UNIVERSITY OF CALIFORNIA, SAN DIEGO

# North Pacific Right Whale Calling Behavior and Habitat Characterization in the Southeastern Bering Sea

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in
Oceanography
by
Lisa Marie Munger

Committee in charge:

John A. Hildebrand, Chair
Jay P. Barlow
David M. Checkley
Paul K. Dayton
James A. Levin
Sue E. Moore
James H. Swift

2007

UMI Number: 3283969

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

The dissertation of Lisa Marie Munger is approved, and it is acceptable in quality and form for publication on microfilm:

Chair

University of California, San Diego

2007

For whatever we lose
(like a you or a me)
It’s always our self
We find in the sea.

*e.e. cummings*

TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# ACKNOWLEDGEMENTS

At the risk of reading like the rambling acceptance speech for an Academy Award or similar, I must express my gratitude and respect for everyone who contributed to this dissertation. Firstly, I thank my graduate advisor, John Hildebrand, for taking me on as a student and introducing me to marine mammal acoustics. John provided much-needed support, feedback, and encouragement, and not only provided a stimulating and challenging "home" lab, but also gave me some incredible opportunities to explore the world. The past six years for me have been filled with adventures, from being splashed by a baby North Pacific right whale (an honor few can claim) to dunking hydrophones under the shore ice of Savoonga with the high school science class. Thanks also to the other members of my dissertation committee: Jay Barlow, Dave Checkley, Jim Swift, Sue Moore, Paul Dayton, and Jim Levin. They provided excellent feedback and each contributed their own expertise and perspective in different areas, from statistics and physical oceanography, to the 'big picture' view of right whales in the context of changing climate and ecology. Sue Moore deserves special thanks for being a champion of whale acoustics and driving force behind the Alaskan right whale monitoring project, and she has been a great source of encouragement and direction. I also could not have written this dissertation without the help of Sean Wiggins, who designed the acoustic recorders with which we collect data, the software with which we process the data, and who deserves recognition as an "honorary committee member" for his contributions as a co-author and intellectual collaborator. I am grateful to Mark McDonald and Dave Mellinger for their valuable input and expertise as well.

Heartfelt thanks to my numerous colleagues in the Hildebrand lab, for providing me with inspiration, friendship, ideas, and many a nacho Tuesday. Melissa Soldevilla, my officemate, deserves special thanks for putting up with me through all the ups and downs. Erin Oleson and Ana Sirovic made completing a Ph.D. look easy. Other partners in crime include Liz Henderson, Simone Baumann, Jessica Burtenshaw, Ethan Roth, Josh Jones, Megan McKenna, Greg Campbell, and Catherine Berchok. I thank Chris Garsha, Allan Sauter, and Kevin Hardy for their engineering and technical expertise, and the many, many interns and assistants that have kept our lab going. Special thanks to Hannah Bassett, who put in many hours of effort during the last few months to finish processing data. Without her initiative and enthusiasm, I'd probably still be stuck looking at spectrograms.

During my tenure as a grad student, I partook in many forms of therapy to alleviate stress. One is scuba diving. Thanks to my stalwart dive buddies, for helping me escape my surface woes and discover a fascinating, awesome, ever-changing world underwater. I learned oceanography better through diving than I ever could have out of a book; things like tides, thermoclines, and plankton blooms take on new meaning when you're swimming through them. Other therapeutic activities included yoga and reading Ph.D. comics, so I thank Arturo Galvez and Jorge Cham, respectively. Best of all, I spent time with friends, especially my closest pals Susan, Tina and O'rya, who provided an outlet for ranting when things were not going great, raving when they were, and who accompanied me on some fabulous umbrella-drink & massage-laden getaways.

On a more personal level, I need to thank Andy Lucas, who was my greatest supporter during this whole endeavor, and whom I love. He kept me fed and in clean

clothes when I could hardly pour myself a glass of water. He kept asking me how my day was, even on the rough days when the answer was barely a grunt. He kept me going. Last but not least, I thank my own family. My aunts, uncles, cousins, grandmas and grandpas, parents, and brother have provided nothing but unconditional love, support and encouragement my whole life. Growing up in my family, my sense of humor has of course been irreparably warped, but more importantly I feel like I have the best family one could ever hope for. They are kind, talented, funny, smart, generous, loving, and open-minded, and I thank them for helping me get this far in life and for cheering me on the whole way. And now, I think I hear an orchestra starting, so it's time to wrap this up.

This work was supported by NOAA Alaska Fisheries Science Center/National Marine Mammal Laboratory (AFSC/NMML) via JIMO budget #NA17RJ1231, North Pacific Marine Research Institute (project T-2100) and North Pacific Research Board (projects R-0307 and F0519), Alaska Department of Fish and Game (ADFG project T-1-6-4; special thanks to Bob Small), and National Fish and Wildlife Foundation.

Chapter 2 is a reprint of the material, in full, as it appears in the journal Canadian Acoustics (2005): Munger, L.M., D.K. Mellinger, S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. Performance of spectrogram cross-correlation in detecting right whale calls in long-term recordings from the Bering Sea. Canadian Acoustics 33:25-34. Content was reformatted to conform to UCSD dissertation standards. The dissertation author was the primary investigator and author of this paper. The coauthors listed supervised the research forming the basis of this chapter.

Chapter 3, in full, has been submitted for publication (Munger, L., S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. North Pacific right whale (*Eubalaena japonica*)

seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea, 2000-2006. Marine Mammal Science, in revision). The dissertation author was the primary investigator and author of this paper. The coauthors listed supervised the research forming the basis of this chapter.

Chapter 4 is in preparation for submission (Munger, L.M., Wiggins, S.M., Moore, S.E., and Hildebrand, J.A. Right whale 'up-call' source levels and detection ranges on the southeastern Bering Sea shelf. Journal of the Acoustical Society of America, in preparation). The dissertation author was the primary investigator and author of this paper. The coauthors listed supervised the research forming the basis of this chapter.

Chapter 5 is in preparation for submission (Munger, L.M., Moore, S.E., and Hildebrand, J.A. Seasonal and interannual variability of North Pacific right whale occurrence and oceanography on the southeastern Bering Sea middle shelf: a conceptual model. Marine Ecology Progress Series, in preparation). The dissertation author was the primary investigator and author of this paper.

# VITA

| | |
|---|---|
| 1999 | Bachelor of Arts, University of Colorado, Boulder |
| 2005 | Teaching Assistant, University of California, San Diego |
| 2007 | Doctor of Philosophy, University of California, San Diego |

# PUBLICATIONS

Munger, L., S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. *submitted*. North Pacific right whale (*Eubalaena japonica*) seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea, 2000-2006. Marine Mammal Science, *in revision*.

Munger, L., D.K. Mellinger, S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. 2005. Performance of spectrogram correlation in detecting right whale calls in long-term recordings from the Bering Sea. Canadian Acoustics 33 (2): 25-34.

Munger, L., A. Cruz, and S. Applebaum. 2004. Mate choice copying in female humpback limia (*Limia nigrofasciata*, family Poeciliidae). Ethology 110: 563-573.

Mellinger, D.K., K.M. Stafford, S.E. Moore, L. Munger, and C.G. Fox. 2004. Detection of North Pacific right whale (*Eubalaena japonica*) calls in the Gulf of Alaska. Marine Mammal Science 20: 872-879.

Prather, J.W., L.M. Munger, and A. Cruz. 2002. Breeding biology of the black-backed lesser goldfinch in ponderosa pine forests on the Colorado front range. Wilson Bulletin 114: 192-196.

Wade, P., M.-P. Heide-Jørgensen, K. Shelden, J. Barlow, J. Carretta, J. Durban, R. LeDuc, L. Munger, S. Rankin, A. Sauter, C. Stinchcomb. 2006. Acoustic detection and satellite-tracking leads to discovery of rare concentration of endangered North Pacific right whales. Biology Letters 2: 417-419.

Wiggins, S.M., M.A. McDonald, L.M. Munger, J.A. Hildebrand, and S.E. Moore. 2004. Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea. Canadian Acoustics, 32 (2): 146-154.

# FIELDS OF STUDY

Major Field: Biology

Studies in Biological Oceanography

Professor John A. Hildebrand, University of California, San Diego

Studies in Ecology and Evolutionary Biology

Professor Alexander Cruz, University of Colorado, Boulder

# ABSTRACT OF THE DISSERTATION

## North Pacific right whale calling behavior and habitat characterization in the southeastern Bering Sea

by

Lisa Marie Munger
Doctor of Philosophy in Oceanography
University of California, San Diego, 2007
Professor John A. Hildebrand, Chair

North Pacific right whales (*Eubalaena japonica*) are critically endangered due to intensive commercial whaling in the 1800s and illegal whaling in the 1960s. Currently the eastern subpopulation probably numbers in the dozens of animals, and little is known about their behavioral ecology. The majority of sightings within the past 50 years have been in the southeastern Bering Sea (SEBS), in shallow waters (< 200 m) over the continental shelf. Moored, passive acoustic recorders were deployed in the SEBS in 2001, 2002, 2004, and 2005 to monitor the middle shelf for right whale calls and recorded for 2 – 11 months per instrument. Deployments were at or near subsurface moorings that recorded oceanographic data including temperature, salinity, and chlorophyll fluorescence. Techniques were developed for efficiently detecting right whale calls in a large data set, and calling behavior was investigated on daily and seasonal scales. Acoustic properties of right whale calls and their propagation on the SEBS shelf were estimated and temporal patterns in right whale calling were examined in relation to oceanographic variables.  Automated call detection was useful at guiding analysts to bouts of right whale calling and additional calls were found by manually searching.  Right whales occurred in the SEBS as early as May and as late as December. Calling rates were significantly higher during darkness than during daylight, suggesting a relationship to behavior that may vary diurnally, such as foraging.  Right whale call source levels were within ranges reported for other balaenid whale species, and calls propagated for long distances (>100 km) on the SEBS middle shelf.  Right whales were detected earlier in years with early ice retreat and a late spring bloom and intermittently throughout summer and fall in all years with recording effort.  Peak right whale calling rates and the most days per month with calls were in late summer.  We hypothesize that right whale occurrence is linked to environmental variables via bottom-up control on production and distribution of copepods, their primary prey.  These results are relevant to conservation and form the basis for future investigations of right whale calling behavior and its relationship to habitat use.

# I. Introduction

Right whales (genus *Eubalaena*, family Balaenidae) were one of the first large whales to be intensively hunted to near-extinction by commercial whaling vessels. Known as the ‘right’ whale to kill, these animals were prized for their high oil yield and baleen, and were relatively easy to hunt because they are slow swimmers, found in coastal areas, and were buoyant after death. Systematic depletion of right whales worldwide began with the Basques as early as the 11th century in the eastern North Atlantic (Aguilar, 1986), and from there expanded gradually to the west and south, with eventual multinational whaling effort throughout all of the world’s oceans. Conservative estimates of right whale catches during roughly the past two centuries are in the tens of thousands: 38000-39000 in the South Atlantic from 1785-1939, 12000 -13000 in the Indian Ocean from 1830-1939, 38,000-39,000 in the South Pacific from 1815-1969, and 15,000-16,000 in the North Pacific from 1840-1969 (Brownell *et al.*, 1986). These numbers do not reflect total mortality of whales that were killed or injured but not landed. A more recent estimate of total right whale mortality in the North Pacific is approximately double the 1986 estimate, between 26,500 and 37,000 right whales for the period of 1840-1909 (Scarff, 2001).

By the start of the 20th century, right whales (*Eubalaena* spp.) were no longer profitable to hunt and, because of their scarcity, were one of the first whales to receive international protection in 1935 by the League of Nations and later by the International Whaling Commission under the 1946 Convention for the Regulation of Whaling (Brownell *et al.*, 1986). The ban on whaling for right whales remains in effect at present due to the lack of recovery in most populations, particularly in the North Atlantic and

North Pacific. Until recently, northern right whales were grouped together as a single species (*E. glacialis*), considered distinct from southern right whales (*E. australis*). Genetic evidence, however, supports further division of northern right whales into separate species, North Atlantic right whales (*Eubalaena glacialis*), and North Pacific right whales (*E. japonica*) (Gaines *et al*., 2005; Rosenbaum *et al*., 2000). Both northern hemisphere species, *E. glacialis* and *E. japonica*, occur in U.S. waters and had been listed as endangered under a single species name, *E. glacialis*, under the Endangered Species Act of 1973; this listing was recently revised to reflect their status as separate species (NMFS, 2006).

North Atlantic right whales (*E. glacialis*) occur along the east coast of the United States and Canada in several areas that overlap commercial shipping lanes and lobster fisheries, and consequently suffer high mortality from ship strikes and entanglement in fishing gear. Their proximity to urban areas has a positive side, however, in that they are relatively accessible for study and occur in some predictable habitats every year. In contrast, North Pacific right whale (*E. japonica*) sightings are fewer and less predictable and occur primarily in remote areas offshore of Alaska away from major human population centers. Therefore, less is known about the current population status, distribution, and habitat use of North Pacific right whales. This dissertation investigates aspects of North Pacific right whale behavioral ecology through the use of passive acoustic monitoring in recent and historic right whale summer habitats. The following introduction provides further background on North Pacific right whales, from commercial whaling history to current understanding of their subpopulation structure, distribution, and acoustic repertoire, and the physical and biological oceanographic characteristics of their primary known habitat, the southeastern Bering Sea.

## North Pacific right whales

Commercial whaling for North Pacific right whales (*E. japonica*) was particularly intensive and devastating in a relatively short time period. Scarff (2001) estimated total right whale mortality in the North Pacific to be between about 26,500 and 37,000 right whales for the period of 1840-1909, accounting for struck-but-lost whales and non-American whaling vessels (Scarff, 2001). Nearly 80% of the total right whale catch in this time period took place in the single decade of 1840-1849, and the cumulative catch for the twenty-year period 1840-1859 accounted for over 90% of the total catch in the entire period from 1840-1909. Productive whaling grounds included the eastern Aleutian islands and southeastern Bering Sea (SEBS), and western Gulf of Alaska (GoA). The latter area was known as the 'Northwest Ground' or 'Kodiak Ground', and during the heyday of commercial whaling some 300-400 ships were hunting right whales there. By 1850, North Pacific right whales had become so depleted in the GoA and SEBS that whaling ships shifted most of their effort further north to hunt bowheads. However, right whales continued to be taken occasionally in the North Pacific until their protection in 1935 (Brueggeman *et al.*, 1986; Omura, 1986). By mid-century, North Pacific right whales may have recovered to low hundreds of animals, but were then illegally hunted by the Soviet Union in the 1960's. Over 600 North Pacific right whales were killed during 1963-66; more than half of them were taken in the western GoA and SEBS (Doroshenko, 2000).

Currently, North Pacific right whales are divided into two subpopulations (or 'stocks'), one in the western and one in the eastern North Pacific, and this population structure is supported by historic whaling data as well as sightings since the cessation of whaling (Brownell *et al*., 2001; Clapham *et al*., 2004). Abundance estimates for these stocks are uncertain, but the western population probably consists of hundreds, whereas the eastern population may consist of fewer than one hundred individuals (Brownell *et al*., 2001). Since the cessation of whaling, sightings of eastern North Pacific right whales have been so rare that each sighting account was considered a publishable event (*e.g.*, Rowntree *et al*., 1980; Woodhouse and Strickley, 1982; Carretta *et al*., 1994; Goddard and Rugh, 1998; Gendron *et al*., 1999; Salden and Mickelsen, 1999; Waite *et al*., 2003). Whaling records indicate that North Pacific right whales migrate seasonally, with a northward movement in spring to high-latitude summer feeding grounds, and a southward movement in autumn (Brownell *et al*., 2001; Clapham *et al*., 2004; Shelden *et al*., 2005). Most whaling effort for North Pacific right whales took place in late spring and summer (May-September), as winter sightings of North Pacific right whales were rare and breeding/calving grounds in the eastern North Pacific were never discovered by commercial whalers. Winter sightings in the eastern North Pacific continue to be rare, geographically scattered, and usually of single animals (Brownell *et al*., 2001), and calving grounds remain a mystery.

The majority of recent eastern North Pacific right whale sightings have been in summer, with over 80% of sightings in the past 50 years reported in the southeastern Bering Sea (SEBS), mainly in the middle-shelf domain (50 m < depth < 100 m) (Goddard and Rugh, 1998; Moore *et al*., 2000; LeDuc *et al*., 2001; Tynan *et al*., 2001; Leduc, 2004;

Wade *et al*., 2006). As a result, directed right whale search effort during the past decade has focused on the SEBS middle-shelf, although some search effort has been conducted for cetaceans throughout the Gulf of Alaska (GoA) and SEBS outer shelf and slope (Barlow, 2005; Leduc, 2004). Right whale sightings and/or acoustic detections have also been reported in the western GoA (Mellinger *et al*., 2004; Waite *et al*., 2003) and in the SEBS outer-shelf region (100-200 m) (Wade *et al*., 2006). At present, 23 eastern North Pacific right whales have been identified by genetic samples, of which 7 are female (Wade *et al*., 2006). The high rate of re-identification of individuals in different years (by photographs and biopsy samples) confirms the low estimates of population size, although recent sightings and genetic confirmation of a few female-calf pairs provides some hope that recovery is possible.

Very little is known about eastern North Pacific right whale seasonal distribution, movements, habitat use, and how factors such as climate variability or anthropogenic disturbances may impact survival. The low probability of North Pacific right whale encounters and relative remoteness of their known habitats in the Bering Sea and Gulf of Alaska are challenging aspects of conducting right whale research. Vessel-based and aerial surveys may operate for days to weeks and hundreds of kilometers of trackline without a right whale sighting. When right whales are encountered, these surveys provide indispensable data such as photographs, biopsy samples, short-term acoustic recordings, behavioral observations and concurrent oceanographic data, but still provide only a ‘snapshot’ in time of the whales’ location, behavior, and environment. Passive, autonomous acoustic monitoring is a complementary research tool that provides a long-term record of occurrence of sound-producing animals, and can be used to investigate aspects of behavioral ecology including spatial and temporal distributions and calling behavior over a range of time scales.

We conducted long term acoustic monitoring to study North Pacific right whales within the predominant sighting area on the southeast Bering Sea middle-shelf, in 2000-2006. We also deployed acoustic recorders in historic habitats in the western Gulf of Alaska (2003) and along the SEBS slope (2004-05). North Pacific right whale calls were previously recorded during a 1999 acoustic and visual survey in the southeast Bering Sea, and are described in McDonald and Moore (2002). The most common right whale call type in the SEBS was an ‘up’ call (85%, n=511), sweeping up in frequency on average from 90 to 150 Hz in 0.7 s. Similarly to North Atlantic right whale calls (Matthews *et al.*, 2001; Vanderlaan *et al.*, 2003), North Pacific right whale calls were clustered in sporadic ‘bouts’ lasting several minutes, with longer silences (tens of minutes to hours) between bouts (McDonald and Moore, 2002). Southern right whales (*E. australis*) produce similar frequency upsweeps (Clark, 1981, 1982), which are thought to be a contact call, based on observations of whales producing this call when approaching or departing from other individuals and playback experiments (Clark, 1983; Clark and Clark, 1980). Further support for the contact function of up-calls is that they are produced by calves and adults of both sexes, and are acoustically well-suited to long-range detection above background noise because the calls are frequency modulated and usually repeated several times in succession (Edds-Walton, 1997). The behavioral context of right whale calls has been relatively better studied in the North and South Atlantic, where more complex and variable call types are produced depending on the complexity of the interaction, such as agonistic, competitive, reproductive (Clark, 1983; Clark, 1981, 1982; Parks *et al.*, 2005; Parks and Tyack, 2005).

North Pacific right whale summer habitats are presumed to be primarily foraging grounds. The Gulf of Alaska and southeastern Bering Sea are both regions of high primary productivity in summer and support high concentrations of zooplankton on which right whales feed. Eastern North Pacific right whale stomach contents were examined from three whales taken in the GoA and six in the SEBS under a Japanese scientific research permit in the 1950's and 60's (Omura *et al.*, 1969). The majority of their prey was composed of calanoid copepods, including *Calanus marshallae*, *Metridia* spp., and *Neocalanus* spp., and a small proportion of stomach contents was krill (*Euphausia pacifica*). Right whales feed by filtering zooplankton from the water onto the fine bristles of their long baleen plates, using a technique known as 'skim-feeding' in which they hold jaws partially open and swim through a prey patch, allowing water to enter the front of their jaws, filter through the baleen and stream out over the sides and back of their lips. Prey densities required for effective right whale feeding are on the order of thousands to millions of copepods per cubic meter (Kenney *et al.*, 1986), and data from North Atlantic right whale foraging observations and zooplankton measurements provide evidence that right whales target prey concentrations of over ~3000 copepods/$m^3$ (Baumgartner and Mate, 2003; Beardsley *et al.*, 1996). North Pacific right whale distributions and movements within summer habitats are likely to reflect the temporal and spatial distribution of copepods, which are influenced in turn by phytoplankton production and physical forcing and are therefore linked to climate and oceanographic variables.

## Southeast Bering Sea

The Bering Sea is an economically important region of the United States, due in major part to the large, productive fisheries there. As a result, the physical and biological oceanography of the Bering Sea have been the focus of several large-scale, government-funded scientific studies. In the 1970's and 1980's, the research programs Outer Continental Shelf Environmental Assessment Program (OCSEAP) and Processes and Resources of the Bering Sea (PROBES), sponsored respectively by Bureau of Land Management and NSF Division of Polar Programs, contributed greatly to the understanding of circulation regimes, nutrient flux, and production on the SEBS shelf (McRoy *et al*., 1986). In the 1990's, the Inner Front Program and Southeast Bering Sea Carrying Capacity (SEBSCC) program (NOAA) conducted further studies to investigate climate change and ecosystem response of the southeast Bering Sea shelf and slope regions (Macklin *et al*., 2002). From the 1990's through present, Fisheries Oceanography Coordinated Investigations (FOCI), a NOAA program, has maintained oceanographic moorings, deployed drifters, and conducted sampling cruises several times per year in the Gulf of Alaska and Bering Sea. These several decades of research effort in the Bering Sea have spanned a wide range of climactic and oceanographic conditions, have contributed to our understanding of ecosystem variability on multiple time scales, and provided a baseline for monitoring ecosystem trends and effects of warming (Stabeno *et al*., 2006; Stabeno and Salo, in press).

## Physical oceanography

The Bering Sea is a semi-enclosed sub-Arctic sea bounded by the continents of Asia (Russia) to the west and North America (Alaska) to the east, with the Alaskan peninsula and Aleutian Island archipelago forming the perimeter of the southern edge of the sea and the Bering Strait bottleneck to the north. The Bering Sea is connected to the North Pacific via numerous passes along the Aleutian chain and to the Arctic via the narrow and shallow Bering Strait. The eastern Bering Sea is characterized by a wide (~500 km), relatively flat, and shallow (< 200 m) continental shelf adjacent to the coast of Alaska. The 'shelf break' or 'slope' is located at about 170º W longitude, where the seafloor slopes more steeply from 200 m to the floor of the Bering Sea basin, over 3000 m in depth and comprising the majority of the western Bering Sea (Figure 1.1).

The direction of water flow overall through the Bering Sea is northward, entering from the North Pacific and exiting the Bering Strait. The southeastern Bering Sea receives input from two Gulf of Alaska currents, the Alaskan Stream and Alaskan Coastal Current (Figure 1.1) (Stabeno and Hunt, 2002; Stabeno *et al.*, 2002b). Most of the flow is directed northward along the slope of the continental shelf as the Bering Slope Current, resulting in upwelling of deep nutrient-rich water and high primary production in summer along the "Green Belt" over the slope of the continental shelf (Springer *et al.*, 1996). Net flow is toward the north/northwest and is strongest along the slope and outer shelf, and along the Alaskan peninsula and coastline; net flow in the central shelf is weak (Schumacher and Kinder, 1983; Stabeno *et al.*, 2001). Although mean flow is weak, tidal currents and diffusion can be substantial on the shelf (Coachman, 1986; Coachman and Walsh, 1981).

The SEBS shelf is divided into three oceanographic domains separated by fronts roughly parallel to the 50 m and 100 m depth contours. The corresponding inner-shelf, middle-shelf and outer-shelf regions undergo dynamic seasonal variation, with different characteristic circulation and production regimes and biological communities. In winter, the water column is rapidly cooled by strong, cold dry winds blowing offshore, and in late winter, by melting ice advected southward onto the shelf from the northern Bering Sea. Wind-driven mixing, tidal diffusion and advection resupply the shelf water with nutrients from deep water from the Bering Sea basin and North Pacific. The SEBS shelf is therefore "reset" each year to similar nutrient and temperature conditions in winter, when the delineation between oceanographic domains is weak (Stabeno *et al.*, 2006).

Storms subside and ice retreats in mid- to late spring as insolation increases, allowing water column stratification over the middle- and outer shelf, and the formation of temperature and salinity fronts on the shelf at approximately the 50m and 100m isobaths. These fronts inhibit cross-shelf exchange and lead to distinct oceanographic regimes within each domain (Coachman and Walsh, 1981). Water over the inner shelf domain (< 50 m depth) in summer is usually well mixed, while over the middle shelf (50 m < depth < 100 m), a warm, wind-mixed surface layer about 25 m deep forms over a cold, nutrient rich bottom layer. The outer shelf (100 < depth < 200 m) is characterized by significant cross-shelf transport and is similar biologically to the oceanic and slope regions. The water column structure over the slope and outer shelf is typically three-layered in summer, with a wind-mixed and warm surface layer overlaying a fine-structured intermediate layer and a bottom cold pool.

The Bering Sea responds on a variety of time scales to atmospheric changes, which impact ice cover and transport, water column vertical structure, and circulation. The interannual variability in ice coverage in the Bering Sea is strongly dependent on the location and strength of the Aleutian low [air pressure center], which is influenced by El Niño/Southern Oscillation (ENSO), via atmospheric teleconnections (Benson and Trites, 2002; Niebauer, 1998). On multi-year scales, climactic oscillations impacting the seasonal light levels, heat fluxes, and wind stress of the Bering Sea include the Arctic Oscillation, Pacific Decadal Oscillation, and ENSO. Over shorter time scales, the strength and frequency of episodic winds play an important role in advection and vertical structure of the water column (Stabeno *et al*., 2002a; Stabeno and Van Meurs, 1999). These physical and climate oscillations on multiple time scales exert considerable influence on the biological communities in the SEBS.

## Biological oceanography

The timing of ice retreat, combined with wind stress and heating, are the dominant controls of the spring phytoplankton bloom on the SEBS shelf. Early spring blooms consist of ice-associated algae (Jin *et al*., 2007) when ice is present late into the spring (April or May) as daylight increases and water becomes weakly salinity-stratified due to ice melt. When ice retreat occurs early in spring (mid-March) or no ice is advected onto the SEBS shelf, light and winter winds limit bloom formation until about May, and the bloom occurs later in warmer water as thermal stratification begins (Hunt *et al*., 2002). During the bloom, nutrients are completely removed from the water column in coastal areas (< 50 m depth) and from the surface warm layer of the deeper middle and outer shelf. The stratification over the middle-shelf and lack of horizontal transport to the middle and inner-shelf domains generally inhibit new nutrient inputs. However, nutrients can occasionally be resupplied to the euphotic zone of the shelf through episodic wind-driven mixing, eddies, on-shelf transport of slope water up submarine canyons, and inflow from Unimak pass (Coachman and Walsh, 1981; Kachel *et al*., 2002; Sambrotto *et al*., 1986; Stabeno *et al*., 2002b; Stabeno and Van Meurs, 1999). As a result, post-bloom primary production on the SEBS shelf can still be a substantial proportion of annual primary production (Mueller-Karger *et al*., 1990; Sambrotto and Goering, 1983).

The different oceanographic domains on the SEBS shelf support distinct zooplankton and predator communities. Large copepods such as *Neocalanus cristatus*, *N. plumchrus*, and *Eucalanus bungii* are found in the oceanic and outer shelf domains, whereas smaller species such as *Pseudocalanus* spp., *Calanus marshallae*, and *Acartia* spp. predominate in the middle and inner shelf domains (Cooney and Coyle, 1982). The outer shelf and slope zooplankton communities are capable of assimilating a large proportion of the spring phytoplankton bloom and transferring energy up the pelagic food web, whereas on the shelf, a substantial portion of the bloom is not grazed by zooplankton and sinks to the benthos, supporting richer benthic communities over the inner- and middle-shelf domains. However, this response of shelf zooplankton to the spring bloom varies depending on the ice-bloom dynamics. When ice retreats early and an open-water, late spring bloom occurs, warmer water temperatures result in faster zooplankton growth and more efficient grazing. In a late ice-retreat year, the bloom occurs early in cold water, when zooplankton growth and grazing are slower. Under the warmer, early ice-retreat regime, recruitment of commercially valuable fish species such as Walleye Pollock was higher than in cold, late-ice retreat years, leading to the recent Oscillating Control Hypothesis (OCH) that recruitment and survival of piscivorous fish may be more strongly limited by bottom-up control, *i.e.* zooplankton availability, under a cold regime, and that top-down control (predation on larval and juvenile stages by adult fish) was a stronger control in warm years (Hunt *et al.*, 2002). The interactions of top-down and bottom-up controls within the SEBS ecosystem are complex and not always correctly predicted by the OCH, however (Mueter *et al.*, 2006), and further investigation of ecosystem dynamics and controlling mechanisms is certainly warranted.

## Ecosystem change

Climate change is having noticeable effects on both the physical and biological components of the Bering Sea ecosystem. Trends include an average withdrawal of sea ice from the southern Bering Sea, a decrease in summer wind speeds, and an average 1° C warming of the sea surface in summer (Hunt *et al.*, 2002), with an overall increase in temperature throughout the water column of about 3º C in the past decade (Stabeno and Salo, accepted). These changes are linked closely to the biological dynamics of the system including phytoplankton blooms, zooplankton production and distribution, and ultimately to North Pacific right whales, with potential impacts on their spatial and temporal distributions, foraging and reproductive success.

## Dissertation outline

The goals of this dissertation were to develop techniques for detecting North Pacific right whale calls in long-term acoustic recordings, to apply the results toward investigation of their seasonal occurrence and calling behavior, and to increase understanding of right whale habitat use in an oceanographic context. The results are reported in chapters 2 through 5 of this dissertation. Each chapter is intended to stand alone as a publication in a scientific journal, and may be somewhat redundant within the introduction and methods sections.

Chapter 2 discusses the development and evaluation of an automated call detection technique for finding right whale up-calls in large data sets. In contrast to species with highly stereotyped calls, such as blue whales or fin whales, right whales produce highly variable call types that increase in complexity with the complexity of the social interaction. We chose the simplest and most common call type, the up-call, on which to focus our detection efforts and as a reliable indication of right whale presence. Even within this call type, frequency and sweep characteristics vary substantially, and humpback whale calls also occur at similar frequencies making automatic detection a challenge. Chapter 2 was published in the journal Canadian Acoustics (Munger *et al.*, 2005) and is reprinted here with permission. The dissertation author was the primary researcher and author of this paper.

Chapter 3 describes the seasonal and daily calling behavior of North Pacific right whales in the Bering Sea. Interesting findings include the occurrence of right whales in the southeast Bering Sea later in the year than previously thought, and statistically significant patterns in diel right whale calling rates. Chapter 3 was submitted in full to the journal Marine Mammal Science. The dissertation author was the primary researcher and author.

Chapter 4 determines source levels of right whale calls and detection range, based on two different techniques for estimating distance to calling animals. The acoustic properties of right whale calls and effective detection range and distance estimates may prove useful in future estimates of abundance based on acoustic data. This chapter is in preparation for submission to Journal of the Acoustical Society of America. The dissertation author was the primary researcher and author.

Chapter 5 relates right whale occurrence to temporal variability in oceanographic habitat variables by comparing time series overlays of right whale calls and minimum abundance with temperature, salinity, chlorophyll concentration, ice retreat, and other data. A discussion is presented of possible linkages of seasonal, interannual, and longer-term climate variability to right whales via control of their primary prey, copepods. The dissertation author was the lead investigator and author of this chapter.

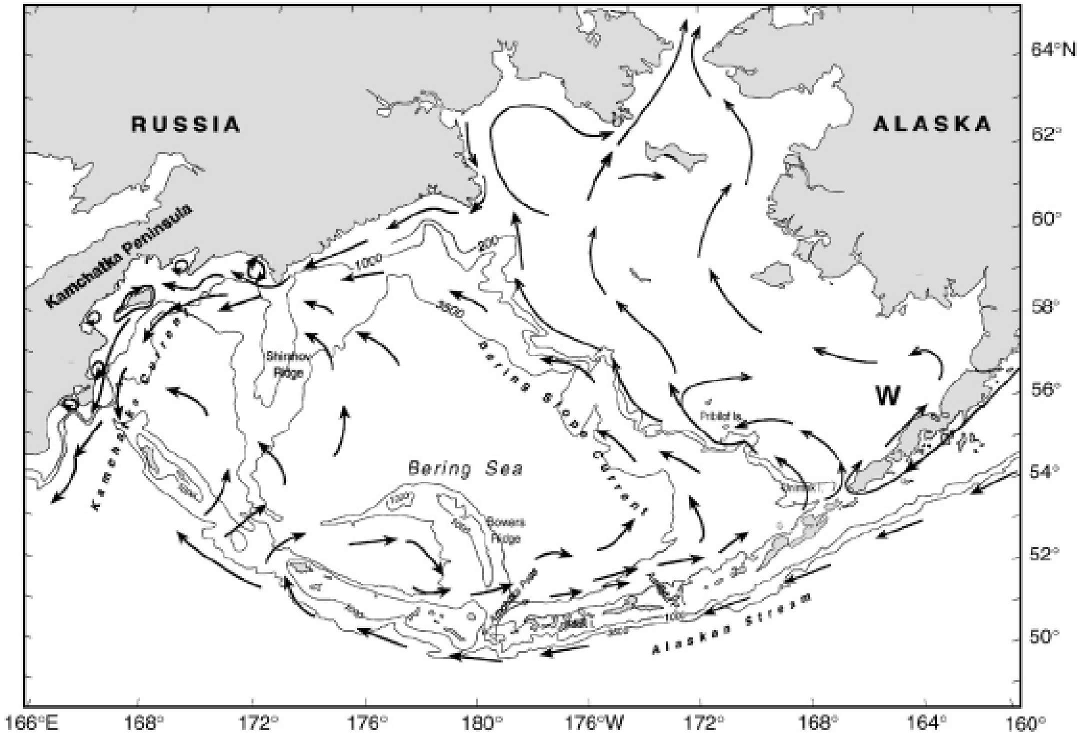


Figure 1.1. Schematic of Bering Sea upper-ocean circulation during summer (from Stabeno and Hunt, 2002).

## References

Aguilar A, 1986. A review of old Basque whaling and its effect on the right whales (*Eubalaena glacialis*) of the north Atlantic. Reports of the International Whaling Commission Special Issue:191-199.

Barlow J, 2005. Cruise Report: Structure of Populations, Levels of Abundance and Status of Humpbacks (SPLASH), Southwest Fisheries Science Center (SWFSC) Marine Mammal Cruise Number 1625. (United States Department of Commerce, NOAA, National Marine Fisheries Service, SWFSC 8604 La Jolla Shores Dr., La Jolla, CA 92037); 13 pp.

Baumgartner MF, Mate BR, 2003. Summertime foraging ecology of North Atlantic right whales. Marine Ecology-Progress Series 264:123-135.

Beardsley RC, Epstein AW, Chen CS, Wishner KF, Macaulay MC, Kenney RD, 1996. Spatial variability in zooplankton abundance near feeding right whales in the Great South Channel. Deep-Sea Research Part II-Topical Studies in Oceanography 43:1601-1625.

Benson AJ, Trites AW, 2002. Ecological effects of regime shifts in the Bering Sea and eastern North Pacific Ocean. Fish and Fisheries (Oxford) 3:95-113.

Brownell RL, Jr, Best PB, Prescott JH, 1986. Report of the Workshop on the Status of Right Whales. In: International Whaling Commission Right whales: past and present status Proceedings of the Workshop on the Status of Right Whales. New England Aquarium, Boston, Massachusetts 15-23 June 1983: Reports of the International Whaling Commission Special Issue No. 10; 1-14.

Brownell RL, Jr., Clapham PJ, Miyashita T, Kasuya T, 2001. Conservation status of North Pacific right whales. Journal of Cetacean Research and Management Special Issue 2:269-286.

Brueggeman JJ, Newby T, Grotefendt RA, 1986. Catch records of the twenty north Pacific right whales from two Alaska whaling stations, 1917-1939. Arctic 39:43-46.

Carretta JV, Lynn MS, LeDuc CA, 1994. Right whale (*Eubalaena glacialis*) sighting off San Clemente Island, California. Marine Mammal Science 10:101-105.

Clapham PJ, Good C, Quinn SE, Reeves RR, Scarff JE, Brownell RL, Jr., 2004. Distribution of North Pacific right whales (*Eubalaena japonica*) as shown by 19th and 20th century whaling catch and sighting records. Journal of Cetacean Research and Management 6:1-6.

