperbolic localization software developed and made available by D. Mellinger was used for localization. This localization method assumed homogeneous sound speed profile (c=1480m/s). The location of the caller was calculated using the Lavenberg-Marquardt nonlinear least-squares optimization of the resulting intersections of the three hyperbolae. Range from the animal to each instrument was calculated from the resulting location. The geometry of the ARP array resulted in a left–right ambiguity for all the localizations. The ambiguity was resolved due to the bathymetric constraints of the environment (Spiesberger, 2001), using Bellhop ray trace modeling (see "Sound propagation modeling" section below). However, the range value is the same for both solutions, so even if the ambiguities in the hyperbolic localization results were not resolved, the source level results would not be affected. We determined the difference in calculated range between two consecutive calls on each instrument. The mean of these differences is reported as the error in the location calculation using hyperbolic localization method. This method was feasible only for blue whale localization.

We compared the two methods using blue whale calls which exhibited multipath arrivals and which could be located using TDOA. The range results were calculated from 14 blue whale calls on three different days using the two methods. (All multipath calls were received on instrument S3.) A chi-square test was performed to determine if the results obtained using these two methods were significantly different.

<u>Source level calculations</u>

The call source level was calculated from the measured received level (*RL*) and the calculated transmission loss (*TL*). The received level was measured for all calls with calculated range. For blue whale calls, 6s of the call over the 25–29Hz frequency band forward from the first downsweep were used. Fin whale calls received level was measured over a frequency band 15–28Hz starting at the beginning of the call and lasting 1s. The hydrophones used for received level measurements were calibrated by M. McDonald at the U.S. Navy facility in Point Loma, CA. System frequency response from 10–250Hz was measured and this calibration was applied to the measured received levels.

The transmission loss can be described as a function of range (*r*) as follows:

$$TL = X \log\left(\frac{r}{r_0}\right),$$

where *X* is the transmission loss coefficient, dependent on the transmission environment, and r_0 is the reference range, taken to be 1m. *X* has the value of 10 under cylindrical and 20 under spherical spreading conditions. While the ranges over which the calls propagated were much larger than the depth of the instruments and thus spherical spreading clearly did not apply, the polar environment is generally upward refracting (Urick, 1983) and is a propagation environment that is intermediate between cylindrical and spherical spreading assumptions. To estimate the value of *X* applicable for this study, we used an empirical method where the transmission loss coefficient was calculated from the relationship between the received levels and the ranges of blue whale calls calculated using hyperbolic localization:

$$X = \frac{RL_2 - RL_1}{\log(r_1) - \log(r_2)}.$$

This empirical value of *X* was verified theoretically using Bellhop incoherent transmission loss models with the appropriate environmental parameters (see section

"Sound propagation modeling" below). In this case, bathymetry was assumed to be upwards sloping, with a steep shelf break on one side.

The source level of each blue whale call was calculated separately from the received level and range data for each instrument, thus giving three estimates. The average of these three values was used as the calculated source level of each call. Standard deviation of each estimate was calculated as well, and their average is reported and compared to the expected variation in the source level based on the error in range estimation. Only one source level estimate was available for each fin whale call because each range was calculated only using a single instrument recording.

Sound propagation modeling

Bellhop ray trace modeling was used to verify if calls produced on the shelf could be heard on the ARPs, to resolve the left-right ambiguity in the hyperbolic localization results and check the flat bottom assumption from the multipath model. For this problem, we assumed the calling whale was 5km from the edge of the shelf (minimum distance from the hyperbolic localization results) and that the depth increased from 500m on the shelf to 3500m off the shelf, over a 15km distance, and then sloped gradually. The following assumptions were the same for both transmission loss modeling, and the resolution of the left-right ambiguity. The ocean and the bottom sound speed properties were range independent. The sound speed profile was obtained from the average of expendable bathythermograph (XBT) casts in the vicinity of the instruments during the seasons when calls were localized. Source depth was 30m, and we used multiple receiver depths and ranges, at 100m and 1km intervals, respectively. The modeling was done for 27Hz (the frequency of the blue whale tonal segment) and 22Hz (the middle frequency of the fin whale call).

D. Results

The range to calling blue and fin whales and the source levels of their calls were calculated using multiple calls. Detections useful for localization and range determination were limited to the austral spring for blue whales and the early fall for fin whales, because those were the times during which there was less calling (Širović *et al.*, 2004), making it possible to find periods without overlapping call sequences from multiple whales.

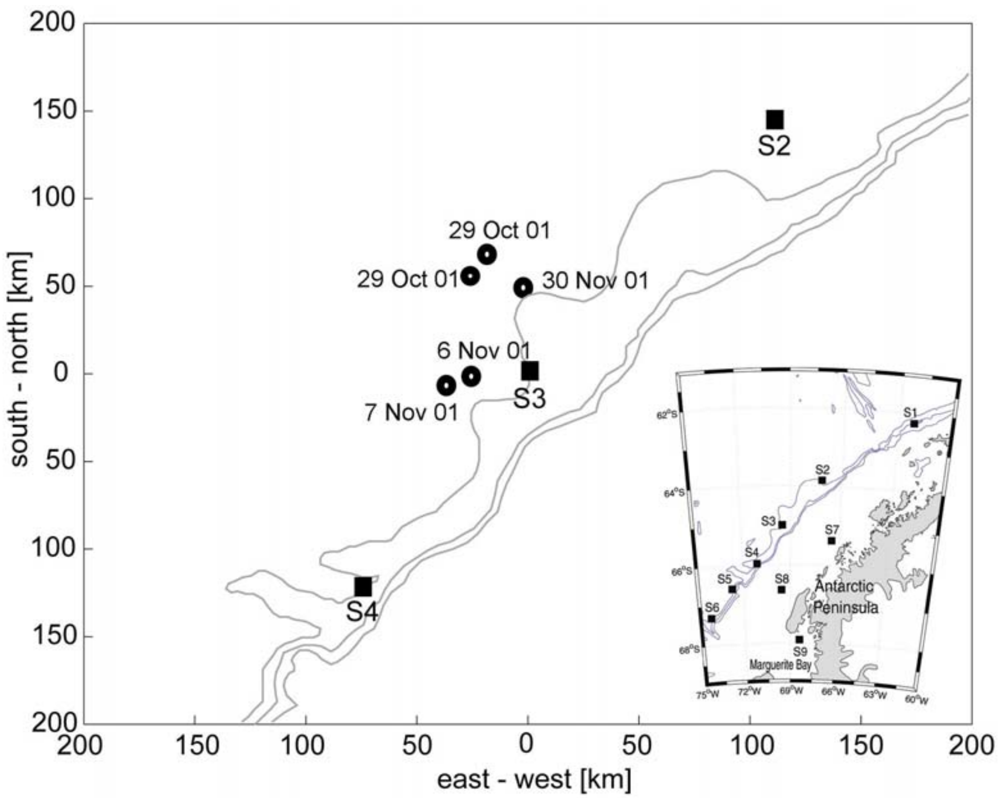

Figure 3.3. Locations of calling whales (circles) and dates when they were recorded. Squares show ARP locations and gray lines are 1000, 2000, and 3000m bathymetry contours. Inset shows a larger area of the Western Antarctic Peninsula where the ARPs numbered S1 to S9 were deployed.

<u>Blue whales</u>

At least five blue whales were localized on four different days in October and November 2001 (Figure 3.3). Owing to the changes in the ARP array geometry, calls from the same blue whale could be heard on multiple instruments (sites 2, 3, and 4) only during the first deployment year. The longest track (a series of whale locations calculated from a number of subsequent calls) lasted 1h 17min, while the shortest was 13min. A total of 84 different blue whale calls were used for localization. Blue whales could be detected up to a range of 200km. This detection range was the result of the narrow area in which calling whales could be localized, which was limited by the array geometry. The average error in the location determination was 2.2km. (We do not report percent error because it was different for each instrument used for localization.) The ray trace diagram, representing propagation under typical spring conditions (Figure 3.2), shows that sounds produced in shallow water do not propagate easily into deep water. Therefore, all localized animals were calling off the shelf, in deep water, from where their calls could be recorded by the ARPs.

The transmission loss coefficient (X), corresponding to the least-squares line of call received levels and logarithmic of calculated ranges, was 17.8dB/m (Figure 3.4). This matched closely the results of the modeled transmission loss at various depths (Figure 3.5). The empirical value at shorter ranges (<80km) was a better fit to propagation at 2000m depth, while at ranges over 80km the fit was better at 200m depth. The difference between propagation at 200 and 2000m, however, was generally not larger than 5dB re: 1m.

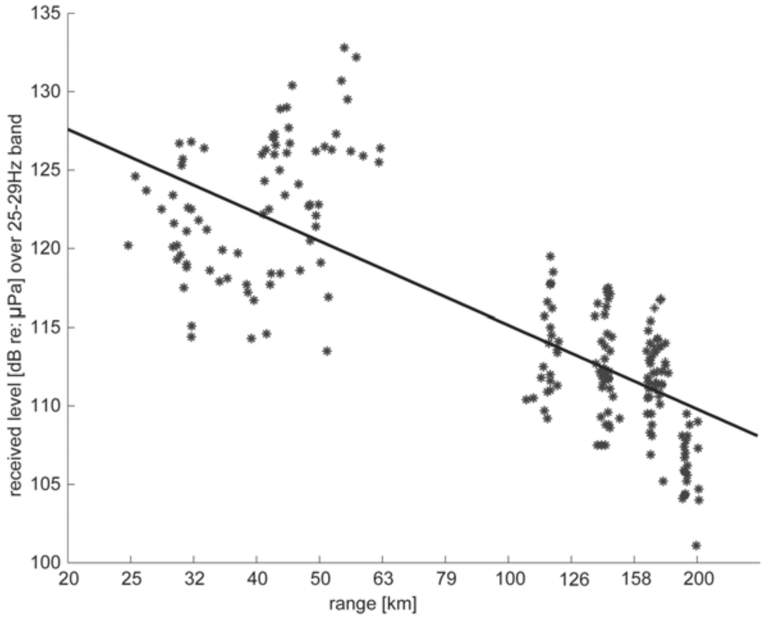

Figure 3.4. Plot of blue whale received levels versus log of calculated range. Black line is the best-fit line through the data; the slope of this line corresponds to the value of the transmission loss coefficient, *X*, and is 17.8dB/m.

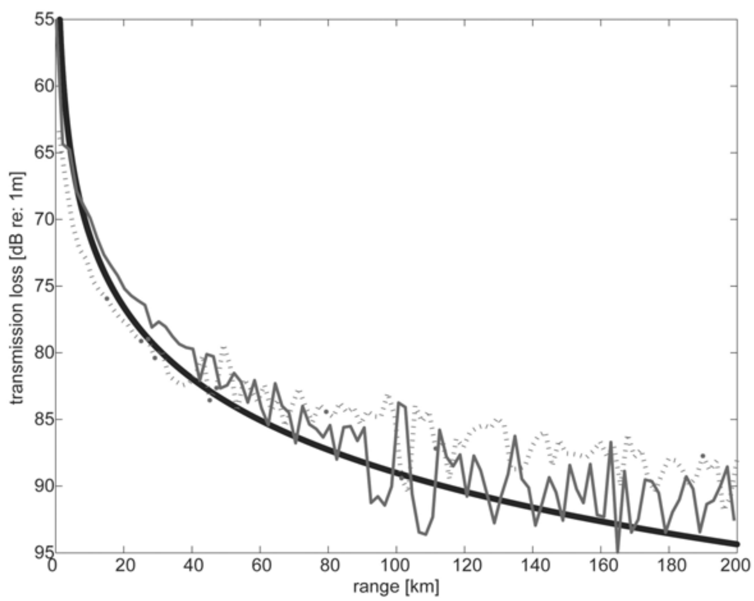

Figure 3.5. Results of Bellhop incoherent transmission loss calculations for Antarctic Peninsula spring conditions at 27Hz. Solid gray line is the transmission loss at 200m depth, and the dashed line is the loss at 2000m depth. Black line is the empirically determined transmission loss, $TL = 17.8 * log(r)$.

The average source level of blue whale calls off the Western Antarctic Peninsula was 189±3dB re: 1µPa at 1m over the 25–29Hz band (Figure 3.6). The average standard deviation of each source level calculation was 2.8dB re: 1µPa at 1m, which estimated the measurement error of our system. The maximum difference in the call source level based on the error in range estimation (at minimum, 20km range) was 0.7B. If the difference in the range to a calling animal between two consecutive calls was greater than 10km, we assumed there were at least two different blue whales calling. We also assumed two calling whales if the intercall interval between the calls was less than 60s (Širović *et al.*, 2004; Rankin *et al.*, 2005). With those assumptions, we found that the received levels of an individual blue whale during a calling bout on one instrument had a maximum variation up to 6dB re:1µPa at 1m.

The average difference between the hyperbolic localization and multipath arrival methods in the calculated range to a blue whale was 4.9km, with a standard deviation of 2.9km. There was no significant difference between the results of these methods (df =13, χ^2 = 9.3, p>0.1). Since the downswept part of the blue whale call used in these measurements is very similar to the fin whale call, it is reasonable to assume that the method works equally well for both species, and that the range results obtained for the two species using these different methods are comparable.

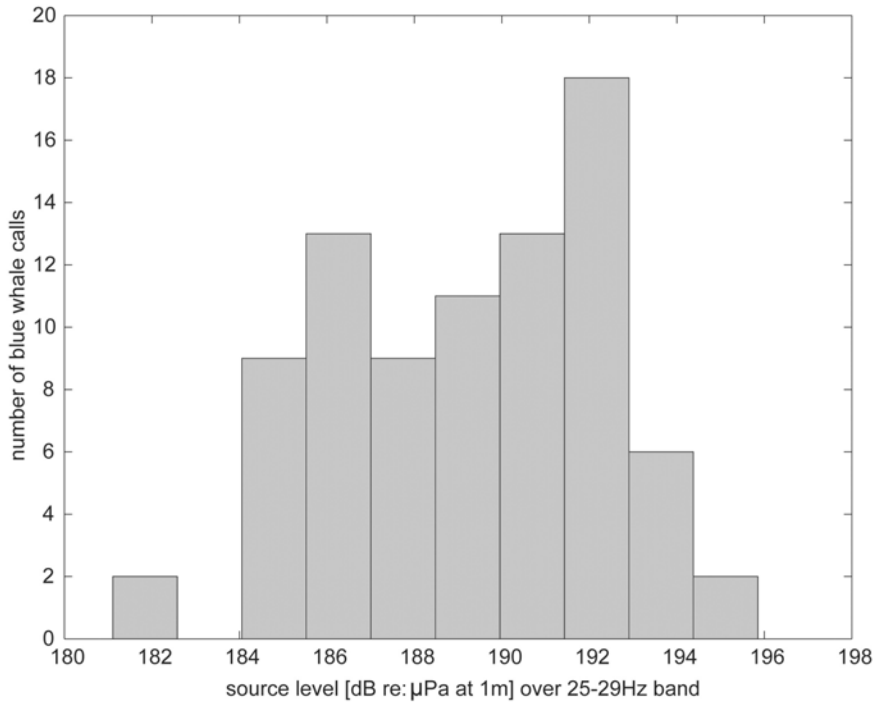

Figure 3.6. Distribution of blue whale call source levels (N=84).

Fin whales

A total of 83 fin whale calls from 12 different days between March and June 2001 were analyzed for range and source levels. The longest period during which ranges to fin whale calls were determined was 21min. The calling sequences, however, were not regular enough to determine whether the calls originated from the same animal, so the variation in received levels is not reported. The maximum distance to which the range to calling fin whales was determined using this method was 56km. The average error in the measurement of multipath arrival times was 0.1s, and the standard error in range determination was 3.4km (6%). There were no differences between the transmission loss at 27 and 22Hz at different depths and different seasons, so we used the transmission loss coefficient calculated from the blue whale data (X = 17.8dB/m) for the estimation of transmission loss for fin whale calls. The average source level of fin whale calls was 189±4dB re: 1μPa at 1m, over the 15–28Hz band. (Figure 3.7).

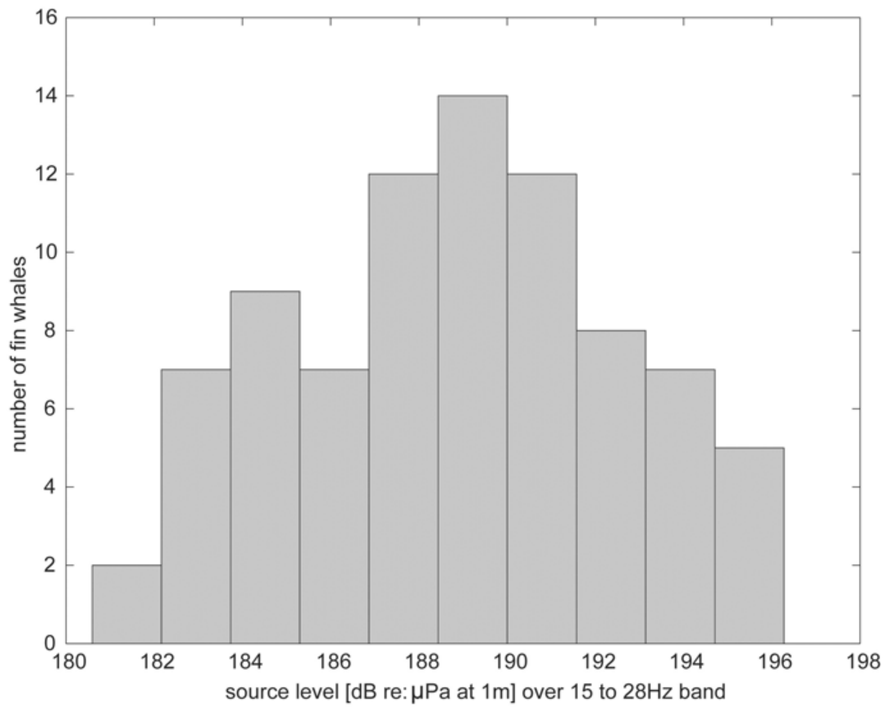

Figure 3.7. Distribution of fin whale call source levels (N=83).

E. Discussion

Blue and fin whale call source levels reported here are among the highest intensity calls reported for these two species. Given the low population densities of these two species in the Southern Ocean (Branch and Butterworth, 2001a), high source level calls could be beneficial for long range propagation and successful communication with conspecifics.

From the source levels reported here and the calculated transmission loss coefficient, it is possible to estimate theoretical maximum range over which these calls could be detected by conspecifics. The average noise levels in this region are 75dB re: 1μPa^2/Hz at 220Hz (McDonald *et al.*, 2005), and at lower frequencies where blue and fin whale calls occur (15-30Hz), they were up to 5dB re: 1μPa^2/Hz higher during periods when call ranges and source levels were calculated for this study. Even though there are no reports on threshold signal-to-noise (S/N) ratios for blue and fin whales, critical ratio functions are similar among vertebrates (Richardson *et al.*, 1995), so if we assume zero threshold S/N ratio for the calls to be intelligible by conspecifics (Miller *et al.*, 1951; Scharf, 1970), these whales could be heard out to a distance of about 1300km. This theoretical range, however, is shortened by the real-life constraints imposed on call propagation by the changes in the physical properties, such as the sound speed profile, at the fronts of the Antarctic Circumpolar Current.

The detection of a call by a conspecific also depends on the ratio between the bandwidth and the duration of the call. Long calls with narrow bandwidth and short, broadband calls can have similar detectability. Blue whale calls have the highest intensity in a very narrow, 1Hz band, but they last several seconds (8–18s). Fin whale calls, on the other hand, are short (<1s), but generally cover 10–15Hz band. So even though the calls have very different temporal and frequency characteristics, they are equally suitable for detection. Production of repetitive calls further increases the probability blue and fin whale calls will be detected by a conspecific.

The range over which calls were detected in this study are comparable to earlier results. Stafford *et al.* (1998) reported detecting blue whales in the North Pacific over ranges of 400 to 600km and Clark (1995) detected them in the Atlantic Ocean at ranges of up to 1000mi. Cummings and Thompson (1971) detected fin whales to a distance of 100mi. The sensors Clark (1995) and Stafford *et al.* (1998) used, however, were placed in the sound channel, and they summed multiple beams to enhance the S/N ratios. Our instruments were in approximately 3000m of water, in the polar region where the sound channel comes close to the surface (Jensen *et al.*, 2000), so the propagation was less than optimal and the signal was not enhanced by processing.

The accuracy in the measured arrival times of both methods was limited by the ability of the human analyst to pick the arrival times. Multipathing, that was the result of the complex propagation environment, made it impossible to use automatized methods for call cross-correlation, such as those used by Tiemann *et al.* (2004). This produced errors of several kilometers in the range estimation, so it was impossible to determine blue and fin whale swim speeds. But as the calls were detected over long ranges, the relative percentage errors are comparable to those in other localization studies (e. g. Clark and Ellison, 2000).

The variation in the call received levels we report for individual blue whales is assumed to be a reasonable proxy for the variation expected in call source levels for that species. By using received levels, however, we eliminated the error introduced by range determination, given that the animals could not move significantly over a period between two consecutive calls (always less than two minutes). We assumed that the 6dB re: 1μPa at 1m variation is a result of a single calling animal, but it is possible there were multiple animals calling close to each other, each at a different source level. Usually, however, the calls were repeated at very regular intervals, which indicate that a single whale was likely calling. Even though many calls showed multipath arrivals, the full range could not be accounted for by the changes in the multipath, because the movement of the whale between calls would not be large enough to cause significant changes in the propagation characteristics over these distances. Variation in source levels has been reported previously for fin whales (Watkins, 1981), so we assume that 6dB re: 1μPa at 1m represents a real variation in the calling level of individual blue whales.

Although we found there was likely some variation in the call source levels within an individual blue whale, we could not establish if there was a seasonal difference in call levels. Our ability to localize and range on animals during very short seasonal periods was not caused by the seasonal changes in the propagation characteristics, but by the number of calling animals. While thousands of calls were present in the data set (Širović *et al.*, 2004), calls could be used for the analyses only when calls were not too abundant, as it was necessary to distinguish between individual calls. Therefore, the methods used here would not be useful in areas with a large number of calling animal, or times with overlapping calls.

Another correlation worth investigating is possible change in the source levels during periods of high acoustic noise. Fin whales present in the northern region of the array create a "noise band" in the 15–28Hz band during peak presence (Širović *et al.*, 2004). If blue whales, for example, use the calls for communication with conspecifics, they would have to overcome that noise by increasing their source levels, or changing their call frequency. The blue and fin whale calls measured in this study, however, occurred at times when there was no fin whale "noise band". It would be interesting to determine if blue and fin whale call source levels exhibit a Lombard effect (higher source levels) during periods of higher noise, which was not possible in this study.

F. Acknowledgements

This work was supported by National Science Foundation Office of Polar Programs grant OPP 99-10007 as part of the Southern Ocean GLOBEC program, with program guidance by Polly Penhale and Roberta Martinelli. Bellhop acoustic modeling software was developed by M. Porter and is available from the Ocean Acoustic Library. The authors would like to thank the Masters and crew of the ARSV *Laurence M. Gould* during LMG01-03, LMG02-01A, and LMG03-02, as well as the staff at Raytheon Polar Services who provided logistical assistance. The manuscript was improved by comments from M.A. McDonald, J. Barlow, and C. Berchok.

The text of Chapter III, in full, is in preparation for submission to the Journal of the Acoustical Society of America (Širović, A., J.A. Hildebrand, S.M. Wiggins. How far can blue and fin whales be heard in the Southern Ocean? Journal of the Acoustical Society of America, in preparation). The dissertation author was the primary researcher and author

and the co-authors listed in this publication supervised the research which forms the basis for this chapter.

IV. Fall habitat of calling blue and fin whales off the Western Antarctic Peninsula

A. Abstract

Two oceanographic survey cruises were conducted off the Western Antarctic Peninsula during the austral falls of 2001 and 2002. Data were collected on depth, temperature, salinity, chlorophyll *a* concentration, krill biomass, zooplankton abundance, and blue and fin whale calls. Temperature, salinity and chlorophyll *a* data were collected using a CTD at stations located approximately 40km apart. Sea surface temperature (SST) was used as a proxy for sea ice cover. Krill biomass and zooplankton abundance were estimated using continuous acoustic backscatter measurements from BIOMAPER-II in two depth ranges: 0–100m and 101–300m. The presence of blue (*Balaenoptera musculus*) and fin whale (*B. physalus*) calls was analyzed from sonobuoy recordings at discrete locations using automatic detection methods. Conditions encountered during the two years were very different. The sea ice did not cover any of the study area in 2001, and it covered its southern end in 2002. Krill biomass and zooplankton abundance were higher in 2001, and high chlorophyll *a* concentrations occurred over a larger area in 2002. There was more blue and fin whale calling in 2002 than in 2001. Whale calls were mostly detected in areas with low krill biomass and zooplankton abundance. Logistic regression analysis revealed four significant variables affecting the distribution of calling blue whales during the two falls. The calls were positively correlated with the depth and the SST, and negatively correlated with the mean zooplankton abundance at depth (101–300m) and the mean krill biomass in the top 100m. The unexpected negative correlation between blue whale calls and krill and zooplankton could occur if feeding animals do not produce calls. It is likely that our survey area did not cover the full range of blue and fin whale habitat off the Western Antarctic Peninsula. Blue whales probably follow the

melting and freezing of the ice through this region and fin whales likely remain further north. These use patterns should be considered in the design of future studies of blue and fin whales habitat preferences off the Western Antarctic Peninsula.

