ATTACHMENT B. Annual Project Report Form (Revised 11.21.19)

1. Project Number:

19120114-C

2. Project Title:

Monitoring Long-term Changes in Forage Fish Distribution, Abundance and Body Condition in Prince William Sound

3. Principal Investigator(s) Names:

Mayumi Arimitsu and John Piatt, U.S. Geological Survey Alaska Science Center

Scott Hatch, Institute for Seabird Research and Conservation

4. Time Period Covered by the Report:

February 1, 2019-January 31, 2020

5. Date of Report:

March 2020

6. Project Website (if applicable):

www.gulfwatchalaska.org

7. Summary of Work Performed:

The Gulf Watch Alaska (GWA) Forage Fish project has three main components including: 1) continuation of the longest time series on forage fish availability to seabirds in the Gulf of Alaska, based on diets of adult and nestling seabirds at Middleton Island in collaboration with Scott Hatch (Institute for Seabird Research and Conservation [ISRC]), 2) ship-based surveys including the Integrated Predator Prey (IPP) survey in Prince William Sound (PWS) in collaboration with the humpback whale (project 19120114-O, John Moran, National Oceanographic and Atmospheric Administration [NOAA], Jan Straley, University of Alaska Southeast [UAS]), and marine bird (project 19120114-E, Mary Anne Bishop, Prince William Sound Science Center [PWSSC]) projects, 3) summer aerial survey validation and acoustic-trawl surveys in PWS. In FY19 project tasks, including contracting, permitting, equipment calibrations, data management and field work, were conducted according to planned schedules and protocols. In this report we focus on 2019 field efforts (Fig. 1), as detailed below.

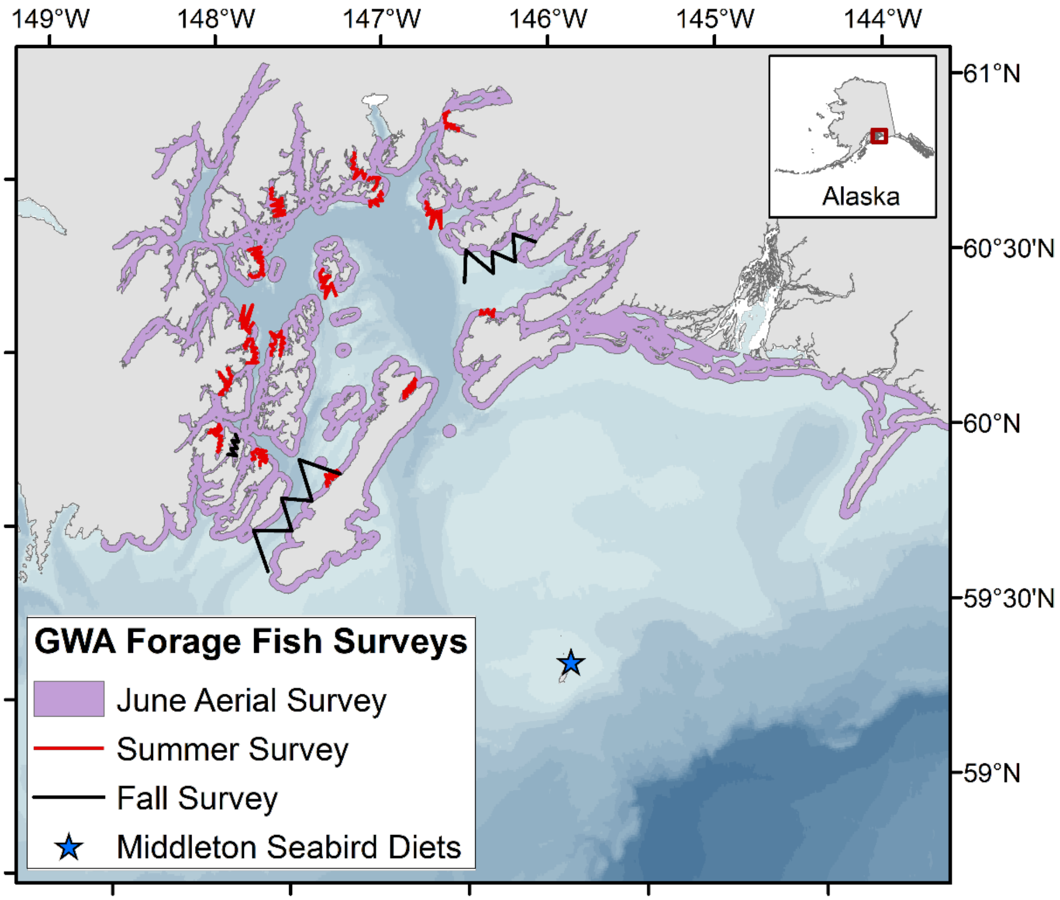


Figure 1. Distribution of Gulf Watch Alaska (GWA) seasonal forage fish survey effort in Prince William Sound and Middleton Island. Bathymetry (Lindquist et al. 2004) is shown in blue with darker shades indicating deeper seafloor depth.

A. Middleton Island Forage Fish

Seabird diet samples at Middleton Island were collected in Apr-Aug 2019. This included 390 diet samples from black-legged kittiwakes and 319 diet samples from rhinoceros auklets. A detailed report on findings from Middleton Island is provided at the end of this report (Appendix, Hatch 2020).

In spring 2019, invertebrates comprised a more typical fraction of the kittiwake diet, declining somewhat between April and May as the fish component increased in the samples. However, in contrast to most years, myctophids seemed to be largely unavailable during that time. Instead, the main constituents of the fish diet were Pacific herring and sand lance. Herring continued to be important fish prey throughout the summer (Fig. 2). Capelin and sand lance were about equally frequent in the summer diet, with 18% and 15% relative occurrence, respectively. As such, capelin made a stronger showing in 2019 than in any year since the onset of the heatwave in 2014. Tagging data indicate that spring foraging by kittiwakes in 2019 was more widespread than previously recorded or anticipated, with some individuals traveling far to the east and west of Middleton or visiting interior waters of PWS. Foraging tracks give the impression of birds sampling intermittently the pelagic zone off the continental shelf, but not staying and foraging extensively, as though food-searching there was generally unproductive. Kittiwake movements during incubation and chick-rearing (Jun-Aug) were similar to patterns observed in 2018, except for the virtual absence this year of foraging beyond the shelf edge.

In 2019, sand lance declined slightly in auklet diets as compared with the previous year, the difference being countered by a modest increase in capelin—seemingly a more or less direct and predictable trade-off that is evident throughout these datasets (Fig. 2). Greenlings were prominent in the auklet (but not kittiwake) diet during 2019, to a degree not seen since 1994. As in 2018, the foraging area of chick-rearing rhinoceros auklets overlapped with that of kittiwakes and was concentrated in nearshore waters of southeast Montague Island from Patton Bay to Cape Cleare. It would appear that age-0 greenlings and gadids were unusually abundant in this area during 2019. We were surprised to find auklets foraging on fish from as far away as 100 km from their nest sites on Middleton. Additional telemetry will likely reveal considerable flexibility in that regard, but the early lesson is that rhinoceros auklets, judging from their reliable success in breeding, are well adapted for coping with local food shortages.

The juxtaposition of time series for kittiwakes and rhinoceros auklets since 1978 (Fig. 2) shows general agreement vis-à-vis the decline of sand lance and, after 2008, the emergence of capelin as a dominant forage species. However, in several recent years, when neither sand lance nor capelin were prevalent, the diets of surface-feeding kittiwakes and diving auklets diverged substantially (Fig. 2). In 2019, the trade-off appeared to occur primarily between herring (more prevalent in kittiwake diet) and juvenile greenlings (taken mainly by auklets).

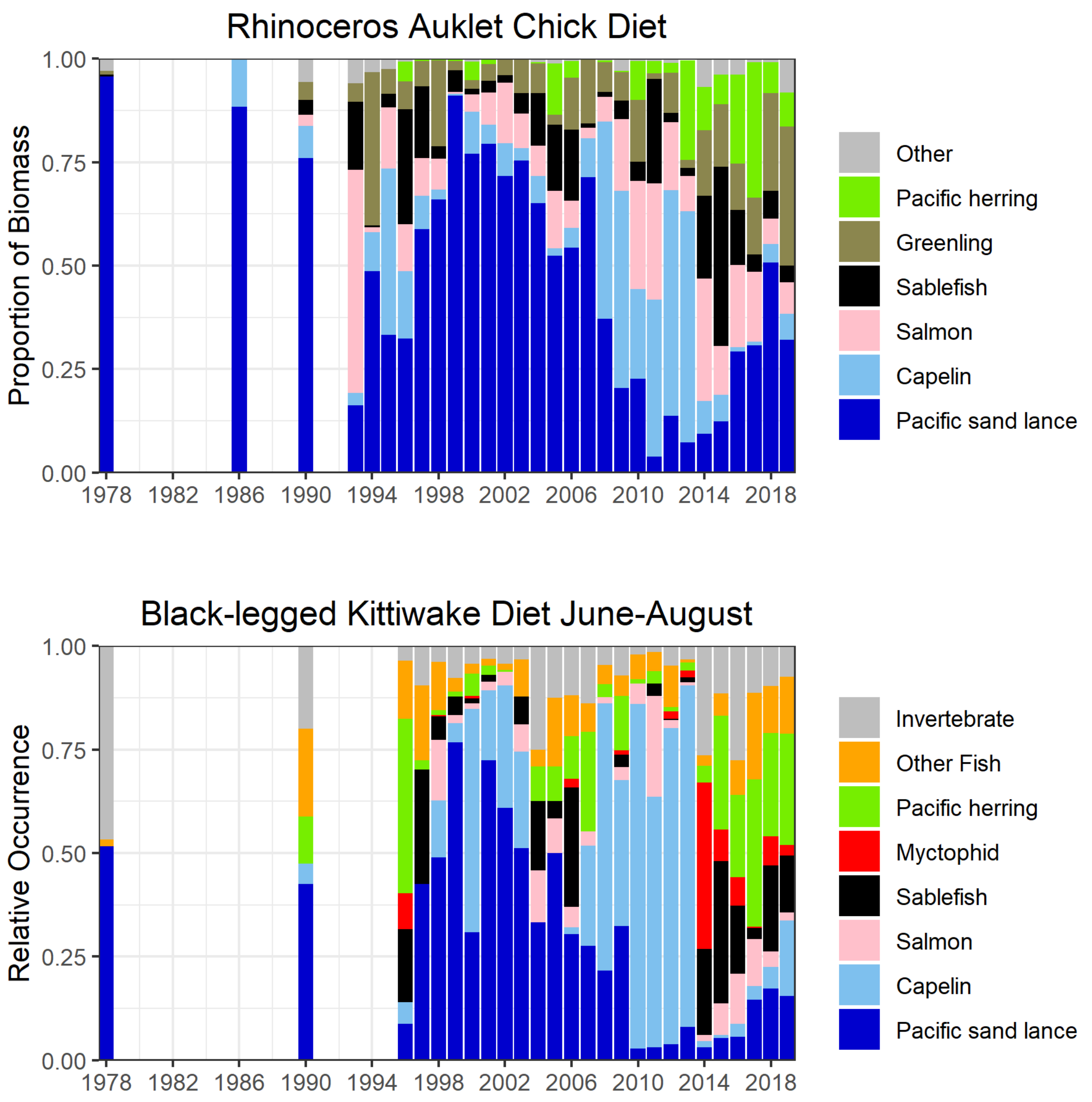


Figure 2. Interannual variation in diet composition of chick-rearing rhinoceros auklets (upper panel) and black-legged kittiwakes (lower panel) on Middleton Island, 1978 to 2019.

Seabird diet information from Middleton Island integrates forage composition and availability over broad areas of the Northern Gulf of Alaska, across coastal, shelf, and slope regions (Hatch 2013, Appendix). An in-depth analysis of auklet diets in relation to tagging data showed that the seabirds can detect prey species in foraging areas where other survey types have found the prey to be sparse or absent (Cunningham et al. 2018). The authors also highlighted the complexities of disentangling diet information in relation to individual specialization and prey switching. Predator diets at Middleton do appear to reflect large-scale synchrony among capelin abundance indices from NOAA trawl surveys that showed an abrupt decline between 2013 and 2015 (McGowan et al. In Press, Arimitsu et al. 2019).

Indices of relative occurrence (kittiwakes) and proportion biomass (auklets) suggest herring availability to seabirds has increased in recent years (Fig. 2). Because herring are generally limited to coastal areas (Ormseth et al. 2016, Doyle et al. 2019), the variability of herring indices in Middleton Island seabird diets is related to the foraging ambit of the birds. For example, GPS data from 2008 and 2011 show that kittiwakes were not foraging in coastal areas but stayed closer to Middleton (Hatch et al. unpublished data), and in those years herring indices were low in both the kittiwake and auklet diets. We hypothesize that in recent years (2015-2019) when the availability of local (offshore) sources of sand lance and capelin were low (Fig. 2), seabirds foraged closer to shore including within PWS (Appendix) where they encountered more herring.

Kittiwake diets are known to track age class of herring and regional differences in forage fish composition (Suryan et al. 2002, 2006). The occurrence (number of occurrences standardized by effort) of age-0 and age-1+ herring in kittiwake diets has generally increased since 2014 (Fig. 3).

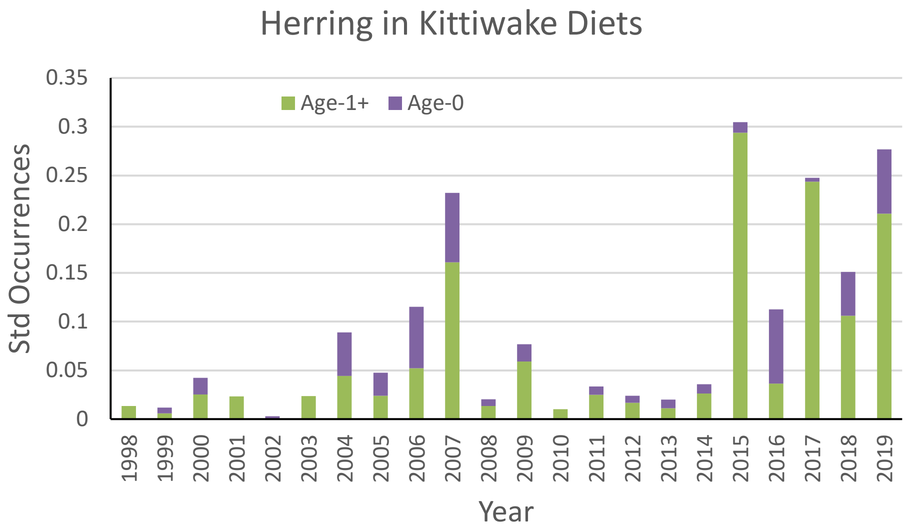


Figure 3. Standardized occurrence (occurrence/effort) of Pacific herring in Middleton Island kittiwake diets over time. Since 2015, tagging data (Hatch et al. unpublished data) suggest kittiwakes have been foraging in coastal areas where herring occur.

Auklets bring whole, fresh fish back to their chicks so fish size can be measured directly. Herring in auklet diets have become more frequent since 2010 (Fig. 2), and length frequencies over time are bimodal (Fig. 4). The small size class (< 100 mm) index value in 2016 was 3.17 times higher than the mean between 2010-2019 (Fig. 5). Similarly, the large size class index values in 2013 and 2017 were 3.1 – 4 times greater than the mean between

2010 - 2019. These years correspond to high values of age-1 herring in PWS aerial surveys (see section C below), and also suggests continued availability and use of the 2016 herring year class by seabirds into 2017.

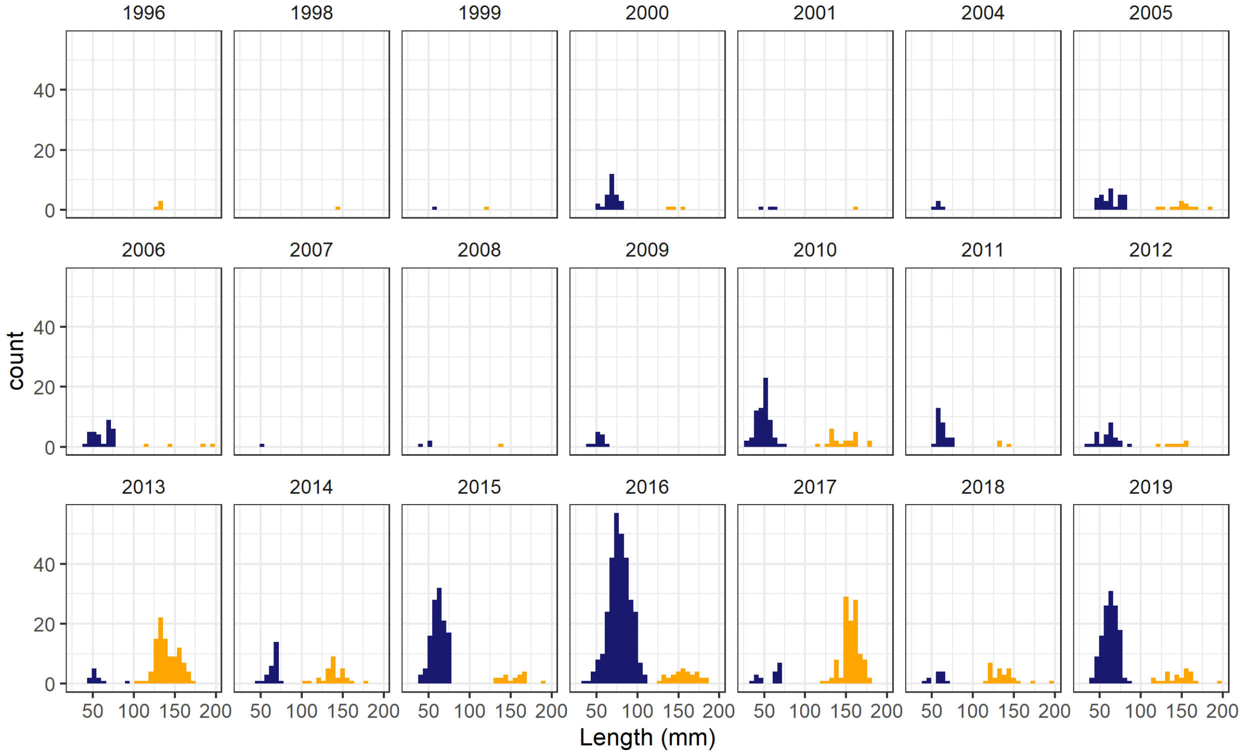


Figure 4. Bimodal length frequency by year for Pacific herring sampled by Rhinoceros Auklets at Middleton Island. Size classes are indicated by colors (age-0 in blue, age 1+ in yellow). Herring have become more frequent in auklet diets since 2010.

