OCS Study
BOEM 2022-020

Arctic Ecosystem Integrated Survey, Phase II: Seabird Community Structure and Seabird-Prey Dynamics




U.S. Department of the Interior
Bureau of Ocean Energy Management
Alaska Regional Office
Anchorage, Alaska 99503-5820

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by

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ABOUT THE COVER

Clockwise from upper left: Alcids flying past Diomede islands in the Bering Strait, photo by K. Kuletz. Gliding northern fulmar, photo by K. Kuletz. Mixed flock with black-legged kittiwakes on ice, photo by E. Labunski. Short-tailed shearwater, photo by Z. Pohlen.

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List of Abbreviations and Acronyms

ACC	Alaska Coastal Current
ACCAP	Alaska Center for Climate Assessment and Policy
AMBON	Arctic Marine Biodiversity Observing Network
AOOS	Alaska Ocean Observing System
AIERP	Arctic Integrated Ecosystem Research Program
AMBON	Arctic Marine Biodiversity Observing Network
Arctic IES	Arctic Integrated Ecosystem Survey
ASGARD	Arctic Shelf Growth, Advection, Respiration and Deposition Rate Experiments
BOEM	Bureau of Ocean Energy Management
CAFF-CBMP	Conservation of Arctic Flora and Fauna-Circumpolar Biodiversity Monitoring Program
Chl-a	Chlorophyll-A
CTD	Conductivity-Temperature-Depth
DBO	Distributed Biological Observatory
ESA	Endangered Species Act
GIS	Geographic Information System
IAA	Interagency Agreement
IARPC	Interagency Arctic Research Policy Committee
LME	Large Marine Ecosystem
LTL	Lower trophic level
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
NPPSD	North Pacific Pelagic Seabird Database
NPRB	North Pacific Research Board
PSG	Pacific Seabird Group
psu	Practical salinity unit
UAF	University of Alaska Fairbanks
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UTL	Upper trophic level
WGICA	Working Group on Integrated Ecosystem Assessment for the Central Arctic Ocean

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List of Presentations and Outreach Efforts

Conference presentations

2021

Kuletz K. 2021. Seabirds in a changing Arctic in “Connecting Alaska’s Marine and Coastal Biodiversity to the Circumpolar Arctic.” Alaska Marine Science Symposium, Anchorage, Alaska, January 2021. Virtual panel presentation.

Kuletz K, Yeates L. 2021. The parallel adventures of short-tailed shearwaters and cross-hemispheric art project: from Australia to Alaska and back in the year of COVID-19. Alaska Marine Science Symposium, Anchorage, Alaska, January 2021. Virtual poster.

Kuletz K, Yeates L. 2021. The parallel adventures of short-tailed shearwaters and cross-hemispheric art project: from Australia to Alaska and back in the year of COVID-19. Pacific Seabird Group Annual Meeting, February 2021. Virtual poster.

Kuletz K, Cushing D, Labunski E. 2021. Short-tailed Shearwater timing and movement though Alaska’s seas, based on at-sea surveys 2007–2019. Pacific Seabird Group Annual Meeting, February 2021. Virtual oral presentation.

Kuletz K, Cushing D, Mueter F, Osnas E, Kimmel D, Labunski E, Levine R, De Robertis A. 2021. Peak ocean temperatures cap long-term warming in the eastern Pacific Arctic and slams seabirds. World Seabird Conference, Symposium on “Mechanisms by which extreme heat anomalies impact seabirds,” October 2021. Virtual oral presentation.

2020

Kuletz K, Cushing D, Mueter F, Osnas E, Kimmel D, Labunski E, Gall A, Renner H, Dragoo D. 2020. Seabirds signal changes in the Pacific Arctic. Alaska Marine Science Symposium, January 2020, Anchorage, Alaska. Oral presentation.

Kuletz K, Cushing D, Mueter F, Osnas E, Kimmel D, Labunski E, Gall A, Renner H, Dragoo D. 2020. Seabird signals in a warming Northern Bering-Chukchi Sea ecosystem. Pacific Seabird Group Meeting, Portland, Oregon, February 2020. Oral presentation.

Kuletz K, Cushing D, Mueter F, Labunski E, Gall A. 2020. Seabirds signal a changing Pacific Arctic. Ocean Sciences Meeting, San Diego, California, February 2020. Oral Presentation. (See Appendix B for a copy of this presentation.)

Farley, E. 2020. Arctic Integrated Ecosystem Research Program: Are we experiencing the future Arctic? Alaska Marine Science Symposium, Anchorage, Alaska, January 2020. Oral presentation.

Lanctot, R, Krietsch J, Valcu M, Kuletz K, Saalfeld S, Cushing D, Robards M, McGuire R, Schulte S, Brown S, Latty C, Harrison A, Kempenaers B. 2020. Use of satellite tagged birds and at-sea surveys to document Red Phalarope distribution and migration routes in the Beaufort, Chukchi and Bering Seas. Alaska Marine Science Symposium, January 2020, Anchorage, Alaska, January 2020. Poster.

Pinchuk AI, Will AP, Takahashi A, Thiebot JB, Kuletz KJ, Kitaysky AS. 2020. Diets of Plankton-eating Auklets Reveal Consequences of Recent Oceanographic Changes in the Alaskan Subarctic. Alaska Marine Science Symposium, Anchorage, Alaska, January 2020. Poster.

Raymond R, Kuletz K, Lanctot R, Labunski E. 2020. BOEM's Alaska Environmental Studies Program: A Review of the at-sea seabird surveys and Red Phalarope tracking study. Ocean Science Meeting, San Diego, California, February 2020. Poster.

2019

Kuletz K, Cushing D, Osnas E, Labunski E, Gall A. 2019. Pacific Arctic seabird communities: a decade of change viewed through the lens of the Distributed Biological Observatory's at-sea surveys. American Ornithological Society Annual Meeting, Anchorage, Alaska, June 2019. Oral presentation.

Labunski E, Kuletz K, Osnas E. 2019. Seasonal offshore distribution and habitat use of Brachyramphus murrelets in Alaska. American Ornithological Society Annual Meeting, Anchorage, Alaska, June 2019. Oral presentation.

Kuletz K, Cushing D, Osnas E, Mueter F, Labunski E, Gall A. 2019. Pacific Arctic seabird communities in a time of change. PICES annual meeting, Victoria, British Columbia, October 2019. Poster.

2018

Kuletz K, Cushing D, Osnas E, Labunski E, Gall A, Morgan T. 2018. Seabirds as indicators for the distributed biological observatory and other long-term marine monitoring programs. Alaska Marine Science Symposium, Anchorage, Alaska, January 2018. Oral presentation.

Kuletz K, Cushing D, Osnas E, Labunski E. 2018. Seabirds as indicators for the Distributed Biological Observatory and other long-term marine monitoring programs. Pacific Seabird Group Annual Meeting, La Paz, Mexico, February 2018. Oral presentation.

