**1. Program Number:**

18120114-C

**2. Project Title:**

LTM Program – Monitoring long-term changes in forage fish distribution, abundance, and body condition in PWS

**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, 2018-January 31, 2019

**5. Date of Report:**

April 1, 2019

**6. Project Website (if applicable):**

www.gulfwatchalaska.org

**7. Summary of Work Performed:**

The Gulf Watch Alaska (GWA) Forage Fish project has two main components including: 1) continuing the longest time series on forage fish abundance in the Gulf of Alaska, based on seabird diets at Middleton Island in collaboration with Scott Hatch (Institute for Seabird Research and Conservation [ISRC]), and, 2) ship-based surveys including the Integrated Predator Prey (IPP) survey in Prince William Sound (PWS) in collaboration with the humpback whale (PI John Moran, National Oceanic and Atmospheric Administration [NOAA], and PI Jan Straley, University of Alaska Southeast [UAS], project 18120114-O), and marine bird (PI Mary Anne Bishop, Prince William Sound Science Center [PWSSC], project 18120114-E) projects. In FY18 project tasks, including contracting, permitting, equipment calibrations, data management and field work, were conducted according to planned schedules and protocols. While our fall sampling is directed to humpback whale focal areas and predator prey aggregations, additional funding for FY19 will support summer sampling and provide PWS-wide indices of forage fish abundance, condition, and important species and age-class validation for the Herring Research and Monitoring (HRM) aerial surveys. In this report, we focus on 2018 field efforts, as detailed below.

**A. Middleton Island Forage Fish**

Seabird diet samples at Middleton Island were collected in April-August 2018. This included 439 diet samples from black-legged kittiwakes and 210 diet samples from rhinoceros auklets. A detailed report on findings from Middleton Island is provided as an appendix (Hatch 2018).

Briefly, kittiwake diets in April and May 2018 showed a relatively high proportion of myctophids, perhaps reflecting those species' resumption of near-surface migration at night (Fig. 1, Appendix). 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 in 2018, and juvenile pink and chum salmon had a poor showing in the kittiwake chick diets. During summer, kittiwake diets (Jun-Aug) and rhinoceros auklet chick diets (Jul-Aug) indicate greater composition of sand lance in 2018 compared to recent years (Fig. 2).

The foraging range of Middleton kittiwakes in 2018 was, on average, more extensive perhaps than in any prior year known from deployments of GPS tracking devices (see Appendix). During incubation, birds used deep-ocean waters regularly, including one record-setting pelagic trip reaching more than 200 km southeast of the island. But the majority of foraging occurred north of the island, particularly along the outer coasts of Hinchinbrook and Montague Islands, and extending to inside waters of PWS to a greater degree than was previously known. Chick-rearing kittiwakes accessed much the same area. The foraging area of rhinoceros auklets overlapped that of kittiwakes, but was largely confined to neritic waters north and northwest of Middleton during both incubation and chick-rearing phases of breeding. Auklets foraged regularly along the southeast coast of Montague Island, up to 100 km from their nest sites on Middleton.
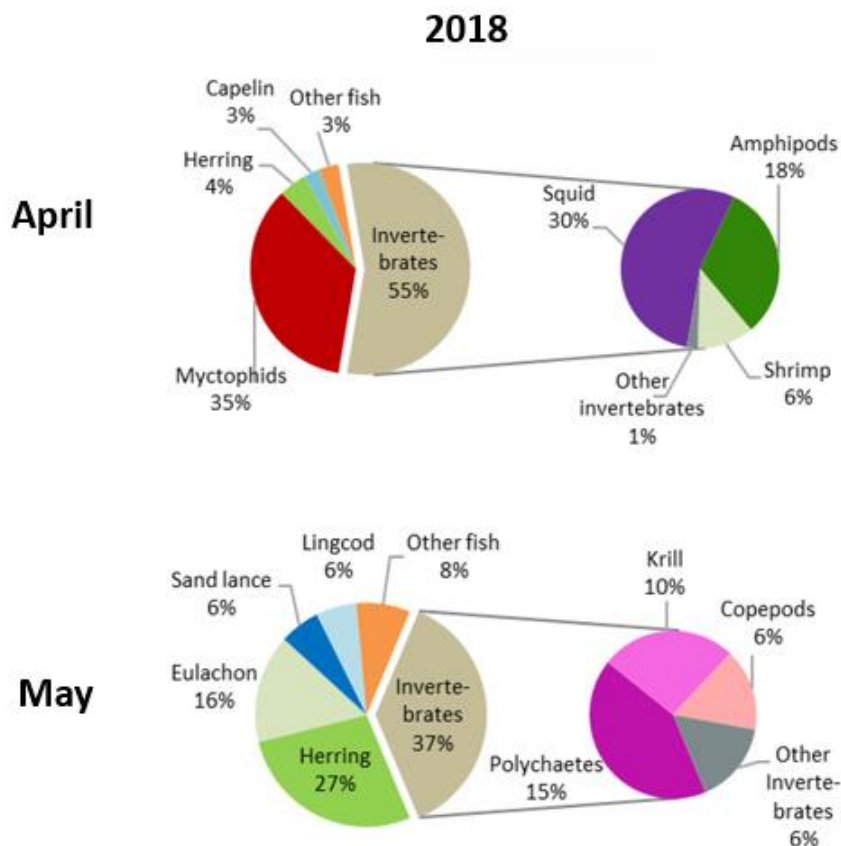


Figure 1. Middleton Island kittiwake diet composition (frequency of occurrence) in April and May 2018.
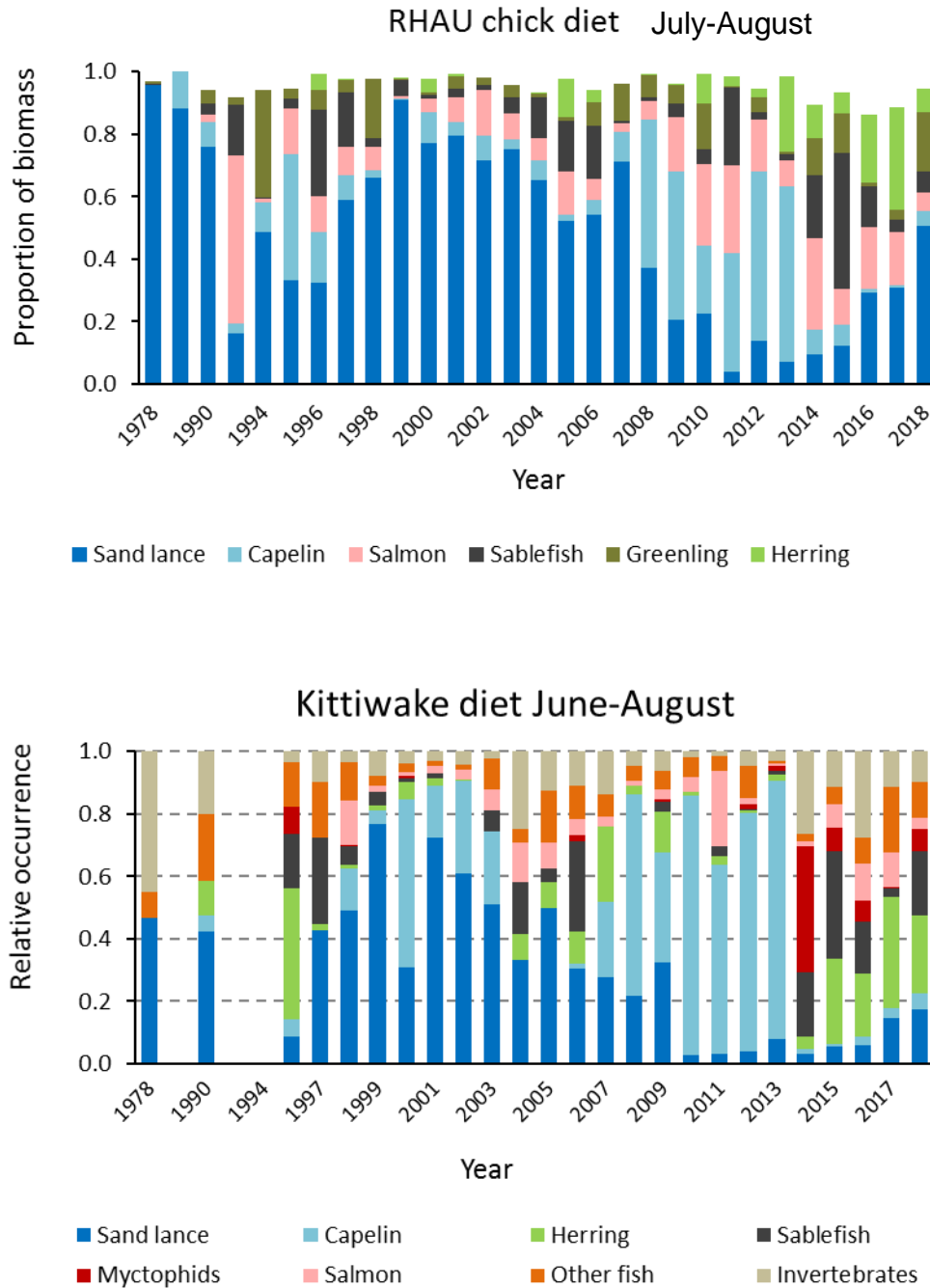
Figure 2. Interannual variation in diet composition of chick-rearing rhinoceros auklets (top) and black-legged kittiwakes (bottom) on Middleton Island 1978 to 2018.

## B. Integrated Predator Prey (IPP) Survey

In September 2018, we conducted the IPP survey in collaboration with the humpback whale and fall/winter marine bird surveys. Although we are still processing most of the datasets we collected, we summarize the effort and preliminary results below.

During a 10-day cruise aboard the M/V *Island C* on September 11-20 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. 3). Echosounder calibration was conducted at the beginning the survey 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 8 (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, photosynthetically 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 nautical area scattering coefficient (NASC) value for graphically representing differences in acoustic scattering characteristics in each region and year. 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.

