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FINAL REPORT
Episodic Upwelling of Zooplankton within a Bowhead Whale Feeding Area Near Barrow, AK

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LONG-TERM GOALS

Our long term goals are to understand (1) the biological-physical oceanographic characteristics and mechanisms on the shelf near Barrow, AK that together produce a favorable feeding environment for the bowhead whale there and (2) the potential impact of climate change, particularly the ongoing reduction in sea ice and variability in the presence of Pacific Water near Barrow, on this feeding environment. This region is a critical feeding area for bowhead whales, particularly during the fall migration (e.g., Lowry et al., 2004). Results from biophysical sampling conducted during August-September 2005- 2008 demonstrated that the oceanography of the shelf is complex, dynamic, and highly variable and that advection is closely coupled to the direction and magnitude of the winds. In addition, oceanographic and atmospheric conditions impact the composition, distribution, and availability of plankton prey for the bowhead whale. Assessment and understanding of interannual and longer-term variability in the physical mechanisms influencing ocean conditions and the resulting distribution and abundance of plankton on the shelf are necessary to predict potential impacts of climate change.

OBJECTIVES

Our overall objectives are to explicitly identify and document the occurrence, frequency, and persistence of wind-driven shelf-slope exchange events at the Barrow Canyon and the Beaufort shelf breaks during the summer and early fall in association with the presence of ice cover, water column stratification, and bowhead whales and to further document short-term and interannual variability in the ocean system and how this variability is associated with changes in climate and ice.

1. Document exchanges of Pacific Water and plankton/krill (acoustic backscatter as a zooplankton proxy) between Barrow Canyon and the adjacent Beaufort shelf over two full years.
2. Document shelf-slope exchanges between the Beaufort Sea and Beaufort shelf.
3. Determine the seasonal occurrence of bowhead whales in the study area via year-round sampling for marine mammal vocalizations using autonomous recorders.
4. Determine the correlations between exchange events and wind speed and direction, wind duration, ice cover, shelf water column stratification, whale presence or absence, and whale prey selection.
5. Conduct surveys along transects running across Barrow Canyon and across the shelf to ground-truth mooring observations and to continue the two-year time series of observations collected during the larger, NSF funded project to further describe interannual variability of hydrographic and associated biological characteristics on the shelf during early September and to provide critical information for validation of oceanographic modeling of the region.

APPROACH

This project is a partnership between the academic PIs listed above (Ashjian, Campbell, Okkonen, and Stafford), collaborators at Oregon State University (B. Sherr and E. Sherr), a collaborator at NOAA (S. Moore), and a collaborator at the North Slope Borough Department of Wildlife Management (C. George).

The objectives are being addressed through three main field approaches: Boat-based Oceanographic Sampling (Task 1), Year-Long Oceanographic Moorings (Task 2), and Bowhead Whale Prey Analysis (Task 3). Data analysis and presentation of results (Task 4) and Outreach (Task 5) are accomplished simultaneously with the three work approaches.

WORK COMPLETED

Boat-based oceanographic sampling was conducted in 2008 and 2009. This work continues to the present through funding from NOAA/BOEM and the NSF Arctic Observing Network (AON) program; the 2013 field season finished on Sept. 7. The additional sampling will permit us to continue to understand oceanographic variability near Barrow, AK. The NOPP-sponsored sampling of 2008 and 2009 is an integral part of that understanding. Analyses of these data are ongoing with the goal of preparation of two manuscripts (one focusing on interannual variability, a second on upwelling of whale prey). Results of the analysis of interannual variability in biological and physical ocean conditions for 2005-2012 (inclusive of years funded by this project) were presented at the 2010 Ocean Sciences Meeting in Portland OR (Ashjian et al., 2010a, Okkonen et al., 2010a), at several Alaska Marine Sciences Meetings in Anchorage AK (Ashjian et al., 2009, 2010a, 2011, 2013; Okkonen et al.,

2009, 2011a), at the 2010 AGU Meeting in San Francisco, CA (Ashjian et al., 2010c, Okkonen et al., 2010b) and at the 2010 State of the Arctic Meeting in Miami, Fl (Ashjian et al., 2010b). Preparation of a manuscript is ongoing.