Clark C, 1983. Communication and Behavior of the Southern Right Whale (*Eubalaena australis*). In: Communication and Behavior of Whales (Payne R, ed). Boulder, Colorado: Westview Press; 163-198.

Clark CW, 1981. Acoustic communication and behavior of the southern right whale. Dissertation Abstracts International B Sciences and Engineering 42:35.

Clark CW, 1982. The Acoustic Repertoire of the Southern Right Whale, a Quantitative-Analysis. Animal Behaviour 30:1060-1071.

Clark CW, Clark JM, 1980. Sound Playback Experiments with Southern Right Whales (*Eubalaena australis*). Science 207:663-665.

Coachman LK, 1986. Circulation, Water Masses, and Fluxes on the Southeastern Bering Sea Shelf. Continental Shelf Research 5:23-108.

Coachman LK, Walsh JJ, 1981. A Diffusion-Model of Cross-Shelf Exchange of Nutrients in the Southeastern Bering Sea. Deep-Sea Research Part a-Oceanographic Research Papers 28:819-846.

Cooney RT, Coyle KO, 1982. Trophic Implications of Cross-Shelf Copepod Distributions in the Southeastern Bering Sea. Marine Biology 70:187-196.

Doroshenko NV, 2000. Soviet whaling for blue, gray, bowhead and right whales in the North Pacific Ocean, 1961-1979. In: Soviet Whaling Data (1949-1979) (Yablokov AV, Zemsky VA, eds). Moscow: Center for Russian Environmental Policy; 96-103.

Edds-Walton PL, 1997. Acoustic communication signals of mysticete whales. Bioacoustics 8:47-60.

Gaines CA, Hare MP, Beck SE, Rosenbaum HC, 2005. Nuclear markers confirm taxonomic status and relationships among highly endangered and closely related right whale species. Proceedings of the Royal Society B-Biological Sciences 272:533-542.

Gendron D, Lanham S, Carwardine M, 1999. North Pacific right whale (*Eubalaena glacialis*) sighting south of Baja California. Aquatic Mammals 25:31-34.

Goddard PD, Rugh DJ, 1998. A group of right whales seen in the Bering Sea in July 1996. Marine Mammal Science 14:344-349.

Hunt GL, Stabeno P, Walters G, Sinclair E, Brodeur RD, Napp JM, Bond NA, 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. Deep-Sea Research Part II-Topical Studies in Oceanography 49:5821-5853.

Jin MB, Deal C, Wang J, Alexander V, Gradinger R, Saitoh S, Iida T, Wan ZW, Stabeno P, 2007. Ice-associated phytoplankton blooms in the southeastern Bering Sea. Geophysical Research Letters 34.

Kachel NB, Hunt GL, Salo SA, Schumacher JD, Stabeno PJ, Whitledge TE, 2002. Characteristics and variability of the inner front of the southeastern Bering Sea. Deep-Sea Research Part II-Topical Studies in Oceanography 49:5889-5909.

Kenney RD, Hyman MAM, Owen RE, Scott GP, Winn HE, 1986. Estimation of prey densities required by western north Atlantic right whales. Marine Mammal Science 2:1-13.

Leduc R, 2004. Report of the results of the 2002 survey for North Pacific right whales. United States Department of Commerce, NOAA, National Marine Fisheries Service, Southwest Fisheries Science Center (SWFSC), 8604 La Jolla Shores Dr., La Jolla, CA 92037; 58 pp.

LeDuc RG, Perryman WL, Gilpatrick JW, Jr., Hyde J, Stinchcomb C, Carretta JV, Brownell RL, Jr., 2001. A note on recent surveys for right whales in the southeastern Bering Sea. Journal of Cetacean Research and Management Special Issue 2:287-289.

Macklin SA, Hunt GL, Overland JE, 2002. Collaborative research on the pelagic ecosystem of the southeastern Bering Sea shelf. Deep-Sea Research Part II-Topical Studies in Oceanography 49:5813-5819.

Matthews JN, Brown S, Gillespie D, Johnson M, McLanaghan R, Moscrop A, Nowacek D, Leaper R, Lewis T, Tyack P, 2001. Vocalisation rates of the North Atlantic right whale (*Eubalaena glacialis*). Journal of Cetacean Research and Management 3:271-281.

McDonald MA, Moore SE, 2002. Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea. Journal of Cetacean Research and Management 4:261-266.

McRoy CP, Hood DW, Coachman LK, Walsh JJ, Goering JJ, 1986. Processes and Resources of the Bering Sea Shelf (Probes) - the Development and Accomplishments of the Project. Continental Shelf Research 5:5-21.

Mellinger DK, Stafford KM, Moore SE, Munger U, Fox CG, 2004. Detection of North Pacific right whale (*Eubalaena japonica*) calls in the Gulf of Alaska. Marine Mammal Science 20:872-879.

Moore SE, Waite JM, Mazzuca LL, Hobbs RC, 2000. Mysticete whale abundance and observations of prey associations on the central Bering Sea shelf. Journal of Cetacean Research and Management 2:227-234.

Mueller-Karger FE, McClain CR, Sambrotto RN, Ray GC, 1990. A Comparison of Ship and Coastal Zone Color Scanner Mapped Distribution of Phytoplankton in the Southeastern Bering Sea. Journal of Geophysical Research-Oceans 95:11483-11499.

Mueter FJ, Ladd C, Palmer MC, Norcross BL, 2006. Bottom-up and top-down controls of walleye pollock (Theragra chalcogramma) on the Eastern Bering Sea shelf. Progress in Oceanography 68:152-183.

Munger LM, Mellinger DK, Wiggins SM, Moore SE, Hildebrand JA, 2005. Performance of spectrogram cross-correlation in detecting right whale calls in long-term recordings from the Bering Sea. Canadian Acoustics 33:25-34.

Niebauer HJ, 1998. Variability in Bering Sea ice cover as affected by a regime shift in the North Pacific in the period 1947-1996. Journal of Geophysical Research-Oceans 103:27717-27737.

NMFS, 2006. Endangered And Threatened Species; Proposed Endangered Status for North Pacific Right Whale. NOAA, Department of Commerce, Federal Register: December 27, 2006; 77694-77704.

Omura H, 1986. History of right whale catches in the waters around Japan. Reports of the International Whaling Commission Special Issue:35-41.

Omura H, Ohsumi S, Nemoto T, Nasu K, Kasuya T, 1969. Black right whales in North Pacific. Scient Rep Whales Res Inst, Tokyo No. 21:1-78.

Parks SE, Hamilton PK, Kraus SD, Tyack PL, 2005. The gunshot sound produced by male North Atlantic right whales (*Eubalaena glacialis*) and its potential function in reproductive advertisement. Marine Mammal Science 21:458-475.

Parks SE, Tyack PL, 2005. Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups. Journal of the Acoustical Society of America 117:3297-3306.

Rosenbaum HC, Brownell RL, Brown MW, Schaeff C, Portway V, White BN, Malik S, Pastene LA, Patenaude NJ, Baker CS, Goto M, Best PB, Clapham PJ, Hamilton P, Moore M, Payne R, Rowntree V, Tynan CT, Bannister JL, DeSalle R, 2000. World-wide genetic differentiation of *Eubalaena*: questioning the number of right whale species. Molecular Ecology 9:1793-1802.

Rowntree V, Darling J, Silber G, Ferrari M, 1980. Rare sighting of a right whale (*Eubalaena glacialis*) in Hawaii. Canadian Journal of Zoology 58:309-312.

Salden DR, Mickelsen J, 1999. Rare sighting of a North Pacific right whale (*Eubalaena glacialis*) in Hawaii. Pacific Science 53:341-345.

Sambrotto RN, Goering JJ, 1983. Interannual variability of phytoplankton and zooplankton production on the southeast Bering Sea shelf. In: From Year to Year: Interannual Variability of the Environment and Fisheries of the Gulf of Alaska and the Eastern Bering Sea (Wooster WS, ed). Seattle: Washington State Sea Grant; 161-177.

Sambrotto RN, Niebauer HJ, Goering JJ, Iverson RL, 1986. Relationships among Vertical Mixing, Nitrate Uptake, and Phytoplankton Growth During the Spring Bloom in the Southeast Bering Sea Middle Shelf. Continental Shelf Research 5:161-198.

Scarff JE, 2001. Preliminary estimates of whaling mortality in the 19th century North Pacific right whale (*Eubalaena japonicus*) fishery, adjusting for struck-but-lost whales and non-American whaling. Journal of Cetacean Research and Management Special Issue 2:261-268.

Schumacher JD, Kinder TH, 1983. Low-Frequency Current Regimes over the Bering Sea Shelf. Journal of Physical Oceanography 13:607-623.

Shelden KEW, Moore SE, Waite JM, Wade PR, Rugh DJ, 2005. Historic and current habitat use by North Pacific right whales *Eubalaena japonica* in the Bering Sea and Gulf of Alaska. Mammal Review 35:129-155.

Springer AM, McRoy CP, Flint MV, 1996. The Bering Sea green belt: shelf-edge processes and ecosystem production. Fisheries Oceanography 5:205-223.

Stabeno PJ, Bond NA, Kachel NB, Salo SA, Schumacher JD, 2001. On the temporal variability of the physical environment over the south-eastern Bering Sea. Fisheries Oceanography 10:81-98.

Stabeno PJ, Hunt GL, 2002. Overview of the Inner Front and Southeast Bering Sea Carrying Capacity Programs. Deep-Sea Research Part II-Topical Studies in Oceanography 49:6157-6168.

Stabeno PJ, Hunt GLJ, Napp JM, Schumacher JD, 2006. Physical forcing of ecosystem dynamics on the Bering Sea shelf. In: The Sea, Vol 14 (Robinson AR, Brink K, eds): The Global Coastal Ocean: Interdisciplinary Regional Studies and Syntheses, Part B, Harvard University Press; 1177–1212.

Stabeno PJ, Kachel NB, Sullivan M, Whitledge TE, 2002a. Variability of physical and chemical characteristics along the 70-m isobath of the southeastern Bering Sea. Deep-Sea Research Part II-Topical Studies in Oceanography 49:5931-5943.

Stabeno PJ, Reed RK, Napp JM, 2002b. Transport through Unimak Pass, Alaska. Deep-Sea Research Part II-Topical Studies in Oceanography 49:5919-5930.

Stabeno PJ, Salo SA, (accepted). On the recent warming of the southeastern Bering Sea shelf. Progress in Oceanography.

Stabeno PJ, Van Meurs P, 1999. Evidence of episodic on-shelf flow in the southeastern Bering Sea. Journal of Geophysical Research-Oceans 104:29715-29720.

Tynan CT, DeMaster DP, Peterson WT, 2001. Endangered right whales an the southeastern Bering Sea shelf. Science 294:1894-1894.

Vanderlaan ASM, Hay AE, Taggart CT, 2003. Characterization of North Atlantic right-whale (*Eubalaena glacialis*) sounds in the Bay of Fundy. IEEE Journal of Oceanic Engineering 28:164-173.

Wade P, Heide-Jorgensen MP, Shelden K, Barlow J, Carretta J, Durban J, Leduc R, Munger L, Rankin S, Sauter A, Stinchcomb C, 2006. Acoustic detection and satellite-tracking leads to discovery of rare concentration of endangered North Pacific right whales. Biology Letters 2:417-419.

Waite JM, Wynne K, Mellinger DK, 2003. Documented sighting of a North Pacific right whale in the Gulf of Alaska and post-sighting acoustic monitoring. Northwestern Naturalist 84:38-43.

Woodhouse CD, Jr., Strickley J, 1982. Sighting of northern right whale (*Eubalaena glacialis*) in the Santa Barbara Channel. Journal of Mammalogy 63:701-702.

# II. Performance of spectrogram cross-correlation in detecting right whale calls in long-term recordings from the Bering Sea

## Abstract

We investigated the performance of spectrogram cross-correlation for automatically detecting North Pacific right whale (*Eubalaena japonica*) calls in long-term acoustic recordings from the southeastern Bering Sea. Data were sampled by autonomous, bottom-mounted hydrophones deployed in the southeastern Bering Sea from October 2000 through August 2002. A human analyst detected right whale calls within the first month (October 2000) of recorded data by visually examining spectrograms and by listening to recorded data; these manual detections were then compared to results of automated detection trials. Automated detection by spectrogram cross-correlation was implemented using a synthetic kernel based on the most common right whale call type. To optimize automated detection parameters, the analyst performed multiple trials on minutes-long and hour-long recordings and manually adjusted detection parameters between trials. A single set of optimized detection parameters was used to process a week-long recording from October 2000. The automated detector trials resulted in increasing proportions of false and missed detections with increasing data set duration, due to the higher proportion of acoustic noise and lower overall call rates in longer recordings. However, the automated detector missed only one calling "bout" (2 or more calls within a 10-minute span) of the 18 bouts present in the week-long recording. Despite the high number of false detections and missed individual calls, spectrogram cross-correlation was useful to guide a human analyst to sections of data with potential

right whale calling bouts. Upon reviewing automatic detection events, the analyst could quickly dismiss false detections and search recordings before and after correct detections to find missed calls, thus improving the efficiency of searching for a small number of calls in long-term (months- to years-long) recordings.

## Introduction

Long-term, passive acoustic recorders are useful tools for monitoring some marine mammal populations, with potential applications ranging from providing information on behavioral ecology and abundance, to near-real-time localization and tracking of calling animals (*e.g.* Thompson and Friedl 1982, Clark *et al.* 1996, Stafford *et al.* 2001, Gillespie and Leaper 2001, Moscrop *et al.* 2004, Mellinger *et al.* 2004a, b). We used autonomous, bottom-mounted Acoustic Recording Packages (ARPs) (Wiggins 2003) to provide long-term recordings of critically endangered North Pacific right whales (*Eubalaena japonica*) (Brownell *et al*. 2001) and other baleen whale species in the southeast Bering Sea. Here, small numbers (tens) of right whales have been regularly observed since 1996 in the middle-shelf region (between the 50 m and 100 m isobaths) in summer months (Goddard and Rugh 1998, LeDuc *et al.* 2001, LeDuc 2004). We deployed and recovered five ARPs from four sites in the right whale sighting region in 2000-2002 (Figure 2.1). The ARPs recorded sound continuously in a frequency range (5 to 250 Hz) encompassing that of most North Pacific right whale calls (McDonald and Moore 2002), and provided 36 instrument-months totaling over 100 gigabytes of data.

Because of a paucity of data on eastern North Pacific right whales, each recorded right whale call could contribute to a better understanding of this population. However, manually detecting each right whale call in this large data set would potentially require hundreds of hours of human effort to scan spectrograms visually and to listen to recordings. In contrast, a computer using automated detection software could potentially process a year-long data set within hours to days, and human effort could be focused on reviewing automated detection results and searching for additional calls near times of automatic call detections. We found that automated call detection using spectrogram cross-correlation was effective for detecting bouts of right whale calling in long-term acoustic recordings from the Bering Sea. This paper evaluates the performance of spectrogram cross-correlation in detecting right whale calls within a subset of Bering Sea ARP data.

North Pacific right whales were first recorded in the Bering Sea in 1999 by McDonald and Moore (2002). The most common right whale call type (85%, n=511) was an ‘up’ call, sweeping up in frequency on average from 90 to 150 Hz in 0.7 s (McDonald and Moore 2002). North Pacific right whale calls and the proportion of different call types were similar to call repertoires of other right whale species (*Eubalaena* spp.) (Clark 1982, Matthews *et al.* 2001). Similarly to North Atlantic right whale calls (Matthews *et al.* 2001, Vanderlaan *et al.* 2003), North Pacific right whale calls were clustered in sporadic ‘bouts’ lasting several minutes, with longer silences (tens of minutes to hours) between bouts (McDonald and Moore 2002).

Automated right whale call detection in Bering Sea acoustic data was challenging for a number of reasons. Right whale call durations were brief (• 1 s), and calls were variable in duration, start and end frequencies, and frequency sweep rates (Figure 2.2, McDonald and Moore 2002). Calls may also have become distorted at the receiver due to the dispersion of normal modes over the flat, shallow continental shelf (Wiggins *et al.* 2004). Overall, calls received on ARPs were infrequent and the total number of calls was low. Flow and strum noise on hydrophones was frequently exacerbated by storms and strong tidal currents characteristic of the Bering Sea middle-shelf (Bond and Adams 2002, Coachman 1986). Also adding to the challenge of automated detection, humpback whales (*Megaptera novaeangliae*) produced sounds (Figure 2.3), including upswept calls, in the same frequency band used by right whales and recorded by the ARPs.

A variety of automated call detection techniques are available, including matched filtering, spectrogram correlation, energy summation, and neural networks (Stafford *et al.* 1998, Mellinger and Clark 2000, Mellinger 2004, Mellinger *et al.* 2004b). The performance of each of these techniques often depends on the characteristics of a particular species' acoustic repertoire and behavior and the physical environment in which they are recorded. For example, matched filtering works well when calls are highly stereotyped, and energy summation works well for species that call often and in a frequency band isolated from other sounds (*e.g.*, calls from other species, ship engine noise, cable strumming) (Mellinger 2004). Some techniques, such as neural networks, require a large training set of calls. Right whale calls in Bering Sea ARP recordings were not well suited to matched filtering, energy summation, or neural networks.

The challenges of right whale call detection in our data set led us to investigate spectrogram cross-correlation with a synthetic kernel because this method a) does not require a large training set of calls, b) may be more suited to detecting brief and infrequent calls in a large and often noisy data set, and c) may be less sensitive to variation and distortion among calls than the other techniques (Mellinger 2004). We configured the automated detector to detect ‘up’ calls, the most common call recorded from North Pacific right whales in the Bering Sea (McDonald and Moore 2002, Munger and Sauter unpub. data, Munger and Rankin unpub. data). In this study, we optimized automated detection parameters using short-duration recordings, and then evaluated the performance of optimized parameters in processing a week-long recording.

## Methods

### Data sets

ARPs were configured to record continuously at a sampling frequency of 500 Hz, with a frequency response of -152 dB re 1 V/µPa, flat within 1 dB over the 5-250 Hz frequency band (Wiggins 2003). Acoustic data were digitized to 16-bit samples and stored on computer hard disks to be analyzed after instrument recovery.

Three subsets of acoustic data from the year-2000 ARP recordings were used to test the automated detector: short-, intermediate-, and long-duration recordings. Short- and intermediate-duration recordings were chosen from previously manually processed data to provide the detector with training sets of calls with which to optimize detection parameters. Short recordings contained right whale ‘up’ calls, humpback whale calls, a combination of both, or no discernible calls; intermediate and long recordings were continuous sections of data containing periods of noise and calls from right and humpback whales.

The first data subset consisted of twelve short (1-to 5-minute) recordings made at different times by four ARPs during October-December 2000. Six of these recordings contained calls in the 80-250 Hz bandwidth, with a total of 26 right whale ‘up’ calls. The other six recordings contained no calls in that frequency range and varied in acoustic noise levels (Figure 2.4). The average overall right whale call rate in the short data set was 1.96 calls per minute.

The second data subset consisted of four intermediate-length recordings, 65 minutes each (Figure 2.2), recorded simultaneously on each of the four ARPs on October 3, 2000. Each of these recordings contained right whale and humpback whale calls in the 80-250 Hz band, including 72 right whale ‘up’ calls. The overall average right whale call rate in intermediate-length recordings was 0.28 calls per minute. The intermediate-length recordings did not have any data in common with the short recordings.

The third data subset was a single recording approximately one week in length, taken from the ARP at site C on 2-9 October 2000. This long recording did not share common data with the short recordings, but did encompass the hour recorded by ARP C in the intermediate-length data set. Whale calls were present in at least five days of the week-long data set; these included humpback calls (Figure 2.3) and 146 right whale ‘up’ calls, the majority of which were recorded during the first three days. The average right whale call rate over the week-long recording was 0.015 calls per minute.

### Manual call detection

After evaluating right whale acoustics literature and discussing right whale call types with colleagues, the human analyst (LMM) visually scanned spectrograms and listened to potential calls throughout the first month of ARP recordings (October 2000). One difficulty in detecting right whale calls was distinguishing between calls of humpback whales and right whales. Humpback whales produced some sounds in the same frequency band as right whales, including short-duration upswept or downswept calls. The most important distinguishing feature in our Bering Sea data set proved to be the temporal pattern of calls. Right whales produced calls (Figure 2.2) in sporadic bouts, whereas humpback whales produced calls in consistent, repeated patterns (Figure 2.3). Patterned humpback calling (song) has been reported in late summer/early fall on other northern feeding grounds as well (Mattila *et al.* 1987, McSweeney *et al.* 1989). In addition, ARP recordings of humpback calls and call series often contained harmonics and higher-frequency components, whereas right whale calls were typically tonal upsweeps without harmonics.

The human analyst (LMM) used a software program (*Triton*, Wiggins 2003) written in MATLAB® (The MathWorks, http://www.mathworks.com) to generate and display spectrograms of the ARP data sets. Time series were transformed into the frequency domain using a Fast Fourier Transform (FFT) with a Hanning window (Oppenheim and Schafer 1999). FFT and window length were both 512 points (1.024 s) and overlap was 75-90%. Graphical gain and contrast were adjusted to give the best resolution of the spectrogram. During visual scanning of sequential spectrograms, the time-frequency display window was 0-250 Hz in frequency and usually 60-120 s in duration. When the analyst detected a potential right whale call in the displayed spectrogram, the call portion of the display was expanded in time and spectral parameters were adjusted to ‘sharpen’ the image--for example, by reducing FFT and window length and increasing the amount of overlap. In addition, potential right whale calls were also played on speakers, to provide the analyst an opportunity to aurally detect and distinguish right whale calls from humpbacks if visual detection was ambiguous.

The analyst noted only right whale 'up' calls for the purposes of this comparative study because the automated detector was configured to detect only 'up' calls. The set of manually-picked right whale 'up' calls provided the basis for comparing automated detection results.

### Automated detection

We used the software program *Ishmael* (Mellinger 2001) for call detection by spectrogram cross-correlation. Spectrograms were generated in *Ishmael* using the same parameters as used in *Triton* to manually detect calls: frame, FFT, and Hanning window length were equal to 512 points (1.024 s), and overlap was 75-94%. ARP spectral data were cross-correlated with a synthetic spectrogram kernel (Mellinger and Clark 2000), which we based on the 'up' calls found in our data sets and consistent with those described in McDonald and Moore (2002). The synthetic call kernel consisted of piecewise, continuous line segment(s) defined by start and end times and their corresponding start and end frequencies (Figure 2.5). Other detection parameters that were adjusted included the instantaneous bandwidth of the synthetic call kernel (Figure 2.5), detection threshold, minimum and maximum duration above the detection threshold, and spectrogram equalization time constant (time-averaging to smooth out background noise) (Van Trees 1968; Mellinger 2001, 2004; Mellinger *et al.* 2004a). The minimum time between detections was set to 0 seconds to avoid missing close or overlapping calls.

The spectrogram cross-correlation output is a time series of the unnormalized cross-correlation, which varies with the closeness of the match between the data and the predefined kernel; function peaks above a user-specified threshold are counted as detection events. If the parameters we chose resulted in zero detection events, we discarded that set of parameters and did not include them in this analysis. When detection events occurred, we adjusted one parameter at a time and observed the resulting effect on detector performance. If performance improved and resulted in fewer false detections and/or missed detections, we adjusted the other parameters in an attempt to further minimize missed detections and false detections.

We ran 62 automated detection trials using the short recordings, 22 trials using the intermediate-length recordings, and 1 trial using the week-long recording. Each automated detection event was saved individually as a short (~10 s) sound file. After each detector trial, a human analyst examined each individual detection event to verify whether the detection was correct. Automated detections were classified as correct detections (right whale 'up' calls) or false detections. False detections were further categorized as other biological sounds, including non-upswept calls or calls identified to be from humpback whales, or noise, in which no call was present.

We compared the performance of various detection parameters by plotting receiver operating characteristic (ROC) curves illustrating the trade-off between false detections and missed calls. False detections were expressed as a percentage of the total number of automated detections. Missed calls were expressed as percentages of the total number of 'up' calls in the data set, which was defined as the number of manually detected 'up' calls. We designated an acceptable missed call threshold of 20%, and defined ‘optimal’ detection parameters as those that minimized false detections while missing fewer than 20% of calls. We set this missed call threshold because right whale calls were rare in our data set and we wished to detect a substantial majority of them; although this caused an increase in false detections, reviewing and discarding false detections was still a simple and relatively fast process for an analyst compared to thoroughly manually processing the entire recording. Optimal parameters from trials using short recordings were included in detector trials run on intermediate-length recordings, and the optimal parameters from trials using intermediate recordings were used to process the week-long recording.

## Results

For ease of interpretation, we separated automated detection results for short (minutes-long) recordings into results using a single synthetic kernel, and those using different kernel types with varying slopes and numbers of segments. The automated detector that performed best on the short recordings used a 1 s, 100-150 Hz synthetic kernel (Table 2.1, Figure 2.6). The optimal parameters (resulting in fewer than 20% missed calls and minimal false detections) with this single kernel type resulted in 19% missed detections (5 of 26 calls) and 25% false detections (7 of 28 total detections) (Figure 2.6, Table 2.2). A large proportion (86%) of false detections contained other biological sounds.

Table 2.3 shows the detection parameters used with synthetic kernels that consisted of one or more segments of varying duration and start/end frequencies. The corresponding ROC curves for those parameters were plotted in Figure 2.7. The optimal synthetic kernel in this case (resulting in fewer than 20% missed calls and minimal false detections), consisted of 2 segments: the first 1 s and 100 to 150 Hz, and the second 0.5 s from 150 to 180 Hz. These parameters resulted in 19% missed detections and 42% false detections (Figure 2.7, Table 2.4), 80% of which were other biological sounds. The varied synthetic call kernels that we tested did not perform as well as the single-segment 1 s, 100-150 Hz kernel.

Detection parameters and results for intermediate-length recordings are shown in Table 2.5, Figure 2.8, and Table 2.6. In addition to varying the same parameters as in short-recording trials, we used spectrogram equalization (time-averaging to smooth background noise) in some trials; this was not done for short recordings because averaging over seconds was inappropriate for recordings lasting tens of seconds. For the same acceptable level of missed detections (20%), the optimal detection parameters resulted in 69% false detections and 19% missed calls. 31% of these false detections in intermediate-length recordings were other biological sounds. (Figure 2.8, Table 2.6). Although we tested varying synthetic kernels, the optimal detection parameters were again based on a single 1 s, 100-150 Hz segment, and did not employ spectrogram equalization.

The detection parameters used for the week-long recording were the optimal parameters resulting from trials using hour-long recordings. The detection results using the week-long recording are summarized in Table 2.7 and displayed as a single data point on Figure 2.8a. False detections comprised 98% of the total number of detections, and approximately 38% of detectable calls were missed. Of the false detections, 10% were other biological sounds. Figure 2.9 compares the number of manual and automated detections of right whale ‘up’ calls over the first three days (when most of the right whale calls were detected) of the week-long ARP recording. We defined a calling ‘bout’ as at least 2 calls within a ten-minute time span; although not all calls in a single bout were detected, the automated detector missed only one of 18 total bouts in the week-long recording, and missed 3 calls occurring singly.

To investigate whether false detection rates were related to acoustic noise levels, we compared noise levels in the recordings by calculating average spectral levels between 100 and 150 Hz over 1-minute time intervals in hour-long recordings and 10-minute intervals in the week-long recording (time intervals were shorter for the hour-long recordings to give better graphical resolution). The percentage of false detections during the intermediate-length test recordings differed significantly between each of the four ARPs, and was highest on ARP A (average false detection proportions: A=89.8%, B=57.0%, C= 59.8%, D= 77.3%; ANOVA, $p<0.05$), which also had the highest average noise level over the hour of recording (Figure 2.10).

Noise levels varied more over one week on an individual instrument (ARP C) than they did between instruments during the hour recorded in the intermediate-length test data (Figure 2.10). During the week recorded on ARP C, a semidiurnal tidal signature was apparent during the first three days of recording, and an overall rise in noise during days 280-282 was caused by a storm. Peaks in noise on days 279 and 280 were related to passing ships—closer inspection of spectrograms revealed long, continuous tones at 60 Hz and higher harmonics typical of engine-related noise.

## Discussion

Using spectrogram correlation with manually optimized detection parameters, the automated detectors we tested performed best on the short (minutes-long) sound recordings, with increasing proportions of false and missed detections as the recording duration increased. The increase in the proportion of false detections with the recording length was expected, because the longer recordings contained longer periods of noise relative to the number of right whale calls present and provided more opportunities for the detector to produce false detections. The short- and intermediate-length recordings were used to optimize detection parameters and consequently represented relatively high rates of right whale calling (approximately 2 calls/minute in the minute(s)-long recordings and 0.3 calls/min in the hour-long recordings), whereas the week-long recording contained 0.02 calls/min. Because the longer data sets contained more calls in total (72 calls in intermediate-length data set and 146 calls in week-long data set), there was increased potential for variation among calls, possibly contributing to the higher proportion of missed detections caused by a mismatch between calls and the synthetic kernel.

The automated detection trials also resulted in high rates of detection of other biological sounds: over 80%, 31%, and 10% of the false detections were biological sounds for short, intermediate, and long recordings, respectively. These other sounds included upswept calls from humpback whales, as well as other call types (down-swept calls, moans, pulses) that potentially could have been made by humpbacks or right whales. Although these were classified as false detections (because they were not right whale ‘up’ calls), a human analyst in practice would likely be interested in reviewing these sounds as well, especially if the goal is to correctly detect and classify each rare right whale call during the post-processing of a large data set.

The automated detector produced over 90% false detections and missed over one-third of the right whale ‘up’ calls in the week-long data recording. These results were poor compared to some other marine mammal acoustic detection studies, in which automated detection software missed relatively fewer calls, categorized a greater proportion of calls correctly, and produced a smaller percentage of false detections (Mellinger and Clark 2000; Niezrecki *et al.* 2003; Mellinger *et al.* 2004a,b). Some factors contributing to the high missed call rate in our study were variability among calls (McDonald and Moore 2002), distortion resulting from waveform dispersion (Wiggins *et al.* 2004), and high acoustic noise levels resulting in decreased signal-to-noise ratios (SNR) of calls.

Acoustic noise recorded by hydrophones in the Bering Sea was often high due to strong tidal currents and frequent storms (Figure 2.10b). The lack of detections in the week-long recording during approximately days 280-282, when the noise level was highest (Figure 2.10), could have been due to masking by that noise or to an actual lack of whale calls. A rise in noise level may decrease the acoustic detection range and could explain the lack of detected calls. High acoustic noise levels also contributed to high false detection rates; during the hour-long recording, ARP A had both the highest false detection rate and highest average noise level in the call frequency band (Figure 2.10). It is not clear whether the relatively higher noise on ARP A was due to differences in instrument calibration or actual differences in acoustic noise. Noise levels varied more over a long duration of time on a single instrument than between instruments during the same short time period (Figure 2.10); therefore any effects of ARP calibration on detector performance were probably overshadowed by the much larger fluctuations in acoustic noise over time due to events such as tides, storms, and passing ships.

Despite the high rates of false and missed detections, automated call detection by spectrogram correlation was nevertheless useful for our complete ARP data set. Although a human analyst reviewed all of the automated detections, this process was considerably more time-efficient than thoroughly scanning the entire data set manually. In our trial using the week-long recording, the detection parameters we used missed only one of 18 right whale calling 'bouts' (Figure 2.9). Automated spectrogram correlation, optimized for a low number of missed detections, was thus helpful in directing a human analyst to periods in the data when additional calls were likely to be found near the automated call detection. The combination of automated detection with manual verification and focused searching has been used effectively in detecting North Pacific right whale calls in the Gulf of Alaska (Waite *et al.* 2003, Mellinger *et al.* 2004b), as well as in other long-term right whale data sets (Clark *et al.* 2000).

Due to the paucity of data on right whales in the eastern North Pacific, our primary goal in developing an automated right whale call detector was to maximize the number of right whale calls detected, and the concomitant increase in high false detection rates was acceptable during this study. Detection techniques other than spectrogram cross-correlation, such as neural networks (Mellinger 2004), may become more feasible as we increase the set of known calls recorded in the presence of North Pacific right whales. Current and future deployments of passive acoustic recorders in the Gulf of

Alaska and Bering Sea will provide new data that will require efficient processing and benefit from improved automated detection techniques. For the ARP data set described in this study, automated detection using spectrogram correlation was useful to direct a human analyst to potential right whale calling bouts and was more time-efficient than manual call detection.

## Acknowledgements

The authors thank NOAA/National Marine Mammal Laboratory for supporting the fabrication, deployment, and recovery of Acoustic Recording Packages in the Bering Sea (JIMO budget #NA17RJ1231). We also thank the North Pacific Marine Research Institute (project #T-2100) and North Pacific Research Board (project #R0307) for supporting data processing, outreach and travel to study areas. The work was also supported by ONR contracts N00014-03-1-0099 and N00014-03-1-0735. This is PMEL contribution #2700.

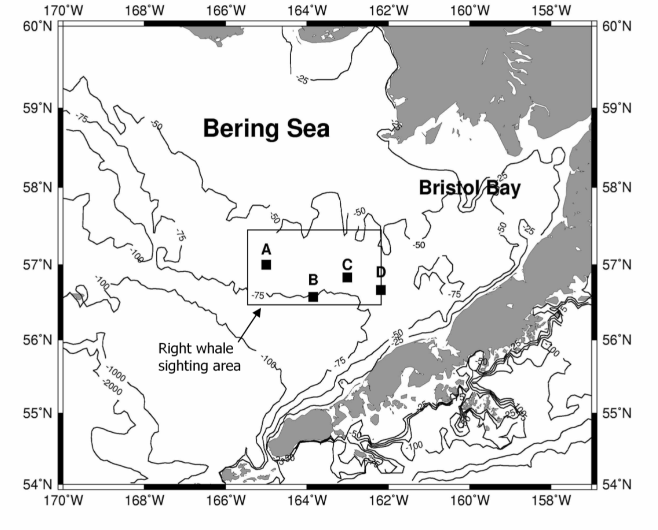


Figure 2.1. ARP sites A through D, year 2000-2002. Recordings in 2000-01 were from all four sites; recordings the following year (2001-02) were from site C only. Bathymetric contours are displayed at 25-meter increments for depths up to 100 m, and at 1000-m increments for depths of more than 100 m. Right whale visual sighting locations in the Bering Sea since 1996 are bounded by the 'sighting area' box.

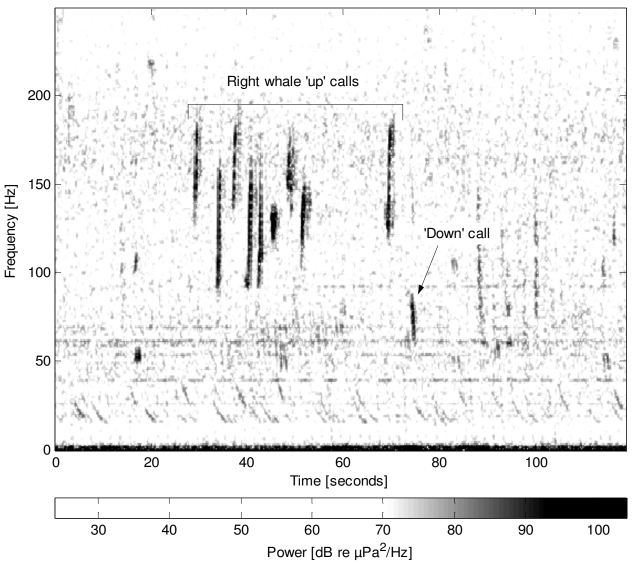


Figure 2.2. Two-minute excerpt of hour-long recording containing right whale calls, recorded by ARP at site C, 3 October 2000. Spectrogram parameters: 512 point frame and FFT length with same size Hanning window, 75% overlap, for a filter bandwidth of 4.0 Hz. Also visible throughout are fin whale downsweeps from 35-15 Hz.

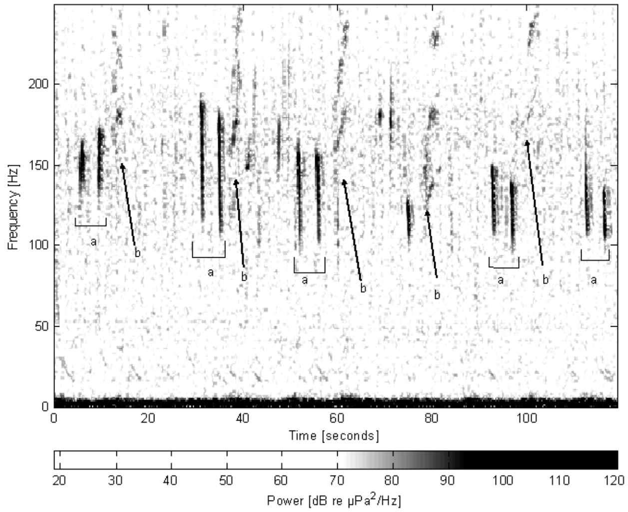


Figure 2.3. Two-minute excerpt containing humpback whale calls from week-long sound recording, recorded by ARP at site C. Repeated calls are labeled ‘a’ and ‘b’ to show pattern. Spectrogram parameters same as in Figure 2.2.