Plots of acoustic fish and macrozooplankton indices reflect interannual variability in depth distribution and magnitude of acoustic backscatterance among regions (Figs. 4 and 5). In general, backscatter due to fish was more patchy, with large swaths of nearly empty water column in 2018 than was observed on the same transects in 2017. We encountered juvenile herring near the Needle in Montague Strait, in Hanning Bay, and in Port Gravina in 2018. Walleye pollock, which typically form a diffuse, weaker scattering layer were notably missing from Bainbridge and Montague Strait subareas in 2018 (e.g., see Fig. 4, Montague 2017 plot).
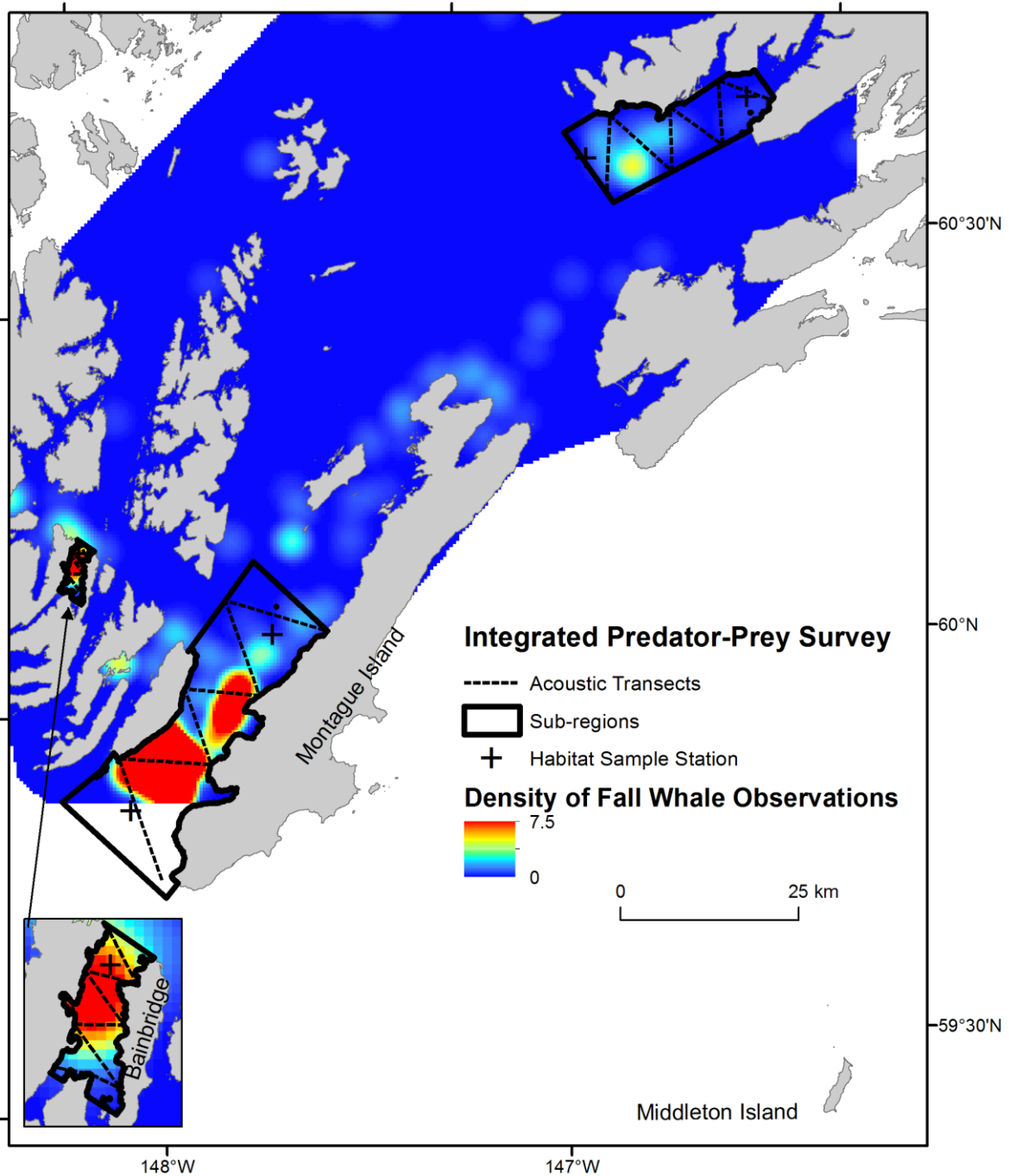
Figure 3. Map of Fall Integrated Predator Prey survey design in Prince William Sound.
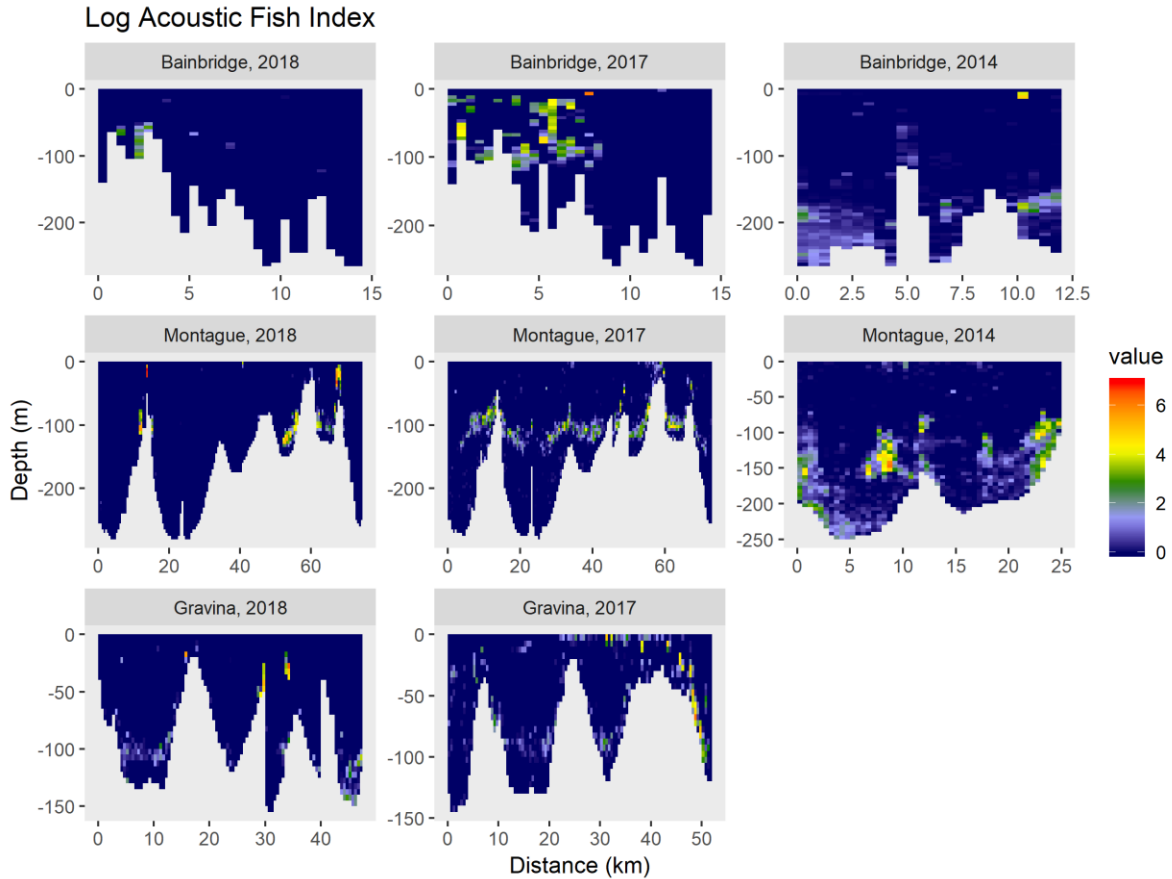
## Log Acoustic Fish Index



Figure 4. Acoustic index of fish relative to water column depth (y-axis) and distance along transects (x-axis, note differing scale for each plot based on effort). The color of each 5 m depth by 0.5 km grid cell represents the log-transformed mean NASC due to organisms with scattering properties of fish with swim bladders. Note that effort in Montague Strait covered only a fraction of the survey area in 2017 and 2018. Below bottom cells are represented in grey.