Presentations for Workshops and Collaborations

Information about the at-sea surveys and our results were also presented during various workshops and collaborations, including:

2021

- Pacific Seabird Group (PSG) annual meeting, virtual. Contributed to presentations for the North Pacific Albatross Working Group, Marbled Murrelet Technical Committee, Kittlitz's Murrelet Technical Committee, Tufted Puffin Technical Committee, and Short-tailed Albatross Recovery Team, February 2021, virtual.
- National Oceanic and Atmospheric Administration (NOAA) Alaska Seabird Bycatch Working Group, March 2021, virtual.
- North Pacific Fisheries Management Council's Science and Statistical Team meeting, April 2021, virtual.

2020

- Distributed Biological Observatory Workshop, Seattle, Washington, January 2020.

- Arctic Marine Biodiversity Observing Network (AMBON) Principal Investigators' meeting, January 2020.
- AIERP Principal Investigators' meeting, Anchorage, Alaska, February 2020.
- PSG annual meeting, Portland, Oregon, February 2020. Contributed to presentations for: the North Pacific Albatross Working Group, Marbled Murrelet Technical Committee, Kittlitz's Murrelet Technical Committee, Tufted Puffin Technical Committee, Short-tailed Albatross Recovery Team, February 2020.
- NOAA Alaska Seabird Bycatch Working Group, March 2020.
- ICES/PICES/PAME/ Working Group on Integrated Ecosystem Assessment for the Central Arctic Ocean (WGICA), report submitted March 2020.
- Arctic Research Policy Committee (IARPC), April 2020.
- Department of Interior Senior Ocean Policy Team, June 2020.
- Alaska Center for Climate Assessment and Policy (ACCAP) and Alaska Ocean Observing System (AOOS), July 2020.
- Alaska Migratory Bird Co-Management Council, September 2020.
- AIERP Principal Investigator meeting, November 2020, virtual.
- Integrated Environmental Assessment of the Northern Bering-Chukchi Sea Large Marine Ecosystem.

2019

- PSG annual meeting, Kauai, Hawaii Contributed to presentations for: the North Pacific Albatross Working Group, Marbled Murrelet Technical Committee, Kittlitz's Murrelet Technical Committee, Tufted Puffin Technical Committee, Short-tailed Albatross Recovery Team, February 2019
- AIERP Principal Investigators' meeting, Anchorage, Alaska, March 2019.
- Circumpolar Seabird Group (Cbird) meeting, Iceland, virtual presentation. Cbird is an Arctic Council Expert Network, of which principal investigator K. Kuletz is the United States Representative, March 2019.
- NOAA's Alaska Seabird Bycatch Working Group meeting, Juneau, Alaska, March 2019.
- North Pacific Fisheries Management Council, Anchorage, Alaska, April 2019.
- Conservation of Arctic Flora and Fauna-Circumpolar Biodiversity Monitoring Program (CAFF-CBMP), U.S. Arctic Marine Biodiversity Monitoring Working Group meeting, Anchorage, Alaska, May 2019.
- Interagency Arctic Research Policy Committee, August 2019, teleconference presentation.
- Alaska Migratory Bird Co-Management Council, Anchorage, Alaska, September 2019.
- Assessment of a seabird mortality event in the Bering and Chukchi seas in 2019.
- PICES workshop: "Scoping an Integrated Environmental Assessment of the Northern Bering-Chukchi Seas Large Marine Ecosystem (LME)."

2018

- Arctic Integrated Ecosystem Project : Arctic Marine Biodiversity Observing Network (AMBON) Principal Investigator workshop, Fairbanks, Alaska, January 2018.
- ICES/PICES/PAME draft report for the 'Working Group for Integrated Ecosystem Assessment of the Central Arctic Ocean' (WGICA).
- North Pacific Albatross Working Group meeting, La Paz, Mexico, February 2018.
- Alaska Seabird Bycatch Working Group meeting, Juneau, Alaska, March 2018.

2017

- AIERP Principal Investigators' meeting, Anchorage, Alaska, October 2017.
- Circumpolar Biodiversity Monitoring Program (Arctic Council), Anchorage, Alaska, October 2017.
- Pacific Arctic Group and Distributed Biological Observatory workshops, Seattle, Washington, November 2017.

Presentations for Outreach and Education

K. Kuletz presented at the Strait Science Series, sponsored by Alaska Sea Grant and the University of Alaska, Fairbanks, Northwest Campus, titled: Responding to warming waters: Seabirds at sea. Nome, Alaska, February 2021 virtual presentation.

K. Kuletz presented at the 'Opportunity for Lifelong Education' (Ole!), University of Alaska, Anchorage, titled: Seabirds and shorebirds of the North Pacific: Class No. 2: Seabird responses to changing conditions. November 2021, virtual.

Presentation on seabird updates for a webinar hosted by the Interagency Arctic Research Policy Committee (IARPC). April 2020.

Presentation to Department of Interior Senior Ocean Policy Team, titled: Seabirds in Alaska – overview of MBM seabird program. June 2020.

Presentation on seabird updates for a Webinar on the Bering Sea, hosted by Alaska Center for Climate Assessment and Policy (ACCAP) and Alaska Ocean Observing System (AOOS). July 2020.

Presentations on Arctic marine birds and an overview of our project to two High School Marine Science Classes in Eagle River, Alaska, February 2019.

Presentation on the 2018 seabird die-off event during the Alaska Zoo Fireside Chat, titled: Sentinels of the Sea: Seabirds, Die-offs and Ecosystem Change, Anchorage, Alaska, March 2019.

K. Kuletz provided an overview on results from AIERP surveys during a webinar for the Interagency Arctic Research Policy Committee (IARPC) Marine Ecosystem Collaboration Team teleconference, August 2019.

Presentation summarizing marine bird and mammal projects, and preliminary results to the Arctic IERP workshop, Anchorage, Alaska, March 2018.

Provided slides about seabirds in the Arctic and our survey program to Sue Moore (NOAA) for a presentation at the 11th Western Alaskan Interdisciplinary Science Conference and Forum, Nome, Alaska, March 2018.

Presented seabird information, and data collected during this project at the NOAA Fisheries Interagency Seabird Working group in La Jolla, California, May 2018.

Martin Reedy provided slides and background material to Libby Logerwell for a community presentation about AIERP in Nome, Alaska, 2017.