Two year-long oceanographic moorings were deployed at 100 m of water along the shelf break (Fig. 1) for two years (August 2008 – September 2010), with deployments, annual servicing, and recoveries done during *USCGC Healy* cruises. Instrumentation on both moorings included an acoustics recorder to archive marine mammal vocalizations and microcat CT sensor to measure water temperature and salinity. The hydrophones were on a 30% duty cycle and recorded from 0.1-4.1 kHz from September 2008-September 2010. The western mooring (A1) was also instrumented with upward-looking Teledyne/RDI 300 kHz ADCP at 7-m above the bottom to aid in monitoring the movement of zooplankton between the slope and shelf and to describe current speeds and directions, particularly those associated with shelf-break upwelling events. Analyses of marine mammal vocalization data from both moorings have been completed. Peer-reviewed manuscripts describing the association of beluga whales with a north-easterly flowing Alaska Coastal Current (Stafford et al., 2013) and the occurrence of bearded seals in the Beaufort Sea (MacIntyre et al., 2013) have been published. Data from the moorings also have been included in several presentations at meetings (Okkonen et al., 2009, 2010a, b, 2011a, 2013).

Bowhead whale prey analysis was conducted by C. George and G. Sheffield on whale stomach contents collected by C. George and local whalers during the IWC sanctioned fall whaling seasons of 2008-2010.

RESULTS

Significant year-to-year variability in the temperature-salinity characteristics in the study area has been observed over the period of our sampling (2005-2013) (Fig. 2). Comparison of temperature-salinity data collected during the Shelf Basin Interactions program (2002-2004) and our data show a trend of increasing temperatures during the period, with some interannual variability. Highest temperatures were observed in 2007, the year in which the second lowest sea ice cover from the years of the satellite record was observed. Upwelling of water along the shelf-break under strong, sustained east wind brings whale prey (euphausiids) on the shelf. If upwelling winds are followed by weak or south winds, the strong, northeastward flowing Alaska Coastal Current is moved up against the shelf break, blocking the dominantly westward-flowing shelf water, forming elevated concentrations of euphausiids on the shelf (e.g., Ashjian et al., 2010d; Okkonen et al., 2011b). Abundances of krill were greater on the shelf following such sequences of upwelling and winds than during other periods (Fig. 3). The prey in the stomachs of harvested on the shelf during the fall subsistence hunt frequently (58% of whales harvested from 2007-2012) was dominated by krill. Of the whales harvested off of the shelf, the stomach contents of 48% were dominated by copepods, 17% by krill, and the remaining 35% contained a mix of copepod and non-copepod prey.

Bowhead (*Balaena mysticetus*) and beluga (*Delphinapterus leuca*) whales are the only Arctic endemic cetaceans that occur regularly in the Beaufort Sea. Each species winters in the Bering Sea and migrates northwards in the spring, returning south in the late autumn. Bearded seals (*Erignathus barbauts*) are a pan-Arctic species found in the Beaufort year-round. Calls/songs from whale species were detected in fall and declined as ice concentration in the mooring vicinity increased. In the spring, however, whale calls/songs were detected beginning in April when the region was still covered with ice, and continued throughout the summer. Bowhead whale song was only recorded in the early spring, from April until

mid-May and detections of calls and songs progressed from west to east as spring turned to summer (Figs. 4). Bearded seals were recorded at relatively low levels in the fall when there was no ice cover over either mooring. They increased dramatically in late December and early January and were the dominant signal during winter when ice concentration approached 100%. Unlike the cetaceans, bearded seal signals decreased abruptly in spring as sea ice disappeared.

Bowhead whales use acoustic signals to maintain contact with each other, for navigation in dark, ice-covered waters, and, likely as a reproductive display by males in spring (Würsig and Clark 1983). The animals recorded on the two moorings are part of the Bering-Chukchi-Beaufort population that winters in the northern Bering Sea and summers, generally, in the Canadian Beaufort where food is reliably available. During both the northward and southward migration, whales pass through the western Beaufort Sea. The decrease in call detections in fall months at both sites can be attributed to the whales migrating west towards the Chukotka Coast before heading south to the Bering Sea for winter (Quakenbush et al. 2010). In the spring, whales migrate northwards, often in heavy ice, by using a series of flaw leads that form along the western coast of Alaska. Bowhead whale calls were detected on the western-most mooring only a day or two before the eastern mooring and suggest a steady migration to the east in both years.

Beluga whales are quite vocal animals, particularly during socializing and feeding. They are less so during migration. In this study beluga whale calls were detected in bouts that may be indicative of feeding behavior (Stafford et al., 2013). In late summer-fall of both years, beluga whale calls were more frequently detected when the Alaska Coastal Current (strong current to the NE), containing warmer, fresher Alaska Coastal Water, moves over the mooring, potentially forming a strong front between ACC and Arctic basin water further offshore where beluga prey are concentrated (Fig. 5). The beluga whales migrating north from the Bering Sea are thought to be from two separate populations: eastern Chukchi and eastern Beaufort. These two populations are thought to have different migratory timing with the eastern Beaufort animals migrating towards the Bering Sea up to two months earlier than the eastern Chukchi animals (Suydam et al., 2001). It is possible that the bouts of calling we recorded are from the different populations as they migrate past. At present, it is unknown if different populations produce calls that are unique to those populations.