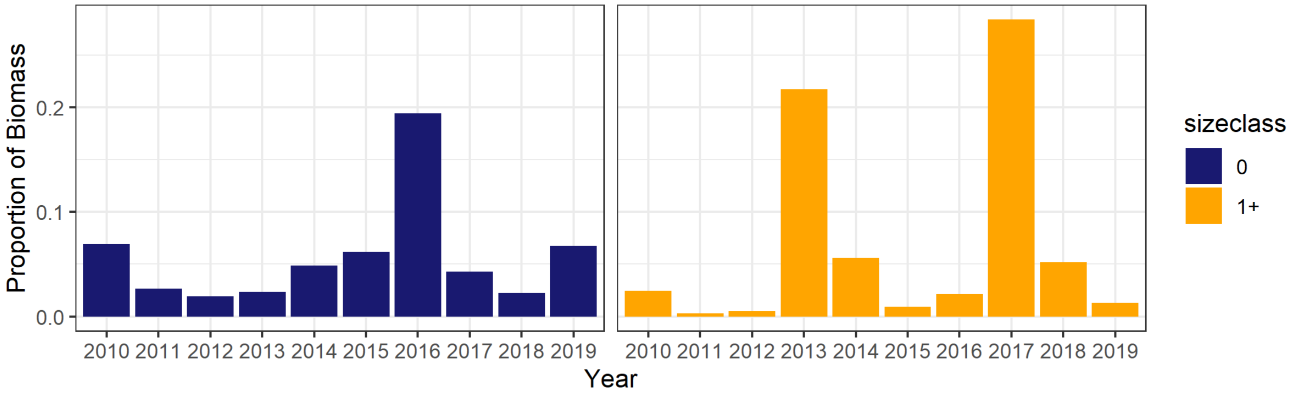


Figure 5. Interannual variation in Pacific herring by size class in diets of chick-rearing rhinoceros auklets.

Although herring have become more important in diets in recent years, they still comprise a relatively small proportion of seabird diets at the offshore colony site. Continued tagging efforts at the colony will help to interpret variability in herring indices among years.

B. Integrated Predator Prey (IPP) Survey

We conducted the IPP survey in collaboration with the humpback whale and fall/winter marine bird surveys from September 15-30, 2019. We are still processing most of the datasets we collected, and below we summarize the effort and preliminary results.

During a cruise aboard the U.S. Geological Survey (USGS) R/V *Alaskan Gyre* we conducted hydroacoustic surveys with a split beam dual frequency echosounder (120-38 kHz Simrad EK60) along transects in three sub-regions in Bainbridge Passage, Montague Strait, and Port Gravina (Fig. 1). Echosounder calibration was conducted using a 38.1 mm tungsten carbide sphere (Foote et al. 1987, Demer et al. 2015). To identify species composition and size of fish and macro-zooplankton we conducted fishing with a variety of sampling methods including an Alouette midwater trawl, small-meshed gill net, cast net, dip net, and jigs of varying hook sizes. Acoustic data were processed in EchoView 10 (Myriax Pty Ltd, Hobart, Tasmania, Australia).

At fixed habitat sampling stations (n = 6) we measured oceanographic conditions with a SBE 19 plus v2 conductivity-temperature-depth profiler (CTD) equipped with fluorometer, turbidity sensor, beam-transmissometer, photosynthetic active radiation (PAR) sensor, dissolved oxygen, pH senor, and water sampler to sample nutrients and chlorophyll a at discrete depths (0, 10, near bottom depths). After each CTD cast we collected zooplankton samples with a 50 m vertical haul of a 150 µ-mesh zooplankton net.

To identify broad-scale differences in fish and macrozooplankton abundance and distribution among years, we classified acoustic backscatter in the water column using frequency response methods described for inshore waters (for more details see De Robertis and Ormseth 2018). Briefly, the frequency response ($\Delta S_{v_{120kHz - 38\,kHz}}$) in each 5 ping by 5 m acoustic sample was computed. Samples in the range of -16 to 8 dB were classified as fish, and samples in the range of 8 to 30 were classified as macrozooplankton (De Robertis et al. 2010). For this analysis we used a minimum threshold of -60 dB for fish, in order to exclude jellyfish that form weak-scattering bands in the upper water column and overlap in acoustic frequency response with fish at lower thresholds, and -80 dB for macrozooplankton. For each 5 m deep by 0.5 km horizontal increment along transects (150 km total) in each region and year, we computed the log-transformed mean NASC (Nautical area scattering coefficient) value to graphically represent differences in acoustic scattering characteristics in each region and year (Figs. 6-7). For comparison, we also included data from 2014, a pilot year when fixed transects had not been established but survey areas overlapped in Bainbridge and Montague Strait.

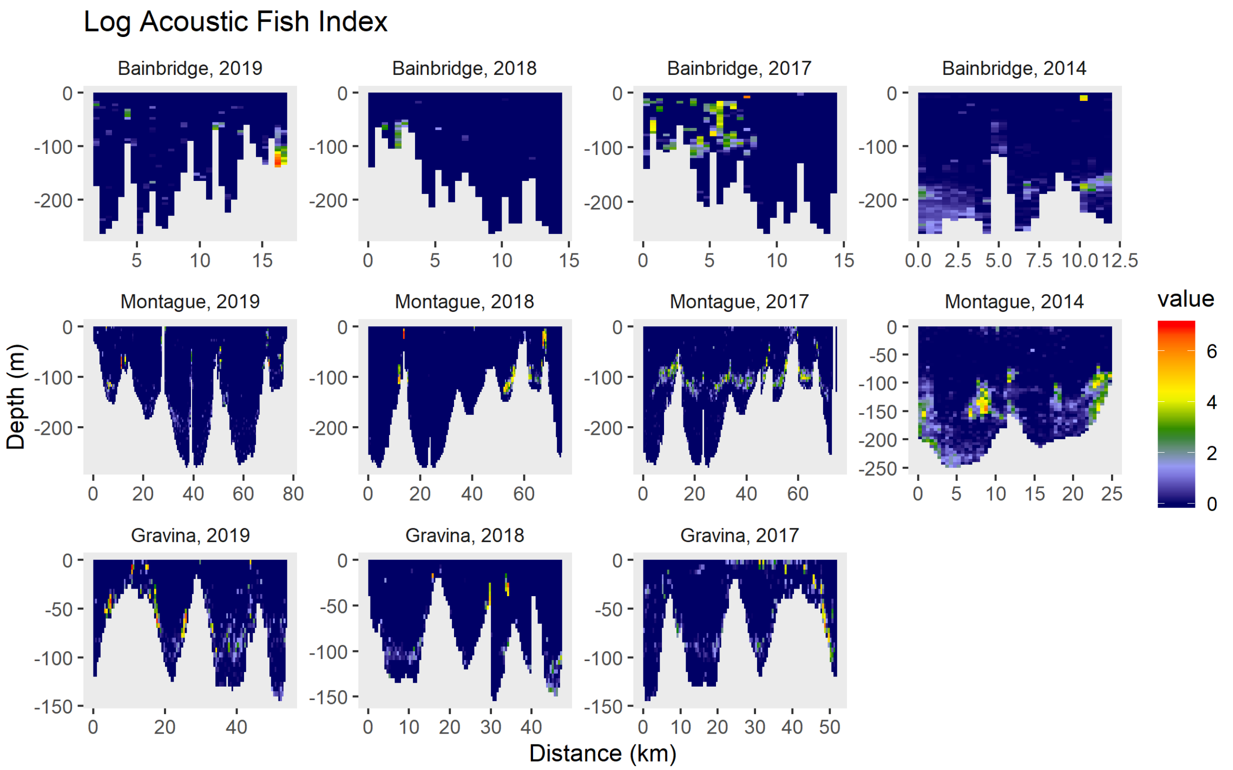


Figure 6. Echograms of log acoustic fish backscatter (color) by depth (y-axis) and transect distance (x-axis) for each subregion (vertical panels) and year (horizontal panels) during the Integrated Predator Prey surveys.

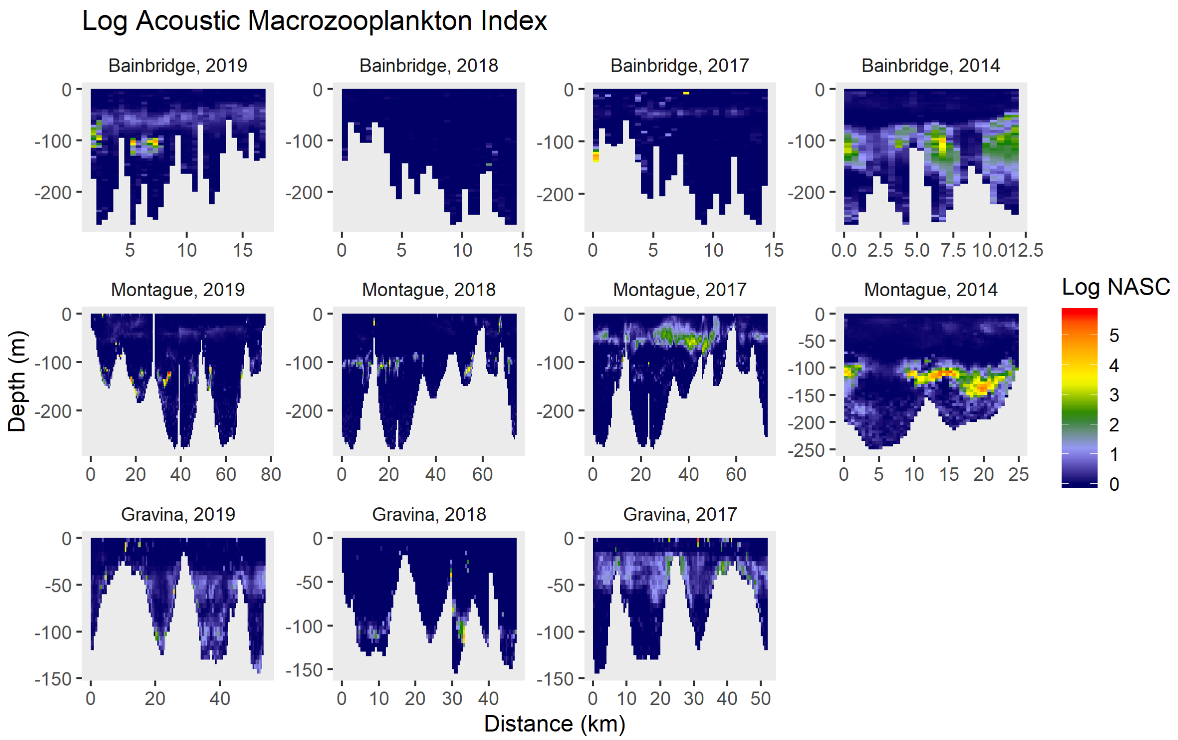


Figure 7. Echograms of log acoustic macrozooplankton backscatter (color) by depth (y-axis) and transect distance (x-axis) for each subregion (vertical panels) and year (horizontal panels) during the Integrated Predator Prey Surveys.

A key finding from this work is that the acoustic macrozooplankton biomass index, which trawl sampling confirmed was primarily composed of euphausiids, was greater during peak humpback whale abundance in 2014 than in any survey year since (Fig. 8).

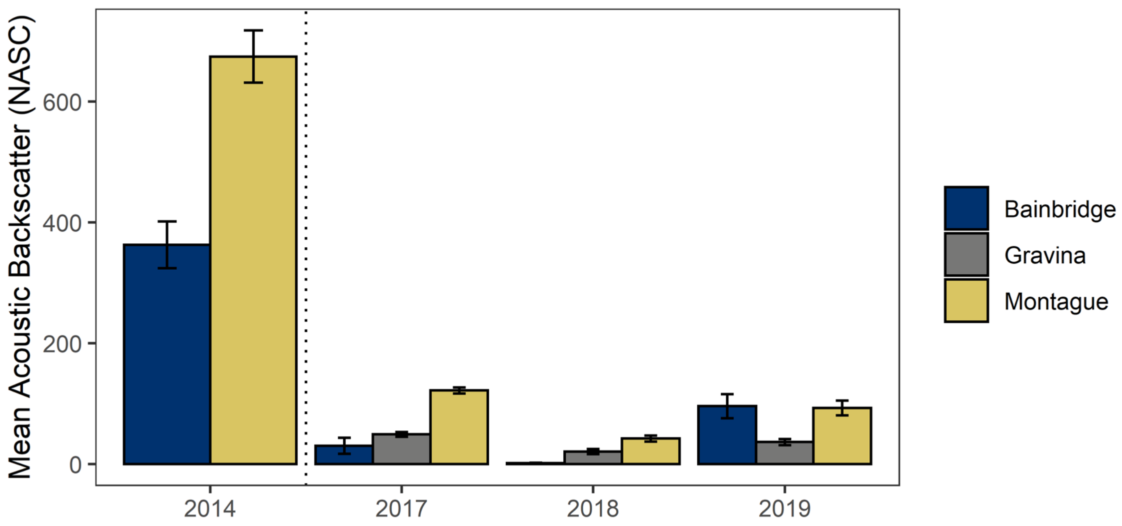


Figure 8. Interannual variability in the macrozooplankton acoustic biomass index in Prince William Sound humpback whale foraging aggregation areas. Data were collected during the September Integrated Predator Prey surveys in 2017-2019 and compared to a pre-heatwave pilot study in 2014 (see text).

C. Summer Aerial Survey Validation and Acoustic-Trawl Survey in PWS

The June aerial surveys for herring and other forage fish occurred in PWS from June 3-28, 2019, and validation efforts occurred from June 4-July 6, 2019. From a 16' inflatable skiff we used jigs (n = 6), video (n = 10), cast nets (n = 1), purse seines (n = 2), gill nets (n = 2) and visual identification (n = 2) to identify 20 schools observed by the pilot. Some schools were validated with more than one method (e.g., video and purse seine). Using multiple validation methods is necessary due to the different species and size classes encountered.

Aerial observers correctly identified 19 schools, including herring age-1 (n = 3), herring age-2+ (n = 4), herring age-0 (n = 1), and sand lance (n = 11). One herring age-0 school was mistaken for a sand lance school by aerial observers. Aerial observers use school characteristics such as distribution, shape and color to identify schools to species, and for herring the size of the fish is determined from bright silver lateral views of individuals.

Similar to previous findings (Norcross et al. 1999, Arimitsu et al. 2018), validation efforts in 2019 indicated that herring and sand lance classification rates during aerial surveys are high. Misclassification of schools is most problematic when age-0 herring recruit to the observable population, which is why surveys for age-1 herring are most effective in June. In June age-0 fish can be too small to observe from the plan if they haven't transformed from their larval state into juvenile fish with scales. In July 2019 herring were still in their larval state, and mean length of age-0 herring during summer surveys was 35 mm (SD: 9 mm), so misclassification rates during June surveys should have been minimized.

An index of aerial forage school density was computed as the sum of school counts standardized by the length (km) of shoreline covered in each year. The data from 2010-2019 show there were peaks in forage density during June 2013 and 2017, mainly attributed to schools identified as age-1 herring (Fig. 9). These peaks correspond with unusually high proportion (>3-4 times the average over the same time period) of age-1+ herring in seabird diets (Fig. 5).

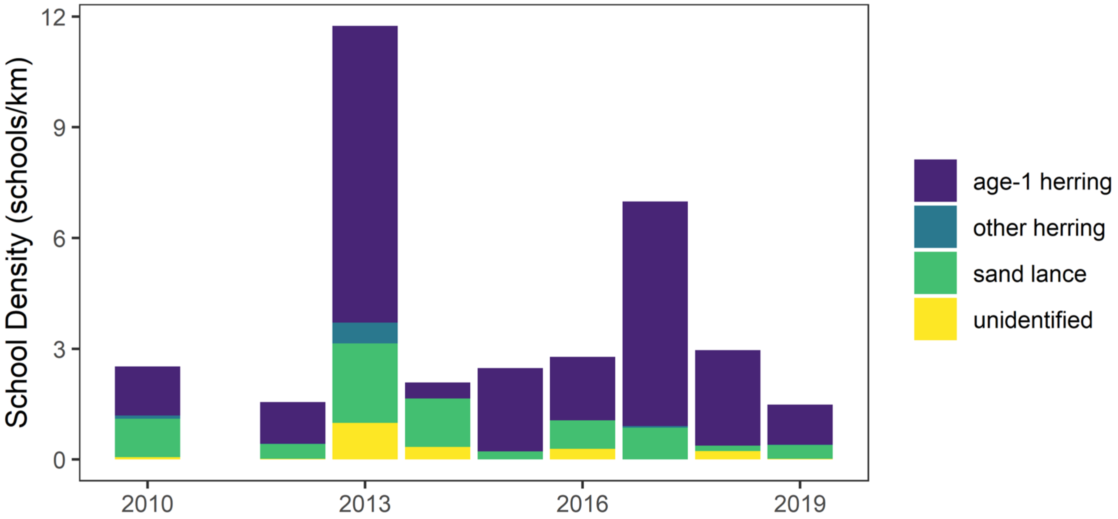


Figure 9. Forage fish school density index from June shoreline aerial surveys in Prince William Sound, Alaska. Aerial Survey data were collected by Scott Pegau, Herring Research and Monitoring Program.

We conducted summer PWS acoustic-trawl surveys aboard the USGS R/V *Alaskan Gyre* from June 23 - July 8, 2019 (see Arimitsu et al. 2018 for details). At the time of this report, data from this aspect of the work were being processed and undergoing QAQC. Highlights from this work are outlined below.

Despite a return of marine heatwave conditions during our 2019 summer survey, we encountered adult capelin in trawls for the first time in several years (Fig. 10). Spawning capelin were collected at Port Etches on July 5, 2019 and Zaikof Bay on July 6, 2019. Although surface waters were unusually high, below 10 m depth our CTD measurements indicated that water temperatures were within the range considered suitable for capelin spawning (8-10 ºC).

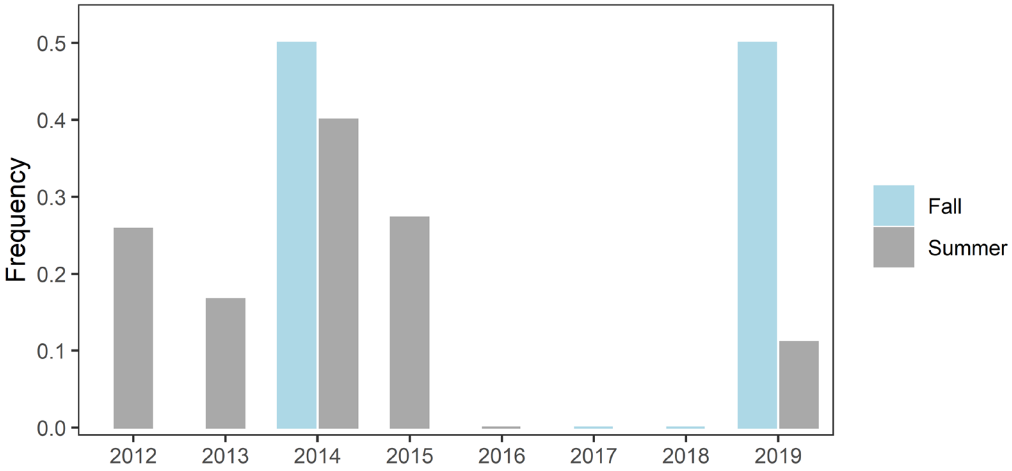


Figure 10. Frequency of age-1+ capelin in trawls during summer and fall surveys in Prince William Sound, Alaska.

In summer 2019 we collected Pacific sand lance samples in order to continue the age-1 sand lance whole fish energy time series. In 2016 we identified an 89% reduction in age-1 Pacific sand lance whole body energy compared to 2012-2014 (von Biela et al. 2019). This change in nutritional value was attributed to poor growth during the marine heatwave, especially in 2016 when age-1 fish were indistinguishable from age-0 fish. By 2018 whole fish energy was normal (Fig. 11). We are still processing data from 2019, but length frequencies of fish collected in that year indicate that larger individuals were present in the population.