Acoustic indices of macrozooplankton also show changes in depth distribution and density of key forage taxa. Trawl samples revealed that this included primarily euphausiids, but also a mix of mysiids, amphipods and other large-bodied zooplankton taxa. In 2018, macrozooplankton layers were nearly absent from Bainbridge and parts of Montague Strait (particularly on the LaTouche Island side). The macrozooplankton scattering layer was denser and occupied a higher position in the water column in 2017 than in 2018 at Montague and Gravina subregions. Although fixed transects were not established until 2017, and survey effort was lower in 2014 (especially in Montague Strait) there was a striking difference in the macrozooplankton scattering layer in 2014 when greatest densities of macrozooplankton were observed over large portions of the water column (Fig. 5). This change in macrozooplankton as the basis for an important change in productivity of the system may help to explain the abrupt decline in humpback whale use in these areas since 2014.
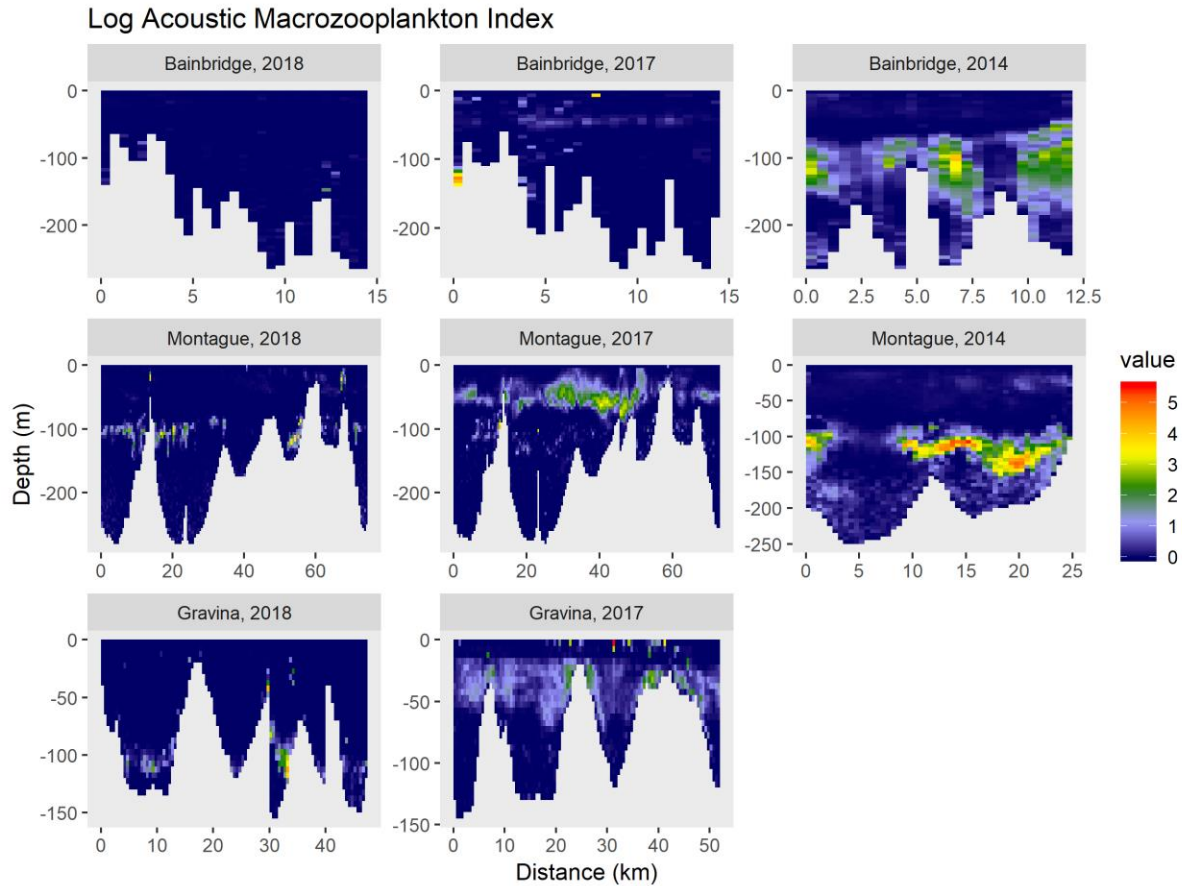
Figure 5. Acoustic index of macrozooplankton relative to water column depth (y-axis) and distance along transects (x-axis, note differing scale for each plot based on effort). Each 5 m depth by 0.5 km grid cell represents the log-transformed mean NASC due to organisms with scattering properties of marcozooplankton (e.g., euphausiids, amphipods, etc.). Note that effort in Montague Strait covered only a fraction of the survey area in 2017 and 2018. Below bottom cells are represented in grey.

We are still actively processing data collected during the September 2018 cruise. For example, in addition to fixed transects in three sub-regions with historically persistent predator aggregations, we also characterized prey density more closely associated with individual or groups of whales along 51 km of focal follows near feeding whales. A more detailed analysis of prey biomass indices, whale/marine bird prey composition, and habitat associations will be conducted when these data are processed.

| 8. | Coordination/Collaboration: |
|---|---|

### A. Projects Within a Trustee Council-funded program

#### 1. Within the Program

The forage fish project is integrated with two predator studies (PI Moran/Straley humpback whale, project 18120114-O and PI Bishop fall/winter marine birds, project 18120114-E), by operating at the same time and locations, and using the same vessels. The IPP surveys require close coordination with the humpback whale and winter bird component team leaders to conduct the work. This collaboration affords efficiencies in field work and facilitates greater understanding of predator-prey interactions in the Sound.

Additionally, now that the Middleton Island seabird diet collections are supported by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) within the forage fish program, these findings are useful for interpreting changes in seabird prey composition in PWS. The marine birds from Middleton are feeding in and around PWS (see Appendix), and therefore the seabird diet data collected at Middleton Island provides prey data that is relevant to marine bird trends in PWS.

#### 2. Across Programs

##### a. Herring Research and Monitoring

The GWA forage fish and humpback whale projects are closely aligned with the Herring Research and Monitoring (HRM) program through data collection and information sharing. We shared sampling platforms with HRM PI Kristin Gorman (PWSSC) on our IPP cruise to facilitate the collection of adult herring for her maturation study. Dr. Gorman conducted gill net sampling each night at anchorages during the cruise, which benefitted our fish sampling effort. In 2019 we will resume summer forage fish surveys in collaboration with HRM PI Scott Pegau (PWSSC).

##### 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.

##### c. Lingering Oil

NA

### B. Projects not Within a Trustee Council-funded program

NA

### C. With Trustee or Management Agencies

The Department of Interior has trust responsibility for migratory birds in Alaska. Under this mandate, and in conjunction with partners at the U.S. Fish and Wildlife Service, information regarding changes in seabird prey during the winter 2015-2016 common murre die-off in PWS and the Gulf of Alaska have been used extensively to understand the underlying cause of this event. The GWA forage fish and the Middleton Island long-term seabird diet data have provided key information on lower quantity and lower quality prey resources available to marine predators during the die-off.

The value of Middleton Island long-term seabird diets is recognized by the NOAA-National Marine Fisheries Service (NMFS) groundfish stock assessment team, and we contributed two time series indicators to the Ecosystems Status Report for the North Pacific Fisheries Management Council (Zador and Yasumiishi 2018). In 2016, the first Gulf of Alaska-wide trends for capelin and sand lance incorporate data from marine predators (piscivorous fish and seabirds) in the region. These data suggest steep declines in occurrence of capelin and sand lance in predator diets beginning in 2014. Another way Middleton Island data have been used to directly inform the NMFS stock assessment process is through the Ecosystem-Socioeconomic Profile summary for sablefish in Alaska (Shotwell et al. 2017). Because age-0 sablefish are difficult to study, Middleton Island seabird diets provide the only time-series information related to recruitment and age-0 growth for this commercially important species. In 2018 young of the year sablefish samples collected in seabird diets were provided to NMFS personnel for developing an index.

We are collaborating with North Pacific Research Board (NPRB) Gulf of Alaska Integrated Ecosystem Research Program (GOIERP) PIs (associated agencies) and are nearing completion of a synthesis of capelin in the Gulf of Alaska which will be submitted for peer-review publication in FY19. We are also providing forage fish and macrozooplankton samples collected during the IPP survey for a NPRB funded study on harmful algal blooms (PIs: Xiuning Du, Oregon State University, and Rob Campbell, PWSSC).

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**9. Information and Data Transfer:**

### A. Publications Produced During the Reporting Period

Arimitsu, M.L., J.F. Piatt, B. Heflin, V. von Biela, S.K. Schoen. 2018. Monitoring long-term changes in forage fish distribution, abundance and body condition in Prince William Sound. *Exxon Valdez* Oil Spill Restoration Project Final Report (Restoration Project 16120114-O), U. S. Geological Survey Alaska Science Center, Anchorage, AK. 64 pp.

Hatch, S.A., M. Arimitsu, J.F. Piatt. 2018. Seabird-derived forage fish indicators from Middleton Island *in* Zador, S. G., and E. M. Yasumiishi. 2018. Ecosystem Status Report 2018: Gulf of Alaska. Report to the North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99301. https://www.fisheries.noaa.gov/resource/data/2018-status-gulf-alaska-ecosystem

Piatt, J.F., M. Arimitsu, W. Sydeman, S.A. Thompson, H. Renner, S. Zador, D. Douglas, S. Hatch, A. Kettle, J. Williams. 2018. Biogeography of Pelagic Food Webs: Forage Fish Distribution and Habitat Use in the North Pacific Revealed by Puffins. Fisheries Oceanography. 27:366-380.

von Biela, V.R., M.L. Arimitsu, J.F. Piatt, B. Heflin, S. Schoen, J. Trowbridge, C. Clawson. In press. Extreme reduction in nutritional value of a key forage fish during the Pacific marine heatwave of 2014-2016. Marine Ecology Progress Series. doi: 10.3354/meps12891

Thompson, S.A., M. Garcia-Reyes, W.J. Sydeman, M. Arimitsu, S. Hatch, J. Piatt. In review. Effects of ocean climate on the size and condition of forage fish in the Gulf of Alaska: regional, species, and age-class comparisons. Submitted to Fisheries Oceanography.

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

Arimitsu, M.L., J.F. Piatt, B.M. Heflin, S.K. Schoen, V.R. von Biela. 2018. Ripples of the North Pacific heatwave: signals from seabirds and their forage base in the Gulf of Alaska. Poster Presentation. Ocean Sciences Meeting, Portland, OR. 11-16 February.

Arimitsu, M.L. 2018. Monitoring forage fish in Alaska: Detecting change in non-commercial prey populations. Oral Presentation. Department of Fisheries and Oceans Canada Forage Fish Workshop. Pacific Biological Station, Nanaimo, BC. 13-15 March. [Invited, travel paid by DFO]

Von Biela, V.R., M.L. Arimitsu, S.K. Schoen, B.M. Heflin, J.F. Piatt. 2018. Declining condition of a key forage fish in the Gulf of Alaska during the North Pacific marine heatwave. Oral Presentation. American Fisheries Society, Anchorage, AK. 21-25 May.

Du, X., R. Campbell, S. Kibler, K. Holderied, D. Hondolero, K. Shuster, R. Robinson, M. Arimitsu, J. Piatt. 2019. Prevalence of paralytic shellfish toxins in the marine food webs of Prince William Sound and Kachemak Bay, Alaska. Poster Presentation. Alaska Marine Science Symposium, Anchorage, AK. 28-31 January.

McGowan, D.W., M.L. Arimitsu, K. Coyle, A.L. Dreary, A. De Robertis, E.D. Golstein, K. Holderied, J.K. Horne, O. Ormseth, J.F. Piatt, L.A. Rogers, M.T. Wilson, S. Zador. 2019. Spatial and temporal dynamics of capelin (*Mallotus villosus*) in the Gulf of Alaska: implications for fisheries and ecosystem-based management. Oral Presentation. Alaska Marine Science Symposium, Anchorage, AK. 28-31 January.

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

NA

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

Final datasets and metadata for GWA 2017 were uploaded to the Gulf of Alaska Data Portal by May 2018. 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.

Additionally, the echointegration, fish catch, nutrients and CTD datasets from the September 2018 Integrated Predator Prey Survey were uploaded to the workspace by February 2019.

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 in February 2019. 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** (EVOSTC FY18 Work Plan)**:** The Panel was gratified to see a broader and stronger use of the Middleton Island monitoring data into the overall project and appreciates the sound science being conducted by the PIs. Huge improvements were made in data management, which can be attributed to the leadership of the Program.