Of the three species discussed here, only bearded seals are found year-round in the Beaufort Sea (Macintyre et al., 2013). To date, evidence points to only males producing the trill calls we recorded and these are associated with reproductive displays. Males may defend territories that are in the vicinity of the ice edge with ready access to open water for hunting prey and ice for hauling out and resting. Bearded seals are known to display in the spring which is mating season but the relatively high number of detections in the fall was previously unreported. The fall calls appear to be shorter and somewhat higher frequency than spring calls suggesting that males, potentially juveniles, are “warming up” or practicing for the spring.

IMPACT/APPLICATIONS

Our work has provided a greater understanding of the physical and biological factors that produce favorable feeding environments for bowhead and beluga whales near Barrow. This will permit educated decisions regarding development of industry, tourism, and commerce in this region by regulators and policy makers. The work also provides greater insight into the potential impact of climate change on the Arctic ecosystem. In addition, the continued documentation of interannual variability of the ocean conditions is of both local (importance to shelf and slope ecosystems) and

broader importance since the region near Barrow is a critical juxtaposition of the Chukchi Sea and Beaufort Seas and is where much of the Pacific Water flowing through the Chukchi Sea from Bering Strait enters the Beaufort Sea, either through Barrow Canyon or from more western locations in the Chukchi Sea. The Pacific Water supplies heat, nutrients, and organic material including plankton (especially the krill that are the preferred prey of the bowhead whale near Barrow) to the Chukchi Sea and ultimately the Arctic Ocean.

RELATED PROJECTS

This NOPP-funded project is a follow on to a previous National Science Foundation funded project examining "Oceanography, Bowhead Whale Distribution, Climate Variability, and Iñupiat Subsistence Whaling", with PIs including Ashjian, Campbell, George, Moore, Okkonen, Sherr, and Sherr for which fieldwork was conducted in 2005 and 2006. Many of the hypotheses explored in this project resulted from data collected during the NSF project. The NOPP project also is a companion to two other projects of ours: an ongoing NSF-funded Arctic Observing Network project to document interannual variability in ocean conditions near Barrow and a recently completed NOAA/BOEM project "Bowhead Whale Feeding in the Western Beaufort Sea" for which the PIs deployed short-term, shallow oceanographic and year-long marine mammal acoustic recording moorings and conducted additional oceanographic fieldwork during the summers of 2008-2011. Additional components of this larger project include aerial surveys of marine mammals/bowhead whales, long-term satellite tagging and short-term suction cup tagging of whales to determine migration paths and feeding behavior, and visual observations of whale behavior and locations from small boats. Together these projects provide a greater understanding of the oceanographic conditions off of Barrow as well as providing opportunities to sample over longer time periods in that region in order to better describe the impact of the strength and magnitude of the wind on upwelling along the Beaufort Shelf and the importance of this mechanism to providing prey on the shelf for the bowhead whale. The ongoing project also complements two other NOPP projects "Circulation, Cross-shelf Exchange, Sea Ice, and Marine Mammal Habitats on the Alaskan Beaufort Sea Shelf" led by R. Pickart and including Stafford and Moore as PIs and "A Comprehensive Modeling Approach Towards Understanding and Prediction of the Alaskan Coastal System Response to Changes in an Ice-diminished Arctic" led by W. Maslowski with J. Cassano and J.J. Walsh as co-PIs. The former project focuses on physical oceanography, upwelling, and bowhead whale distribution in a region further to the east of Barrow using a combination of year-long oceanographic and whale acoustic recorder moorings and field observations. Not only does the work of the Pickart NOPP project together with this project extend the spatial range of observations, field logistics were conducted in collaboration. For example, the Healy cruises that deployed moorings for this project also deployed the moorings for the Pickart NOPP in a very fruitful collaboration between the two projects. Several CTD casts were conducted near the Pickart NOPP moorings during the transit of the 2008 *R/V Annika Marie* from Barrow to Prudhoe Bay. The latter project applies state-of-the-art regional modeling of sea ice, ocean, atmosphere and ecosystem to provide a system approach to advance the knowledge and predictive capability of the diverse impacts of changing sea ice cover on the bio-physical marine environment of coastal Alaska. Hydrography acquired during surveys conducted from the *R/V Annika* Marie has been regularly forwarded to Maslowski for comparison with model output. Data from the moorings are included in the ongoing dissertation research of H. McEachen (University of Alaska Fairbanks).