Martin Reedy wrote a blog for the NPRB website about AIERP seabird surveys. September 2017. Accessible at: https://blog.arctic.nprb.org/blog/

Websites and Press Articles

During the AIERP surveys (2017–2019) and subsequent collaboration and outreach activities, PI K. Kuletz and other USFWS seabird observers and biologists were interviewed for stories about observed changes in northern Alaska's oceans, or posted blogs during survey cruises. In addition, a series of seabird mortality events ("die-offs") occurred along the coastlines and islands of the AIERP study area. These events were unusual for the region and became a concern for local communities and subsistence harvesters as well as signaling ecological changes. Dead birds were also recorded at sea during the Arctic Shelf Growth Advection, Respiration, and Deposition Rate Experiments (ASGARD) and Arctic Integrated Ecosystem Survey (Arctic IES) projects (see cruise reports, Appendix 6). Several of our AIERP-related publications included this aspect of observed changes in the marine ecosystem (Duffy-Anderson et al. 2019; Huntington et al. 2020; Kuletz et al. 2020; Romano et al. 2020). In response to public interest, PI K. Kuletz and others posted multiple 'Seabird Die-off Fact Sheets' and press releases, and were interviewed by a variety of local and national news organizations, with the following articles posted online:

- August 2017: "Seabirds Found Dead On Nome Beach," The Nome Nugget, http://www.nomenugget.com/news/seabirds-found-dead-nome-beach
- December 2017: A public information sheet by the U.S. Fish and Wildlife Service, in response to concerns in coastal subsistence-based communities [no longer available online, 1 March 2022]
- August 2018: "2018 Alaska Seabird Die-off Factsheet," https://www.fws.gov/alaska/stories/2018-alaska-seabird-die/
- August 2018: K. Kuletz was interviewed by four news outlets, including KTUU (Anchorage, Alaska), about the seabird die offs. Some of the resulting stories are available at:
    - https://www.washingtonpost.com/national/energy-environment/us-wildlife-officials-eye-ongoing-alaska-seabird-die-off/2018/08/10/
    - https://abcnews.go.com/US/wireStory/us-wildlife-officials-eye-ongoing-alaska-seabird-die-57136527
    - https://www.ktoo.org/2018/08/09/hundreds-of-dying-seabirds-found-across-northern-alaska/
- September 2018 An article about the 2018 seabird die-off in Alaska was posted online by Audubon following interviews: https://www.audubon.org/news/in-alaska-starving-seabirds-and-empty-colonies-signal-broken-ecosystem
- May 2019: "Why Hundreds of Puffins Washed Up Dead on an Alaskan Beach," *The Atlantic*, https://www.theatlantic.com/science/archive/2019/05/hundreds-puffins-washed-dead-alaskan-beach/590356/
- July 2019: "From Krill to Whales, Marine Life is Washing Up Dead in the Bering Strait," KNOM radio posted online, https://www.knom.org/wp/blog/2019/07/05/from-krill-to-whales-marine-life-is-washing-up-dead-in-the-bering-strait/
- August 2019: USFWS Seabird observer Marty Reedy and the seabird surveys of the Arctic Integrated Ecosystem Research Program were featured on the North Pacific Research Board's web site: https://blog.arctic.nprb.org/blog/2019/8/5/the-sound-of-science

- September 2019: A public information sheet by the U.S. Fish and Wildlife Service, in response to concerns in coastal subsistence-based communities, https://www.nps.gov/subjects/aknatureandscience/upload/9Sep2019-Die-Off-USFWS-Factsheet-508C-revised-29Aug.pdf
- September 2019: For Fifth Year in a Row, Alaska Sees Mass Die-offs of Seabirds, KNOM website. https://www.knom.org/wp/blog/2019/09/17/fifth-year-in-a-row-for-seabird-die-offs-in-alaska,
- September 2019: Alaska Public Radio: https://www.alaskapublic.org/2019/09/17/its-starvation-biologists-in-alaska-see-significant-another-seabird-die-offs/
- November 2019: "From Alaska to Australia, anxious observers fear mass shearwater deaths," The Guardian, 23 Nov 2019. https://www.theguardian.com/environment/2019/nov/24/alaska-australia-anxious-observers-fear-mass-shearwater-deaths
- September 2020: An updated public information sheet by the U.S. Fish and Wildlife Service, in response to concerns in coastal subsistence-based communities, https://www.fws.gov/alaska/sites/default/files/2020-09/2020%20Alaska%20Seabird%20Die-off%20Update_1.pdf
- February 2021: "Offshore Seabirds Feel Effects of Warmer Ocean Waters," KNOM website. https://www.knom.org/wp/blog/2021/02/22/offshore-seabirds-feel-effects-of-warmer-ocean-waters/,
- August 2021: "Emaciated Seabirds Are Turning Up Dead On Western Alaska Beaches for Fifth Straight Summer," Anchorage Daily News, https://www.adn.com/alaska-news/rural-alaska/2021/08/31/emaciated-seabirds-are-turning-up-dead-on-western-alaska-beaches-for-fifth-straight-summer
- December 2021: "Climate Change Transforms Ecosystems in the Arctic and Beyond," LA Times, https://www.latimes.com/environment/story/2021-12-17/north-pacific-arctic-ecosystem-collapse-climate-change

List of Publications

The following publications were based in part on at-sea seabird data collected during this project, or used some component of that data.

Danielson SL, Grebmeier JM, Iken K, Berchok C, Britt L, Dunton KH, Farley E, Fujiwara A, Hauser D, Itoh M, Kikuchi T, Kotwicki S, Kuletz KJ, Mordy C, Nishino S, Peralta-Ferriz C, Pickart RS, Stabeno R, Stafford KM, Whiting A, Woodgate R. In review. Monitoring the Alaskan Arctic marine environment and ecosystem with a distributed observation network. Oceanography. (Submitted in October 2021)

Duffy-Anderson JT, Stabeno P, Andrews III AG, Cieciel K, Deary A, Farley E, Fugate C, Harpold C, Heintz R, Kimmel D, Kuletz K, Lamb J, Paquin M, Porter S, Rogers L, Spear A, Yasumiish E. 2019. Responses of the Northern Bering Sea and southeastern Bering Sea pelagic ecosystems following record-breaking low winter sea ice. Geophysical Research Letters 46(16):9833-42. https://doi.org/10.1029/2019GL083396

Gall AE, Prichard AK, Kuletz KJ, Danielson SL. In review. Influence of water masses on the summer structure of the seabird community in the northeastern Chukchi Sea. Deep Sea Research Part II Special Issue.

Huntington HP, Danielson SL, Wiese FK, Baker M, Boveng P, Citta JJ, De Robertis A, Dickson DM, Farley E, George JC, Iken K, Kimmel DG, Kuletz K, Ladd C, Levine R, Quakenbush L, Stabeno P, Stafford KM, Stockwell D, Wilson C. 2020. Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. Nature Climate Change 10(4):342–348. https://doi.org/10.1038/s41558-020-0695-2

Johansen M, Irgens M, Strøm H, Anker-Nilssen T, Artukhin Y, Barrett R, Barry T, Black J, Danielsen J, Descamps S, Dunn T, Ekker M, Gavrilo M, Gilchrist G, Hansen E, Hedd A, Irons D, Jakobsen J, Kuletz K, Mallory M, Merkel F, Olsen B, Parsons M, Petersen Æ, Provencher J, Robertson G, Rönkä M (2020). International Black-legged Kittiwake Conservation Strategy and Action Plan, Circumpolar Seabird Expert Group. Conservation of Arctic Flora and Fauna, Akureyri, Iceland. ISBN 978-9935-431-85-1.