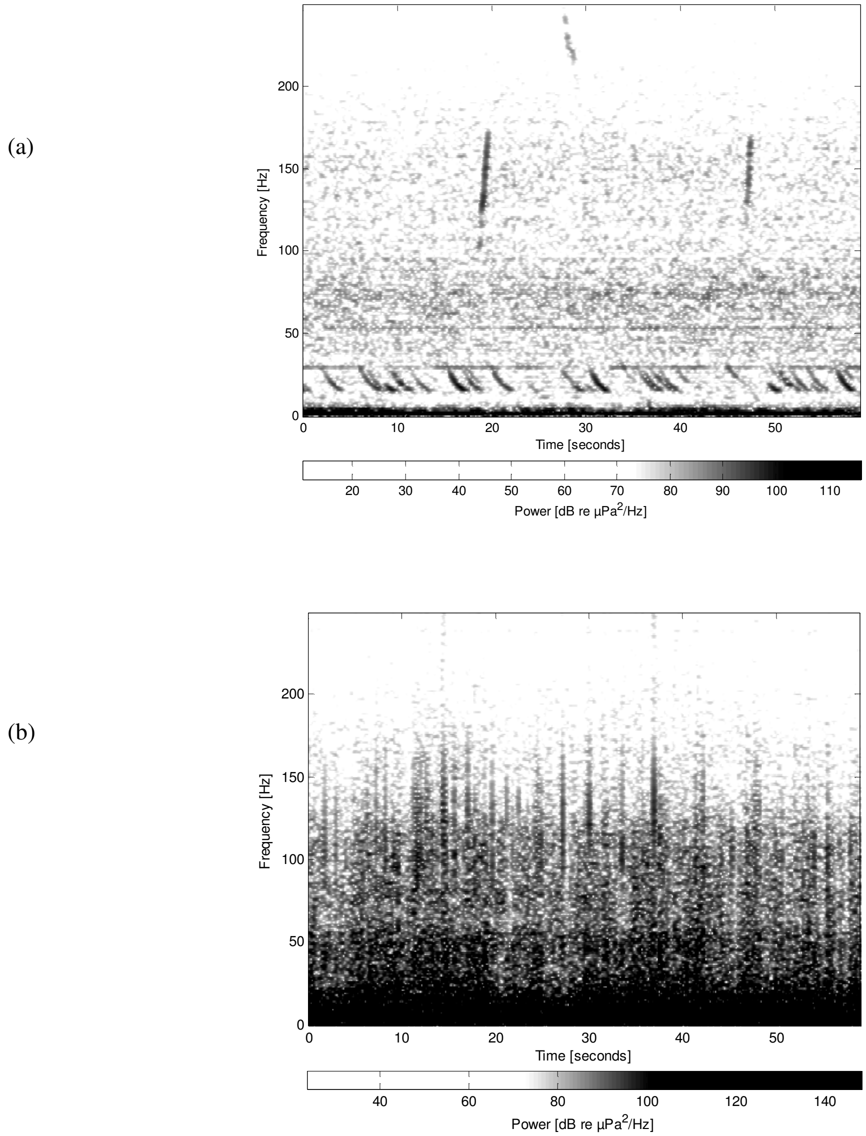


Figure 2.4. Two examples of sixty-second recordings containing a) right whale ‘up’ calls at approximately 18 s and 47 s, and b) only noise. Spectrograms parameters same as in Figure 2.2 except 90% overlap.

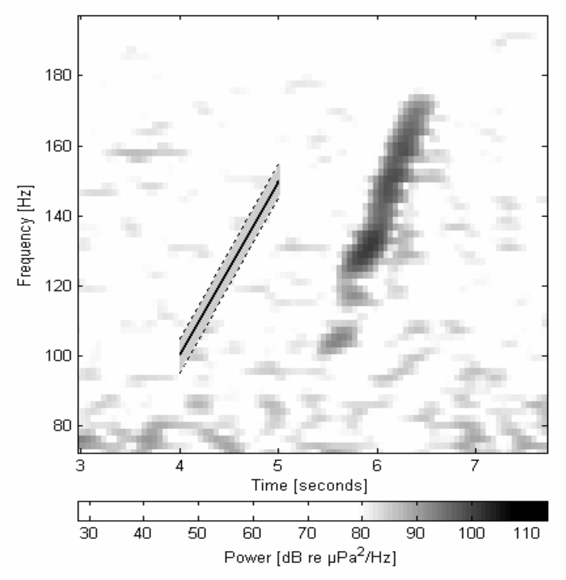
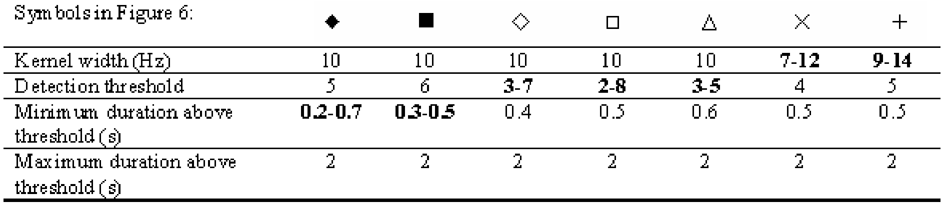


Figure 2.5. Synthetic call kernel (light gray) from 100 to 150 Hz, lasting 1 s, with 'kernel bandwidth' of 10 Hz bounded by dotted lines. The synthetic kernel precedes a spectrogram of a right whale call, enlarged from Figure 2.4a at 18 s. Spectrogram parameters: 256-point frame, FFT, and Hanning window length, and 90% overlap, for a filter bandwidth of 7.9 Hz.

Table 2.1. Detection parameters tested in short recording trials; the synthetic call kernel in all of these tests was a 1 s, 100-150 Hz line segment as in Figure 2.5. The ranges of varying parameters are shown in bold type. Symbols correspond to markers in Figure 2.6.



| Symbols in Figure 6: | ◆ | ■ | ◇ | □ | △ | × | + |
|---|---|---|---|---|---|---|---|
| Kernel width (Hz) | 10 | 10 | 10 | 10 | 10 | **7-12** | **9-14** |
| Detection threshold | 5 | 6 | **3-7** | **2-8** | **3-5** | 4 | 5 |
| Minimum duration above threshold (s) | **0.2-0.7** | **0.3-0.5** | 0.4 | 0.5 | 0.6 | 0.5 | 0.5 |
| Maximum duration above threshold (s) | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

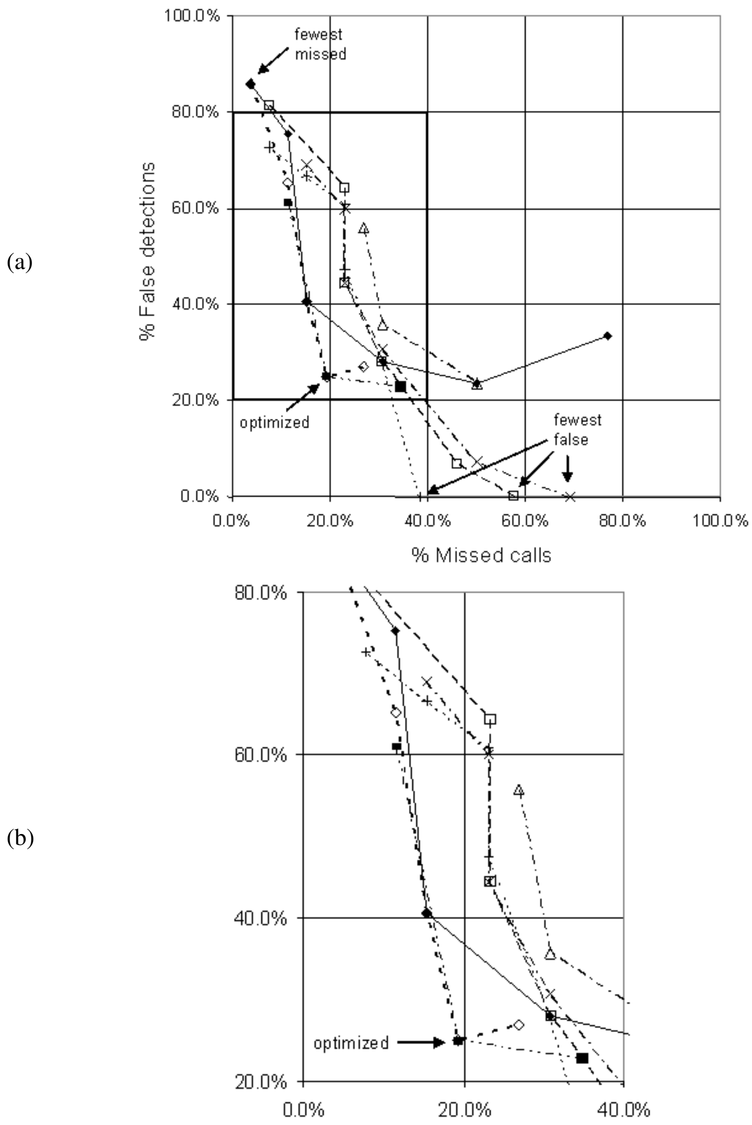
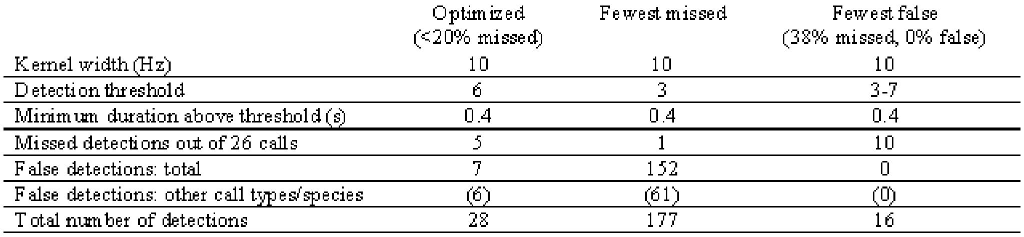


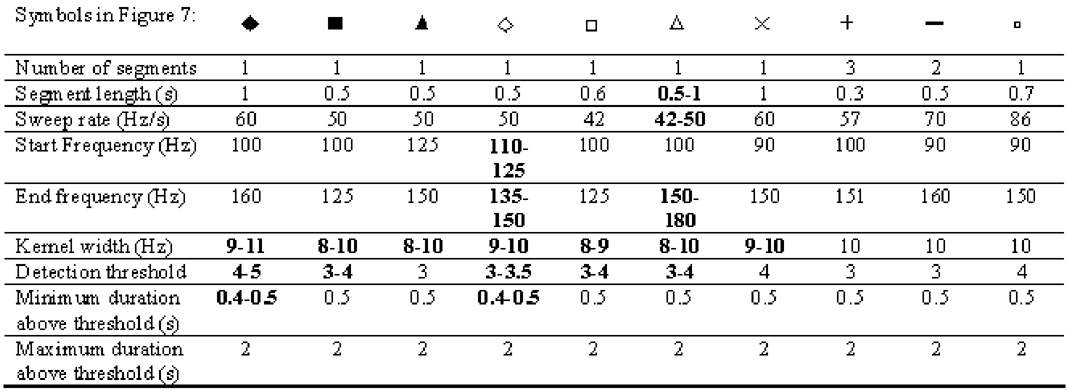
Figure 2.6. a) Results of automated detection trials using short recordings, and parameters and symbols from Table 2.1. Each curve is the result of varying one detection parameter and measuring resulting rates of false detections and missed calls. False detections are expressed as a percentage of the total number of automated detections; missed calls are expressed as a percentage of the total number of manually detected calls. Results for 'optimized', 'fewest missed', and 'fewest false' data points are given in Table 2.2. b) Area within thickened line in 6a is expanded in Figure 2.6b.

Table 2.2. Detection parameters and results for the ‘optimized’ data point (using a predefined threshold of 20% missed calls), ‘fewest missed’ calls, and ‘fewest false’ detections (Figure 2.6) using short recordings and synthetic kernel of 1 s, 100-150 Hz. False detection total includes other biological sounds, which are reported in parentheses.



| | Optimized (<20% missed) | Fewest missed | Fewest false (38% missed, 0% false) |
|---|---|---|---|
| Kernel width (Hz) | 10 | 10 | 10 |
| Detection threshold | 6 | 3 | 3-7 |
| Minimum duration above threshold (s) | 0.4 | 0.4 | 0.4 |
| Missed detections out of 26 calls | 5 | 1 | 10 |
| False detections: total | 7 | 152 | 0 |
| False detections: other call types/species | (6) | (61) | (0) |
| Total number of detections | 28 | 177 | 16 |

Table 2.3. Range of detection parameters tested in short recording trials when varying the structure of the synthetic call kernel. The ranges of varying parameters are shown in bold type. Symbols correspond to markers in Figure 2.7.



| Symbols in Figure 7: | ◆ | ■ | ▲ | ◇ | □ | △ | × | + | ━ | ▫ |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of segments | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 2 | 1 |
| Segment length (s) | 1 | 0.5 | 0.5 | 0.5 | 0.6 | **0.5-1** | 1 | 0.3 | 0.5 | 0.7 |
| Sweep rate (Hz/s) | 60 | 50 | 50 | 50 | 42 | **42-50** | 60 | 57 | 70 | 86 |
| Start Frequency (Hz) | 100 | 100 | 125 | **110-125** | 100 | 100 | 90 | 100 | 90 | 90 |
| End frequency (Hz) | 160 | 125 | 150 | **135-150** | 125 | **150-180** | 150 | 151 | 160 | 150 |
| Kernel width (Hz) | **9-11** | **8-10** | **8-10** | **9-10** | **8-9** | **8-10** | **9-10** | 10 | 10 | 10 |
| Detection threshold | **4-5** | **3-4** | 3 | **3-3.5** | **3-4** | **3-4** | 4 | 3 | 3 | 4 |
| Minimum duration above threshold (s) | **0.4-0.5** | 0.5 | 0.5 | **0.4-0.5** | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Maximum duration above threshold (s) | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

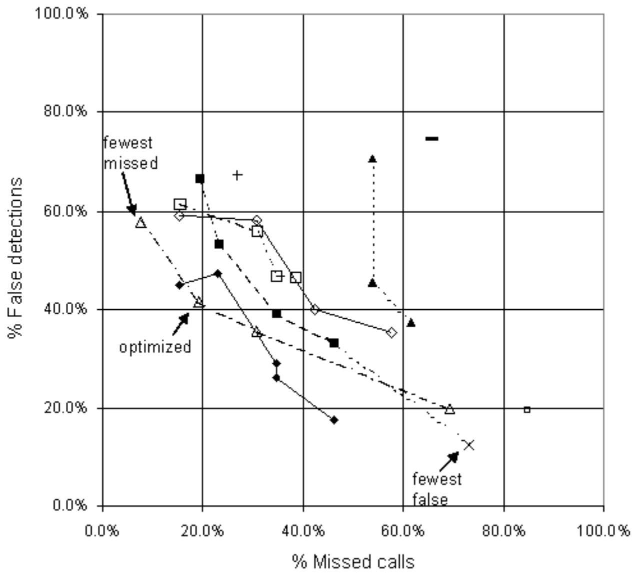
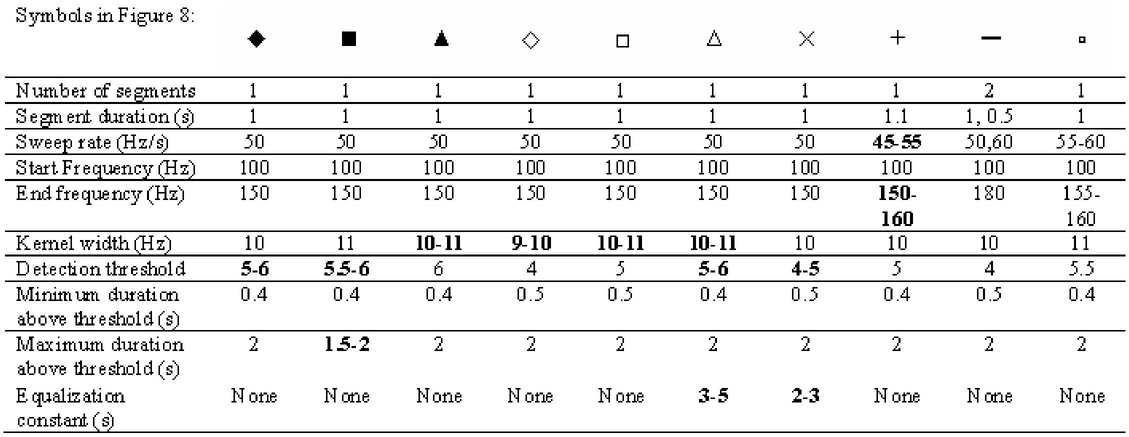


Figure 2.7. Results of automated detection trials using short recordings and varying the synthetic kernel structure. Symbols as in Table 2.3, and terminology in Figure 2.6. Some of the 'curves' here consist of a single point. Results for 'optimized', 'fewest missed', and 'fewest false' data points are given in Table 2.4.

Table 2.4. Detection parameters and results for the 'optimized' data point (using predefined threshold of 20% missed calls), 'fewest missed' calls, and 'fewest false' detections (Figure 2.7) using short recordings and varying the synthetic kernel structure. False detection total includes other biological sounds, which are reported in parentheses.

| | Optimized (<20% missed) | Fewest missed | Fewest false |
|---|---|---|---|
| Number of segments | 2 | 2 | 1 |
| Segment durations (s) | 1, 0.5 | 0.6, 0.5 | 1 |
| Start-middle-end frequency (Hz) | 100-150-180 | 100-125-150 | 90-150 |
| Kernel width (Hz) | 10 | 9 | 9 |
| Detection threshold | 4 | 3 | 4 |
| Minimum duration above threshold (s) | 0.5 | 0.5 | 0.5 |
| Missed detections out of 26 calls | 5 | 2 | 19 |
| False detections: total | 15 | 33 | 1 |
| False detections: other call types/species | (12) | (17) | (1) |
| Total number of detections | 36 | 57 | 8 |

Table 2.5. Detection parameters tested in intermediate-length recording trials. The ranges of varying parameters are shown in bold type. Symbols correspond to markers in Figure 2.8.



| Symbols in Figure 8: | ◆ | ■ | ▲ | ◇ | □ | △ | × | + | — | ▫ |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of segments | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 |
| Segment duration (s) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1.1 | 1, 0.5 | 1 |
| Sweep rate (Hz/s) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | **45-55** | 50,60 | 55-60 |
| Start Frequency (Hz) | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| End frequency (Hz) | 150 | 150 | 150 | 150 | 150 | 150 | 150 | **150-160** | 180 | 155-160 |
| Kernel width (Hz) | 10 | 11 | **10-11** | **9-10** | **10-11** | **10-11** | 10 | 10 | 10 | 11 |
| Detection threshold | **5-6** | **5.5-6** | 6 | 4 | 5 | **5-6** | **4-5** | 5 | 4 | 5.5 |
| Minimum duration above threshold (s) | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.4 |
| Maximum duration above threshold (s) | 2 | **1.5-2** | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Equalization constant (s) | None | None | None | None | None | **3-5** | **2-3** | None | None | None |

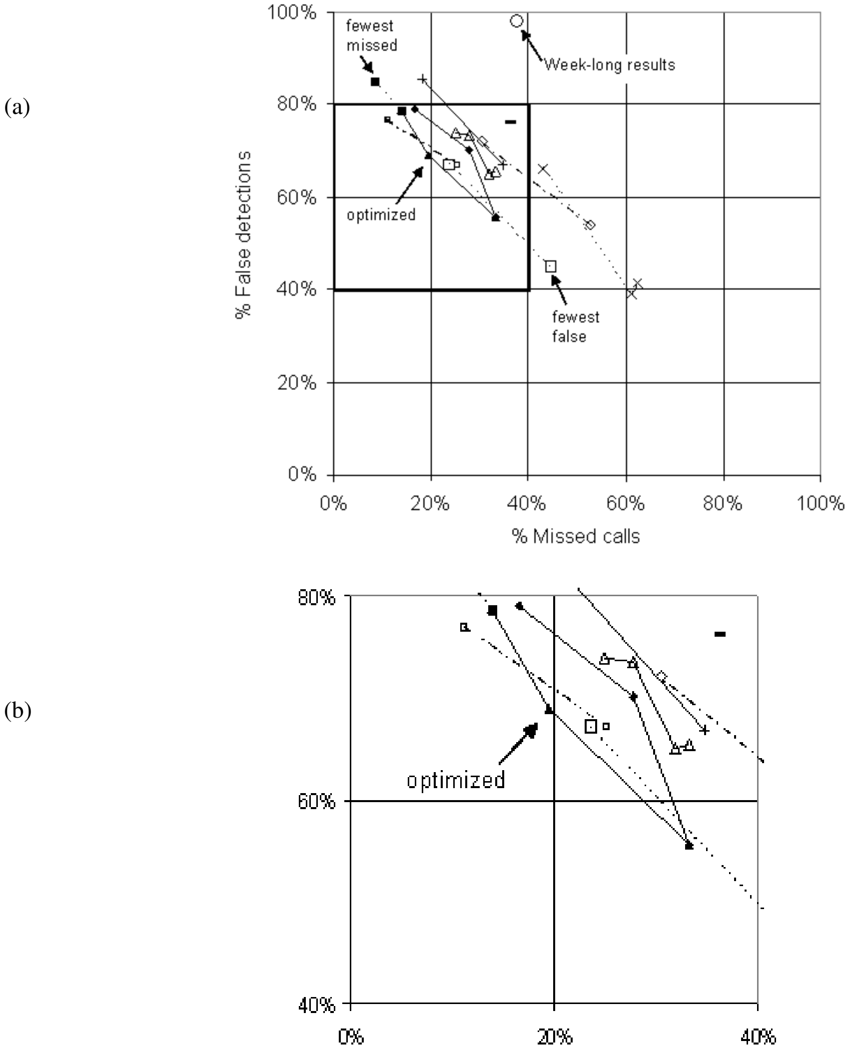
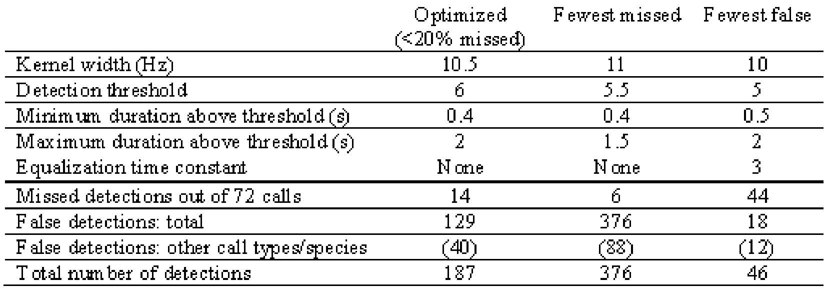


Figure 2.8. a) Results of automated detection trials using intermediate-length (symbols in Table 2.5) and week-long (marked by single open circle) recordings. Terminology same as in Figure 2.6. Some of the ‘curves’ here consist of a single point. Results for intermediate-length points labeled ‘optimized’, ‘fewest missed’, and ‘fewest false’ are given in Table 2.6. Results from week-long data set (open circle) given in Table 2.7. b) Area within thickened line in 8a is expanded in Figure 2.8b.

Table 2.6. Detection parameters and results for the ‘optimized’ data point (using predefined threshold of 20% missed calls), ‘fewest missed’ calls, and ‘fewest false’ detections (Figure 2.8) using intermediate-length recordings. The synthetic kernel in all three cases was 1 s, 100-150 Hz, although alternative synthetic kernels were also tested. False detection total includes other biological sounds, which are reported in parentheses.



| | Optimized (<20% missed) | Fewest missed | Fewest false |
|---|---|---|---|
| Kernel width (Hz) | 10.5 | 11 | 10 |
| Detection threshold | 6 | 5.5 | 5 |
| Minimum duration above threshold (s) | 0.4 | 0.4 | 0.5 |
| Maximum duration above threshold (s) | 2 | 1.5 | 2 |
| Equalization time constant | None | None | 3 |
| Missed detections out of 72 calls | 14 | 6 | 44 |
| False detections: total | 129 | 376 | 18 |
| False detections: other call types/species | (40) | (88) | (12) |
| Total number of detections | 187 | 376 | 46 |

Table 2.7. Detection results for week-long recording. Detection parameters are same as ‘optimized’ parameters from trials using intermediate-length recordings (Table 2.6).

| Results for week-long recording: | |
|---|---|
| Missed detections out of 146 calls | 55 |
| False detections: total | 4566 |
| False detections: other call types/species | (458) |
| Total number of detections | 4657 |

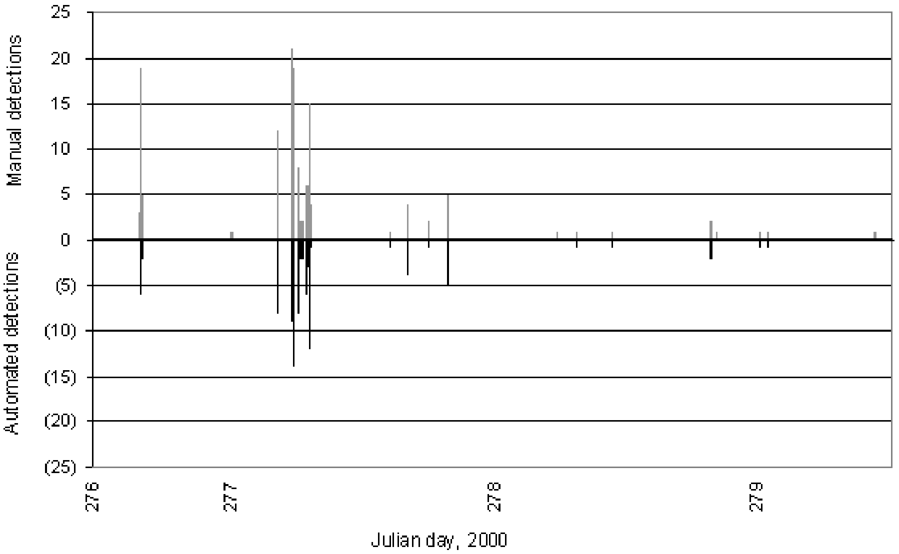


Figure 2.9. Manual detections per ten-minute time bin (gray bars, upper half of plot) in the first three days of the week-long recording, and automated detections (black bars, lower half of plot) within the same recording, using ‘optimized’ parameters from intermediate-length recording trials. In this recording, one ‘bout’ of calls, defined as at least two calls per ten-minute span, was missed on day 276, out of 18 bouts total within the entire week. Four single calls were also missed by the detector on days 277-279. On day 282 (not pictured), two calls were detected manually, one of which was detected automatically.

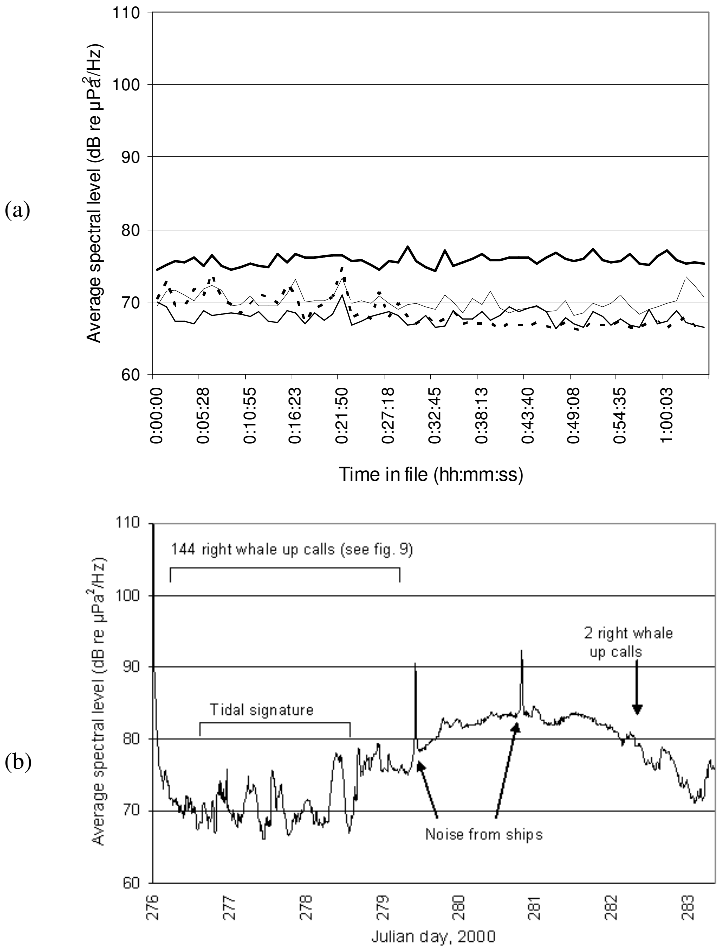


Figure 2.10. a) Noise levels between 100-150 Hz on each ARP during intermediate-length (65-minute) recordings, recorded simultaneously on each instrument. b) Noise levels between 100-150 Hz on ARP C during week-long recording. Tidal signature and spikes in noise from ships are labeled, as are days of right whale calls. Overall increase in noise on days 280-282 due to storm. Intermediate-length recordings taken from day 277, hour 0400-0505.

## References

Bond, N.A. and J.M. Adams. 2002. Atmospheric forcing of the southeast Bering Sea Shelf during 1995–99 in the context of a 40-year historical record. Deep-Sea Res. II 49: 5869–5887.

Brownell, R.L., P.J. Clapham, T. Miyashita, and T. Kasuya. 2001. Conservation status of North Pacific right whales. J. Cetacean Res. Manage. (Special Issue) 2:269-286.

Clark, C. W., R. Charif, S. Mitchell, and J. Colby. 1996. Distribution and behavior of the bowhead whale, *Balaena mysticetus*, based on analysis of acoustic data collected during the 1993 spring migration off Point Barrow, Alaska. Rep. Int. Whal. Commn. 46: 541-552.

Clark, C.W. 1982. The acoustic repertoire of the southern right whales, a quantitative analysis. Anim. Behav. 30: 1060-1071.

Clark, C.W., D. Gillespie, A. Moscrop, T. Fowler, T. Calupca, and M. Fowler. 2000. Acoustic sampling of right whale vocalizations in the Great South Channel using sea-floor pop-up recorders. Report of the Right Whale Consortium, Boston, Massachusetts.

Coachman, L.K. 1986. Circulation, water masses, and fluxes on the southeastern Bering Sea shelf. Continental Shelf Res. 5: 23-108.

Gillespie, D. and R. Leaper (eds.). 2001. Report of the Workshop on Right Whale Acoustics: Practical Applications in Conservation. International Fund for Animal Welfare, Yarmouth Port, MA 02675, USA. 23 pp.

Goddard, P.D., and D.J. Rugh. 1998. A group of right whales seen in the Bering Sea in July 1996. Marine Mamm. Sci. 14: 344-349.

LeDuc, R.G. 2004. Report of the results of the 2002 survey for North Pacific right whales. NOAA Technical Memorandum NMFS-SWFSC-357, NMFS Southwest Fisheries Science Center, La Jolla.

LeDuc, R.G., W.L. Perryman, J.W. Gilpatrick, Jr., J. Hyde, C. Stinchcomb, J.V. Carretta, and R.L. Brownell, Jr. 2001. A note on recent surveys for right whales in the southeastern Bering Sea. J. Cetacean Res. Manage. (Special Issue) 2: 287-289.

Matthews, J.N., S. Brown, D. Gillespie, M. Johnson, R. McLanaghan, A. Moscrop, D. Nowacek, R. Leaper, T. Lewis, and P. Tyack. 2001. Vocalisation rates of the North Atlantic right whale (*Eubalaena glacialis*). J. Cetacean Res. Manage. 3: 271-282.

Mattila, D. K., L. N. Guinee, and C. A. Mayo. 1987. Humpback whale songs on a North Atlantic feeding ground. J. Mamm. 684: 880–883.

McDonald, M.A., and S.E. Moore. 2002. Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea. J. Cetacean Res. Manage. 4: 261-266.

McDonald, M.A. 2004. DIFAR hydrophones applied to whale research. Canad. Acoust. 32: 155-160.

McSweeney, D. J., K. C. Chu, W. F. Dolphin, and L.N. Guinee. 1989. North Pacific humpback whale songs: a comparison of southeast Alaskan feeding ground songs with Hawaiian wintering ground songs. Marine Mamm. Sci. 5: 139–148.

Mellinger, D.K. 2001. Ishmael 1.0 User's Guide. NOAA Technical Report OAR-PMEL-120, NOAA Pacific Marine Environmental Laboratory, Seattle. Also available online at http://cetus.pmel.noaa.gov/cgi-bin/MobySoft.pl. 30 pp.

Mellinger, D.K. 2004. A comparison of methods for detecting right whale calls. Canad. Acoust. 32: 55-65.

Mellinger, D.K., and C.W. Clark. 2000. Recognizing transient low-frequency whale sounds by spectrogram correlation. J. Acoust. Soc. Am. 107: 3518-3529.

Mellinger, D.K., K.M. Stafford, and C.G. Fox. 2004a. Seasonal occurrence of sperm whale (*Physeter macrocephalus*) sounds in the Gulf of Alaska, 1999-2001. Marine Mamm. Sci. 20: 48-62.

Mellinger, D.K., K.M. Stafford, S.E. Moore, L. Munger, and C.G Fox. 2004b. Detection of North Pacific right whale (*Eubalaena japonica*) calls in the Gulf of Alaska. Marine Mamm. Sci. 20: 872-879.

Moscrop, A., J. Matthews, D.Gillespie, and R. Leaper. 2004. Development of passive acoustic monitoring systems for northern right whales. Canad. Acoust. 32: 17-22.

Niezrecki, C., R. Phillips, and M. Meyer. 2003. Acoustic detection of manatee vocalizations. J. Acoust. Soc. Amer. 114: 1640-1647.

Oppenheim, A.V., and R.W. Schafer. 1999. *Discrete-Time Signal Processing*, 2nd ed. Prentice-Hall, Englewood Cliffs.

Stafford, K.M., C.G. Fox, and D.S. Clark. 1998. Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. J. Acoust. Soc. Am. 104: 3616-3625.

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

Thompson, P.O. and W.A. Friedl. 1982. A long term study of low frequency sounds from several species of whales off Oahu, Hawaii. Cetology 45: 1-19.

Vanderlaan, A.S.M., A.E. Hay, and C.T. Taggart. 2003. Characterization of North Atlantic right-whale (*Eubalaena glacialis*) sounds in the Bay of Fundy. IEEE J. Oceanic Engr. 28: 164-173.

Van Trees, H.L. 1968. *Detection, Estimation, and Modulation Theory, Vol. I.* Wiley: New York.

Waite, J.M., K. Wynne, and D.K. Mellinger. 2003. Documented sighting of a North Pacific right whale in the Gulf of Alaska and post-sighting acoustic monitoring. Northwestern Naturalist 84: 38-43.

Wiggins, S. 2003. Autonomous Acoustic Recording Packages (ARPs) for long-term monitoring of whale sounds. Mar. Tech. Sci. J. 37: 13-22.

Wiggins, S.M., M.A. McDonald, L.M. Munger, J.A. Hildebrand, and S.E. Moore. 2004. Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea. Canad. Acoust. 32: 146-154.

Chapter 2, in full, is a reprint of the material as it appears in the journal Canadian Acoustics, 2005: Munger, L.M., D.K. Mellinger, S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. Performance of spectrogram cross-correlation in detecting right whale calls in long-term recordings from the Bering Sea. Canadian Acoustics 33:25-34. Content was reformatted to conform to UCSD dissertation standards. The dissertation author was the primary investigator and author of this paper. The coauthors listed supervised the research forming the basis of this chapter.

# III. North Pacific right whale (*Eubalaena japonica*) seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea, 2000-2006

## Abstract

We assessed North Pacific right whale (*Eubalaena japonica*) calling on seasonal and daily timescales in the southeastern Bering Sea (SEBS) using passive acoustic recordings from moored hydrophones deployed between October 2000 and January 2006. We detected right whale calls on the SEBS middle-shelf (<100 m depth) on multiple occasions from May through December, but only on one day in June 2005 on the SEBS slope (>1000 m). Calling rates on the middle-shelf were highest (>300 calls/day) in August, September, and December. Right whale calls occurred on more days per month from July through October (• 6 days), than from May-June and November-December (• 3 days). Calls were usually detected on 1-3 consecutive days with median silent intervals of 6.5 days. Right whale calling rates (calls/hour) were significantly higher during dark nighttime hours than during other times of day. These data indicate that right whales occur in the SEBS later in the year than previously known, and suggest that they intermittently pass over the middle-shelf, usually remaining there for only a few days at a time. Right whale densities and occurrence rates on the middle shelf appear to be greatest from mid-summer through early fall, based on higher call detection rates.