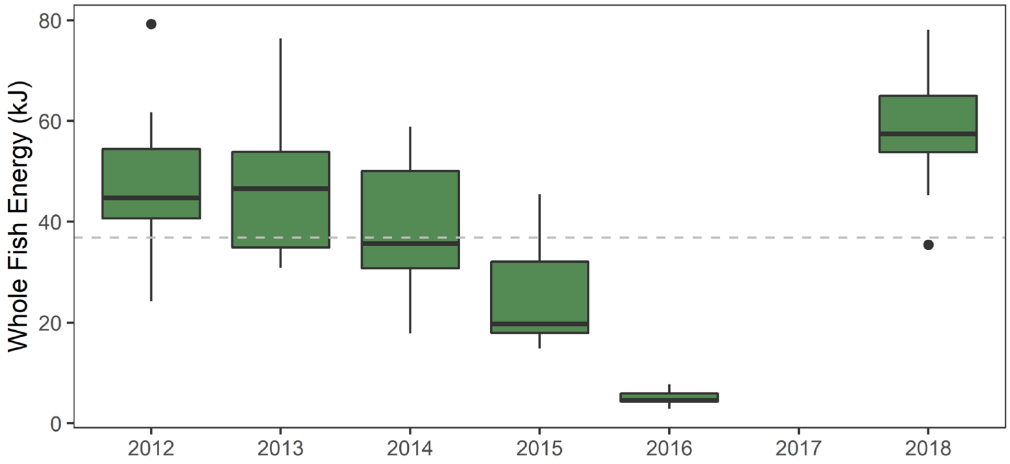


Figure 11. Interannual variability in whole fish energy of Prince William Sound age-1 Pacific sand lance in July. No sampling occurred in 2017.

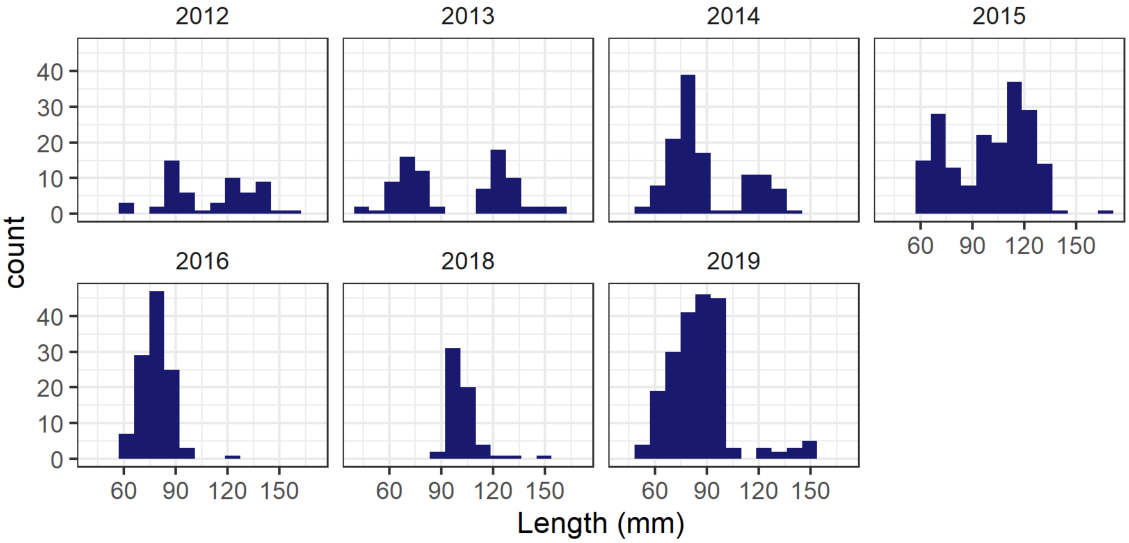


Figure 12. Summer (July) Pacific sand lance length frequency distributions by year for Prince William Sound.

Data collected on forage fish will provide important context for understanding the response of marine ecosystems to current and future warming events. For example, when 0.5 – 1.2 million common murres died during the North Pacific marine heatwave (Piatt et al. 2020), monitoring by this project provided data to conclude that widespread malnutrition, reproductive failures, and mortality of predators was due to lower availability and lower quality of prey resources in the Gulf of Alaska (Arimitsu et al. 2019). Continued monitoring of forage fish as part of the GWA program is essential for understanding trends in both prey and predators and mechanisms by which the marine ecosystem responds to perturbations.

8. Coordination/Collaboration:

A. Long-term Monitoring and Research Program Projects

1. Within the Program

This project is a component of the integrated GWA long-term monitoring program. This project shares research platform and common goals of the humpback whale (Moran and Straley, project 19120114-O) and fall/winter marine bird (Bishop, project 19120114-E) projects also associated with the IPP surveys. Summer forage fish surveys and information regarding Middleton Seabird diets and PWS acoustic-trawl surveys also provide a means to understand trends in piscivorous marine birds (Kaler and Kuletz, project 19120114-M).

2. Across Programs

a. Herring Research and Monitoring

We continue collaborative work with Scott Pegau and the Herring Research and Monitoring program's aerial surveys for juvenile herring and other forage fish (project 19160111-F). In July 2019 we also coordinated closely with Kristin Gorman (PWSSC) to aid in collection of adult herring for a maturation study (project 19170111-D).

b. Data Management

This project coordinates with the data management program by submitting data and preparing metadata for publication on the Gulf of Alaska Data Portal and DataONE within the timeframes required.

B. Individual Projects

We provided forage fish and macrozooplankton samples for studies regarding algal toxins in food webs (North Pacific Research Board (NPRB) study PIs: Xiuning Du, Oregon State University, and Rob Campbell, PWSSC; USGS study PIs: Sarah Schoen, Matt Smith, Caroline van Hemert).

We are working with the Northern Gulf of Alaska Long Term Ecological Research (National Science Foundation funded) team to assess connectivity between our collective forage fish monitoring efforts. For example, we are taking a lead role in processing fish catches (bycatch) from Methot trawls intended to sample jellyfish. This work will facilitate a better understanding of the relationship between seabird diets at Middleton and the distribution of forage fish from trawls.

C. With Trustee or Management Agencies

We contributed indicators to NOAA's Gulf of Alaska Ecosystem Status Report to the North Pacific Fisheries Management Council for 2019 (Zador et al. 2019, https://access.afsc.noaa.gov/REFM/REEM/ecoweb/index.php): Seabird-Derived Forage Fish Indicators from Middleton Island. We also calculate an annual juvenile sablefish growth index that is used in the ecosystem and socioeconomic profile of the sablefish stock assessment for Alaska (Shotwell et al. 2019)

We are also collaborating with Gulf of Alaska Integrated Ecosystem Program PIs on a synthesis of capelin in the Gulf of Alaska (Olav Ormseth, David McGowan, NOAA Alaska Fisheries Science Center). This collaboration has led to an increased focus on capelin dynamics in the Kodiak area using NOAA survey data, with the updated time series (2000-2019) reported in the GWA forage fish synthesis chapter.

The GWA forage fish work is also complimentary to a related USGS-Outer Continental Shelf and Bureau of Ocean Energy Management study of forage fish and seabird trends in areas of oil and gas development within Cook Inlet. Additionally, our continued coordination and collaboration with GWA PIs (Kris Holderied, NOAA, project 19120114-J, and Kathy Kuletz, U.S. Fish and Wildlife Service, project 19120114-N) in Cook Inlet and Kachemak Bay increases the scope of marine ecosystem monitoring in the Northern Gulf of Alaska.

We are collaborating with researchers at NOAA Auke Bay Labs to provide time-series data on forage fish diet, isotope, and proximate composition using samples collected by seabirds at Middleton Island since the late 1990s. These data will provide information on trophic changes relevant to marine predators of commercial value and in the northern Gulf of Alaska.

9. Information and Data Transfer:

A. Publications Produced During the Reporting Period

1. Peer-reviewed Publications

McGowan, D.W., E.D. Goldstein, M.L. Arimitsu, A.L. Deary, O. Ormseth, A. De Robertis, J.K. Horne, L.A. Rogers, M.T. Wilson, K.O. Coyle, K. Holderied, J.F. Piatt, W.T. Stockhausen, and S.G. Zador. *In Press*. Spatial and temporal dynamics of Pacific capelin (*Mallotus catervarius*) in the Gulf of Alaska: implications for ecosystem-based fishery management. Marine Ecology Progress Series.

Piatt, J.F., J.K. Parrish, H.M. Renner, S.K. Schoen, T.T. Jones, M.L. Arimitsu, K.J. Kuletz, B. Bodenstein, M. García-Reyes, R.S. Duerr, R.M. Corcoran, R.S.A. Kaler, G J. McChesney, R.T. Golightly, H.A. Coletti, R.M. Suryan, H.K. Burgess, J. Lindsey, K.Lindquist, P.M. Warzybok, J. Jahncke, J. Roletto, and W.J. Sydeman. 2020. Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. PloS ONE 15:e0226087.

Thompson, S.A., M. García-Reyes, W.J. Sydeman, M L. Arimitsu, S.A. Hatch, and J.F. Piatt. 2019. Effects of ocean climate on the length and condition of forage fish in the Gulf of Alaska. Fisheries Oceanography 28:658–671.

Van Hemert, C., S.K. Schoen, R.W. Litaker, M.M. Smith, M.L. Arimitsu, J.F. Piatt, W.C. Holland, D.R. Hardison, and J.M. Pearce. 2020. Algal toxins in Alaskan seabirds: Evaluating the role of saxitoxin and domoic acid in a large-scale die-o ff of Common Murres. Harmful Algae 92:101730.

von Biela, V.R., M.L. Arimitsu, J.F. Piatt, B.M. Heflin, and S.K. Schoen. 2019. Extreme reduction in nutritional value of a key forage fish during the Pacific marine heatwave of 2014–2016. Marine Ecology Progress Series 613:171–182.

2. Reports

Arimitsu, M.L., J.F. Piatt, and S. Hatch. 2019. LTM Program – Monitoring long-term changes in forage fish distribution, abundance, and body condition in PWS. *Exxon Valdez* Oil Spill Restoration Project Annual Report (Project 18120114-C), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, AK.

Arimitsu, M., J. Piatt, R. Suryan, S. Batten, M.A. Bishop, R. Campbell, H. Coletti, D. Cushing, K. Gorman, S. Hatch, S. Haught, R. Hopcroft, K. Kuletz, C. Marsteller, C. McKinstry, D. McGowan, J. Moran, W.S. Pegau, A. Schaeffer, S. Schoen, J. Straley, and V. von Biela. 2019. Synchronous collapse of forage species disrupts trophic transfer during a prolonged marine heatwave. *In*: The Pacific Marine Heatwave: Monitoring During a Major Perturbation in the Gulf of Alaska. Long-Term Monitoring Program (Gulf Watch Alaska) Synthesis Report *Exxon Valdez* Oil Spill Trustee Council Program 19120114 (Eds: Suryan, R.M., M.R. Lindeberg, and D.R. Aderhold). *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

Suryan, R., M. Arimitsu, H. Coletti, R. Hopcroft, M. Lindeberg, S. Batten, M.A. Bishop, R. Brenner, R. Campbell, D. Cushing, S. Danielson, D. Esler, T. Gelatt, S. Hatch, S. Haught, K. Holderied, K. Iken, D. Irons, D. Kimmel, B. Konar, B. Laurel, J. Maniscalco, C. Matkin, C. McKinstry, D. Monson, J. Moran, D. Olsen, S. Pegau, J. Piatt, L. Rogers, A. Schaeffer, S. Straley, K. Sweeney, M. Szymkowiak, B. Weitzman, J. Bodkin, S. Zador. 2019. Ecosystem response to a prolonged marine heatwave in the Gulf of Alaska. *In*: The Pacific Marine Heatwave: Monitoring During a Major Perturbation in the Gulf of Alaska. Long-Term Monitoring Program (Gulf Watch Alaska) Synthesis Report *Exxon Valdez* Oil Spill Trustee Council Program 19120114 (Eds: Suryan, R.M., M.R. Lindeberg, and D.R. Aderhold). *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

3. Popular articles

John Piatt and Mayumi Arimitsu provided interviews for a Science Magazine article on the effects of the ‘Blob’ on marine ecosystems:

W. Cornwall. 2019. Ocean heatwaves like the Pacific’s deadly ‘Blob’ could become the new normal. Science Magazine. doi:10.1126/science.aaw8401. https://www.sciencemag.org/news/2019/01/ocean-heat-waves-pacific-s-deadly-blob-could-become-new-normal?utm_campaign=NewsfromScience&utm_source=JHubbard&utm_medium=Twitter&fbclid=IwAR3QxH9cP6IWoqpwQp-HJ3BulkcFEaxvVntNM2zxlJNKRqkLtevn5kRnTjE .

Mayumi Arimitsu provided *Last Chance Endeavors, Inc*. with an interview for a podcast about whale prey, forage fish, and seabird die offs. Arimitsu talked about research on changes in forage fish populations that were first signaled by large die-offs of seabirds during the 2014-2016 North Pacific marine heatwave – aka "The Blob." Last Chance Endeavors mission is to connect students to the environment. Listen to the podcast at: https://www.lastchanceendeavors.com/podcast/episode/2507d869/mayumi-arimitsu-research-ecologist-at-whalefest-2019-or-why-are-the-birds-dead-or-episode-028 .

John Piatt responded to 22 media requests in response to the January 15, 2020, journal press release and publication in PLoS ONE "Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016." Outlets include Science News, InsideClimate News, Associated Press, New Scientist, Los Angeles Times, Mother Jones, Anchorage Daily News, Alaska Public Media, OPB Oregon Public Broadcasting, The Oregonian (OregonLive), ABC Australia, Austria 1 Radio, Agence France-Presse, KQED San Francisco Public TV and Radio, G1 News Brazil and more.

- Link to Journal News Release - https://www.eurekalert.org/pub_releases/2020-01/p-mhl010820.php
- University of Washington News Release - https://www.washington.edu/news/2020/01/15/the-blob-food-supply-squeeze-to-blame-for-largest-seabird-die-off/
- Science News by Jonathan Lambert - https://www.sciencenews.org/article/massive-marine-heat-wave-blob-unprecedented-seabird-die-off
- InsideClimate News by Sabrina Shankman - https://insideclimatenews.org/news/15012020/seabird-death-ocean-heat-wave-blob-pacific-alaska-common-murre
- Associated Press Don Joling - https://www.usnews.com/news/news/articles/2020-01-15/researchers-tie-massive-pacific-seabird-die-off-to-heat-wave
- New Scientist by Adam Vaughn https://www.newscientist.com/article/2229980-marine-heatwave-known-as-the-blob-killed-a-million-us-seabirds/
- Los Angeles Times by Jennifer Lu - https://www.latimes.com/environment/story/2020-01-15/seabird-deaths-2015-pacific-ocean-blob-warm-water-murres-study
- Mother Jones by Jackie Mogensen - https://www.motherjones.com/environment/2020/01/a-new-study-death-of-1-million-common-murres/
- Anchorage Daily News by Morgan Krakow - https://www.adn.com/alaska-news/science/2020/01/15/pacific-seabird-die-off-linked-to-a-warm-water-blob-study-says/

- Alaska Public Media by Kavitha George - https://www.alaskapublic.org/2020/01/15/massive-sea-bird-die-off-linked-to-food-scarcity-during-the-blob-new-study-says/
- ABC Australia by Nick Kilvert - https://www.abc.net.au/news/science/2020-01-16/blob-seabird-murre-die-off-climate-change-marine-heatwave/11867264
- OPB Oregon Public Broadcasting – https://www.opb.org/news/article/pacific-ocean-marine-heatwave-north-coast-seabirds-blob/?t=578295
- The Oregonian - https://www.oregonlive.com/environment/2020/01/unprecedented-marine-heatwave-likely-killed-1-million-west-coast-seabirds.html
- The Conversation - https://theconversation.com/worst-marine-heatwave-on-record-killed-one-million-seabirds-in-north-pacific-ocean-129842
- Austria 1 Radio - https://www.radio.net/p/oe1wissenaktuell
- Agence France-Presse - https://news.mb.com.ph/2020/01/16/climate-change-linked-heatwave-caused-mass-starvation-of-seabirds/
- KQED Public TV and Radio - https://www.kqed.org/science/1955893/thousands-of-dead-birds-washed-up-on-pacific-coast-linked-to-ocean-heat-wave
- G1 News Brazil - https://g1.globo.com/natureza/noticia/2020/01/15/massa-de-agua-quente-do-pacifico-afetou-ecossistema-e-matou-de-fome-62-mil-aves-marinhas-diz-pesquisa.ghtml
- German Public Radio (Deutschlandfunk) - https://www.deutschlandfunk.de/marine-hitzewelle-blob-verursacht-massensterben-von.676.de.html?dram:article_id=468065
- https://www.businessinsider.com/ap-starvation-suspected-in-massive-die-off-of-alaska-seabirds-2016-1
- Courthouse News Service - https://www.courthousenews.com/persistent-pacific-marine-heatwave-killed-1-million-seabirds/

90 other outlets picked up the story via news releases: some of them are listed below:

- New York Times: https://www.nytimes.com/aponline/2020/01/15/us/ap-us-pacific-seabird-mass-die-off.html
- Washington Post: https://www.washingtonpost.com/national/health-science/researchers-tie-massive-pacific-seabird-die-off-to-heat-wave/2020/01/15/8f4f3c6a-37ca-11ea-a1ff-c48c1d59a4a1_story.html
- Newsweek: https://www.newsweek.com/blob-us-west-coast-million-seabirds-study-1482358
- The HILL - https://thehill.com/changing-america/sustainability/climate-change/478576-a-million-seabirds-died-over-the-pacific
- U.S. News and World Report -https://www.usnews.com/news/news/articles/2020-01-15/researchers-tie-massive-pacific-seabird-die-off-to-heat-wave
- USA Today - https://www.usatoday.com/story/news/nation/2020/01/16/blob-hot-water-killed-million-seabirds-pacific-2015-and-2016/4491618002/

- The Guardian: https://www.theguardian.com/environment/2020/jan/16/hot-blob-ocean-seabirds-killed-new-zealand-north-america
- BBC News: https://www.bbc.com/news/science-environment-51140869
- CNN: https://www.cnn.com/2020/01/16/world/blob-seabird-study-intl-hnk-scli-scn/index.html
- Newsweek - https://www.newsweek.com/blob-us-west-coast-million-seabirds-study-1482358
- USA Today: https://www.usatoday.com/story/news/nation/2020/01/16/blob-hot-water-killed-million-seabirds-pacific-2015-and-2016/4491618002/
- Science Alert - https://www.sciencealert.com/the-blob-has-been-implicated-in-an-unprecedented-mass-seabird-death?perpetual=yes&limitstart=1
- Science Blog- https://scienceblog.com/513519/the-blob-food-supply-squeeze-to-blame-for-largest-seabird-die-off/
- Science Daily - https://www.sciencedaily.com/releases/2020/01/200115140502.htm
- Seattle Times- https://www.seattletimes.com/nation-world/nation/researchers-tie-massive-pacific-seabird-die-off-to-heat-wave/
- KTUU: https://www.ktuu.com/content/news/Researchers-tie-massive-Pacific-seabird-die-off-to-heat-wave-567012951.html
- ABC13 (Houston, Texas): https://abc13.com/weather/researchers-tie-massive-pacific-seabird-die-off-to-heat-wave/5855848/

B. Dates and Locations of any Conference or Workshop Presentations where EVOSTC-funded Work was Presented

1. Conferences and Workshops

Arimitsu, M. 2020. Northern Gulf of Alaska forage fish sampling in 2018, connectivity between LTER and GWA Ecosystem Monitoring Programs. Oral Presentation. NGOA LTER PI meeting. Fairbanks, AK. 21 January.