REFERENCES

Ashjian, C.J., Campbell, R.G., George, J.C., Moore, S.E., Okkonen, S.R., Sherr, B.F., Sherr. E.B. 2009. Impact of inter-annual variability in ocean conditions on bowhead feeding near Barrow Alaska. Alaska Marine Science Symposium, Jan. 19-22, 2009.

Ashjian, C.J., Campbell, R.G., Okkonen, S.R., Sherr, B.F., Sherr, E. B. 2010a. Year-to-year variability of ocean biology across Barrow Canyon and the western Beaufort Shelf: 2005-2009. Ocean Sciences Meeting, Portland OR, Feb. 22, 2010.

Ashjian, C.J., Braund, S.R., Campbell, R.G., George, J.C., Kruse, J.A., Maslowski, W, Moore, S.E., Nicolson, C.R., Okkonen, S.R., Sherr, B.F., Sherr, E.B., Spitz, Y.H. 2010b. Environmental Variability, Bowhead Whale Distributions, and Iñupiat Subsistence Whaling near Barrow, AK. State of the Arctic, March 16-19, 2010, Miami, FL.

Ashjian, C.J., Campbell, R.G., Okkonen, S.R., Sherr, B.F., Sherr, E. B. Year-to-year variability of ocean biology across Barrow Canyon and the western Beaufort Shelf: 2005-2009. 2010c. EOS Trans. AGU, 91(26), Ocean Sci. Meet. Suppl., Abstract IT14C-06.

Ashjian, C.J., Braund, S.R., Campbell, R.G., George, J.C., Kruse, J. Maslowski, W., Moore, S.E., Nicolson, C.R., Okkonen, S.R., Sherr, B.F., Sherr, E.B., Spitz, Y. 201d. Climate variability, oceanography, bowhead whale distribution, and Iñupiat subsistence whaling near Barrow, AK. Arctic 63: 179-194.

Ashjian, C.J., Campbell, R.G., Okkonen, S.R., Sherr, B.F., Sherr, E. B. 2011. Year-to-year variability of ocean conditions across Barrow Canyon and the western Beaufort Shelf: 2005-2010. Alaska Marine Science Symposium, January 19, 2011.

Ashjian, C, Campbell, R., Okkonen, S. Alatalo, P. Year to year variability of krill abundance at a bowhead whale feeding hotspot near Barrow, AK: 2005- 2012. January 21, 2013, Alaska Marine Science Symposium.

Lowry, LF, Sheffield G, George JC. 2004. Bowhead whale feeding in the Alaskan Beaufort Sea, based on stomach contents analyses. J. Cet. Res. Man. 6(3): 215–223.

MacIntyre, K.Q., Stafford, K.M., Berchok, C.L., Boveng, P.L. 2013. Year-round acoustic detection of bearded seals (*Erignathus barbatus*) in the Beaufort Sea 2008-2010. S Polar Biology 26: 1161-1173. doi 10.1007/s00300-013-1337-1.

Okkonen, S.R., C. J. Ashjian, R.G. Campbell, D. Jones. Upwelling and aggregation of zooplankton on the western Beaufort shelf as inferred from moored acoustic Doppler current profiler measurements. 2009. Alaska Marine Science Symposium, Jan. 19-22, 2009, Anchorage, AK.

Okkonen, S.R., Ashjian, C.J., Campbell, R.G. 2010a. Year-to-year variability of late summer hydrography across Barrow Canyon and the western Beaufort Shelf: 2005-2009. Ocean Sciences Meeting, Portland OR, Feb. 22, 2010.

Okkonen, S.R., Ashjian, C.J., Campbell, R.G. 2010b. Sea ice as a tracer for circulation features associated with the Barrow area Bowhead whale feeding hotspot. AGU Fall Meeting, December 16, 2010.

Okkonen, S.R., Ashjian, C.J., Campbell, R.G. 2011a. Does the Alaska Coastal Current carry krill to the Arctic? Alaska Marine Science Symposium, January 18, 2011.

Okkonen, S.R., Ashjian, C.J., Campbell, R.G., Clarke, J., Moore, S.E., Taylor. 2011b. Satellite observations of circulation features associated with the Barrow area bowhead whale feeding hotspot. Remote Sensing of Environment 115: 2168-2174.

Okkonen, S.R. 2013. Late summer near-shore circulation on the western Beaufort shelf and exchange with Elson Lagoon. Alaska Marine Science Symposium, Jan. 21-25, 2013, Anchorage, AK.

Quakenbush, L.T., Citta, J.J. George, J.C., Small, R.J., Heide-Jørgensen, M. P. 2010. Fall and winter movements of bowhead whales (*Balaena mysticetus*) in the Chukchi Sea and within a potential petroleum development area. Arctic 63: 289-307.