## Introduction

North Pacific right whales (*Eubalaena japonica*) are among the world's most endangered large whale species due to intensive commercial whaling in the nineteenth century and further depletion by illegal whaling in the 1960's (Doroshenko 2000, Brownell *et al.* 2001, Scarff 2001). Nineteenth- and 20th-century catch and sighting data suggest that at least two right whale populations exist in the North Pacific, one in the west and the other in the east (Brownell *et al.* 2001, Clapham *et al.* 2004). Abundance estimates for these populations are uncertain, but the western population probably consists of a few hundreds of individuals, whereas the eastern population is even smaller (Brownell *et al.* 2001). Currently in the eastern North Pacific, 23 individual right whales have been identified by photographs and biopsy samples (Wade *et al.* 2006), and sightings of at least three mother-calf pairs during surveys within the last decade provide hope that the population may be capable of recovery (LeDuc 2004, Wade *et al.* 2006). Little is known about the seasonal distribution of eastern North Pacific right whales, especially with regard to migration routes and wintering grounds (Brownell *et al.* 2001, LeDuc *et al.* 2001, Shelden *et al.* 2005).

Like other right whale species (*Eubalaena* sp.), eastern North Pacific right whales appear to migrate seasonally, with recent and historic sightings indicating a northward movement in spring to high-latitude summer feeding grounds, and a southward movement in autumn (Townsend 1935, Brownell *et al.* 2001, Clapham *et al.* 2004, Shelden *et al.* 2005). Data from 1835-1852, during peak whaling for North Pacific right whales, suggest that right whales occurred in the eastern Bering Sea as early as April and were abundant there by May (Scarff 1991). The southeastern Bering Sea (SEBS) and western Gulf of Alaska (GoA) historically supported high concentrations of right whales from June through September; the western GoA was known to whalers in the 19th century as the lucrative 'Northwest Ground' or 'Kodiak Ground'. Small numbers of right whales have been seen in most summers since 1996 in the SEBS (Goddard and Rugh 1998, Moore *et al.* 2000, Tynan *et al.* 2001, LeDuc *et al.* 2001, LeDuc 2004, Barlow 2005, Wade *et al.* 2006), with occasional recent sightings in the western GoA (Waite *et al.* 2003). The latest reported right whale sighting of the year in the SEBS was in October 1999 (Brownell *et al.* 2001). North Pacific right whales have rarely been seen in winter, either historically or recently, and winter sightings in the eastern North Pacific have been geographically scattered and are usually comprised of single animals (Brownell *et al.* 2001). In a 2004 satellite-transmitter tag study of two North Pacific right whales, the whales traveled around the SEBS middle and outer shelf regions, but did not leave the Bering Sea during 40 days of monitoring in August-September (Wade *et al.* 2006).

Most of our current knowledge of eastern North Pacific right whales is based on visual surveys, which are conducted primarily in summer months in the Bering Sea and Gulf of Alaska (*e.g.*, LeDuc *et al.* 2001, LeDuc 2004, Barlow 2005), and when weather and light conditions are favorable for vessels and aircraft. During the 19th and 20th centuries, the majority of right whale sightings in the Bering Sea were reported in June through September, the months with highest search effort (Scarff 1991, Brownell *et al.* 2001, Shelden *et al.* 2005). Recently designated critical habitat areas in the southeast Bering Sea and western Gulf of Alaska are based on visual sightings of right whales since 1970 (Federal Register, July 06, 2006). Traditional cetacean visual surveys provide photographic, genetic, and observational data (*e.g.*, LeDuc *et al.* 2001, McDonald and

Moore 2002), but are constrained to operate in good weather and daylight, and are usually limited to a few to several weeks in duration due to vessel, aircraft and personnel expense and schedules. Because of these constraints in visual sighting data, it is unclear whether right whales are consistently present in the SEBS throughout the summer, and whether they are present at other times of year. As a complementary tool to visual surveys, long-term, passive acoustic recorders can operate continuously for months to years, through poor weather and darkness, and thus are useful for monitoring the seasonal distribution and daily calling behavior of calling cetaceans (*e.g.,* Thompson and Friedl 1982, Clark *et al.* 1996, Stafford *et al.* 2001, Mellinger *et al.* 2004*a, b*, Širović *et al.* 2004).

We present results from the first long-term acoustic monitoring study of critically endangered North Pacific right whales in the southeast Bering Sea. The use of autonomous acoustic moorings allowed us to conduct almost year-round monitoring at several geographic locations, thus obtaining data on temporal and spatial distribution of right whales that visual surveys alone could not provide. We deployed moored hydrophones between October 2000 and January 2006 at nine sites in the SEBS ranging from 70 m to 1880 m in depth, and one site in the western Gulf of Alaska (800 m). We show that right whale calling in the SEBS exhibits seasonal and diel patterns, and provide evidence that right whales were present at times of year and locations where they have not recently been known to occur.

## Methods

We analyzed data from seafloor-moored, long-term, acoustic recording packages (ARPs) (Wiggins 2003, Wiggins & Hildebrand 2007) deployed at six locations in the

SEBS middle-shelf region (~70 m), three locations along the SEBS outer shelf and slope (125 m and >1500 m), and one site southeast of Kodiak Island in the western GoA (800 m) (Figure 3.1). Mooring site names, locations, recording dates, sampling rates and number of call detections are summarized in Table 3.1. We resampled high-frequency (>1 kHz) recordings to a sampling rate of 1 kHz prior to further processing, using an 8th order lowpass Chebyshev type I forward and backward filter.

Right whale calls in the Bering Sea were first recorded in 1999 using directional frequency analysis and recording (DIFAR) sonobuoys deployed from a ship (McDonald and Moore 2002). During the 1999 survey and subsequent surveys in 2002 and 2004, DIFAR sonobuoys were used to localize calls from right whales that were confirmed by visual sightings (McDonald and Moore 2002, Wade *et al.* 2006). Over eighty percent of right whale calls recorded during these surveys were frequency-modulated ‘up-calls’ (Figure 3.2), with variable frequency and sweep rate characteristics on average from 90-150 Hz and about 0.7 s in duration (*e.g.,* McDonald and Moore 2002). Other call types, such as down-swept calls and constant-tonal ‘moans’, also were produced and were usually interspersed with up-calls. Therefore, we used up-calls in this study to indicate right whale presence.

We detected potential right whale up-calls in long-term recordings using two methods. The first was to compute “long-term spectral averages” (LTSAs) of acoustic recordings by computing Fast Fourier Transforms (FFTs) and then averaging successive FFTs into a single spectral average and displaying successive spectral averages as spectrograms (Wiggins and Hildebrand 2007). To compute the FFTs we applied a Hanning window, 0% overlap, and 1 Hz frequency bins (for FFT length of 0.5 s and 1 s for data sampled at 500 Hz and 1000 Hz, respectively); successive FFTs were averaged over 120 seconds. Displaying data in the LTSA format allowed the analyst (LMM) to quickly visually scan through years of recordings, note times of potential right whale calling, and easily open the detailed data files for additional evaluation of calls. The second technique used for call detection was automatic spectrogram correlation using the software program *Ishmael* (Mellinger 2001). We cross-correlated spectrogram data from the acoustic recorders with a synthetic spectrogram kernel based on the North Pacific right whale up-call (Munger *et al.* 2005). Automatic detections were saved as individual sound files.

All data were processed using both of the above techniques, and potential right whale calls were reviewed using *Triton*, a Matlab-based acoustic data display & analysis software program (Wiggins 2003) or using *Ishmael*. We analyzed positive call detections aurally and visually using short-duration (seconds to minutes), higher-resolution spectrograms (*e.g.*, Figures 2 & 3) to identify right whale calls and searched for additional calls by browsing short-duration spectrograms for at least one day before and one day after call detection times. Data were scanned until no calls were found for 24 h.

All potential right whale calls were analyzed to distinguish them from similar-appearing humpback whale (*Megaptera novaeangliae*) calls (Figure 3.3). The main differences used to distinguish the two species are in their frequency range and temporal patterns. Most North Pacific right whale calls (Figure 3.3a) are less than 250 Hz (McDonald and Moore 2002) and, like those of other right whale species (*Eubalaena* sp.), occur in bouts lasting several minutes with variable silent intervals up to several hours in length (Matthews *et al.* 2001, Vanderlaan *et al.* 2003), whereas humpback whales produce calls with greater frequency range (up to several kHz) and songs that are characterized by consistently structured ‘phrases’ and the cyclical repetition of phrases over long (minutes to hours) periods (Payne and McVay 1971). Humpback singing has been reported primarily in low-latitude winter breeding grounds, but has also been recorded on higher-latitude summer feeding grounds (Mattila *et al.* 1987, McSweeney *et al.* 1989, Clark and Clapham 2004). In the Bering Sea, humpback whales produce song fragments containing frequencies < 250 Hz (Figure 3.3b), which appear similar to low-frequency components of humpback whale songs in other areas in the North Pacific (*e.g.*, Cerchio *et al.* 2001, Fristrup *et al.* 2003).

Potential right whale call times (Coordinated Universal Time, UTC) were picked by cursor in a spectrogram display to within ± 0.5 s and each call was rated ‘most certain’, ‘probable’, or ‘possible’, in order of decreasing certainty that the call was made by a right whale. ‘Most certain’ right whale calls were up-calls or ‘down-up’ calls similar to those recorded in the presence of right whales during prior surveys (*e.g.,* McDonald and Moore 2002, Munger unpub. data[1]) and had a relatively high signal-to-noise ratio (SNR). ‘Probable’ right whale calls were either non-upswept right whale call types co-occurring with up-calls, or were more difficult to identify due to lower SNR or nearby detections of humpback whale calls. ‘Possible’ right whale calls may have resembled right whale calls or portions of right whale calls, but were either too difficult to distinguish from humpback whale calls or had low SNR such that the analyst was not confident of the calling species. We did not include ‘probable’ and ‘possible’ right whale calls (19% and 38% of total detections; Table 3.1) in the results presented in this paper.

Therefore the total numbers of true right whale calls are probably underestimated, but seasonal and daily patterns were not affected by excluding lower-rated calls as they were interspersed with ‘most certain’ calls.

Diel patterns in right whale calling were analyzed using SEBS middle-shelf recordings. For each day with calls, we obtained the time (UTC) of sunrise, sun transit (maximum altitude of sun relative to horizon), sunset, and start & end of nautical twilight (-12° sun altitude relative to horizon) at the instrument site using data from the U.S. Naval Observatory website (http://aa.usno.navy.mil). Calls were categorized as occurring during ‘dawn’ (sun altitude between -12° and 0° prior to rise), ‘morning’ (sun altitude increasing from 0° to transit), ‘afternoon’ (sun altitude decreasing from transit to 0°), ‘dusk’ (0° to -12° following sunset), and ‘dark’ (sun below -12° to horizon). To obtain calling rates in calls/hour, we normalized the number of calls within each category to the corresponding duration of that period on the day on which calls were sampled. We then subtracted the overall calling rate (calls/hour) for that day to obtain a mean-adjusted calling rate, in order to correct for variation in the total number of calls recorded each day. We used a Kruskal-Wallis test (Zar 1999) to rank and compare mean-adjusted calling rates among diel periods, and a Tukey-Kramer multiple comparison test to determine which, if any of the diel periods showed significant difference in mean rank of mean-adjusted right whale calling rates.

---

[1] Munger, L.M. Sonobuoy recordings of North Pacific right whales during 2002 and 2004 NOAA cetacean surveys in the SEBS.

## Results

A total of 3685 'most certain' right whale calls were detected, primarily by instruments on the SEBS middle-shelf at ~ 70 m depth. Only seven right whale calls were recorded at MM4 (1590 m depth) south of the Pribilof Islands, on 14 June 2005, and no right whale calls of any quality rating were detected on two other SEBS outer shelf/slope instruments (MM2, 125 m and MM3, 1880 m) in May- December 2004 or off Kodiak Island (802 m) in April-August 2003 (Table 3.1).

The number of right whale calls per day and sampling effort are shown for the SEBS middle-shelf instruments in Figure 3.4. The overall seasonal occurrence of right whale calls is shown in Figure 3.4(a), with calls per day plotted from the instrument with the maximum calling rate for that day across recording years. The earliest SEBS middle-shelf right whale calls of any year were recorded on 23 May 2004, and the latest right whale calls of any year were recorded on 15 December 2005. The highest calling rates (> 300 calls/day) were in August, September and December.

Calls per day and recording effort for each year at SEBS middle-shelf sites are shown in Figure 3.4(b). In 2000 and early 2001, maximum calls/day are plotted for a single instrument to avoid duplicating counts of calls recorded by more than one instrument. Effort in January 2006 at sites BSM-2 and BSM-4 is not shown; no right whale calls were detected during this time. The longest continuous deployments were August 2001 - July 2002 (site C) and April 2005 – January 2006 (site BSM-2); peak calling rates in these recordings occurred during August and September. Right whale calls were not detected in January through April in 2001, 2002, and 2005. Right whale calling was episodic throughout the season, with typical durations of 1-3 consecutive days and up to 5 days. The longest consecutive periods of right whale calling were in late summer and early autumn. Intervals between days with calls ranged from 2 to 49 days, with a median value of 6.5 days.

The number of days per month (not necessarily consecutive) with right whale calls at each SEBS site is shown in Figure 3.5. The months with the highest proportion of right whale calling days were July through October, with up to 11 calling days per month. The months with fewest right whale calling days were May, June, November, and December; calls were detected on no more than 3 days during these months. Right whale calls were recorded on at least one day per month in October through December 2005 at site BSM-4, and on one day in June 2005 along the slope south of the Pribilof Islands. No calls were detected in January through April (not shown in Figure 3.5).

Mean-adjusted right whale calling rates recorded on the SEBS middle-shelf (including BSM-4) showed significant diel variation (Figure 3.6; Kruskal-Wallis test; Chi-square = 23.85, df = 4, $P \ll 0.001$). Sample size was 68 for each diel period except for darkness (n= 51), due to the occurrence of some days with calls in mid-summer when the sun altitude did not decrease below -12° overnight. Median mean-adjusted calling rates for dawn, morning, afternoon, dusk and dark periods were -0.208, -0.167, -0.188, -0.167 and 0.147 calls/hour, respectively. The mean rank for mean-adjusted calling rates during darkness was significantly higher than all other time periods; no other time periods had significantly different mean ranks from one another (darkness mean rank = 218.4; dawn, morning, afternoon & dusk = 138.7, 153.8, 157.3, and 156.0 respectively; Tukey-Kramer multiple comparison test).

## Discussion

Long-term acoustic recordings from 2000-2006 provide a record of right whale presence on the southeast Bering Sea shelf from late May through November in more than one year, and in one year as late as December. The detection of right whale calls as early as May is consistent with recent and historic sighting data, although a few sightings of right whales in the Bering Sea have been reported as early as April (Scarff 1991, Brownell *et al.* 2001). The presence of right whales in the SEBS in November and December has not been previously reported, and this finding underscores the usefulness of acoustic monitoring during times of year when visual search effort is typically not conducted.

Right whale calls were recorded at site BSM-4 on several days in October through December 2005 and at site MM4 (~1600 m depth south of Pribilof Is.) on one day in June 2005. These sites are outside the currently designated critical habitat boundary for right whales in the Bering Sea and may represent important portions of their habitat that warrant further acoustic monitoring and visual search effort. Although we did not detect any right whale calls in 5 months of recording in 2003 near Kodiak Island, right whales have been visually and acoustically detected there during other efforts (Waite *et al.* 2003, Mellinger *et al.* 2004*b*, Munger unpub. data) and right whale research effort should also be continued in this region.

The low numbers or lack of right whale call detections on some recorders may be related to differences in acoustic detection range. When range, r, to a sound source is greater than water depth, acoustic propagation approaches a cylindrical spreading model and transmission loss (TL), in decibels (dB) is close to 10log(r), whereas for r less than water depth, sound spreads spherically and TL • 20log R (Clay and Medwin 1977). Right whale calls may be more likely to be detected on the southeast Bering Sea shelf (depth < 100 m) than on deeper instruments (depth >1500 m), because this region is relatively flat and shallow for hundreds of kilometers, providing an acoustic waveguide that channels right whale calls and other low-frequency sounds for long distances (Wiggins *et al.* 2004). Right whale calls were routinely detected at ranges of 20 km on sonobuoys in a 1999 SEBS survey (McDonald and Moore 2002) and have been received on ARPs at ranges up to 60 km on the SEBS shelf (Wiggins *et al.* 2004) and at similar or greater ranges on sonobuoys deployed during vessel-based surveys in the SEBS in 2002 and 2004 (Munger unpub. data). We estimate the average detection range of 'most certain' right whale calls for SEBS middle-shelf hydrophones at up to 50 km; at times of low ambient noise this range may increase.

The low overall numbers of right whale calls detected on the SEBS middle-shelf and episodic occurrence of days with calls in this study may reflect the low population size for eastern North Pacific right whales. We detected only hundreds of North Pacific right whale calls in each year of this study, whereas tens to hundreds of thousands of calls were recorded throughout a single migration season for bowhead whales in the western Arctic (Clark *et al.* 1996), blue and fin whales in the Antarctic (Širović *et al.* 2004), and blue whales offshore California (Wiggins *et al.* 2005). These latter populations of bowhead, blue and fin whales number in the thousands, compared to the probable population size of fewer than 100 eastern North Pacific right whales.

The highest right whale calling rates were on SEBS middle-shelf instruments during August, September and December, and may be due to an increase in the total number of calling whales within range or an increase in call production rate by individuals, or both. In a 1999 study in the North Atlantic, right whale sound production rates were positively correlated with aggregation size, with single whales producing 0-10 calls/h, 2-10 whales producing up to ~ 60 calls/h, and > 10 whales producing up to 700 calls/h (Matthews *et al.* 2001). If this is true of North Pacific right whales, our recordings suggest that fewer whales are present in the study area at any time early in the season, compared with larger aggregations in late summer and occasionally even later in the year (*i.e.*, December 2005), when they presumably begin migrating off the SEBS shelf. However, calling rates are also likely to be related to behavior, group composition, and other factors. Our call counts are based primarily on upswept calls, which comprise > 80% of North Pacific right whale calls and are the most common right whale call type across right whale species. These calls are thought to function as contact calls in southern right whales (Clark 1983). Other call types, such as ‘gunshot’, ‘down’, ‘constant’, ‘high’, or ‘pulsive’ calls, or blows and slaps (Clark 1982, Parks *et al.* 2005), were associated with relatively more complex social interactions such as mating displays or aggression in southern and North Atlantic right whales (*E. australis* and *E. glacialis*, respectively), and the relationship between calling rates and behavior, group size, composition, and activity level was correspondingly more complex as well (Clark 1983, Matthews *et al.* 2001, Parks and Tyack 2005).

Right whale calling on the SEBS shelf instruments is episodic, suggesting that they are traveling in and out of recording range or may be silent for days to weeks. Silent intervals between days with calls ranged from 2 to 49 days during continuous recording over the right whale ‘season’, and up to six months from late fall through winter and early spring. In previous studies when right whales were known to be within recording range, silent intervals between right whale calling bouts were up to several hours in duration (McDonald and Moore 2002, Munger unpub. data); thus we presume that silences of at least 2-3 days indicate that right whales were not present within recording range. In May through July, right whale calls were detected on up to 3 consecutive days at most, suggesting that the whales travel occasionally through the SEBS middle-shelf study area during late spring/early summer but do not remain there for long periods. The greatest numbers of days with right whales were in July through October, and longest consecutive number of right whale calling days (3-5 days) were in September-October, suggesting that right whales travel through most frequently and remain in this area longer in late summer and early fall.

Right whale calling rates showed a minimum during daylight hours and a maximum during dark nighttime hours (Figure 3.6), suggesting that individual whales call more frequently at night, or that more individuals call at night. Either possibility implies a diel cycle to right whale acoustic behavior in the SEBS. Calling rates in North Atlantic and southern right whales also increase at night (Clark 1983, Matthews *et al.* 2001); and diel calling patterns have been reported for other baleen whale species as well (Au *et al.* 2000, Stafford *et al.* 2005, Wiggins *et al.* 2005). One potential explanation for right whale diel calling behavior is that they may feed on vertically-migrating copepods, their primary prey, during the day when prey are concentrated at depth (*e.g.*, Baumgartner *et al.* 2003) and are less likely to produce calls while foraging at depth. An alternative hypothesis is that right whale calling rates are related to behavioral displays or interaction that includes visual cues, and higher calling rates at night may be a reallocation of display effort when visual cues are ineffective.

## Conclusions

Long-term acoustic recordings of North Pacific right whale calls demonstrate that right whales occur intermittently on the SEBS middle-shelf from May through December and appear to pass through the study area most frequently and remain for longer durations in July-October. We also provide evidence that right whales are at least occasionally present over the Bering Sea shelf break/slope, where they were historically abundant (Scarff 1991, Clapham *et al.* 2004, Shelden *et al.* 2005). During the long periods of silence (days to weeks) between right whale calling episodes, we hypothesize that right whales travel throughout the southeast Bering Sea, including regions of the middle and outer shelf outside of the recording range of our instruments, and along the SEBS slope, where a relatively smaller area was monitored due to greater acoustic transmission loss. Acoustic recordings also provide information on the relative abundance of right whales and their behavior on shorter time scales. Higher right whale calling rates on the SEBS middle-shelf in August, September, and December may indicate larger right whale aggregation sizes, and higher nightly calling rates suggest a diel component to right whale behavior, perhaps related to foraging or social context.

Further research (*e.g.*, simultaneous acoustic monitoring and visual observation) is needed in order to understand the behavioral context of North Pacific right whale calls and potentially quantify the relationship of calling types/rates to abundance and habitat use. In addition, work relating acoustic recordings to oceanographic data may be useful in understanding and predicting right whale habitat, and could suggest locations for future acoustic monitoring. Continued research effort using a variety of techniques (*e.g.,* acoustic monitoring and visual search effort, satellite telemetry, photographic and genetic identification) should be conducted in areas of recent right whale occurrence as well as in historically important regions to explore for right whale presence. Results are pertinent to management decisions, such as critical habitat designation, that rely on an understanding of the spatial and temporal distribution of North Pacific right whales.

## Acknowledgements

This work was supported by NOAA Alaska Fisheries Science Center/National Marine Mammal Laboratory (AFSC/NMML) via JIMO budget #NA17RJ1231, North Pacific Marine Research Institute (project T-2100) and North Pacific Research Board (projects R-0307 and F0519), Alaska Department of Fish and Game (ADFG project T-1-6-4; special thanks to Bob Small), and National Fish and Wildlife Foundation. We thank Phyllis Stabeno and her colleagues from NOAA Pacific Marine Environmental Laboratory for their collaboration in integrating whale acoustic recorders into their moorings and sharing ship time. NOAA Southwest Fisheries Science Center and AFSC/NMML provided opportunities for LMM to record right whales during cetacean surveys in Alaska; we thank the cruise leaders Jay Barlow, Rick LeDuc, Lisa Ballance, Robert Pitman and Paul Wade, acousticians Allan Sauter, Kate Stafford and Shannon Rankin, and others who were involved in planning and conducting these surveys. Thanks also to the officers and crew of the NOAA research vessels McArthur, McArthur II, and Miller Freeman; the University of Hawaii R/V Kilo Moana, and the fishing vessels Aleutian Mariner and Alaskan Enterprise. Mark McDonald shared data and feedback at the beginning of analysis. Jay Barlow, David Checkley, and Melissa Soldevilla provided helpful comments on this manuscript.

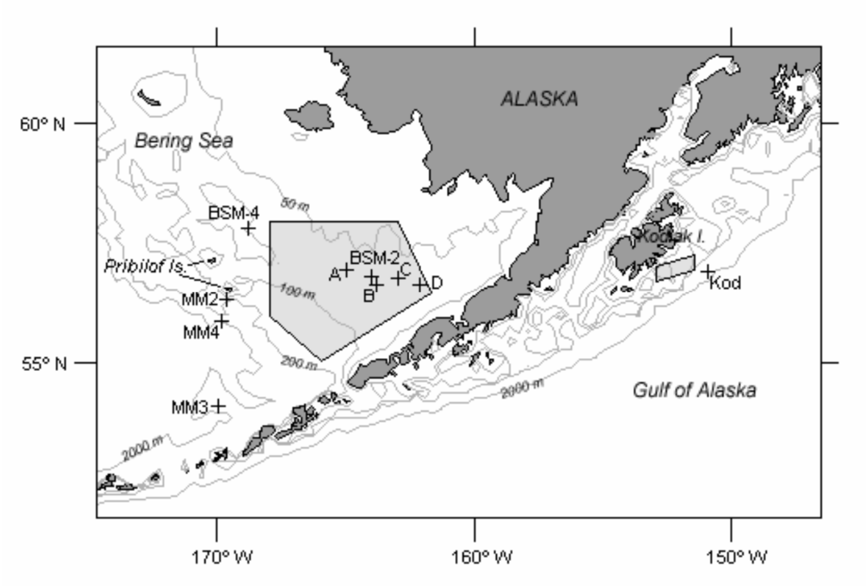


Figure 3.1. Map of study area. Depth contours shown are 50 m, 100 m, 200 m, and 2000 m (bathymetry data from Smith and Sandwell 1997). '+' symbols represent long-term acoustic recorder deployments, 2000-2006 (see Table 3.1). Shaded polygons are federally designated right whale critical habitat, enclosing 182 of 184 SEBS right whale sightings and 5 of 14 GoA right whale sightings since 1970 (Federal Register 07/06/2006).

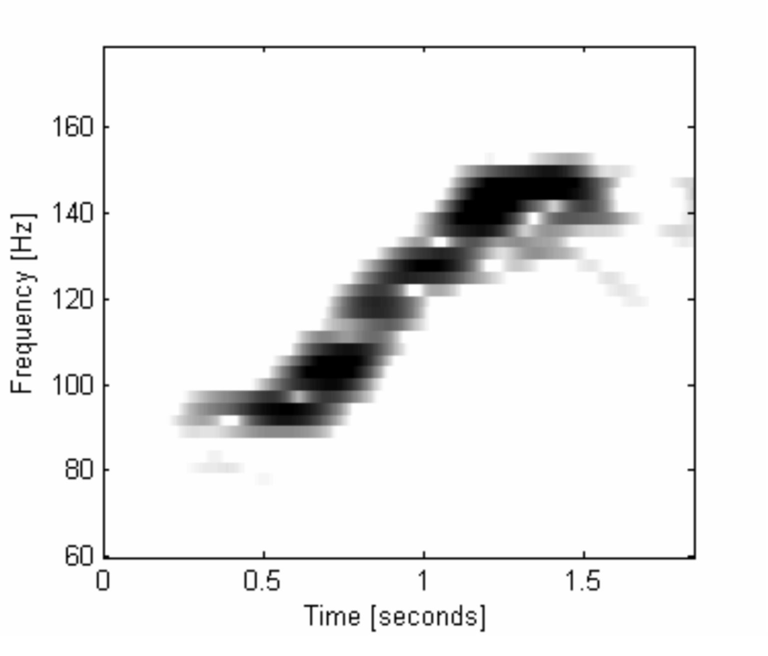


Figure 3.2. Spectrogram of single right whale up-call. Sampling rate = 500 Hz, 180-point FFT and same length Hanning window for 0.36 s window length, 99% overlap.

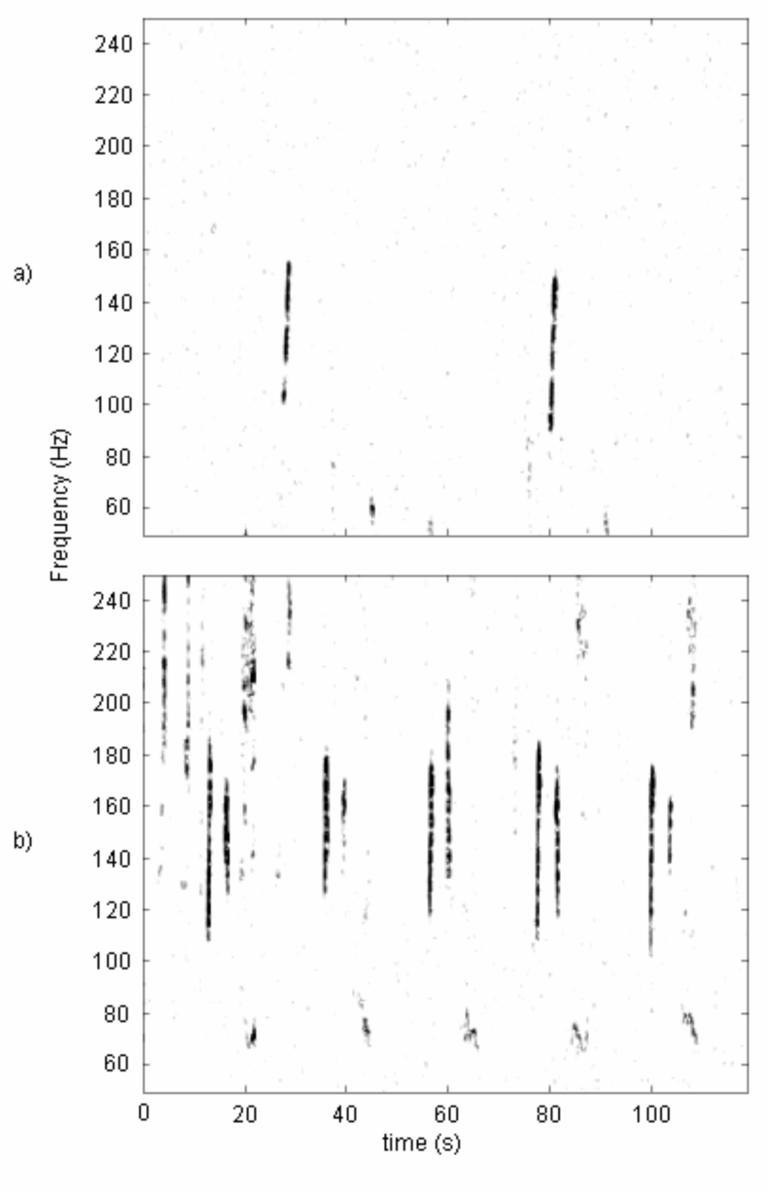


Figure 3.3. a) Right whale 'up' calls recorded by ARP at site C, August 2001. Spectrogram generated using Hanning window, FFT and frame size=600 points, 90% overlap. Original sampling rate = 500 Hz. b) Humpback song components recorded by ARP at site 'B', October 2000. Same sampling rate and spectrogram parameters as (a).

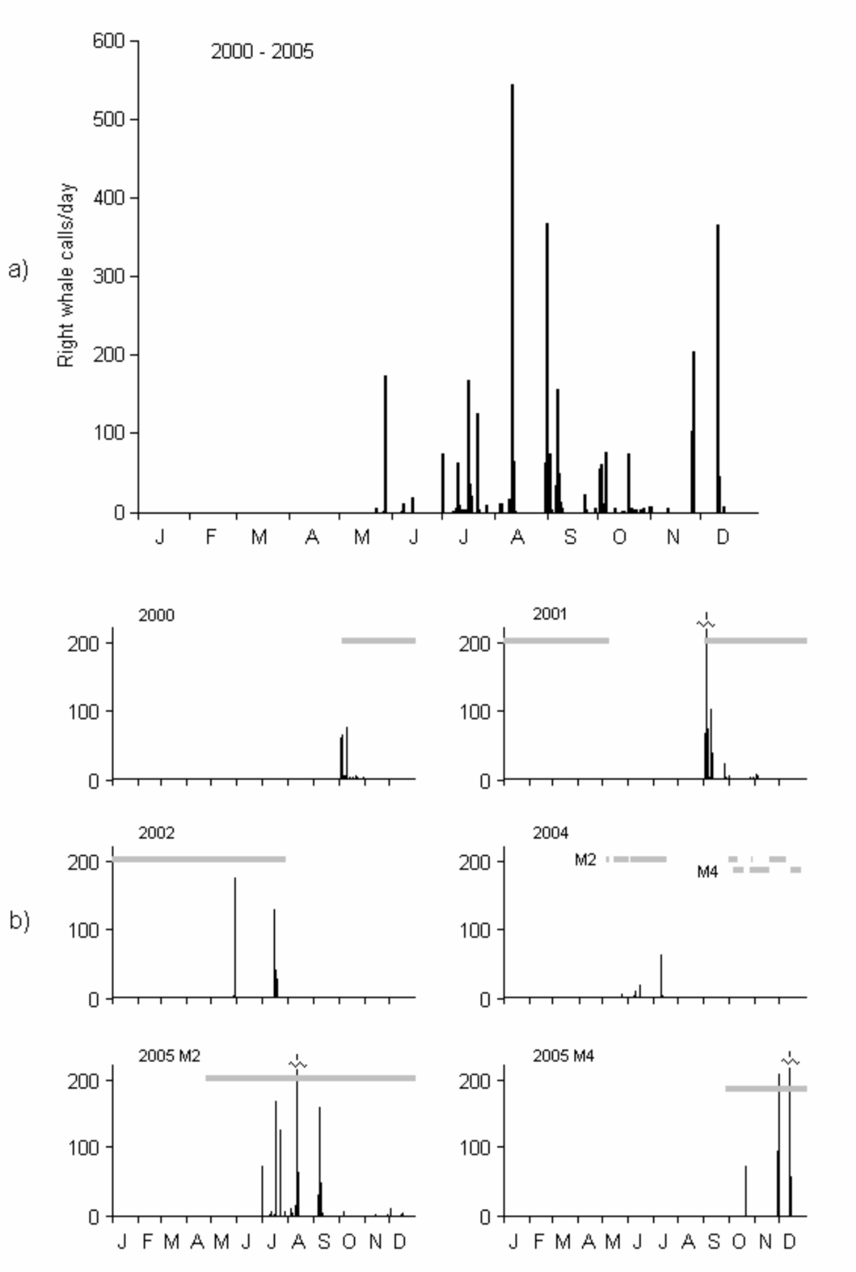
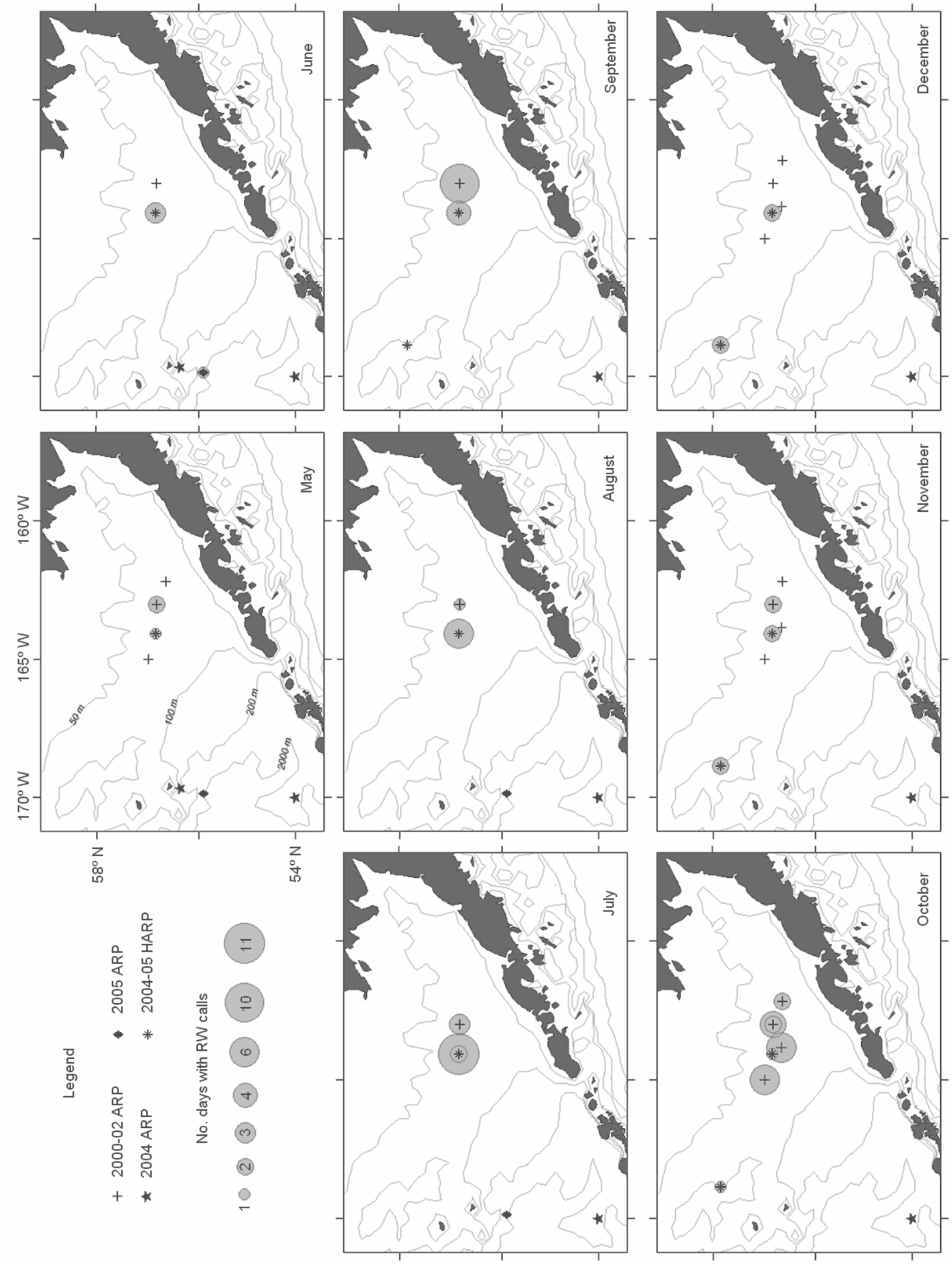


Figure 3.4. a) maximum number of 'most certain' right whale calls/day among SEBS middle-shelf recording sites (instrument depth <100 m), 2000-2005. b) calls/day for each year with recording effort; horizontal bars are recording duration; vertical bars are right whale calls/day (in 2000, data are calls/day from instrument with maximum calling rate on that day). Recording effort in January 2006 not shown; no calls detected in that month.