Arimitsu, M., M.A. Bishop, D. Cushing, S. Hatch, R. Kaler, K. Kuletz, C. Matkin, J. Moran, D. Olsen, J. Piatt, A. Schaefer, and J. Straley. 2020. Changes in marine predator and prey populations in the Northern Gulf of Alaska: Gulf Watch Alaska Pelagic update 2019. Poster Presentation. Alaska Marine Science Symposium. Anchorage, AK. 27-31 January.

Arimitsu, M., J. Piatt, R. Suryan, D. Cushing, S. Hatch, K. Kuletz, C. Marsteller, J. Moran, S. Pegau, M. Rogers, S. Schoen, J. Straley, V. von Biela. 2019. Reduced energy transfer through forage fish disrupted marine food webs during the North Pacific marine heatwave. Oral Presentation. PICES annual meeting. Victoria, BC, Canada. 16-27 October.

Du, X., R. Campbell, S. Kibler, K. Holderied, D. Hondolero, R. Robinson, C. Guo, C. Walker, M. Arimitsu, and J. Piatt. 2020. Prevalence of paralytic shellfish toxins in

the marine food web of southcentral and southwest Alaska NPRB #1801: project update. Poster Presentation. Alaska Marine Science Symposium. Anchorage, AK. 27-31 January.

Piatt, J., and M. Arimitsu. 2019. The ectothermic vise: regulation of seabirds by forage fish in hot water. Oral Presentation. Pacific Seabird Group meeting, Kauai, HI. 28 February – 2 March.

Piatt, J., M. Arimitsu, S. Schoen, V. von Biela, J. Parrish, H. Renner. 2019. Mass mortality and breeding failure of seabirds during and after the 2014-2016 marine heatwave. Oral Presentation. Joint American Fisheries Society-The Wildlife Society Meeting. Reno, NV. 1-4 October.

Piatt, J., J.K. Parrish, H.M. Renner, S.K. Schoen, T.T. Jones, M.L. Arimitsu, K.J. Kuletz, B. Bodenstein, M. García-Reyes, R.S. Duerr, R.M. Corcoran, R.S.A. Kaler, G.J. McChesney, R.T. Golightly, H.A. Coletti, R.M. Suryan, H K. Burgess, J. Lindsey, K. Lindquist, P.M. Warzybok, J. Jahncke, J. Roletto, and W.J. Sydeman. 2019. Was an "ectothermic vise" responsible for the mass mortality and breeding failure of seabirds in Alaska following the NE Pacific marine heat wave of 2014-2016? Oral Presentation. PICES annual meeting. Victoria, BC, Canada. 16-27 October.

Straley, J., J. Moran, R. Suryan, M. Arimitsu, C. Gabriele, J. Neilson, R. Cartwright. 2019. Understanding population-level changes in response to ecosystem perturbations: Humpback whale monitoring during the North Pacific Marine Heatwave. Oral Presentation. Joint American Fisheries Society-The Wildlife Society Meeting. Reno, NV. 1-4 October.

Suryan, R., M. Lindeberg, M. Arimitsu, H. Coletti, R. Hopcroft, D. Aderhold, K. Hoffman. 2020. Ecosystem Response to a Prolonged Marine Heatwave in the Gulf of Alaska: Perspectives from Gulf Watch Alaska. Oral Presentation. Alaska Marine Science Symposium. Anchorage, AK. 27-31 January.

Sydeman, W., S.A. Thompson, S. Zador, K. Shotwell, M. Arimitsu, H. Renner, J. Piatt, S. Hatch, and Y. Watanuki. 2019. Oral Presentation. Potential application of seabird data on groundfish stock assessments. PICES annual meeting. Victoria, BC, Canada. 16-27 October.

Thompson, S.A., M. García-Reyes, W.J. Sydeman, M.L. Arimitsu, S.A. Hatch, and J.F. Piatt. 2019. Effects of ocean climate on the length and condition of forage fish in the Gulf of Alaska. Poster Presentation. PICES annual meeting. Victoria, BC, Canada. 16-27 October.

Van Hemert, C., M. Smith, R. Dusek, S. Schoen, M. Arimitsu, R. Kaler, J Piatt, K. Kuletz, J. Pearce, G. Sheffield, G. Baluss, L. Divine, D. Hardison, R.W. Litaker. 2020. Harmful algal blooms and Alaskan seabirds: An emerging issue in northern waters? Harmful algal blooms and Alaskan seabirds: An emerging issue in northern waters? Oral Presentation. Alaska Marine Science Symposium. Anchorage, AK. 27-31 January.

Van Hemert, C., M. Smith, S. Schoen, R. Dusek, J. Piatt, M. Arimitsu, W. Litaker, J. Pearce. 2019. Harmful algal blooms in northern waters: an emerging issue for Alaskan seabirds? Oral Presentation. International Conference of the Wildlife Disease Association, Tahoe City, CA. 4-9 August.

von Biela, V., M. Arimitsu, J. Piatt, B. Heflin, S. Schoen, J. Trowbridge, and C. Clawson. 2019. Extreme reduction in nutritional value of a key forage fish during the Pacific Marine Heatwave of 2014-2016. Oral Presentation. Joint American Fisheries Society-The Wildlife Society Meeting. Reno, NV. 1-4 October.

von Biela, V., J. Piatt, M. Arimitsu, and L. Ball. 2019. Fish and wildlife responses to prolonged heatwaves: A window to the future? Symposium Organizers. Joint American Fisheries Society-The Wildlife Society Meeting. Reno, NV. 1-4 October.

2. Public presentations

Arimitsu, M., 2019. Forage fish in changing seas. Invited Speaker. Sitka Whalefest, Sitka, AK. 31 October – 2 November.

C. Data and/or Information Products Developed During the Reporting Period, if Applicable

No new contributions for this reporting period. We continue to update annual ecosystem indicators for the NOAA Ecosystem Status Report (Zador et al. 2019) as stated in section 8.C.

D. Data Sets and Associated Metadata that have been Uploaded to the Program's Data Portal

Final datasets and metadata for GWA 2018 were uploaded to the data portal by November 2019 (https://portal.aoos.org/gulf-of-alaska#metadata/3ca497e2-3421-4fa4-a550-f4d397a73c07/project/folder_metadata/2638365). These include:

- Echointegration data from predator-prey acoustic transects. Acoustic data were obtained from a split beam dual frequency hydroacoustic system (Simrad® EK60) operating at 38 (12° beam width) and 120 (7° beam width) kHz frequencies. Tranducers were calibrated at the start of each survey.

- Fish catch and morphological data from various net sampling methods including aluette trawl, cast net, dip net, jig, and gill net.
- Zooplankton biomass. Samples were collected with a 150 micron mesh 0.25 m diameter paired ring net on a 50 m. vertical haul during daylight hours.
- CTD profiles. Oceanographic conditions were sampled with a Seabird Electronics SBE19Plus v2 (2017-2018) CTD equipped with various sensors (e.g., oxygen, pH, fluorescence, turbidity, beam transmission and photosynthetically active irradiance).
- Inorganic nutrient concentration, including phosphate, nitrate, nitrite and silicic acid.

During this reporting period we also made substantial progress on the Middleton Island seabird diet data and associated metadata, which were both uploaded to the workspace by February 2019 (https://workspace.aoos.org/project/4688/folder/2816515/seabirddietdata_middletonisland_2017-2021). These data include diet samples from black-legged kittiwakes, rhinoceros auklets, and tufted puffins on Middleton Island, and they consist of the following: collection date, bird species, bird age, prey item taxa, prey age class, prey sex, prey length (mm), and prey mass (g). The time interval includes samples collected during the spring and summer months from 1978-2018.

10. Response to EVOSTC Review, Recommendations and Comments:

Science Panel Comment (FY20): *The Science Panel appreciates the PIs response to last year's comments. The panel noted that seabird diets show an increase in the relative abundance of herring in seabird diets, whereas HRM projects are not seeing an increase in herring. This is something that is worth investigating together with the HRM projects. Please include this comparison and potential interpretations of its causes in your FY19 annual report. This sort of comparison should also be included in the science synthesis paper. There are many possible explanations, but they point to the likelihood that bird diets may not provide useful proxies for fish abundance.*

PI Response (FY20: We have addressed this issue in the text of the report (see p. 4-6).

Science Panel Comment (FY19): *The Science Panel recognizes the importance of annual ground-truthing of aerial surveys, and supports reinstating aerial surveys especially given that HRM has secured funding from RCAC for aerial surveys. The Science Panel wondered about the interannual spatial and temporal consistency of acoustic surveys. Shouldn't they be conducted over as broad an area as possible? It was noted that a lot of PWS has not been surveyed. Specifically how much of PWS is surveyed, including the deeper areas? Can the PIs advise whether this is important?*

PI Response (FY19: From our original 2012-2016 research program we concluded that a reduced and targeted set of summer acoustic transects would be an efficient way to conduct forage fish surveys over a broader area within PWS. These acoustic transects were designed with prior information on the distribution of forage fish in PWS, and were meant to sample high density forage fish areas important to breeding marine birds during summer in PWS (Fig. 1, Summer).

The summer surveys (conducted in 2014-2016) include 463 km of transects at 16 locations throughout the Sound. They target nearshore and relatively shallow areas because that's where the majority of forage fish biomass is concentrated in the Sound during summer. Accordingly, the shallow nearshore areas contain greater densities of marine birds than deeper offshore areas during summer as these are predators of sand lance, capelin, and juvenile herring.

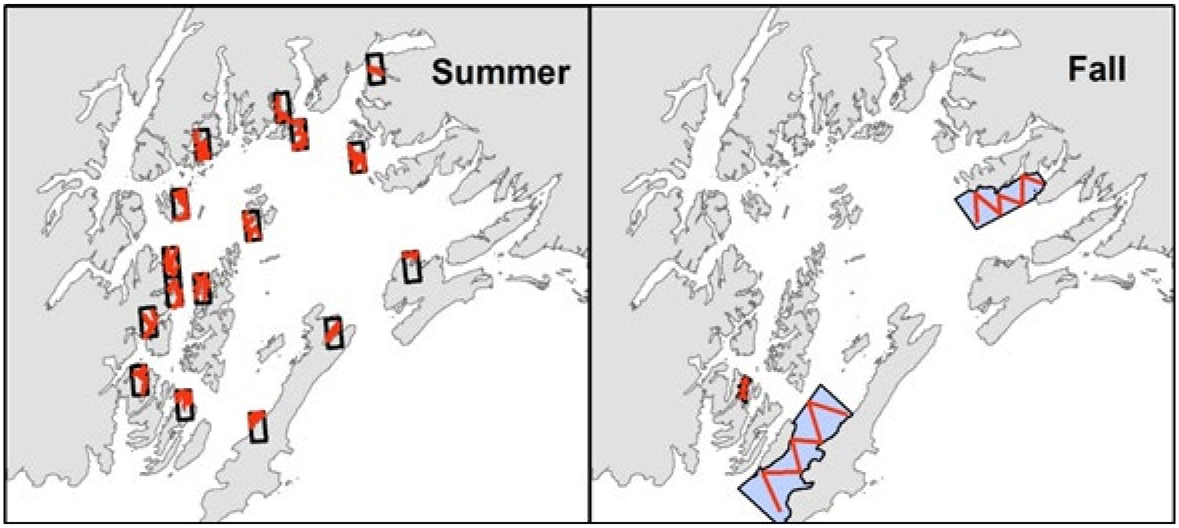


Figure 1. Summer (left) and fall (right) acoustic transects (red lines). In addition to planned fall surveys in humpback whale hotspots, the proposed work would add data collection efforts to conduct summer acoustic transects, which were discontinued in 2017 but reinstated in 2019.

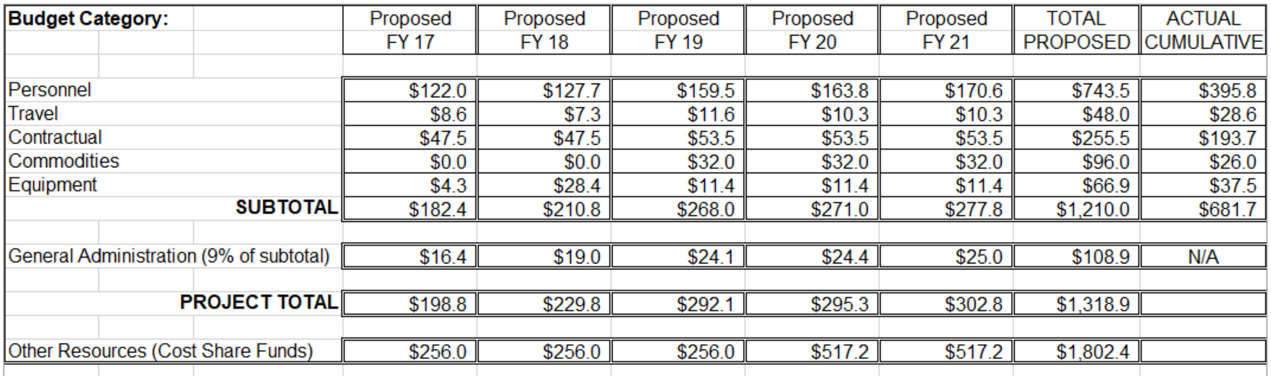
The Integrated Predator Prey surveys (Fig.1, Fall) began in the second funding cycle (FY17-21) with the purpose of better integrating the humpback whale, forage fish, and fall marine bird surveys. They were designed around three historically important humpback whale feeding areas where krill and juvenile and adult herring occur in coastal (<50m) and deeper waters (<300m) of PWS. The fall surveys include 139 km of transects in Montague Strait, Bainbridge Passage, and Port Gravina.

Science Panel Comment (FY19): *The Science Panel is also curious to know what is the value added of this project over data already captured by herring surveys as most of the forage fish found in this project appear to be herring. Can the herring data be used to help assess forage fish abundance? The Science Panel realizes that the goals of these two projects are different, but could data and perhaps vessels be shared between this project and the HRM herring surveys?*

PI Response (FY19): Herring are very important prey in many areas of PWS and when populations are at high levels, they are the dominant prey item. However, herring alone does not support predator populations in PWS, as capelin, krill, and sand lance, are also important prey species. Our proposed survey work does not duplicate herring research. The HRM program's aerial and GWA acoustic surveys of herring and forage fish are complementary as they sample different scale, habitats, and target species/size classes during the same time period. Broad-scale aerial surveys are useful for counting schools of juvenile herring and Pacific sand lance along shorelines. Finer-scale acoustic trawl surveys are better suited for capelin, juvenile walleye pollock, juvenile and adult herring, and krill. HRM acoustic surveys occur during spring and focus on herring spawning; the other important prey for predators in PWS that are noted above are not quantified by these herring-specific acoustic surveys. It would not be possible for GWA and HRM to share vessels for acoustic surveys because of differences in timing of surveys and survey objectives involving multi- vs. single-species surveys.

11. Budget:

Please see provided program workbook. Current expenditures of some line items exceed ± 10% deviation from the originally proposed amount in cases where reporting accounts lagged behind actual expenses, inconsistencies between federal and *Exxon Valdez* Oil Spill Trustee Council fiscal year start dates, and because USGS budget system categories differ from those shown on the *Exxon Valdez* Oil Spill Trustee Council proposal. All expenditures are within keeping to our planned budget. These costs will even out over time, and we expect to spend the total proposed budget amount by the end of the project.



Budget Category:	Proposed FY 17	Proposed FY 18	Proposed FY 19	Proposed FY 20	Proposed FY 21	TOTAL PROPOSED	ACTUAL CUMULATIVE
Personnel	$122.0	$127.7	$159.5	$163.8	$170.6	$743.5	$395.8
Travel	$8.6	$7.3	$11.6	$10.3	$10.3	$48.0	$28.6
Contractual	$47.5	$47.5	$53.5	$53.5	$53.5	$255.5	$193.7
Commodities	$0.0	$0.0	$32.0	$32.0	$32.0	$96.0	$26.0
Equipment	$4.3	$28.4	$11.4	$11.4	$11.4	$66.9	$37.5
SUBTOTAL	$182.4	$210.8	$268.0	$271.0	$277.8	$1,210.0	$681.7
General Administration (9% of subtotal)	$16.4	$19.0	$24.1	$24.4	$25.0	$108.9	N/A
PROJECT TOTAL	$198.8	$229.8	$292.1	$295.3	$302.8	$1,318.9	
Other Resources (Cost Share Funds)	$256.0	$256.0	$256.0	$517.2	$517.2	$1,802.4	

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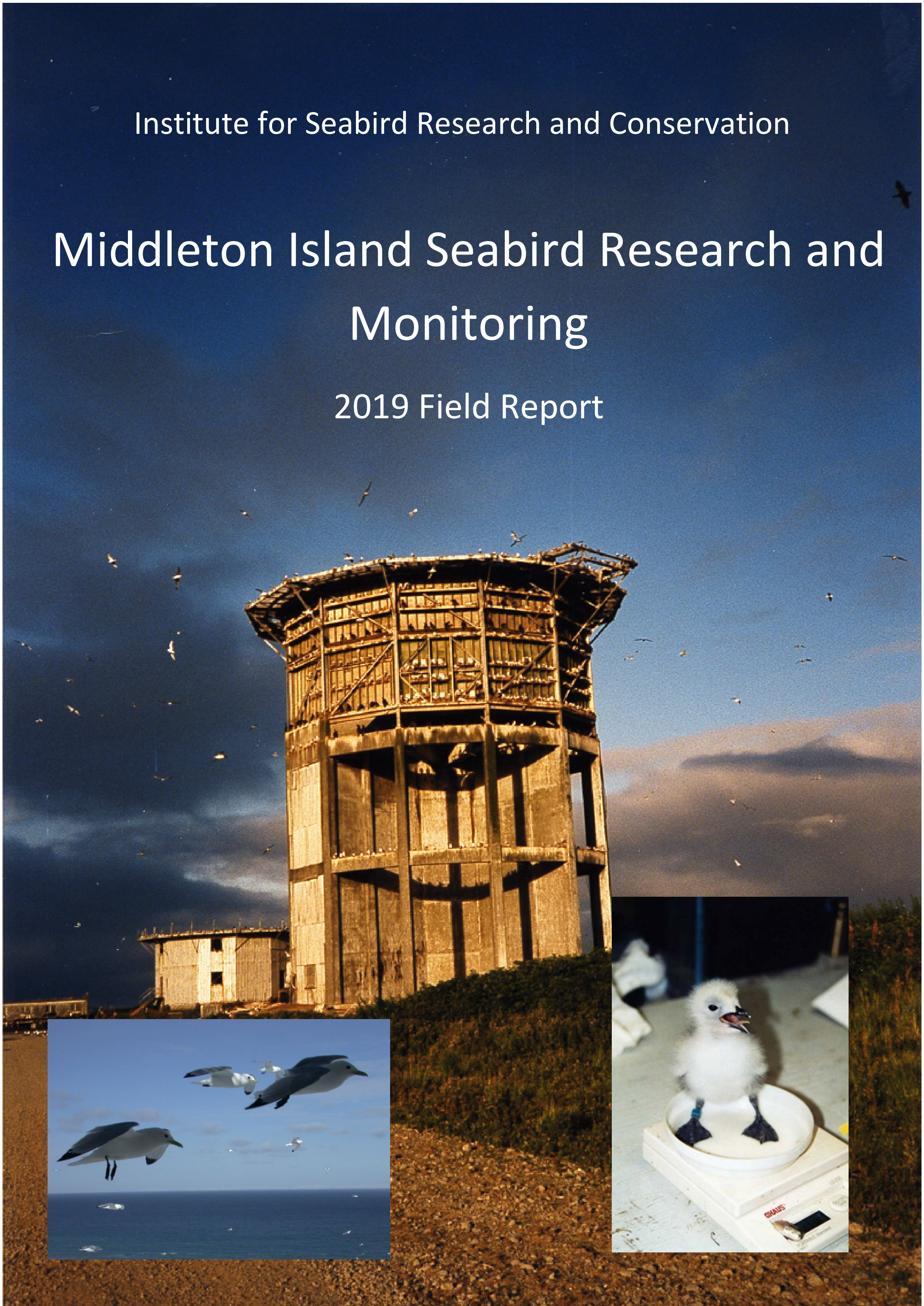
Appendix



Institute for Seabird Research and Conservation

Middleton Island Seabird Research and Monitoring

2019 Field Report

INTRODUCTION

The Middleton Island Marine Biological Station is a facility owned and managed by the Institute for Seabird Research and Conservation (ISRC) in support of long-term seabird research and monitoring in the Gulf of Alaska. The 2019 season marked the third year the project has contributed to Gulf Watch Alaska, a 20-year effort (2012-2031) funded by the *Exxon Valdez* Oil Spill Trustee Council. The program is intended to uncover and monitor natural and anthropogenic factors affecting ecosystem functioning in the Gulf of Alaska and Prince William Sound. The particular contribution of the Middleton project includes quantifying dietary shifts in predator species, especially black-legged kittiwakes and rhinoceros auklets, as indicators of forage fish dynamics in the region.