B. Introduction

The earliest scientific understanding of the associations between baleen whales and their environment came from the *Discovery* investigations, the goal of which was systematic exploration of the Southern Ocean resources, particularly ones linked to the whaling industry (Kemp *et al.*, 1929). Well-known whaling grounds were associated with prominent physical features, such as the upwelling at the Antarctic divergence and steep bathymetry (Kellogg, 1929; Beklemishev, 1960), as well as high abundance of krill (Marr, 1962), which are the primary food source for baleen whales in the Southern Ocean (Mackintosh and Wheeler, 1929; Mackintosh, 1965; Kawamura, 1994). Both blue (*Balaenoptera musculus*) and fin whales (*B. physalus*) are pelagic species, but their ecological separation occurs spatially, blue whales are found closer to the ice edge than fin whales (Mackintosh and Wheeler, 1929; Beklemishev, 1960; Mackintosh, 1965; 1966; Laws, 1977; Kasamatsu *et al.*, 1988), and in food preference, fin whales eat larger krill (Beklemishev, 1960; Laws, 1977).

The productivity of the Southern Ocean is affected both by the circulation patterns and the sea ice dynamics (Nicol *et al.*, 2000b; Constable *et al.*, 2003). In the Antarctic Peninsula region, the Antarctic Circumpolar Current (ACC) flows to the northwest along the shelf break and the Upper Circumpolar Deep Water (UCDW), oceanic, warm (1.5-2°C), and salty (34.6-34.7) water intrusions can be found on the shelf at depths greater than 200m (Hofmann and Klinck, 1998b). Inshore and shelf regions of the Antarctic Peninsula, as well as the areas of the retreating ice edge, generally have higher rates of primary productivity than open waters off the shelf (Holm-Hansen *et al.*, 1997; Constable *et al.*, 2003). The area around Marguerite Bay gets entirely covered by the sea ice in the winter, even though the ice forms relatively late and melts early (Comiso *et al.*, 1990; Stammerjohn and Smith, 1996). The Western Antarctic Peninsula (WAP) is also a region of relatively high krill biomass (Marr, 1962; Loeb *et al.*, 1997; Lascara *et al.*, 1999; Atkinson *et al.*, 2004). The seasons, ocean circulation, fronts, and phytoplankton distribution all impact krill distribution in this region (Holm-Hansen *et al.*, 1997; Loeb *et al.*, 1997; Ichii *et al.*, 1998). Lower krill biomass occurs in the fall, and generally larger krill are found offshore from the small krill (Lascara *et al.*, 1999).

Physical processes that function in prey aggregation also influence krill predator distributions (Ichii *et al.*, 1998; Ainley and DeMaster, 1999; Friedlaender *et al.*, 2006; Nicol, 2006). The ice edge is an area of high krill and krill predator densities (de la Mare, 1997; Ainley and DeMaster, 1999; Brierley *et al.*, 2002; Ackley *et al.*, 2003; Thiele *et al.*, 2004). Most of the current integrative ecology in the Antarctic waters has focused on humpback (*Megaptera novaeangliae*) and minke whales (*B. bonaerensis*), since they are currently more abundant than blue and fin whales in the Southern Ocean (Moore *et al.*, 1999; Branch and Butterworth, 2001a; Murase *et al.*, 2002; Thiele *et al.*, 2004). Continental slope that coincides with the ice edge is an important feeding ground for minke whales, and humpback whales are associated with the areas of high krill and chlorophyll *a* density (Bushuev, 1990; Thiele *et al.*, 2000; Murase *et al.*, 2002). In the WAP region, both humpback and minke whales are associated with high zooplankton (which included both krill and other zooplankton) volume backscatter, distance to the ice edge, and bathymetry (Friedlaender *et al.*, 2006).

Recent work on rorqual habitat preferences in the northern hemisphere, focusing on humpback, blue, and fin whales, also shows that physical processes that function in prey aggregation affect whale distribution (Woodley and Gaskin, 1996; Croll *et al.*, 1998). Work in the North Pacific indicates that blue and fin whale distributions are influenced by the mesoscale chlorophyll *a* distribution, as well as the cold, upwelled, krill-rich waters that are determined by the bathymetric features (Smith *et al.*, 1986; Croll *et al.*, 1998; Fiedler *et al.*, 1998; Moore *et al.*, 2002a; Moore *et al.*, 2002b; Burtenshaw *et al.*, 2004). Humpback whale distribution in the California Current system is related also to bathymetric features and the sea surface temperature (Tynan *et al.*, 2005). Recently, spatially explicit analytical techniques have started to be used not only to quantify relationships between various cetacean species and their environment, but also to generate predictive habitat models of cetacean use (Forney, 2000; Gregr and Trites, 2001; Hamazaki, 2002; Tynan *et al.*, 2005; Ferguson *et al.*, 2006; Friedlaender *et al.*, 2006; Redfern *et al.*, 2006b).

Blue and fin whale sightings are relatively rare in the Southern Ocean (Branch and Butterworth, 2001a; Thiele *et al.*, 2004), but both species can be reliably detected in this remote region from their acoustic calls (Širović *et al.*, 2004; Širović *et al.*, 2006). Blue whales in the Southern Ocean produce several call types (Ljungblad *et al.*, 1998; Rankin *et al.*, 2005). One type, "27Hz tonal", is up to 18s long and consists of a flat tone generally followed by a couple of downswept segments, and it is usually repeated at regular intervals (Širović *et al.*, 2004; Rankin *et al.*, 2005). Similar low frequency, repetitive calls (termed songs) produced by blue whales off California are attributed to males and are presumed to function as mating displays (McDonald *et al.*, 2001; Oleson *et al.*, 2006). Blue whales also produce variable, frequency modulated, "D calls" that last up to 4s and sweep downward in frequency from 100 to 40Hz (Rankin *et al.*, 2005; Širović *et al.*, 2006). D calls off California and in the Southern Ocean have been associated with feeding blue whales and are produced by both sexes (Rankin *et al.*, 2005; Oleson *et al.*, 2006). Fin whales in the Southern Ocean produce short (1s), repetitive, downswept (30–15Hz) calls (Širović *et al.*, 2004; Širović *et al.*, 2006). There is some indication that these repetitive calls could be produced by males in other regions (Watkins *et al.*, 1987; Croll *et al.*, 2002).

The Southern Ocean Global Ocean Ecosystems Dynamics (SO GLOBEC) program was designed to test hypotheses about the interactions between the Antarctic krill (*Euphausia superba*) and their environment and predators, and provide a benchmark for future multidisciplinary research in the Antarctic (Hofmann *et al.*, 2002). The field program consisted of multiple, multidisciplinary oceanographic cruises along the WAP. The goal of this study was to investigate the distribution of blue and fin whales in the US Southern Ocean GLOBEC study area on the WAP shelf in the austral falls of 2001 and 2002, and to describe the relationship between the blue and fin whale distributions and the physical and biological variables. In particular, the relationships with: bathymetry, sea ice and sea surface temperature (SST), UCDW intrusions, surface chlorophyll *a* concentrations, krill biomass and abundance of other zooplankton (e.g. copepods, siphonophores, fish) were investigated. Krill were separated from the rest of the zooplankton because they are the primary prey species for blue and fin whales in the Southern Ocean (Kawamura, 1994).

C. Methods

Data were collected during two SO GLOBEC survey cruises aboard the RVIB *Nathaniel B. Palmer* in the Western Antarctic Peninsula region near Marguerite Bay (Figure 4.1), in the austral falls of 2001 and 2002 (NBP0103: from 23 April to 6 June 2001 and NBP0202: from 9 April to 21 May 2002). The surveys were designed to provide a broad-scale, synoptic look at an area approximately 2,300km x 2,200km (Figure 4.1), collecting data on the hydrography, nutrients, primary production, zooplankton, and top-predator distribution characteristics. In these analyses, only the data from the southward pass through the survey grid were used, to ensure contemporaneous coverage. In the paper, when referring only to the survey year, it is implicit that the period being discussed is the survey months of April and May, not the entire year.

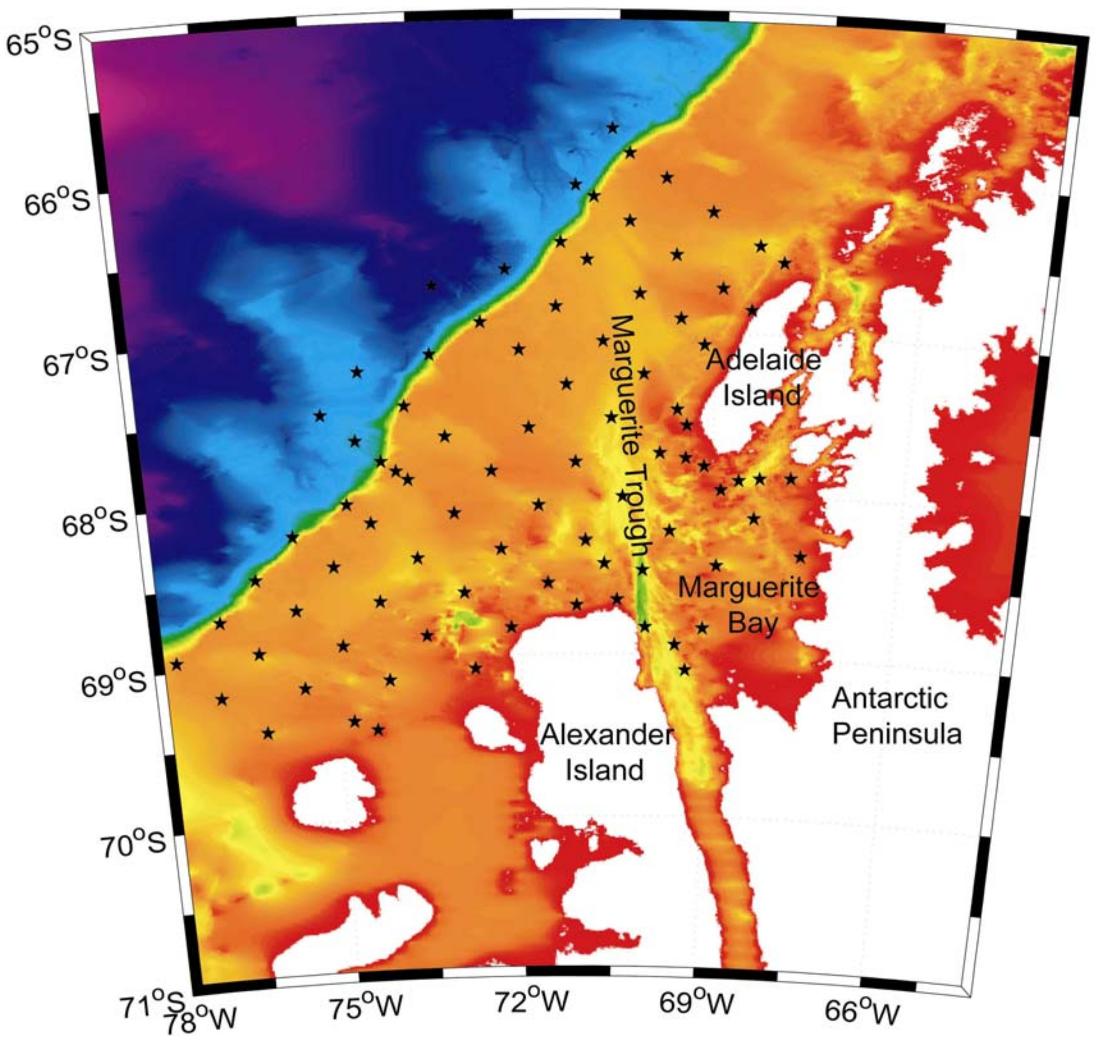

Figure 4.1. Survey area of the US Southern Ocean GLOBEC cruises, with color from red to violet indicating increasing depths. Stars represent locations of CTD survey stations, which is the area featured on subsequent figures. Land is white. Prominent feature of the Western Antarctic Peninsula region is the continental shelf, about 400–500m deep, with a couple of deep troughs extending towards Marguerite Bay from the very steep shelf break.

Environmental data collection

Hydrographic data collected during the two years covered much of the same area on the WAP shelf, north and south of Marguerite Bay, as well as within the Bay. The survey started at the north end of the region and moved southward in both years. Thirteen transects were conducted across-shelf, perpendicular to the coastline and the shelf break. Stations were mostly spaced at 40km intervals, with some stations at 10km intervals to provide finer resolution of rapidly changing areas, such as the shelf break region (Klinck *et al.*, 2004). The survey consisted of 81 hydrographic stations in 2001, and 92 stations in 2002. Temperature and salinity measurements were made using a SeaBird 911+ Niskin / Rosette conductivity–temperature–density (CTD) sensor system. The Rosette system consisted of 24 10-liter Niskin bottles and water samples were taken at standardized depths. Chlorophyll *a* concentrations were measured from the water samples using a Turner Designs Digital 10-AU-05 Fluorometer. More details on data collection, as well as the information on instrument calibration, are given in US SO GLOBEC Reports Number 2 and 6 (2001; 2002). In this study, sea surface temperature (SST; ºC) and surface chlorophyll *a* concentration (Chl-*a*; µg/l) were reported. We considered SST > -1.7ºC as a proxy for sea ice cover. During the fall, freezing conditions, this provided a good correspondence to regions with the observed sea ice cover (Thiele *et al.*, 2004; Friedlaender *et al.*, 2006), but it is not necessarily a good sea ice proxy under the spring, melting conditions. Also, the temperature maximum below 200m depth (T_{max200}; ºC), and the salinity at 50m (Sal_{50}) were determined. $T_{max200} > 1.8$ºC is representative of the ACC waters, and the waters with T_{max200} between 1.5 and 1.8ºC are indicative of the UCDW (Chapman *et al.*, 2004). Bathymetry data were collected using SeaBeam multibeam system mounted on the hull of the ship (Bolmer *et al.*, 2004).

Acoustic backscatter and target strength data were collected using BIOMAPER-II, which was equipped with five pairs of transducers with center frequencies at 43kHz, 120kHz, 200kHz, 420kHz, and 1MHz (Lawson *et al.*, 2004). BIOMAPER-II was "towyoed" up and down through the water column between 20 and 400m depths, while the ship was steaming between the hydrographic stations at speeds of 4 to 6kts. The transducer pairs were mounted on the top and the bottom of the instrument, providing the view above and below the instrument. More information on instrument calibration and data collection is given in Lawson *et al.* (2004). Acoustic methods were developed from measurements of volume backscatter and target strength at 43 and 120kHz that yielded estimates of krill biomass (Lawson, 2006). Integration of the volumetric biomass estimates over different depth ranges yielded areal biomass projections (g/m^2), which were then averaged over 20km along-track intervals. Details on acoustic methods for estimations of krill biomass and the limitations and uncertainties in the available data are detailed in Lawson *et al.* (2004) and Lawson (2006). In these analyses, the mean krill biomass (g/m^2) at 0–100 and 101–300m depth ranges was used. Since the method does not distinguish between animals with similar size and scattering type, no distinction is made between krill species (e.g. *E. superba* or *E. crystallorophias*) and the word krill is used in its generic sense. The remainder of the volume backscatter signal was used as a proxy for other zooplankton species with different target strengths, such as copepods, siphonophores, and also included fish (Ashjian *et al.*, 2004; Lawson *et al.*, 2004). What is referred to as zooplankton abundance in this paper is actually the mean volume backscatter (dB) integrated over the same two depth ranges as krill, and also averaged over 20km along-track intervals. The centers of the 20km intervals were sonobuoy deployment locations for which BIOMAPER-II data were available. This yielded 36 and 41 points with concurrent active and passive acoustic data in 2001 and 2002 survey years, respectively. Hydrographic data were used for the calculations of temperature, salinity and chlorophyll *a* concentration estimates at sonobuoy deployment locations as well, using the IDW interpolation method discussed in the "Spatial analysis" section below.

Passive acoustic data collection and analysis

Blue and fin whale calls were analyzed from sonobuoy recordings made during the two survey cruises. Sonobuoys are expendable, radio-linked underwater listening devices that were deployed when whales were visually detected, before CTD stations, and sporadically throughout the cruises, to provide coverage of the entire surveyed area. Two types of sonobuoys were used: omnidirectional (AN/SSQ-57B) and directional (DIFAR, AN/SSQ-53D) sonobuoys. Omnidirectional sonobuoys have a broader frequency response than the directional sonobuoys (10–20,000Hz and 10–2,400Hz, respectively). A total of 59 sonobuoys were deployed on the southbound pass of the NBP0103: two omnidirectional and fifty-seven DIFAR. During the southbound portion of the NBP0202, a total of 47 sonobuoys were deployed: forty-four omnidirectional and three DIFAR. Four omnidirectional and three DIFAR sonobuoys failed upon deployment during both cruises, giving a failure rate of 9% and 5%, respectively.

Custom electronics and software were used to record and analyze the sonobuoy data during and after the cruises. Two antennae were available for the reception of the sonobuoy radio signal aboard the RVIB *Nathaniel B. Palmer*, a 162–173.5MHz eight-element black anodized directional Yagi, and a 138–174MHz two dipole omnidirectional SRL-210-A2 Sinclair antenna. The maximum range for the radio transmission during these cruises was 16nmi for the Yagi, and 10nmi for the Sinclair, but the range was dependent on the weather conditions. We used software controlled ICOM IC-PCR1000 scanner radio receiver, modified to provide improved low frequency response, for the reception of the sonobuoy signal. Data were recorded continuously while receiving the signal to digital audiotapes at 48kHz sample rate using Sony PCM-300 and PCM-M1 digital audio recorders during NBP0103 and NBP0202, respectively. Upon each deployment the following information was recorded: time, latitude, longitude, and bottom depth at deployment; sonobuoy type and channel; and reason for deployment. Also, ship speed and course, as well as general weather and sea ice conditions were noted. After deployment, the sonobuoys transmitted their radio signal to the underway ship for a maximum of 8h before scuttling and sinking.

After the cruise, data were digitized and converted into 35min wav files by playing the audio tapes on a Sony PCM-M1 and re-digitizing the analog signal using the real-time signal recording feature in software program *Ishmael* (Mellinger, 2001). Since the calls of interest occurred at frequencies <100Hz, data were first filtered with an eighth order Chebyshev type I low-pass filter, and then decimated by a factor of 80. The new sample rate of the data was thus 600Hz. The decimated data were run through an automatic cross-correlation detector available in *Ishmael* (Mellinger and Clark, 1997; 2000) and a 1.7MHz Pentium 4 personal computer with Creative Sound Blaster Live! sound card. Parameters of call characteristics used for the blue whale tonal and fin whale downswept call detection kernels were the same as those described in Širović *et al.* (2004). The detection threshold was set low to detect all the calls, and therefore yielded a lot of false alarms. Detections were saved as individual wav files and verified by visual inspection of spectrograms. The files that did not contain blue or fin whale calls were deleted and not used in further analyses. This automatic detection method was used for the blue whale tonal and the fin whale downswept calls only. Since the irregular frequency and temporal characteristics of blue whale D calls make them difficult to detect automatically, their presence was determined by visual scanning of all the data. D calls were identified as downswept calls lasting 1–4s, ranging in frequency between 100 and 40Hz, and periods when these calls were recorded were noted. Only presence or absence of fin and blue whale calls on sonobuoys is reported. Locations of sonobuoys on which different calls were detected were noted and were used in plotting and analyses with the environmental data.

One limitation of the acoustic data is that they provide information only on the presence of whales. If no calls are detected, the whales could either be absent or not calling. In this paper we use the number of detection locations as a proxy for whale abundance in the survey area during that year. More information, however, is needed on the blue and fin whale calling behavior and rates of call production for better interpretations of calling data.

Spatial analysis

All the physical and biological data used in this study (Table 4.1) were imported into ESRI ArcView 9.1 (ESRI, 2005). Values of all the environmental data were used to create interpolated raster surfaces using the Inverse Distance Weighted (IDW) function in the Spatial Analyst toolbox. IDW was used because in ecological data, the similarity between points decreases with an increasing distance. We used a cell size (resolution) of 20km for krill and zooplankton, and 40km for the thermohaline properties and Chl-*a*. Areas with high whale calling presence were calculated also using the IDW function, with the assumption that calls on one sonobuoy represent only one calling whale. Individual locations of sonobuoys with whale call detections were compared qualitatively with environmental conditions during the two surveys.

We used logistic regression to explore the nature of the relationships between blue whale call presence and the environmental variables. Due to the overall small number of fin whale detections, and the small number of blue whale detections in 2001, data for the two years were pooled and only blue whale data were analyzed. First, a null model was built based only on the presence of calling blue whales, with an assumed binomial error structure. Correlations between environmental variables were calculated to check for colinearity and only variables with correlation <0.7 were used in model fitting (Weisberg, 2005). A forward-backward stepwise selection process was used to find the model with the best fit to the data from the available variables. The best model fit was determined using Akaike's Information Criterion (AIC) at each step (Akaike, 1973). Since AIC has a tendency to over-fit the data, we sequentially tested all the variables for significance (α=0.05) using a χ^2-test for reduction of overall deviance (McCullagh and Nelder, 1989). We calculated the squared multiple correlation coefficient, R^2, to estimate the proportion of the variation in the blue whale presence explained by the final model. The final model was checked for autocorrelation in the residuals and the regression coefficients were standardized to the same units for easier inter-comparison (Selvin, 1998). All the analyses were done using *S-PLUS 6 for Windows* (Insightful Corporation, 2001).

Table 4.1. List of physical and biological variables used in the analyses. Units, and resolution at which data were collected are given, and it is noted whether the variable was used for model fitting.

Variable	Unit	Resolution	Model
Depth	m	Continuous, along-track sample	Y
Sea surface temperature (SST)	ºC	40km sampling, IDW interpolation	Y
Tmax below 200m (T_{max200})	ºC	40km sampling, IDW interpolation	Y
Salinity at 50m (Sal_{50})	N/A	40km sampling, IDW interpolation	N
Surface chlorophyll *a* (Chl-*a*)	µg/l	40km sampling, IDW interpolation	Y
Mean krill biomass 0-100m (mk1)	g/m^2	Continuous sample, 20km average	Y
Mean krill biomass 101-300m (mk3)	g/m^2	Continuous sample, 20km average	Y
Mean backscatter 0-100m (mz1)	dB	Continuous sample, 20km average	Y
Mean backscatter 101-300m (mz3)	dB	Continuous sample, 20km average	Y

D. Results

Qualitative comparison

The hydrographic conditions were very different between the two survey years. In 2001, the sea ice formed relatively late (Perovich *et al.*, 2004). Even though NBP0103 started a couple of weeks later in the season than NBP0202, no sea ice had formed during the 2001 cruise, but by the time of the 2002 cruise, the sea ice had already covered the southern portion of the survey area. In the fall of 2001, krill biomass and zooplankton abundance were higher, but the total areal extent of the high Chl-*a* concentrations was lower. More blue and fin whale calls were detected in 2002, but no blue or fin whales were sighted by experienced marine mammal visual observers during either cruise (Thiele *et al.*, 2004). During both years the ACC was flowing just off the shelf break and there was evidence of the UCDW intrusions onto the shelf.

There were distinct differences in the blue and fin whale distributions between the two years. During 2001, no fin whale calls were detected, and blue whale calls were detected on just three sonobuoys (Figure 4.2). On one sonobuoy, deployed off the shelf break in the middle of the survey area, the calls were “27Hz tonals” (for simplicity referred to as “tonals” through the rest of the chapter.) D calls were detected on two different sonobuoys, deployed in the vicinity of Alexander Island. In 2002, blue whale tonal calls were detected on 21 sonobuoys, mostly in the northern and middle shelf areas. Also, D calls were detected on four of those sonobuoys. The locations of sonobuoys on which blue whale calls were detected occurred along Marguerite Trough, the trough west of Alexander Island, and off the shelf break (Figure 4.2). Fin whale calls were detected on four sonobuoys, all along Marguerite Trough (Figure 4.3). Unlike the repetitive fin whale calls detected on sonobuoys in the northern section of Marguerite Trough, only a single fin whale call was detected on the sonobuoy inside Marguerite Bay.