Stafford, K.M., Okkonen, S.R., Clarke, J.T. 2013. Correlation of a strong Alaska Coastal Current with the presence of beluga whales (*Delphinapterus leucas*) near Barrow, Alaska. Marine Ecology Progress Series, www.doi.org: 10.3354/meps10076.

Suydam, R.S., Lowry, L.F., Frost, K.J., O'Corry-Crowe, G.M. Pikok, D. 2001. Satellite tracking of eastern Chukchi Sea beluga whales into the Arctic Ocean. Arctic 54:237-243.

Würsig, B., Clark, C.W. 1993. Behavior. In The Bowhead Whale The Society for Marine Mammalogy, Special Publication No. 2. (eds Burns, J.J., Montague, J.J., and Cowles, C.J.), pp. 157-199. Lawrence, Kansas: Allen Press.

PUBLICATIONS

MacIntyre, K.Q., Stafford, K.M., Berchok, C.L., Boveng, P.L. 2013. Year-round acoustic detection of bearded seals (*Erignathus barbatus*) in the Beaufort Sea 2008-2010. S Polar Biology 26: 1161-1173. doi 10.1007/s00300-013-1337-1.

Stafford, K.M., Okkonen, S.R., Clarke, J.T. 2013. Correlation of a strong Alaska Coastal Current with the presence of beluga whales (*Delphinapterus leucas*) near Barrow, Alaska. Marine Ecology Progress Series, www.doi.org: 10.3354/meps10076.

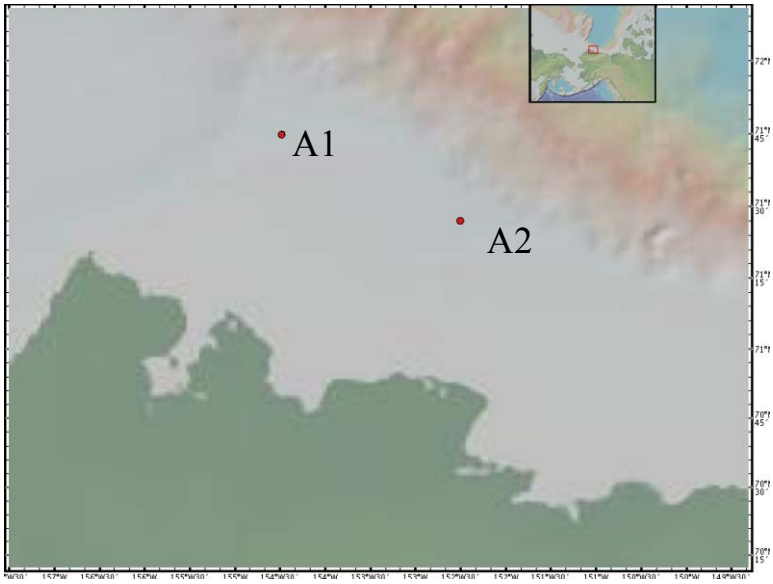

Figure 1. Locations (red circles) of moorings along the Beaufort Shelf break on which hydrophones to detect marine mammal vocalizations were deployed.