Kuletz KJ, Cushing DA, Labunski EA. 2020. Distributional shifts among seabird communities of the Northern Bering and Chukchi seas in response to ocean warming during 2017–2019. Deep Sea Research II 181:104913. https://doi.org/10.1016/j.dsr2.2020.104913

Piatt JF, Douglas DC, Arimitsu ML, Kissling, ML, Madison EN, Schoen SK, Kuletz KJ, Drew GS. 2021. Kittlitz's Murrelet seasonal distribution and post-breeding Migration from the Gulf of Alaska to the Arctic Ocean. Arctic 74(4):482–495. https://doi.org/10.14430/arctic73992

Romano M, Renner HM, Kuletz KJ, Parrish JK, Jones T, Burgess HK, Cushing DA, Causey D. 2020. Die-offs and reproductive failure of murres in the Bering and Chukchi Seas in 2018. Deep Sea Research II:181–182. https://doi.org/10.1016/j.dsr2.2020.104877

The U.S. Geological Survey announced the public release of the North Pacific Pelagic Seabird Database v3, which includes seabird data from this project through 2019. The user's guide, seabird distribution maps, and access to data can be found at:

- Drew, G.S., Piatt, J.F. 2020. North Pacific Pelagic Seabird Database (NPPSD): U.S. Geological Survey data release (ver. 3.0, February 2020), https://doi.org/10.5066/F7WQ01T3

Publications in Prep

Kuletz KJ. et al. *In prep.* The influence of environmental drivers on shearwater abundance and distribution in the Chukchi Sea.

Kuletz KJ. et al. *In prep.* Distribution of seabird foraging guilds in response to environmental and prey conditions in the northern Bering and Chukchi seas.

List of Reports

This project relied on collaboration with the Arctic Shelf Growth Advection Respiration Deposition Rate Experiments (ASGARD) and Arctic Integrated Ecosystem Survey (Arctic IES) vessel-based research and monitoring projects, typically requiring cruise reports within a month of completing the cruise. K. Kuletz and the USFWS team provided individual cruise reports (Appendix 6), portions of which were incorporated into the multi-disciplinary project report; many of these are now available online through the respective projects. These cruise reports include species counts, and distribution maps of selected species specific to the cruise. Information on marine mammal sightings, including those beyond the seabird transect window, were also included in the cruise reports.

- ASGARD 2017 Cruise Report

- ASGARD 2018 Cruise Report
- Arctic IES 2017 Cruise Report
- Arctic IES 2019 Cruise Report

In addition, quarterly reports were made to the Bureau of Ocean Energy Management (BOEM) and semi-annual progress reports and final reports to the North Pacific Research Board (NPRB), as the primary funder of AIERP. Because this report is required to be comprehensive and stand alone, components of the Arctic IES final report (Farley et al. 2022) have been incorporated into this report.

Study Objectives

The goal of this Interagency Agreement (IAA) was to support an at-sea survey program for seabird observations to provide pertinent information on the distribution, timing and abundance of marine birds in the Beaufort and Chukchi Sea planning areas (see Figure 1.1). This was accomplished by providing the seabird component for two integrated ecosystem studies: Arctic Shelf Growth, Advection, Respiration and Deposition Rate Experiments (ASGARD) and the Arctic Integrated Ecosystem Survey: Phase II, Upper Trophic Levels (Arctic IES). Results provide the Bureau of Ocean Energy Management (BOEM) with current data on the distribution and abundance of marine birds, and secondarily for marine mammals, within BOEM's Arctic planning areas. The seabird data were processed, submitted, and archived in the North Pacific Pelagic Seabird Database (NPPSD), and will be submitted to the BOEM Environmental Sciences, Alaska Region Seabird Database.

Specific Study Objectives under Interagency Agreement M17PG00017:

- Contact and coordinate with Arctic Integrated Ecosystem Research Program (AIERP) research programs using vessels in the Bering, Chukchi, or Beaufort seas to place seabird observers on the vessels during research cruises. Conduct seabird surveys from these ships to obtain density estimates and distribution patterns of all marine birds.
- Estimate the spatial distribution, species composition, and seasonal changes in species and abundance for marine birds in designated and potential planning areas.
- Process the data for entry into the NPPSD for future accessibility to facilitate management decisions and to develop a geodatabase for BOEM use.
- Coordinate with project Principal Investigators [of the ASGARD and Arctic IES studies] to integrate seabird data with oceanographic and prey data.

Related Study Objectives

This report addresses the seabird component of AIERP, which includes two major projects: the Lower Trophic Level project (LTL; A92) and the Upper Trophic Level (UTL) project, titled Arctic IES II (Arctic IES; A93). In addition, an ‘Appendix Project’ of AIERP was ASGARD. This BOEM Project AK-16-07c provided the seabird component for both ASGARD and Arctic IES. The projects were conducted over two field seasons: 2017 and 2018 for ASGARD, and 2017 and 2019 for Arctic IES. The seabird component of both studies sought to determine the spatial distribution, species composition, and seasonal changes in species abundance in planning areas in the northern Bering and Chukchi seas. The seabird component also addresses several of the overall hypotheses and objectives of each project. Details of the goals and methods are available in the proposals and annual Fieldwork Plans at: Arctic Integrated Ecosystem Research Program Work Plan.

Arctic IES Study Objectives

The full list of objectives, hypotheses, and final report of Arctic IES (Farley et al. 2022) will be available online after review. The overall goal of Arctic IES is to " better understand the mechanisms and processes that structure the ecosystem and influence the distribution, abundance, and life history of lower (phytoplankton, zooplankton) and upper trophic species (fishes, seabirds, mammals), and their potential vulnerability to the rapidly changing environment of marine ecosystems in the Arctic." The objectives and hypotheses that specifically relate to BOEM Project AK-16-07c are:

Objective 6: Quantify the distribution, abundance, and prey association of seabirds in the Pacific Arctic Region in relation to oceanographic conditions, prey abundance, and feeding guilds.

Hypothesis 4: Seabird community structure and seabird-prey dynamics: *The current predominance of planktivorous seabirds in the Arctic may shift back towards piscivorous seabirds if warming sea temperatures restructure the food web.*

ASGARD Study Objectives

The ASGARD project was designed to address the NPRB Arctic Program's overarching questions: "How do physical, biological and ecological processes in the Chukchi Sea influence the distribution, life history, and interactions of species or species guilds critical to subsistence and ecosystem function? The objectives relevant to BOEM Project AK-16-07c were:

- Support additional Arctic IERP research projects with moored and ship-based measurement platforms.
- Form coordinated data collection and analysis collaborations with national and international partners.
- Enhance the Distributed Biological Observatory (DBO) program by occupying DBO stations at a time of year in which few samples have been collected previously.