Figure 3.5. Number of days with ‘most certain’ right whale calls by month at each recording site. Calls recorded at same site during same month in different years are shown by more than one filled circle around site. In October 2000, instruments had overlapping recording ranges and filled circles may represent same days across instruments. No right whale calls detected in January-April (not shown).



Legend
2000-02 ARP
2004 ARP
2005 ARP
2004-05 HARP
No. days with RW calls
1
2
3
4
6
10
11
58° N
54° N
170° W
165° W
160° W
50 m
100 m
200 m
2000 m
May
June
July
August
September
October
November
December

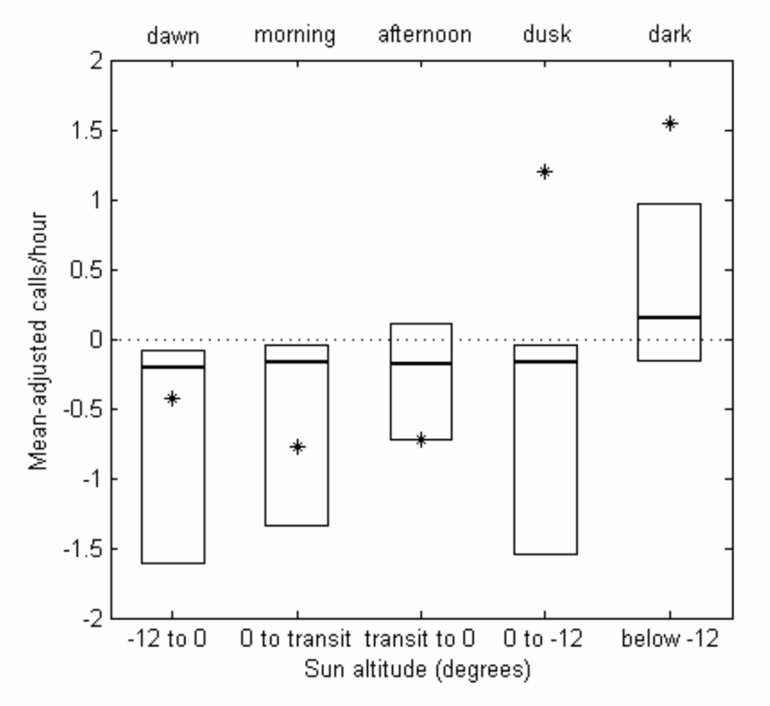


Figure 3.6. Boxplot of mean-adjusted calls/hour during dawn, morning, afternoon, dusk (*n* = 68) and dark periods (*n* = 51). Lower and upper bounds of boxes represent lower and upper quartiles, respectively; bold lines are median values and asterisks are mean values. Outliers, not shown, ranged from -15 to 26 (dawn), -15 to 10 (morning), -19 to 5 (afternoon), -15 to 58 (dusk), and -3 to 23 (dark). Note that means (asterisks) in dusk and dark periods are skewed above upper quartile due to high outlier values.

Table 3.1. ARP site names, sampling rates, locations & depth, recording dates, and number of right whale calls detected.

| site | sampling rate (kHz) | location | depth (m) | recording begin | recording end | right whale call detections | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 'most certain' | 'probable' | 'possible' |
| A | 0.5 | 57° 00.00' N<br>164° 59.97' W | 70 | 10/01/00 | 05/08/01 | 109 | 178 | 395 |
| B | 0.5 | 56° 40.37' N<br>163° 50.74' W | 70 | 10/02/00 | 12/13/00 | 127 | 133 | 219 |
| C | 0.5 | 56° 49.89' N<br>163° 00.48' W | 70 | 10/02/00<br>08/31/01 | 05/03/01<br>07/28/02 | 70<br>1116 | 0<br>438 | 173<br>670 |
| D | 0.5 | 56° 40.05' N<br>162° 10.80' W | 70 | 10/02/00 | 05/07/01 | 54 | 19 | 57 |
| Kod | 1 | 56° 57.02' N<br>150° 59.81' W | 802 | 04/19/03 | 08/31/03 | 0 | 0 | 0 |
| MM2 | 1 | 56° 21.48' N<br>169° 39.74' W | 125 | 05/01/04 | 06/09/04 | 0 | 0 | 0 |
| MM3 | 1 | 54° 0.00' N<br>170° 0.00' W | 1880 | 05/03/04 | 12/27/04 | 0 | 31 | 234 |
| BSM-2 | 80<br>32<br>40 | 56° 51.60' N<br>164° 03.60' W | 72 | 04/26/04<br>9/28/04<br>04/23/05 | 7/28/04<br>12/05/04<br>01/16/06 | 99<br>0<br>1313 | 96<br>0<br>416 | 221<br>0<br>797 |
| BSM-4 | 32<br>40 | 57° 51.18' N<br>168° 52.20' W | 70 | 10/3/04<br>9/24/05 | 12/23/04<br>1/25/06 | 0<br>790 | 31<br>285 | 234<br>511 |
| MM4 | 0.5 | 55° 54.07' N<br>169° 52.01' W | 1590 | 4/30/05 | 08/02/05 | 7 | 2 | 4 |

## References

Au, W.W.L., J. Mobley, W.C. Burgess, M.O. Lammers, and P.E. Nachtigall. 2000. Seasonal and diurnal trends of chorusing humpback whales wintering in waters off western Maui. Marine Mammal Science 16:530-544.

Barlow, J. 2005. Cruise report: Marine Mammal Cruise Number 1625: Structure of Populations, Levels of Abundance and Status of Humpbacks (SPLASH), Cruise Number: AR-04-05. March 25, 2005. Southwest Fisheries Science Center (SWFSC) sponsored by U.S. Department of Commerce, NOAA, NMFS, SWFSC Protected Resources Division (PRD). SWFSC, 8604 La Jolla Shores Drive, La Jolla, California 92038.

Baumgartner, M.F., T.V.N. Cole, R.G. Campbell, G.J. Teegarden, and E.G. Durbin. 2003. Associations between North Atlantic right whales and their prey, *Calanus finmarchicus*, over diel and tidal time scales. Marine Ecology Progress Series 264:155-166.

Brownell, R.L. jr., P.J. Clapham, T. Miyashita, and T. Kasuya. 2001. Conservation status of North Pacific right whales. Journal of Cetacean Research and Management (special issue) 2:269-286.

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

Clapham, P.J., C. Good, S.E. Quinn, R.R. Reeves, J.E. Scarff, and R.L. Brownell, jr. 2004. Distribution of North Pacific right whales (*Eubalaena japonica*) as shown by 19th and 20th century whaling catch and sighting records. Journal of Cetacean Research and Management 6:1–6.

Clark, C.W. 1982. The Acoustic Repertoire of the Southern Right Whale, a Quantitative Analysis. Animal Behavior 30:1060-1071.

Clark, C.W. 1983. Acoustic communication and behavior of the southern right whale (*Eubalaena australis*). Pages 163-198 *in* R. Payne, ed. Communication and Behavior of Whales. Westview Press, Boulder, CO.

Clark, C.W., R. Charif, S. Mitchell, and J. Colby. 1996. Distribution and behavior of the bowhead whale, *Balaena mysticetus*, based on analysis of acoustic data collected during the 1993 spring migration off Point Barrow, Alaska. Report of the International Whaling Commission 46:541-552.

Clark, C.W., and 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 of London series B 271:1051-1057.

Clay, C.S., and H. Medwin. 1977. Acoustical Oceanography: Principles and Applications. John Wiley & Sons, Inc., New York.

Doroshenko, N.V. 2000. Soviet whaling for blue, gray, bowhead and right whales in the North Pacific Ocean, 1961-1979. Pages 96-103 *in* A.V. Yablokov and V.A. Zemsky, eds. Soviet Whaling Data (1949-1979). Center for Russian Environmental Policy, Moscow.

Federal Register / Vol. 71, No. 129 / Thursday, July 6, 2006 / Rules and Regulations DEPARTMENT OF COMMERCE National Oceanic and Atmospheric Administration 50 CFR Part 226 [Docket No. 051018271–6157–02; I.D. 101405C] RIN 0648–AT84 Endangered and Threatened Species; Revision of Critical Habitat for the Northern Right Whale in the Pacific Ocean AGENCY: National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Commerce. ACTION: Final rule. pp 38277-38297.

Fristrup, K.M., L.T. Hatch, and C.W. Clark. 2003. Variation in humpback whale (*Megaptera novaeangliae*) song length in relation to low-frequency sound broadcasts. Journal of the Acoustical Society of America 113:3411-3424.

Goddard, P.D., and D.J. Rugh. 1998. A group of right whales seen in the Bering Sea in July 1996. Marine Mammal Science 14:344-349.

LeDuc, R.G. 2004. Report of the results of the 2002 survey for North Pacific right whales. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-357. Available from Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, California 92038.

LeDuc, R.G., W.L. Perryman, J.W. Gilpatrick, jr., J. Hyde, C. Stinchcomb, J.V. Carretta, and R.L. Brownell, jr. 2001. A note on recent surveys for right whales in the southeastern Bering Sea. Journal of Cetacean Research and Management (special issue) 2:287-289.

Matthews, J.N., S. Brown, D. Gillespie, M. Johnson, R. McLanaghan, A. Moscrop, D. Nowacek, R. Leaper, T. Lewis, and P. Tyack. 2001. Vocalisation rates of the North Atlantic right whale (*Eubalaena glacialis*). Journal of Cetacean Research and Management 3:271-282.

Mattila, D.K., L.N. Guinee, and C.A. Mayo. 1987. Humpback whale songs on a North Atlantic feeding ground. Journal of Mammalogy 684:880–883.

McDonald, M.A. and S.E. Moore. 2002. Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea. Journal of Cetacean Research and Management 4:261-266.

McSweeney, D.J., K.C. Chu, W.F. Dolphin, and 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. 2001. Ishmael 1.0 User's Guide. NOAA Technical Report OAR-PMEL-120, Seattle, WA. 26 pp. Available online at http://cetus.pmel.noaa.gov/cgi-bin/MobySoft.pl.

Mellinger, D.K., K.M. Stafford, and C.G. Fox. 2004*a*. Seasonal occurrence of sperm whale (*Physeter macrocephalus*) sounds in the Gulf of Alaska, 1999-2001. Marine Mammal Science 20:48-62.

Mellinger, D.K., K.M. Stafford, S.E. Moore, L. Munger, and C.G. Fox. 2004*b*. Detection of north Pacific right whale (*Eubalaena japonica*) calls in the Gulf of Alaska. Marine Mammal Science 20:872-879.

Moore, S.E., J.M. Waite, L.L. Mazzuca, and R.C. Hobbs. 2000. Mysticete whale abundance and observations of prey associations on the central Bering Sea shelf. Journal of Cetacean Research and Management 2:227-234.

Munger, L.M., D.K. Mellinger, S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. 2005. Performance of spectrogram cross-correlation in detecting right whale calls in long-term recordings from the Bering Sea. Canadian Acoustics 33:25-34.

Parks, S.E., and P.L. Tyack. 2005. Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups. Journal of the Acoustical Society of America 117:3297-3306.

Parks, S.E., P.K. Hamilton, S.D. Kraus, and P.L. Tyack. 2005. The gunshot sound produced by male North Atlantic right whales (*Eubalaena glacialis*) and its potential function in reproductive advertisement. Marine Mammal Science 21:458-475.

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

Scarff, J.E. 1991. Historic distribution and abundance of the right whale (*Eubalaena glacialis*) in the North Pacific, Bering Sea, Sea of Okhotsk and Sea of Japan from the Maury whale charts. Report of the International Whaling Commission. 41:467-89.

Scarff, J.E. 2001. Preliminary estimates of whaling-induced mortality in the 19th century North Pacific right whale (*Eubalaena japonicus*) fishery, adjusting for struck-but-lost whales and non-American whaling. Journal of Cetacean Research and Management (special issue) 2:261-268.

Shelden, K.E.W., S.E. Moore, J.M. Waite, P.R. Wade, and D.J. Rugh. 2005. Historic and current habitat use by North Pacific right whales, *Eubalaena japonica*, in the Bering Sea and Gulf of Alaska. Mammal Review 35:129-155.

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.

Smith, W.H.F. and D.T. Sandwell. 1997. Global Seafloor Topography from Satellite Altimetry and Ship Depth Soundings. Science 277:1956-1962.

Stafford, K.M., S.L. Nieukirk, and 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., S.E. Moore, and C.G. Fox. 2005. Diel variation in blue whale calls recorded in the eastern tropical Pacific. Animal Behavior 69:951-958.

Thompson, P.O. and W.A. Friedl. 1982. A long term study of low frequency sounds from several species of whales off Oahu, Hawaii. Cetology 45:1-19.

Townsend, C.H. 1935. The distribution of certain whales as shown by logbook records of American whaleships. Zoologica (NY) 19:1-50 + 6 maps.

Tynan, C.T., D.P. DeMaster, and W.T. Peterson. 2001. Endangered right whales on the southeastern Bering Sea shelf. Science 294:1894.

Vanderlaan, A.S.M., A.E. Hay, and C.T. Taggart. 2003. Characterization of North Atlantic Right Whale (*Eubalaena glacialis*) Sounds in the Bay of Fundy. IEEE Journal of Oceanic Engineering 28:164-173.

Wade, P., M.P. Heide-Jorgensen, K. Shelden, J. Barlow, J. Carretta, J. Durban, R. LeDuc, L. Munger, S. Rankin, A. Sauter, and C. Stinchcomb. 2006. Acoustic detection and satellite-tracking leads to discovery of rare concentration of endangered North Pacific right whales. Biology Letters 2:417-419.

Waite, J.M., K. Wynne, and D.K. Mellinger. 2003. Documented sighting of a North Pacific right whale in the Gulf of Alaska and post-sighting acoustic monitoring. Northwestern Naturalist 84:38-43.

Wiggins, S. 2003. Autonomous Acoustic Recording Packages (ARPs) for Long-Term Monitoring of Whale Sounds. Marine Technical Science Journal 37:13-22.

Wiggins, S.M. and J.A. Hildebrand. 2007. High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring. International Symposium on Underwater Technology 2007 and International Workshop on Scientific Use of Submarine Cables & Related Technologies 17-20 April 2007, Tokyo, Japan, Institute of Electrical and Electronics Engineers, pp. 551-557.

Wiggins, S.M., M.A. McDonald, L.M. Munger, J.A. Hildebrand, and S.E. Moore. 2004. Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea. Canadian Acoustics 32:146-154.

Wiggins, S.M., E.M. Oleson, M.A. McDonald, and J.A. Hildebrand. 2005. Blue whale (*Balaenoptera musculus*) diel call patterns offshore of southern California. Aquatic Mammals 31:161-168.

Zar, J.H. 1999. Biostatistical Analysis. Prentice Hall, New Jersey.

Chapter 3, in full, has been submitted for publication (Munger, L., S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. North Pacific right whale (*Eubalaena japonica*) seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea, 2000-2006. Marine Mammal Science, in revision). The dissertation author was the primary investigator and author of this paper. The coauthors listed supervised the research forming the basis of this chapter.

# IV. Right whale ‘up-call’ source levels and detection ranges on the southeastern Bering Sea shelf

## Abstract

We calculated source levels and detection range for North Pacific right whale (*Eubalaena japonica*) calls on the southeast Bering Sea shelf, using two different techniques for estimating range to calling animals. The first technique localized calling whales in two dimensions based on differences in arrival times of the call on three or more widely separated hydrophones. The second technique was based on waveform dispersion of normal modes in a shallow waveguide, and allowed for range estimates to calls on a single hydrophone. From data recorded in October 2000, right whale ‘up’-call rms and peak-to-peak source-levels (n = 7) ranged from 182 - 190 and 186 – 194 dB re 1 μPa at 1 m, respectively, for calls localized using time-difference of arrivals. Calls recorded in September 2001 (n = 130) had ranges in rms and peak-to-peak source levels of 180-192 and 194-208 dB re 1 μPa at 1m, respectively, for call source distances estimated using the normal mode modeling technique. Our calculated rms source levels are within the range reported for sounds produced by other balaenid whales (including bowheads and other right whale species). The maximum detection range in our study was 190 km, and the average detection range was about 100 km. Detection range was dependent upon ambient ocean noise at the hydrophone, which ranged from 72 to 91 dB re 1 $\mu Pa^2/Hz$, measured within the same frequency band of the calls (90 – 170 Hz on average). Our detection range is higher than previously reported ranges in shallow-water whale acoustic studies, owing to relatively low transmission loss of approximately $15*\log_{10}(\text{range})$ for low-frequency sounds on the Bering Sea shelf.

## Introduction

The eastern stock of North Pacific right whales (*Eubalaena japonica*) is among the most endangered large whale populations in the world, with probably fewer than one hundred individuals (Clapham *et al*., 1999; Brownell *et al*., 2001). Encounter rates during traditional visual line-transect surveys are so low that statistically robust abundance estimates are not feasible for this population. Passive acoustic monitoring using autonomous recorders can increase the probability of detecting right whales by operating continuously for long periods with detection ranges much greater than visual sighting range, and has potential applications in estimating whale abundance. Determining the detection range, *i.e.* the distance between acoustic recorders and calling animals, is a key step toward this goal. Estimating detection range requires understanding of the acoustic properties of right whale calls and sound propagation characteristics in the study area. Essential data include source levels of calls, the acoustic transmission loss at the study site, and ambient noise at the receiver.

North Pacific right whales produce a variety of call types similar to the repertoires of southern right whales and North Atlantic right whales (*E. australis* and *E. glacialis*, respectively). The most common right whale call type during non-reproductive behavior is a low-frequency (50-500 Hz), FM upsweep lasting slightly less than one second in duration (Clark, 1983; McDonald and Moore, 2002). This ‘up-call’ is well suited to long-distance propagation because of the low frequency (Edds-Walton, 1997), is produced by calves and adults, males and females, and is therefore thought to be primarily a contact call (Clark, 1982; Clark, 1983). The contact function of up-calls is supported by field observations of southern right whales producing these calls when approaching each other and ceasing to call when together (Clark, 1983), and by playback experiments (Clark and Clark, 1980). Reported source levels for right whale calls vary by call type, species and region; southern right whale 'belch-like utterance' source levels were reported at 172 – 187 dB re 1 μPa at 1m (Cummings *et al.*, 1972); North Atlantic right whale tonal calls (including 'up' calls) were found to be 137-162 dB re 1 μPa at 1m and broadband 'gunshot' sounds were 174-192 dB re 1 μPa at 1m (Parks and Tyack, 2005). Detection range for right whale calls also varies depending on region, with maximum detection ranges of up to 30 km in the Bay of Fundy (Laurinolli *et al.*, 2003), and greater than 50 km in the southeast Bering Sea (Wiggins *et al.*, 2004); both of which are shallow-water environments (< 200 m).

The majority of recent North Pacific right whale sightings and acoustic detections have been in the southeastern Bering Sea (SEBS), in the middle- and outer-shelf domains where water depths are 50-150 m (Goddard and Rugh, 1998; Moore *et al.*, 2000; LeDuc *et al.*, 2001; McDonald and Moore, 2002; Moore *et al.*, 2002; Barlow, 2005; Wade *et al.*, 2006). This habitat is thought to be primarily a feeding ground for right whales. Because the SEBS shelf is shallow and relatively flat for hundreds of kilometers, the region acts as an acoustic waveguide, trapping sound between the air/sea surface and seafloor and channeling it for long distances (Wiggins *et al.*, 2004). This region is therefore well-suited for long-range underwater communication, and may serve as an important habitat for right whale social and reproductive behavior as well as foraging.

We conducted long-term passive acoustic monitoring in the SEBS from 2000 through 2005 to provide information on seasonal occurrence, calling behavior and relative abundance of these critically endangered whales. We present estimates for right whale up call source levels and transmission loss in the SEBS, based on a subset of acoustic data recorded in 2000-2002 from recorders with the same hardware configuration and component types. Because ‘up’ calls were the most common call type as well as the most easily distinguished from other whale species’ calls, we focused on them for this analysis and used only calls that the analyst was most confident were produced by right whales (Munger *et al.*, submitted). We also report average background noise levels in the right whale calling band and estimate the acoustic detection range of instruments during average, minimum and maximum measured noise within the right whale calling band.

## Methods

In October 2000, we deployed four passive, seafloor-mounted Acoustic Recording Packages (ARPs) (Wiggins, 2003) at approximately 70m depth in the southeast Bering Sea (Figure 4.1). These instruments sampled continuously at 500 Hz and operated for ~ 7 months, until May 2001. The ARPs were spaced approximately 60 km from one another in the east-west direction, and 20-40 km in the north-south direction. This geometry was intended to bisect a wide ‘corridor’ to maximize the chances of detecting right whales and not necessarily to function as an array for localizing calls; however, acoustic propagation on the SEBS shelf was better than anticipated (100+ km) such that several right whale calls were detected on more than one ARP. In August 2001 through July 2002, we collected data using a single ARP, with the same hydrophone model and hardware configuration as the previous year's deployments, at location 'C' (Figure 4.1).

We detected right whale calls using a combination of automated techniques and manually inspecting spectrograms (Munger *et al*., submitted; Munger *et al*., 2005). We used two different techniques to estimate range to calling animals. The first technique localized calls received during the first deployment period on three or more ARPs based on the difference in call arrival times. The second technique estimated range to calls received on one hydrophone, based on dispersion of normal modes within each call due to waveguide propagation on the SEBS shelf (Wiggins *et al*., 2004).

### Time difference of arrivals (TDOA)

Right whale calls were detected on four ARPs in October 2000. Arrivals of the same call(s) on multiple hydrophones (Figure 4.2) were determined by visually analyzing spectrograms and matching call start and end frequencies, peak frequencies and spectrogram contour shape (inflection points, etc.). Right whale calls were infrequent and did not overlap in time, and also varied substantially in start and end frequencies and sweep rates, allowing them to be distinguished by the analyst and matched across instruments. Calls in quick succession (< 1 or 2 minutes) were also distinguishable by having the same intervals between each call in the series in each ARP recording. Call arrival times on each hydrophone were picked in the call spectrogram at the same frequency to within ±2 Hz.

Right whale calls received on three or more ARPs were localized using time difference of arrivals (TDOA) between hydrophones and an assumed uniform sound velocity of 1470 m/s based on temperature and salinity measurements for the southeast Bering Sea during October from Bering Sea subsurface moorings maintained by NOAA PMEL (data online at www.pmel.noaa.gov/foci/foci_moorings/foci_moorings.shtml). A Matlab routine (written by David Mellinger) calculated and plotted constant time-difference hyperbolae in two-dimensional space based on TDOA between pairs of hydrophones (Figure 4.3). Because the water depth was shallow (70 m) relative to horizontal distances (tens of kilometers), localizing in two dimensions is a good approximation. There are only 2 linearly independent hyperbolae for an array of three hydrophones, such that a plot of three hyperbolae representing the three time-difference pairs produces a single intersection point, which we took to be the whale location. We then plotted error regions representing +0.5s and -0.5 s error on time arrivals, to account for potential error on arrival time picks and instrument clock drift correction (determined to be less than 1 s/day, based on time offset measured at end of deployment and assumed linear clock drift throughout recording period). The localization routine was repeated for all right whale calls received on at least 3 ARPs and identifiable as the same call(s), and a distance was calculated from the call to each hydrophone from the intersection point of the hyperbolae.

### Normal mode dispersion model (NMDM)

We also estimated ranges to calls by modeling dispersion of normal modes in a shallow water waveguide (Wiggins *et al.*, 2004). At ranges up to the water depth, spherical spreading is a good approximation for acoustic propagation. However, at ranges several times greater than water depth, as was the case for calls traveling tens of kilometers over the shallow (70 m) SEBS middle-shelf, sound propagation is bounded by the air-sea surface and the seafloor and approaches a cylindrical spreading model. At long ranges, the numerous reflections off the boundary surfaces lead to constructive and destructive interference of groups of sound rays, such that frequency-dependent dispersion of normal modes is apparent in the signal waveforms and spectrograms. The normal modes arise from the 'natural modes of vibration' of the bounded medium and are solutions to the cylindrical wave equation (Clay and Medwin 1977). The group velocity of each mode is frequency-dependent (Figure 4.4) within the bandwidth used by right whales (~ 50 – 200 Hz), such that decreasing sound frequencies travel increasingly slowly until reaching a velocity minimum (the Airy frequency, or inflection points of curves in Figure 4.4). Below the Airy frequency, group velocity rapidly increases to the sound velocity in the sediment (Wiggins *et al.*, 2004).

We used a Matlab routine (Wiggins *et al.*, 2004) to calculate the group velocity of each mode (Figure 4.4) based on the following equations:

Group velocity of *m*th mode, $u_m = \dfrac{d\omega}{dk_m}$

Angular frequency $\omega = \dfrac{\gamma_m c_1}{\cos(\theta)}$

Horizontal wave number $k_m = \left[\left(\dfrac{\omega}{c_1}\right)^2 - \gamma_m{}^2\right]^{1/2}$

Vertical wave number $\gamma_m = \left(\pi(m-1) + \dfrac{\pi}{2} + \phi\right)\dfrac{1}{h}$

Phase shift at seafloor $\phi = \tan^{-1}\left(\dfrac{\rho_1 c_1 g_2}{\rho_2 c_2 \cos(\theta)}\right)$

Imaginary part of Snell's Law cosine at seafloor $g_2 = \left[ \left( \frac{c_2}{c_1} \right)^2 \sin^2(\theta) - 1 \right]^{1/2}$

Our default input parameters were sound speed in water = $c_1$ = 1470 m/s, water density = $\rho_1 = 1026$ kg/m$^3$, sound speed in sediment = $c_2$ = 1675 m/s, sediment density = $\rho_2$ = 1500 kg/m$^3$, and water depth = $h$ = 70 m. Equations were evaluated for a set of incident angles $\theta_c \le \theta \le \pi/2$ (Wiggins *et al.*, 2004). The critical angle, $\theta_c$, is the angle of incidence of sound rays (taken from normal to seafloor), above which sound rays do not refract back into the water column (found using Snell's law, $\sin\theta_c = \frac{c_1}{c_2}$). Source depth was assumed to be 15 m and receiver depth was 60 m; these parameters affect mode intensity depending on frequency and mode number, but do not affect the horizontal range estimate and therefore the assumption of source depth was not important in this analysis.

We picked mode arrivals in the call spectrogram at the same frequency across the received call, and used the difference in modal arrival times and the calculated group velocities for each mode to calculate the horizontal range to the caller, range $= R = \frac{u_i u_j}{|u_i - u_j|} |t_i - t_j|$ , where $u$ = group velocity and $t$ = arrival times, respectively, for *i*th and *j*th modes (Wiggins *et al.*, 2004). We created a synthetic model of the initial sweep of each call based on the frequencies and sweep rate of the received call spectrogram. We modeled the distortion of the synthetic 'initial call' contour using the range calculated from mode arrival-time picks, and overlaid this modeled call on the actual call spectrogram. Range and synthetic call contour parameters were adjusted manually to improve the model fit. Example NMDM overlay plots are shown in Figure 4.5 for three different right whale call spectrograms at three different ranges. We applied the normal mode model to calls recorded in October 2000 (the hyperbolic localization data subset) as well as right whale calls recorded by a single ARP deployed the following year at site ‘C’ (Figure 4.1).

### Normal mode dispersion model sensitivity

We conducted a sensitivity analysis of the normal mode model to the parameters $c_1$, $c_2$, $\rho_1$, $\rho_2$ and $h$ (sound speed in water, sediment, water density, and sediment density, respectively). We varied one parameter at a time, keeping the other default values, and observed the resulting change in modal group velocities and estimated range for a given time difference between mode arrivals. We varied water sound speed from 1450 to 1490 m/s, sediment sound speed from 1650-1700 m/s, water density from 1016 to 1036 kg/m$^3$, sediment density from 1450 to 1550 kg/m$^3$, and water depth from 65 to 75 m. The minimum and maximum sound speeds were calculated based on depth and minimum and maximum values of temperature and salinity (Mackenzie, 1981) recorded by moorings over the course of a year in the southeast Bering Sea.

### Source level calculation

The received level of each call was obtained by first band-pass filtering the data with filter corner frequencies within 5-10 Hz of the start and end frequency of the call (referred to as the ‘right whale calling band’). We converted time series data to absolute sound pressure levels based on laboratory calibration of ARPs, with a measured conversion of -72.3 dB re counts$^2$/μPa$^2$, flat within ±1 dB within the frequency band 50 to 250 Hz (McDonald, 2006; Wiggins, 2003). ARP configurations were the same in both years of deployments. We calculated peak-to-peak (p-p) and root mean square (rms) received levels, as well as energy flux density (EFD) (Madsen, 2005), using the bandpassed time series data. Root-mean-square time windows were determined from calculating call amplitude 10 dB down from the peak amplitude within the Hilbert-transformed call spectral envelope. The energy flux density calculation was EFD = $\mathrm{SPL}_{\mathrm{rms}}$ (dB) + $10\log_{10}(T)$, where $T$ is the time window duration of the call in seconds.

We calculated source levels for right whale calls using the sonar equation: $RL = SL - TL$, where $RL$ = received level, $SL$ = source level, and $TL$ = transmission loss, all expressed in dB. We estimated transmission loss empirically as a function of range, using $TL = x\log_{10}\left(\frac{r}{R_0}\right)$, where $r$ = horizontal range (m), $R_0$ = reference range (taken as 1 m), and the coefficient $x$ varies, depending on local acoustic propagation properties, typically between 10 for cylindrical spreading ($r >>$ depth) and 20 for spherical spreading ($r <$ water depth). To find the transmission loss coefficient $x$, we plotted received sound pressure levels ($RL$) versus $\log_{10}(r)$ and fit a linear regression using least-squares minimization. We calculated source level of each call by adding the received level to transmission loss, and took the average source level across instruments if recorded by more than one ARP.

We repeated the source level and transmission loss calculation (including linear regression to estimate transmission loss coefficient) independently for peak-to-peak, rms, and energy flux density measurements, for right whale calls localized using TDOA on multiple ARPs (deployed 2000), and for call ranges estimated from normal mode modeling on data from a single ARP (deployed 2001).

### Detection range

We measured background noise in the right whale calling band within a few seconds of each call. Time series data were bandpass filtered with corner frequencies within 10 Hz of the start and end frequency of the call, and a root-mean-square measurement was obtained from time series for background noise immediately before or after the call, and converted to a sound pressure level. We subtracted $10*\log_{10}$(filter banwidth) to calculate noise per Hz (dB re $\mu Pa^2/Hz$). The 'most certain' right whale calls analyzed in this study were at least 2 dB and on average 5 dB above background noise. We calculated a maximum and average detection range based on signal-to-noise ratios of 2 dB above minimum background noise and 5 dB above average background noise in the right whale calling band.

## Results

### TDOA uncertainty

A total of 7 localizable, 'most certain' right whale calls were detected in recordings on three or more hydrophones (only one of these calls was detected on all 4 hydrophones) from 2-Oct-00 through 4-Oct-00. The 7 calls were produced as six distinct call series, separated by a minimum of 30 minutes. An example of TDOA-based localization results for two of these call series is shown in Figure 4.3. The intersection points of hyperbolae assuming zero error on time arrivals are plotted as filled triangles.

Hyperbola shaded regions represent error of ± 0.5 s on time arrivals. Distance errors varied depending on array geometry relative to the call source (Figure 4.3), with average percent error of 11.5% and rms error of 13.9%. The two call series shown in Figure 4.3 were produced over 24 h apart at an approximate distance of 20 km from one another. It is possible that these and the other calls localized using TDOA were produced by a single individual, as they were all localized to roughly the same vicinity over a 3-day span. Unfortunately, the right whale calls that were localized using TDOA were not suitable for normal mode modeling, because of the few calls identified as right whales and detected on three or more instruments, only one mode arrival was clearly visible in the spectrogram (*e.g.*, Figure 4.2).

### NMDM sensitivity

We estimated ranges using the normal mode dispersion model (NMDM) to 130 right whale calls recorded in September 2001. Due to the relatively high calling rates in this period (Munger *et al.*, submitted) and variation in calling distance, it is likely that these calls came from multiple whales. We found that the NMDM was relatively unaffected by changes in estimates of the water and sediment sound speeds and densities, resulting in < 5% difference in range estimates (Table 4.1). The model was more sensitive to variations in seafloor depth, with a change of ± 5 m resulting in up to a 14% difference in estimated range. The Airy frequency (inflection point at minimum group velocity) in higher mode numbers (4 and above) varied noticeably with changes in water sound velocity, and for mode 4 was about 10 Hz higher for 1490 m/s than for 1450 m/s (Table 4.1). Range estimates were most affected by the choice of mode numbers, which was constrained by the fit of the normal mode model to the data (*e.g.*, Figure 4.5).

### Source levels and transmission loss

RMS received pressure levels of calls at distances determined by TDOA and NMDM are plotted versus the logarithm of range and fitted by a linear regression in Figure 4.6. The linear regression was repeated for each data set and measurement type (peak-peak, rms, and EFD) to obtain independent transmission loss coefficients. Source levels were calculated for each call by adding received level to transmission loss and results are displayed as histograms in Figure 4.7. Linear regression coefficients, $R^2$, average source levels at 1 m, and sample size are displayed for rms, peak-to-peak, and energy flux density measurements using each ranging technique in Table 4.2. RMS source level estimates were the most consistent between distance-estimation methods, ranging from 180 to 192 dB re 1 $\mu Pa_{rms}$ at 1 m, and were on average 184 dB re 1 $\mu Pa_{rms}$ at 1 m. Transmission loss coefficients estimated using TDOA and NMDM distances and rms received levels were 15.1 and 15.8, respectively. Average peak-to-peak source levels were ~5 to 16 dB higher, respectively, than rms values. Average energy flux density was slightly higher than rms source level for the TDOA set of calls, and 6 dB lower than rms for NMDM calls. The transmission loss coefficients ranged from 14 to 17 depending on measurement type and ranging technique, and the average was 15.5 for all measurements.

### Detection range

Average, minimum and maximum hydrophone noise levels in the right whale calling band (on average 90-170 Hz) during periods with right whale calls are shown in Table 4.3. Noise received levels varied between 72 and 91 dB re 1 $\mu Pa^2/Hz$, were on average 80 dB re 1 μPa$^2$/Hz overall, and were highest in late summer/early fall of 2001. The maximum observed range in our data, calculated using hyperbolic localization and TDOA of calls recorded in October 2000, was ~190 km, which corresponded to relatively low background noise of 73 dB re 1 μPa$^2$/Hz over the call bandwidth at the time the call was received. Our theoretical maximum detection range, calculated for a received level of at least 2 dB above minimum background noise integrated over the right whale calling band and using the average transmission loss coefficient of 15.5 and source level of 184 dB re 1 μPa$_{rms}$ (from Table 4.2), would be over 500 km. However, this theoretical detection range is very sensitive to the estimated transmission loss coefficient, with a 1% change in transmission loss coefficient resulting in a 100 km change in detection range. The average theoretical detection range for calls, based on received levels 5 dB above average background noise, is ~100 km, which was also the upper limit of our distance estimates using the NMDM method (Figure 4.6).

## Discussion

Our estimated source levels for North Pacific right whale ‘up’ calls were 180-192 dB, on average 184 dB re 1 μPa$_{rms}$ at 1 m, and are within the range of values reported for southern right whale calls (172-187 dB re 1 μPa at 1 m) and bowhead whale calls (128-178, 152-185, and 158-189), both summarized in Richardson et al. (1995). These source levels are higher than the values of 137-162 dB re 1 μPa$_{rms}$ at 1 m, reported by Parks and Tyack (2005) for tonal calls of North Atlantic right whales. The 5 to 16 dB difference between rms and peak-peak source levels illustrates the variability in this relationship for pulsed, non-stationary calls (Madsen, 2005), and our finding is similar to that reported by

(Au *et al*., 2006) for humpback whale song, for which peak-to-peak measurements were up to 17-20 dB higher than rms values.