Additional lines of research in 2019 were possible by way of research personnel and financial support contributed by McGill University (National Science Education and Research Council of Canada, NSERC), Bucknell University, Queen's University (CA), the University of Ottawa, and Swansea University (UK). Those efforts included instrumentation of several species with GPS trackers and accelerometers and extensive research on the physiology and behavioral ecology of black-legged kittiwakes. Cooperators from the Prince William Sound Science Center (PWSSC) deployed GLS trackers on tufted puffins to ascertain the winter movements of that species, with financial support from the North Pacific Research Board (NPRB). With the partial exception of GPS tracking results for kittiwakes and rhinoceros auklets, the outcomes of those special investigations are not included in this report.

In 2019, the Middleton research station was occupied by members of the field crew from 5 April through 15 August.

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RESULTS AND DISCUSSION

PRODUCTIVITY

Rhinoceros Auklet—In general, rhinoceros auklets have consistently high breeding success on Middleton, and their population is increasing (currently ~20,000 individuals). At 0.61 chicks/egg laid (Table 1), production in 2019 was a little lower than the long-term average of 0.66 (n = 23 years, 1995-2019). The installation of nest boxes for rhinoceros auklets (n = 57) on the property this season will greatly facilitate productivity measures and other research on this species in future years (Appendix Fig. 1).

Tufted Puffin—For 5 years prior to 2015, the virtual absence of fish-carrying adults seen around the island was a clear indication of scant chick production by tufted puffins on Middleton. During the five seasons subsequent to that period, puffins have achieved at least a partial return to normal production— between 0.17 and 0.43 late-stage chicks produced per egg-laying pair— despite ocean conditions unfavorable to surface-feeders such as black-legged kittiwakes (see below). Production of 0.32 chicks per egg in 2019 continued that trend, and despite their comparatively poor breeding performance (vis-à-vis rhinoceros auklets), puffin numbers have increased substantially on Middleton—i.e., roughly 20,000 individuals today versus 5,000 in the 1970s.

Pelagic Cormorant—Since 2002, pelagic cormorants have been monitored in the tower colony. Numbers (31-145 nest-building pairs) have varied greatly (less so in recent years), whereas breeding success (from ~0.45 to 1.43 fledglings per nest built) is relatively constant (Table 2). Production in 2019 (0.84 fledglings/nest) was similar to the previous year and only a little below the long-term average of 1.05 fledglings/nest. On average, about 90 nests are constructed annually by cormorants on the tower, versus 75 nests in 2019. Thorough banding of adults and chicks done annually on the tower will support a future analysis and report of cormorant survivorship spanning the years since 2002.

Black-legged Kittiwake—Among 73 fed pairs of kittiwakes on the Middleton tower, production was 0.93 fledglings/nest in 2019, whereas 326 unfed pairs produced 0.35 chicks/nest (Table 3). The difference between groups indicated poor foraging conditions in 2019 for surface-feeding kittiwakes, as contrasted with divers such as rhinoceros auklets and pelagic cormorants. This season extended a period of poor breeding performance of kittiwakes that began with the emergence in 2014 of an unusual warm-water event in the northeast Pacific. In 2018, there were signs of a nascent return to more normal foraging conditions, but see below.

DIETS

Black-legged Kittiwake—In most years since 1996, regurgitated food samples have been collected from adult and/or nestling kittiwakes on the tower from April or May through August (Table 4). From an evaluation of alternate methods of analyzing and reporting diet results (Hatch 2013, Appendix 2), the preferred metric for kittiwakes is prey relative occurrence, for which the relevant sample units are numbers of identified prey types in a given sample (Table 5).

On average, Middleton kittiwakes take about equal amounts of Pacific sand lance, capelin, and invertebrates, and lesser amounts of herring, sablefish, salmon, and myctophids, depending on stage of the season (Fig. 1). A salient finding during the previously mentioned warm-water event was the virtual disappearance of capelin from the kittiwake diet on Middleton, following 6 prior years when capelin were abundant (Fig. 2).

Middleton Island is close to the continental shelf break, and for a few weeks after they arrive in spring kittiwakes typically forage over deep ocean waters at night, taking vertically migrating prey such as lanternfish (myctophids), squids, polychaetes, and crustaceans (Fig. 1). This was clearly the case in 2012, a year in which kittiwakes switched to capelin as the primary prey during incubation and chick-rearing (Fig. 2). Notably, because it had never been seen previously, capelin dominated throughout the following year, including even the spring arrival stage (a sizable sample having been obtained in late March 2013). In 2014, the spring diet reverted to a mix of myctophids and invertebrates, and for the first and only time observed, kittiwakes continued to rely on pelagic prey throughout the summer, apparently because prey usually obtained in the neritic (shelf) zone during June-August failed to materialize. In 2015, yet another previously unknown sequence occurred, as neither myctophids nor capelin were available early in the season, and large herring supplemented a predominantly invertebrate diet. During later stages of breeding in 2015, large herring and first-year sablefish comprised the bulk of the diet (Fig. 2).

The 2016 season was another extreme year within an ongoing, exceptional warming event. Increased use of invertebrates seen over the course of the heatwave crested that year with a virtual absence of fish in the diet during both April (Fig. 3) and May (Fig. 4). Typically, the two main contributors to the invertebrate fraction of the diet are squids and polychaetes (the latter being a pelagic species apparently obtained only at night). In 2016, it seemed the kittiwake diet in the first week or two after the birds' spring arrival at the colony (which normally occurs in late March) consisted almost exclusively of polychaetes. By May, squids were the dominant invertebrates and main prey overall (Figs. 3 & 4). As in other years, small numbers of the amphipod *Paracallisoma alberti* appeared regularly in the spring diet. The occurrence of the hydrozoan *Velella velella* was a first in 2016, and was unexpected because the species is normally associated with warmer water than what usually occurs in the northern Gulf of Alaska.

In 2017, squids and polychaetes were less prominent in the early-season diet than in several of the immediately preceding, warm-water years. Instead, the dominant fraction of the invertebrate diet that year consisted of crustaceans such as shrimp, amphipods, and copepods (Figs. 3 & 4).

The prevalence of copepods, especially during May, was notable because historically those prey have occurred but rarely in the kittiwake diet at Middleton. Copepods arguably would be a food source of last resort for a bird predator accustomed to having ready access to forage fish like myctophids or herring or energy-rich polychaetes. Also notable in 2017 was the regular occurrence of threespine sticklebacks during April (Fig. 3). Being abundant inhabitants of the intertidal zone and brackish ponds around the island, sticklebacks are an ever-present food source on Middleton, albeit one that is largely ignored by kittiwakes except perhaps when the birds struggle to find much else in the way of oceanic prey. The paucity and generally small mass of regurgitated food samples found around the grounds of the research station was further evidence of poor foraging conditions in spring 2017.

The spring diet of kittiwakes in 2018 showed a continuing rebound of myctophids (Fig. 3), perhaps reflecting those species' resumption of near-surface migration at night. Such behavior would have been encouraged that year by cool-water conditions, at least in comparison to extreme years of the heatwave, spanning 2014 through 2016. The invertebrate fraction of the diet consisted mainly of squid and amphipods during April, but switched substantially to polychaetes, krill and copepods by May 2018. Temporally, an even finer-grained depiction of kittiwake prey during prebreeding would portray the fact that kittiwakes seem to forage opportunistically on whatever invertebrate prey happen to be swarming abundantly at the surface over periods of a few nights or up to a week or two. In May 2018, kittiwakes began taking substantial amounts of fish (herring, eulachon, sand lance, and lingcod), and the number and size of samples obtained from the grounds around the Middleton station indicated a relative abundance of food as compared with several preceding years.

During incubation and chick-rearing in 2018, the kittiwake diet favored herring, sablefish, and sand lance (Fig. 2). Consistent with results since 2014, a notable scarcity of capelin continued that year, and juvenile pink and chum salmon had a poor showing in the chick diet (July and August).

Invertebrates comprised a more typical fraction of the kittiwake diet in spring 2019, declining somewhat between April and May as the fish component increased in the samples (Figs. 3 & 4). However, myctophids seemed to be largely unavailable during that time, when the main constituents of the fish diet were Pacific herring and sand lance. In fact, kittiwakes made little effort to forage in the pelagic zone during the prelaying period in 2019 (see below). Herring continued to be important fish prey throughout the summer (Fig. 2). Capelin and sand lance were about equally prevalent in the summer diet, with 18% and 15% relative occurrence, respectively. As such, capelin made a stronger showing in 2019 than in any year since the onset of the heatwave in 2014.

Rhinoceros Auklets—Auklet diets are monitored by collecting bill-loads from chick-provisioning adults, usually once or twice a week from early July through early or mid-August. Sampling in 2019 yielded 319 bill loads and ground samples, comprising about 11 kg of auklet prey in total

(Table 6). Overall, the auklet diet at Middleton is composed largely of a few species of forage fish, especially Pacific sand lance, capelin, salmon (including both pink and chum), and sablefish, in that order of importance (Fig. 5). The years 2014 through 2017 saw significant breaks from the past, with historically dominant species—sand lance and capelin—being largely supplanted by sablefish, salmon, and herring (Fig. 6).

Since 1978, nearly 135 kg of auklet prey samples have been collected on Middleton (Table 6), and auklet diet monitoring provides our single best indicator of forage fish dynamics in the region. By all appearances, sand lance were the overwhelmingly dominant forage species in the late 1970s through the early 1980s. Following a period of reduced availability in the mid 1990s, sand lance made a strong comeback by the end of that decade. Sand lance steadily declined in importance after 2000, however, and contributed little to seabird diets during a cold-water phase that materialized in 2008 (Fig. 6). The appearance of about 30% sand lance in the auklet diet in 2016-2017, and more than 50% by weight in 2018 is consistent with a known association of sand lance with warm-water conditions (Hatch 2013). While herring appear superficially to have benefitted from the recent warming of surface waters (Fig. 7), the absence of such a signal in herring data generally (PWSSC 2018) suggests that shifts in foraging locations have occurred that may account for the increased capture of herring by auklets and kittiwakes from Middleton (see below). Also noteworthy in 2019 was an unusual spike in the occurrence of juvenile gadids—as yet unidentified to species, but definitely not walleye pollock—in the diet of rhinoceros auklets (Fig. 7).

The juxtaposition of time series for kittiwakes and rhinoceros auklets since 1978 (Fig. 6) shows general agreement vis-à-vis the decline of sand lance and, after 2008, the emergence of capelin as a dominant forage species. However, in several recent years, when neither sand lance nor capelin were prevalent, the diets of surface-feeding kittiwakes and diving auklets diverged substantially (Fig. 6). In 2019, the trade-off appeared to occur primarily between herring (more prevalent in kittiwake diet) and juvenile greenlings (taken mainly by auklets).

FORAGING AMBITS OF KITTIWAKES AND AUKLETS

Spring foraging by kittiwakes in 2019 was more widespread than previously recorded or anticipated, with some individuals traveling far to the east and west of Middleton or visiting interior waters of Prince William Sound (Fig. 8). Foraging tracks give the impression of birds sampling intermittently the pelagic zone off the continental shelf, but not staying or foraging extensively, as though food-searching there was generally unproductive. Kittiwake movements during incubation and chick-rearing (Jun-Aug) were similar to patterns observed in 2018, except for the virtual absence this year of deep-ocean foraging (Figs. 8 & 9). A comparison with 2008—a year with cold water and abundant capelin—shows how markedly the foraging patterns of Middleton kittiwakes can change depending on prevailing ocean conditions. In the former year, spring foraging occurred almost exclusively in the pelagic zone, then shifted to the continental shelf prior to egg-laying (Fig. 9). Also striking is the contrast in foraging ranges at mid season. Whereas chick-rearing kittiwakes in 2008 foraged within about 50 km of the island, and herring were all but absent from the diet, more recently (2015-2019, to our knowledge) such parents have made regular trips to coastal waters from Montague and Hinchinbrook islands to Cape St. Elias (Fig. 9), where presumably they obtained the Age 1+ herring that appear in the diet (Fig. 2).

It is noteworthy that visits by kittiwakes to barrier islands and beaches at the Copper River mouth probably occur every year during a narrow period in spring when pre-spawning eulachon aggregate at that location (Willson et al. 2006).

As in 2018, the foraging area of chick-rearing rhinoceros auklets overlapped that of kittiwakes and was concentrated in nearshore waters of southeast Montague Island from Patton Bay to Cape Cleare (Fig. 10). That would seem to be the location where age-0 greenlings and gadids were unusually abundant in 2019. We remain a bit surprised to find auklets delivering fish from as far as 100 km from their nest sites on Middleton. Additional telemetry will likely find considerable flexibility in that regard, but the early lesson is that rhinoceros auklets, consistent with their reliable success in breeding, are well adapted for coping whenever local food shortages occur. Similar to kittiwakes, the information they furnish as prey samplers is relevant to a sizable portion of the northern Gulf.

OCEAN REGIME INDICATORS

Using data from Middleton Island seabird monitoring through 2011, Hatch (2013) described an apparent regime shift in the Gulf of Alaska ecosystem that occurred around 2008. This transition entailed: (1) a switch from mostly positive PDO indices (since 1977) to negative values after 2008, (2) the emergence of capelin as a dominant prey species at Middleton, and (3) markedly improved breeding performance by black-legged kittiwakes. These patterns persisted for at least 6 years (i.e., through 2013) and, with occasional interludes of opposing conditions, can be expected to continue for another 2 decades or longer (Hatch 2013). One such interlude is now evident for the period 2014-2017, a widespread anomaly nicknamed “The Blob.” Examples of dramatic species range shifts associated with this warm-water event are listed in Bond et al. (2015), to which we can add the first-ever appearance of male California sea lions (*Zalophus californianus*) among ~100 Steller sea lions hauling out on Middleton in April, May and June of 2016. A similar complement of California sea lions was observed among the males hauling out on Middleton in April 2017.

Anomalous conditions are also reflected in monthly PDO indices and in seabird indicators from Middleton Island—namely, dietary capelin and kittiwake productivity—both of which dropped precipitously beginning in 2014 (Table 7, Fig. 11). The prevalence of invertebrates (mainly polychaetes and squids, but also including copepods and the normally warm-water hydrozoan *Velella velella*) in the spring diet during 2016-2017 is especially noteworthy. As nocturnal vertical migrants from mesopelagic depths, myctophids are available to foraging kittiwakes only at night, and then only if the fish rise to within a meter or so of the ocean surface. Evidently, anomalous surface conditions in 2015 and 2016 prevented myctophids from doing so in April, and mesopelagic fish have remained a relatively minor component of the spring diet through 2019, April 2018 being a partial exception. Although indications in 2018 were of a gathering return to normal conditions in the Gulf, patterns in recent months portend another heatwave, prompting references in the popular media to “Son of Blob” (e.g., Yulsman 2019). The continued large effect of supplemental feeding on laying dates, clutch sizes, and productivity in 2017-2019 (Table 8) confirms the continued difficulty kittiwakes are having in acquiring sufficient energy for breeding.

The comparison of breeding performance in fed and unfed kittiwake pairs on Middleton furnishes a powerful indicator of ocean conditions, for the simple reason that kittiwakes prefer to feed themselves. In poor years, characterized by positive PDO, low capelin availability, and poor kittiwake breeding performance, the difference between fed and unfed treatment groups is accentuated, and vice versa (Table 8, Fig. 12). The events of 2014-2019 have only increased the strength and predictive power of relations among the PDO, prey dynamics, and kittiwake breeding performance (Table 9). As of fall 2018, the PDO showed signs of a possible return to ocean conditions expected if a predominantly negative phase of the PDO would prevail in spite of temporary disruptions such as the warm-water anomaly so notorious of late. Thus, we look forward to the next iteration, if it comes, of this natural experiment, when a return to cold water conditions, capelin, and high kittiwake performance would more or less clinch these simple, yet portentous, relationships. As noted, a predominantly cold phase of the PDO is expected to last through the 2030s, all else being equal. Global warming and climate change could have countervailing effects, however, with far-reaching consequences for seabirds, marine mammals, and fisheries. It remains to be seen whether the recent and exceptional warm-water event, the effects of which still linger in the Gulf of Alaska, is really an “anomaly” or, rather, a window on the future.

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Table 1. Productivity of rhinoceros auklets and tufted puffins breeding on Middleton Island in 2015-2019.