Study Chronology

This OCS Study (BOEM Project AK-16-07c) was proposed in March 2017 and initiated through an Interagency Agreement (IAA) between the USFWS and BOEM in April 2017. The original period of performance was designated from June 14, 2017 to June 14, 2021. Modifications to the IAA were made annually to provide funds to continue the at-sea surveys through fall 2020. There were two no-cost extensions due to disruptions caused by the Covid-19 pandemic, and to accommodate the integration of collaborator's results and data into this final report. The current period of performance ends March 30, 2022 (Modification 6).

The impetus for this study was to provide BOEM with updated information on seabirds in offshore planning areas (see Figure 1.1) and to provide the seabird component to the ASGARD and Arctic IES projects. We also conducted surveys during transits to and from ports of call during ASGARD and Arctic IES cruises (see Figure 1.2). Details on transits outside the AIERP study area and related observations are provided in cruise reports (Appendix 6) and summary tables (Appendix 1), but otherwise we focus on the AIERP study area. All seabird data collected during this project has been submitted to the BOEM Anchorage office and to the North Pacific Pelagic Seabird Database (NPPSD). It has also been archived on the Alaska Ocean Observing System Arctic IES Workspace and published under the DOI system. The four published data sets for the seabird component of AIERP are:

- ASGARD 2017: https://doi.org/10.24431/rw1k59r
- ASGARD 2018: https://doi.org/10.24431/rw1k59q
- Arctic IES 2017: https://doi.org/10.24431/rw1k59w
- Arctic IES 2019: https://doi.org/10.24431/rw1k59t

During the AIERP project, the USFWS concurrently conducted surveys in the same study region as part of a broader project also funded by BOEM, AK-17-03 (IAA M17PG00039). The data from these two projects were complementary and thus were typically combined for some analyses to address AIERP objectives and hypotheses. Project AK-16-07c also follows years of USFWS offshore seabird surveys which were funded via grants and BOEM IAAs, including:

- North Pacific Research Board (NPRB) Project No. 637, (2006–2008; Kuletz et al. 2008)
- Seabird components of the Bering Sea Integrated Ecosystem Research Project (BSIERP, 2008-2010), including Project B64 (Seabird Broad-scale Distribution; Kuletz and Labunski 2014), Project B92 (Seabird and Cetacean Foraging Response to Prey Persistence; Sigler et al. 2012) and Projects B67 and B77 (Patch Dynamics Study; Trites et al. 2015)
- OCS Study BOEM 2017-004, IAA M10PG00050 (2010-2016; Kuletz and Labunski 2017)
- OCS Study BOEM 2017-011, IAA M14PG00031 (2014-2016; Renner et al. 2017)

Abstract

This project was funded via an Interagency Agreement with the Bureau of Ocean Energy Management (BOEM) to support seabird surveys as part of two integrated ecosystem studies: Arctic Shelf Growth, Advection, Respiration and Deposition Rate Experiments (ASGARD) and Arctic Integrated Ecosystem Survey (Arctic IES). Results provide BOEM with current data, as well as seasonal and interannual comparisons, on the distribution and abundance of marine birds, and secondarily for marine mammals, within BOEM's Arctic planning areas. The seabird data were archived in the North Pacific Pelagic Seabird Database, and bird and mammal data were archived with the BOEM Environmental Sciences Management, Alaska Region Database. We conducted surveys during June 2017 and 2018 for ASGARD, and August–September 2017 and 2019 for Arctic IES. In addition, we integrated a study of chick diets for crested (*Aethia cristatella*) and least auklets (*Aethia pusilla*) nesting on St. Lawrence Island during 2016–2019. Finally, we integrated environmental and prey data collected during the four research cruises, for which analysis is on-going. Both ASGARD and Arctic IES projects address the North Pacific Research Board Arctic Program's overarching question: "How do physical, biological and ecological processes in the Chukchi Sea influence the distribution, life history, and interactions of species or species guilds critical to subsistence and ecosystem function?"

From June 2017 through September 2019, we surveyed a total of 16,870 km including 14,247 km within the study area. We observed 38 marine bird species and 53,973 birds on-transect. For both projects, 5–9 species accounted for 90% of total birds, with the most abundant including thick-billed murre (*Uria lomvia*), crested auklet, least auklet, black-legged kittiwake (*Rissa tridactyla*) and short-tailed shearwater (*Ardenna tenuirostris*). Species richness was slightly higher but diversity slightly lower in August–September than in June, largely due to the influx of shearwaters, with the exception of high diversity in June 2017. During June, least auklets represented ~22–34% of total birds, whereas in August–September, short-tailed shearwaters composed 64–69% of total birds. Shearwaters composed an increasing proportion of total birds moving from south to north, and were the highest proportion of total birds in the northern Chukchi Sea. Planktivores outnumbered piscivores during 3 of 4 cruises, due to high numbers of auklets and short-tailed shearwaters. In general, piscivorous birds were more dispersed and occurred at lower densities than planktivores, except near colonies at Cape Thompson and Cape Lisburne, where only piscivorous birds nest. These patterns suggest that prey availability was more highly aggregated for planktivores, and more dispersed for piscivores. Benthivores (seaducks) had the lowest densities among foraging guilds during all cruises, and were primarily observed near the Chukchi coast and in flight.

On- and off-transect, we recorded 10 marine mammal species and 733 individuals, of which 184 were on-transect. Gray whales were the most frequently recorded cetacean, distributed in the Chirikov Basin and southern Chukchi Sea in June and in lower numbers in the northern Chukchi Sea during August–September. Walruses were the most numerous marine mammal recorded, and were encountered more frequently during August–September in the northern Chukchi Sea near Barrow Canyon and Hanna Shoal.

In June 2017, total marine bird density was low (9.3 birds/km^2). Total density during June 2018 was high (22.2 birds/km^2), with low diversity, due to high numbers of auklets in offshore waters. During June of both years, the highest densities occurred in the Chirikov Basin and Bering Strait, with 30-km grid cells of up to 100 birds/km^2. During August–September, mean total density was 18.2 birds/km^2 in 2017 and 13.1 birds/km^2 in 2019, with highest densities occurring farther north in Hope Basin, near Herald and Hanna shoals, and over Barrow Canyon. These same areas were identified as 'hotspots' of high density during earlier surveys.

Participating in the ASGARD surveys provided a unique opportunity to obtain data on seabirds in the northern Bering and southern Chukchi regions during early summer, a period for which there is little data. The greater interannual contrast in seabird diversity and abundance between years during June may be

indicative of the sensitivity of the avian community to timing of sea ice retreat in the study area in early summer. The studies coincided with an unprecedented heatwave in the Bering and Chukchi seas, leading to a massive influx of adult walleye pollock (*Theragra chalcogramma*) into the northern Bering Sea, and juvenile pollock into the Chukchi Sea in 2017. In August–September 2019, juvenile pollock had shifted to the northern Chukchi Sea, likely beyond foraging range of nesting piscivorous birds. Concurrently, small-bodied copepods predominated throughout the study area and larger *Calanus* copepods decreased, which may have led to nesting failure of auklets in 2018 and 2019, and low use of the Chukchi Sea by these planktivores. The spatial extent of the crested auklet-dominated community contracted during the anomalously warm years of 2017–2019, as did the least auklet-dominated community in the Bering Strait region. Auklet diet composition shifted from mesoplankton (e.g., copepods and hyperiids) in 2000–2004/2016 (Sheffield-Guy et al. 2009), to micronekton (juvenile euphausiids) during 2017–2019. The change in prey species coincided with changes in oceanographic conditions associated with fewer large-bodied copepods.