Estimates of source levels for a given species and call type may vary by tens of dB, due in part to variation in sound production between and within individual whales, and also due to uncertainty in measuring source levels in the wild. Variation in individual source levels may depend on call type and function, hearing sensitivity, and real or perceived signal-to-noise ratio (SNR). For example, blue whales are known to produce A and B calls at 190 dB re 1 μPa at 1 m or higher, but blue whale audible downsweep calls (D calls) in the St. Lawrence river were 156-166 dB re 1μPa at 1 m (Berchok *et al*., 2006). Uncertainty in source level estimates can arise from localization error to the whale, inaccurate assumptions about acoustic propagation at the study site, and from uncertainty in instrument frequency response and calibration. Another challenge in estimating source levels and comparing them with previously reported values is that there is no single standard measurement, and some measurements may be more appropriate for some sounds than others (*e.g.*, for tonal, stationary or long signals; transient, frequency-modulated signals, broadband clicks, amplitude-modulated calls, etc.). For a transient, pulsed signal that varies in energy content by frequency, such as a typical right whale call, there are problems associated with measuring the rms sound pressure level (Madsen, 2005). RMS of a pure sinusoid signal is 9 dB below peak-peak, but for a transient, pulsed call the rms level can be up to 20 dB or more below. Most reported values are root-mean-squared values, which are averaged over a time window, but the time window duration is not always reported.

Right whale calls in the SEBS become distorted with increasing distance due to waveguide dispersion, with multiple mode arrivals on the receiver appearing as a series of energy pulses with ‘quiet’ intervals in between. We therefore report source levels using three techniques for measuring sound pressure levels, *i.e.* peak-to-peak, root-mean-square, and energy flux density, as a basis for comparison with other studies and also to illustrate variation in amplitude with frequency over time for even an individual call. The latter measurement, energy flux density, provides information on the time-integrated total energy contained in a call and may be a more appropriate measure of what an animal actually hears (Madsen, 2005).

The southeast Bering Sea shelf provides a unique environment for long-range underwater acoustic propagation, with an extremely wide (500 km) shelf that is nearly uniformly flat and shallow (< 100 m) over most of its extent. Our average theoretical detection range of about 100 km and maximum observed localization range of ~ 190 km (for a call localized using 3 hydrophones) are high compared to other shallow-water whale studies, due to the unique bathymetry on the SEBS shelf. Maximum detection ranges of 20-30 km have been reported for right whales in other, shallow-water studies such as right whales in the Grand Manan Basin region of the Bay of Fundy, where the seafloor is sloped to a depth of 220 m in the center of a ~40-50 km wide channel (Laurinolli *et al.*, 2003). Detection ranges of 20-30 km have also been reported in regions over shelf breaks and slopes (*e.g.* in a study of fin whale calls off Hawaii, where hydrophone was located on the slope at 800 m depth; slope from 400 m to > 3000 m in 20 km (McDonald and Fox, 1999). Acoustic detection ranges on the southeast Bering slope (depth > 1000 m) and in the Aleutian Basin to the southwest are therefore likely to have detection ranges more similar to these 20-30 km ranges.

Recorded noise (including flow noise, hydrophone strumming, and ship noise) varied by instrument location, time of year, and on shorter time scales due to tidal cycles, storms and vessel traffic. On average, noise in the right whale calling band was 80 dB re 1 $\mu Pa^2/Hz$ and the average detection range of right whale calls by a human analyst was ~100 km. Spikes in noise, due to the close passage of ships or increased hydrophone strum (tension on hydrophone cable causing a snap-back or strumming effect similar to a guitar string) due to tidal currents and/or storms, were up to ~110 dB re 1 μPa over the entire calling bandwidth; at this noise level, whales would have to be close (~ 6 km) to the hydrophone for calls to be detectable. The months with highest noise were January and February; months with lowest noise were July and August. This was probably due to increased wind and storms during winter months as is typical for the Bering Sea.

Our source level estimates using the TDOA method are provisional, due to the small sample size (n = 7) of right whale calls that were suitable for localization, and poor array geometry when calls were in-line with hydrophone pairs resulting in high error on some distance estimates. However, results obtained using the NMDM ranging technique (n = 131) corroborate these source level estimates. The normal mode model was least sensitive to changes in parameters that vary by season in the southeast Bering Sea, *i.e.* water sound speed and density, and most sensitive to a parameter that was fairly uniform and unchanging over the timescale of our study, *i.e.* water depth. However, small variations in water depth over the monitored area may have contributed to some error in our NMDM range estimates, but presumably not a systematic error that would bias the source level estimate.

Identifying the correct modal number was the most important parameter in NMDM range estimates. Mode excitation at a given frequency depends on depth of the source and the receiver (Wiggins *et al*. 2004). We assumed a constant source depth of 15 m (and knew the receiver depth to be at about 60 m), but the actual depth at which the call was produced may have influenced which modes were visible above background noise and modeled by the analyst. Overall, multiple modes were most visible in calls at modeled ranges of about 20 - 50 km, and resulted in the most consistent range estimates. At ranges < 15-20 km, modes were so clustered together in time that it was difficult to distinguish and separate them, and at longer ranges often only one mode would be clearly visible in the spectrogram.

Knowing call source levels, transmission loss and ambient noise at the study site allows estimates of distance to calls to count the (minimum) number of calling groups or individual animals present, as well as to determine the detection range of receivers and hence the size of the area being monitored. Distance to the target, size of the monitored area, and probability of detection are all important parameters in distance sampling for abundance estimation (Buckland *et al*., 2001). We now have two techniques to estimate distances to right whales in our acoustic data set, and can estimate minimum numbers of whale groups using one or the other technique and corroborate using the second technique. Knowing our detection range allows us to calculate a minimum density of whales within the area monitored acoustically.

## Conclusions

These results demonstrate two independent methods for localizing and ranging to calling right whales in the SEBS, based on multiple sensors and TDOA estimation, and based on a single sensor observing the signal dispersion with NMDM. Right whale ‘up’-call rms source levels ranged from 180 – 192 dB re 1 $\mu Pa_{rms}$ at 1m and the averages were in agreement between the two methods at 184 dB re 1 $\mu Pa_{rms}$ at 1 m. The maximum detection range for a localized call in our study was 190 km, and the average detection range was about 100 km, dependent upon noise at the hydrophone within the right whale calling band. Ambient noise on the southeast Bering Sea shelf during the period of our study was 72 – 91 dB re 1 $\mu Pa^2/Hz$ within the right whale up-call frequency band from 90-170 Hz. Despite these relatively high ambient noise levels, our detection range for right whale calls is about an order of magnitude higher than other shallow-water acoustic studies of calling whales. We measured efficient propagation of right whale calls, with average propagation loss of about $15*\log_{10}$(range), on the Bering Sea shelf. The 100+ km propagation of right whale calls on the SEBS shelf may be an important attribute of this habitat, allowing whales to communicate at long distances, possibly to find mates or prey patches. Because the southeast Bering Sea is a shallow waveguide, anthropogenic noise from ships, drilling, and other activities may propagate for long distances and the frequencies for many of these activities are within the same range used by North Pacific right whales and other marine mammals. Increases in anthropogenic noise (*e.g.* from increased vessel traffic or other industrial activities) may reduce the ranges at which whales can communicate and locate each other on the Bering Sea shelf.

## Acknowledgements

This work was supported by NOAA Alaska Fisheries Science Center/National Marine Mammal Laboratory (AFSC/NMML) via JIMO budget #NA17RJ1231, North Pacific Marine Research Institute (project T-2100) and North Pacific Research Board (projects R-0307 and F0519), Alaska Department of Fish and Game (ADFG project T-1-6-4; special thanks to Bob Small), and National Fish and Wildlife Foundation. Sean Wiggins and Mark McDonald provided helpful comments on this manuscript and expertise in acoustics and instrumentation.

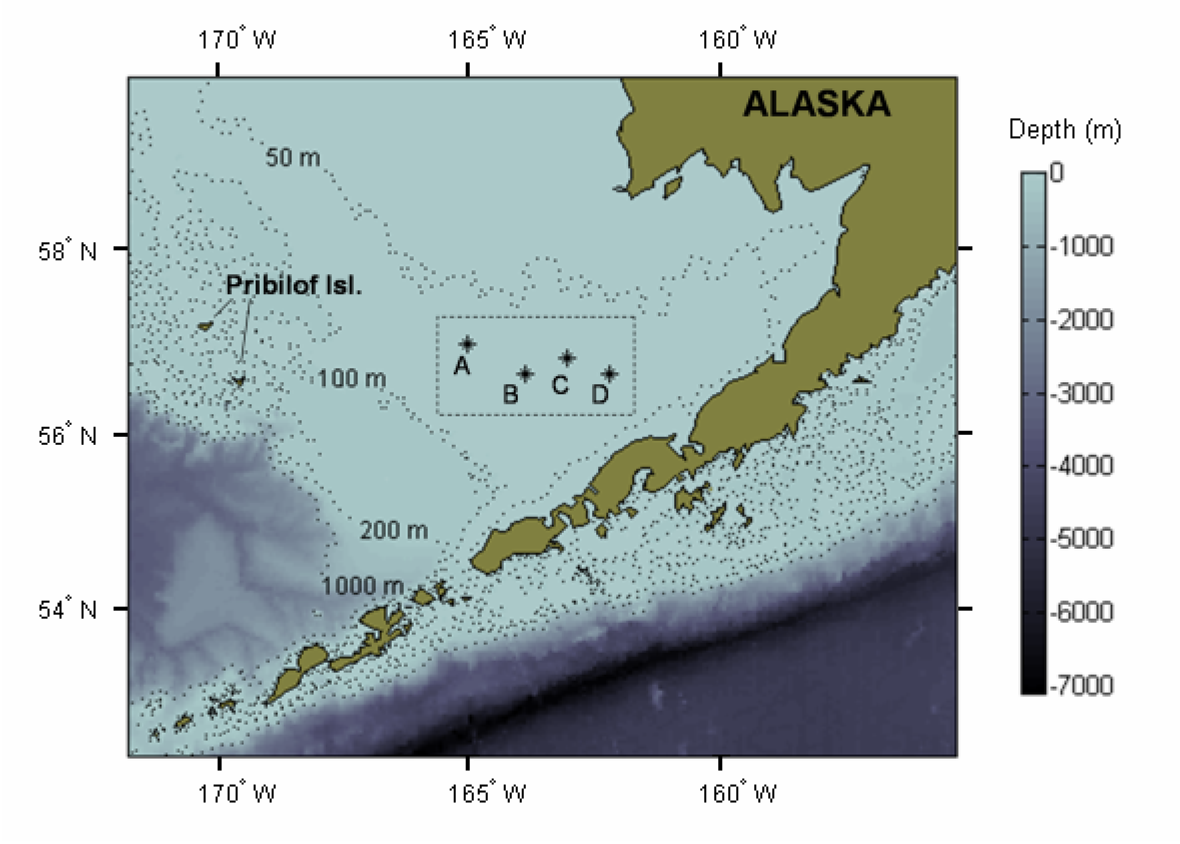


Figure 4.1. ARP deployment locations (asterisks) in 2000-02, and bathymetry (from Smith and Sandwell 1997) in southeastern Bering Sea. The dashed-line region is enlarged in Figure 4.3.

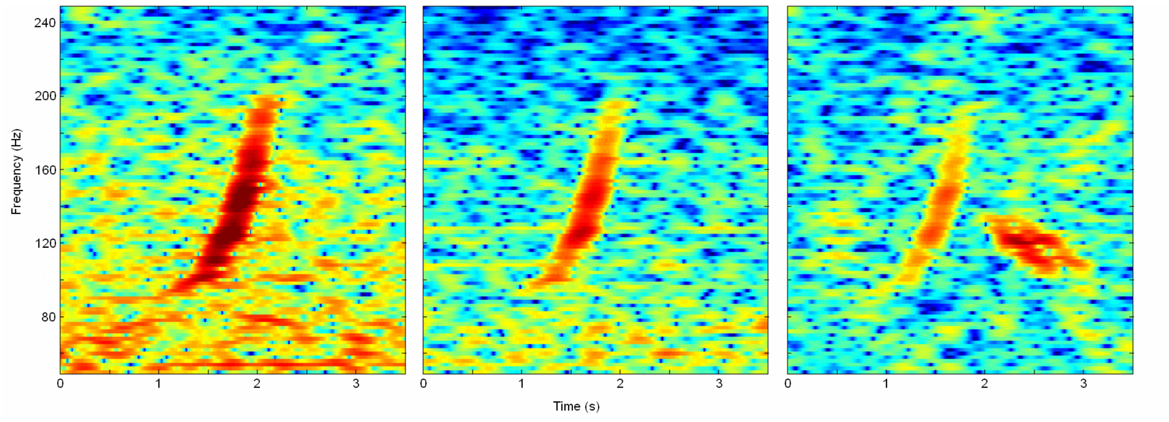


Figure 4.2. Right whale up-call recorded at ARP sites A, B, and C in the southeastern Bering Sea. A second call from an unidentified species was recorded on C. Sample frequency Fs = 500 Hz, fft & Hanning window length = 250 points, overlap = 98%, same spectrogram gain and contrast across panels for comparable intensity color-scale.

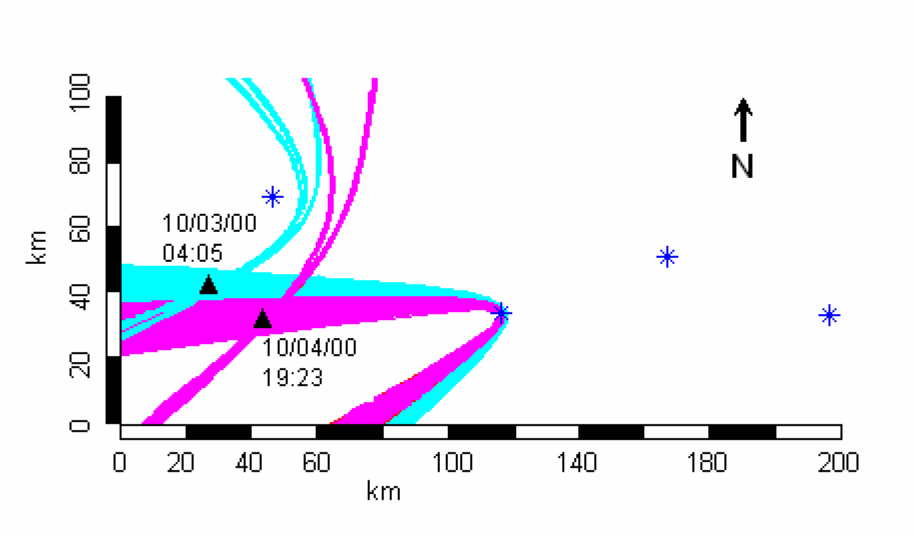


Figure 4.3. Right whale positions (triangles) based on TDOA, for two of the 7 right whale calls that were localized. Call reception times are indicated next to triangles. Hydrophone locations are represented by asterisks. Blue or pink shaded regions represent ± 0.5 s error on arrival times for each hydrophone pair time-difference. Pink regions are for call received on 3 western hydrophones; blue regions are for the call received on all 4 hydrophones.

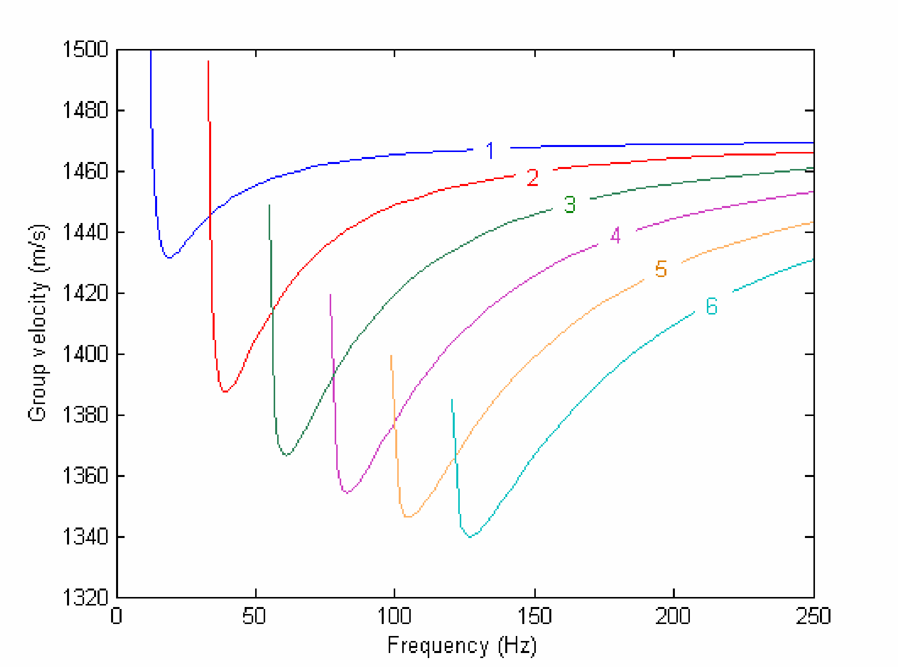


Figure 4.4. Dependence of group velocities of modes 1 through 6 on frequency, assuming sound speed in water = $c_1$ = 1470 m/s, water density = $\rho_1$ = 1026 kg/m$^3$, sound speed in sediment = $c_2$ = 1675 m/s, sediment density = $\rho_2$ = 1500 kg/m$^3$, and water depth = *h* = 70 m. See (Wiggins *et al*., 2004) for details of modeling.

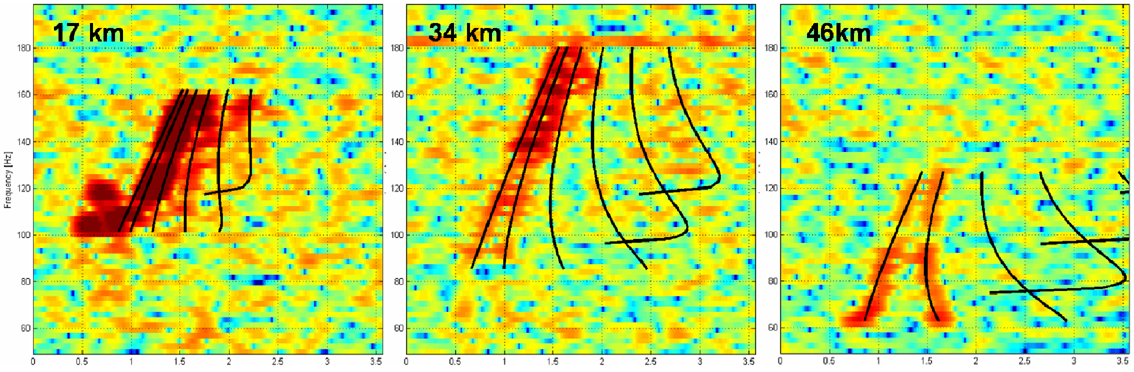


Figure 4.5. Spectrograms of three different right whale calls with overlaid normal mode models. Spectrogram parameters: 220-pt FFT, 98% overlap, same spectrogram gain and contrast across panels, such that sound intensity color scales are comparable.

Table 4.1. Sensitivity of normal-mode range estimates to changes in model parameters. Default parameters are: $c_1 = 1470$ m/s, $\rho_1 = 1026$ kg/m$^3$, $c_2 = 1675$ m/s, $\rho_2 = 1500$ kg/m$^3$, and h = 70m. Group velocity of nth mode = u (m/s), last two columns are rearrangement of equation for range as function of mode group velocities and difference in mode arrival times (see text, Methods, Normal Mode Dispersion Model subsection), and percent change in range at a given difference in mode arrival times.

| Parameter | Mode no. | u (m/s) | Airy freq (Hz) | $r / \| t_i-t_j \|= u_i^* u_j/\|u_i-u_j\|$ | %Δr at given Δt |
|---|---|---|---|---|---|
| $c_1$=1470 | mode1 | 1465 | 19 | | |
| | mode2 | 1448 | 39 | 129349 | (default parameters) |
| | mode3 | 1419 | 61 | 71132 | |
| | mode4 | 1378 | 83 | 47128 | |
| $c_1$=1450 | mode1 | 1445 | 18 | | |
| | mode2 | 1429 | 36 | 129057 | -0.2% |
| | mode3 | 1401 | 58 | 71501 | 0.5% |
| | mode4 | 1359 | 78 | 45332 | -3.8% |
| $c_1$=1490 | mode1 | 1485 | 20 | | |
| | mode2 | 1468 | 42 | 129743 | 0.3% |
| | mode3 | 1438 | 65 | 70848 | -0.4% |
| | mode4 | 1397 | 88 | 48524 | 3.0% |
| $\rho_1$=1016 | mode1 | 1465 | 19 | | |
| | mode2 | 1449 | 39 | 131805 | 1.9% |
| | mode3 | 1419 | 61 | 69695 | -2.0% |
| | mode4 | 1378 | 83 | 46881 | -0.5% |
| $\rho_1$=1036 | mode1 | 1465 | 19 | | |
| | mode2 | 1448 | 39 | 128574 | -0.6% |
| | mode3 | 1419 | 61 | 69898 | -1.7% |
| | mode4 | 1378 | 83 | 47211 | 0.2% |
| $c_2$=1650 | mode1 | 1465 | 20 | | |
| | mode2 | 1449 | 41 | 128609 | -0.6% |
| | mode3 | 1420 | 65 | 72430 | 1.8% |
| | mode4 | 1380 | 88 | 48997 | 4.0% |
| $c_2$=1700 | mode1 | 1465 | 18 | | |
| | mode2 | 1448 | 37 | 123316 | -4.7% |
| | mode3 | 1418 | 58 | 69607 | -2.1% |
| | mode4 | 1375 | 79 | 45254 | -4.0% |
| $\rho_2$=1450 | mode1 | 1465 | 19 | | |
| | mode2 | 1448 | 40 | 126286 | -2.4% |
| | mode3 | 1419 | 61 | 70377 | -1.1% |
| | mode4 | 1378 | 83 | 47218 | 0.2% |
| $\rho_2$=1550 | mode1 | 1465 | 19 | | |
| | mode2 | 1449 | 39 | 130964 | 1.2% |
| | mode3 | 1419 | 61 | 70653 | -0.7% |
| | mode4 | 1378 | 83 | 46779 | -0.7% |
| h=65 | mode1 | 1464 | 20 | | |
| | mode2 | 1445 | 42 | 111984 | -13.4% |
| | mode3 | 1412 | 65 | 61105 | -14.1% |
| | mode4 | 1366 | 89 | 41649 | -11.6% |
| h=75 | mode1 | 1466 | 18 | | |
| | mode2 | 1451 | 36 | 140804 | 8.9% |
| | mode3 | 1425 | 57 | 80746 | 13.5% |
| | mode4 | 1388 | 77 | 53162 | 12.8% |

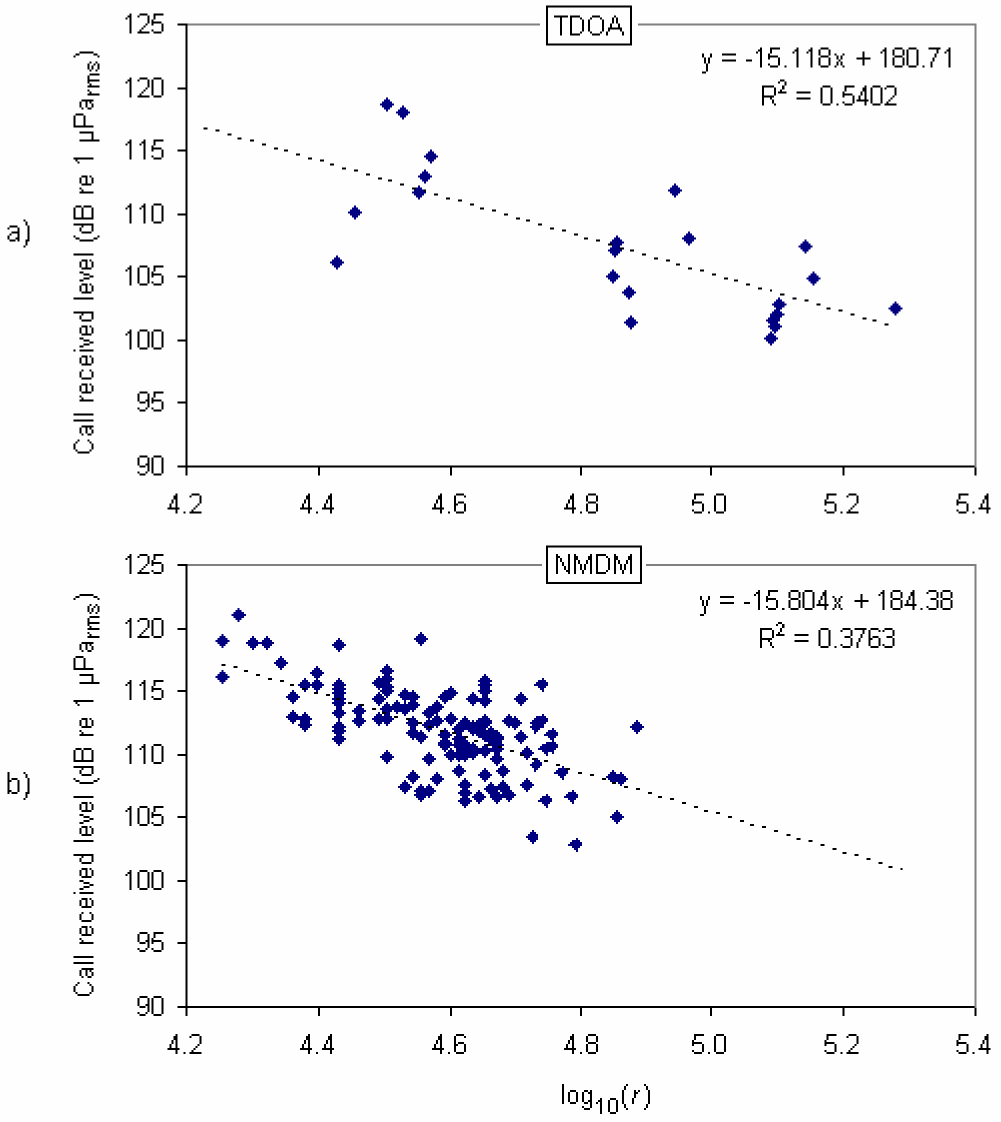


Figure 4.6. Call received levels (dB re 1 μPa$_{rms}$) plotted versus log$_{10}$(*r*), where *r* is the distance to the hydrophone calculated from a) intersection of hyperbolae based on TDOA, and b) using the normal mode dispersion model. Linear regression (dashed line) equations and R$^2$ values displayed in upper right of each panel.

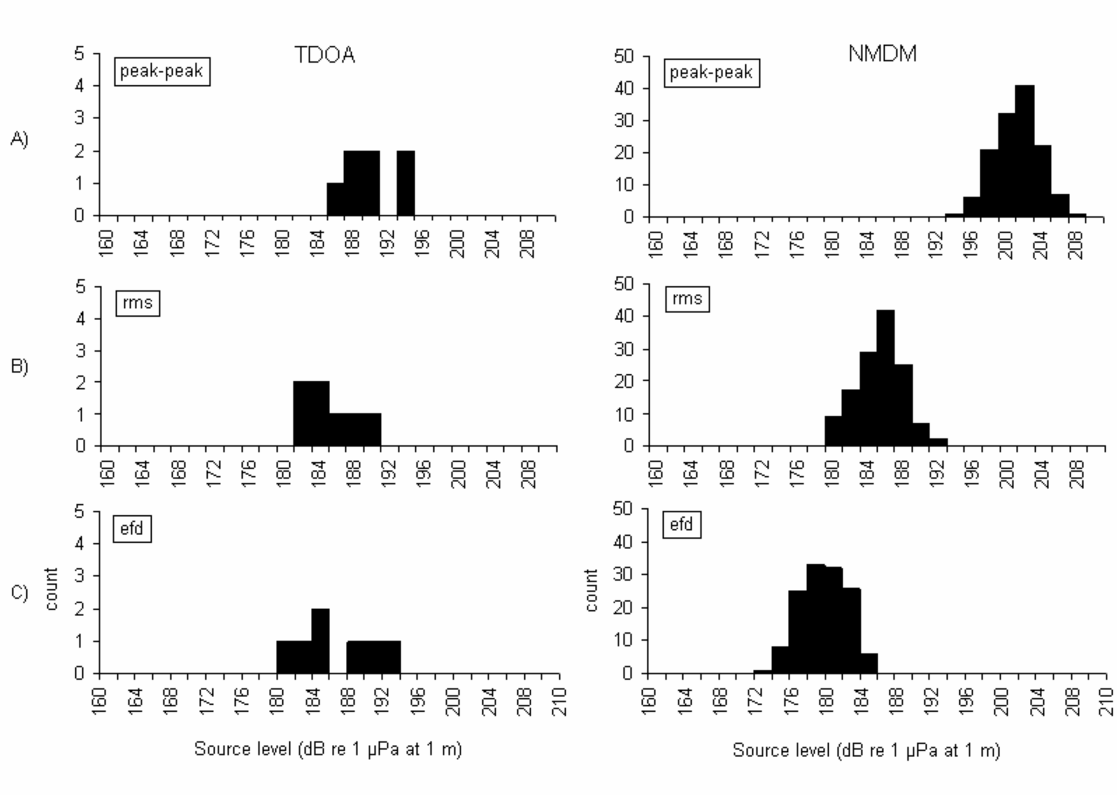


Figure 4.7. Histograms of calculated call source levels, equal to received level plus transmission loss, using range estimates based on TDOA (left) and NMDM (right), for a) peak-peak, b) root-mean-square, and c) energy flux density received level measurements. Note difference in vertical scale in TDOA plots (left).

Table 4.2. Linear regression coefficients and $R^2$ value, estimated source levels at 1 m, and sample size (n) for peak-peak, rms and energy flux density received levels, using the two different ranging methods: time difference of arrival (TDOA) and normal mode dispersion model (NMDM). TDOA source levels are averaged across the 3 or 4 receivers and may differ from y-intercept given by linear regression in Figure 4.6.

Received Level: $RL = SL - TL = -x\log_{10}(r) + b$

| Ranging technique | Measurement type | $x$ | Source level (dB re 1 μPa · 1m) | $R^2$ | Sample size (n) |
|---|---|---|---|---|---|
| TDOA | peak-peak | 14.0 | 188.5 | 0.53 | 7 |
| TDOA | rms | 15.1 | 184.0 | 0.54 | |
| TDOA | energy flux density | 17.0 | 187.7 | 0.63 | |
| NMDM | peak-peak | 16.6 | 200.1 | 0.42 | 131 |
| NMDM | rms | 15.8 | 184.4 | 0.38 | |
| NMDM | energy flux density | 14.3 | 177.9 | 0.33 | |

Table 4.3. Average, minimum and maximum background noise in right whale call band in ARP recordings.

| Recording period | Average noise (dB re $\mu Pa^2$ / Hz) ± SD | Min | Max | n |
|---|---|---|---|---|
| Oct 2000 | 77.9 ± 3.1 | 73.2 | 82.6 | 25 |
| Aug – Nov 2001 | 81.9 ± 2.7 | 77.5 | 91.1 | 354 |
| May – July 2002 | 78.7 ± 3.2 | 72.1 | 86.3 | 397 |

## References

Au WWL, Pack AA, Lammers MO, Herman LM, Deakos MH, Andrews K, 2006. Acoustic properties of humpback whale songs. Journal of the Acoustical Society of America 120:1103-1110.

Barlow J, 2005. Cruise Report: Structure of Populations, Levels of Abundance and Status of Humpbacks (SPLASH), Southwest Fisheries Science Center (SWFSC) Marine Mammal Cruise Number 1625. (UNITED STATES DEPARTMENT OF COMMERCE NOaAA, NATIONAL MARINE FISHERIES SERVICE SFC, eds); 1-13.

Berchok CL, Bradley DL, Gabrielson TB, 2006. St. Lawrence blue whalevocalizations revisited: Characterization of calls detected from 1998 to 2001. Journal of the Acoustical Society of America 120:2340-2354.

Brownell RL, Jr., Clapham PJ, Miyashita T, Kasuya T, 2001. Conservation status of North Pacific right whales. Journal of Cetacean Research and Management Special Issue 2:269-286.

Buckland ST, Anderson DR, Burnham KP, Laake JK, Borchers DL, Thomas L, 2001. Introduction to Distance Sampling. Oxford: Oxford University Press.

Clapham PJ, Young SB, Brownell RL, 1999. Baleen whales: conservation issues and the status of the most endangered populations. Mammal Review 29:35-60.

Clark C, 1983. Communication and Behavior of the Southern Right Whale (*Eubalaena australis*). In: Communication and Behavior of Whales (Payne R, ed). Boulder, Colorado: Westview Press; 163-198.

Clark CW, 1982. The Acoustic Repertoire of the Southern Right Whale, a Quantitative-Analysis. Animal Behaviour 30:1060-1071.

Clark CW, Clark JM, 1980. Sound Playback Experiments with Southern Right Whales (*Eubalaena australis*). Science 207:663-665.

Cummings WC, Fish JF, Thompson PO, 1972. Sound production and other behavior of southern right whales, Eubalena glacialis. Transactions S. Diego. Soc nat Hist 17:1-14.

Edds-Walton PL, 1997. Acoustic communication signals of mysticete whales. Bioacoustics 8:47-60.

Goddard PD, Rugh DJ, 1998. A group of right whales seen in the Bering Sea in July 1996. Marine Mammal Science 14:344-349.

Laurinolli MH, Hay AE, Desharnais F, Taggart CT, 2003. Localization of North Atlantic Right whale sounds in the bay of fundy using a sonobuoy array. Marine Mammal Science 19:708-723.

LeDuc RG, Perryman WL, Gilpatrick JW, Jr., Hyde J, Stinchcomb C, Carretta JV, Brownell RL, Jr., 2001. A note on recent surveys for right whales in the southeastern Bering Sea. Journal of Cetacean Research and Management Special Issue 2:287-289.

Mackenzie KV, 1981. 9-Term Equation for Sound Speed in the Oceans. Journal of the Acoustical Society of America 70:807-812.

Madsen RT, 2005. Marine mammals and noise: Problems with root mean square sound pressure levels for transients. Journal of the Acoustical Society of America 117:3952-3957.

McDonald MA, 2006. Calibration of Acoustic Recording Packages (ARPs) at Pt. Loma Transducer Evaluation Center (TRANSDEC). In: SIO Technical Report. La Jolla, CA: Scripps Institution of Oceanography, Marine Physical Laboratory; 1-16.

McDonald MA, Fox CG, 1999. Passive acoustic methods applied to fin whale population density estimation. Journal of the Acoustical Society of America 105:2643-2651.

McDonald MA, Moore SE, 2002. Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea. Journal of Cetacean Research and Management 4:261-266.

Moore SE, Waite JM, Friday NA, Honkalehto T, 2002. Cetacean distribution and relative abundance on the central-eastern and the southeastern Bering Sea shelf with reference to oceanographic domains. Progress in Oceanography 55:249-261.

Moore SE, Waite JM, Mazzuca LL, Hobbs RC, 2000. Mysticete whale abundance and observations of prey associations on the central Bering Sea shelf. Journal of Cetacean Research and Management 2:227-234.

Munger L, Wiggins S, Moore SE, Hildebrand JA, (submitted). North Pacific right whale (*Eubalaena japonica*) seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea, 2000-2006. Marine Mammal Science.

Munger LM, Mellinger DK, Wiggins SM, Moore SE, Hildebrand JA, 2005. Performance of spectrogram cross-correlation in detecting right whale calls in long-term recordings from the Bering Sea. Canadian Acoustics 33:25-34.

Parks SE, Tyack PL, 2005. Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups. Journal of the Acoustical Society of America 117:3297-3306.

Richardson WJ, Greene, C. R., jr., Malme, C. I., Thomson, D. H., 1995. Marine Mammals and Noise. San Diego, CA: Academic Press.

Wade P, Heide-Jorgensen MP, Shelden K, Barlow J, Carretta J, Durban J, Leduc R, Munger L, Rankin S, Sauter A, Stinchcomb C, 2006. Acoustic detection and satellite-tracking leads to discovery of rare concentration of endangered North Pacific right whales. Biology Letters 2:417-419.

Wiggins S, 2003. Autonomous acoustic recording packages (ARPs) for long-term monitoring of whale sounds. Marine Technology Society Journal 37:13-22.

Wiggins SM, McDonald MA, Munger LM, Moore SE, Hildebrand JA, 2004. Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea. Canadian Acoustics 32:146-154.

Chapter 4 is in preparation for submission (Munger, L.M., Wiggins, S.M., Moore, S.E., and Hildebrand, J.A. Right whale ‘up-call’ source levels and detection ranges on the southeastern Bering Sea shelf. Journal of the Acoustical Society of America, in preparation). The dissertation author was the primary investigator and author of this paper. The coauthors listed supervised the research forming the basis of this chapter.