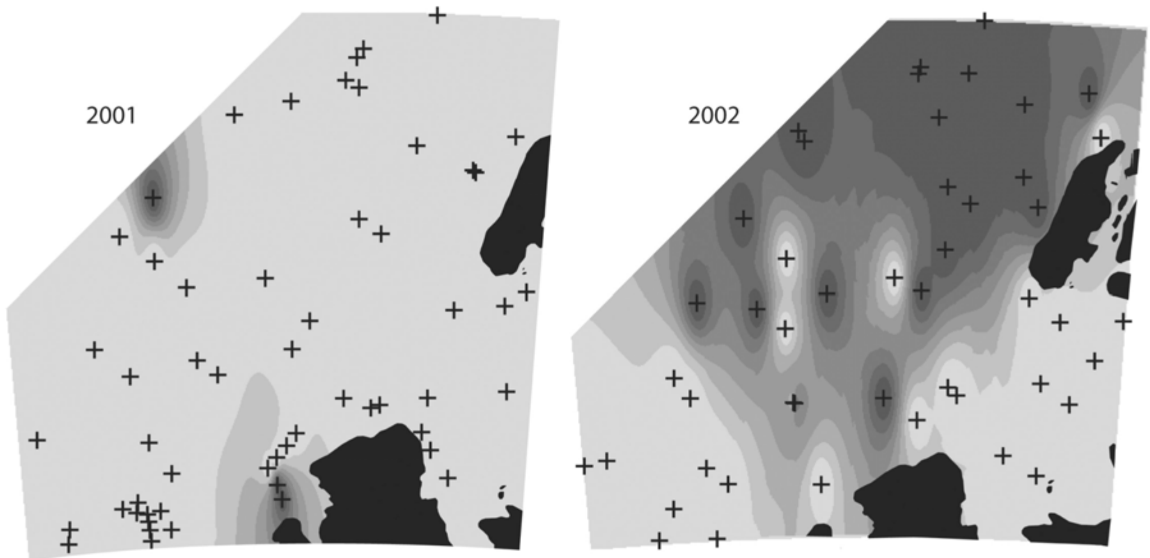

Figure 4.2. Areas with high calling blue whale presence during the two survey years are shown with darker shading based on IDW. Pluses are locations of all sonobuoy deployments during that survey. Black areas represent land.

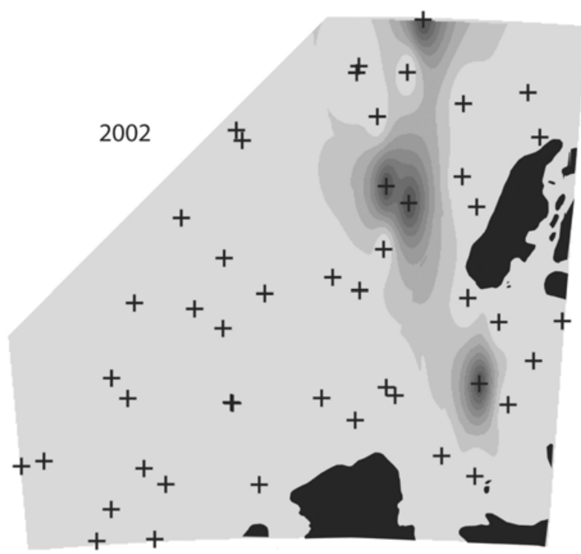

Figure 4.3. Areas with high calling fin whale presence during the second survey year are shown with darker shading based on IDW. Other symbols are the same as in Figure 4.2.

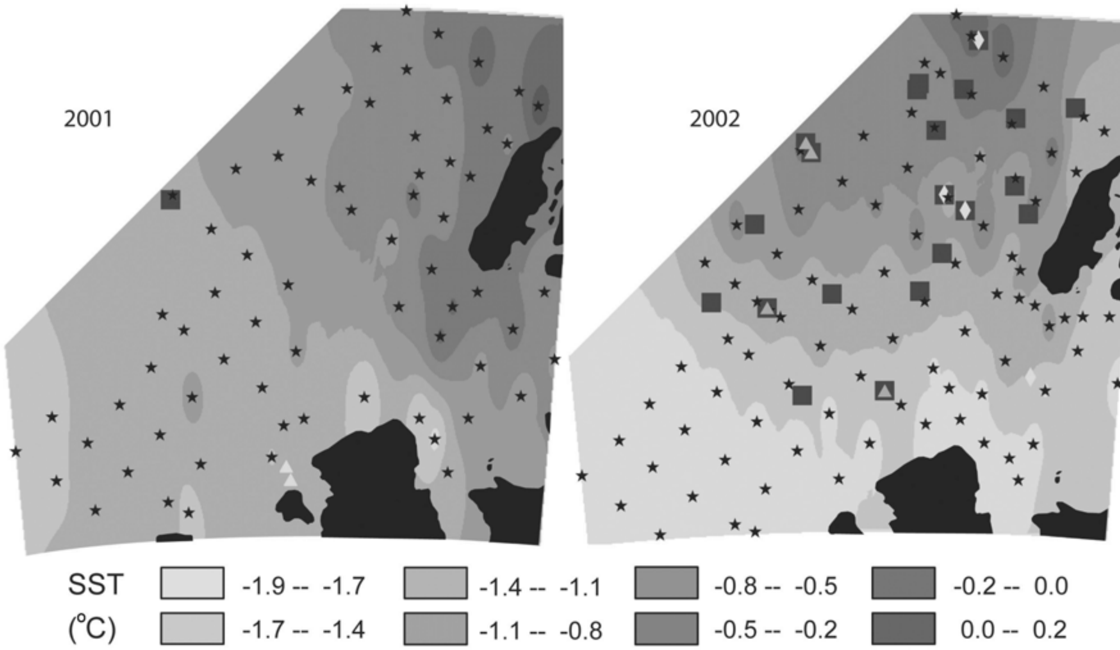

Figure 4.4. Sea surface temperature (sea ice cover proxy) during the two survey years, smoothed with IDW. Stars represent locations of CTD survey stations. Squares are sonobuoy deployment locations on which blue whale tonals were detected, triangles are blue whale D calls, and diamonds are fin whale downswept call. Black areas represent land.

Using SST<-1.7˚C as a proxy for sea ice, it is evident that in 2001, the survey area was largely free of the sea ice (Figure 4.4). The sea ice covered the southern part of Marguerite Bay and much of the southwestern portion of the survey grid in the fall of 2002. All the whale call detections occurred in ice-free waters, but there were more detections in the year when the sea ice was already forming. Figure 4.5 shows the ACC (T_{max200}>1.8˚C) flowing just off the shelf break during both surveys, with a somewhat stronger signal in 2002. During both surveys, the UCDW intrusions onto the shelf occurred along Marguerite Trough, starting at the shelf break in the northwest end of the survey area, and extending into the Bay along the western side of Adelaide Island. Most of the fin and blue whale calls were associated with the regions of the ACC and the UCDW intrusions (Figure 4.5).

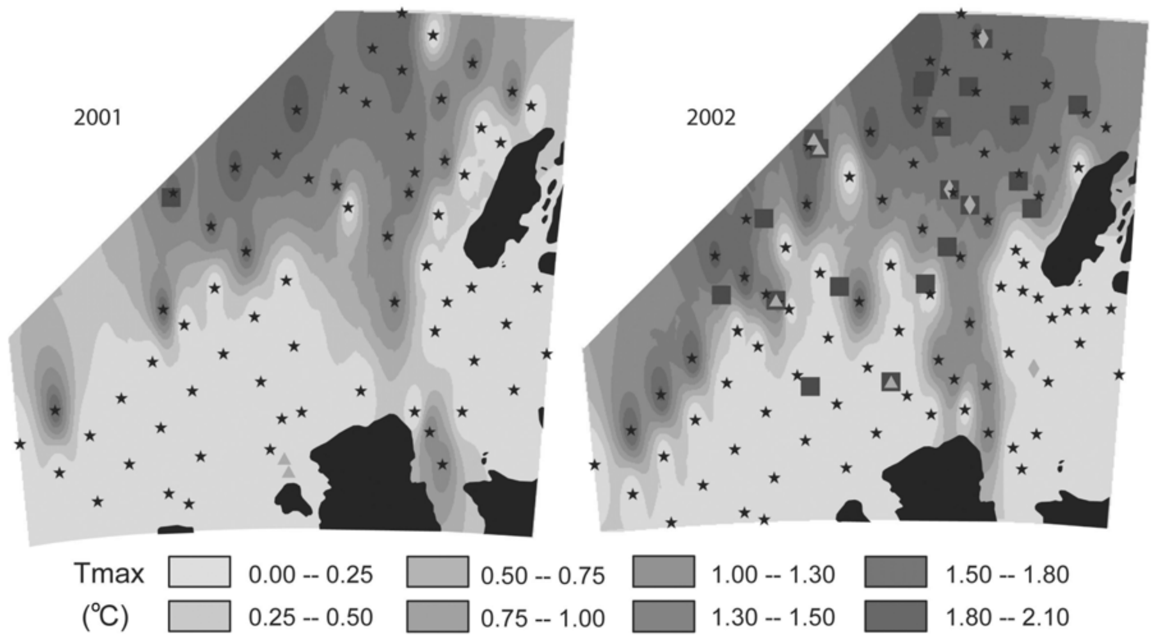

Figure 4.5. Temperature maximum below 200m (UCDW proxy) during the two survey years, smoothed with IDW. Symbols are the same as in Figure 4.4.

While maximum surface Chl-*a* concentrations between the two years were similar (2.01 and 2.16 μg/l in 2001 and 2002, respectively), during 2002, high Chl-*a* concentrations extended over a larger area (Figure 4.6). In 2001, the blue whale call detections occurred outside the areas of high Chl-*a* concentrations. In 2002, locations of sonobuoys on which fin whale calls were detected were associated with high Chl-*a* concentrations, while blue whale call detections occurred both in areas of high and low Chl-*a* concentrations.

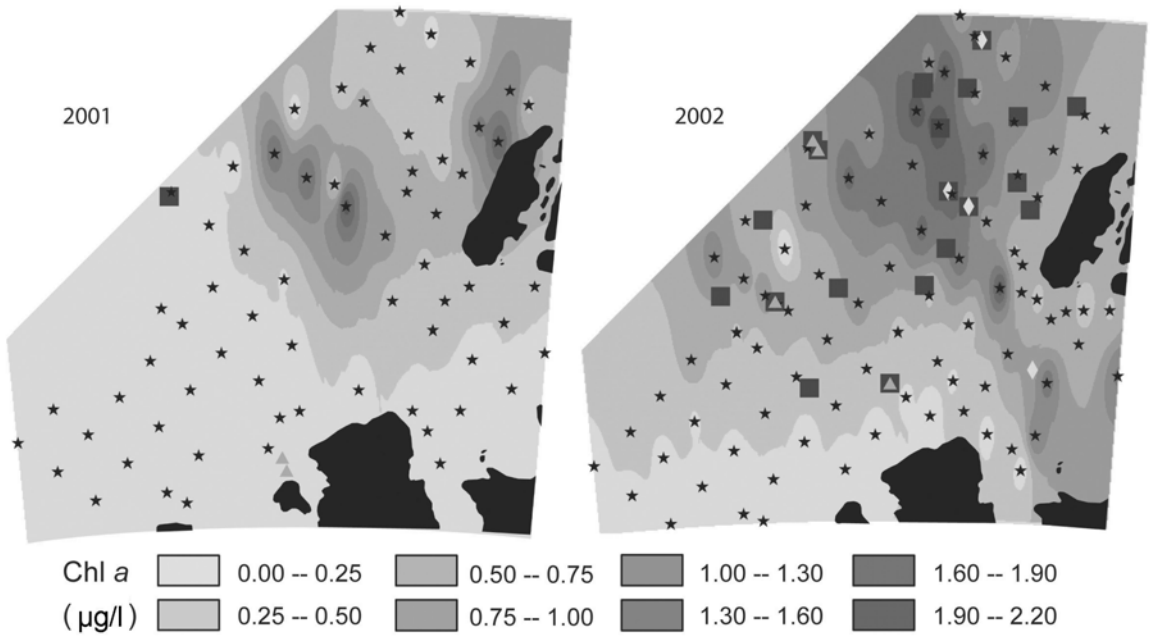

Figure 4.6. Surface chlorophyll *a* concentrations during the two survey years, smoothed with IDW. Symbols are the same as in Figure 4.4.

Krill and zooplankton had higher biomass and abundance, respectively, during 2001 than 2002 (Figures 4.7 through 4.10). Generally, during both years, the highest concentrations occurred on the northwest side of Alexander Island, along the west and north shores of Adelaide Island, and in south Marguerite Bay. Both the mean krill biomass and the mean zooplankton abundance were higher in the 100–300m depth range than in the top 100m. Highest krill biomass in both years occurred off western Alexander and northern Adelaide Islands. Zooplankton abundance was highest in the top 100m in the southern parts of the survey area (Figure 4.8), especially in 2002, at the southeastern end of Marguerite Bay (Figure 4.9). In 2001, zooplankton abundance at depth (101–300m) was high throughout most of the survey region, but it was the highest at the southern end (Figure 4.10). In both years, small krill aggregations dominated numerically, but the small numbers of very large aggregations contributed majority of the biomass (Lawson, pers. comm.).

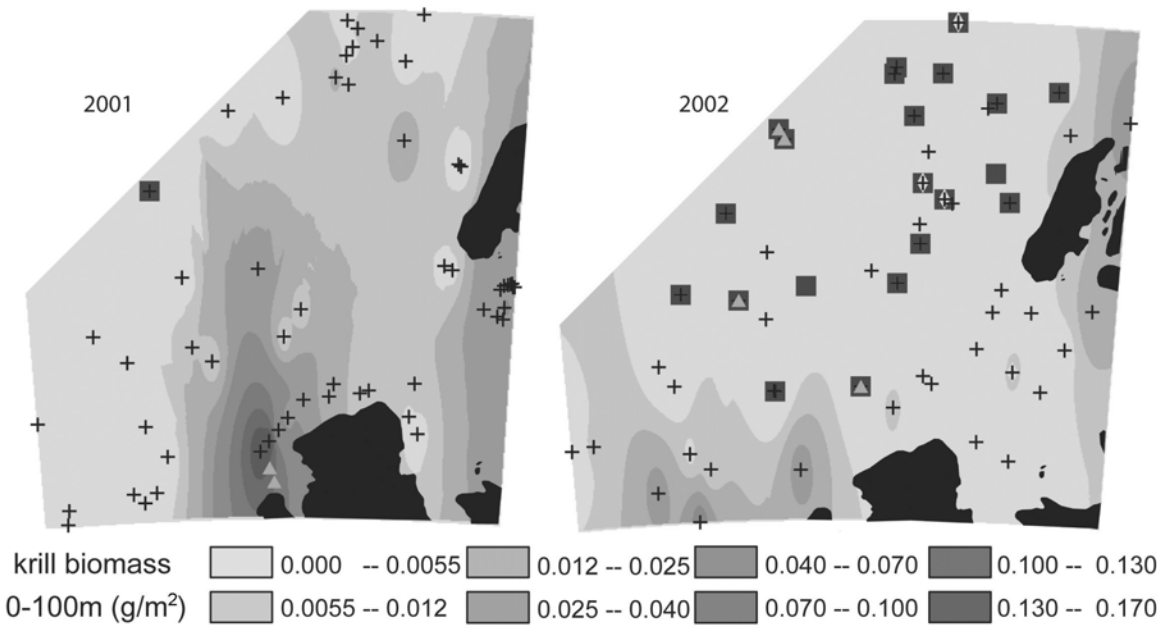

Figure 4.7. Mean krill biomass in the top 100m during the two survey years, smoothed with IDW. Pluses represent center locations of the 20km along-track intervals over which the mean krill biomass was calculated. Squares are sonobuoy deployment locations on which blue whale tonals were detected, triangles are blue whale D calls, and diamonds are fin whale downswept call. Black areas represent land.

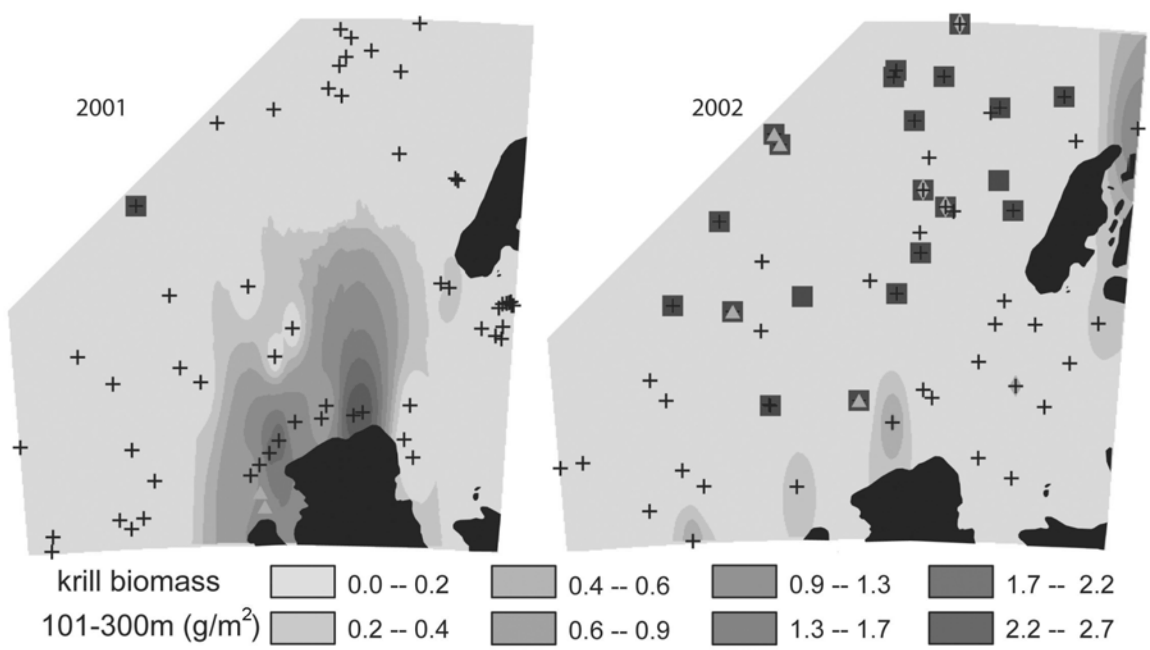

Figure 4.8. Mean krill biomass at depth (101–300m) during the two survey years, smoothed with IDW. Symbols are same as in Figure 4.7.

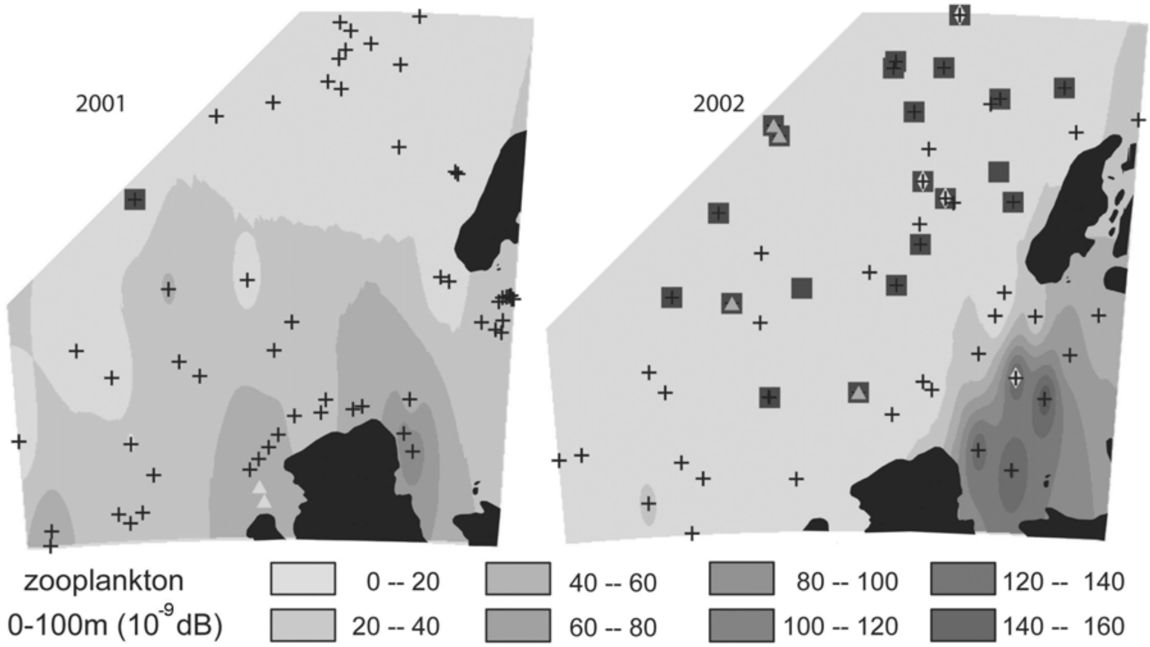

Figure 4.9. Mean zooplankton abundance in the top 100m during the two survey years, smoothed with IDW. Symbols are the same as in Figure 4.7.

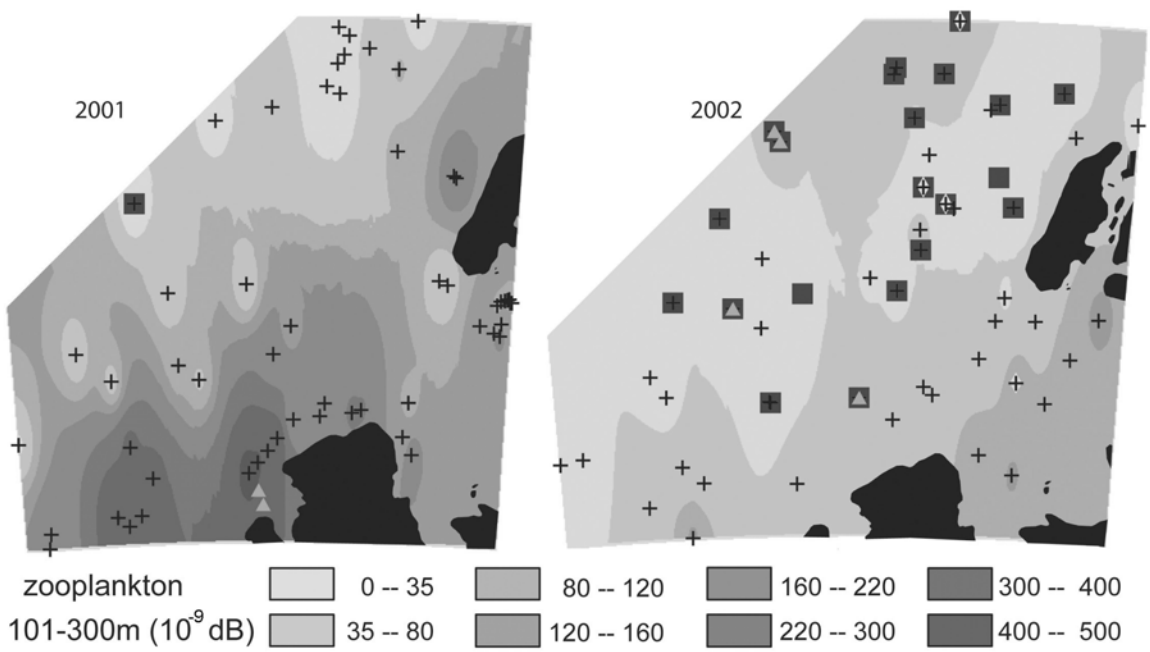

Figure 4.10. Mean zooplankton abundance at depth (101–300m) during the two survey years, smoothed with IDW. Symbols are the same as in Figure 4.7.

During 2001, blue whale D calls were detected in the area with the highest krill biomass and zooplankton abundances, but the next year, D calls were detected in areas with low krill biomass and zooplankton abundances. In 2002, the northwest shelf, where most blue whale tonals and fin whale calls were detected, had 0g/m^2 krill biomass. All other regions where blue whale tonals and D calls were detected in 2002 had low krill biomass, both in the surface 100m and in the 100–300m depth range (Figures 4.7 and 4.8).

Modeling results

Table 4.2. Results of the stepwise linear regression modeling, showing all the significant variables. The added contribution of each variable to the model fit is evaluated from the change in the deviance by the addition of that variable. mz3 is the mean backscatter in 101–300m depth range, mk1 is the mean krill biomass from 0–100m depth, and SST is sea surface temperature.

Model	Coefficient	df	Deviance	p-value
Null		76	83.743	
+Depth	0.582	75	71.536	0.0005
+mz3	-2.481	74	58.051	0.0002
+mk1	-32.560	73	45.248	0.0003
+SST	1.458	72	34.564	0.0011

Eight of the available nine environmental variables were used for the model fitting (Table 4.1). T_{max200} and Sal_{50} had correlation of 0.740, indicating they are both related to the UCDW intrusions, so only T_{max200} was used in the model selection process. The variables that were found to be significantly explanatory of the calling blue whale presence were: depth, the mean krill biomass in the 0–100m range, the mean zooplankton abundance in the 101–300m range, and the sea surface temperature ($\chi^2 = 49.179$, df = 4, $p<0.0001$; Table 4.2). While the depth and the sea surface temperature were positively correlated with the presence of the calling blue whales, krill and zooplankton were negatively correlated (Figure 4.11; Table 4.2). We found that over 58% of the blue whale presence data were explained by the model ($R^2 = 0.587$).