The seabird studies provide evidence of rapid changes in seabird distribution in response to changes in physical oceanography, prey species, and the influx of large predatory fish. Concurrent with our studies, reproductive success of seabirds in the northern Bering Sea was poor, and seabird die-offs occurred in the Bering Strait region. Die-offs also occurred, particularly in 2019, south of our study area, with short-tailed shearwaters comprising over half of all recorded mortality. The majority of examined birds died of starvation, and the 2019 die-off in southeastern Bering Sea may have reduced the number of short-tailed shearwaters that could complete the full migration into the Chukchi Sea that year. The high abundance of both seabirds and marine mammals in the Bering Strait region, including Hope Basin, highlights, once again, the importance of careful mitigation of human activities in this region. The cumulative effects on seabirds of changes in oceanographic conditions, prey types and distribution, and human activities will need to be considered when assessing potential impacts of proposed oil and gas energy developments.

1 Introduction

1.1 Need for information on seabirds in lease sale areas

The National Environmental Policy Act (NEPA) of 1969 (42 USC 4321-4347) requires that all Federal Agencies use a systematic, interdisciplinary approach that integrates natural and social sciences in any planning and decision-making that may have an effect on the human environment. The Bureau of Ocean Energy Management (BOEM) regularly drafts environmental impact statements, convenes environmental assessment teams, conducts literature surveys, and leads special studies. Data on the distribution of marine birds is needed for Endangered Species Act (ESA) Section 7 consultations, NEPA analyses, and other documentation. These data may be used to develop mitigation measures to reduce potential impacts to listed and candidate species under the ESA as well as Priority Species identified by the USFWS (11 Tier-I species and 14 Tier-2 species). To provide information used in environmental impact statements and environmental assessments under NEPA, and to assure protection of marine birds under the ESA of 1973 (16 USC 1531-1543), BOEM Environmental Studies Program funds numerous studies involving acquisition and analysis of data on marine birds and other environmental data. This project was funded via an Interagency Agreement with the Bureau of Ocean Energy Management (BOEM) to support seabird surveys as part of two integrated ecosystem studies: Arctic Shelf Growth, Advection, Respiration and Deposition Rate Experiments (ASGARD) and Arctic Integrated Ecosystem Survey (Arctic IES).

Marine bird species listed under the ESA in Alaska include spectacled eider (*Somateria fischeri*), Steller's eider (*Polysticta stelleri*), and short-tailed albatross (*Phoebastria albatrus*). The information obtained from these surveys may assist in developing mitigation measures and strategies to reduce potential impacts to listed species. Basic information on marine bird timing and duration of use within designated (Chukchi and Beaufort seas) and potential (North Aleutian Basin) Planning Areas is necessary to better define the impacts of perturbations and ultimately population effects. In this report, we refer to 'marine birds' when including all major taxa that rely on the marine environment during some portion of their lives; this includes birds that spend considerable time inland during nesting season, such as loons (Family Gaviidae), waterfowl and seaducks (Family Anatidae), phalaropes (genus *Phalaropus*), and jaegers (genus *Stercorarius*), and 'true' seabirds that nest along the coast, typically in colonies, and spend the majority of their lives at sea (i.e, Procellariidae, Phalacrocoracidae, Laridae, Alcidae).

Breeding seabirds are generally monitored at colonies yet they spend most of the year dispersed offshore, and roughly half of all seabirds at sea are not actively breeding in a given year. Other marine bird species occur at sea seasonally, thus management of marine birds requires knowledge of their spatial and temporal patterns at sea. The North Pacific Pelagic Seabird Database (NPPSD), managed by the U.S. Geological Survey (USGS), consolidates and archives marine bird survey data and the most recent version includes data collected by USFWS, 2006–2020 (Drew and Piatt 2020).

The ASGARD and Arctic IES seabird surveys provide a more complete and current data set on marine bird use of sub-Arctic and Arctic marine areas of Alaska. Offshore resource exploration and extraction, increases in shipping traffic and tourism, and concern over subsistence hunting and food resource availability are additional reasons for obtaining science-based knowledge of marine birds in this region.

1.2 The Arctic Integrated Ecosystem Research Project

This study collected data on the distribution, abundance, and habitat use of marine birds through two multi-disciplinary vessel-based projects under the North Pacific Research Board's Arctic Integrated Ecosystem Research Project (AIERP). Seabird data were collected through a research partnership and collaboration with ASGARD and Arctic IES. We present seabird survey data, consider relationships to oceanographic and prey data collected during the cruises, and discuss our results with respect to the findings of other AIERP study components.

The lower trophic level (LTL) component of AIERP examined the climatological, physical, chemical and biological processes that influence the flow of energy from primary producers to zooplankton and ichthyoplankton in the Chukchi Sea and how warming climate will influence these processes. The upper trophic level (UTL) component (fishes, seabirds, mammals) examined the mechanisms and processes that structure the ecosystem and influence the distribution, abundance, and life history of LTL and UTL organisms and their potential vulnerability to the rapidly changing environment of marine ecosystems in the Arctic. Seabirds, as part of the UTL, respond to biological and physical changes in the ecosystem and thus serve as sentinels that provide a record of ecosystem response to rapid climate change in the Pacific Arctic Region (Moore et al. 2014).

It is likely that climate warming in the Arctic will impact the abundance and distribution of UTL species. Seabird distribution is often influenced by oceanographic characteristics that promote productivity and concentrate prey (Piatt et al. 1991; Gall et al. 2013). In the Chukchi Sea, 'hotspots' of seabird abundance can vary among foraging guilds (i.e., surface or diving foragers) and between summer (breeding season) and fall (post- breeding and migration) (Kuletz et al. 2015). Such hotspots of seabird foraging activity are often associated with persistent bathymetric features such as shelf breaks and underwater canyons that enhance the availability of prey (Kuletz et al. 2015). During the Phase I Arctic study (2012–2013), the distribution of planktivorous and piscivorous seabirds reflected the distribution of their prey at broad spatial scales (Arctic IES reports: see https://web.sfos.uaf.edu/wordpress/arcticeis/). Gall et al. (2017) also revealed a decadal-scale shift in the offshore seabird community of the Chukchi Sea from a predominantly piscivorous seabird community to one dominated by planktivores.