# V. Seasonal and interannual variability of North Pacific right whale occurrence and oceanography on the southeastern Bering Sea middle shelf: a conceptual model

## Abstract

We investigated occurrence of North Pacific right whale (*Eubalaena japonica*) calls with respect to oceanographic variables in the southeastern Bering Sea (SEBS) middle-shelf region in 2000-2006 using data from acoustic and biophysical moorings. Passive acoustic recorders were deployed in 2000 and 2001 near NOAA Pacific Marine Environmental Laboratory (PMEL) biophysical mooring 2 (M2), and in 2004 and 2005 acoustic recorders were incorporated into M2 and mooring 4 (M4). Acoustic recording was continuous for periods of 220 to 332 days at/near M2 (2000-01, 01-02, and 05-06) and 124 days at M4 (2005-06), except in 2004, when continuous recording was over six shorter (2-45 d) periods intermittently throughout the deployment. We collated time series plots of daily right whale calling rates with daily-averaged temperature, salinity, and fluorescence (as a proxy for phytoplankton abundance) measured at several depths at M2 and M4. Right whale calls were detected in late May 2002 and late May and early June 2004, which were years with late spring (mid-late May) phytoplankton blooms. In the single year with an earlier, relatively lower-magnitude spring bloom (2005), July was the earliest month in which right whale calls were detected. Right whale calls were detected intermittently for 2-3 day periods in July through October of all years, when SEBS middle-shelf water was well-stratified into a surface warm layer and a bottom cold layer. Peak right whale calling rates were in August and September of 2001 and 2005, following post-spring, additional phytoplankton blooms in summer of both years. In 2005, a second peak in right whale calling occurred in mid-December, about 2 months

after the end of a prolonged summer/fall bloom. We hypothesize that springtime right whale presence on the SEBS shelf in years with late spring blooms is related to higher production and growth rates of copepods during a warmer-water, oceanic phytoplankton bloom after winters with at least moderate ice cover. The intermittent occurrence of right whales in summer and fall in stratified water may be related to their foraging on copepods concentrated in the bottom cold layer (as a result of either daily or ontogenetic vertical migration), with additional summer blooms possibly associated with right whale occurrence through fall due to increased prey availability or quality.

## Introduction

### Cetacean habitat models

Cetacean habitat models are useful for investigating how cetaceans interact with and respond to their environment, and are facilitated by the increasing availability of oceanographic data sets from *in situ* and/or remote sensors, improvements in statistical, mapping and database software, and increasing data storage capacity and processing speed within instruments and computers. Habitat models range from simple conceptual models that describe patterns in cetacean distribution and/or abundance in relation to oceanographic variables (e.g., collated maps of oceanographic properties and cetacean distributions), to more complex analytical models (modeling techniques and studies reviewed in Redfern *et al*., 2006). These models have applications that range from investigating habitat association patterns and formulating hypotheses, to predicting cetacean occurrence based on relevant oceanographic measurements. Potential benefits of habitat modeling include predicting the likelihood of cetacean occurrence in a given area using easily accessible data (including remotely sensed, historic and other existing data sets), informing management decisions such as critical habitat designation and disturbance mitigation strategies, and continuing to improve our understanding of cetacean behavioral ecology.

Models usually include physical and biological oceanographic variables as the independent (predictor) variables, and cetacean distributions in space and time as the dependent (response) variable. Oceanographic data sets used in models frequently include one or more of the following: bottom depth and slope characteristics, *in situ* water column measurements (*e.g.,* of temperature, salinity, currents), and remotely sensed surface variables and/or features such as temperature, eddies, fronts (Doniol-Valcroze *et al.*, 2007; Gregr and Trites, 2001), ocean color (as a proxy for chlorophyll concentration) (*e.g.*, Littaye *et al.*, 2004), and ice extent (for high-latitude species) (*e.g.* Barber *et al.*, 2001; Friedlaender *et al.*, 2006; Moore *et al.*, 2000). Cetacean distribution data are often collected using line-transect surveys conducted from aerial or vessel platforms; opportunistic data are sometimes available for certain species, e.g. from historic commercial whaling records or recent opportunistic sightings. The relationship of cetacean foraging distributions to environmental variables is usually hypothesized to be related to prey distributions, but as direct prey measurements are often not available, the link between cetaceans and prey is often inferred via correlations with phytoplankton and oceanographic features and dynamics that likely lead to accumulation of their prey. Cetacean distributions on calving grounds, on the other hand, are hypothesized to be related to site characteristics that enhance reproductive success and calf survival.

## Southern and North Atlantic right whale habitat models

Habitat associations for right whales (*Eubalaena* spp.) have been investigated at a variety of locations and a range of spatial and temporal scales. North Atlantic right whale (*E. glacialis*) distribution on foraging grounds is linked to distributions of the copepod *Calanus finmarchicus*, their primary prey, and the physical oceanographic regimes that influence prey abundance and distributions. At broad spatial scales (hundreds to thousands of square kilometers), North Atlantic right whale summer distributions were correlated with bathymetry, sea surface temperature, vertically stratified water, low bottom-water temperature, and copepod distributions (Baumgartner et al., 2003; Baumgartner and Mate, 2005; Moses and Finn, 1997; Murison and Gaskin, 1989; Woodley and Gaskin, 1996). In studies of individual North Atlantic right whale foraging behavior, whale position and/or dive depth data and concurrent zooplankton and physical measurements demonstrated selective feeding by right whales in highly concentrated patches of *C. finmarchicus* stage 4 (C4) and 5 (C5) copepodids at particular depths (Beardsley et al., 1996; Baumgartner and Mate, 2003), and right whale and copepod distributions were related over diel and tidal time scales (Baumgartner *et al*. 2003). On wintering grounds, southern right whale (*E. australis*) females with calves prefer shallow, protected coastal habitats (Elwen and Best, 2004a, b; Patenaude and Baker, 2001; Rowntree et al., 2001), presumably because of energetic benefits and lower risk of injury to young calves. However, interaction with conspecifics may be at least as important in determining reproductive success as environmental characteristics (Elwen and Best, 2004c). Shifts in nursery habitat distribution may reflect a response to human or natural disturbance (Rowntree et al., 2001) or changes in stock structure and/or recovery patterns (Patenaude and Baker, 2001).

Recently, Greene and others developed a conceptual model relating North Atlantic right whale calving rates to climate change by synthesizing research on climate, physical and biological oceanography and the interactions therein, and right whale sightings data (Greene and Pershing, 2004; Greene et al., 2003b). They provided evidence that right whale calving rates are correlated with the North Atlantic Oscillation (NAO) climate mode, through its influence on temperature and distribution of water masses, in turn influencing the abundance of *C. finmarchicus* (Greene and Pershing, 2000; Greene et al., 2003a). Their model incorporated aspects of the right whale reproductive cycle (including a 3-year calving interval) and a *C. finmarchicus* abundance index (based on *in situ* measurements) to predict annual right whale calving rates, and was in good agreement with observed data (Greene and Pershing, 2004){Greene, 2003 #552). The positive phase of the winter NAO index was correlated with warmer shelf water and higher copepod abundance in northwest Atlantic right whale feeding areas and led to above-average right whale calving rates the following year(s), whereas negative NAO years were followed by declines in right whale calving rates. Since the late 1970s, the winter NAO index has been in a predominantly positive phase, thought to be associated with global warming, but climate variability may be increasing as a consequence of global warming, and in recent years (2000-2005) the NAO has been in a downward trend with more frequent negative years (NOAA National Weather Service, www.cpc.noaa.gov/products/site_index.shtml). Conservation strategies for North Atlantic right whales rely primarily on reducing mortality related to ship strikes and fishing gear entanglements, but Greene and Pershing (2004) and Greene et al. (2003) suggest that climate fluctuations can also impact right whale recovery (or lack thereof) and should be factored into management decisions.

## Right whales in the eastern North Pacific

Compared with other *Eubalaena* species, little is known about the habitat associations of North Pacific right whales (*E. japonica*), and much of the current knowledge is based on compiled, historic sightings and catch data collected prior to the 1970s. North Pacific right whale summer distributions in the eastern North Pacific during commercial whaling, prior to the mid-20th century, included the Gulf of Alaska (GoA) slope and abyssal plain, the southeast Bering Sea (SEBS) slope and shelf, and the eastern Aleutian Islands (Clapham *et al*., 2004; Scarff, 1991; Shelden *et al*., 2005). Since the 1960s, the majority of North Pacific right whale sightings have been on the SEBS shelf, in the middle and outer-shelf domains, although this may be related to a bias in sighting effort. Several right whale sightings and/or acoustic detections have also been reported in the western GoA over the last decade (Barlow, 2005; Mellinger et al., 2004; Waite et al., 2003). Based on sightings data since listing of right whales as an endangered species in 1973, NOAA National Marine Fisheries Service designated critical habitat areas for North Pacific right whales in the SEBS (~ 71750 km$^2$)and GoA near Kodiak Island (~23400 km$^2$) (NMFS, 2006).

These known regions of right whale occurrence vary markedly in bathymetry, from a narrow shelf that slopes from 200 m to over 5000 m in the GoA basin, to a flat and shallow (< 100 m) continental shelf in the SEBS hundreds of kilometers wide. The GoA, SEBS basin and slope, and SEBS shelf (further divided into outer-, middle- and inner-shelf domains) differ in zooplankton community composition and oceanographic regimes as well, and little data exists on right whale diets in these different habitats. Six right whales caught in July-August 1962-63 over the Bering Sea slope and plain (depth • 2000 m) had exclusively consumed *Neocalanus cristatus*, a large-bodied oceanic copepod, whereas stomachs from three right whales caught near Kodiak Island in the western GoA contained small to moderate amounts of *N. plumchrus* (Omura 1969). *Calanus marshallae* was the dominant copepod in zooplankton samples collected near right whales on the SEBS middle shelf (50 to 100 m depth) in 1997 and 1999 (Tynan et al., 2001), and is closely related to *C. finmarchicus* in the North Atlantic.

Although North Pacific right whale sightings have been concentrated in a small remnant of their former range on the SEBS middle shelf, their low population size and broad individual travel distances translate to low reliability of finding right whales even within known regions of occurrence. In more than one survey within the past decade, weeks of visual search effort were conducted in known right whale habitats in the SEBS without resulting in right whale sightings (LeDuc 2004, P. Clapham pers. comm.). Right whale call occurrence in long-term acoustic recordings on the SEBS middle shelf was intermittent over short durations (2-6 days), with intervals between call detections ranging from 2 to 49 days over a season (and months-long over the winter) (Chapter 3), suggesting that animals were traveling in and out of instrument detection range of 100 km on average (Chapter 4). Wade *et al.* (2006) reported the movements of a satellite-monitored tagged right whale that traveled broadly over the middle and outer-shelf regions during the 40 days of tag function, with total track length in the hundreds of kilometers.

Right whales may be traveling broadly to exploit dense patches of their prey, zooplanktonic crustaceans, and their occurrence in the SEBS is likely associated with concentrations of late-stage copepods and/or euphausiids and the oceanographic production and physical regimes that influence them. In the SEBS, large-bodied copepods including *N. cristatus*, *N. plumchrus*, and *Eucalanus bungii* dominate the slope and outer-shelf zooplankton biomass, whereas on the middle shelf, euphausiids (*Thysanoessa raschii*) are dominant in early spring (April and May) but decrease to less than 50% of the zooplankton biomass in June (Vidal and Smith, 1986). The copepod *Calanus marshallae* is the other dominant zooplankton taxon on the middle shelf and is the only large herbivorous copepod found there (Cooney and Coyle, 1982; Smith and Vidal, 1986), and is presumed to overwinter on the middle shelf to the lack of cross-shelf transport (Vidal and Smith, 1986). The final molt occurs early in the year and adult females produce eggs over a long duration beginning as early as February; however, recruitment to copepodite stages usually coincides with the spring phytoplankton bloom (Baier and Napp, 2003).

Copepod and euphausiid growth and abundance are controlled by water temperature and food availability, and therefore are linked to the dynamics of sea ice and weather in the SEBS through their influence on the timing and duration of phytoplankton blooms (Smith and Vidal, 1984). Late ice retreat leads to an early, ice-associated phytoplankton bloom in cold water, whereas no ice or early ice retreat is followed by a late, open-water bloom as the water column begins to warm and stratify (Hunt *et al.*, 2002; Stabeno *et al*., 2001). Nutrients in the surface layer are depleted by phytoplankton during the spring bloom; however, occasional winds in summer can mix the surface layer deeper, resulting in nutrient availability from the bottom layer and high production later in the year. High summer copepod abundance in the SEBS middle-shelf region has been associated both with high winter ice cover (Baier and Napp, 2003) and warmer spring and summer temperatures (Smith and Vidal, 1986; Napp *et al*. 2002). *C. marshallae* was observed to produce a second cohort in a warm year with a second bloom (Smith and Vidal, 1986). Euphausiid abundance and growth rates on the middle shelf were also higher in a warm year compared to a cool year (Smith, 1991).

## Rationale for North Pacific right whale conceptual model

The Bering Sea is a dynamic habitat with high temporal variability, and responds to weather and climate oscillations over daily, interannual, and multi-year time scales (Stabeno *et al*., 2001), with concomitant impacts on biological communities. The response of North Pacific right whales to variability in foraging habitat may include shifts in spatial and temporal distribution over a variety of scales, and may also include variation in reproductive success. Climate variability and trends are potentially important factors in the recovery of North Pacific right whales, and better understanding is needed of how right whales respond to habitat variability to inform conservation efforts, formulate research plans, and potentially predict right whale population response to climate change. However, visual search effort for right whales at best provides a ‘snapshot’ in time of whale occurrence and oceanographic conditions, and does not capture variation in habitat dynamics and right whale response through time.

In contrast to typical right whale survey effort, which often includes a broad spatial component and is conducted over days to weeks (and, frequently, at the same time(s) each year for North Atlantic and southern right whales), our sampling regime was acoustically monitoring at point location(s) continuously for months-long, multi-season durations. We deployed long-term acoustic recorders within known North Pacific right whale habitat on the SEBS middle-shelf and recorded for periods of several months to nearly a year, with months-long intervals between deployments, from October 2000 to January 2006. We investigate the relationship of right whale *temporal* distribution to oceanographic variables by presenting seasonal and interannual comparisons of environmental measurements and right whale calling rates, as an indication of presence (and, potentially, relative abundance—see (Matthews et al., 2001). We synthesize our findings into a conceptual model of right whale habitat use of the SEBS middle-shelf and hypothesize how their temporal occurrence is related to oceanographic variables that influence copepod availability.

## Methods

We deployed moored Acoustic Recording Packages (ARPs) (Wiggins, 2003), configured to passively record sound continuously at a 500 Hz or above sampling rate, at six locations on the SEBS middle-shelf with bottom depth of about 70 m (Figure 5.1). Acoustic monitoring was conducted near M2 from October 2000 through early May 2001 and September 2001 through July 2002. In 2004 and 2005, ARPs were incorporated into subsurface biophysical moorings (maintained by NOAA Pacific Marine Environmental Laboratory) at sites M2 and M4. Recording at M2 was from May 2004 through

December 2004 (with intermittent gaps in recording due to instrument error), and late April 2005 through January 2006; recording at M4 was from October 2004 through December 2004 (with gaps) and late September 2005 through January 2006 (Table 5.1). We detected right whale calls in the recordings using a combination of automated call detection software and by visually browsing spectrograms (Munger *et al.*, 2005), and report calling rates based only on calls identified with high certainty to be from right whales (Chapter 3).

We obtained raw oceanographic data from M2 and M4 for the time periods with acoustic monitoring (fall 2000-spring 2006), including year-round water temperature and salinity at a range of depths, current speed and direction between 8 and 15 m depth, almost year-round fluorescence data (as a proxy for chlorophyll and hence phytoplankton production) at 10-12 m and 24 m, and summer surface weather conditions. Sensors on moorings sampled at schedules from every 10 minutes to hourly.

### Seasonal comparison

We calculated daily averages of temperature, salinity, and fluorescence measured at several depths by moorings M2 and M4 (current and weather data were not included in our analysis) and plotted several months-long time series of values from near the surface (1 to 14 m depth), intermediate depth (24 - 30 m), and near-bottom (51 - 65 m). Right whale daily calling rates are plotted over the mooring data as vertical bars. Right whale calling rates in 2000-02 are reported from ARP sites A, B, or C, which were less than 70 km from M2, and in 2004-06 were recorded by instruments incorporated into M2 and M4. We present comparisons of fall and winter months (October through March) and spring and summer months (April through September) for each year with recording effort and for site M4 when available.

### Interannual comparison

From the NOAA Bering Climate website (www.beringclimate.noaa.gov/data), we obtained time of ice retreat in the vicinity of mooring M2 and yearly anomalies calculated for the SEBS ice cover index (1954-2006), winter SST at M2 (1950-2006), mean May SST (1970-2006), and summer bottom temperature from SEBS trawl surveys (1982-2005). We used these data and mooring data from M2 and M4 to construct timelines for each study year showing right whale calling rates and oceanographic ‘events’ including ice retreat, phytoplankton blooms (as indicated by fluorescence peaks in the mooring time series data), and complete mixing of the water column in fall (constant temperature and salinity with depth). Also indicated on yearly timelines are positive or negative anomalies in the winter sea ice cover index, winter SST, May SST, and summer bottom temperature.

### Conceptual model

We synthesize right whale calling rates and environmental data from interannual and seasonal comparisons into a conceptual model of right whale habitat temporal dynamics, with hypothesized linkages to copepods based on previous studies. The model shows the progression of oceanographic phenomena and right whale occurrence over a year, under different scenarios including years with warm, early ice retreat and cool, late ice retreat. Relative abundance of right whales is inferred from calling rates (Matthews et al. 2001, Munger unpub. data).

## Results

### Seasonal comparisons

Right whale calling and oceanographic time series in fall and winter months (October through March) of three different years are shown in Figure 5.2. Right whale calling rates (calls/day) are reported from site A, B, or C (whichever had highest number of calls on a given day) in fall 2000 and site C only in fall 2001; oceanographic data are from M2. Acoustic recording effort in 2000-01 and 2001-02 was continuous over the time scale of the plots. In 2005-06, acoustic recording was continuous from October 2005 through mid-January 2006. Right whale calls were detected as late as October or early November in 2000 and 2001, when fluorescence remained low throughout fall and winter and the water column was fully mixed in early November (Figure 5.2a,b). In 2005, right whales were detected later in the year (mid-December) and calling rates were higher at M4; fluorescence was elevated during that year from August to mid-October (Figure 5.2c,d and Figure 5.3d) and the water column became fully mixed in mid-October, earlier than was typical in other years.

Spring and summer (April-September) right whale calling rates and oceanographic time series are shown in Figure 5.3. In 2001 and 2002, the initial spring bloom, as indicated by a fluorescence peak, was in late May, followed by a second bloom in June or July (Figures 5.3a,b). In 2004, there was a late May bloom and the water column was subsequently well-stratified, with low chlorophyll concentrations, throughout the summer, although in late September fluorescence began to increase (Figure 5.3c). In 2005 the initial spring bloom occurred in early May and was low in magnitude relative to a second bloom beginning in August (Figure 5.3d). Right whale call detections in late May of 2002 and 2004 roughly coincided with the spring bloom (Figures 5.3b,c); however, right whale calls in 2005 were not detected until July, well after the initial bloom (Figure 5.3d). In 2005, peak right whale calling rates occurred in mid-August, when the surface wind-mixed layer deepened and fluorescence increased (Figure 5.3d).

### Interannual comparisons

The years of this study (2000-2005) were characterized predominantly by low winter ice cover in the SEBS, warm surface temperatures in late winter through summer, and warm summer bottom temperatures (Figure 5.4). However, winter ice cover was above average in 2000 (no recording effort until October) and 2002 (continuous recording effort from start of year through mid-summer). Ice cover was low in 2004 but the timing of arrival and retreat was close to average, whereas 2005 had comparatively late arrival of ice, short ice season (~5 days) and record low ice cover (Rodionov et al., 2005) . Ice was not present directly over M2 in any of the years with acoustic effort but the ice edge was very close in 2002 (Stabeno and Salo, in press).

Right whales were not detected in January through April in years with recording effort during these months (Figure 5.5). Recording effort was continuous in spring through mid-summer or later in 2002, 2004 and 2005. During these three years, the earliest right whales were detected was late May in years 2002 and 2004 (and also in early June 2004); both were years with a mid- to late-May spring bloom. Right whale calls were detected in July through October in all years with effort during one or more of these months. Peak calling rates at or near M2 were in August 2001 and September 2005, and at M4 the highest calling rate was in December 2005. In 2001 and 2005, late-summer and fall right whale detections (including those occurring through mid-December) were preceded by blooms in mid-summer, although calls in December occurred one to two months after the end of the bloom (Figure 5.5, 5.2). In 2000 and 2001, right whale calls were detected at the latest in late October or early November, prior to the water column becoming well-mixed by storms; of these two years, 2001 had a summer bloom and 2000 did not.

## Conceptual model

We developed a conceptual model depicting temporal variation in right whale presence in the SEBS over the course of a year (Figure 5.6), including hypothetical dynamics of their copepod prey based on previous studies. Two timelines are shown in each panel, representing different scenarios in timing of various oceanographic ‘events’ such as ice retreat, blooms, and wind-driven mixing. Beyond the timing of ice retreat and the initial spring bloom, events are not tightly coupled, *e.g.* a wind mixing event and a subsequent bloom could occur in summer within either scenario regardless of winter ice cover and timing of ice retreat that year.

## Discussion

The springtime presence of right whales in the SEBS appears to be related to the timing of the spring phytoplankton bloom. Right whales were detected earlier in years with a late spring bloom (2002 and 2004), and later in a year with an early spring bloom (2005). Ice cover and the duration of ice presence may also have played a role in determining the earliest right whale detections. Of the two years with spring right whale occurrence, one (2002) had above-average winter ice cover, and the other (2004) had near-average duration of the ice season. The early-bloom year without springtime right whales (2005) had record low ice cover and a short (only ~ 5 d) ice season (Rodionov et al. 2005). Right whales were detected intermittently in July-October in all years with effort, and peak right whale calling rates were in August or September. The latest right whale calls were detected in the year was usually in October or early November, with the exception of 2005, when right whales were detected as late as mid-December on both M2 and M4.

The occurrence of right whales on the SEBS shelf in spring (late May/early June) may be associated with late spring blooms, when warmer water temperature increases the metabolic rates and development times of copepods (Baier and Napp, 2003; Vidal and Smith, 1986), resulting in tighter coupling of the spring bloom to the pelagic food chain (Overland and Stabeno, 2004). In a cool year, *C. marshallae* biomass and growth rates had a delayed response to the spring bloom, increasing about a month after the bloom (Vidal and Smith, 1986). In a year with more rapid warming (but a bloom at roughly the same time), *C. marshallae* summer concentrations were higher than during the cool year (Smith and Vidal, 1986). Napp *et al.* (2002) also found increased spring concentrations of *C. marshallae* on the SEBS shelf in 1994-1998, a warm period, relative to 1980-1981, a cool period. Euphausiids on the Bering slope and middle shelf, another potential right whale prey item, also had higher growth rates and abundance at warmer temperatures (Kang et al., 2006; Smith, 1991).

Temperature is not the only factor influencing right whale prey abundance. Right whales were detected near M2 in spring 2002 but not in 2005, a year in which the bloom occurred slightly earlier, along with earlier surface warming (Figure 5.3). This observation suggests that despite the occurrence of the bloom in warm water, late-stage copepods were not at high enough concentrations in spring 2005 for right whale foraging. This may be due to food limitation, increased predation, or insufficient physical forcing to concentrate copepods into dense enough patches for right whale feeding. The relatively lower spring fluorescence peak and its shorter duration in 2005 (Figure 5.3c) suggest that the spring bloom was lower in magnitude, supporting the hypothesis that low food availability may have limited growth & abundance of herbivorous *C. marshallae*. 2002 was also a year with higher ice cover than average (Figure 5.4), whereas 2005 had record low ice cover (Rodionov et al. 2005). In previous studies, summer *C. marshallae* abundance was positively correlated with ice cover, although the mechanism linking them is not yet understood (Baier and Napp, 2003). Conditions in spring 2002 may therefore have supported higher spring copepod recruitment and growth than in 2005, leading to right whale presence earlier in 2002 coinciding with the late-May bloom (Figures 5.3, 5.5).

Right whales were detected intermittently in July through October in all years with recording effort during one or more of these months. By this time, the majority of *C. marshallae* are C5 (Smith and Vidal, 1986), and the water column over the middle-shelf is well stratified, with a warm (> 10º C), wind-mixed upper layer about 20-25 m deep, and a cold (< 3º C), tidally-mixed bottom layer. In some of the years in our study, right whale occurrence in summer coincided with or followed a second bloom (*e.g.* Figure 5.2c,d, Figure 5.3d), possibly leading to a second cohort of *C. marshallae* on which right whales may have been foraging, or to increased food availability for grazing copepods and therefore higher energy content of prey. However, right whales were also detected in summers during periods without elevated fluorescence or evidence of mixing, so a second bloom is not a prerequisite for right whale occurrence.

In order for a right whale to forage effectively, copepods must be aggregated in dense patches (Baumgartner and Mate, 2003; Beardsley *et al*., 1996; Kenney *et al*., 1986). Distribution of copepods within the water column is determined by copepod behavior (*e.g.*, daily and ontogenetic vertical migration) as well as physical forcing mechanisms. In recent studies in the North Atlantic, right whales foraged more intensively on deep, concentrated layers of *C. finmarchicus* during the daytime than during the night, when vertically-migrating copepods were more dispersed throughout the water column (Baumgartner *et al*., 2003; Baumgartner and Mate, 2003). Right whale calling rates on the SEBS shelf were highest at night (Chapter 3), and one potential explanation is that right whales were feeding more during the day on copepods concentrated at depth, and do not produce calls as frequently while feeding.

Temperature stratification of the water column and other physical forcing mechanisms also play an important role in copepod distribution and therefore right whale foraging. North Atlantic right whales that left the Bay of Fundy during summer were more likely to visit areas with high surface stratification and low bottom temperatures (Baumgartner and Mate, 2005). The authors hypothesized that diapausing *Calanus* *finmarchicus* may be more abundant in cold water or be better quality prey for right whales due to slower copepod metabolism of stored lipids at lower temperatures. In the SEBS, right whales were detected intermittently on the shelf throughout the summer months when the water column was well-stratified, perhaps feeding on copepods concentrated in the cold bottom layer as a result of either daily vertical migration (or diapause later in the year). Variation in right whale occurrence and copepod densities at depth also were related to the tidal period (Baumgartner *et al.*, 2003). A similar mechanism may be in effect on the SEBS shelf, as tidal currents there are substantial and may also result in periodic concentration of zooplankton corresponding to the semidiurnal tides in that region.

Acoustic detections of right whales on the SEBS shelf lasted no more than a few days at a time, potentially because whales were traveling broadly to exploit patchy copepod aggregations. Studies of right whale movements using satellite-monitored radio tags have shown that right whales (*E. japonica*, *E. glacialis*) may traverse over long distances of up to hundreds or thousands of kilometers within several weeks, and move rapidly between foraging habitats (Baumgartner and Mate, 2005; Mate *et al.*, 1997; Wade *et al.*, 2006). The middle-shelf is only one of many potential foraging grounds for right whales. Historically, right whales foraged along the highly productive SEBS shelf break and outer-shelf region, and recent sightings of right whales on the outer shelf (Wade *et al.*, 2006) and acoustic detection of right whale calls on the SEBS slope (hydrophone depth > 1000 m) suggest that right whales are continuing to use these habitats (Chapter 3). Right whales also have been acoustically and visually detected in the western GoA in recent years (Mellinger *et al.*, 2004; Waite *et al.*, 2003), another historically important right whale summer habitat and 19th-century commercial whaling ground (Scarff, 1991; Shelden *et al*., 2005). The bathymetry, oceanographic regimes, and zooplankton communities and their life history traits are quite different in these regions compared to the SEBS middle-shelf, and further study of right whale distributions in other habitats may reveal different patterns of habitat use.

An alternative hypothesis for the presence of right whales, other than foraging, is for communication and behavior perhaps related to reproduction or maintaining social bonds. High calling rates, as were detected in September 2001, August 2005, and December 2005 may be positively related to right whale aggregation size (Matthews et al. 2001), or a result of increased calling by individual whales. The duration of right whale calling was also longer in late summer and early fall than other time periods monitored (Chapter 3), including a 5-day period with right whale calls in October 2000 that was not preceded by a summer bloom (Figure 5.2a). Larger aggregation sizes may be related to reproduction or other behavior in addition to potential foraging. Southern and North Atlantic right whales occur in large aggregations thought to be related to reproduction, in summer habitats as well as winter breeding & calving grounds, during which they produce a variety of complex call types (Clark, 1981, 1982; Parks and Tyack, 2005). We analyzed only right whale up-calls in this study, but we did record other call types including frequency downsweeps and short 'moans', and it is possible that other call types were produced above the bandwidth analyzed. The SEBS shelf may be an advantageous habitat for right whale communication, regardless of behavioral context, due to the long-range acoustic propagation of 100 km or more for right whale calls (Chapter 4).

The right whale habitat associations in the SEBS that we discuss here are presented as hypotheses requiring further investigation, as we a) monitored largely within a single oceanographic domain and do not have broader spatial coverage in different habitats for comparison, and b) do not have zooplankton data sampled concurrently at the appropriate temporal and spatial scales to investigate right whale foraging. Primary production is only a proxy for secondary production, and the abundance and distribution of zooplankton are affected by predation, zooplankton behavior, and physical forcing as well as food availability and temperature. In addition, fluorescence data were only available at shallow depths (< 14 m) for several of the monitored periods (e.g., Figures 5.2, Figure 5.3a). Subsurface (~24 m) chlorophyll maxima/blooms may have been undetected in some years, as fluorescence was frequently higher at 24 m depth than the shallower sensor (Figure 5.3b, c, d).

The SEBS shelf in 2000-05 underwent dramatic warming, decrease in sea ice extent and increasing lateness in the year of the appearance of ice (if any), and a decrease in summer wind speeds (Bond and Adams, 2002; Hunt *et al.*, 2002; Luchin *et al.*, 2002; Stabeno *et al.*, 2001). However, in 2006-07, air and water temperatures in the SEBS cooled, with yearly depth-averaged temperature at M2 returning to a pattern resembling the late 1990's, and 2007 was an extensive ice year (Overland et al., 2007). These ecosystem shifts may have implications for right whale foraging by affecting zooplankton abundance, development and distribution. Evidence since 2000 suggests that summer zooplankton biomass on the SEBS middle-shelf has decreased (J. Napp, pers. comm.), and could be related to the recent warm regime via controls on ice cover, retreat, and bloom dynamics, and/or due to warmer summer bottom temperatures increasing metabolic rates of diapausing copepods and potentially reducing survivorship. North Pacific right whales may be able to respond to some of these changes by shifting their foraging grounds, but overall decreases in zooplankton abundance or prey quality (lipid content) could have negative impacts on right whale health and reproductive rates, which have been linked to climate effects on food availability for North Atlantic right whales (Greene *et al*., 2003) and southern right whales (Leaper et al., 2006).

## Conclusions

The timing of right whale occurrence on the SEBS middle-shelf is likely related to the dynamics of copepods, their primary prey. Copepod abundance, growth rates and distributions are dependent in large part on primary production and physical forcing, and are linked to climate via the dynamics of ice cover, timing of ice retreat, and water temperatures. Right whales were detected as early in the year as May in years with early ice retreat and late blooms, but only after winters with high ice cover or average duration of ice season. Right whales were detected intermittently throughout summer and early fall, when the water column on the SEBS middle shelf is well-stratified, in all years with effort. In some cases, right whale occurrence in mid-summer to late fall was preceded by wind-driven mixing and phytoplankton blooms in summer, perhaps resulting in higher copepod availability or quality. Right whales were detected as late as December one year, about two months after a sustained, late-summer/fall bloom and earlier water-column mixing than usual.

The SEBS is a dynamic habitat with high variability on multiple time scales, but is undergoing recent trends related to climate change that may affect right whale foraging in this habitat. Continued long-term acoustic and oceanographic monitoring in this area could provide valuable data for assessing the impacts of climate change on right whale habitat use. Tracking right whale movements through the use of satellite-monitored tags, as well as concurrent zooplankton sampling near right whales at appropriate vertical and temporal scales, would provide better information on the broader habitat patterns of right whales and their foraging behavior, respectively. Finally, right whale calling behavior on the SEBS shelf may also serve a social or reproductive function, and further study of the behavioral context of right whale calls may allow for a better understanding of how right whales are using their habitat and to infer behavior more confidently from autonomous acoustic recordings. Long-term, continuous acoustic and oceanographic monitoring seems particularly effective for habitat characterization of North Pacific right whales, given their rarity and the difficulty & expense of conducting vessel and aerial surveys to their relatively more remote habitats with frequently poor sighting conditions. Examining temporal right whale habitat associations in the SEBS from long-term records at a constant location is useful for observing patterns and formulating hypotheses to be tested as part of ongoing North Pacific right whale research.

## Acknowledgements

This work was supported by NOAA Alaska Fisheries Science Center/National Marine Mammal Laboratory (AFSC/NMML) via JIMO budget #NA17RJ1231, North Pacific Marine Research Institute (project T-2100) and North Pacific Research Board (projects R-0307 and F0519), Alaska Department of Fish and Game (ADFG project T-1-6-4; special thanks to Bob Small), and National Fish and Wildlife Foundation. We are extremely grateful to Phyllis Stabeno and her colleagues at NOAA PMEL for their collaboration in incorporating acoustic recorders into FOCI moorings in 2004-2006 and for providing us with oceanographic data sets from moorings. NOAA Southwest Fisheries Science Center and AFSC/NMML provided opportunities for LMM to record right whales during cetacean surveys in Alaska; we thank the cruise leaders Jay Barlow, Rick LeDuc, Lisa Ballance, Robert Pitman and Paul Wade, acousticians Allan Sauter, Kate Stafford and Shannon Rankin, and others who were involved in planning and conducting these surveys. Thanks also to the officers and crew of the NOAA research vessels McArthur, McArthur II, and Miller Freeman and the Alaskan Enterprise.

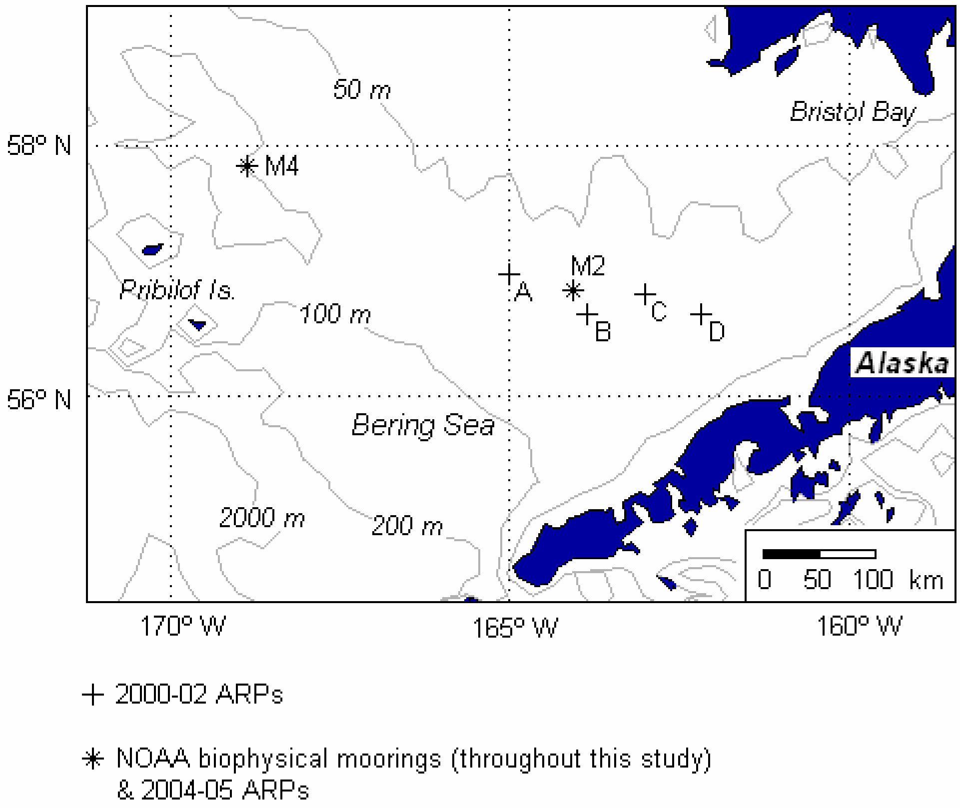


Figure 5.1. ARP and biophysical mooring deployment sites on the SEBS middle-shelf.