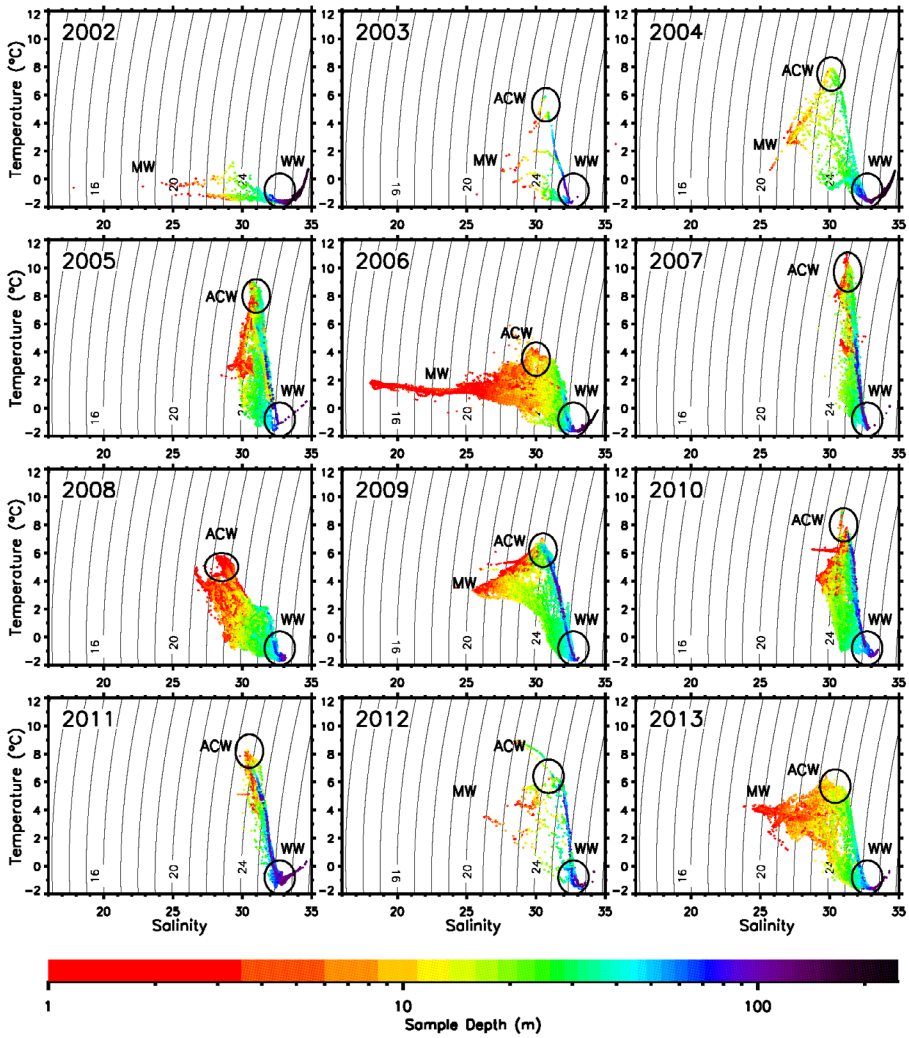

Figure 2. Temperature-salinity plots of each year's CTD data, including data collected during the NSF funded Shelf Basin Interactions Program (2002-2004) and companion projects to this NOPP work (2005-2007, 2010-2013). Representative water masses are Alaska Coastal Water (ACW), Winter Water (WW), and sea ice Melt Water (MW). Curved lines are isopycnals (constant sigma-t). Color indicates water depth at each data location. Highest ACW temperature (~12 °C) was observed in 2007; lowest ACW temperature (~4°C) was observed in 2006, with the greatest amount of sea ice Melt Water also seen in that year.