**PI Response:** Thank you for the comment.

## 11. Budget:

| 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 | $230.1 | |
| Travel | | | $8.6 | $7.3 | $11.6 | $10.3 | $10.3 | $48.0 | $9.5 | |
| Contractual | | | $47.5 | $47.5 | $53.5 | $53.5 | $53.5 | $255.5 | $98.3 | |
| Commodities | | | $0.0 | $0.0 | $32.0 | $32.0 | $32.0 | $96.0 | $0.0 | |
| Equipment | | | $4.3 | $28.4 | $11.4 | $11.4 | $11.4 | $66.9 | $25.0 | |
| | | SUBTOTAL | $182.4 | $210.8 | $268.0 | $271.0 | $277.8 | $1,210.0 | $363.0 | |
| | | | | | | | | | | |
| General Administration (9% of | | | $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 | $256.0 | $256.0 | $1,280.0 | | |

Current expenditures of some line items exceed ± 10% deviation from the originally proposed amount in cases where reporting accounts lagged behind actual expenses, or due to inconsistencies between federal and EVOSTC fiscal year start dates, and because USGS budget system categories differ from those shown on the EVOSTC proposal. All expenditures are within keeping to our planned budget. Due to the government shut down some costs had not been charged to the account at the time of this report, however, these costs will even out over time and we expect to spend the total proposed budget amount by the end of the project.

## Literature Cited

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Hatch, S. A. 2018. Middleton Island Seabird Research and Monitoring 2018 Field Report. Institute for Seabird Research and Conservation. Anchorage, AK.

Shotwell, S. K., B. Fissel, and D. H. Hanselman. 2017. Ecosystem-Socioeconomic Profile of the Sablefish stock in Alaska. Appendix 3C in Assessment of the Sablefish stock in Alaska. 605 W 4th Ave, Suite 306, Anchorage AK 99501.

Zador, S. G., and E. M. Yasumiishi. 2016. Ecosystem Considerations 2016, Stock Assessment and Fishery Evaluation Report. North Pacific Fisheries Management Council. 605 W 4th Ave, Suite 306, Anchorage AK 99501.

Appendix



Middleton Island Seabird Research and Monitoring

2018 Field Report

## INTRODUCTION

The 2018 season marked the second year that seabird research and monitoring on Middleton Island 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 2018 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, the National Center for Scientific Research (CNRS-France) and the French Polar Institute (IPEV). 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 2018, the Middleton research station was occupied by members of the field crew from 5 April through 15 August.

## 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 0.54 chicks/egg laid, production in 2018 was a little lower than the long-term average of 0.68 (Table 1).

*Tufted Puffin*—Tufted puffins have struggled in recent years to rear young on Middleton. 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. With production of 0.35 chicks/egg in 2015, 0.24 in 2016.17 in 2017 (Table 1), puffins seemed recently to achieve at least a partial return to normal production, despite ocean conditions unfavorable to surface-feeders such as black-legged kittiwakes (see below). Continuing that trend, puffins in 2018 raised 0.43 chicks per egg laid, and despite their comparatively poor performance during breeding (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, where both numbers (~50-140 pairs) and breeding success (from ~0.1 to nearly 2 chicks per egg-laying pair) are highly variable (Table 2). Production in 2018 (0.8 chicks/nest) was halved from the previous year but close to the long-term average of 1.1 chicks/pair. On average, about 90 nests are constructed annually by cormorants on the tower, versus 84 nests in 2018. 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 72 fed pairs of kittiwakes on the Middleton tower, production was 0.99 fledglings/nest in 2018, whereas 134 unfed pairs produced 0.31 chicks/nest (Table 3). The difference between groups indicated poor foraging conditions in 2018 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. There were signs, however, of a nascent return to more normal foraging conditions, especially early in the 2018 season, as reported below.


DIETS

*Black-legged Kittiwake*—In most years since 2000, regurgitated food samples have been collected from adult and/or nestling kittiwakes on the tower during all months April 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, with 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 has been 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 the ongoing, exceptional warming event. Increased use of invertebrates seen over the course of this event 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 polycheates (the latter being a pelagic, swimming species apparently obtained only at night). In 2016, it appeared that 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 unexpected because the species is normally associated with warmer waters than usually occur 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 (Fig. 5). 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 three-spine sticklebacks during April (Fig. 5). 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 this year by cool-water conditions, at least in comparison to extreme years of the "warm blob" effect, 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 pre-breeding 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 this year, and juvenile pink and chum salmon had a poor showing in the chick diet (July and August).

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*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 2018 yielded 210 bill loads and ground samples, comprising about 7 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 124 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). Pacific herring seem also to have benefitted from the recent warming of surface waters in the region (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).

FORAGING AMBITS OF KITTIWAKES AND AUKLETS

The foraging range of Middleton kittiwakes in 2018 was, on average, more extensive perhaps than in any prior year known from deployments of GPS tracking devices. During incubation, birds used deep-ocean waters regularly, including one record-setting pelagic trip reaching more than 200 km southeast of the island (Fig. 8). But the majority of foraging occurred north of the island, particularly along the outer coasts of Hinchinbrook and Montague Islands, and extending to inside waters of Prince William Sound to a greater degree than was previously known. Chick-rearing kittiwakes accessed much the same area. The continued use of pelagic foraging during that time is thought to be exceptional, but was no doubt similar to, if less pronounced, than a situation that prevailed also during 2014, when the chick diet included myctophids and pelagic invertebrates in abundance (Fig. 2).

The foraging area of rhinoceros auklets overlapped that of kittiwakes, but was all but confined to neritic waters north and northwest of Middleton during both incubation and chick-rearing phases of breeding (Fig. 9). We were mildly surprised to find auklets foraging regularly along the southeast coast of Montague Island, up to 100 km from their nest sites on Middleton. Additional telemetry will likely find considerable flexibility in this regard, but the early lesson is that rhinoceros auklets, consistent with their reliable success at reproduction, are well adapted for coping with local food shortages when they 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 another 2 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." (Bond et al. 2015). Examples of dramatic species range shifts associated with this warm-water event are listed in Bond et al. (2015), to which we added 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 in 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. 10). 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 remained a relatively minor component of the spring diet through 2017. During most years there is an increase in the PDO monthly index in winter, with a temporally local peak around the time when kittiwakes are returning to colonies and preparing to breed in the northern Gulf of Alaska (Fig. 11). This pattern was less pronounced in 2017 and especially 2018, suggesting a possible return to normal background (i.e., "post-blob") conditions is in the offing. However, the continued large effect of supplemental feeding on laying dates and clutch sizes in 2017 and 2018 (Table 8) confirms the continued difficulty kittiwakes are having in acquiring sufficient energy for breeding.

That 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 2014-2018 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 shows signs of a possible return to ocean conditions expected if a predominantly negative phase of the PDO ultimately prevails in spite of temporary disruptions such as the warm-water anomaly so notorious of late. Thus, we look forward to the next iteration, possibly in 2019, 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 predicted to last through the 2030s, all else being equal. Global warming could potentially have a counteracting effect, 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 a window on the future.

**LITERATURE CITED**

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Table 1. Productivity of rhinoceros auklets and tufted puffins breeding on Middleton Island in 2015-2018.

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

Table 2. Breeding performance of pelagic cormorants on the Middleton tower, 2002-2018.[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 | 0.11 | 0.898 | 84 | 0.8 | 0.09 | 0.784 |
| Totals | 1,344 | 149.8 | 0.97 | 8.61 | 1,437 | 3.2 | 0.13 | 1.202 | 1,437 | 1.1 | 0.12 | 1.061 |

[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, 1996-2018.[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 |

[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 – 2018.

| Year | Adults | | | June | | | July | | | August | | | Total |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | 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 |
| Total | 114 | 946 | 725 | 312 | 157 | 469 | 434 | 2093 | 2527 | 86 | 569 | 655 | 5436 |

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 2018.

| Year | | | Prey type identifications | | | | |
|------|-------|-------|------|------|------|--------|-------|
| | 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 |
| Total | 129 | 1354 | 835 | 565 | 3218 | 863 | 6964 |

Table 6. Food samples (bill loads, partial bill loads, and ground samples) obtained annually from rhinoceros auklets on Middleton Island from 1978 through 2018.

| 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 |
| All years | 4390 | 123,880.8 |

Table 7. Time series of kittiwake productivity, dietary capelin and PDO index during the breeding season on Middleton Island from 1978 through 2018.

| 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 |

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 |
| Mean | -3.72 | 0.33 | 0.42 |

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 38 years between 1978 and 2018.

| Variable | Statistic | Variable | |
| | | Chick production | Capelin in diet |
| --- | --- | --- | --- |
| Capelin in diet | | | |
| | Pearson's $r$ | 0.691 | --- |
| | $P$ (2-tailed) | <0.001 | --- |
| | n (years) | 25 | --- |
| PDO (Jun-Aug) | | | |
| | Pearson's $r$ | -0.594 | -0.700 |
| | $P$ (2-tailed) | <0.001 | <0.001 |
| | n (years) | 39 | 25 |

# 1978 - 2018

## All months



Sablefish 5%
Salmon 3%
Herring 7%
Other fish 9%
Myctophids 9%
Sand lance 24%
Capelin 19%
Invertebrates 24%

## April

Herring 3%
Other fish 2%
Sand lance 10%
Capelin 19%
Invertebrates 38%
Myctophids 28%

## May

Myctophids 8%
Herring 9%
Other fish 10%
Capelin 30%
Invertebrates 24%
Sand lance 19%

## Jun-Aug

Salmon 5%
Myctophids 3%
Sablefish 8%
Other fish 9%
Herring 10%
Invertebrates 13%
Sand lance 29%
Capelin 23%