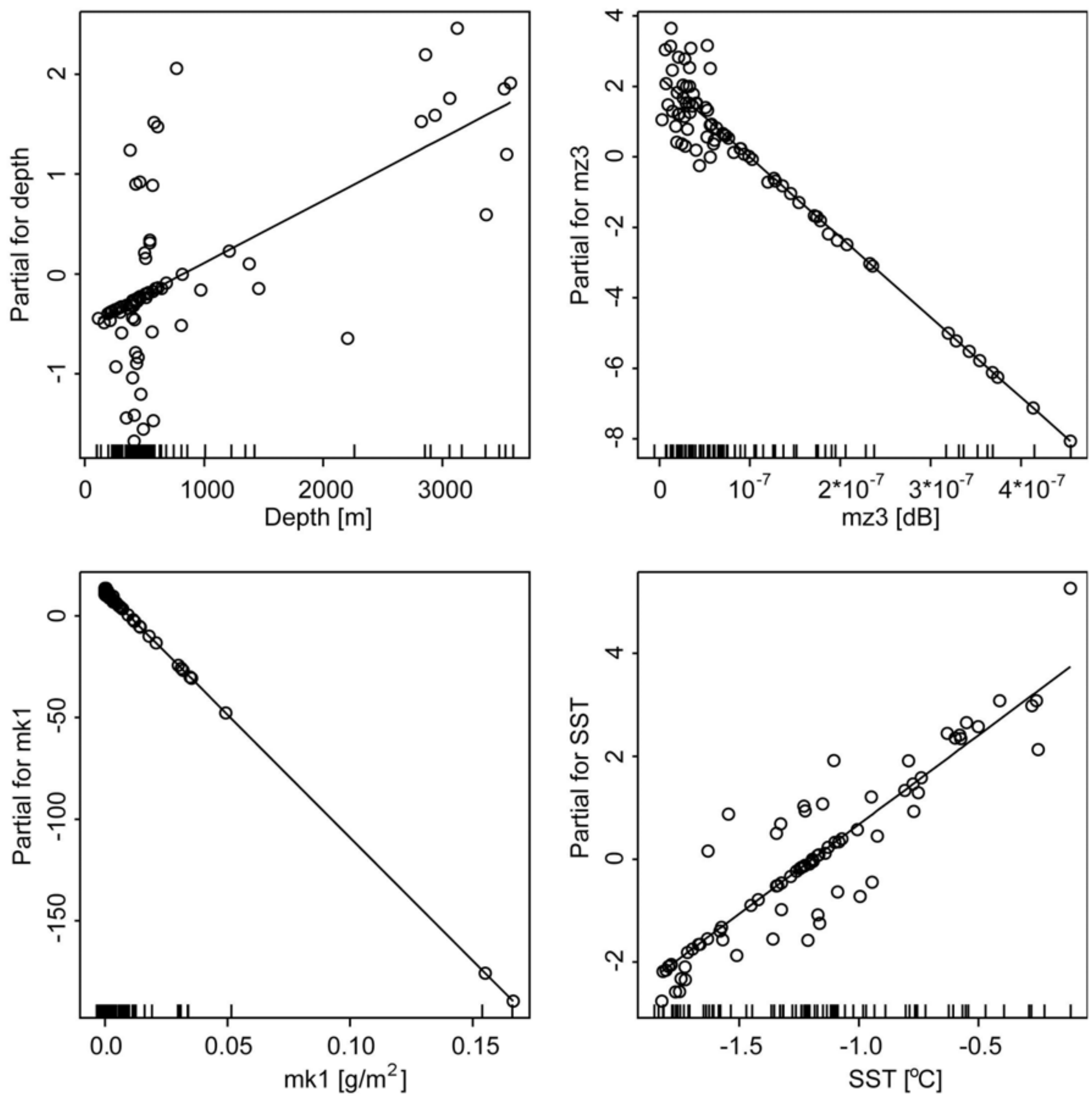

Figure 4.11. The mean-adjusted partial fits (straight line) for all the significant predictor variables. Circles are partial residues and short vertical lines along the x-axis show number of observations at each value of the variable.

E. Discussion

Oceanographic surveys in the falls of 2001 and 2002 showed a high degree of interannual variability in this region of the Southern Ocean. One notable difference in the conditions between the two survey years was the timing of the sea ice formation (Perovich *et al.*, 2004). The sea ice cycle is an important feature that affects physical and biological processes (Nicol *et al.*, 2000b; Nicol, 2006). Generally, differences in the sea ice cover in these surveys were paralleled by the differences in the distribution and abundance of Chl-*a*, krill, zooplankton and calling whales. High krill and zooplankton also coincided with the areas of steep bathymetry, such as Marguerite Trough, in both years (Ashjian *et al.*, 2004; Lawson *et al.*, 2004). On top of the significant negative relationship between the calling blue whales and the zooplankton, there was also an apparent negative relationship between the zooplankton and Chl-*a* (Lawson, 2006). (The linkage between Chl-*a* and the calling blue whales, however, was not significant.) This may indicate a degree of top-down control in the area, with zooplankton depleting the Chl-*a* concentrations (Beklemishev, 1960; Carpenter *et al.*, 1985; Estes *et al.*, 1998), but additional factors (e.g. behavior) could also contribute to the observed distributions.

<u>Blue whale distribution</u>

Correlations between the calling blue whale distribution and the bathymetry and the SST are consistent with the findings from the North Pacific (Croll *et al.*, 1998; Fiedler *et al.*, 1998; Redfern *et al.*, 2006a). The difference was that the SST was negatively correlated with the blue whale distribution in temperate and tropical regions. All the whale detections in this study occurred in the warmer, ice-free waters. This difference in the direction of the correlation is likely due to the fact that in the polar region in the fall, low surface temperature is not an expression of upwelled, nutrient rich waters, but rather indicates sea ice formation. Positive correlation with depth is consistent with the notion that blue whales are a pelagic species (Mackintosh, 1965).

A number of studies found that rorquals in different geographic regions are associated with their prey at various scales, ranging from a few km to thousands of km (Croll *et al.*, 1998; Tynan, 1998; Nicol *et al.*, 2000a; Nicol *et al.*, 2000b; Reid *et al.*, 2000; Friedlaender *et al.*, 2006; Redfern *et al.*, 2006a). Positive correlations at fine scales, however, are harder to demonstrate (Reid *et al.*, 2000; Baumgartner *et al.*, 2003). At very small, foraging scales, swarm size, density, and prey orientation may become important (Reid *et al.*, 2000), however, the scale used in this study (10s of km), should be large enough to test the relationships between the whales and the krill. Negative correlation between calling blue whales and krill biomass and zooplankton abundance could be the result of several factors. The Western Antarctic Peninsula is an area with very high krill abundance (Marr, 1962; Atkinson *et al.*, 2004) and blue whales may not require very high prey concentrations for successful foraging. In 2002, however, the krill biomass in much of the northern part of the survey area, where most blue whale calls were detected, was 0 g/m^2. Although it is possible that existing krill patches were missed by the very narrow BIOMAPER-II tracks, the consistent absence of krill over several track lines strengthens the idea there were no krill in this region. The lack of krill, therefore, could be caused by whale foraging.

Blue and fin whales come to the Southern Ocean primarily to feed (Kawamura, 1994), but they most likely do not spend all their time foraging. Therefore, it is necessary to consider other behavioral contexts of whale presence in the WAP region. Evidence from California suggests that blue whales producing tonal, song-like calls may not be feeding, but are moving through the area (McDonald *et al.*, 1995). Thus, we would not expect necessarily to find calling blue whales in the areas with high krill biomass. Blue whales making D calls are more likely to be feeding (Oleson *et al.*, 2006). Rankin *et al.*

(2005) recorded both tonal and D calls in the vicinity of apparently feeding animals. During our surveys, two out of six times blue whale D calls were detected, they were associated with high krill biomass and zooplankton abundance. It has been found previously that blue and fin whales are tightly linked to krill in the Antarctic during the spring and the summer (Hardy and Gunther, 1935), but it is possible that by the fall, the whales are well fed and more likely to engage in other behaviors. Also, the krill are more abundant in costal regions in the fall (Lascara *et al.*, 1999; Lawson, 2006), but the whales may be less likely to move to those areas to feed.

If we assume feeding and tonal calling are mutually exclusive, low whale call detections in 2001 could indicate the whales were still feeding, or they were further south, closer to the ice edge. The whales could use the ice edge as a reliable location of aggregated prey (Brierley *et al.*, 2002; Nicol, 2006). Our survey probably covered smaller area than the total area used by the foraging blue whales in the WAP region. These whales do not typically travel over great distances longitudinally, but they are capable of extensive latitudinal movements (Brown, 1954). Bimodal distribution of blue whale calls recorded on the bottom-moored instruments in the larger WAP area (Širović *et al.*, 2004) indicates that the whales could be moving through our survey area with the retreating and advancing ice edge. Therefore, if they are swimming rather than foraging when they produce tonal calls, we would not expect to find an association with prey aggregations from acoustic surveys.

Fin whale distribution

Fin whale calls were appeared positively associated with Marguerite Trough, high Chl-*a* concentrations, and UCDW intrusions. The association with the bathymetric features is consistent with findings in other regions (Woodley and Gaskin, 1996; Moore *et al.*, 2002a). The importance of these parameters, however, could not be assessed qualitatively due to the small number of fin whale call detections. The small number of detections could indicate that this region is not a prime fin whale habitat in the WAP region. This is consistent with previous findings that fin whales tend to remain further north from the ice edge (Beklemishev, 1960; Mackintosh, 1965) and in this region mostly occur at the northern tip of the peninsula (Širović *et al.*, 2004). Future studies aimed at understanding fin whale habitat preferences should focus on the areas north of Marguerite Bay.

Humpback and minke whale habitat preferences were analyzed from the same region and during the same time period (Friedlaender *et al.*, 2006). Like the blue and fin whales, the distribution of humpback and minke whales was related to the ice edge and bathymetry, but humpback and minke whale had a positive relationship with zooplankton. These analyses, however, were based on sighting data, not acoustics. Different baleen whale survey methods (visual versus acoustics) may sample animals in different behavioral states, which could account for the differences in their zooplankton linkages.

<u>Data limitations</u>

There were several problems associated with the acoustic volume backscatter data collected during these surveys. The 43kHz transducer did not function properly in 2001 and, therefore, krill biomass data were not as reliable as in 2002 (Lawson, 2006). Also, while it is clear that *E. superba* is the primary prey species of blue and fin whales in the Southern Ocean (Kawamura, 1994), it is unclear which krill species were observed with active acoustics. Size estimates from the acoustic data, as well as net tows and Video Plankton Recorder data, indicate that deep, dense, costal patches, that dominate biomass estimates, are likely *E. superba* (Ashjian *et al.*, 2004, G. Lawson, pers. comm.), but some aggregations off Alexander Island could have been *E. crystallorophias* (Ashjian *et al.*, 2004). Information on zooplankton species composition would be useful for a more accurate interpretation of the negative relationships between calling whales and krill and other zooplankton.

There was a mismatch between the scales over which BIOMAPER-II and hydrographic data were collected, and ranges over which blue and fin whales could be detected. Temperature, salinity and Chl-*a* data were collected mostly at 40km intervals. BIOMAPER-II data were collected continuously along transects, but they were subsequently averaged over 20km, centered at the sonobuoy deployment locations. Blue and fin whale calls in the Southern Ocean propagate over long distances (see Chapter III). Transmission loss in the shallow, shelf waters is higher than in the deep water, and the sonobuoy monitoring range in this study extended over tens or hundreds of km. The relationship between the sonobuoy location and the environmental parameters, therefore, does not necessarily reflect the exact relationship between the whales and the environment, which makes it more challenging to use acoustic data for habitat modeling. No blue or fin whales were sighted during the surveys (Thiele *et al.*, 2004), so passive acoustics were the only method available to investigate these relationships. However, passive acoustics should be used only for mesoscale comparisons between whales and their environment, and small-scale linkages should be attempted only if calling whales can be acoustically localized.

Physical and biological variables are autocorrelated over different spatial scales. Thermohaline properties tend to autocorrelate over large spatial scales and krill abundance, for example, can vary over very small scales (Haury *et al.*, 1978; Dickey, 1990). In order to use relevant scales when modeling whale habitat, it is important to know the operational scale of the response variable (Baumgartner *et al.*, 2003; Redfern *et al.*, 2006a). The primary goals of the SO GLOBEC program were not focused on the ecology of baleen whales, so the sampling strategy was not optimized for these purposes.

In future studies of blue and fin whale habitat associations, it would be important to know the scales over which whale distributions change, so that adequate sampling protocols can be adopted, with the minimum sampling resolution corresponding to the whale integration scales.

These surveys provided a static look at fall conditions during two years. Ecological processes in the Southern Ocean are dynamic and therefore these results should be considered only in the context of these individual cases. The differing ice conditions between the years provided some insight into the system variability. Habitat relationships, however, would have to be followed over many years to definitively conclude what parameters really are important in describing and predicting blue and fin whale distributions (Hardy and Gunther, 1935).

F. Acknowledgements

This work was supported by the National Science Foundation – Office of Polar Programs. Logistic support was provided by Raytheon Polar Services. We thank the Masters and crews of NBP0103 and NBP0202, as well as the support and science staff aboard those cruises. Catherine Berchok collected the passive acoustic data during the 2001 fall cruise. Thanks to Gareth Lawson and Peter Wiebe for providing the BIOMAPER-II data. CTD and chlorophyll *a* data were collected and processed by John Klinck and Maria Vernet, respectively, and are available on the US SO GLOBEC website. The text of the chapter was improved by comments from G. Lawson and J. Barlow. Mention of trade names does not constitute endorsement for use.

V. Baleen whales in the Scotia Sea in January and February 2003

A. Abstract

Different species of baleen whales display distinct spatial distribution patterns in the Scotia Sea during the austral summer. Passive acoustic and visual surveys for baleen whales were conducted aboard the RRS *James Clark Ross* in the Scotia Sea and around South Georgia in January and February 2003. Identified calls from four species were recorded during the acoustic survey including southern right (*Eubalaena australis*), blue (*Balaenoptera musculus*), fin (*B. physalus*) and humpback whales (*Megaptera novaeangliae*). These acoustic data included up calls by southern right whales, downswept D and tonal calls by blue whales, two possible types of fin whale downswept calls and humpback whale moans and grunts. Visual detections included southern right, fin, humpback and Antarctic minke whales (*B. bonaerensis sp.*). Most acoustic and visual detections occurred either around South Georgia (southern right and humpback whales) or south of the southern boundary of the Antarctic Circumpolar Current (ACC) and along the outer edge of the ice pack (southern right, blue, humpback and Antarctic minke whales). Fin whales were the exception, being the only species acoustically and visually detected primarily in the central Scotia Sea, along the southern ACC front. In addition to identifiable calls from these species, two types of probable baleen whale calls were detected: 50Hz upswept and pulsing calls. We propose that minke whales may produce the pulsing calls based on similarities to minke whale calls recorded in the North Atlantic Ocean. There was an overlap between locations of fin whale sightings and recordings and locations of 50Hz upswept calls in the central Scotia Sea, but these calls were most similar to calls attributed to blues whales in other parts of Antarctica. More study is required to determine if baleen whales produce these two call types, and if so, which species of baleen whale. The efficiency of acoustics and visual surveys varied by species,

with blue whales being easier to detect using acoustics, Antarctic minke whales being best detected during visual surveys and other species falling in between these two extremes.

B. Introduction

South Georgia was one of the prime commercial whaling grounds in the early 20th century, and during this time most stocks of baleen whales were depleted from the area (Moore *et al.*, 1999). According to International Whaling Commission (IWC) records, the total numbers of baleen whales taken from Area II (which encompasses the area from 0 to 60ºW south of 40ºS, including South Georgia and the Scotia Sea; see Figure 5.1a) since 1931 were 518 southern right (*Eubalaena australis*), 32,810 blue (*Balaenoptera musculus*), 149,678 fin (*B. physalus*) and 1,305 humpback whales (*Megaptera novaeangliae*). These data, however, do not include Soviet catches since World War II, which were often falsely reported until the 1990's, slightly overestimating blue and fin whale and grossly underestimating humpback whale catches (Yablokov, 1994). While there are no current population estimates for Area II, the total whale sightings during four summer-season IWC cruises in Area II in the 1980's and 1990's (Branch and Butterworth, 2001a) were 14 southern right, 18 blue, 31 fin, 38 humpback, and 1,621 Antarctic minke whales (*B. bonaerensis sp.*).

The focus of the JR82 cruise aboard the RRS *James Clark Ross* was to study the large scale distribution and transport of Antarctic krill (*Euphausia superba*), as well as ecosystem dynamics of the Scotia Sea (Anonymous, 2003). The study area links two well studied and krill-rich regions of the Southern Ocean, the Antarctic Peninsula and South Georgia, that have been the focus of ecosystem research since the Discovery expeditions of the 1930's (Mackintosh, 1936). In the Scotia Sea the Antarctic current system loops north, steered away from the winter pack ice zone by the bathymetry and the Antarctic

Peninsula land mass projection (Orsi *et al.*, 1995). This region features both high rates of primary productivity and high densities of krill in spring and summer (El-Sayed and Weber, 1982; Priddle *et al.*, 1988; Hewitt *et al.*, 2004; Holm-Hansen *et al.*, 2004b). In addition to the work in the Scotia Sea, the cruise included a fine-scale sampling section near South Georgia, in the Western Core Box (WCB), part of the British Antarctic Survey's (BAS) long-term fine-scale ecological monitoring program (Reid *et al.*, 2000).

The goal of the marine mammal acoustic monitoring program during JR82 was to conduct an along-track passive acoustic survey for cetaceans using opportunistic deployments of sonobuoys. These recordings can provide insight into the acoustic repertoire as well as the spatial distribution of various species of cetaceans. Acoustic survey was focused on southern right, blue, fin, humpback, and minke whales, since calls from these species have not previously been reported in this area. In other locations, each species produces distinctive low-frequency (<1kHz) calls, which are the only calls that have been analysed in this study. During daylight hours there was concurrent visual survey for cetaceans conducted by a team of two experienced IWC observers.

The majority of previous cetacean visual surveys in the Scotia Sea have been conducted under the auspices of the IWC in collaboration with German, US and UK polar and multidisciplinary research programs, e.g. as part of Commission for the Convention on Antarctic Marine Living Resources (CCAMLR) and Southern Ocean Global Ocean Ecosystem Dynamics (SO GLOBEC) studies (Kasamatsu *et al.*, 1988; Kasamatsu *et al.*, 1996; Reid *et al.*, 2000; Pankow and Kock, 2001; Secchi *et al.*, 2001; Reilly *et al.*, 2004). Generally, blue and Antarctic minke whales are known to occur further south than fin whales, which are not commonly associated with sea ice; humpback whales can occur over a range of latitudes; and southern right whales occur near island groups (Kellogg, 1929; Kasamatsu *et al.*, 1988; Kasamatsu *et al.*, 1996; Moore *et al.*, 1999). Whaling records also indicate that blue, fin and humpback whales associate with the southern boundary of the Antarctic Circumpolar Current (ACC) (Tynan, 1998). All of these species have been sighted previously in the Scotia Sea. Fin whale sightings occurred further to the north of humpback whales in the vicinity of Elephant Island in December 1996 (Pankow and Kock, 2001). Minke whale sightings were common east of the Antarctic Peninsula, while humpback whale sightings were common around South Shetlands and South Georgia in surveys conducted from 1997 to 2000 (Secchi *et al.*, 2001; Reilly *et al.*, 2004).

Call characteristics

Calls of some baleen whale species have been studied extensively (reviewed in Richardson *et al.*, 1995). Calls from southern right whales off Argentina have been described by many authors (e. g. Cummings *et al.*, 1971; Payne and Payne, 1971; Cummings *et al.*, 1972; Clark, 1982; 1983). The most commonly described southern right whale call is the up call, sweeping in frequency from 50 to 200Hz and lasting 0.5 to 1.5s. This call has been associated with swimming animals and appears to be a contact call (Clark, 1983). Blue whales make low frequency (below 100Hz), long duration (10–20s), repetitive calls that vary between regions (Kibblewhite *et al.*, 1967; Edds, 1982; Alling *et al.*, 1991; Stafford *et al.*, 1998; McDonald *et al.*, 2006), and they also produce a shorter and less stereotyped call (D call) whose general characteristics are consistent between regions (Thompson *et al.*, 1996; Thode *et al.*, 2000; McDonald *et al.*, 2001; Mellinger and Clark, 2003; Rankin *et al.*, 2005). There are no blue whale recordings from the South Atlantic Ocean, but blue whale calls have been recorded south of 60ºS in the region between 0–30ºW and at 38ºW in the Weddell Sea (Ljungblad *et al.*, 1998; Clark and Fowler, 2001). These calls consist of three segments: a 28Hz tone that lasts approximately 8s, immediately followed by a short (1s) downsweep to 19Hz and a slightly downswept tonal from 19 to 18Hz, lasting about 8s. The same type of call has been reported at other locations around Antarctica (Matusoka *et al.*, 2000; Širović *et al.*, 2004; Rankin *et al.*, 2005), although all three components may not always be present. Rankin *et al.* (2005) suggested the '28Hz tonal' is the identifying feature. Fin whales produce regular, short (1s duration) downsweeps ranging in frequency from approximately 40 to 15Hz, the exact frequency range and repetition rate dependant on the geographic location (Thompson *et al.*, 1992). These calls occur throughout the Northern Hemisphere (Watkins, 1981; Edds, 1988; McDonald *et al.*, 1995) but the only report from the Southern Hemisphere is from the Western Antarctic Peninsula (Širović *et al.*, 2004). Stafford *et al.* (1999a) reported pulse series similar to calls produced by fin whales on hydrophones south of the equator in the eastern tropical Pacific, however, fin whale sightings are rare in this area (Wade and Gerrodette, 1993). There are also reports of higher frequency (75–40Hz) calls produced by fin whales from the North Atlantic (Watkins, 1981).

Humpback whales are among acoustically the best studied baleen whale species (e. g. Payne and McVay, 1971; Winn and Winn, 1978; McSweeny *et al.*, 1989; Clapham and Mattila, 1990; Helweg *et al.*, 1998; Cerchio *et al.*, 2001). Even though songs from low-latitude breeding grounds have been the focus of most research, there is evidence of singing from high-latitude feeding grounds (Mattila *et al.*, 1987; McSweeny *et al.*, 1989; Clark and Clapham, 2004). In the Southern Hemisphere, recent acoustic work on humpback whales has included the Atlantic, Indian and Pacific waters (Helweg *et al.*, 1998; Noad *et al.*, 2000; Cato *et al.*, 2001; Razafindrakoto *et al.*, 2001; Darling and Sousa-Lima, 2005). Leaper *et al.* (2000) reported 'moan' type calls from humpbacks off South Georgia, but otherwise humpback whale calls in the Antarctic are under-sampled. Antarctic minke whales in the Ross Sea produce very short downsweeps (~0.3s) that have variable starting and ending frequencies, generally between 130 and 60Hz (Schevill and Watkins, 1972; Leatherwood *et al.*, 1981). Other minke whale recordings from the

Southern Hemisphere are not of the Antarctic minke but dwarf minke whale (*B. acutorostrata*) from lower latitudes and generally include more complex and higher frequency calls (Gedamke *et al.*, 2001). No calls from any of these species have been reported previously from the Scotia Sea since past acoustic surveys in the area focused on frequencies higher than 300Hz and did not focus on baleen whales (Leaper and Scheidat, 1998; Leaper *et al.*, 2000). Although knowledge of baleen whale calling in this area is scant, whaling data indicate that it was once a very productive whaling ground and that it was historically abundant in baleen whales (Kellogg, 1929; Mackintosh, 1966; Horwood, 1986).

C. Methods

The JR82 cruise departed Stanley, Falkland Islands, on 7 January 2003. Eight long transects across the Scotia Sea from north of the southern Antarctic Circumpolar Current front (sACCf) to approximately 63°S were completed during the first part of the cruise along 4,300 miles of transect (Anonymous, 2003). During the second stage of the cruise, four pairs of 80km transects were conducted in the WCB (Figure 5.1b). Data collected during the cruise included: conductivity-temperature-depth profiles, expendable bathythermograph profiles, acoustic Doppler current profiler data, nutrient analyses, phytoplankton biomass, primary production, krill abundance and growth. Sonobuoys were deployed when marine mammals were visually detected, prior to arrival to oceanographic stations, as well as occasionally throughout the cruise. The visual survey was conducted during daylight hours when weather conditions were favorable. The JR82 cruise ended on 23 February 2003 in Stanley, Falkland Islands.