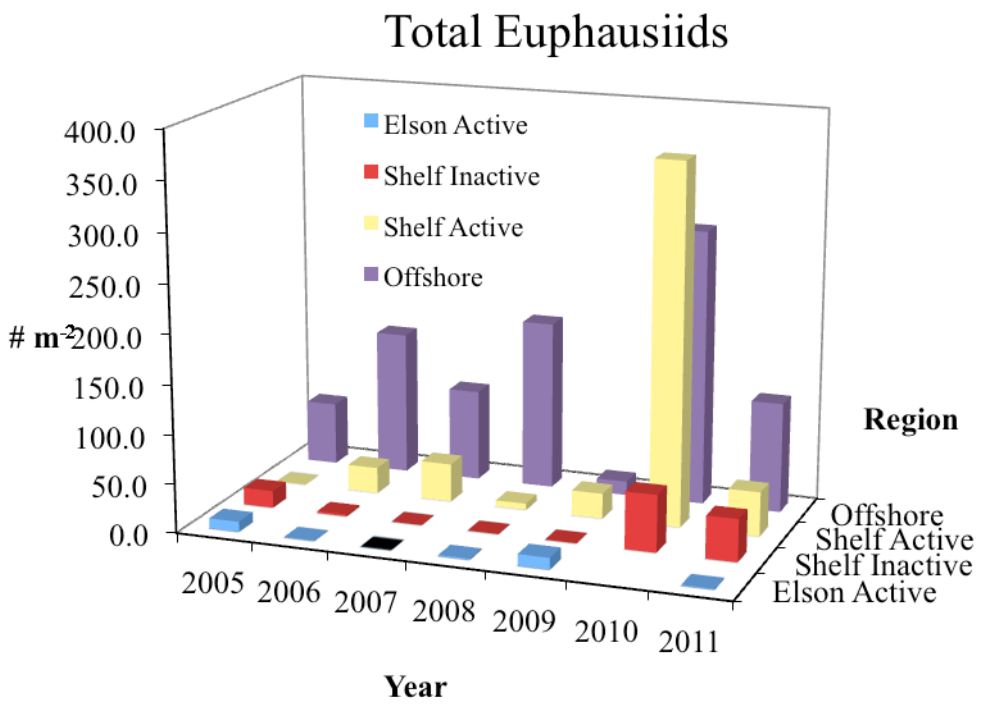

Figure 3. Total water column abundances of euphausiids (furcilia and juveniles/adults) in different regions and under different wind conditions in the study area for 2005-2011, including the field years of this project. "Offshore" data were collected in deeper water off of the shelf, "Shelf Active" data were collected on the shelf during periods when the "krill trap" was active (upwelling of water/krill followed by low or south winds that produces convergence of flow between the ACC in Barrow Canyon and the western Beaufort Shelf and concentration of krill on the shelf (Ashjian et al., 2010)). "Shelf inactive" data were collected during periods when the krill trap was inactive and no convergence of flow was occurring on the shelf. "Elson active" data were collected in very shallow (< 6 m) water close to Elson Lagoon during periods when the krill trap was active. Bowhead whales have been observed feeding in this shallow water during these periods.

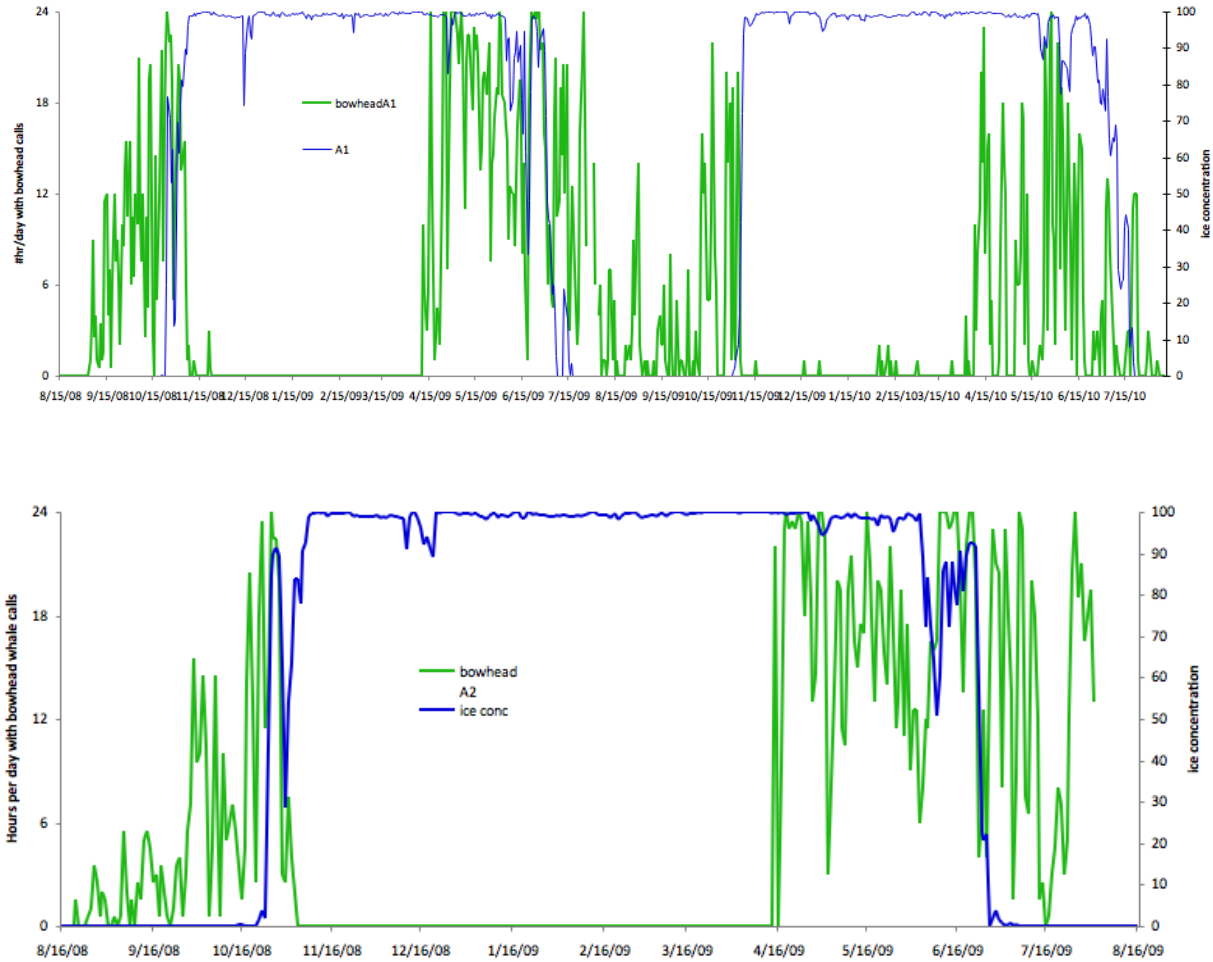

Figure 4. Number of hours per day with bowhead whale call or song detections (green line) and ice concentration (blue line) within 30 km of mooring sites. Upper panel: Mooring site A1, 2008-2010. Lower panel: Mooring site A2, 2008-2009. Bowhead whale call/song detections decreased in fall as ice cover increased but increased in both springs while ice cover was still extensive.