If warming seas lead to longer ice-free conditions and generally higher productivity, this trend of more planktivorous seabirds could continue. An alternative hypothesis (proposed in Arctic IES) is that these conditions will lead to smaller zooplankton and thus less suitable prey to support high densities of planktivorous seabirds, resulting in a shift back towards a predominantly piscivorous seabird community. While changes in environmental conditions and prey undoubtedly affect breeding birds, our study focused on offshore waters, which includes both breeding and non-breeding populations. By examining the offshore distribution and species composition of birds, and their responses to different environmental conditions, we can provide information on how birds may be affected by changing climate and human activities.

In this study, we determined the current species composition, species richness and diversity, and distribution and abundance of seabirds during summers of 2017–2019. We examine seasonal changes by comparing early summer (June, ASGARD surveys) to late summer (August–September, Arctic IES surveys). We also compare seabird distribution and abundance offshore between two years; for early summer we compare the two ASGARD survey results (2017, 2018) and for late summer we compare the two Arctic IES survey results (2017, 2019). In addition, we present results from a study we facilitated that examined diets of crested and least auklets nesting on St. Lawrence Island during 2016–2019, which overlapped with our AIERP seabird surveys.

1.3 Study area

1.3.1 Physical properties

The primary AIERP study area was the eastern Chukchi Sea, and to a lesser extent (during ASGARD), the northern Bering Sea (Figure 1.1). Based on AIERP sampling stations and physical and oceanographic features, we delineated three sub-regions within our study area (Figure 1.2): the Northern Bering (St. Lawrence Island to Bering Strait), the Southern Chukchi (Bering Strait to north Ledyard Bay) and Northern Chukchi (Ledyard Bay to Pt. Barrow and extending off the Chukchi shelf).

The continental shelf ecosystem of the northern Bering and Chukchi seas is influenced by three water masses that are defined primarily by salinity and temperature characteristics— the Anadyr Water, Bering Shelf Water, and Alaska Coastal Water (Coachman et al. 1975; Weingartner et al. 1999; Figure 1.3). These water masses advect nutrients, heat, and plankton biomass northward from the Bering Sea, supporting high productivity in the Chirikov Basin north of St. Lawrence Island and through Bering Strait into the Chukchi Sea (Springer and McRoy 1993). Anadyr Water is relatively cold, saline, and rich in nutrients; Bering Shelf Water has similar properties (Coachman & Shigaev 1992; Weingartner 1997). The Alaska Coastal Water originates in the Gulf of Alaska (Figure 1.3), carries river input into the eastern Bering Sea, and is relatively warm, fresh, and nutrient-poor (Springer et al. 1984; Coachman & Shigaev 1992; Weingartner 1997). North of Bering Strait, Anadyr Water and Bering Shelf Water merge into Bering Sea Water, which bifurcates as the flow moves north towards the Arctic Basin (Coachman et al. 1975). These two currents pass around a shallow shelf (40 m depth) on the eastern Chukchi Shelf known as Hanna Shoal (Figure 1.3), making the shoal a particularly rich area of the eastern Chukchi Sea (Schonberg et al. 2014). Alaska Coastal Water flows northward through the Bering Strait and continues close to shore in the Alaska Coastal Current (ACC). The ACC splits near Pt. Barrow, with branches heading west and east along the Beaufort shelf. The Beaufort and northern Chukchi seas are also influenced by easterly flowing deep Atlantic water and the westerly flowing Beaufort Gyre in the Arctic Basin (Figure 1.3). The properties, extent, and mixing of these water masses varies seasonally and interannually due to changes in atmospheric circulation, regional wind patterns, and timing and spatial extent of sea ice (Weingartner et al. 1999, 2005; Woodgate et al. 2005).

Seasonally, sea ice cover changes dramatically, which has direct and indirect consequences for seabirds and marine mammals. Open water areas (polynyas) occur throughout winter in the Chukchi and Beaufort seas (Stringer and Groves 1991), but historically, solid sea ice cover typically extended into the middle of the Bering Sea by March. However, in recent years, sea ice has not extended that far south, and during 2018 there was little to no winter sea ice south of the Bering Strait (Stabeno and Bell 2019). In the past, sea ice retreated northward in the spring, with Bering Strait remaining blocked by ice until mid-June, but in June 2018, the strait was ice-free (Stabeno and Bell 2019). Seasonally, the sea ice continues to retreat northward throughout summer in the Arctic unevenly (depending on bathymetry, wind and currents), with minimum ice coverage in late September. The extent of sea ice during the preceding winter and the timing of its annual retreat affects the physical properties of regional water masses for the remainder of the year (Weingartner et al. 2005; Arrigo et al. 2008).

1.3.2 Lower trophic levels and fishes

Major biogeographic domains of the pelagic ecosystem can shift in geographic location as a result of seasonal variability in the underlying physical dynamics (Day et al. 2013; Hunt et al. 2014). The biogeography of the northern Bering and Chukchi seas appears to be linked to water mass properties and latitudinal gradients (Sigler et al. 2011). Sea ice extent and timing influences water masses, and thereby biotic communities, thus shaping conditions into late summer and early fall. During summer, the zooplankton and pelagic fish communities in this region reflect the underlying hydrography, with strong gradients running from nearshore to offshore, and south to north (Sigler et al. 2016). From zooplankton to seabirds, Sigler et al. (2016) identified three biogeographic communities: those associated with the ACC (warm, fresh, nutrient-poor), the Chirikov Basin/Southern Chukchi Sea (cold, salty, nutrient-rich), and the Northern Chukchi shelf associations.