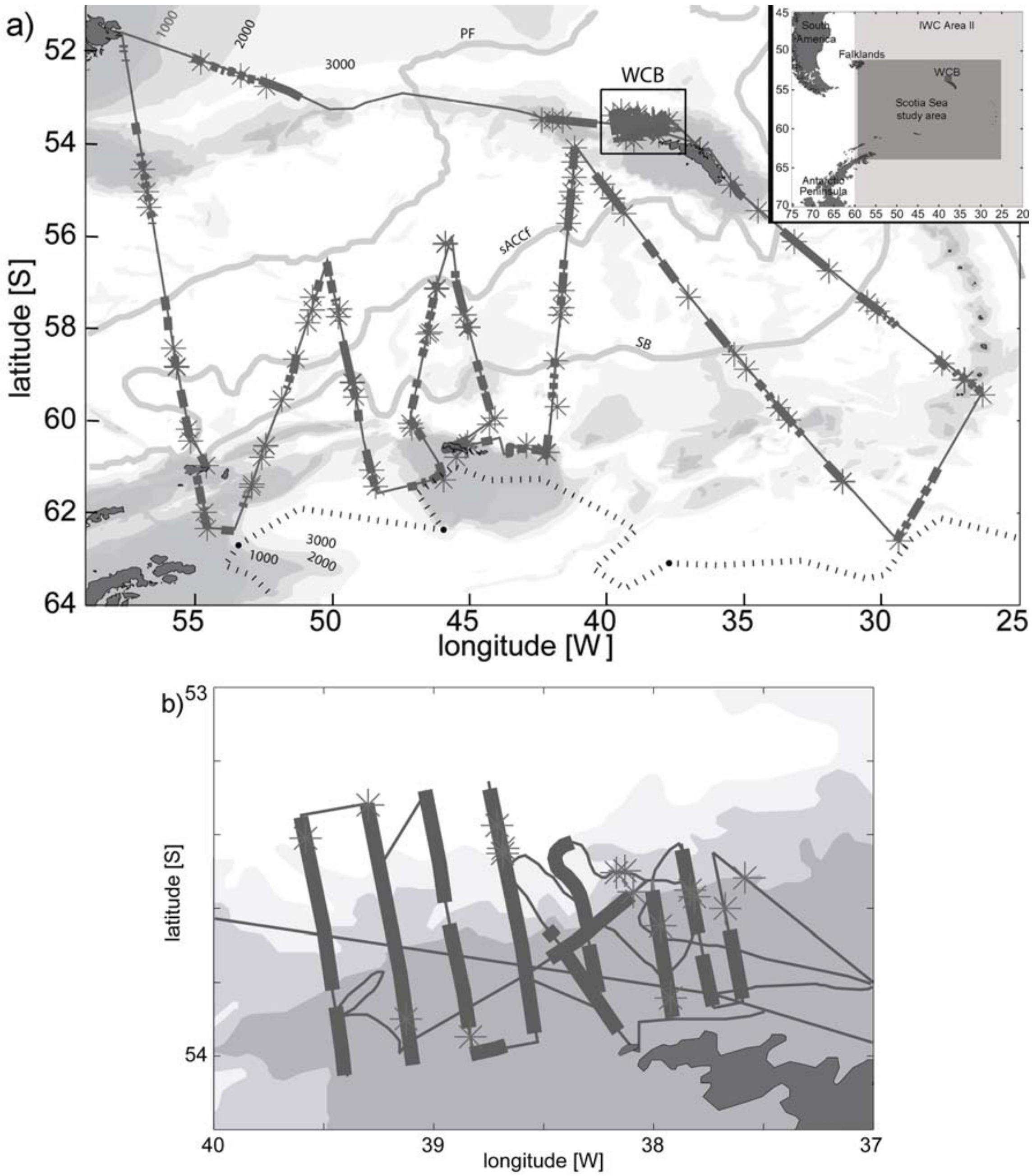

Figure 5.1. Cruise track across a) the Scotia Sea and b) the Western Core Box (WCB), with locations of sonobuoy deployments (stars) and tracks of visual survey effort (thick line segments). Bathymetry is shaded in 1000m isobath increments and land is the darkest shading. Thick grey lines represent major fronts in the area, after Orsi *et al.* (1995): PF = polar front; sACCf = southern Antarctic Circumpolar Current front; SB = southern boundary of the ACC. The broken black line is the inferred ice edge (15% cover) on 1 February 2003 from the NSIDC satellite image. Inset image shows a larger area including nearby continents and indicating locations of surveys, as well as IWC Area II.

Acoustic survey

Two types of sonobuoys were used during this cruise due to their differences in direction-finding capabilities and frequency response characteristics. Omnidirectional sonobuoys (AN/SSQ-57B) have a broadband frequency response from 10 to 20,000Hz, but it is not possible to determine the direction of the sound source using individual omnidirectional sonobuoys. DIFAR (directional frequency analysis and recording; AN/SSQ-53D) sonobuoys, on the other hand, have directional detection capabilities within individual sonobuoys and a frequency response from 10 to 2,400Hz. Sound bearing relative to the sonobuoy can be determined from direction sensors and an internal compass located within the sensor package of the DIFAR sonobuoys (McDonald, 2004). Sonobuoy specifications require the bearing error to be less than 10º. Using these bearings, acoustic data can be correlated to visual observations of marine mammals.

A set of custom electronics and software were used to record and analyze the sonobuoy data. The antenna used for the reception of the sonobuoy radio signal during the cruise was a 160MHz omnidirectional Cushcraft Ringo Ranger ARX-2B. The maximum range for the radio transmission during the cruise was approximately 8nmi, but was variable dependant on weather conditions. We used software controlled ICOM IC-PCR1000 scanner radio receiver, modified to provide improved low frequency response, for reception of sonobuoy signal (frequency response from 10–1000Hz ±1dB). Data were recorded continuously on digital audiotapes while receiving the signal using a Sony PCM-M1 digital audio recorder (frequency response from 20–22,000Hz ±1.0dB at 48kHz sample rate) and reviewed in real-time using *SpectraPlus* software package. When DIFAR sonobuoys were deployed, bearings to interesting sounds were calculated in real-time using Greeneridge Sciences DIFAR demultiplexing software and beam forming code developed by M. McDonald. Upon each deployment the following items were recorded: time, latitude, longitude and depth at deployment; sonobuoy type, channel, time and depth settings; speed of the ship; the reason for deployment. After deployment, the sonobuoys transmitted their radio signal to the underway ship for a maximum of 8h before scuttling and sinking.

During the post-processing analyses, recordings of interest were reviewed using *SpectraPlus* with 32,768-point FFT, 90% overlap and Hanning window. Periods that were not monitored in real-time during the cruise were reviewed. Frequency and temporal characteristics were measured for calls with a good signal-to-noise ratio using the above spectral parameters. For southern right whale up calls, both types of fin whale calls, blue whale D calls and 50Hz upswept calls, the starting and ending frequency and the duration of the calls were measured. The middle point of the tonal frequency was measured for blue whale calls along with the duration of the call and it was also noted if the downswept part of the call was present. Intercall interval was measured for blue whale 28Hz tonal, fin whale low and high frequency and 50Hz upswept calls. For pulsing calls, the energy band over which pulsing occurred was measured and the pulse duration and rate were calculated. We reported the averages and standard deviations for all call characteristics. Due to the variability in the duration of blue whale D calls, we also reported the duration range. Also, we have plotted the locations at which different call types occurred. *Ishmael* software (Mellinger, 2001) was used for verification of bearing calculations, as well as the calculation of bearings to additional calls. All reported bearings are in true degrees. Data were decimated before making spectrograms of representative calls.

The noise levels from the RRS *James Clark Ross* were generally low and decreased as the ship moved away from the sonobuoy. The noise did not affect the quality of recordings, except when using the bow thrusters at stations. As most of the cruise took place in ice-free waters, there was no ice breaking noise to decrease the signal-to-noise ratio. The data from periods when the noise of the ship was too loud to distinguish possible calls were not used for analyses.

Comparison with visual survey

Acoustic data were compared to the visual sightings data (the two data sets, however, were not collected independently). Two experienced observers conducted the visual survey during all daylight hours according to a standard line transect methodology for cetaceans (Buckland *et al.*, 2001). Each observer's search area included a 90º arc from the trackline to abeam of the ship and extending all the way to the horizon. Search was conducted in passing mode with *Fujinon* 7x50 binoculars from the bridge roof (eye height 18.3m). *Nikon* 10x50 binoculars were available for species identification and group size estimation. Sightings data were entered to a laptop computer running the *WinCruz* software program, recording casual-effort and off-effort sightings separately. Sightings data reported in this paper were collected while observers were on full-effort, unless otherwise stated. For fin and southern right whales the sightings of 'like fin' and 'like right whale' were pooled together with the confirmed sightings of respective species. For minke whales, sightings of the following categories were pooled: 'minke (ordinary)'; 'like minke'; 'like ordinary minke'; 'undetermined minke'.

Acoustic and visual data were compared to oceanographic and sea ice data. The positions of mean locations of three main oceanographic fronts (Polar Front, PF; southern Antarctic Circumpolar Current front, sACCf; the southern boundary of the ACC, SB) were obtained from Orsi *et al.* (1995). The location of the ice edge (defined as 15% or less sea ice cover) on 1 February 2003 was determined from National Snow and Ice Data Center daily sea ice concentration satellite image with 25km resolution (Comiso, 1991, updated 2002). Locations of these features were plotted on the same maps as the locations of visual and acoustic whale detections for qualitative comparison.

D. Results

A total of 107 sonobuoys were deployed during JR82 cruise, 80 omnidirectional and 27 DIFAR, and there were 167 hours total of acoustic effort (Figure 5.1). Of the deployed sonobuoys, four DIFARs and 12 omnidirectionals failed (15% failure rate for each type). Baleen whale calls detected during the cruise included: southern right whale up calls (Figure 5.2a); blue whale 28Hz tonal and D calls (Figure 5.2b and 5.2c); low and high frequency fin whale calls (Figures 5.2d and 5.2e); humpback whale calls (Figure 5.2f). Two types of calls were acoustically detected that cannot be attributed to a particular species, but, since we propose they are likely to come from baleen whales, their characteristics are described and locations of occurrence are also shown. We refer to these calls as 50Hz upswept and pulsing calls (Figures 5.2g and 5.2h). Calls from sperm whales, as well as some other unidentified odontocetes were recorded during the cruise, but were not analyzed for this paper. The visual survey resulted in 220 hours of survey effort and a total of 217 sightings of groups or individuals. Baleen whales sighted were: southern right, fin, sei, humpback and minke whales.

<u>Southern right whales</u>

Southern right whales were detected visually and acoustically at three locations: in the vicinity of South Orkneys; in the vicinity of South Georgia; in the southeastern Scotia Sea (Figure 5.3a). There was a total of 20 sightings of 33 southern right whales while the only call type recognized as a southern right whale calls was the up call (Figure 5.2a). Southern right whales were detected twice visually and acoustically during the same time, but during every southern right whale occurrence other species of whales were sighted in the vicinity as well. During one such visual encounter, on 13 February 2003, a deployment of a directional sonobuoy made it possible to calculate bearings to calling whales. They were compared to locations of the two groups of southern right whales detected by the visual observers (who were off-effort at the time) and we found that the bearing of one group of three calls at 165±8°, corresponded to the bearing of one of the two visually detected groups, which were observed at 176° and 260°. (A group of 14 sei whales (*B. borealis*) was detected by the observers during the same time period at 235°.)

A total of 31 up calls from three different days of recordings were measured to determine their temporal and frequency characteristics. The average starting frequency of the calls was 92±11Hz, the ending frequency was 173±11Hz and the average duration was 0.7±0.1s. The average sweep rate of the up calls was 125±24Hz/s.

Blue whales

Most blue whale acoustic detections occurred along the southern edges of the survey area in the Scotia Sea, with two detections in the northern area closer to South Georgia (Figure 5.3b). There were no blue whale sightings throughout the cruise, so it was not possible to relate any of these acoustic detections to visual ones. Two different call types detected during JR82 cruise were from blue whales, the 28Hz tonal call and the D call. Blue whale 28Hz tonal calls were detected on seven sonobuoys and temporal and frequency characteristics were analyzed from 29 calls. Generally, only the flat, 27.7±0.1Hz tonal component was visible, lasting an average 8±1s (Figure 5.2b). Average intercall interval was 65s. The downsweept part ('28Hz downsweep' in Rankin *et al.*, 2005) was visible in 14 analyzed calls. D calls occurred on five sonobuoys, and four of these also had 28Hz tonal detections (Figure 5.3b). Fifty D calls from four sonobuoys were analyzed. These calls varied in duration from 1.0–3.7s (with average 2.1±0.8s), and their frequency changed from 80±8Hz to 38±7Hz (Figure 5.2c). The average sweep rate was 23±10Hz/s. Five out of 50 analyzed D calls started with a short upsweep in frequency and one started with a flat tone before the main, downswept part. The flat tone was at the same frequency as the beginning of the downsweep and the upsweeps were variable in their duration and frequency range. These calls did not have regular intercall intervals.

Blue whale calls were detected on two occasions on directional sonobuoys, on 26 and 30 January 2003. Bearings to both 28Hz tonal and D calls were calculated on 26 January. Bearings to seven 28Hz tonals were calculated around 19:30 GMT, while the ship was on the 110° heading, and were found to belong to at least two different animals with bearings 10±18° (calculated from 3 calls) and 335±10° (from 4 calls). There were no D calls at this time. Bearings to four 28Hz tonal calls around 21:00 GMT were found to be 319±7°, while bearings to four D calls during that period were 313±5°. Ship's heading during this time was 90°. On 30 January it was possible to determine the bearings to four 28Hz tonal calls over a one-hour period, and they changed between 147° and 128°. The ship's bearing during this period was steady at around 270°.

Fin whales

In general, sightings of fin whales occurred in the central Scotia Sea and correspond well to areas where two types of fin whale calls were detected on 10 sonobuoys (Figure 5.3c). Low frequency fin whale calls occurred on eight of these sonobuoys, all of them deployed in the central Scotia Sea. A total of 49 low frequency fin whale calls were measured to determine their frequency characteristics. The calls were repetitive downsweeps in frequency from 31±2Hz to 15±1Hz (Figure 5.2d). Downsweeps lasted on average 0.7±0.1s and had a sweep rate of 25±4Hz/s and intercall interval 13.0±0.9s. On five occasions fin whale sightings were made within an hour of call recordings, and once other identified species of cetaceans (pilot whales, *Globicephala melas*, and hourglass dolphins, *Lagenorhynchus cruciger*) were sighted. Fin whale calls were recorded twice on directional sonobuoys, but the visual observers sighted no fin whales at those times.

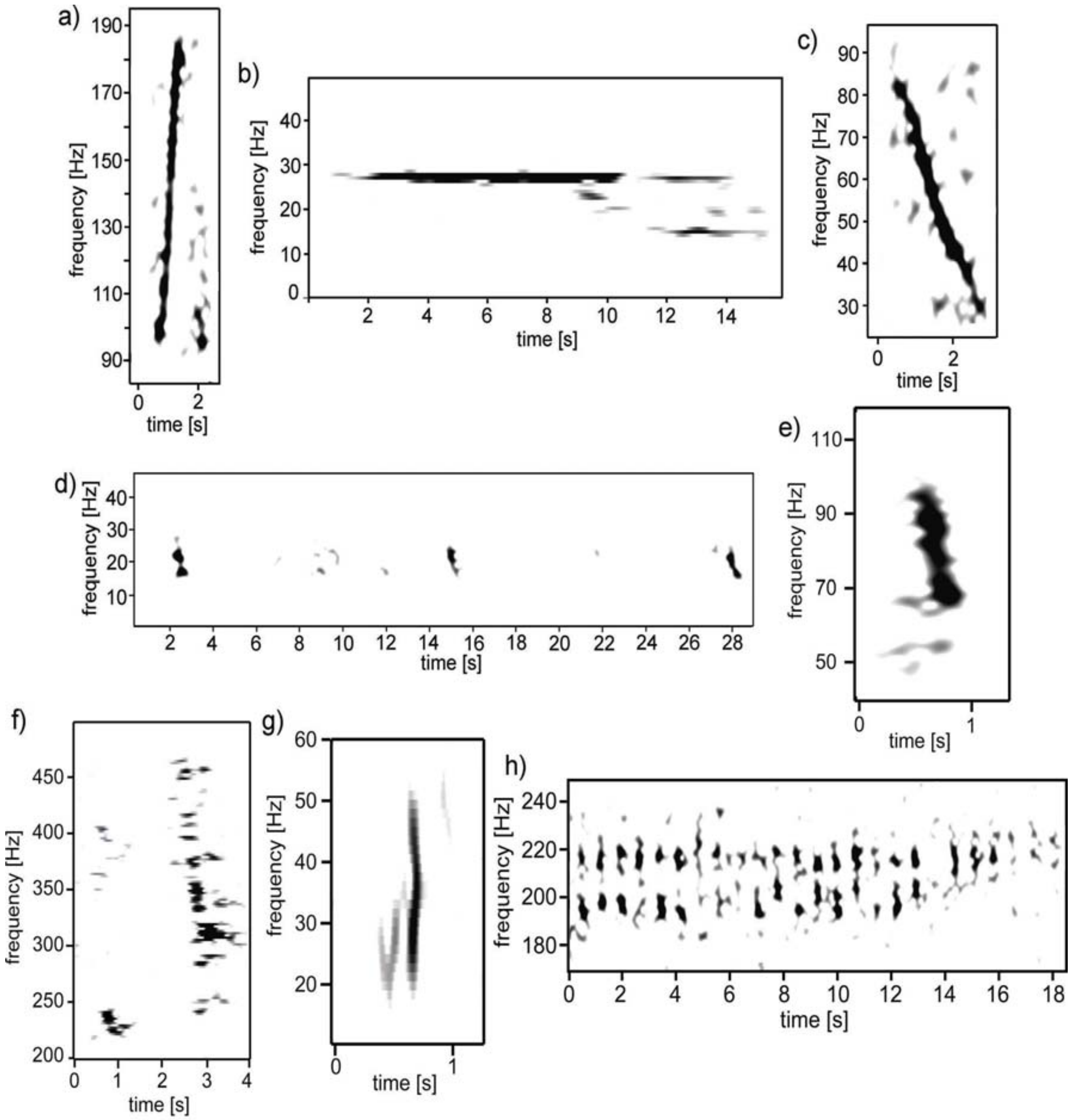

Figure 5.2. Spectrograms of calls recorded during JR82 cruise: a) southern right whale up call (600-point FFT, 99% overlap, Hanning window); b) blue whale 28Hz tonal call (parts of the downsweep and the second tonal are also visible; 2,400-point FFT, 95% overlap, Hanning window); c) blue whale D call (600-point FFT, 99% overlap, Hanning window); d) fin whale low frequency call (900-point FFT, 95% overlap, Hanning window); e) fin whale high frequency call (300-point FFT, 99% overlap, Hanning window); f) sample of humpback whale calls (600-point FFT, 95% overlap, Hanning window); g) unidentified 50Hz upswept call (200-point FFT, 99% overlap, Hanning window); h) unidentified pulsed calls (600-point FFT, 99% overlap, Hanning window).

Higher frequency fin whale calls were detected on two additional sonobuoys (Figure 5.3c). At both occurrences of these calls there were no lower frequency fin whale calls, but only fin whales were visually detected within an hour before or after the acoustic detection. (One of these sightings was during a period when the visual observers were not on full-effort.) Only 14 calls of this type were available for analysis. They were regularly repeated downswept calls that ranged on average from 102±15Hz to 51±3Hz over 0.6±0.1s, with the average sweep rate of 80±17Hz/s (Figure 5.2e). Their intercall interval was 4.6±0.9s. Unfortunately, both recordings of the high frequency calls were made on omnidirectional sonobuoys so it was impossible to relate them to the visual fin whale detections. During the cruise, visual observers sighted 15 groups of fin whales, for a total of 36 animals.

Humpback whales

The areas where humpback whale calls were detected acoustically generally correspond to areas of humpback sightings: around South Georgia, near South Shetland Islands in the southwest, as well as in the southeast corners of the surveyed area (Figure 5.3d). The calls detected during this cruise attributed to humpback whales were a variety of grunts and moans ranging in frequency from approximately 100 up to 600Hz (Figure 5.2f). Grunts and moans that were detected repetitively in the above frequency range and lasted longer than 1s and that could not be attributed to any other species were subjectively assigned as humpback whale calls. Humpback whale calls occurred on 15 sonobuoys deployed during the cruise (Figure 5.3d). A total of 12 groups and 38 humpbacks were visually detected during JR82 cruise.

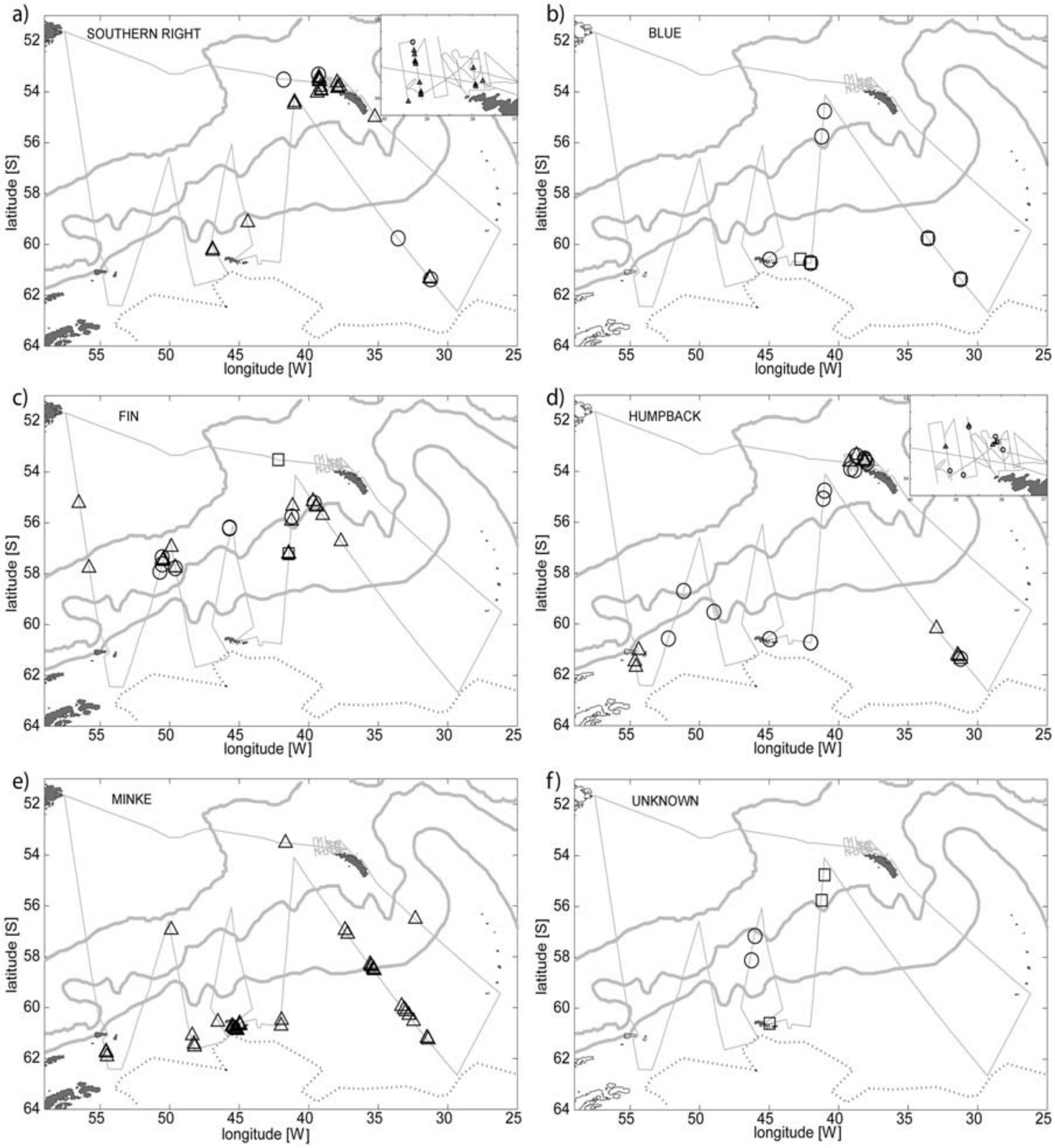

Figure 5.3. Locations of acoustic (circles and squares) and visual (triangle) sightings: a) southern right; b) blue (circles are tonal call and squares D call locations); c) fin (circles are low frequency and squares high frequency call locations); d) humpback; e) minke whales. f) Locations of 50Hz up (circles) and pulsing calls (squares). Insets on a) and d) show sightings in the WCB. Thin grey line is the cruise track, thick grey lines represent major fronts in the area: PF; sACCf; SB and the broken black line is the inferred ice edge on 1 February 2003 from the NSIDC satellite image (same as Figure 1).