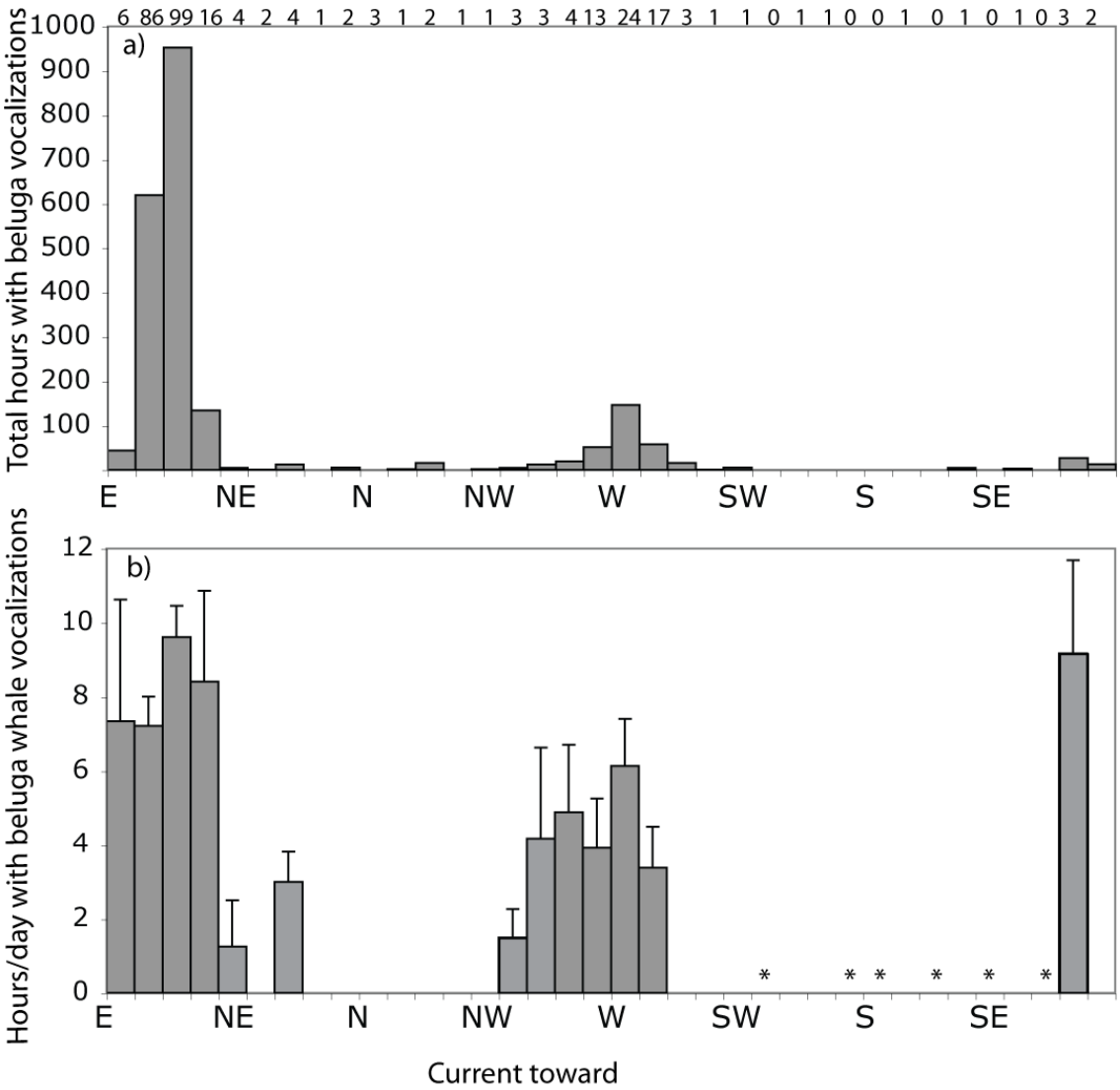

Figure 5. a) Histogram of total number of hours with at least one beluga whale vocalization as a function of current direction (10° bins). Number of days available for each direction are shown on the top of the plot; b) Mean number of hours per day for all current directions with 3 or more days available (directions for which no data were available are indicated with *). Bars are 95% confidence intervals. (from Stafford et al., 2013)