Table 5.1. Acoustic recording durations, location and depth at each deployment site. M2 and M4 collected physical and fluorescence data throughout the years of this study. For more detailed report of right whale call detections by site, see Chapter 3.

| site | Recording period (no. days) | location | depth (m) |
|---|---|---|---|
| A | 10/01/00 – 05/08/01 (220 days) | 57º 00.00’ N<br>164º 59.97’ W | 70 |
| B | 10/02/00 – 12/13/00 (73 d) | 56º 40.37’ N<br>163º 50.74’ W | 70 |
| C | 10/02/00 – 05/03/01 (214 d)<br>08/31/01 – 07/28/02 (332 d) | 56º 49.89’ N<br>163º 00.48’ W | 70 |
| D | 10/02/00 – 05/07/01 (218 d) | 56º 40.05’ N<br>162º 10.80’ W | 70 |
| M2 | 05/03/04 – 05/08/04 (6 d)<br>05/13/04 – 05/30/04 (18 d)<br>06/01/04 – 07/15/04 (45 d)<br>9/28/04 – 10/08/04 (11 d)<br>10/25/04 – 10/26/04 (2 d)<br>11/15/04 – 12/05/04 (21 d)<br>04/23/05 – 01/16/06 (269 d) | 56º 51.60’ N<br>164º 03.60’ W | 72 |
| M4 | 10/3/04 – 10/15/04 (13 d)<br>10/23/04 – 11/15/04 (24 d)<br>12/11/04 – 12/23/04 (13 d)<br>9/24/05 – 1/25/06 (124 d) | 57º 51.18’ N<br>168º 52.20’ W | 70 |

Figure 5.2. Seasonal comparison of right whale calls (black vertical bars, right axes) and daily-averaged temperature (T, ºC), salinity (S, practical salinity units), and fluorescence (F, Volts) (colored lines, left vertical axes) at given depths during fall and winter months (October through March). A) In 2000-01, calls/day are reported from ARP site A, B or C (whichever rate was highest on given day); oceanographic data from M2. B) Calls/day in 2001-02 from ARP at site C, oceanographic data from M2. C) Calls/day in 2005-06 and oceanographic data both sampled at M2. D) Calls/day in 2005-06 and oceanographic data both sampled at M4. Shaded areas represent no acoustic recording effort.

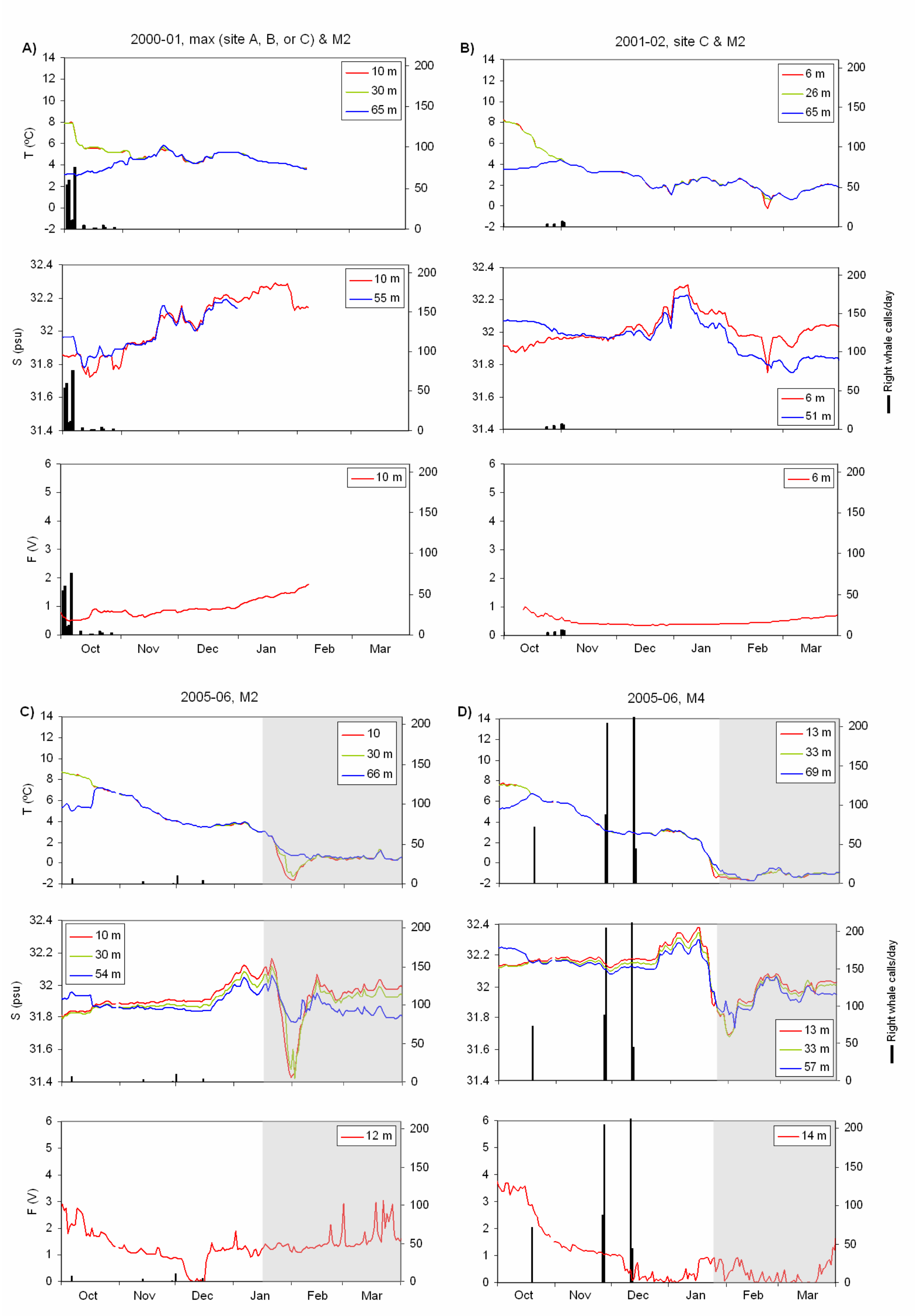
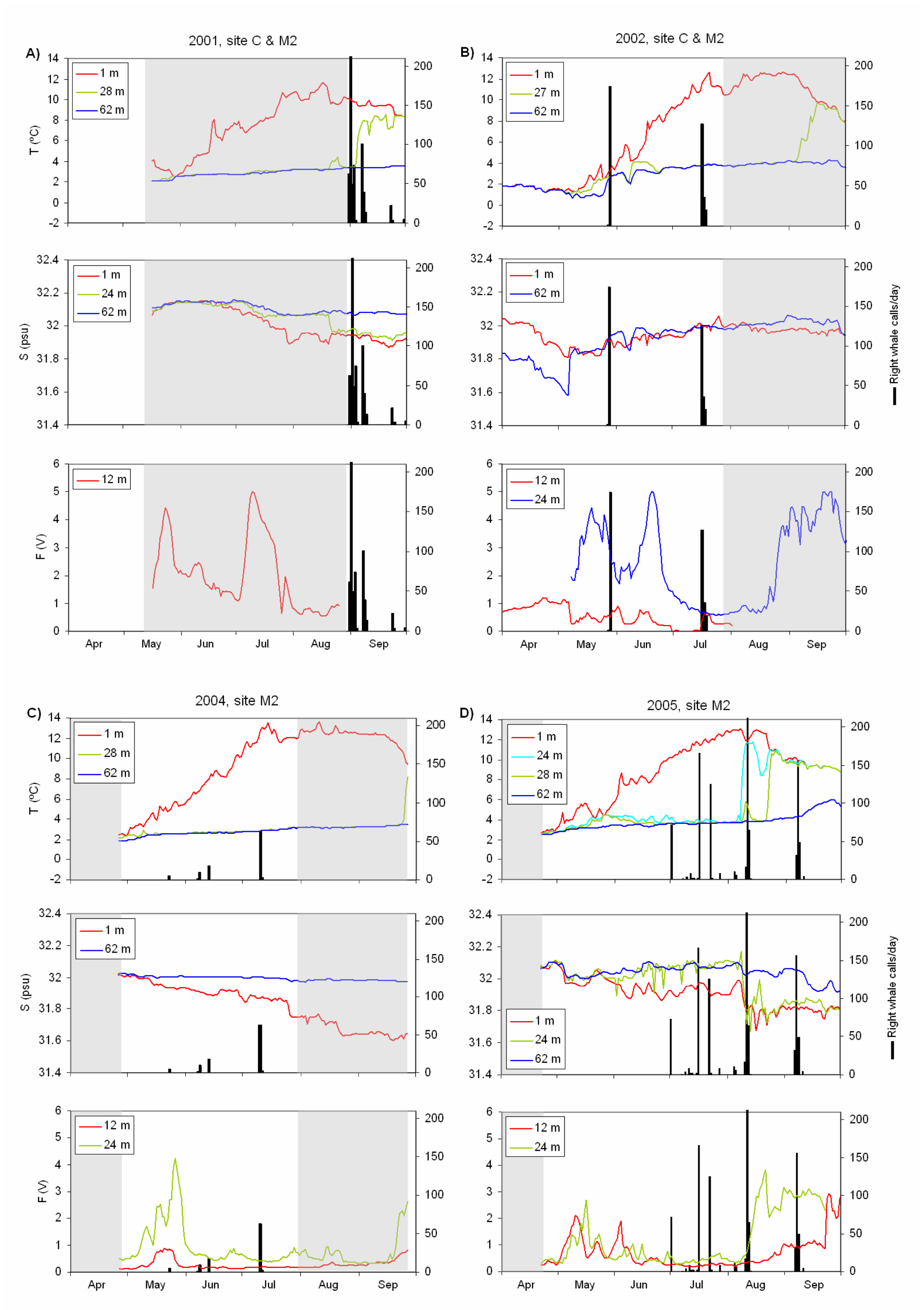

A)
2000-01, max (site A, B, or C) & M2
B)
2001-02, site C & M2
C)
2005-06, M2
D)
2005-06, M4
T (°C)
S (psu)
F (V)
Right whale calls/day
10 m
30 m
65 m
55 m
6 m
26 m
51 m
10
66 m
54 m
12 m
13 m
33 m
69 m
57 m
14 m
14
12
10
8
6
4
2
0
-2
32.4
32.2
32
31.8
31.6
31.4
6
5
4
3
2
1
0
200
150
100
50
0
Oct
Nov
Dec
Jan
Feb
Mar

Figure 5.3. Seasonal comparison of right whale calls (black vertical bars, right axes) and daily-averaged temperature (T, ºC), salinity (S, practical salinity units), and fluorescence (F, Volts) (colored lines, left vertical axes) at given depths during spring and summer months (April through September). Shaded areas represent no acoustic recording effort. A) Calls/day in 2001 from ARP site C; oceanographic data from M2. B) Calls/day in 2002 from ARP site C, oceanographic data from M2. C) Calls/day in 2004 and oceanographic data both sampled at M2. D) Calls/day in 2005 and oceanographic data both sampled at M2. Short-term (~days) salinity fluctuations in 2005 at 24 m are probably sensor error (D. Kachel, pers. comm.).


A)
2001, site C & M2
B)
2002, site C & M2
C)
2004, site M2
D)
2005, site M2
T (ºC)
S (psu)
F (V)
Right whale calls/day
1 m
28 m
27 m
24 m
62 m
12 m
14
12
10
8
6
4
2
0
-2
32.4
32.2
32
31.8
31.6
31.4
6
5
4
3
2
1
0
200
150
100
50
0
Apr
May
Jun
Jul
Aug
Sep

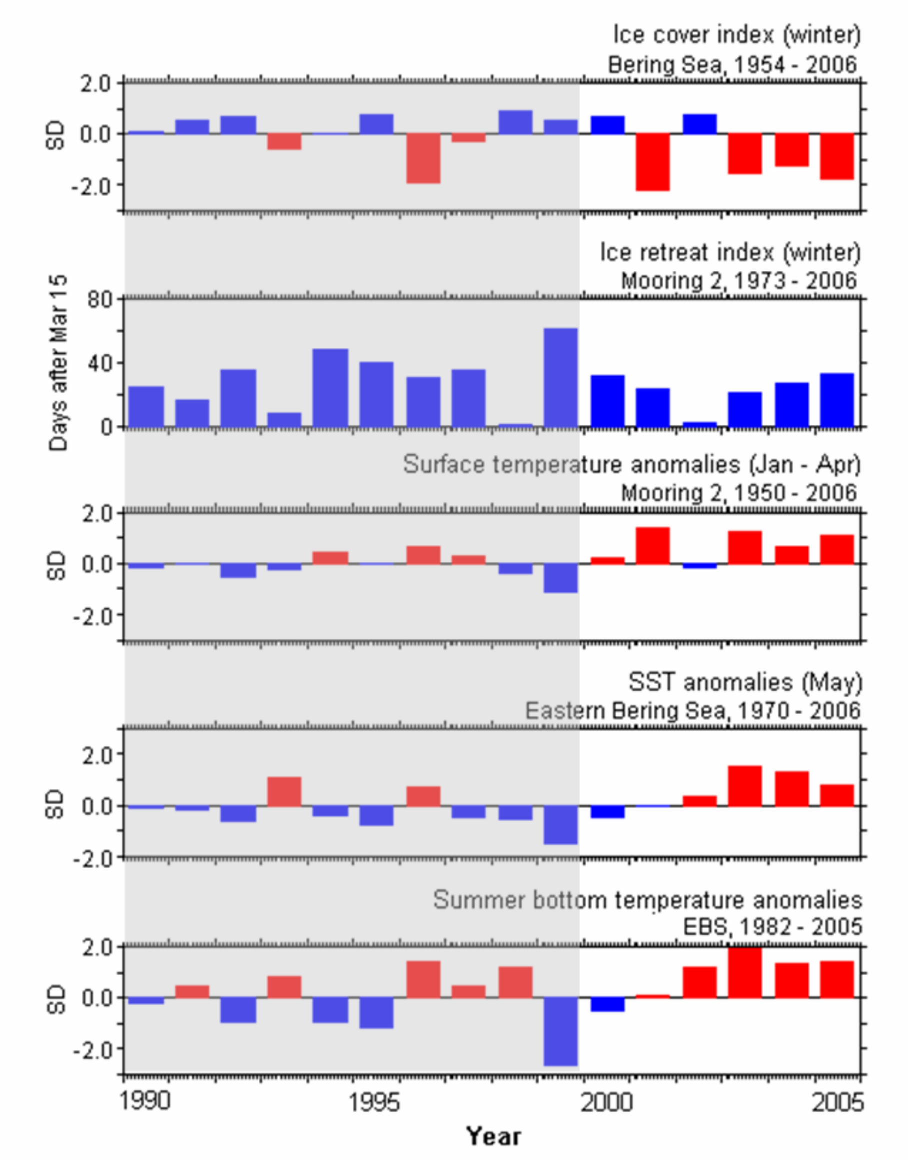


Figure 5.4. SEBS ice cover index (SD = standard deviation), ice retreat (in days after March 15), winter sea surface temperature (SST) anomalies, May SST anomalies, and summer bottom temperature anomalies for 1990-2005. The decade prior to this study (shaded gray) is included for longer-term context. Note that years in this study are predominantly warm, low ice-cover years except for 2000 (no recording effort until October) and 2002. From http://www.beringclimate.noaa.gov/data/.

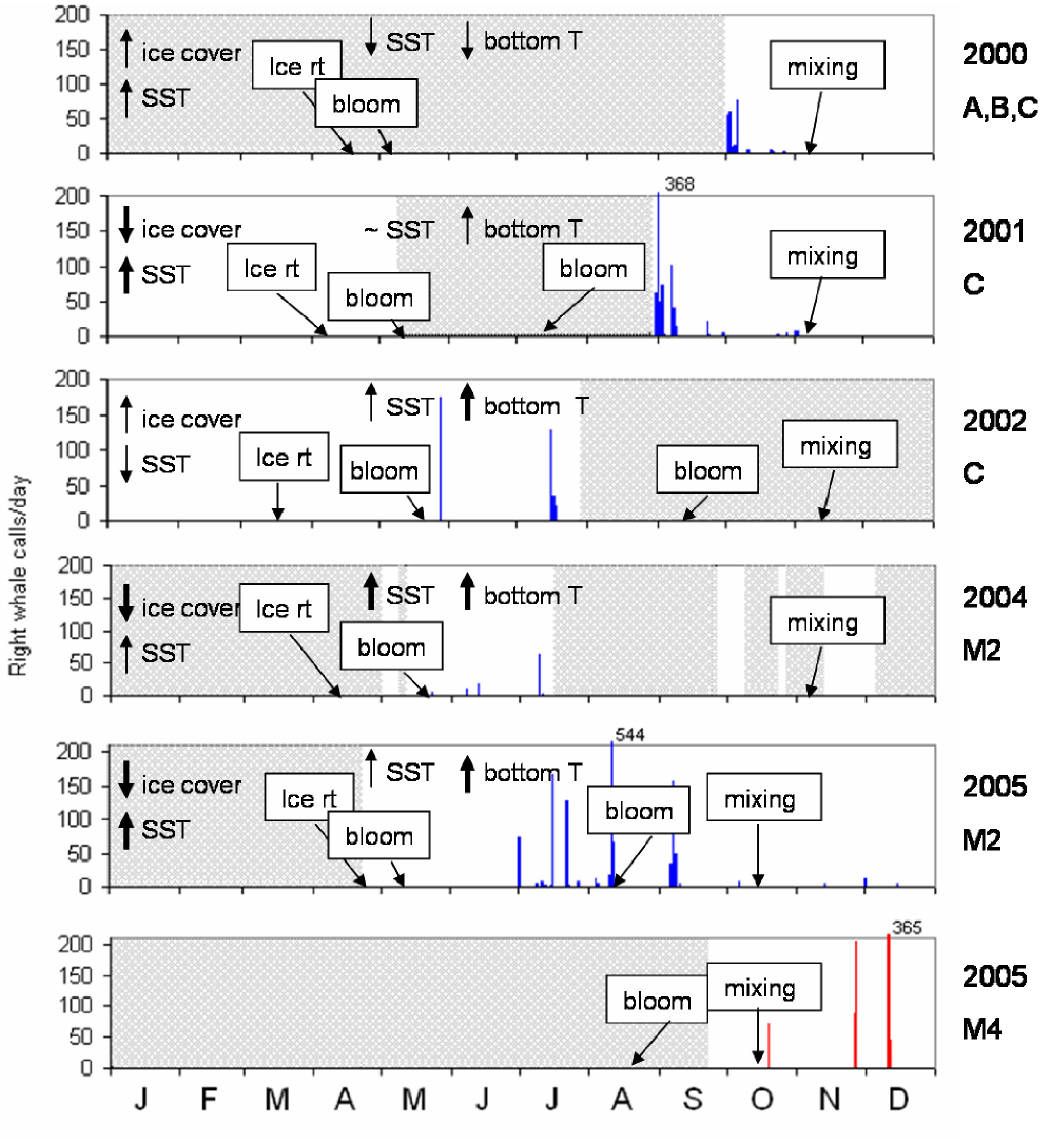
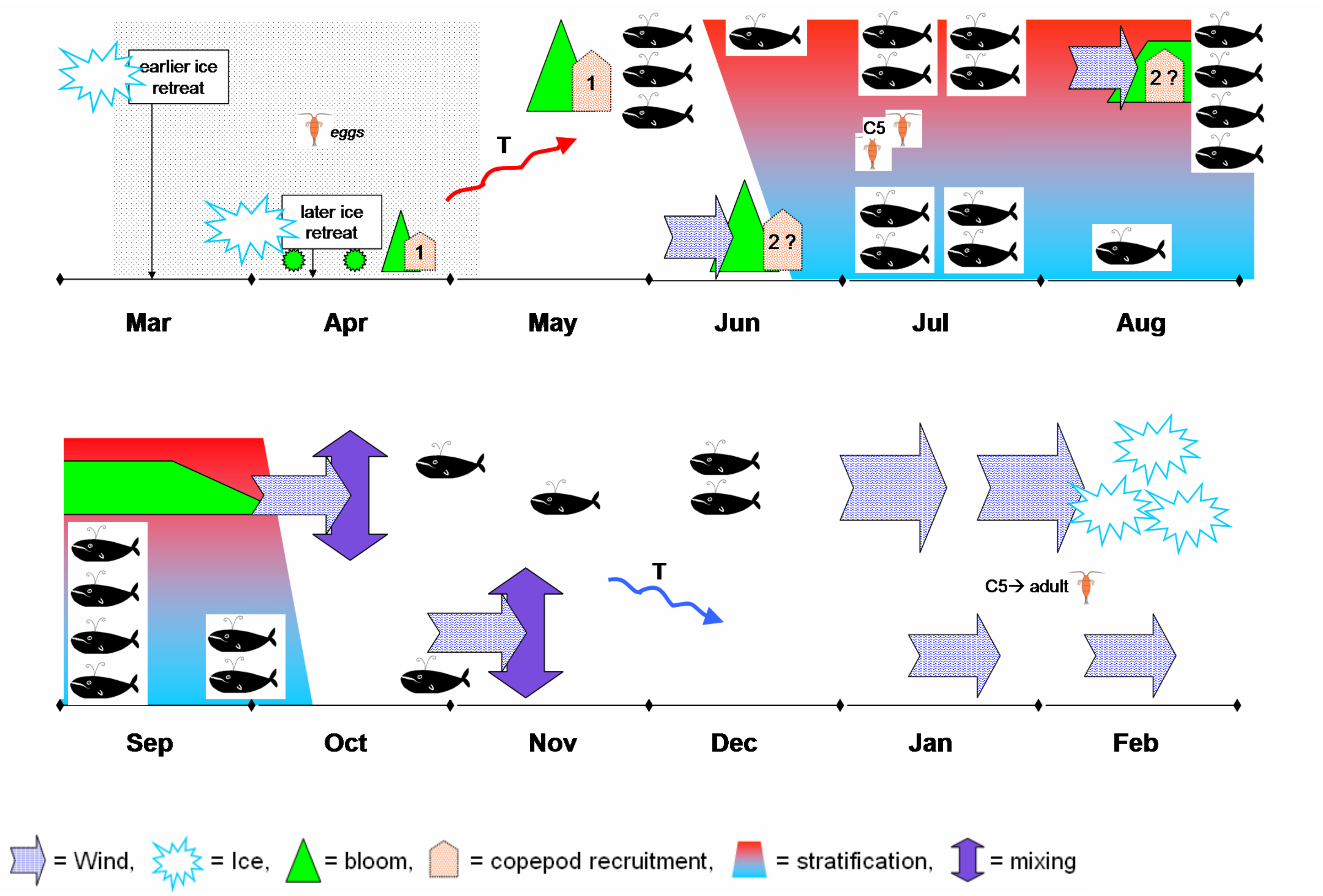


Figure 5.5. Interannual comparison of right whale calls/day (from ARP sites given at right of each plot), winter ice cover and sea surface temperature (SST) anomalies, May SST anomaly, summer bottom temperature anomaly, and timing of ice retreat, blooms, and fall mixing (when surface and bottom temperature and salinities equalize). Shaded areas represent no acoustic recording effort.

Figure 5.6. Conceptual model of right whale occurrence and habitat for one year on the SEBS shelf, with hypothesized copepod dynamics based on previous studies. Each panel is divided into upper and lower timelines, with the timing of ice retreat, spring blooms, and wind-driven mixing shifted between the upper and lower timelines to illustrate different scenarios. ‘Events’ occurring with roughly the same chronology in either scenario, such as copepod egg production, warming or cooling (indicated by red and blue wavy arrows labeled ‘T’), and summer stratification, are depicted by symbols centered between timelines or spanning both timelines. Relative abundance of right whales (number of whale symbols) is inferred from calling rates.


earlier ice retreat
eggs
later ice retreat
1
T
1
2 ?
C5
2 ?
Mar
Apr
May
Jun
Jul
Aug
T
C5→ adult
Sep
Oct
Nov
Dec
Jan
Feb
= Wind,
= Ice,
= bloom,
= copepod recruitment,
= stratification,
= mixing

## References

Baier CT, Napp JM, 2003. Climate-induced variability in *Calanus marshallae* populations. Journal of Plankton Research 25:771-782.

Barber DG, Saczuk E, Richard PR, 2001. Examination of beluga-habitat relationships through the use of telemetry and a geographic information system. Arctic 54:305-316.

Barlow J, 2005. Cruise Report: Structure of Populations, Levels of Abundance and Status of Humpbacks (SPLASH), Southwest Fisheries Science Center (SWFSC) Marine Mammal Cruise Number 1625. (United States Department of Commerce, NOAA, National Marine Fisheries Service); 1-13.

Baumgartner MF, Cole TVN, Campbell RG, Teegarden GJ, Durbin EG, 2003. Associations between North Atlantic right whales and their prey, *Calanus finmarchicus*, over diel and tidal time scales. Marine Ecology-Progress Series 264:155-166.

Baumgartner MF, Cole TVN, Clapham PJ, Mate BR, 2003. North Atlantic right whale habitat in the lower Bay of Fundy and on the SW Scotian Shelf during 1999-2001. Marine Ecology-Progress Series 264:137-154.

Baumgartner MF, Mate BR, 2003. Summertime foraging ecology of North Atlantic right whales. Marine Ecology-Progress Series 264:123-135.

Baumgartner MF, Mate BR, 2005. Summer and fall habitat of North Atlantic right whales (*Eubalaena glacialis*) inferred from satellite telemetry. Canadian Journal of Fisheries and Aquatic Sciences 62:527-543.

Beardsley RC, Epstein AW, Chen CS, Wishner KF, Macaulay MC, Kenney RD, 1996. Spatial variability in zooplankton abundance near feeding right whales in the Great South Channel. Deep-Sea Research Part II-Topical Studies in Oceanography 43:1601-1625.

Bond NA, Adams JM, 2002. Atmospheric forcing of the southeast Bering Sea Shelf during 1995-99 in the context of a 40-year historical record. Deep-Sea Research Part II-Topical Studies in Oceanography 49:5869-5887.

Clapham PJ, Good C, Quinn SE, Reeves RR, Scarff JE, Brownell RL, Jr., 2004. Distribution of North Pacific right whales (*Eubalaena japonica*) as shown by 19th and 20th century whaling catch and sighting records. Journal of Cetacean Research and Management 6:1-6.

Clark CW, 1981. Acoustic communication and behavior of the southern right whale. Dissertation Abstracts International B Sciences and Engineering 42:35.

Clark CW, 1982. The Acoustic Repertoire of the Southern Right Whale, a Quantitative Analysis. Animal Behaviour 30:1060-1071.

Cooney RT, Coyle KO, 1982. Trophic Implications of Cross-Shelf Copepod Distributions in the Southeastern Bering Sea. Marine Biology 70:187-196.

Doniol-Valcroze T, Berteaux D, Larouche P, Sears R, 2007. Influence of thermal fronts on habitat selection by four rorqual whale species in the Gulf of St. Lawrence. Marine Ecology-Progress Series 335:207-216.

Elwen SH, Best PB, 2004a. Environmental factors influencing the distribution of southern right whales (Eubalaena australis) on the south coast of South Africa I: Broad scale patterns. Marine Mammal Science 20:567-582.

Elwen SH, Best PB, 2004b. Environmental factors influencing the distribution of southern right whales (Eubalaena australis) on the south coast of South Africa II: Within bay distribution. Marine Mammal Science 20:583-601.

Elwen SH, Best PB, 2004c. Female southern right whales Eubalanena australis: Are there reproductive benefits associated with their coastal distribution off South Africa? Marine Ecology-Progress Series 269:289-295.

Friedlaender AS, Halpin PN, Qian SS, Lawson GL, Wiebe PH, Thiele D, Read AJ, 2006. Whale distribution in relation to prey abundance and oceanographic processes in shelf waters of the Western Antarctic Peninsula. Marine Ecology-Progress Series 317:297-310.

Goddard PD, Rugh DJ, 1998. A group of right whales seen in the Bering Sea in July 1996. Marine Mammal Science 14:344-349.

Greene CH, Pershing AJ, 2000. The response of Calanus finmarchicus populations to climate variability in the northwest Atlantic: basin-scale forcing associated with the North Atlantic Oscillation. ICES Journal of Marine Science 57:1536-1544.

Greene CH, Pershing AJ, 2004. Climate and the conservation biology of North Atlantic right whales: the right whale at the wrong time? Frontiers in Ecology and the Environment 2:29-34.

Greene CH, Pershing AJ, Conversi A, Planque B, Hannah C, Sameoto D, Head E, Smith PC, Reid PC, Jossi J, Mountain D, Benfield MC, Wiebe PH, Durbin E, 2003a. Trans-Atlantic responses of Calanus finmarchicus populations to basin-scale forcing associated with the North Atlantic Oscillation. Progress in Oceanography 58:301-312.

Greene CH, Pershing AJ, Kenney RD, Jossi JW, 2003b. Impact of climate variability on the recovery of endangered North Atlantic right whales. Oceanography 16:96-101.

Gregr EJ, Trites AW, 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.

Hunt GL, Stabeno P, Walters G, Sinclair E, Brodeur RD, Napp JM, Bond NA, 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. Deep-Sea Research Part II-Topical Studies in Oceanography 49:5821-5853.

Kang YS, Kim S, Lee W, 2006. Seasonal and spatial variations of zooplankton in the central and southeastern Bering Sea during the mid-1990s. Deep-Sea Research Part I-Oceanographic Research Papers 53:795-803.

Kenney RD, Hyman MAM, Owen RE, Scott GP, Winn HE, 1986. Estimation of prey densities required by western north Atlantic right whales. Marine Mammal Science 2:1-13.

Leaper R, Cooke J, Trathan P, Reid K, Rowntree V, Payne R, 2006. Global climate drives southern right whale (Eubalaena australis) population dynamics. Biology Letters 2:289-292.

Leduc R, 2004. Report of the results of the 2002 survey for North Pacific right whales. NOAA Fisheries, SWFSC 8604 La Jolla Shores Dr. La Jolla, CA 92037; 1-58.

Littaye A, Gannier A, Laran S, Wilson JPF, 2004. The relationship between summer aggregation of fin whales and satellite-derived environmental conditions in the northwestern Mediterranean Sea. Remote Sensing of Environment 90:44-52.

Luchin VA, Semiletov IP, Weller GE, 2002. Changes in the Bering Sea region: atmosphere-ice-water system in the second half of the twentieth century. Progress in Oceanography 55:23-44.

Mate BR, Nieukirk SL, Kraus SD, 1997. Satellite-monitored movements of the northern right whale. Journal of Wildlife Management 61:1393-1405.

Matthews JN, Brown S, Gillespie D, Johnson M, McLanaghan R, Moscrop A, Nowacek D, Leaper R, Lewis T, Tyack P, 2001. Vocalisation rates of the North Atlantic right whale (Eubalaena glacialis). Journal of Cetacean Research and Management 3:271-281.

Mellinger DK, Stafford KM, Moore SE, Munger LM, Fox CG, 2004. Detection of North Pacific right whale (*Eubalaena japonica*) calls in the Gulf of Alaska. Marine Mammal Science 20:872-879.

Moore SE, DeMaster DP, Dayton PK, 2000. Cetacean habitat selection in the Alaskan Arctic during summer and autumn. Arctic 53:432-447.

Moore SE, Waite JM, Friday NA, Honkalehto T, 2002. Cetacean distribution and relative abundance on the central-eastern and the southeastern Bering Sea shelf with reference to oceanographic domains. Progress in Oceanography 55:249-261.

Moses E, Finn JT, 1997. Using geographic information systems to predict North Atlantic right whale (*Eubalaena glacialis*) habitat. Journal of Northwest Atlantic Fishery Science 22:37-46.

Munger L, Wiggins S, Moore SE, Hildebrand JA. (Chapter 3, this thesis). North Pacific right whale (*Eubalaena japonica*) seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea, 2000-2006. *submitted to* Marine Mammal Science.

Munger LM, Mellinger DK, Wiggins SM, Moore SE, Hildebrand JA, 2005. Performance of spectrogram cross-correlation in detecting right whale calls in long-term recordings from the Bering Sea. Canadian Acoustics 33:25-34.

Murison LD, Gaskin DE, 1989. The distribution of right whales and zooplankton in the Bay of Fundy, Canada. Canadian Journal of Zoology 67:1411-1420.

Napp JM, Baier CT, Brodeur RD, Coyle KO, Shiga N, Mier K, 2002. Interannual and decadal variability in zooplankton communities of the southeast Bering Sea shelf. Deep-Sea Research Part II-Topical Studies in Oceanography 49:5991-6008.

NMFS, 2006. Endangered And Threatened Species; Proposed Endangered Status for North Pacific Right Whale. NOAA, Department of Commerce, Federal Register: December 27, 2006; 77694-77704.

Omura H, 1958. North Pacific right whale. Sci Rep Whales Res Inst, Tokyo No. 13:1-52.

Omura H, Ohsumi S, Nemoto T, Nasu K, Kasuya T, 1969. Black right whales in North Pacific. Scient Rep Whales Res Inst, Tokyo No. 21:1-78.

Overland JE, Bengtsson L, Przybylak R, Walsh JJ, 2007. Arctic Report Card 2007: atmosphere. (NOAA Department of Commerce). Available online at http://www.arctic.noaa.gov/reportcard/atmosphere.html.

Overland JE, Stabeno P, 2004. Is the climate of the Bering Sea warming and affecting the ecosystem? EOS, Transactions, American Geophysical Union 85:309-316.

Parks SE, Tyack PL, 2005. Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups. Journal of the Acoustical Society of America 117:3297-3306.

Patenaude NJ, Baker CS, 2001. Population status and habitat use of southern right whales in the sub-Antarctic Auckland Islands of New Zealand. Journal of Cetacean Research and Management Special Issue 2:111-116.

Redfern JV, Ferguson MC, Becker EA, Hyrenbach KD, Good C, Barlow J, Kaschner K, Baumgartner MF, Forney KA, Ballance LT, Fauchald P, Halpin P, Hamazaki T, Pershing AJ, Qian SS, Read A, Reilly SB, Torres L, Werner F, 2006. Techniques for cetacean-habitat modeling. Marine Ecology Progress Series 310:271-295.

Rodionov S, Stabeno P, Overland JE, Bond NA, Salo S, 2005. Eastern Bering Sea - 2005. In: Science Reports on the Bering Sea Climate Status and Trends. www.beringclimate.noaa.gov/reports/: NOAA; 1-8.

Rowntree VJ, Payne RS, Schell DM, 2001. Changing patterns of habitat use by southern right whales (Eubalaena australis) on their migratory ground at Peninsula Valdes, Argentina, and in their long-range movements. Journal of Cetacean Research and Management Special Issue 2:133-143.

Scarff JE, 1991. Historic distribution and abundance of the right whale (*Eubalaena glacialis*) in the North Pacific, Bering Sea, Sea of Okhotsk and Sea of Japan from the Maury Whale Charts. Report of the International Whaling Commission 41:467-489.

Shelden KEW, Moore SE, Waite JM, Wade PR, Rugh DJ, 2005. Historic and current habitat use by North Pacific right whales *Eubalaena japonica* in the Bering Sea and Gulf of Alaska. Mammal Review 35:129-155.

Smith SL, 1991. Growth, Development and Distribution of the Euphausiids *Thysanoessa raschi* (M-Sars) and *Thysanoessa inermis* (Kroyer) in the Southeastern Bering Sea. Polar Research 10:461-478.

Smith SL, Vidal J, 1984. Spatial and Temporal Effects of Salinity, Temperature and Chlorophyll on the Communities of Zooplankton in the Southeastern Bering Sea. Journal of Marine Research 42:221-257.

Smith SL, Vidal J, 1986. Variations in the Distribution, Abundance, and Development of Copepods in the Southeastern Bering Sea in 1980 and 1981. Continental Shelf Research 5:215-239.

Stabeno PJ, Bond NA, Kachel NB, Salo SA, Schumacher JD, 2001. On the temporal variability of the physical environment over the south-eastern Bering Sea. Fisheries Oceanography 10:81-98.

Stabeno PJ, Salo SA, (in press). On the recent warming of the southeastern Bering Sea shelf. Progress in Oceanography.

Tynan CT, DeMaster DP, Peterson WT, 2001. Endangered right whales an the southeastern Bering Sea shelf. Science 294:1894-1894.

Vidal J, Smith SL, 1986. Biomass, Growth, and Development of Populations of Herbivorous Zooplankton in the Southeastern Bering Sea During Spring. Deep-Sea Research Part a-Oceanographic Research Papers 33:523-556.

Wade P, Heide-Jorgensen MP, Shelden K, Barlow J, Carretta J, Durban J, Leduc R, Munger L, Rankin S, Sauter A, Stinchcomb C, 2006. Acoustic detection and satellite-tracking leads to discovery of rare concentration of endangered North Pacific right whales. Biology Letters 2:417-419.

Waite JM, Wynne K, Mellinger DK, 2003. Documented sighting of a North Pacific right whale in the Gulf of Alaska and post-sighting acoustic monitoring. Northwestern Naturalist 84:38-43.

Wiggins S, 2003. Autonomous acoustic recording packages (ARPs) for long-term monitoring of whale sounds. Marine Technology Society Journal 37:13-22.

Woodley TH, Gaskin DE, 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.

Chapter 5 is in preparation for submission (Munger, L.M., Moore, S.E., and Hildebrand, J.A. Seasonal and interannual variability of North Pacific right whale occurrence and oceanography on the southeastern Bering Sea middle shelf: a conceptual model. Marine Ecology Progress Series, in preparation). The dissertation author was the primary investigator and author of this paper.