Minke whales

A total of 43 groups (76 total animals) of minke whales were visually detected during JR82, most of them along the southern edge of the survey area close to the ice edge. No confirmed Antarctic minke whale calls were detected on the sonobuoys (Figure 5.3e). In the southeastern section of the survey area, minke whales were seen further away from the ice edge, in the central sector of the Scotia Sea.

Other calls

Two other call types were heard on sonobuoys on multiple occasions, 50Hz upswept and pulsing calls. They cannot be linked positively to a particular baleen whale species, but we believe it is likely that baleen whales produced these calls because they contain typical baleen whale call characteristics: low-frequency and repetitiveness.

The 50Hz upswept calls occurred on two sonobuoys deployed in the central Scotia Sea (Figure 5.3f). There were no visual sightings of whales near the sonobuoys on which these calls were heard, and there were higher frequency odontocete calls on one of the sonobuoys deployed nearby. The 50Hz upswept calls did not coincide with any other baleen whale calls. It was possible to determine frequency and temporal characteristics of 12 of these calls and they generally started at 26±4Hz, ended at 52±4Hz and lasted 0.5±0.1s (Figure 5.2g). They were repeated at intervals ranging from 62 to 78s, with usually 2–3 calls in a sequence.

Pulsing sounds were detected on three occasions (Figure 5.3f). The pulsing was concentrated mainly in the 140–240Hz energy band, but it was highly variable within a pulsing bout (Figure 5.2h). The average pulse duration and rate were calculated using 44 individual pulses and the duration was 0.31±0.04s while the pulse rate was 1.8±0.2pulses/s. The pulses were equally spaced throughout a call series and there was no evidence of slowing down or speeding up through the series. All three times these calls occurred on the same sonobuoys as blue whale 28Hz tonal calls, and twice they were acoustically detected on the same sonobuoys as humpback whale calls.

E. Discussion

This was the first time that an acoustic survey for baleen whales was conducted in the Scotia Sea. In addition to multiple recordings of known baleen whale calls, we recorded two call types from unknown sources. The acoustic survey, in conjunction with the visual survey, enabled us to assess the spatial distributions of southern right, blue, fin, humpback and Antarctic minke whales in the area and to compare the differences among the species. More work on call rates, gender bias, and seasonal variation in calling is needed, however, before acoustics can be used for population abundance estimates.

<u>Sources of calls</u>

Acoustic surveys offer an opportunity to study baleen whales even when whales are not available for observation by more traditional visual survey methods (e.g. due to dark, high sea state, low visibility). One of the problems acoustic surveys face is that calls cannot always be linked reliably to a particular species of whale since the animals often are not seen and heard at the same time. Sometimes, however, it is possible to link the bearing of a calling animal and a visual sighting of known species.

Up calls are well documented to be produced by southern right whales at other locations in the Southern Hemisphere (Cummings *et al.*, 1971; Payne and Payne, 1971; Clark, 1982; 1983). Southern right whales also were heard on a directional sonobuoy and seen concurrently on one occasion during the cruise. Even though a group of sei whales was visually detected in the vicinity at the same time, they were at a different bearing from detected calls. While little is known on sei whale calls, McDonald *et al.* (2005) reported sei whale calls off Antarctic Peninsula to be higher frequency (around 200Hz) and have different characteristics than the up call reported here. The similarity of the calls we detected during this survey to calls attributed to southern right whales in other reports, and the evidence from the bearing measurements we took from an acoustic and visual detection of these animals during this cruise, are strong evidence that southern right whales produced these up calls.

Since no blue whales were sighted during this cruise, we had to rely on previous reports of their calls in the Antarctic to link the sounds we heard to blue whales. Rankin *et al.* (2005) suggest that the 28Hz tonal call, similar to ones heard on multiple sonobuoys during this cruise, are a diagnostic feature in detecting blue whales. Given the flat tonal nature of the call, one possible mistake would be to confuse the ship's noise for a blue whale tonal, since the ship produced a tone at 27Hz while the bow thrusters were on at sampling stations. In this study we used additional identifying features such as predictable repetitiveness of the call (Širović *et al.*, 2004), duration of the tonal less than 10s or presence of the downswept part of the call (28Hz downsweep, after Rankin *et al.*, 2005). Also when possible, bearings were calculated to the 28Hz tonal calls and compared to the ship's bearing. Even though it is possible a calling blue whale and the ship could be on the same bearing, in instances when this happened we erred on the side of caution and did not report a blue whale call. From calls recorded while at sampling station with bow thrusters on, we reported only ones that satisfied at least two of the above conditions. Presence of 28Hz tonal calls was analyzed independently of the presence of D calls, and we found that the two types of calls coincided on four sonobuoys. Downsweeps similar to our D calls have been reported as coming from blue whales at other locations worldwide (Thompson *et al.*, 1996; McDonald *et al.*, 2001; Mellinger and Clark, 2003; Rankin *et al.*, 2005). Confusion of blue whale D calls with calls from other species is more likely than for 28Hz tonals. Southern right whales, for example, are known to produce some low frequency downswept calls (e. g. Cummings *et* *al.*, 1972; Clark, 1983), but these are generally in the 200–100Hz frequency range and last less than 1.5s. So even though there is some overlap with the location of right whale calls and blue whale D calls, we do not think that the 1.0–3.7s duration calls that were heard in the frequency range below 100Hz could be attributed to southern right whales, but are indeed blue whale D calls. Confusion with high frequency fin whale calls is avoided because D calls have longer duration and are not repeated at regular intervals.

Recorded fin whale calls could not be linked to visual sightings of these animals, but the low frequency calls are similar to the ones reported from fin whales at other worldwide locations (Walker, 1963; Edds, 1988; Thompson *et al.*, 1992), although they differ from calls reported off the Western Antarctic Peninsula in the absence of the 89Hz component (Širović *et al.*, 2004). High frequency calls are similar to the fin whales calls reported by Watkins (1981) but the frequencies are higher in this case (downsweep from 105 to 50Hz compared to 75 to 40Hz) and the duration is longer (0.6s compared to 0.3s). Two incidental sightings of fin whales around the time of these calls strengthen the case that fin whales produced these calls and their distribution followed the general pattern of fin whale distribution in the central Scotia Sea.

Calls similar to both 50Hz upswept and pulsing calls have been reported previously as produced by baleen whales (Winn and Perkins, 1976; Mellinger *et al.*, 2000; Rankin *et al.*, 2005) and their frequency and temporal characteristics are consistent with those generally reported from baleen whales. Pulsing calls occurred on the same sonobuoys as blue whale calls, but we do not think that blue whales produced these calls. Pulsing has previously been reported as produced by common minke whales, but in those instances the pulsing rate was 2.2 pulses/s, slightly higher than the one reported here (Winn and Perkins, 1976). Also, it has been implied that similar pulsing calls, with pulsing rates between 1.5 and 4.5 pulses/s, could be minke whale songs, as they have been recorded mostly in lower latitudes (Mellinger *et al.*, 2000; Gedamke *et al.*, 2001). If these pulses are from a minke whale, then this is the first recording of this species producing a song-like call at a high latitude. Even though similar pulsing sounds appear to be rather ubiquitous, they are not commonly associated with visual sightings of minke whales (Folkow and Blix, 1991; Mellinger *et al.*, 2000) and during our cruise were recorded mostly in an area with no Antarctic minke whale sightings. It would be helpful to determine the source of this pulsing call, as well as the sources of pulsing sounds recorded elsewhere.

There were no baleen whale sightings in the vicinity of the sonobuoys on which 50Hz upswept calls were heard, but Rankin *et al.* (2005) reported similar upswept calls, from 23 to 57Hz with 1.6s duration, as coming from blue whales in the Antarctic. While the frequency range of the calls is similar, calls reported here are three times shorter. The frequency range of this call is lower than what has been reported previously for minke or southern right whales. Although minke whales are not known to make upsweeps, the short duration of the calls makes them resemble minke whale downsweep calls (Schevill and Watkins, 1972; Edds-Walton, 2000). Antarctic minke whale acoustics are very poorly understood and it is possible that they could be making these calls. Southern right whales also produce upsweeps, but their upsweeps tend to be higher frequency and longer duration, so we do not think it is likely the 50Hz upswept calls were produced by southern right whales. Edds (1988) reported upsweeps from fin whales in the St. Lawrence estuary and Thompson *et al.* (1992) reported that 17% of calls heard from fin whales in the Gulf of California were upsweeps. Much shorter duration of these calls than blue whale calls reported in Rankin *et al.* (2005), short intercall interval and their location in the areas where mostly fin whales occurred during this survey make it possible these calls were produced by fin whales. A more focused study, with dedicated ship time for visual observations and acoustic work with DIFAR sonobuoys, would be required to determine whether both the pulsing and 50Hz upswept calls are made by a species of baleen whale.

Whale distributions and environmental parameters

Locations of baleen whale calls and sightings provided a comparison of differences in spatial distribution among species. Comparison of these locations with major environmental parameters, such as the oceanographic fronts, the location of the ice edge and bathymetry, can offer insight into habitat use differences between the species. There was a difference in the distribution of fin whales in comparison to all other species of baleen whales. Fin whales were prevalent in the central part of the Scotia Sea, in deeper waters along the southern Antarctic Circumpolar Current front (sACCf). This is in contrast to Tynan's (1998) observations from the whaling data indicating that blue, fin and humpback whales are associated with the southern boundary of the ACC. All other species were found south of the southern boundary, around the South Orkneys and in areas of the Scotia Sea close to the ice edge. Humpback and southern right whales were found also in shallow areas around South Georgia, between the polar front and the sACCf, consistent with previous findings (Kellogg, 1929; Kasamatsu *et al.*, 1996).

During this survey no fin whales were detected near the ice edge, where all other baleen whale species were commonly located. This is consistent with the knowledge that fin whales are more pelagic in comparison to other baleen whales and generally are not associated with the sea ice (Kellogg, 1929; Mackintosh, 1965). The association of fin whales with sACCf average location in this survey is not surprising, but it is worthy of further investigation. The marginal ice zone along the retreating ice edge is known to be a biologically productive zone, and this area is further enriched by the shallow upwelling of the Upper Circumpolar Deep Water (UCDW) associated with the southern boundary (Laws, 1985; Smith and Nelson, 1985; Tynan, 1998). Such a rich area has the potential to sustain a large animal biomass and diversity. The sACCf, on the other hand, is characterized by a deeper UCDW upwelling. Before reaching the central Scotia Sea this front passes along the continental shelf of the Antarctic Peninsula, where it is enriched with iron and other limiting micronutrients (Holm-Hansen *et al.*, 2004b). While the productivity in the central Scotia Sea may be less than the marginal ice zone, the combination of deep UCDW upwelling and micronutrient enrichment gives this deep water region a potential for sustaining baleen whales. Fin whales, with their ability to make relatively deep dives (Panigada *et al.*, 1999), could potentially exploit the productivity brought on by the deep upwelling and in turn avoid competition with other species that prefer the area near the southern boundary (Laws, 1977; Costa and Crocker, 1996).

Acoustic methods for population estimation are still under development, since parameters such as the whale calling rates and daily and seasonal calling patterns are not well understood (Barlow and Taylor, 2005). Direct comparison of acoustic and visual surveys is further complicated by a difference in range over which the two operate. While visual surveys cover a range of several km, a more typical range for acoustic survey of baleen whales with sonobuoys is several tens of km (McDonald, 2004). There are also differences in the availability of animals for either type of survey due to their diving preferences and differences in the frequency of calling. However, we can do a simple comparison of the numbers of groups detected by each method if we assume a detection of a species on one sonobuoy is one acoustic group. (This introduces a low bias to the acoustic survey, but this bias could be reduced using only DIFAR sonobuoys.) Blue whales, for example, appear to be a better subject for acoustic surveys as eight groups were detected acoustically and none visually. Minke and southern right whales, with zero and four acoustic, and 43 and 20 visual groups, respectively, seem to be better suited for visual surveys. Humpback and fin whales fall in the middle, with 15 and 10 acoustic, and

12 and 15 visual groups, respectively. There was a bias in this acoustic survey, however, since it was not independent of the visual survey and sonobuoys often were deployed deliberately after a visual sighting.

The efficiency of acoustic and visual surveys varies between species, as exemplified by blue and minke whales. While blue whales were heard on a number of occasions during the cruise, they were never seen. Due to the sound speed profile characteristics in polar regions, making the area an upward refracting environment (Richardson *et al.*, 1995), the area that was monitored acoustically was likely 1-2 orders of magnitude larger than the area surveyed visually. This could explain why blue whales were heard acoustically but were never seen by the visual observers as their low frequency calls propagate better than calls from other species. Also, a low density of blue whales in the Antarctic (Branch and Butterworth, 2001a) would give a low likelihood of a visual encounter with this species. Antarctic minke whales, on the other hand, were seen commonly during the survey but were not heard. While they are the most abundant of the baleen whales in the Antarctic (Branch and Butterworth, 2001b), their known Antarctic calls are short, occur irregularly (Schevill and Watkins, 1972) and therefore can be difficult to detect with sonobuoys.

Acoustic surveys from underway ships complement visual surveys for cetaceans, since they provide larger scale coverage and can be conducted when the conditions are not appropriate for visual survey (e.g. darkness, rough seas, poor visibility). Sonobuoys are better suited for surveys of baleen whales than towed arrays, since ship noise interferes with the low frequency whale calls and this noise diminishes as ship steams away from the sonobuoy. Concurrent visual and acoustic efforts are necessary, however, to investigate the sources of different call types, as well as to devise methods for population estimation using acoustics. Even though there are currently no means to estimate population sizes from a sonobuoy survey, it is possible to determine areas where certain call types are heard commonly and to estimate the spatial distribution of various baleen whale species if a consistent acoustic sampling program is used.

F. Acknowledgements

This work was funded by the National Science Foundation Office of Polar Programs grant OPP 99-10007 with program guidance by Polly Panhale as part of the SO GLOBEC program, and logistic support for the cruise was provided by Raytheon Polar Services. We thank the officers and crew aboard the RRS *James Clark Ross* for assistance, the British Antarctic Survey, the International Whaling Commission Southern Ocean Collaboration Program (IWC SOC), and chief scientist Angus Atkinson for providing space aboard the vessel, as well as scientific support. Deborah Salmon was part of the acoustic team while Koen Van Waerebeek and Russell Leaper conducted the visual survey for the IWC SOC. We thank Captain William Gaines for help with sonobuoy procurement and the IWC for providing the visual sightings and historic catch data. Sue E. Moore (NOAA / NMFS and University of Washington), Jay Barlow (NOAA / NMFS / SWFSC) and two anonymous reviewers provided helpful comments on the manuscript. A.Š. thanks Koen Van Waerebeek for inspiration to publish these results.

The text of Chapter V, in full, has been accepted for publication in the Journal of Cetacean Research and Management (Širović, A., J.A. Hildebrand, and D. Thiele. 2006. Baleen whales in the Scotia Sea in January and February 2003. Journal of Cetacean Research and Management, in press). The dissertation author was the primary researcher and author and the co-authors listed in this publication supervised the research which forms the basis for this chapter.

VI. Conclusions

A. Dissertation synthesis

During the 30 years since the cessation of whaling on blue and fin whales in the Southern Ocean, only occasional visual surveys have been conducted in the area, and small numbers of animals have been sighted (Branch and Butterworth, 2001a). Passive acoustics, however, provide a cost-efficient way to monitor blue and fin whale populations in this remote region. Chapters II and III, provided the first extensive descriptions of the Southern Ocean blue and fin whale temporal and frequency call characteristics, as well as measurements of call source levels. Blue and fin whale calls in the Southern Ocean have high intensities (189dB re: 1μPa at 1m over the 25–29Hz and 15–28Hz bands, respectively) and potentially can propagate over long distances (up to 1300km; chapter III). Using these calls, I investigated the presence and distribution of calling blue and fin whales around the Antarctic Peninsula between March 2001 and February 2003. Blue whales were present year-round, with highest calling during the austral spring and fall, while fin whale calls occurred during the late summer and fall (chapter II). The long annual presence (177 days/year) of blue whales in the Southern Ocean should be taken into account in future estimates of the effects these predators have on krill populations. The results of chapter II also offered a baseline estimate of relative population densities and can serve for future comparisons and investigations into population recovery or decline.

I investigated various parameters that could affect the distribution of baleen whales in the Antarctic in chapters II, IV, and V. Both blue and fin whale calls were negatively correlated with sea ice concentrations, they generally occurred in regions that are free of sea ice, but there were more calls during the year with more extensive sea ice cover (chapters II and IV). Also, both species were generally detected in deeper waters (chapters II and IV). There was also an apparent large-scale separation between blue and fin whale populations, with fin whales generally occurring further north (chapters II and V). This north-south separation is consistent with previous findings (Mackintosh and Wheeler, 1929; Beklemishev, 1960; Mackintosh, 1965; 1966; Laws, 1977; Kasamatsu *et al.*, 1988). The distribution of calling blue and fin whales was related to prey distribution, but the direction of the correlation was opposite from that expected. Blue whale calls detected on sonobuoys during the austral falls of 2001 and 2002 were negatively correlated with krill biomass and the distribution of other zooplankton (chapter IV). Previous studies of baleen whale habitat were based on visual surveys and usually found positive correlations between the whales and their prey (Woodley and Gaskin, 1996; Croll *et al.*, 1998; Fiedler *et al.*, 1998; Friedlaender *et al.*, 2006). This discrepancy could be the result of the behavioral states that correspond to calling in whales (e.g. the whales that are calling, are not feeding). More data are needed on calling ecology, however, for better understanding of this relationship.

The spatial sampling bias in the long-term recordings (chapter III), made it difficult to determine the extent to which current blue and fin whale distributions are determined by the past exploitation history. Most whaling in this area occurred at the northern extent of the monitored region and on the shelf, where the Acoustic Recording Package (ARP) coverage was sparse. The ARP deployment locations enabled more extensive recording of whale calls off the shelf, in the areas with lower past exploitation history, but some blue and fin whale calls were also detected on the shelf (chapters II and IV). Deployment of recording instruments on the northern shelf would have enabled estimation of the differences in blue and fin whale distributions between different areas of the Western Antarctic Peninsula (WAP) shelf region.

B. Observation and analyses needs

Deployment of scientific instruments in a new region has a potential for new discoveries, but it can also offer design challenges. It is easier to develop a satisfactory sampling strategy with prior knowledge of the range of conditions that will be encountered during the study. This dissertation was based largely on observations made using a novel technology, deployed in a new area. Even though the initial design turned out not to be ideal, a large amount of new information was collected.

A large part of my dissertation was based on the passive acoustic data collected using the ARPs. The ARP deployment locations were decided with no a priori knowledge of blue and fin whale calling patterns in the region, because the species were never previously recorded in the WAP. As the number of visual sightings from multiple survey cruises that occurred in the area before the beginning of the US SO GLOBEC program was very small, the ARPs were deployed with an intention to cover as wide an area as possible. They were also positioned in the areas that were known to be preferred oceanographic domains of baleen whales, blue whales in particular (Tynan, 1998). Even with a wide coverage area, it was assumed that the number of recorded calls would be relatively small (total <1000 calls/year). Neither the large number of calls (chapter II), nor the very long propagation ranges (chapter III) were anticipated when designing the study.

The deployed array was not intended initially for localization of calling animals. Better tracking and localization would have been possible if the instruments were spaced in a square array, rather than a line (chapter III). The spacing of the instruments and timing errors made it impossible to localize the animals on a fine-scale. The errors in clock timing could have been improved with better instrument clocks, but the accuracy of the arrival time determination was limited by multipathing propagation. Therefore the array spacing and detection ranges would have to remain relatively large (approximately

100km). The best positioning of such and a large aperture array would have been in an area with intermediate calling densities (e.g. near site S4). Also, it would have been interesting to have a four-instrument array on the shelf (e.g. near site S7), to localize the whales calling on the shelf, and to investigate propagation and calling density differences between the shelf and deep waters. A broader spacing of ARPs across different ecological domains (e.g. shelf break, Marguerite Trough, shelf, inland passages) would have allowed a sampling of different habitats and could have provided and opportunity to investigate whale habitat preference over long time scales.

Sonobuoy deployment protocols (chapters IV and V) were not fully developed during the first survey cruise, so the effort in the area was not even. Biases in the number of sonobuoy deployments in certain parts of the survey area during the 2001 cruise occurred because of high humpback whale calling in those areas. Better contemporaneous coverage with sonobuoys and BIOMAPER-II also would have provided a larger sample size for the logistic regression modeling (chapter IV). Multidisciplinary cruises provide a valuable way of obtaining simultaneous information on multiple environmental parameters that affect all components of an ecosystem, and are good venues for the pursuit of data collection for habitat modeling purposes. Data collection on the scales relevant for all the ecosystem components, however, remains an important challenge (Redfern *et al.*, 2006a).

Habitat modeling described in chapter IV was limited in time by the absence of calling blue and fin whales during the winter cruises in both 2001 and 2002, and the absence of survey cruises in the spring and the summer. Comparisons across seasons, however, could test the hypothesis that calling animals are not associated with their prey. In spring, the whales may be more likely to feed, but we know that that blue whales call during the spring as well (chapter II). It would be interesting to see if the calling animals are negatively correlated with their prey in the spring. Also, larger sample sizes of different call types are needed to determine if there are differences in the associations of those different calls types with the environmental parameters.

Passive acoustic data have a tremendous potential to provide long-term information on baleen whale ecology. On top of the simple species presence results, they also could offer information on relative population sizes, behavioral states, and seasonal changes in whale behavior. To make these data more useful for population estimation, however, information on calling rates is required. Ecologically meaningful interpretation of these data currently is constrained by the lack of knowledge on the behavioral context of calling. More information on gender specificity of calls, as well as contemporaneous acoustic recordings and visual observations of behavior are needed.

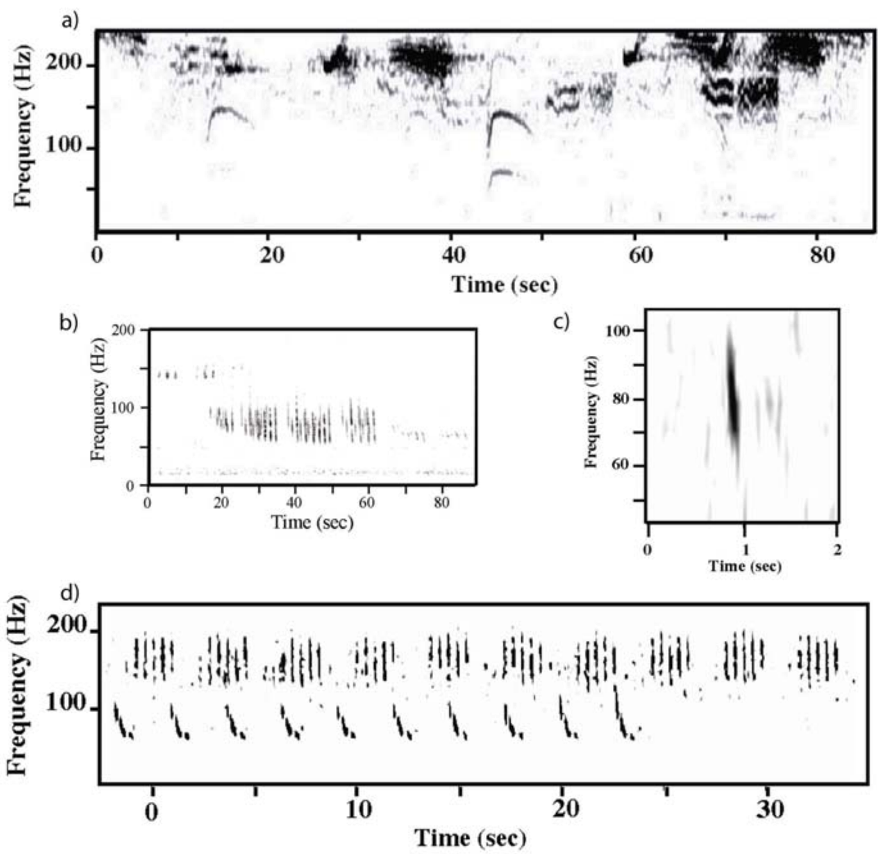

Figure 6.1. Spectrograms of calls of other marine mammals recorded on the ARPs deployed off the Western Antarctic Peninsula: a) crabeater seal; b) humpback whale; c) minke whale; and d) unknown calls.