Figure 1. Overall composition of food samples obtained from black-legged kittiwakes (relative occurrence, April – August) on Middleton Island from 1978 to 2018.
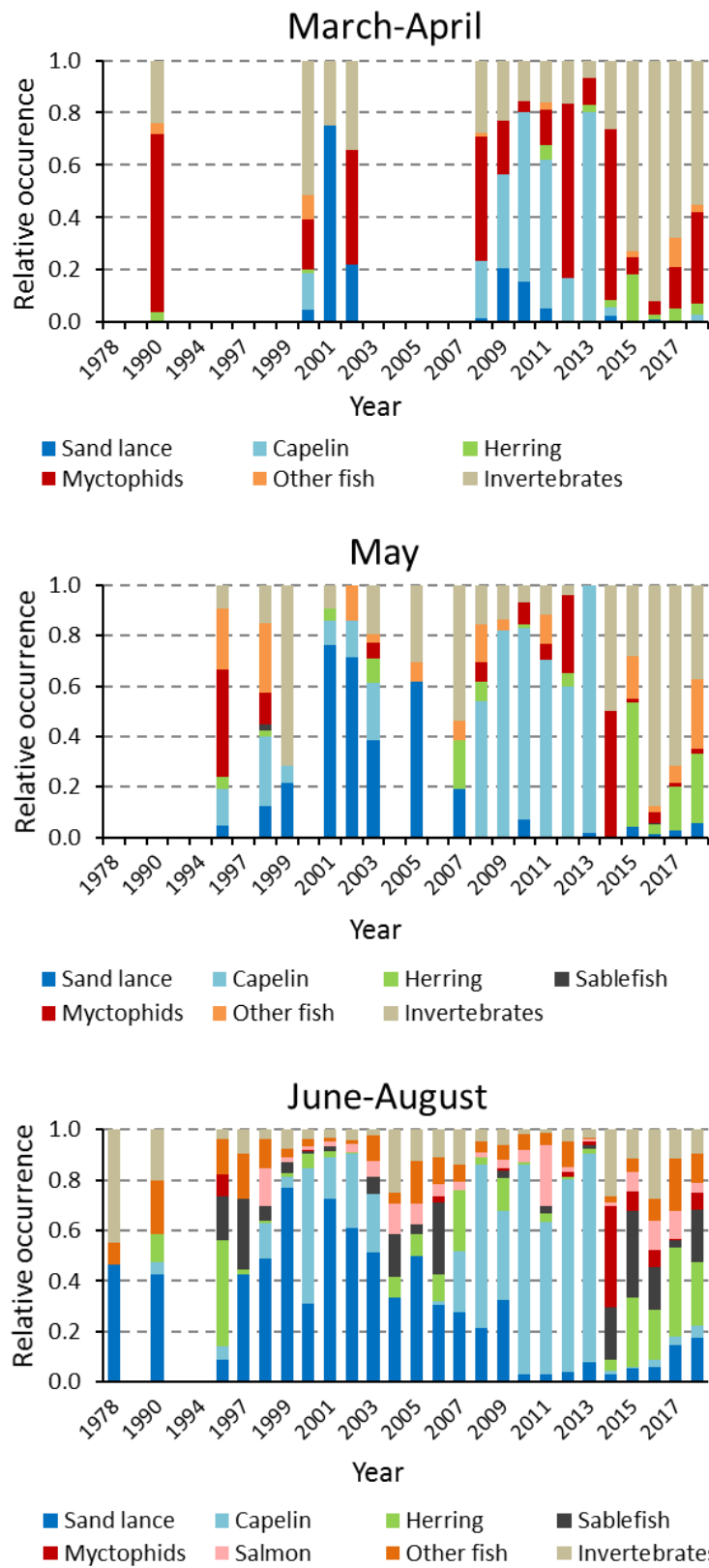
Figure 2. Interannual variation in kittiwake diet composition at three stages of breeding on Middleton Island, 1978 to 2017. Sample sizes as listed in Tables 4 and 5.
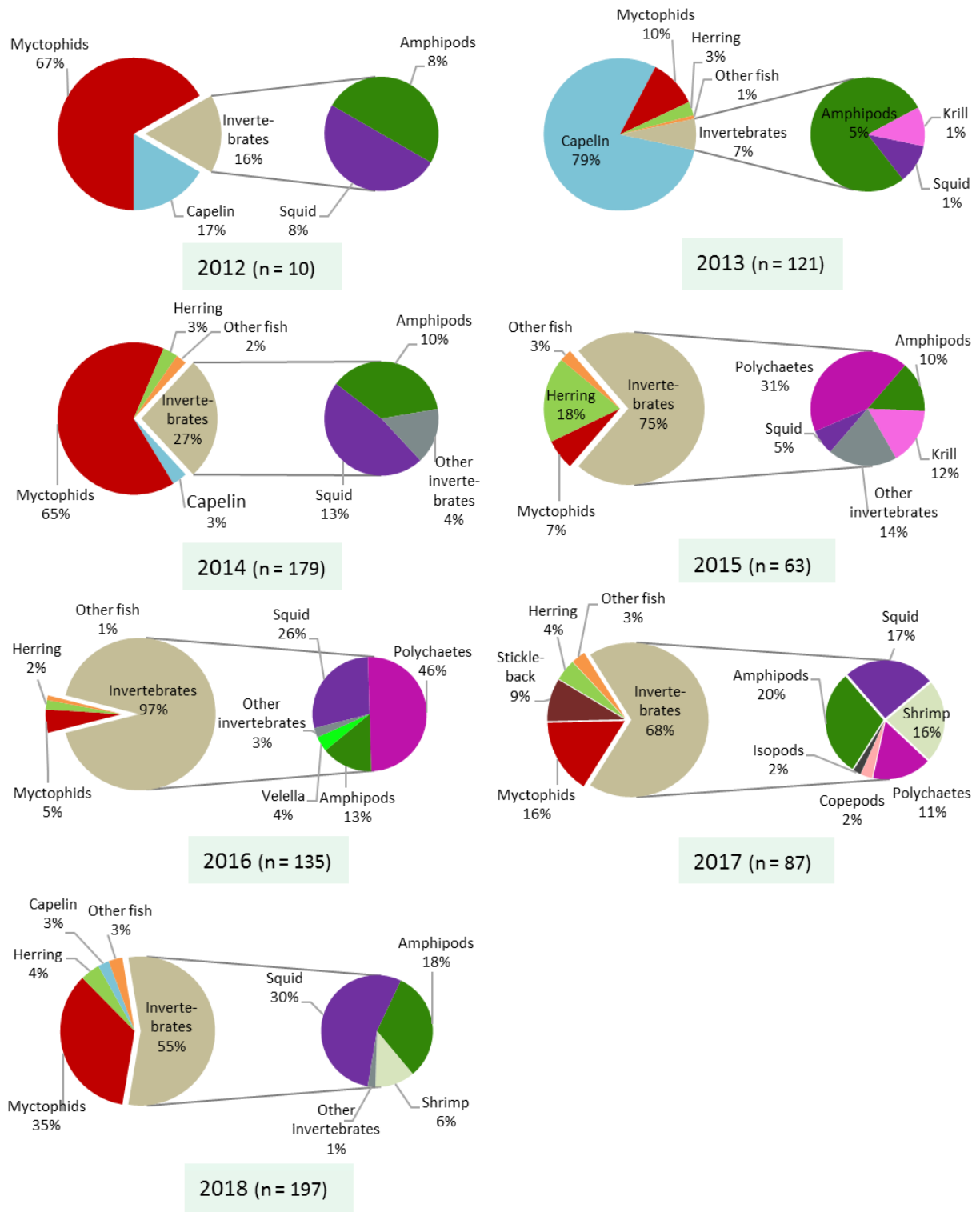
Figure 3. Variation in the relative occurrence and composition of fish and invertebrates in the diet of black-legged kittiwakes on Middleton Island from spring arrival through April in 2012-2018.