	Rhinoceros auklet					Tufted puffin				
Parameter	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019
Burrows with eggs	60	61	62	61	72	52	82	71	71	60
Eggs hatched	42	38	40	35	51	21	27	17	17	19
Late-stage chicks	38	33	32	33	44	18	20	12	12	19
Chicks/egg laid	0.63	0.54	0.52	0.54	0.61	0.35	0.24	0.17	0.43	0.32

Table 2. Breeding performance of pelagic cormorants on the Middleton tower, 2002-2019.[a]

	A-egg date (Julian day)				Clutch size				Chicks fledged/nest built			
Year	n	Mean	SE	SD	n	Mean	SE	SD	n	Mean	SE	SD
2002	77	139.7	0.95	8.325	86	3.7	0.18	1.707	86	1.6	0.15	1.371
2003	78	138.2	0.97	8.540	80	4.0	0.16	1.441	80	1.9	0.16	1.400
2004	62	144.0	0.88	6.941	76	2.8	0.18	1.607	76	0.4	0.07	0.650
2005	31	142.5	1.32	7.352	31	3.5	0.18	1.028	31	1.2	0.23	1.283
2006	92	148.3	0.90	8.635	101	3.0	0.12	1.228	101	1.1	0.12	1.156
2007	142	147.8	0.93	11.130	144	3.8	0.11	1.275	144	1.6	0.12	1.425
2008	145	146.4	0.94	11.370	145	3.8	0.10	1.165	145	1.6	0.11	1.319
2009	113	155.0	0.68	7.223	128	2.9	0.11	1.232	128	1.4	0.10	1.175
2010	71	154.7	0.72	6.037	71	2.6	0.10	0.851	71	0.1	0.05	0.445
2011	95	161.3	0.96	9.314	109	2.5	0.12	1.281	109	0.5	0.07	0.741
2012	85	159.4	0.86	7.884	85	3.0	0.12	1.107	85	0.5	0.08	0.765
2013	89	150.3	0.73	6.842	90	3.4	0.09	0.880	90	1.9	0.12	1.167
2014	--	--	--	--	--	--	--	--	~87	~1.2	0.13	1.170
2015	58	155.0	0.91	6.910	85	2.1	0.16	1.470	85	0.6	0.09	0.823
2016	53	152.8	1.62	11.78	53	2.9	0.17	1.210	53	0.9	0.14	1.050
2017	69	150.9	1.08	8.951	69	3.3	0.10	0.845	69	1.6	0.16	1.306
2018	84	150.8	1.14	10.492	84	3.4	0.10	0.898	84	0.8	0.09	0.784
2019	75	149.3	1.03	8.918	75	3.6	0.10	0.841	75	0.4	0.10	0.838
Totals	1,419	149.8	0.98	8.63	1,512	3.2	0.13	1.180	1,512	1.1	0.12	1.048

[a] The estimate of fledglings in 2014 is 102 chicks from 87 nests built, a relatively crude figure that should not be taken as strictly comparable to other years. The estimate is based on a final (premature) count of chicks in tower nests on 14 July, >3 weeks before final checks in other years. Additional mortality that would have occurred before fledging was perhaps offset by 10 nests still being incubated on 14 July, which are assumed to have produced no fledged chicks.

Table 3. Breeding performance of supplementally fed and unfed pairs of black-legged kittiwakes on the Middleton tower, 1996-2019.[a]

	Unfed pairs												Fed pairs											
	Julian lay date				Clutch size[a]				Chicks fledged				Julian lay date				Clutch size[a]				Chicks fledged			
Year	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.	n	Mean	s.e.	s.d.
1996	59	159	0.75	5.728	63	1.73	0.07	0.574	63	0.60	0.08	0.636	25	157	1.07	5.342	27	1.74	0.11	0.594	27	1.22	0.15	0.801
1997	59	158	0.44	3.386	65	1.48	0.08	0.664	65	0.32	0.06	0.503	25	155	1.09	5.427	25	1.80	0.08	0.408	25	0.96	0.16	0.790
1998	59	160	0.92	7.032	70	1.29	0.09	0.745	70	0.36	0.06	0.539	27	155	1.12	5.797	29	1.69	0.14	0.761	29	0.62	0.12	0.622
1999	65	169	0.59	4.771	156	0.47	0.05	0.606	156	0.21	0.04	0.468	44	161	1.01	6.684	46	1.61	0.09	0.614	46	0.59	0.11	0.717
2000	135	151	0.63	7.322	152	1.68	0.06	0.706	152	0.99	0.07	0.814	67	149	0.66	5.403	71	1.83	0.07	0.609	71	1.18	0.10	0.833
2001	166	153	0.46	5.942	174	1.78	0.04	0.560	174	1.03	0.06	0.853	67	151	0.41	3.342	71	1.93	0.07	0.569	71	1.28	0.10	0.848
2002	168	149	0.66	8.581	179	1.73	0.04	0.586	179	0.97	0.06	0.796	70	149	0.94	7.825	72	1.83	0.06	0.475	72	0.97	0.09	0.769
2003	95	157	0.47	4.600	102	1.67	0.06	0.603	102	0.50	0.06	0.609	66	152	0.74	6.003	69	1.81	0.07	0.550	69	0.91	0.10	0.836
2004	88	154	0.42	3.949	102	1.58	0.07	0.750	102	0.18	0.04	0.432	68	151	0.70	5.742	69	1.99	0.04	0.364	69	0.97	0.10	0.804
2005	214	157	0.30	4.321	221	1.67	0.04	0.553	221	0.37	0.04	0.553	71	151	0.57	4.775	72	1.86	0.05	0.421	72	1.03	0.08	0.712
2006	216	158	0.38	5.537	233	1.56	0.04	0.627	233	0.47	0.04	0.587	71	151	0.43	3.642	73	1.90	0.05	0.446	73	1.14	0.10	0.822
2007	172	163	0.43	5.606	197	1.34	0.05	0.693	197	0.42	0.04	0.606	63	158	0.74	5.900	73	1.58	0.08	0.725	73	0.77	0.10	0.874
2008	125	153	0.58	6.498	130	1.73	0.05	0.554	130	0.78	0.06	0.707	70	150	0.70	5.887	71	1.92	0.06	0.470	71	0.90	0.10	0.813
2009	90	155	0.57	5.439	98	1.69	0.07	0.649	98	0.20	0.04	0.405	75	150	0.81	7.056	76	1.89	0.04	0.386	76	0.75	0.08	0.656
2010	68	148	0.87	7.160	74	1.81	0.07	0.612	74	0.78	0.09	0.815	58	150	1.07	8.174	61	1.82	0.07	0.563	61	0.89	0.10	0.819
2011	41	158	0.64	4.092	42	1.62	0.08	0.539	42	0.50	0.09	0.552	47	152	1.26	8.624	48	1.83	0.07	0.519	48	0.92	0.11	0.794
2012	72	153	0.78	6.582	78	1.82	0.07	0.619	78	0.87	0.09	0.779	72	152	0.86	7.262	75	1.88	0.06	0.544	75	0.93	0.09	0.811
2013	63	148	1.06	8.413	68	1.84	0.06	0.507	68	1.00	0.10	0.792	67	148	0.97	7.965	70	1.97	0.06	0.538	70	1.04	0.10	0.842
2014	--	--	--	--	--	--	--	--	143	0.45	0.04	0.526	--	--	--	--	--	--	--	--	--	--	--	--
2015	296	153	0.29	4.986	352	1.51	0.04	0.762	352	0.21	0.02	0.422	70	152	0.47	3.895	72	1.90	0.05	0.449	72	0.96	0.09	0.740
2016	79	165	0.73	6.444	155	0.74	0.06	0.806	155	0.08	0.02	0.301	73	156	0.99	8.434	74	1.80	0.05	0.437	74	0.81	0.06	0.541
2017	72	161	0.52	4.407	104	0.95	0.07	0.755	104	0.22	0.04	0.417	72	155	0.58	4.948	74	1.82	0.04	0.371	74	0.76	0.08	0.679
2018	113	155	0.56	5.981	134	1.48	0.06	0.752	134	0.31	0.04	0.492	72	151	0.70	5.958	72	1.97	0.03	0.238	72	0.99	0.08	0.687
2019	326	154	0.3	5.471	368	1.61	0.04	0.691	368	0.35	0.03	0.511	73	150	0.46	3.921	73	1.99	0.04	0.312	73	0.93	0.09	0.805

[a] Mean clutch size includes zero-egg nests, reflecting both breeding propensity and egg production by laying pairs

Table 4. Temporal distribution of diet samples from black-legged kittiwakes on Middleton Island, 1978 – 2019.

	Adults			June			July			August			
Year	Mar	April	May	Adults	Chicks	Total	Adults	Chicks	Total	Adults	Chicks	Total	Total
1978								38	38		2	2	40
1989		2	2				5		5				9
1990		17	7	18		18	21	9	30				72
1992			1							3		3	4
1994		3											3
1996			19					37	37		17	17	73
1997			4	4	3	7	3	107	110	1	35	36	157
1998			32	11	16	27	13	130	143	7	64	71	273
1999			11	11		11	9	51	60	2	45	47	129
2000		41	7	13	1	14	4	87	91		29	29	182
2001		10	19	7	23	30	10	321	331		31	31	421
2002		26	14	2	22	24	1	193	194		22	22	280
2003		4	22	24	3	27	22	15	37	5	2	7	97
2004		9	8		1	1	11	7	18				36
2005		4	12	3		3	5	10	15	1	2	3	37
2006			6	6	8	14		100	100		19	19	139
2007		1	21	4		4	13	3	16	1	3	4	46
2008		44	10	4	2	6	2	40	42	2	13	15	117
2009		36	21	16	2	18	22	27	49	2	7	9	133
2010		39	51	39	34	73	27	128	155	4	36	40	358
2011		32	14	3		3	9	18	27	8	13	21	97
2012		10	75	5	10	15	60	238	298	11	67	78	476
2013	114	7	64	50	17	67	23	110	133	8	26	34	419
2014		179	6	1	1	2	3	100	103	14	14	28	318
2015		63	63	12	4	16	33	32	65	4	12	16	223
2016		135	129	27	5	32	42	123	165	3	26	29	490
2017		87	67	34	0	34	69	77	146	6	31	37	371
2018		197	40	18	5	23	27	92	119	4	53	57	436
2019		58	45	11	11	22	17	187	204	7	54	61	390
Total	114	1004	770	323	168	491	451	2280	2731	93	623	716	5826

Table 5. Numbers of prey types identified in kittiwake food samples—the basis for computations of relative occurrence—by month on Middleton Island from 1978 through 2019.

	Prey type identifications						
Year	March	April	May	June	July	August	Total
1978					56	4	60
1989		4	3		10		17
1990		25	9	34	46		114
1992			1			4	5
1994		7					7
1996			21		38	19	78
1997			4	9	132	47	192
1998			40	34	190	111	375
1999			14	15	75	65	169
2000		64	7	16	108	41	236
2001		12	21	30	409	44	516
2002		41	14	24	222	28	329
2003		6	31	34	47	9	127
2004		11	10	2	22		45
2005		5	13	3	17	4	42
2006			7	17	143	24	191
2007		1	26	4	21	4	56
2008		69	13	6	44	15	147
2009		48	22	23	65	11	169
2010		45	58	78	160	48	389
2011		37	17	3	34	29	120
2012		12	80	20	339	89	540
2013	129	7	64	68	139	44	451
2014		218	6	2	156	39	421
2015		77	71	23	88	20	279
2016		202	158	45	260	46	711
2017		134	74	46	207	48	509
2018		329	51	29	190	70	669
2019		68	48	29	289	83	517
Total	129	1422	883	594	3507	946	7481

Table 6. Food samples (bill loads, partial bill loads, and ground samples) obtained annually from rhinoceros auklets on Middleton Island from 1978 through 2019.

Year	No. samples	TotalMass (g)
1978	72	3109.2
1986	4	97.7
1990	17	199.4
1993	70	1407.2
1994	190	3680.1
1995	146	2217.1
1996	78	1488.0
1997	138	1707.6
1998	315	7816.6
1999	100	2688.3
2000	106	2537.8
2001	126	3888.6
2002	95	2706.7
2003	121	3461.6
2004	107	2889.9
2005	95	2749.3
2006	113	4393.8
2007	100	2470.0
2008	130	4514.9
2009	111	3079.4
2010	175	6297.6
2011	115	3430.8
2012	260	7011.6
2013	248	8732.3
2014	180	5920.0
2015	334	9351.0
2016	306	8988.5
2017	328	10,056.8
2018	210	6,989.0
2019	319	10785.9
All years	4709	134,666.7

Table 7. Time series of kittiwake productivity, dietary capelin and PDO index during the breeding season on Middleton Island from 1978 through 2019.

Year	Mean PDO index (Jun-Aug)	Productivity	Capelin in diet (Jun-Aug)
1978	-0.55	0.14	0.0000
1979	0.51	--	--
1980	0.17	--	--
1981	0.90	0.47	--
1982	0.06	0.30	--
1983	2.57	0.03	--
1984	-0.01	0.76	--
1985	0.69	0.04	--
1986	0.83	0.05	--
1987	1.86	0.00	--
1988	0.52	0.21	--
1989	0.43	0.00	--
1990	0.27	0.00	0.0500
1991	-0.40	0.22	--
1992	1.53	0.24	--
1993	2.46	0.01	--
1994	-0.09	0.32	--
1995	1.06	0.17	--
1996	0.58	0.60	0.0526
1997	2.63	0.32	0.0000
1998	0.05	0.42	0.1373
1999	-0.97	0.19	0.0452
2000	-0.76	0.99	0.5394
2001	-0.85	1.03	0.1677
2002	-0.02	0.97	0.2956
2003	0.84	0.50	0.2333
2004	0.44	0.20	0.0000
2005	0.69	0.37	0.0000
2006	0.25	0.47	0.0163
2007	0.46	0.42	0.2414
2008	-1.57	0.78	0.6462
2009	-0.25	0.20	0.3535
2010	-0.85	0.78	0.8322
2011	-1.43	0.50	0.6061
2012	-1.44	0.87	0.7634
2013	-1.02	1.00	0.8247
2014	0.73	0.45	0.0152
2015	1.65	0.21	0.0076
2016	1.27	0.08	0.0313
2017	0.33	0.22	0.0332
2018	0.08	0.31	0.0519
2019	0.83	0.35	0.1820

Table 8. Effects of supplemental feeding on laying dates, clutch sizes and overall productivity of black-legged kittiwakes on the Middleton tower since 1996.

	Treatment effect (Fed - Unfed pairs)		
Year	Julian lay date	Clutch size	Chicks fledged
1996	-2.30	0.01	0.62
1997	-3.23	0.32	0.64
1998	-5.19	0.40	0.26
1999	-8.78	1.14	0.38
2000	-2.03	0.15	0.19
2001	-2.65	0.15	0.25
2002	0.79	0.10	0.00
2003	-4.58	0.14	0.41
2004	-2.87	0.41	0.79
2005	-6.67	0.19	0.66
2006	-7.09	0.34	0.67
2007	-4.90	0.24	0.35
2008	-3.13	0.19	0.12
2009	-4.40	0.20	0.55
2010	2.24	0.01	0.11
2011	-5.55	0.21	0.42
2012	-1.55	0.06	0.06
2013	0.15	0.13	0.04
2014	--	--	--
2015	-1.62	0.39	0.75
2016	-8.52	1.06	0.73
2017	-6.00	0.87	0.54
2018	-4.00	0.49	0.68
2019	-4.70	0.38	0.58
Mean	-3.76	0.33	0.43

Table 9. Pearson correlations among the Pacific Decadal Oscillation (PDO) index (June to August), relative occurrence of dietary capelin, and kittiwake chick production on Middleton Island over 40 years between 1978 and 2019.

		Variable	
Variable	Statistic	Chick production	Capelin in diet
Capelin in diet			
	Pearson's *r*	0.691	---
	P (2-tailed)	<0.001	---
	n (years)	26	---
PDO (Jun-Aug)			
	Pearson's *r*	-0.594	-0.692
	P (2-tailed)	<0.001	<0.001
	n (years)	40	26

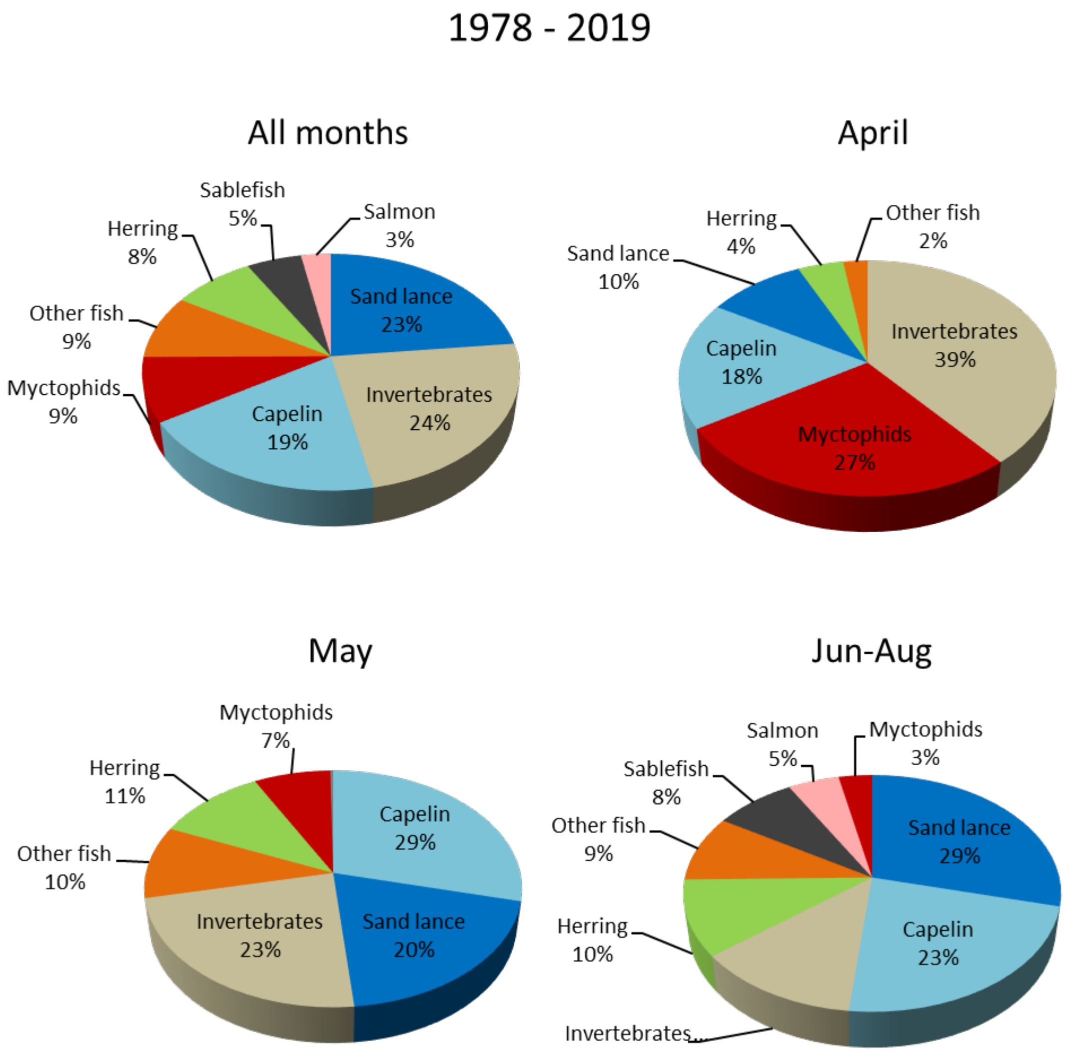

Figure 1. Overall composition of food samples obtained from black-legged kittiwakes (relative occurrence, April – August) on Middleton Island from 1978 to 2019.