Finally, while my work focused mainly on blue and fin whales, the ARP data also contained low frequency calls of other marine mammals, such as crabeater seals (*Lobodon carcinophaga*), humpback whales (*Megaptera novaeangliae*), and minke whales (*B. bonaerensis*) (Figure 6.1a through c). Also, a number of calls from unknown sources were recorded on the ARPs (Figure 6.1d) and on sonobuoys (chapter V). Analyses of the seasonal presence and spatial distribution of these calls could offer new insights into the migratory and behavioral patterns of various species and further investigations focused on determining the sources of unknown calls could yield new information on some well-known species.

References

Ackley, S. F., J. L. Bengtson, P. Boveng, M. Castellini, K. L. Daly, S. S. Jacobs, G. L. Kooyman, J. Laake, L. B. Quentin, R. M. Ross, D. B. Siniff, B. S. Stewart, I. Stirling, J. J. Torres, P. K. Yochem, 2003. A top-down, multidisciplinary study of the structure and function of the pack-ice ecosystem in the eastern Ross Sea, Antarctica. Polar Record 39, 219-230.

Ainley, D. G., D. P. DeMaster, 1999. The upper trophic levels in polar marine ecosystems. In: Smith Jr., W. O. (Ed.) Polar Oceanography Part B, Chemistry, Biology and Geology. Academic Press, San Diego, CA, pp. 599-630.

Akaike, H., 1973. Information theory and an extension of the maximum likelihood principle. In: Csaaki, F. (Ed.) Second International Symposium on Information Theory. Akadeemiai Kiadi, Budapest, Hungary, pp. 267-281.

Alling, A., E. M. Dorsey, J. C. D. Gordon, 1991. Blue whales (*Balaenoptera musculus*) off the northeast coast of Sri Lanka: Distribution, feeding and individual identification. UNEP Marine Mammal Technical Report 3, 247-258.

Anonymous, 2003. Large scale distribution in the Scotia Sea; JR82 scientific cruise report. British Antarctic Survey, Cambridge, UK, p. 166. [Available from: basarchives@bas.ac.uk].

Ashjian, C. J., G. A. Rosenwaks, P. H. Wiebe, C. S. Davis, S. M. Gallager, N. J. Copley, G. L. Lawson, P. Alatalo, 2004. Distribution of zooplankton on the continental shelf off Marguerite Bay, Antarctic Peninsula, during austral fall and winter 2001. Deep-Sea Research II 51, 2073-2089.

Atkinson, A., V. Siegel, E. Pakhomov, P. Rothery, 2004. Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature 432, 100-103.

Barlow, J., B. L. Taylor, 2005. Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey. Marine Mammal Science 21, 429-445.

Baumgartner, M. F., T. V. N. Cole, P. J. Clapham, B. R. Mate, 2003. North Atlantic right whales habitat in the lower Bay of Fundy and on the SW Scotia Shelf during 1999-2001. Marine Ecology Progress Series 264, 137-154.

Beardsley, R. C., R. Limeburner, W. B. Owens, 2004. Drifter measurements of surface currents near Marguerite Bay on the western Antarctic Peninsula shelf during austral summer and fall, 2001 and 2002. Deep-Sea Research II 51, 1947-1964.

Beklemishev, C. W., 1960. Southern atmospheric cyclones and the whale feeding grounds of the Antarctic. Nature 187, 530-531.

Best, P. B., 1993. Increase rates in severely depleted stocks of baleen whales. ICES Journal of Marine Science 50, 169-186.

Bolmer, S. T., R. C. Beardsley, C. Pudsey, P. Mooris, P. H. Wiebe, E. E. Hofmann, J. Anderson, A. Maldonado, 2004. High-resolution bathymetry map for the Marguerite Bay and adjacent west Antarctic Peninsula shelf for the Southern Ocean GLOBEC program. Woods Hole Oceanographic Institution, Woods Hole, MA, p. 76.

Bowen, W. D., D. B. Siniff, 1999. Distribution, population biology and feeding ecology of marine mammals. In: Reynolds III, J. E. and Rommel, S. A. (Eds.), Biology of Marine Mammals. Smithsonian Institution Press, pp. 423-484.

Branch, T. A., D. S. Butterworth, 2001a. Estimates of abundance south of 60ºS for cetacean species sighted frequently on the 1978/79 to 1997/98 IWC/IDCR-SOWER sighting surveys. Journal of Cetacean Research and Management 3, 251-270.

Branch, T. A., D. S. Butterworth, 2001b. Southern hemisphere minke whales: standardised abundance estimates from the 1978/79 to 1997/98 IDCR-SOWER surveys. Journal of Cetacean Research and Management 3, 143-174.

Branch, T. A., K. Matsuoka, T. Miyashita, 2004. Evidence for increases in Antarctic blue whales based on Bayesian modeling. Marine Mammal Science 20, 726-754.

Brierley, A. S., P. G. Fernandes, M. A. Brandon, F. Armstrong, N. W. Millard, S. D. McPhail, P. Stevenson, M. Pebody, J. Perrett, M. Squires, D. G. Bone, G. Griffiths, 2002. Antarctic krill under sea ice: elevated abundance in a narrow band just south of ice edge. Science 295, 1890-1892.

Brown, S. G., 1954. Dispersal in blue and fin whales. Discovery Reports 26, 355-384.

Brown, S. G., 1962a. A note on migration of fin whales. Norsk Hvalfangst-Tidende 51, 13-16.

Brown, S. G., 1962b. The movements of blue and fin whales within the Antarctic zone. Discovery Reports 33, 1-54.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers, L. Thomas, 2001. Introduction to distance sampling: Estimating abundance of biological populations. Oxford University Press, Oxford, UK, p. 432.

Burtenshaw, J. C., E. M. Oleson, J. A. Hildebrand, M. A. McDonald, R. K. Andrew, B. M. Howe, J. A. Mercer, 2004. Acoustic and satellite remote sensing of blue whale seasonality and habitat in the Northeast Pacific. Deep-Sea Research II, 967-986.

Bushuev, S. G., 1990. Distribution and feeding of minke whales on the feeding grounds in Antarctic Area I. Paper SC/42/SHMi4 presented to the IWC Scientific Committee, p. 44. [Available from: secretariat@iwcoffice.org].

Carpenter, S. R., J. F. Kitchell, J. R. Hodgson, 1985. Cascading trophic interactions and lake productivity. BioScience 35, 634-639.

Cato, D. H., 1998. Simple methods of estimating source levels and location of marine animal sounds. Journal of the Acoustical Society of America 104, 1667-1678.

Cato, D. H., R. Paterson, P. Paterson, 2001. Vocalisation rates of migrating humpback whales over 14 years. Memoirs of the Queensland Museum 47, 481-489.

Cerchio, S., J. K. Jacobsen, T. F. Norris, 2001. Temporal and geographical variation in songs of humpback whales, *Megaptera novaeangliae*: synchronous change in Hawaiian and Mexican breeding assemblages. Animal Behaviour 62, 313-329.

Chapman, E. W., C. A. Ribic, W. R. Fraser, 2004. The distribution of seabirds and pinnipeds in Marguerite Bay and their relationship to physical features during austral winter 2001. Deep-Sea Research II 51, 2261-2278.

Charif, R. A., D. K. Mellinger, K. J. Dunsmore, K. M. Fristrup, C. W. Clark, 2002. Estimated source levels of fin whale (*Balaenoptera physalus*) vocalizations: adjustments for surface interference. Marine Mammal Science 18, 81-98.

Clapham, P. J., D. K. Mattila, 1990. Humpback whale songs as indicators of migration routes. Marine Mammal Science 6, 155-160.

Clapham, P. J., C. S. Baker, 2001. How many whales were killed in the Southern Hemisphere in the 20th century? Paper SC/53/O14 presented to IWC Scientific Committee, p. 3. [Available from: secretariat@iwcoffice.org].

Clark, C. W., 1982. The acoustic repertoire of the southern right whale, a quantitative analysis. Animal Behaviour 30, 1060-1071.

Clark, C. W., 1983. Acoustic communication and behavior of the southern right whale (*Eubalaena glacialis*). In: Payne, R. (Ed.) Communication and behavior of whales. Westview press, Boulder, CO, pp. 163-198.

Clark, C. W., W. T. Ellison, 1988. Number and distributions of bowhead whales, *Balaena mysticetus*, based on the 1985 acoustic study off Pt. Barrow, Alaska. Report of the International Whaling Commission 38, 365-370.

Clark, C. W., W. T. Ellison, 1989. Numbers and distribution of bowhead whales, *Balaena mysticetus*, based on the 1986 acoustic study off Pt. Barrow, Alaska. Report of the International Whaling Commission 39, 297-303.

Clark, C. W., 1990. Acoustic behavior of mysticete whales. In: Thomas, J. and Kastelein, R. (Eds.), Sensory abilities of cetaceans. Plenum Press, New York, pp. 571-583.

Clark, C. W., 1995. Matters arising out of the discussion of blue whales. Report of the International Whaling Commission 45, 210-212.

Clark, C. W., K. M. Fristrup, 1997. Whales '95: A combined visual and acoustic survey of blue and fin whales off Southern California. Report of the International Whaling Commission 47, 583-600.

Clark, C. W., R. A. Charif, 1998. Acoustic monitoring of large whales to the west of Britain and Ireland using bottom-mounted hydrophone arrays, October 1996 - September 1997. JNCC Report No. 281, p. 23.

Clark, C. W., W. T. Ellison, 2000. Calibration and comparison of the acoustic location methods used during the spring migration of the bowhead whale, *Balaena mysticetus*, off

Pt. Barrow, Alaska, 1984-1993. Journal of the Acoustical Society of America 107, 3509-3517.

Clark, C. W., M. Fowler, 2001. Status of archival and analysis effort of acoustic recordings during SOWER and IWC cruises 1996-2000. Paper SC/53/IA28 presented to IWC Scientific Committee. p. 9. [Available from: secretariat@iwcoffce.org].

Clark, C. W., P. J. Clapham, 2004. Acoustic monitoring on a humpback whale (*Megaptera novaeangliae*) feeding ground shows continual singing into late spring. Proceedings of the Royal Society, London, Series B Biological Sciences 271, 1051-1057.

Comiso, J., 1991, updated 2002. DMSP SSM/I daily polar gridded sea ice concentrations. J. Maslanik and J. Stroeve (Eds.), Boulder, CO: National Snow and Ice Data Center. Digital Media.

Comiso, J. C., N. G. Maynard, W. O. Smith Jr., C. W. Sullivan, 1990. Satellite ocean color studies of Antarctic ice edges in summer and autumn. Journal of Geophysical Research 95, 9481-9496.

Constable, A. J., S. Nicol, P. G. Strutton, 2003. Southern Ocean productivity in relation to spatial and temporal variation in the physical environment. Journal of Geophysical Research 108 (C4), 8079-8100.

Costa, D. P., D. E. Crocker, 1996. Marine mammals of the Southern Ocean. In: Ross, R. M., Hofmann, E. E. and Quentin, L. B. (Eds.), Foundations for Ecological Research West of the Antarctic Peninsula, vol 70. American Geophysical Union, Washington, DC, pp. 287-301.

Croll, D. A., B. R. Tershy, R. P. Hewitt, D. A. Demer, P. C. Fiedler, S. E. Smith, W. Armstrong, J. M. Popp, T. Kiekhefer, V. R. Lopez, J. Urban, D. Gendron, 1998. An integrated approach to the foraging ecology of marine birds and mammals. Deep-Sea Research II 45, 1353-1371.

Croll, D. A., C. W. Clark, A. Acevedo, B. R. Tershy, S. Flores, J. Gedamke, J. Urban, 2002. Only male fin whales sing loud songs. Nature 417, 809.

Croxall, J. P., P. N. Trathan, E. J. Murphy, 2002. Environmental change and Antarctic seabird populations. Science 297, 1510-1514.

Cummings, W. C., J. F. Fish, P. O. Thompson, 1971. Bio-acoustics of marine mammals of Argentina: R/V Hero cruise 71-3. Antarctic Journal 6, 266-268.

Cummings, W. C., P. O. Thompson, 1971. Underwater sounds from the blue whale, *Balaenoptera musculus*. Journal of the Acoustical Society of America 50, 1193-1198.

Cummings, W. C., J. F. Fish, P. O. Thompson, 1972. Sound production and other behavior of southern right whale *Eubalena glacialis*. San Diego Society of Natural History Transactions 17, 1-14.

Curtis, K. R., B. M. Howe, J. A. Mercer, 1999. Low-frequency ambient sound in the North Pacific: long time series observation. Journal of the Acoustical Society of America 106, 3189-3200.

Daly, K. L., M. C. Macaulay, 1991. Influence of physical and biological mesoscale dynamics on the seasonal distribution and behavior of *Euphausia superba* in the antarctic marginal ice zone. Marine Ecology Progress Series 79, 37-66.

Darling, J. D., R. S. Sousa-Lima, 2005. Songs indicate interaction between humpback whale (*Megaptera novaeangliae*) populations in the western and eastern South Atlantic Ocean. Marine Mammal Science 21, 557-566.

Dawbin, W. H., 1966. The seasonal migratory cycle of humpback whales. In: Norris, K. S. (Ed.) Whales, Dolphins, and Porpoises. University of California Press, Berkeley, pp. 145-170.

de la Mare, W. K., 1997. Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from whaling records. Nature 389, 57-60.

Dickey, T. D., 1990. Physical-optical-biological scales relevant to recruitment in large marine ecosystems. In: Gold, B. D. (Ed.) Large marine ecosystems; patterns, processes and yields. American Association for the Advancement of Science, Washington, DC., pp. 82-98.

Edds, P. L., 1982. Vocalizations of the blue whale, *Balaenoptera musculus*, in the St. Lawrence River. Journal of Mammalogy 63, 345-347.

Edds, P. L., 1988. Characteristics of finback *Balaenoptera physalus* vocalizations in the St. Lawrence estuary. Bioacoustics 1, 131-149.

Edds-Walton, P. L., 2000. Vocalization of minke whales *Balaenoptera acutorostrata* in the St. Lawrence estuary. Bioacoustics 11, 31-50.

El-Sayed, S. Z., L. H. Weber, 1982. Spatial and temporal variations in phytoplankton biomass and primary productivity in the southwest Atlantic and the Scotia Sea. Polar Biology 1, 83-90.

ESRI, 2005. ArcView GIS, (9.1 edn). Environmental Systems Research Institute, Inc., Redlands, CA.

Estes, J. A., M. T. Tinker, T. M. Williams, D. F. Doak, 1998. Killer whale predation on sea otters linking oceanic and nearshore ecosystems. Science 282, 473-476.

Ferguson, M. C., J. Barlow, P. C. Fiedler, S. B. Reilly, T. Gerrodette, 2006. Spatial models of delphinid (family Delphinidae) encounter rate and group size in the eastern tropical Pacific Ocean. Ecological Modelling 193, 645-662.

Fiedler, P. C., S. B. Reilly, R. P. Hewitt, D. Demer, V. A. Philbrick, S. Smith, W. Armstrong, D. A. Croll, B. R. Tershy, B. R. Mate, 1998. Blue whale habitat and prey in the California Channel Islands. Deep-Sea Research II 45, 1781-1801.

Folkow, L. P., S. A. Blix, 1991. Norwegian whale sighting and acoustic surveys in the Atlantic Ocean during the winter of 1989/90. Report of the International Whaling Commission 41, 531-538.

Forney, K. A., 2000. Environmental models of cetacean abundance: reducing uncertainty in population trends. Conservation Biology 14, 1271-1286.

Fox, C. G., H. Matsumoto, T.-K. A. Lau, 2001. Monitoring Pacific Ocean seismicity from an autonomous hydrophone array. Journal of Geophysical Research (Solid Earth) 106 (B3), 4183-4206.

Fraser, W. R., W. Z. Trivelpiece, D. G. Ainley, S. G. Trivelpiece, 1992. Increases in Antarctic penguin populations: reduced competition with whales or a loss of sea ice due to environmental warming? Polar Biology 11, 525-531.

Frazer, L. N., P. I. Pecholcs, 1990. Single-hydrophone localization. Journal of the Acoustical Society of America 88, 995-1002.

Friedlaender, A. S., P. N. Halpin, S. Qian, G. L. Lawson, P. H. Wiebe, D. Thiele, A. J. Read, 2006. Whale distribution in relation to prey and oceanographic processes in the Western Antarctic Peninsula shelf waters. Marine Ecology Progress Series, in press.

Gaskin, D. E., 1982. The ecology of whales and dolphins. Heinemann Educational Books Ltd., London, p. 459.

Gedamke, J., D. P. Costa, A. Dunstan, 2001. Localization and visual verification of a complex minke whale vocalization. The Journal of the Acoustical Society of America 109, 3038-3047.

Godlewska, M., 1996. Vertical migrations of krill (*Euphausia superba* Dana). Polish Archives of Hydrobiology 43, 9-63.

Gordon, A. L., M. Visbeck, B. Huber, 1997. Export of Weddell Sea water along and over the South Scotia Ridge. Antarctic Journal of the United States review, 72-74.

Gregr, E. J., A. W. Trites, 2001. Predictions of critical habitat for five whale species in the waters of coastal British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 58, 1265-1285.

Hamazaki, T., 2002. Spatiotemporal prediction models of cetacean habitats in the mid-western North Atlantic Ocean (from Cape Hatteras, North Carolina, USA to Nova Scotia, Canada). Marine Mammal Science 18, 920-939.

Hardy, A. C., E. R. Gunther, 1935. The plankton of the South Georgia whaling grounds and adjacent waters, 1926-1927. Discovery Reports 11, 1-456.

Hart, T. J., 1934. On the phytoplankton of the south-west Atlantic and the Bellingshausen Sea. Discovery Reports 8, 1-208.

Hart, T. J., 1935. On the diatoms of the skin film of whales, and their possible bearing on problems of whale movements. Discovery Reports 10, 247-282.

Haury, L. R., J. A. McGowan, P. H. Wiebe, 1978. Patterns and processes in the time-space scales of plankton distributions. In: Steele, J. H. (Ed.) Spatial patterns in plankton communities. Plenum Press, New York, NY, pp. 277-327.

Helweg, D. A., D. H. Cato, P. F. Jenkins, C. Garrigue, R. D. McCauley, 1998. Geographic variation in South Pacific humpback whale song. Behaviour 137, 1-27.

Hewitt, R. P., J. Watkins, M. Naganobu, V. Sushin, A. S. Brierley, D. Demer, S. Kasatkina, Y. Takao, C. Goss, A. Malyshko, M. Brandon, S. Kawaguchi, V. Siegel, P. Trathan, J. Emery, I. Everson, D. Miller, 2004. Biomass of Antarctic krill in the Scotia Sea in January/February 2000 and its use in revising an estimate of precautionary yield. Deep-Sea Research II 51, 1215-1235.

Hofmann, E. E., C. M. Lascara, J. M. Klinck, 1992. Palmer LTER: Upper-ocean circulation in the LTER region from historical sources. Antarctic Journal of the United States, 239-241.

Hofmann, E. E., J. M. Klinck, C. M. Lascara, D. A. Smith, 1996. Water mass distribution and circulation west of the Antarctic Peninsula and including Bransfield Strait. In: Quentin, L. B. (Ed.) Foundations for Ecological Research West of the Antarctic Peninsula, vol 70. American Geophysical Union, Washington, DC, pp. 61-80.

Hofmann, E. E., J. M. Klinck, 1998a. Thermohaline Variability of the Waters Overlying the West Antarctic Peninsula Continental Shelf. In:Ocean, Ice, and Atmosphere: interactions at the antarctic continental margin, vol 75. American Geophysical Union, Washington, DC, pp. 67-81.

Hofmann, E. E., J. M. Klinck, 1998b. Hydrography and circulation of the Antarctic continental shelf: 150E to the Greenwich meridian. In: Robinson, A. R., and Kenneth H. Brink (Ed.) The Sea, vol 11. John Wiley & Sons, Inc., pp. 997-1042.

Hofmann, E. E., J. M. Klinck, D. P. Costa, K. L. Daly, J. J. Torres, W. R. Fraser, 2002. U.S. Southern Ocean Global Ocean Ecosystem Dynamics program. Oceanography 15 (2), 64-74.

Hofmann, E. E., E. J. Murphy, 2004. Advection, krill, and Antarctic marine ecosystems. Antarctic Science 16, 487-499.

Holm-Hansen, O., B. G. Mitchell, C. D. Hewes, D. M. Karl, 1989. Phytoplankton blooms in the vicinity of Palmer Station, Antarctica. Polar Biology 10, 49-57.

Holm-Hansen, O., B. G. Mitchell, 1991. Spatial and temporal distribution of phytoplankton and primary production in the western Bransfield Strait region. Deep-Sea Research 38, 961-980.

Holm-Hansen, O., C. D. Hewes, V. E. Villafane, E. W. Helbling, N. Silva, T. Amos, 1997. Distribution of phytoplankton and nutrients in relation to different water masses in the area around Elephant Island, Antarctica. Polar Biology 18, 145-153.

Holm-Hansen, O., M. Kahru, C. D. Hewes, S. Kawaguchi, T. Kameda, V. A. Sushin, I. Krasovski, J. Priddle, R. Korb, R. P. Hewitt, B. G. Mitchell, 2004a. Temporal and spatial distribution of chlorophyll-*a* in surface waters of Scotia Sea as determined by both shipboard measurement and satellite data. Deep-Sea Research II 51, 1323-1331.

Holm-Hansen, O., M. Naganobu, S. Kawaguchi, T. Kameda, I. Krasovski, P. Tchernyshkov, J. Priddle, R. Korb, M. Brandon, D. Demer, R. P. Hewitt, M. Kahru, C. D. Hewes, 2004b. Factors influencing the distribution, biomass, and productivity of phytoplankton in the Scotia Sea and adjoining waters. Deep-Sea Research II 51, 1333-1350.

Horwood, J. S., 1986. The distribution of the southern blue whale in relation to recent estimates of abundance. Scientific reports of the Whales Research Institute 37, 155-165.

Ichii, T., K. Katayama, N. Obitsu, H. Ishii, M. Naganobu, 1998. Occurrence of Antarctic krill (*Euphausia superba*) concentration in the vicinity of the South Shetland Islands: relationship to environmental parameters. Deep-Sea Research I 45, 1235-1262.

Insightful Corporation, 2001. S-PLUS 6 for Windows Guide to Statistics, vol. 1. Insightful Corporation, Seattle, WA.

IWC, 2001. Report of the sub-committee on the comprehensive assessment of whale stocks - other stocks. Journal of Cetacean Research and Management 3 (suppl), 209-228.

Jensen, F. B., W. A. Kuperman, M. B. Porter, H. Schmidt, 2000. Computational ocean acoustics Modern Acoustics and Signal Processing. Springer-Verlag, New York, p. 578.

Kahru, M., 2000. Windows Image Manager - Image display and analysis program for Microsoft Windows with special features for satellite images. WWW page, http://wimsoft.com.

Kasamatsu, F., D. Hembree, G. Joyce, L. Tsunoda, R. Rowlett, T. Nakano, 1988. Distribution of cetacean sightings in the Antarctic: results obtained from the IWC/IDCR minke whale assessment cruises, 1978/79 to 1983/84. Report of the International Whaling Commission 39, 449-473.

Kasamatsu, F., G. G. Joyce, P. Ensor, J. Mermoz, 1996. Current occurrence of baleen whales in Antarctic waters. Report of the International Whaling Commission 47, 293-304.

Katona, S. K., J. A. Beard, 1990. Population size, migrations and feeding aggregations of the humpback whale (*Megaptera novaeangliae*) in the western North Atlantic Ocean. Report of the International Whaling Commission 12 (special issue), 295-305.

Kawamura, A., 1980. A review of food of Balaenopterid whales. Scientific reports of the Whales Research Institute 32, 155-197.

Kawamura, A., 1994. A review of baleen whale feeding in the Southern Ocean. Report of the International Whaling Commission 44, 261-271.

Kellogg, R., 1929. What is known of the migrations of some of the whalebone whales. Smithsonian Institution Annual Report 1928, 467-496.

Kemp, S., A. C. Hardy, N. A. Mackintosh, 1929. Discovery investigations: objects, equipment and methods. Discovery Reports 1, 141-232.

Kibblewhite, A. C., R. N. Denham, D. J. Barnes, 1967. Unusual low-frequency signals observed in New Zealand waters. The Journal of the Acoustical Society of America 41, 644-655.

Klinck, J. M., E. E. Hofmann, R. C. Beardsley, B. Salihoglu, S. Howard, 2004. Water-mass properties and circulation on the west Antarctic Peninsula continental shelf in austral fall and winter 2001. Deep-Sea Research II 51, 1925-1946.

Lascara, C. M., E. E. Hofmann, R. M. Ross, L. B. Quentin, 1999. Seasonal variability in the distribution of Antarctic krill, *Euphausia superba*, west of the Antarctic Peninsula. Deep-Sea Research I 46, 951-984.

Laws, R. M., 1961. Reproduction, growth and age of southern fin whales. Discovery Reports 31, 327-486.