# May
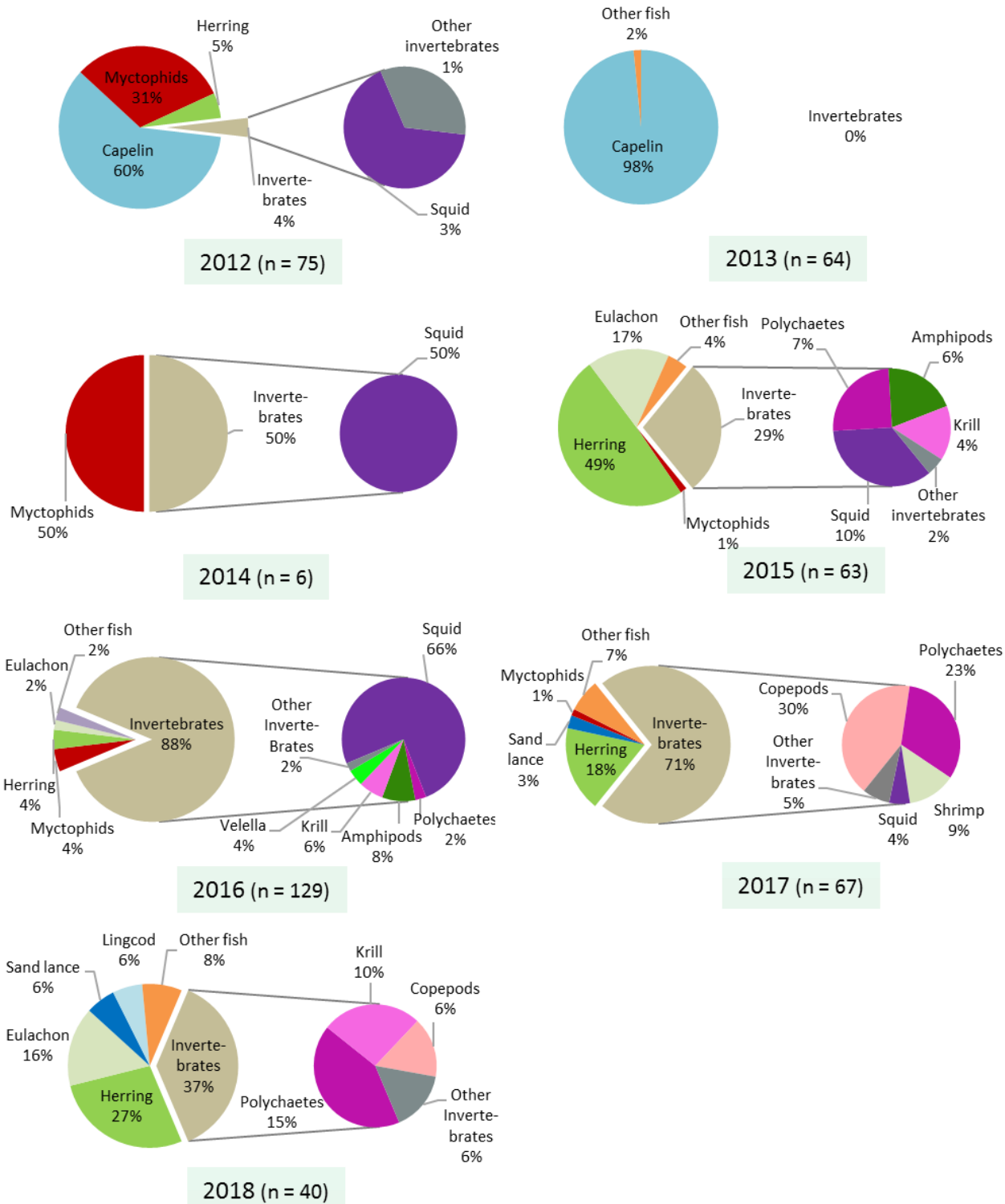


Figure 4. Variation in the relative occurrence and composition of fish and invertebrates in the diet of black-legged kittiwakes on Middleton Island during May in 2012-2018.
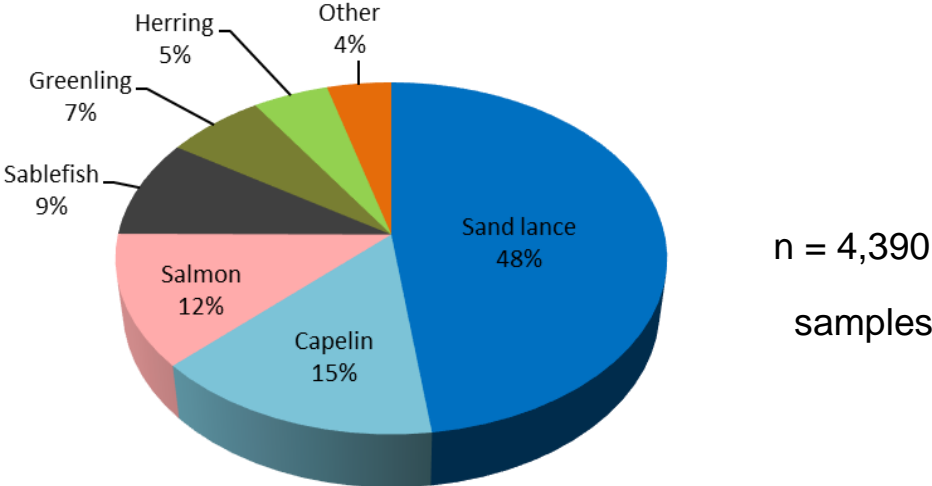
Figure 5. Overall composition of food samples obtained from chick-rearing rhinoceros auklets (% biomass, July-August) on Middleton Island from 1978 through 2018.