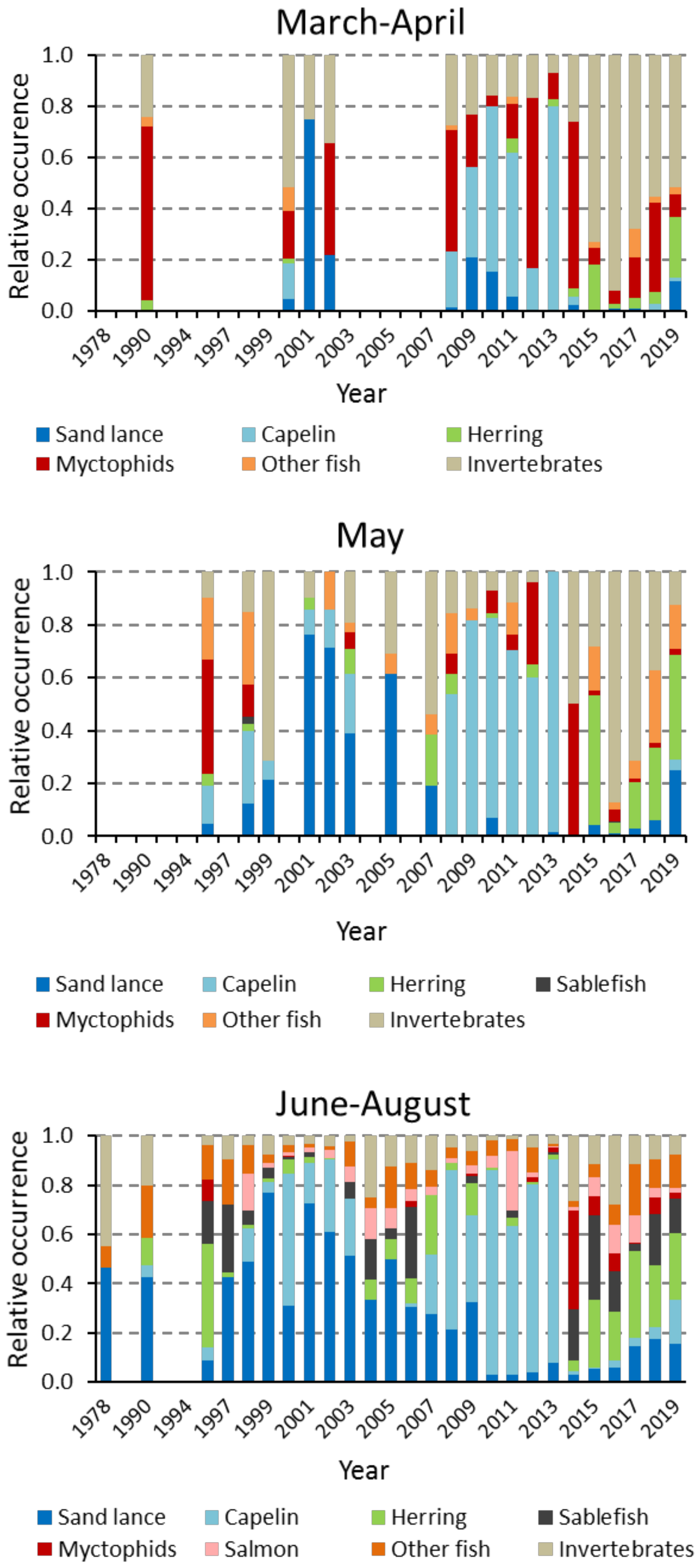

Figure 2. Interannual variation in kittiwake diet composition at three stages of breeding on Middleton Island, 1978 to 2019. Sample sizes as listed in Tables 4 and 5.

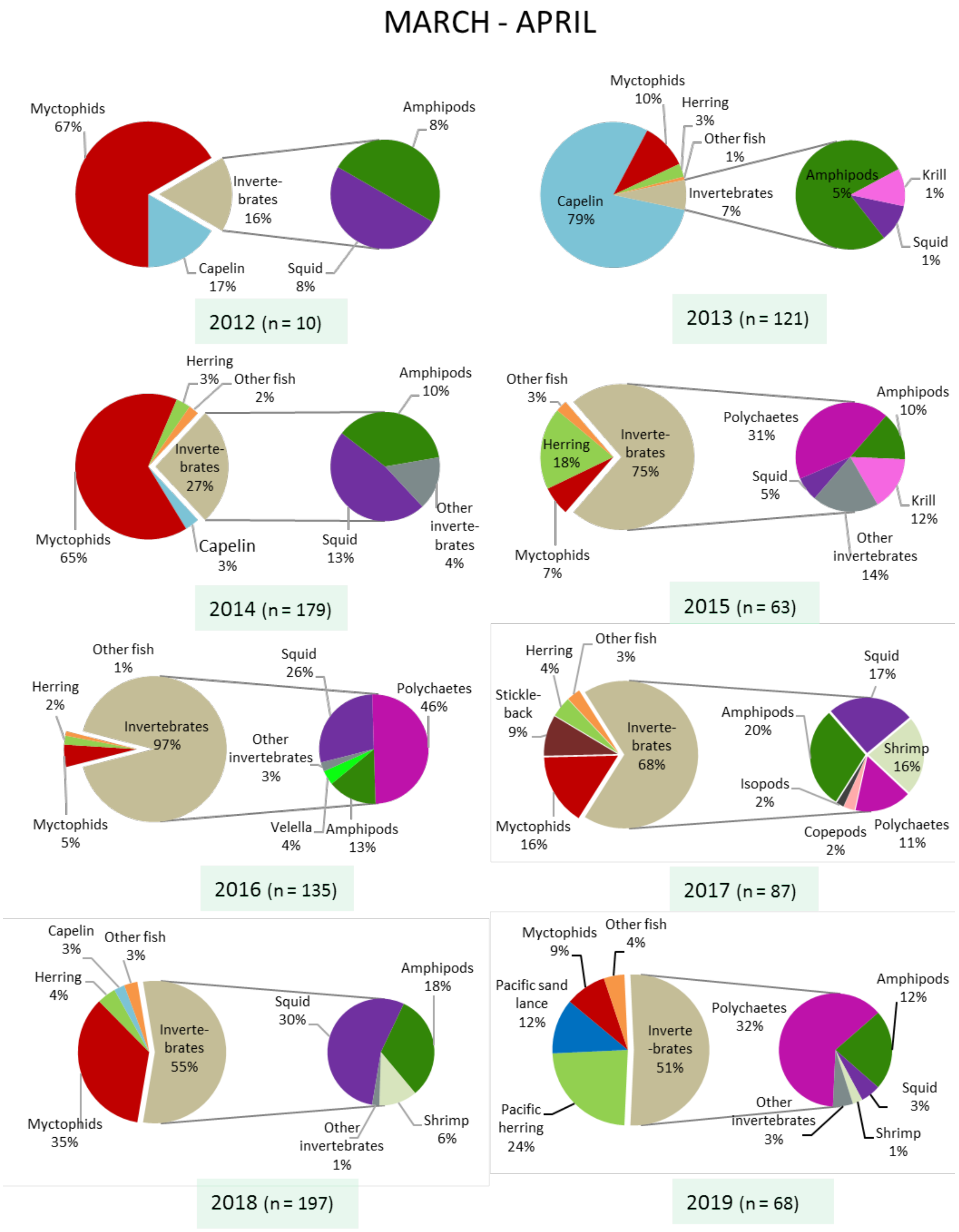

Figure 3. Variation in the relative occurrence and composition of fish and invertebrates in the diet of black-legged kittiwakes on Middleton Island from spring arrival through April in 2012-2019.

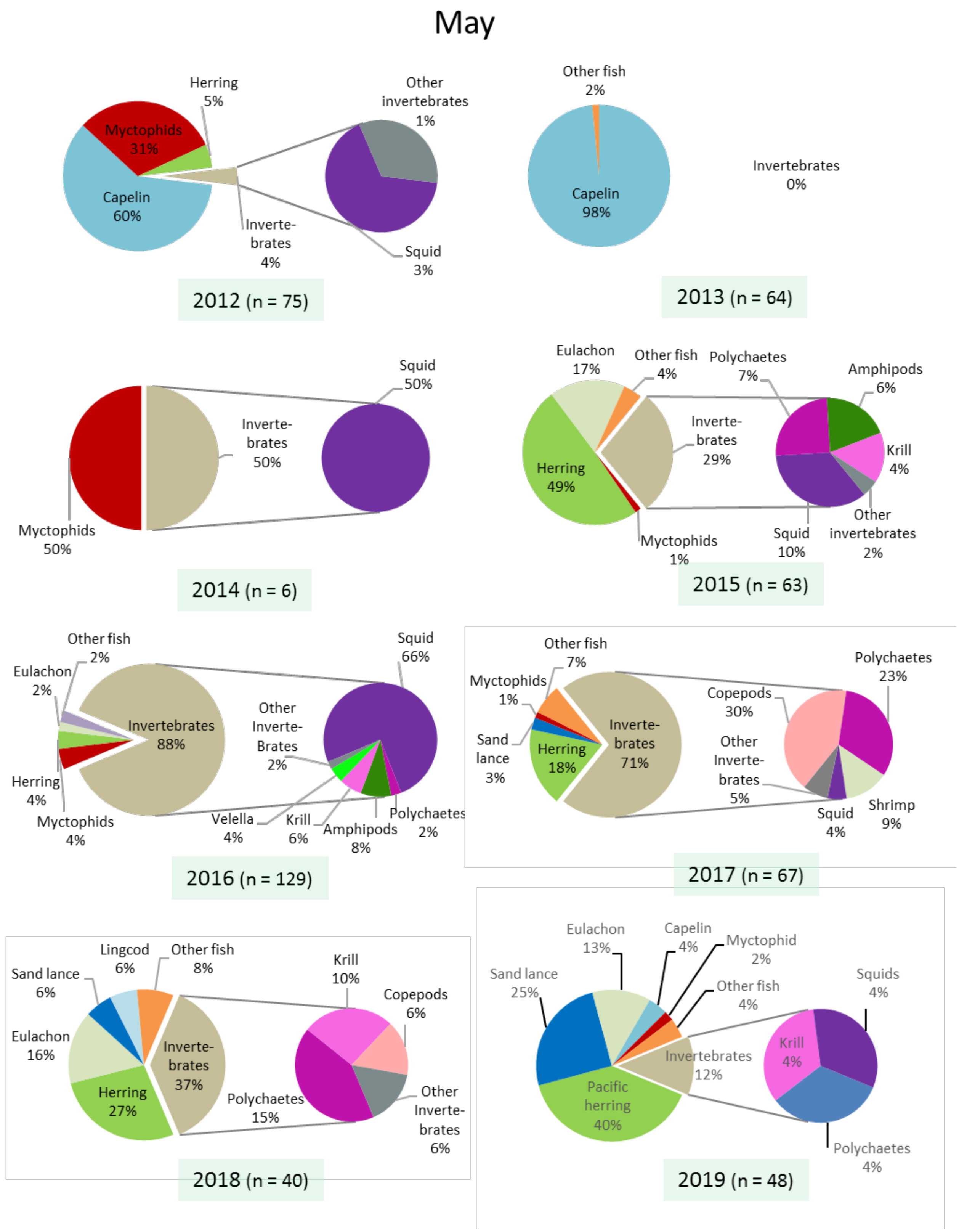

Figure 4. Variation in the relative occurrence and composition of fish and invertebrates in the diet of black-legged kittiwakes on Middleton Island during May in 2012-2019.

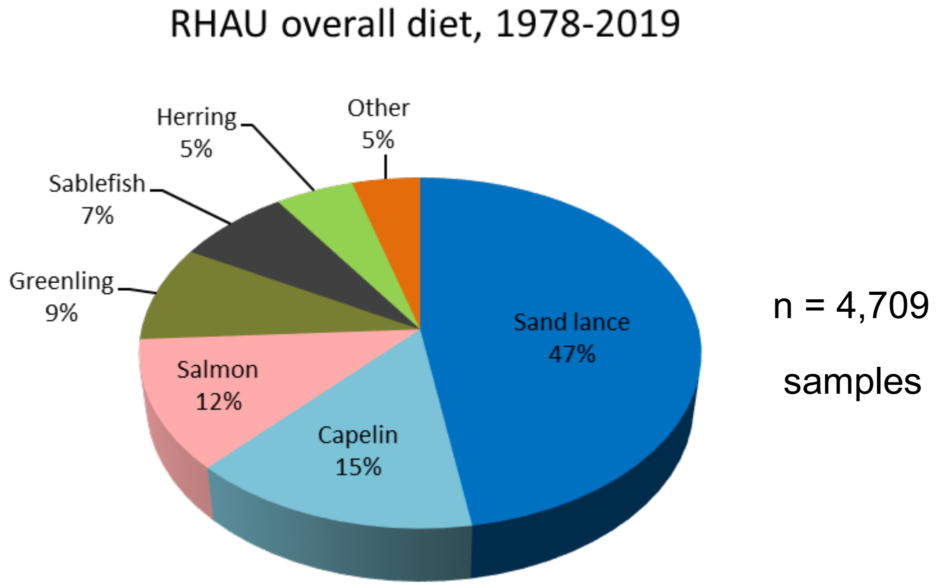

Figure 5. Overall composition of food samples obtained from chick-rearing rhinoceros auklets (% biomass, July-August) on Middleton Island from 1978 through 2019.

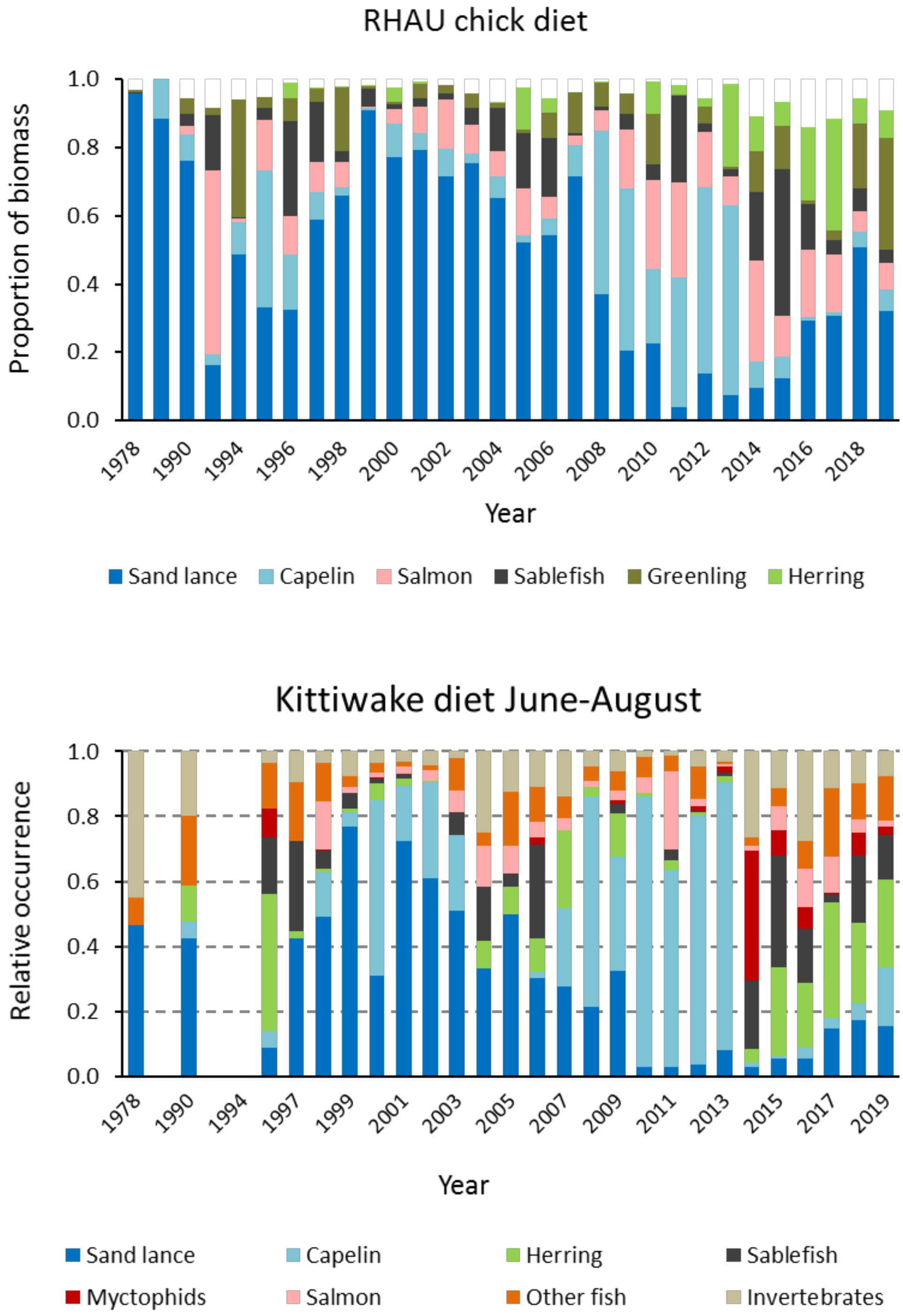

Figure 6. Interannual variation in diet composition of chick-rearing rhinoceros auklets on Middleton Island, 1978 to 2019, with a similar time series for black-legged kittiwakes (lower panel) for comparison. Sample sizes as listed in Tables 4, 5 and 6.

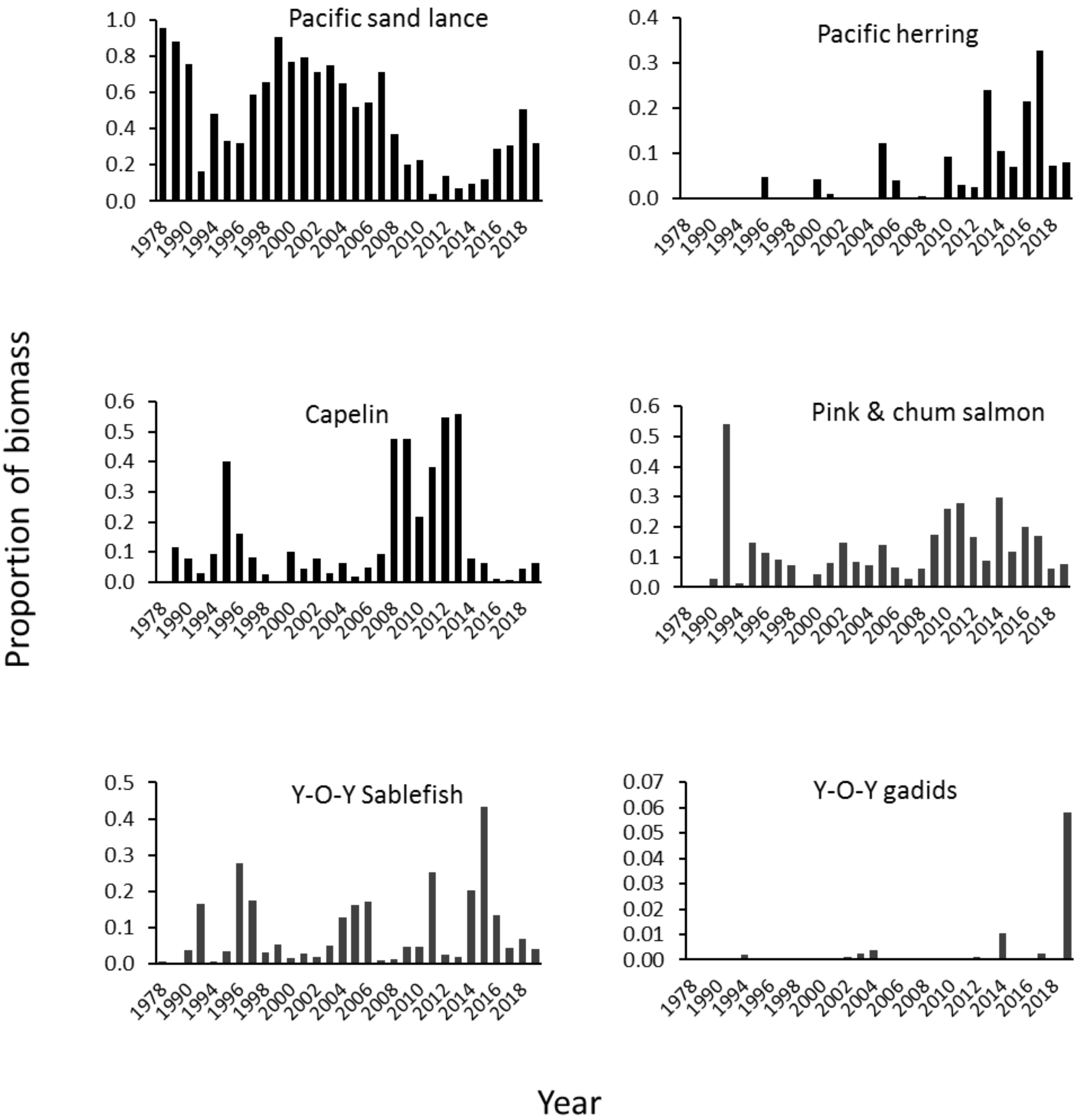

Figure 7. Indices of prey species occurrence in the nestling diet of rhinoceros auklets on Middleton Island from 1978 through 2019.