Laws, R. M., 1977. The significance of vertebrates in the Antarctic marine ecosystem. In: Lano, G. A. (Ed.) Adaptations within Antarctic ecosystems. Smithsonian Institution, Washington, DC, pp. 411-438.

Laws, R. M., 1985. The ecology of the Southern Ocean. American Scientist 73, 26-40.

Lawson, G. L., P. H. Wiebe, C. Ashjian, S. M. Gallager, C. S. Davis, J. D. Warren, 2004. Acoustically-inferred zooplankton distribution in relation to hydrography west of the Antarctic Peninsula. Deep-Sea Research II 51, 2041-2072.

Lawson, G. L., 2006. The Gareth Lawson Thesis Project, Dissertation. Woods Hole Oceanographic Institution. Massachusetts Institute of Technology, Boston, MA.

Leaper, R., M. Scheidat, 1998. An acoustic survey for cetaceans in the Southern Ocean Sanctuary conducted from the German government research vessel Polarstern. Report of the International Whaling Commission 49, 431-437.

Leaper, R., D. Gillespie, V. Papastavrou, 2000. Results of passive acoustic surveys for odontocetes in the Southern Ocean. Journal of Cetacean Research and Management 2, 187-196.

Leatherwood, S., J. A. Thomas, F. T. Awbrey, 1981. Minke whales off northwestern Ross Island. Antarctic Journal 16, 154-156.

Ljungblad, D., C. W. Clark, H. Shimada, 1998. A comparison of sounds attributed to pygmy blue whales (*Balaenoptera musculus brevicauda*) recorded south of the Madagascar Plateau and those attributed to 'true' blue whales (*Balaenoptera musculus*) recorded off Antarctica. Report of the International Whaling Commission 49, 439-442.

Loeb, V., V. Siegel, O. Holm-Hansen, R. P. Hewitt, M. Fraser, W. Z. Trivelpiece, S. G. Trivelpiece, 1997. Effects of sea-ice extent and krill or salp dominance on the Antarctic food web. Nature 387, 897-900.

Mackintosh, N. A., J. F. G. Wheeler, 1929. Southern blue and fin whales. Discovery Reports 1, 257-540.

Mackintosh, N. A., 1936. Distribution of macroplankton in the Atlantic sector of the Antarctic. Discovery Reports 9, 65-160.

Mackintosh, N. A., S. G. Brown, 1956. Preliminary estimates of the southern populations of the larger baleen whales. Norsk Hvalfangst-Tidende 45, 469-480.

Mackintosh, N. A., 1965. The stocks of whales. Fishing News (Books) Ltd., London, p. 232.

Mackintosh, N. A., 1966. The distribution of southern blue and fin whales. In: Norris, K. S. (Ed.) Whales, Dolphins, and Porpoises. University of California Press, Berkeley, pp. 125-144.

Marr, J. W. S., 1962. The natural history and geography of Antarctic krill (*Euphausia superba* Dana). Discovery Reports 32, 33-464.

Mate, B. R., B. A. Lagerquist, J. Calambokidis, 1999. Movements of North Pacific blue whales during the feeding season off Southern California and their southern fall migration. Marine Mammal Science 15, 1246-1257.

Matsuoka, K., H. Murase, S. Nishiwaki, T. Fukuchi, H. Shimada, 2000. Development of a retrievable sonobuoy system for whale sounds recording in polar region. Paper SC/52/O7 presented to the IWC Scientific Committee. p. 7. [Available from: secretariat@iwcoffice.org].

Mattila, D. K., L. N. Guinee, C. A. Mayo, 1987. Humpback whale songs on the North Atlantic feeding grounds. Journal of Mammalogy 68, 880-883.

McCullagh, P., J. A. Nelder, 1989. Generalized linear models, (Second edn). Chapman & Hall/CRC Press, Boca Raton, FL, p. 511.

McDonald, M. A., J. A. Hildebrand, S. C. Webb, 1995. Blue and fin whales observed on a seafloor array in the Northeast Pacific. Journal of the Acoustical Society of America 98, 1-10.

McDonald, M. A., C. G. Fox, 1999. Passive acoustic methods applied to fin whale population density estimation. Journal of the Acoustical Society of America 105, 2643-2651.

McDonald, M. A., J. Calambokidis, A. M. Teranishi, J. A. Hildebrand, 2001. The acoustic calls of blue whales off California with gender data. Journal of the Acoustical Society of America 109, 1728-1735.

McDonald, M. A., 2004. DIFAR hydrophone usage in whale research. Canadian Acoustics 32, 155-160.

McDonald, M. A., J. A. Hildebrand, S. M. Wiggins, D. Thiele, D. Glasgow, S. E. Moore, 2005. Sei whale sounds recorded in the Antarctic. Journal of the Acoustical Society of America 118, 3934-3940.

McDonald, M. A., S. L. Mesnick, J. A. Hildebrand, 2006. Biogeographic characterization of blue whale song worldwide: using song to identify populations. Journal of Cetacean Research and Management, in press.

McSweeny, D. J., K. C. Chu, W. F. Dolphin, L. N. Guinee, 1989. North Pacific humpback whale songs: a comparison of southeast Alaskan feeding ground songs with Hawaiian wintering ground songs. Marine Mammal Science 5, 139-148.

Mellinger, D. K., C. W. Clark, 1997. Methods for automatic detection of mysticete sounds. Marine and Freshwater Behaviour and Physiology 29, 163-181.

Mellinger, D. K., C. D. Carson, C. W. Clark, 2000. Characteristics of minke whale (*Balaenoptera acutorostrata*) pulse trains recorded near Puerto Rico. Marine Mammal Science 16, 739-756.

Mellinger, D. K., C. W. Clark, 2000. Recognizing transient low-frequency whale sounds by spectrogram correlation. Journal of the Acoustical Society of America 107, 3518-3529.

Mellinger, D. K., 2001. Ishmael 1.0 User's guide. NOAA Technical Memorandum OAR PMEL-120. [Available from: NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115-6349].

Mellinger, D. K., C. W. Clark, 2003. Blue whale (*Balaenoptera musculus*) sounds from the North Atlantic. Journal of the Acoustical Society of America 114, 1108-1119.

Miller, G. A., G. A. Heise, W. Lichten, 1951. The intelligibility of speech as a function of the context of the test materials. Journal of Experimental Psychology 41, 329-335.

Mizroch, S. A., D. W. Rice, J. M. Breiwick, 1984. The blue whale, *Balaenoptera musculus*. Marine Fisheries Review 46 (4), 15-19.

Moore, M. J., S. D. Berrow, B. A. Jensen, P. Carr, R. Sears, V. J. Rowntree, R. Payne, P. K. Hamilton, 1999. Relative abundance of large whales around South Georgia (1979-1998). Marine Mammal Science 15, 1287-1302.

Moore, S. E., K. M. Stafford, M. E. Dahlheim, C. G. Fox, H. W. Braham, J. J. Polovina, D. E. Bain, 1998. Seasonal variation in reception of fin whale calls at five geographic areas in the North Pacific. Marine Mammal Science 14 (3), 617 - 627.

Moore, S. E., J. M. Waite, N. A. Friday, T. Honkalehto, 2002a. Cetacean distribution and relative abundance on the central eastern and southeastern Bering Sea shelf with reference to oceanographic domains. Progress in Oceanography 55, 249-261.

Moore, S. E., W. A. Watkins, M. A. Daher, J. R. Davies, M. E. Dahlheim, 2002b. Blue whale habitat associations in the Northwest Pacific: analysis of remotely sensed data using a Geographic Information System. Oceanography 15, 20-25.

Murase, H., K. Matsuoka, T. Ichii, S. Nishiwaki, 2002. Relationship between the distribution of euphausiids and baleen whales in the Antarctic (35°E - 145°W). Polar Biology 25, 135-145.

Murphy, E. J., J. L. Watkins, M. P. Meredith, P. Ward, P. N. Trathan, S. E. Thorpe, 2004. Southern Antarctic Circumpolar Current Front to the northeast of South Georgia: Horizontal advection of krill and its role in the ecosystem. Journal of Geophysical Research - Oceans 109 (C1), C01029.

Murray, A. W. A., J. L. Watkins, D. G. Bone, 1995. A biological acoustic survey in the marginal ice-edge zone of the Bellingshausen Sea. Deep-Sea Research II 42, 1159-1175.

Nemoto, T., 1957. Foods of baleen whales in the Northern Pacific. Scientific reports of the Whales Research Institute 12, 33-89.

Nicol, S., Y. Endo, 1999. Krill fisheries: Development, management and ecosystem implications. Aquatic Living Resources 12, 105-120.

Nicol, S., T. Pauly, N. L. Bindoff, P. G. Strutton, 2000a. "BROKE" a biological/oceanographic survey off the coast of East Antarctica (80-150°E) carried out in January-March 1996. Deep-Sea Research II 47, 2281-2298.

Nicol, S., T. Pauly, N. L. Bindoff, S. Wright, D. Thiele, G. W. Hosie, P. G. Strutton, E. Woehler, 2000b. Ocean circulation off east Antarctica affects ecosystem structure and sea-ice extent. Nature 406, 504-507.

Nicol, S., 2006. Krill, currents, and sea ice: *Euphausia superba* and its changing environment. BioScience 56, 111-120.

Noad, M. J., D. H. Cato, M. M. Bryden, M.-N. Jenner, K. C. S. Jenner, 2000. Cultural revolution in whale songs. Nature 408, 537.

Norris, T. F., M. McDonald, J. Barlow, 1999. Acoustic detections of singing humpback whales (*Megaptera novaeangliae*) in the eastern North Pacific during their northbound migration. Journal of the Acoustical Society of America 106, 506-514.

Northrop, J., W. C. Cummings, P. O. Thompson, 1968. 20-Hz signals observed in the Central Pacific. Journal of the Acoustical Society of America 43, 383 - 384.

Oleson, E. M., J. Calambokidis, W. C. Burgess, M. A. McDonald, C. A. LeDuc, J. A. Hildebrand, 2006. Behavioral context of Northeast Pacific blue whale call production. Marine Ecology Progress Series, in press.

Orsi, A. H., T. Whitworth III, W. D. Nowlin Jr, 1995. On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep-Sea Research I 42, 641-673.

Pakhomov, E. A., A. Atkinson, B. Meyer, B. Oettl, U. Bathmann, 2004. Daily rations and growth of larval krill *Euphausia superba* in the Eastern Bellingshausen Sea during austral autumn. Deep-Sea Research II 51, 2185-2198.

Panigada, S., M. Zanardelli, S. Canese, M. Jahoda, 1999. How deep can baleen whales dive? Marine Ecology Progress Series 187, 309-311.

Pankow, H., K.-H. Kock, 2001. Results of a cetacean sightings survey in the Antarctic Peninsula region in November-December 1996. Paper SC/52/E23 presented to the IWC Scientific Committee. p. 19. [Available from: secretariat@iwcoffice.org].

Payne, R., K. Payne, 1971. Underwater sounds of southern right whales. Zoologica (N.Y.) 58, 159-165.

Payne, R., D. Webb, 1971. Orientation by means of long range acoustic signaling in baleen whales. Annals of the New York Academy of Sciences 188, 110-141.

Payne, R. S., S. McVay, 1971. Songs of humpback whales. Science 173, 585-597.

Perovich, D. K., B. C. Elder, K. J. Claffey, S. E. Stammerjohn, R. C. Smith, S. F. Ackley, H. R. Krouse, A. J. Gow, 2004. Winter sea-ice properties in Marguerite Bay, Antarctica. Deep-Sea Research II 51, 2023-2039.

Peterson, R. G., 1988. On the transport of the Antarctic Circumpolar Current through Drake Passage and its relation to wind. Journal of Geophysical Research 93, 13993-14004.

Pickard, G. L., W. J. Emery, 1990. Descriptive physical oceanography, (5th (SI) enlarged edn). Butterworth Heinmann, Oxford, p. 320.

Pollard, R. T., J. F. Read, J. T. Allen, G. Griffiths, A. I. Morrison, 1995. On the physical structure of a front in the Bellingshausen Sea. Deep-Sea Research II 42, 955-982.

Prezelin, B. B., E. E. Hofmann, C. Mengelt, J. M. Klinck, 2000. The linkage between Upper Circumpolar Deep Water (UCDW) and phytoplankton assemblages on the west Antarctic Peninsula continental shelf. Journal of Marine Research 58, 165-202.

Priddle, J., J. P. Croxall, I. Everson, R. B. Heywood, E. J. Murphy, P. A. Prinec, C. B. Sear, 1988. Large-scale fluctuation in the distribution and abundance of krill - a discussion of possible causes. In: Sahrhage, D. (Ed.) Antarctic Ocean and Resources Variability. Springer, Berlin, pp. 169-182.

Rankin, S., D. Ljungblad, C. W. Clark, H. Kato, 2005. Vocalizations of Antarctic blue whales, *Balaenoptera musculus intermedia*, recorded during the 2001-2002 and 2002-2003 IWC-SOWER circumpolar cruises, Area V, Antarctica. Journal of Cetacean Research and Management 7, 13-20.

Razafindrakoto, Y., H. C. Rosenbaum, D. A. Helweg, 2001. First description of humpback whale song from Antongil Bay, Madagascar. Marine Mammal Science 17, 180-186.

Redfern, J. V., M. C. Ferguson, J. Barlow, L. T. Ballance, T. Gerrodette, 2006a. Absence of scale dependence in cetacean-habitat models for the eastern tropical Pacific Ocean. Marine Ecology Progress Series, submitted.

Redfern, J. V., M. C. Ferguson, E. A. Becker, K. D. Hyrenbach, C. Good, J. Barlow, K. Kaschner, M. F. Baumgartner, K. A. Forney, L. T. Ballance, P. Fauchald, P. N. Halpin, T. Hamazaki, A. J. Pershing, S. S. Qian, A. J. Read, S. B. Reilly, L. Torres, F. Werner, 2006b. Techniques for cetacean-habitat modeling. Marine Ecology Progress Series 310, 271-295.

Reid, J. L., W. D. Nowlin Jr., 1971. Transport of water through the Drake Passage. Deep-Sea Research 18, 51-64.

Reid, K., A. S. Brierley, G. A. Nevitt, 2000. An initial examination of relationships between the distribution of whales and Antarctic krill *Euphausia superba* at South Georgia. Journal of Cetacean Research and Management 2, 143-149.

Reilly, S., S. Hedley, J. Borberg, R. Hewitt, D. Thiele, J. Watkins, M. Naganobu, 2004. Biomass and energy transfer to baleen whales in the South Atlantic sector of the Southern Ocean. Deep-Sea Research II 51, 1397-1409.

Reilly, S. B., V. G. Thayer, 1990. Blue whale (*Balaenoptera musculus*) distribution in the Eastern Tropical Pacific. Marine Mammal Science 6, 265-277.

Richardson, W. J., J. Charles R. Greene, C. I. Malme, D. H. Thomson (eds.), 1995. Marine mammals and noise. Academic Press, San Diego, CA. p. 576.

Ross, R. M., L. B. Quentin, C. M. Lascara, 1996. Distribution of Antarctic krill and dominant zooplankton west of the Antarctic Peninsula. In: Quentin, L. B. (Ed.) Foundation for Ecological Research West of the Antarctic Peninsula, vol 70. American Geophysical Union, Washington, DC, pp. 199-217.

Scharf, B., 1970. Critical bands. In: Tobias, J. V. (Ed.) Foundations of modern auditory theory, vol 1. Academic Press, New York, NY, pp. 157-202.

Schevill, W. E., W. A. Watkins, 1972. Intense low-frequency sounds from an Antarctic minke whale, *Balaenoptera acutorostrata*. Breviora 388, 1-8.

Secchi, E. R., L. Dalla Rosa, P. G. Kinas, M. C. O. Santos, A. N. Zerbini, M. Bassoi, I. B. Moreno, 2001. Encounter rates of whales around the Antarctic Peninsula with special reference to humpback whales, *Megaptera novaeangliae*, in the Gerlache Strait: 1997/98 to 1999/2000. Memoirs of the Queensland Museum 47, 571-578.

Selvin, S., 1998. Modern applied biostatistical methods using *S-Plus*. Oxford University Press, New York, NY, p. 461.

Siegel, V., 1988. A concept of seasonal variation of krill (*Euphausia superba*) distribution and abundance west of the Antarctic Peninsula. In: Sahrhage, D. (Ed.) Antarctic ocean and resources variability. Springer-Verlag, Berlin Heidelberg, pp. 219-230.

Siegel, V., B. Bergstrom, J. O. Stromberg, P. H. Schalk, 1990. Distribution, size frequencies and maturity stages of krill, Euphausia superba, in relation to sea-ice in the northern Weddell Sea. Polar Biology 10, 549-557.

Siegel, V., 2000. Krill (Euphausiacea) life history and aspects of population dynamics. Canadian Journal of Fisheries and Aquatic Sciences 57 (Suppl. 3), 130-150.

Sievers, H. A., W. D. Nowlin, 1984. The stratification and water masses at Drake Passage. Journal of Geophysical Research 89, 10489-10514.

Širović, A., J. A. Hildebrand, S. M. Wiggins, M. A. McDonald, S. E. Moore, D. Thiele, 2004. Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. Deep-Sea Research II 51, 2327-2344.

Širović, A., J. A. Hildebrand, D. Thiele, 2006. Baleen whales in the Scotia Sea in January and February 2003. Journal of Cetacean Research and Management, in press.

Smith, D. A., E. E. Hofmann, J. M. Klinck, C. M. Lascara, 1999. Hydrography and circulation of the West Antarctic Peninsula continental shelf. Deep-Sea Research I 46, 925-949.

Smith, R. C., P. Dustan, D. Au, K. S. Baker, E. A. Dunlap, 1986. Distribution of cetaceans and sea-surface chlorophyll concentrations in the California Current. Marine Biology 91, 385-402.

Smith, R. C., H. M. Dierssen, M. Vernet, 1996. Phytoplankton biomass and productivity in the western Antarctic Peninsula region. In: Quentin, L. B. (Ed.) Foundations for Ecological Research West of the Antarctic Peninsula, vol 70. American Geophysical Union, Washington, DC, pp. 333-356.

Smith, R. C., K. S. Baker, H. M. Dierssen, S. E. Stammerjohn, M. Vernet, 2001. Variability of primary production in an Antarctic marine ecosystem as estimated using a multi-scale sampling strategy. American Zoologist 41, 40-56.

Smith, W. O., D. M. Nelson, 1985. Phytoplankton bloom produced by a receding ice-edge in the Ross Sea: spatial coherence with the density. Science 277, 163-167.

Spiesberger, J. L., 2001. Hyperbolic location errors due to insufficient numbers of receivers. Journal of the Acoustical Society of America 109, 3076-3079.

Springer, A. M., J. F. Piatt, V. P. Shuntov, G. B. Van Vliet, V. L. Vladimirov, A. E. Kuzin, A. S. Perlov, 1999. Marine birds and mammals of the Pacific Subarctic Gyres. Progress in Oceanography 43, 443-487.

Stafford, K. M., C. G. Fox, D. S. Clark, 1998. Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. Journal of the Acoustical Society of America 104, 3616-3625.

Stafford, K. M., S. L. Nieukirk, C. G. Fox, 1999a. Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. Journal of the Acoustical Society of America 106, 3687-3698.

Stafford, K. M., S. L. Nieukirk, C. G. Fox, 1999b. An acoustic link between blue whales in the Eastern Tropical Pacific and the Northeast Pacific. Marine Mammal Science 15, 1258-1268.

Stafford, K. M., S. L. Nieukirk, C. G. Fox, 2001. Geographic and seasonal variation of blue whale calls in the North Pacific. Journal of Cetacean Research and Management 3, 65-76.

Stafford, K. M., D. R. Bohnenstiehl, M. Tolstoy, E. Chapp, D. K. Mellinger, S. E. Moore, 2004. Antarctic-type blue whale calls recorded at low latitudes in the Indian and eastern Pacific Oceans. Deep-Sea Research I 51, 1337-1346.

Stammerjohn, S. E., R. C. Smith, 1996. Spatial and temporal variability of western Antarctic Peninsula sea ice coverage. In: Quentin, L. B. (Ed.) Foundations for Ecological Research West of the Antarctic Peninsula, vol 70. American Geophysical Union, Washington, DC, pp. 81-104.

Thiele, D., E. T. Chester, P. C. Gill, 2000. Cetacean distribution off Eastern Antarctica (80-150°E) during the austral summer of 1995/1996. Deep-Sea Research II 47, 2543-2572.

Thiele, D., E. T. Chester, S. E. Moore, A. Širovic, J. A. Hildebrand, A. Friedlaender, 2004. Seasonal variability in whale encounters in the Western Antarctic Peninsula. Deep-Sea Research II 51, 2311-2325.

Thode, A. M., G. L. D'Spain, W. A. Kuperman, 2000. Matched-field processing, geoacoustic inversion, and source signature recovery of blue whale vocalizations. Journal of the Acoustical Society of America 107, 1286-1300.

Thompson, P., L. T. Findley, O. Vidal, 1992. 20-Hz pulses and other vocalizations of fin whales, *Balaenoptera physalus*, in the Gulf of California, Mexico. Journal of the Acoustical Society of America 92, 3051-3057.

Thompson, P., L. T. Findley, W. C. Cummings, 1996. Underwater sounds of blue whales, *Balaenoptera musculus*, in the Gulf of California, Mexico. Marine Mammal Science 12, 288-293.

Tiemann, C. O., M. B. Porter, L. N. Frazer, 2004. Localization of marine mammals near Hawaii using an acoustic propagation model. Journal of the Acoustical Society of America 115, 2834-2843.

Tynan, C. T., 1998. Ecological importance of the southern boundary of the Antarctic Circumpolar Current. Nature 392, 708-710.

Tynan, C. T., D. G. Ainley, J. A. Barth, T. J. Cowles, S. D. Pierce, L. B. Spear, 2005. Cetacean distributions relative to ocean processes in the northern California Current System. Deep-Sea Research II 52, 145-167.

Urick, R. J., 1983. Principles of underwater sound, (3rd edn). Peninsula Publishing, Los Altos, CA, p 423.

US SO GLOBEC, 2001. Report of RVIB Nathaniel B. Palmer cruise NBP01-03 to the Western Antarctic Peninsula, p. 167.

US SO GLOBEC, 2002. Report of RVIB Nathaniel B. Palmer cruise NBP02-02 to the Western Antarctic Peninsula, p. 180.

Wade, P. R., T. Gerrodette, 1993. Estimates of cetacean abundance and distribution in the eastern tropical Pacific. Report of the International Whaling Commission 43, 477-493.

Walker, R. A., 1963. Some intense, low-frequency, underwater sounds of wide geographic distribution, apparently of biological origin. Journal of the Acoustical Society of America 35, 1816-1824.

Watkins, W. A., W. E. Schevill, 1972. Sound source location by arrival-times on a non-rigid three-dimensional hydrophone array. Deep-Sea Research 19, 691-706.

Watkins, W. A., 1981. Activities and underwater sounds of fin whales. Scientific reports of the Whales Research Institute 33, 83-117.

Watkins, W. A., P. Tyack, K. E. Moore, J. E. Bird, 1987. The 20-Hz signal of finback whales (*Balaenoptera physalus*). Journal of the Acoustical Society of America 82, 1901 - 1912.

Watkins, W. A., M. A. Daher, G. M. Reppucci, J. E. George, D. L. Martin, N. A. DiMarzio, D. P. Gannon, 2000. Seasonality and distribution of whale calls in the North Pacific. Oceanography 13 (1), 62-67.

Weisberg, S., 2005. Applied linear regression, (3rd edn). Wiley - Interscience, Hoboken, NJ, p. 310.

Whitehead, H., C. Glass, 1985. The significance of the Southeast Shoal of the Grand Bank to humpback whales and other cetacean species. Canadian Journal of Zoology 63, 2617-2625.

Whitehouse, M. J., J. Priddle, C. Symon, 1996. Seasonal and annual change in seawater temperature, salinity, nutrient and chlorophyll a distribution around South Georgia, South Atlantic. Deep-Sea Research II 43, 425-443.

Wiggins, S., 2003. Autonomous Acoustic Recording Packages (ARPs) for long-term monitoring of whale sounds. Marine Technology Society Journal 37 (2), 13-22.

Winn, H., E., P. J. Perkins, 1976. Distribution and sounds of the minke whale, with a review of mysticete sounds. Cetology 19, 1-12.

Winn, H., E., L. K. Winn, 1978. The song of humpback whale (*Megaptera novaeangliae*) in the West Indies. Marine Biology 47, 97-114.

Woodley, T. H., D. E. Gaskin, 1996. Environmental characteristics of North Atlantic right and fin whale habitat in the lower Bay of Fundy, Canada. Canadian Journal of Zoology 74, 75-84.

Yablokov, A. V., 1994. Validity of whaling data. Nature 367, 108.