## RHAU chick diet

Legend: Sand lance, Capelin, Salmon, Sablefish, Greenling, Herring

## Kittiwake diet June-August

Legend: Sand lance, Capelin, Herring, Sablefish, Myctophids, Salmon, Other fish, Invertebrates
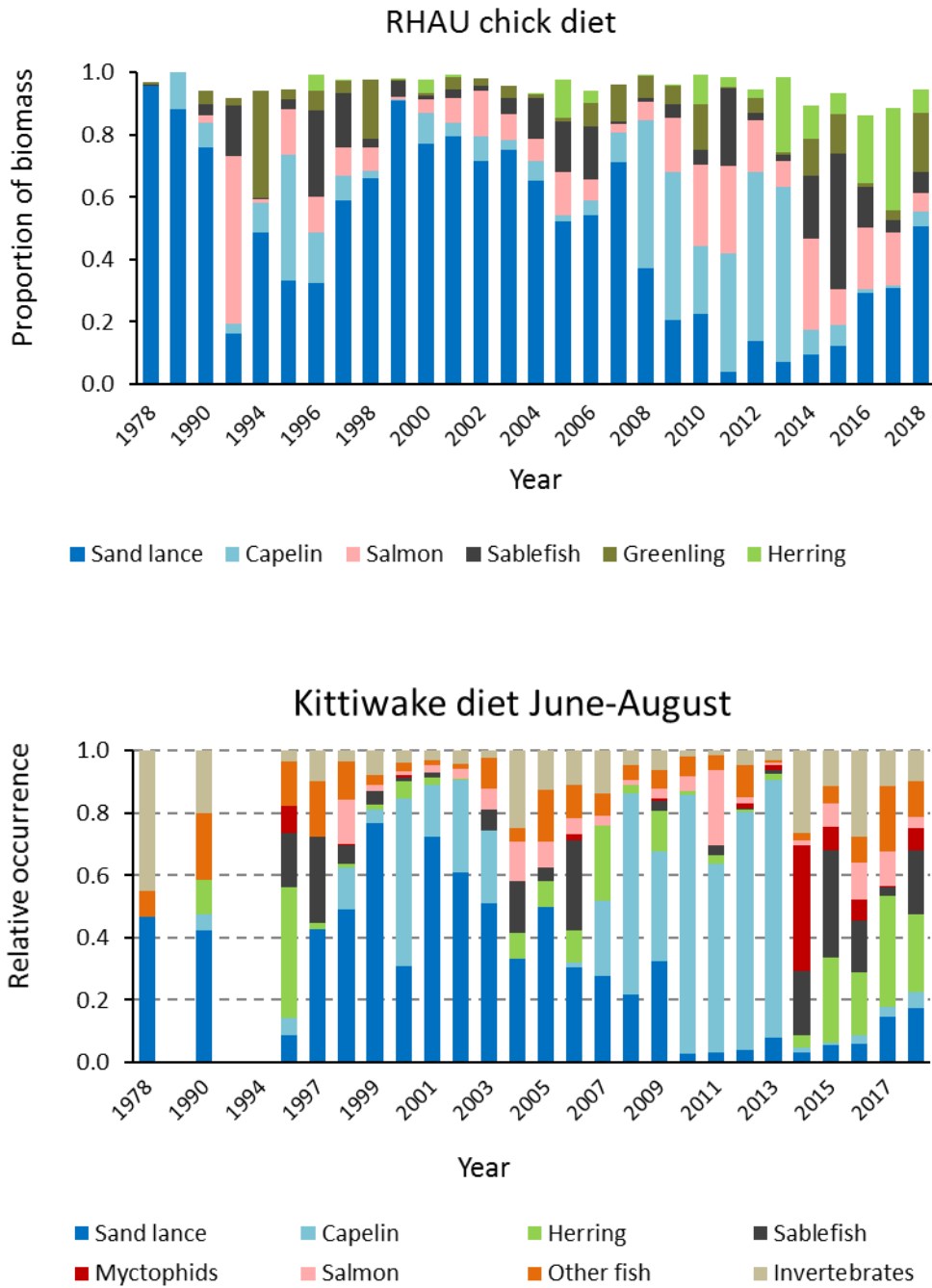
Figure 6. Interannual variation in diet composition of chick-rearing rhinoceros auklets on Middleton Island, 1978 to 2018, with a similar time series for black-legged kittiwakes (lower panel) for comparison. Sample sizes as listed in Tables 4, 5 and 6.
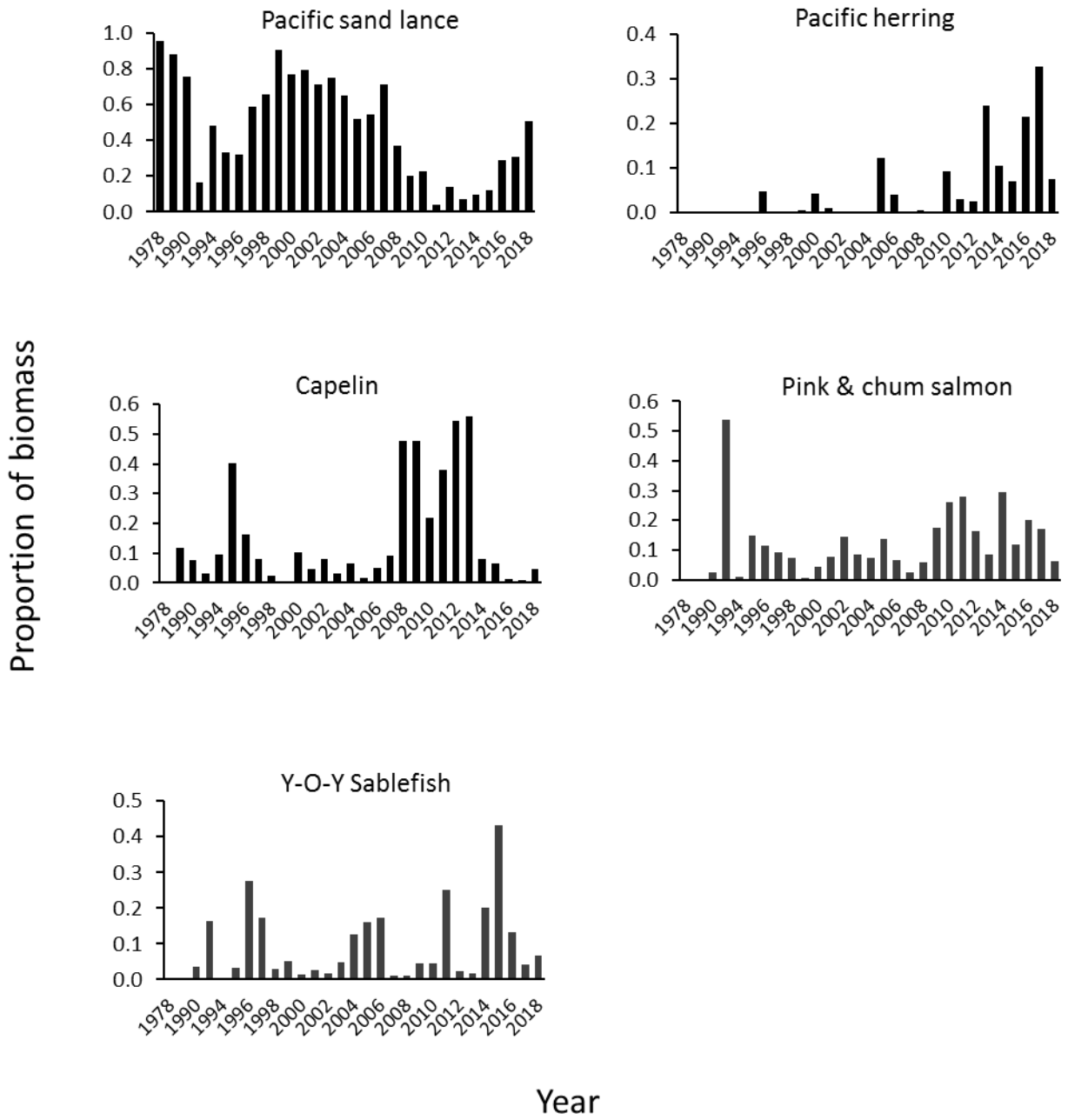
Figure 7. Indices of prey species occurrence in the nestling diet of rhinoceros auklets on Middleton Island from 1978 through 2018.
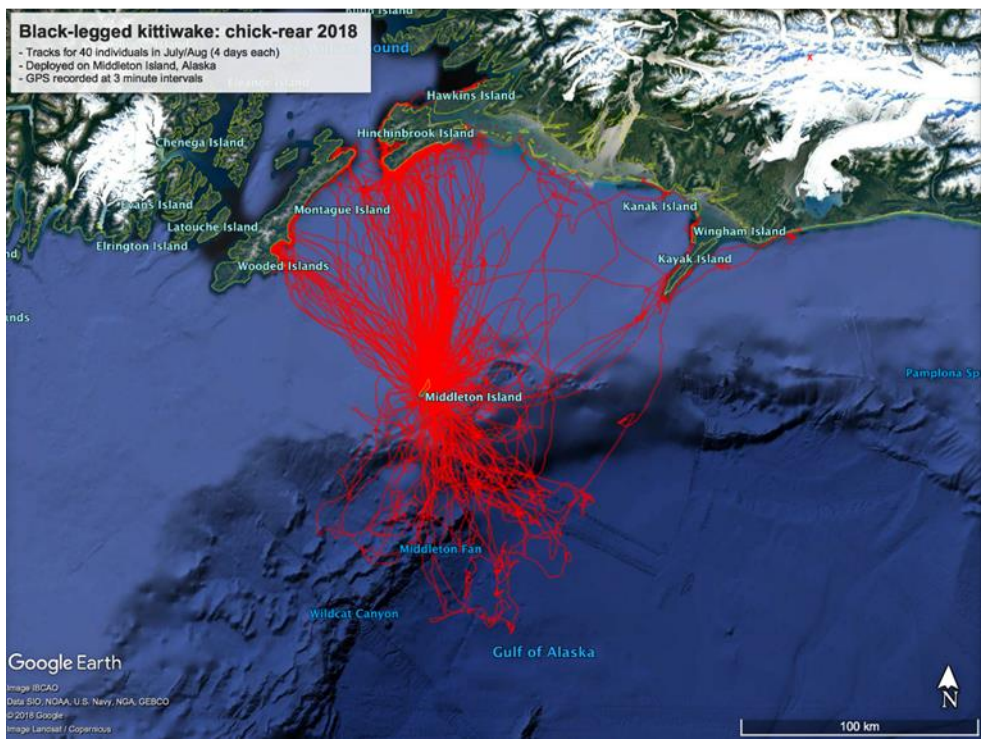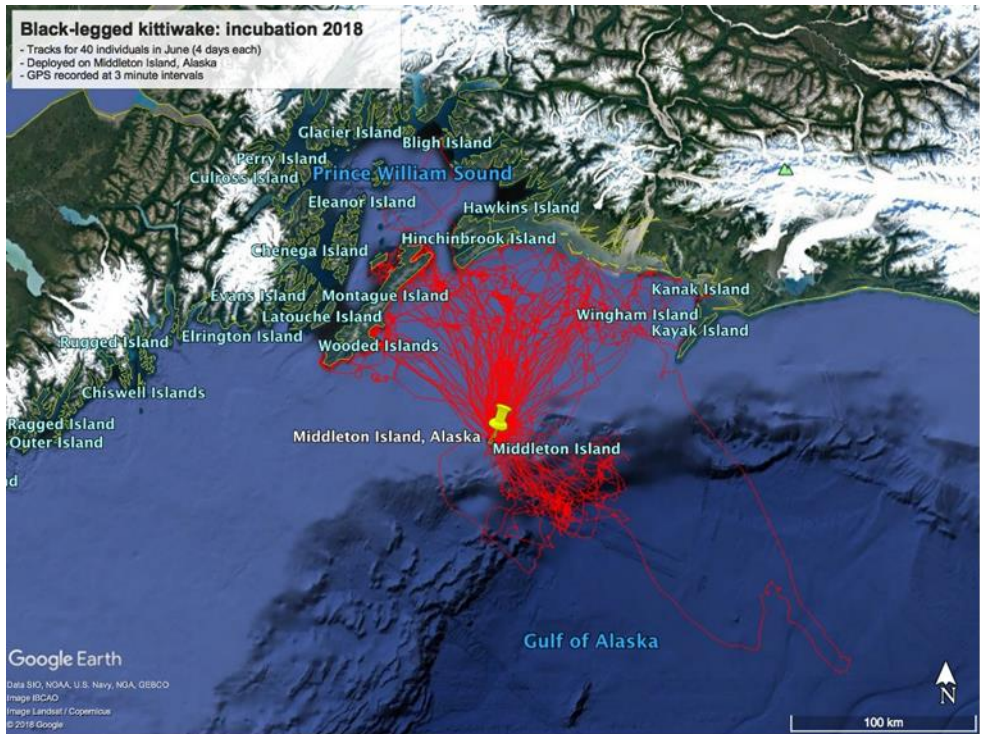
Figure 8. Foraging areas of Middleton Island kittiwakes during incubation (upper panel) and chick-rearing (lower panel) as revealed by GPS tracking devices deployed on 40individuals at each stage of breeding in 2018.
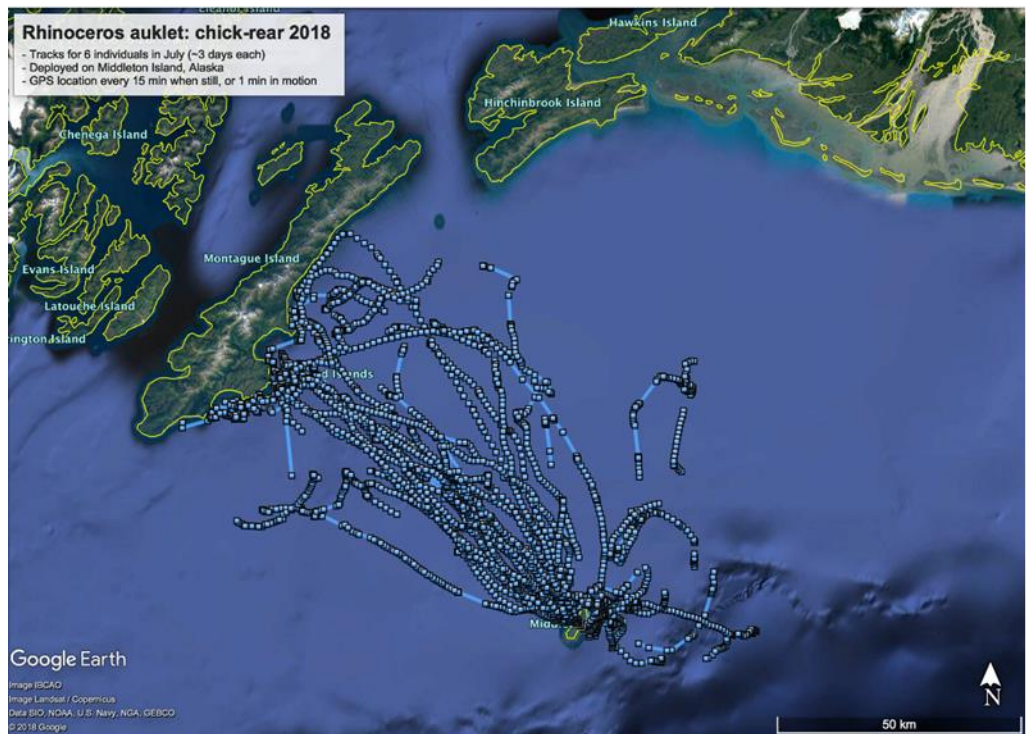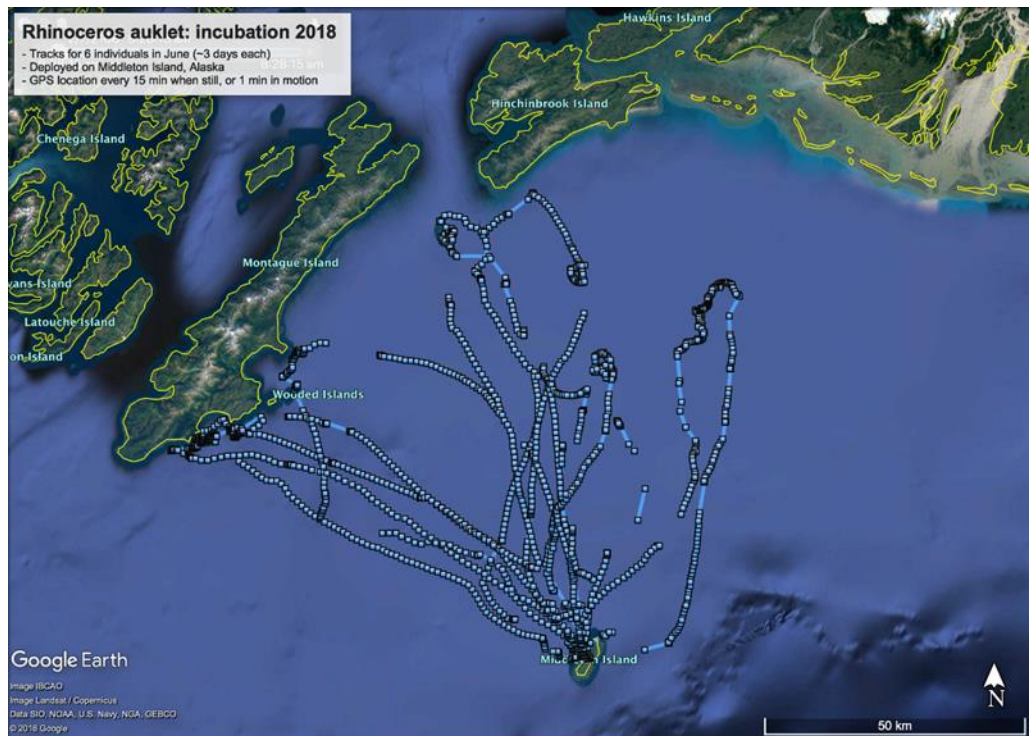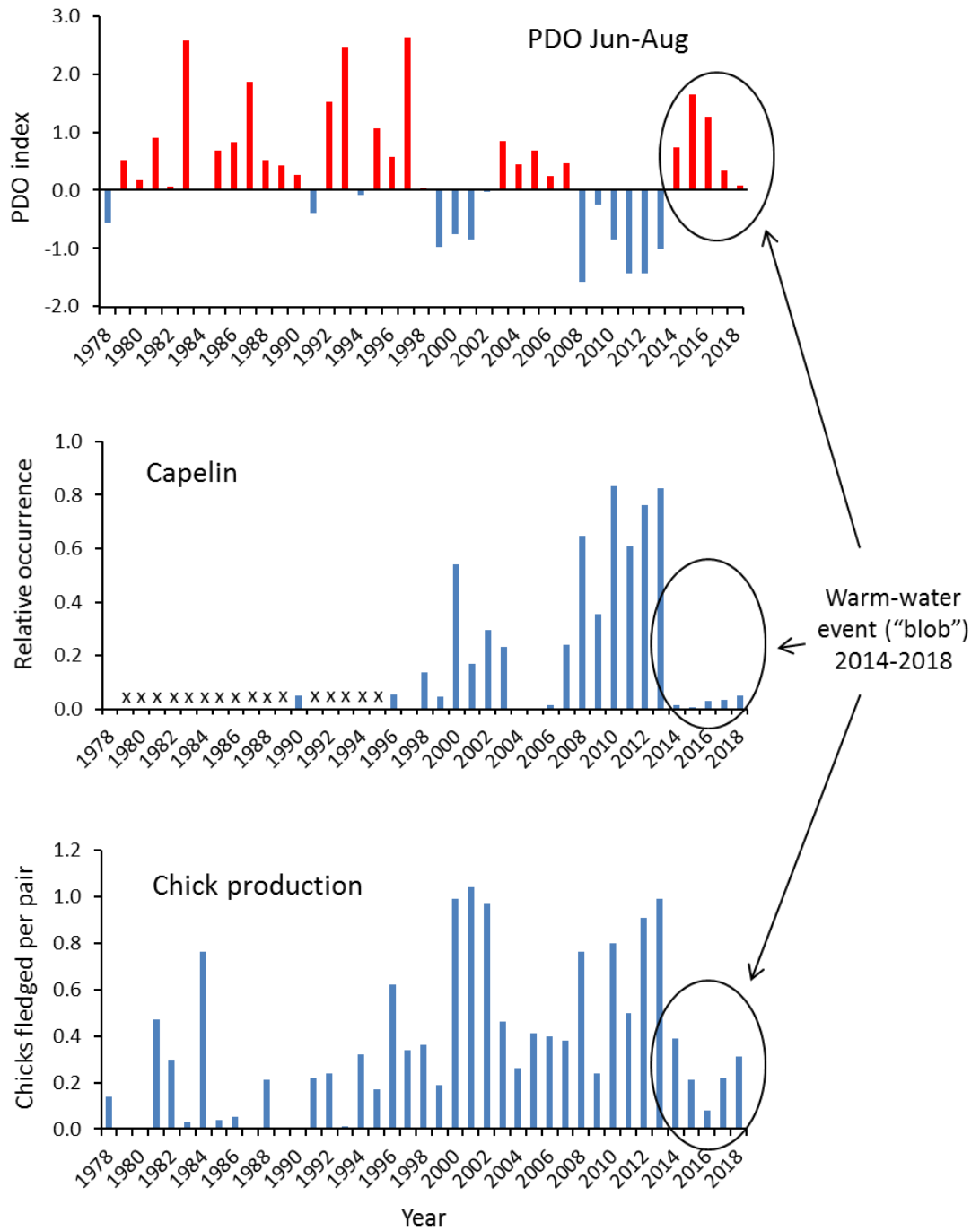
Figure 9. Foraging areas of rhinoceros auklets during incubation (upper panel) and chick-rearing (lower panel) as revealed by GPS tracking devices deployed on 6 individuals at each stage of breeding in 2018.