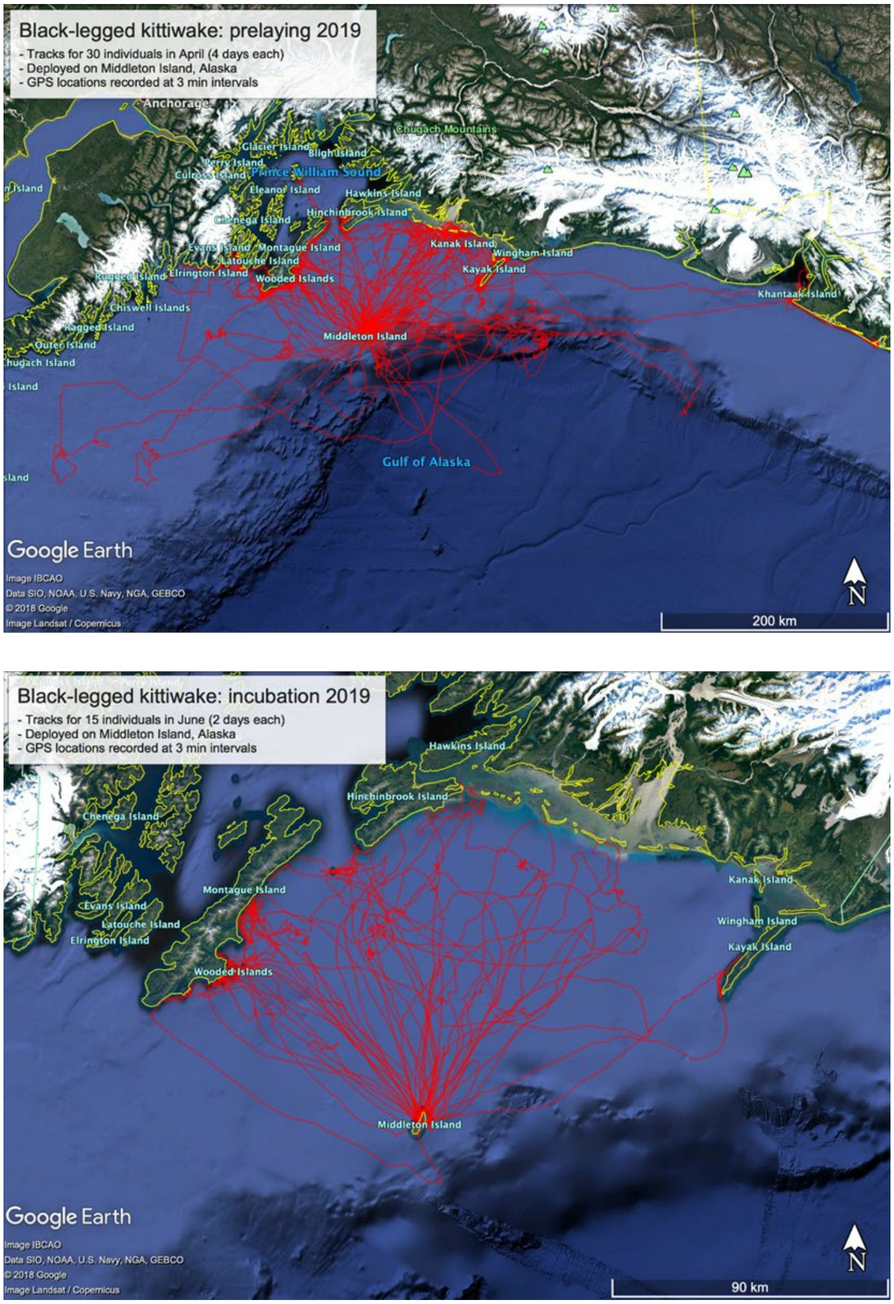

Figure 8. Foraging areas of Middleton Island kittiwakes during the prelaying period (upper panel) and incubation (lower panel) as revealed by GPS tracking devices deployed on 45 individuals in 2019.

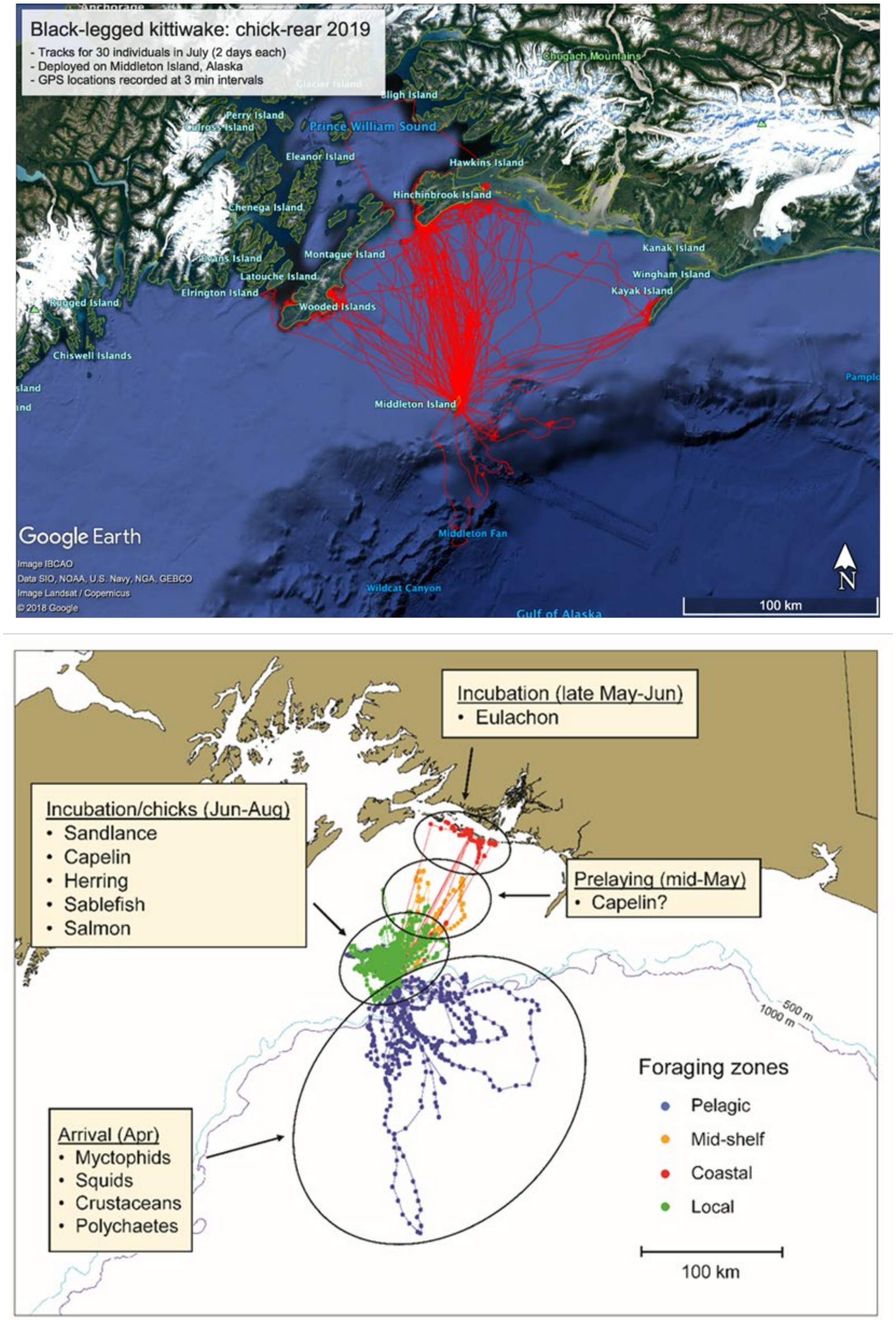

Figure 9. Foraging areas of Middleton Island kittiwakes during chick-rearing in 2019 (upper panel), and for comparison, use of pelagic and neritic foraging habitats by Middleton kittiwakes according to stage of breeding in 2008.

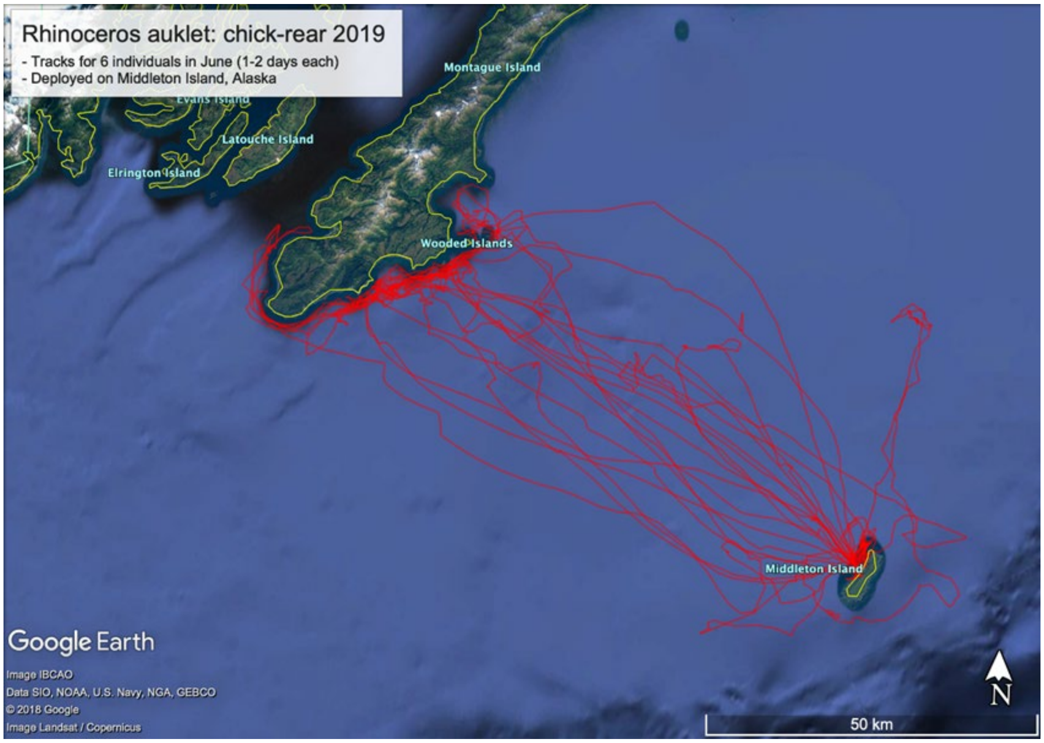

Figure 10. Foraging areas of rhinoceros auklets during chick-rearing as revealed by GPS tracking devices deployed on 6 individuals in 2019.

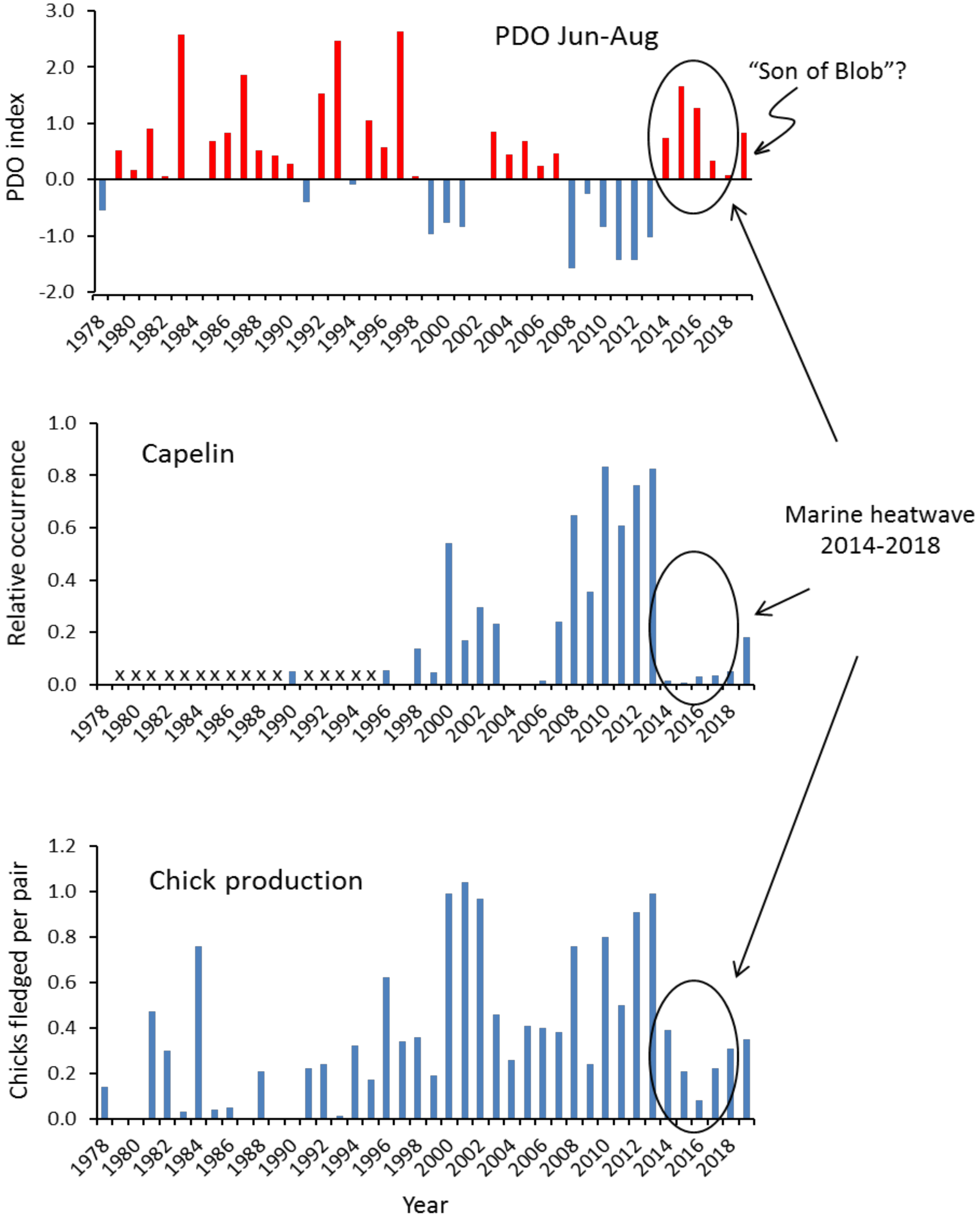

Figure 11. Relations among the Pacific Decadal Oscillation (PDO) index (June – August), the relative occurrence of dietary capelin, and the annual production of chicks by kittiwakes on Middleton Island, 1978 to 2019. Missing data denoted by 'x'.

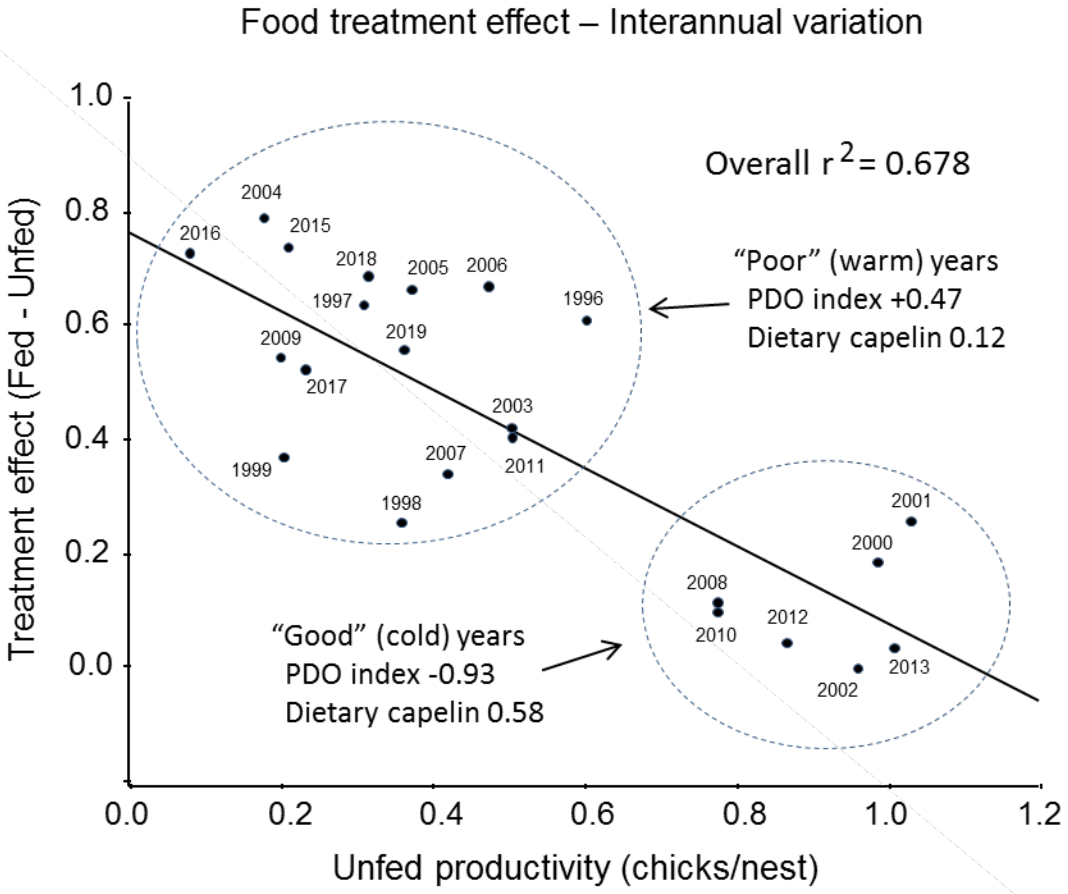

Fig. 12. Effect of supplemental food treatment on kittiwake breeding performance on Middleton Island in 23 years since 1996. Productivity of unfed pairs is a proxy for quality of the foraging environment. Treatment effect is the difference in productivity between supplementally fed and unfed pairs. "Poor" years are characterized by warm ocean conditions (PDO index June-August), a low proportion of capelin in the diet, and a marked effect of food treatment on kittiwake production. "Good" years have cool ocean conditions, a higher proportion of dietary capelin, and reduced or no difference in breeding performance of fed and unfed pairs.

Appendix Fig. 1. Nest boxes for rhinoceros auklets and tufted puffins are being installed at the Middleton station to facilitate future research and monitoring of these species.