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Figure 10. 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 2017. Missing data denoted by 'x'.
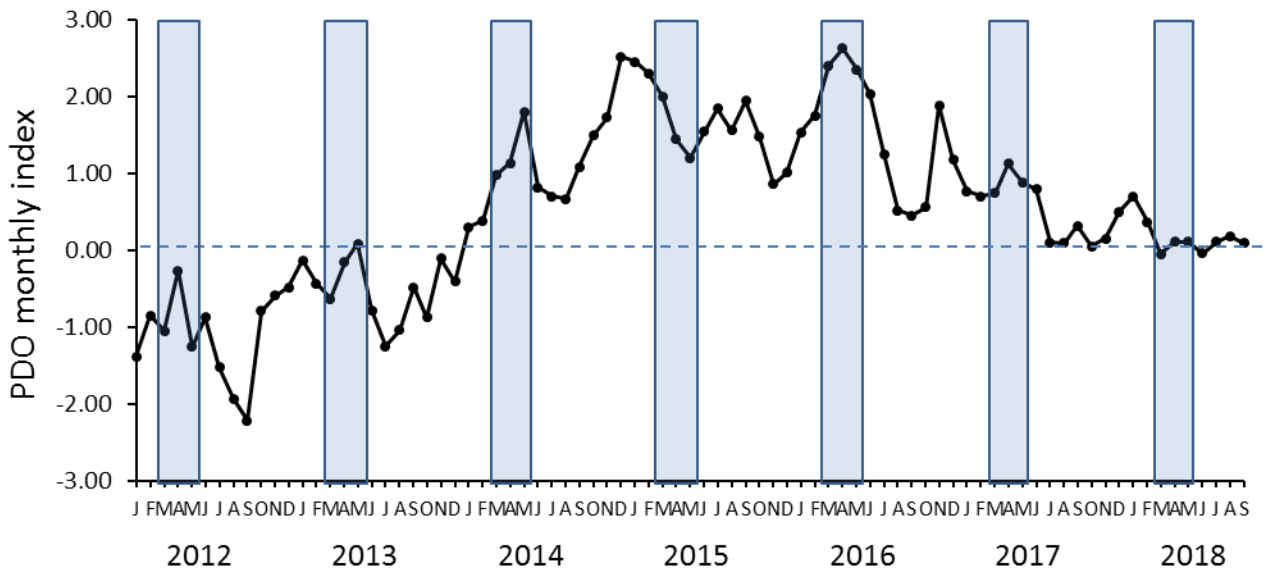
Figure 11. Pacific decadal oscillation (PDO) monthly index from January 2012 through September 2018, illustrating changes during the warm-water event from 2014-2018 and conditions prevailing during the spring prebreeding period (March – May) of kittiwakes on Middleton Island.
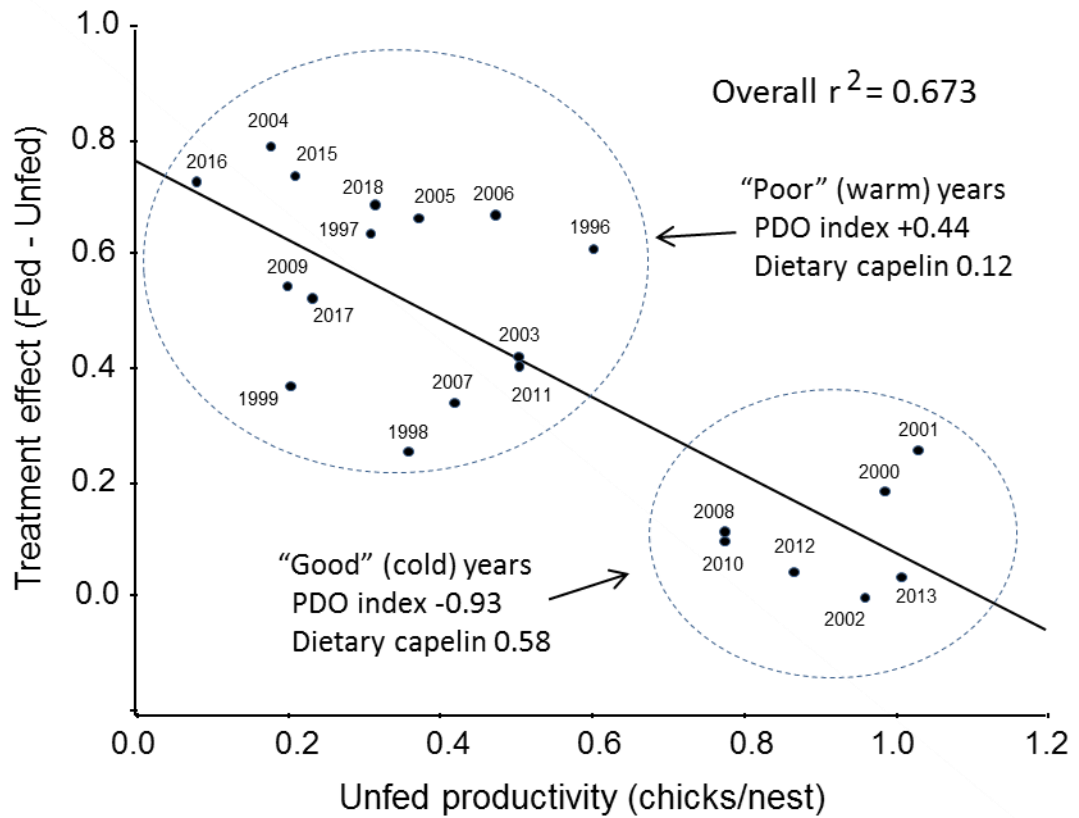
Fig. 12. Effect of supplemental food treatment on kittiwake breeding performance on Middleton Island in 23 years since 1996. Productivity of unfed pairs is a proxy for quality of the foraging environment. Treatment effect is the difference in productivity between supplementally fed and unfed pairs. "Poor" 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.