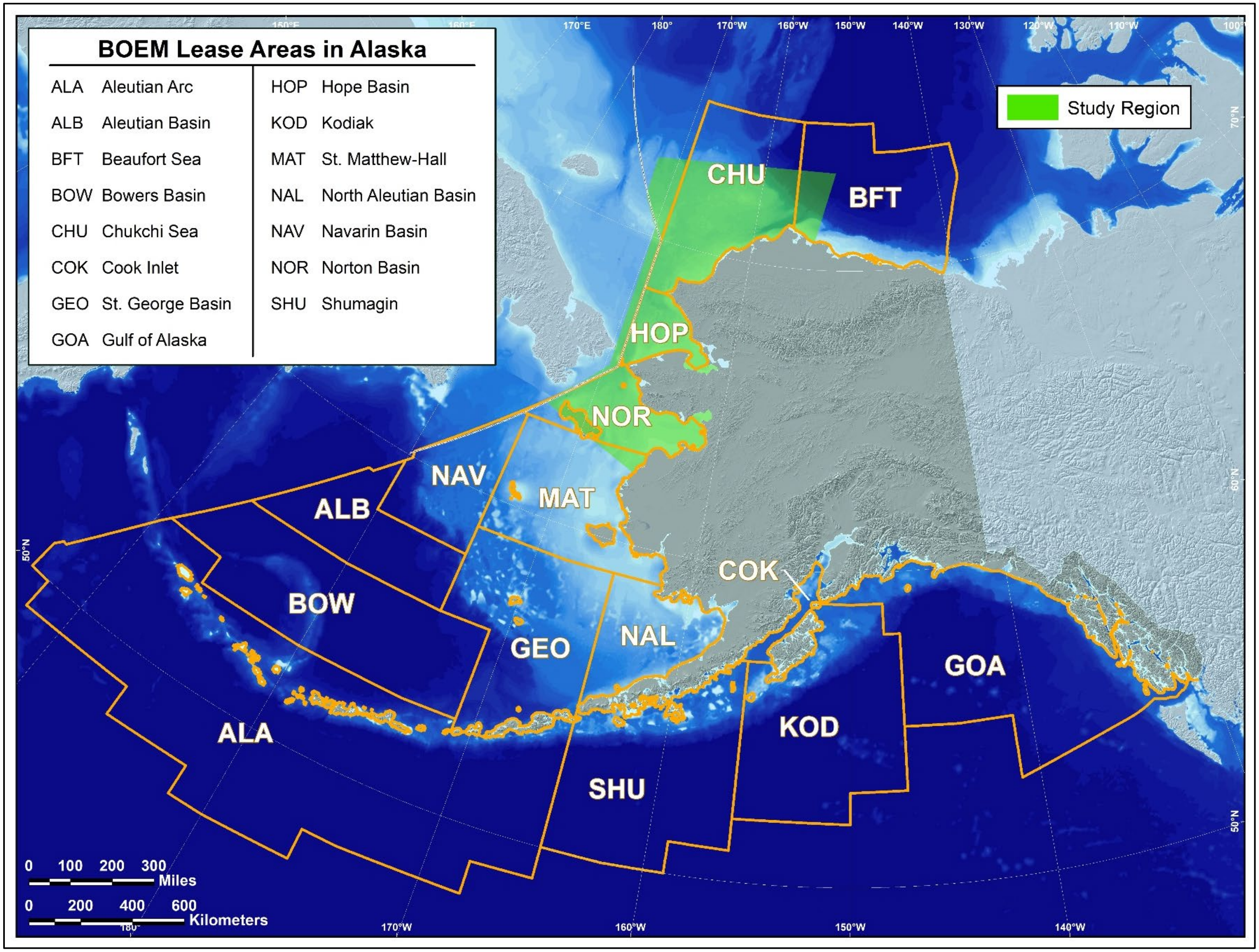

Figure 1.1. The study area for AIERP 2017–2019 within the BOEM offshore planning areas in Alaska.

Figure 1.2. The study area boundaries for AIERP 2017–2019 showing locations of oceanographic sampling stations.

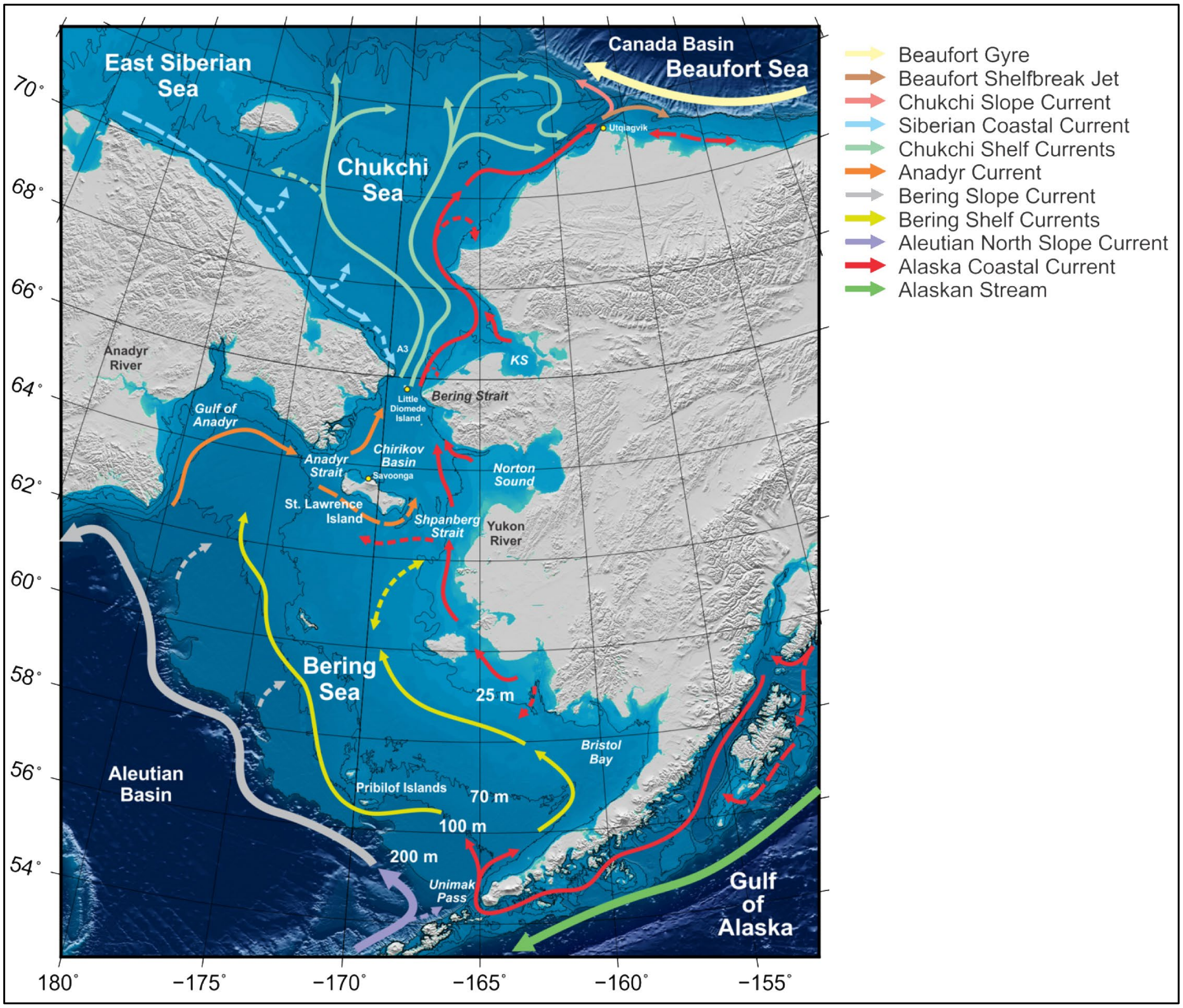

Figure 1.3. Major currents, ocean regions, and place names in the northern Bering and Chukchi seas.
From Danielson et al. 2020 (with permission from S. Danielson, University of Alaska Fairbanks).

Overall, zooplankton densities are greatest just north of Bering Strait and in high salinity Bering Sea waters, although their distribution and abundance varies within and among years (Eisner et al. 2013; Hopcroft et al. 2010). Zooplankton communities are strongly associated with specific water masses, e.g., large copepods are most abundant in high salinity Anadyr Water, while small copepods tend to be in low salinity Alaska Coastal Water (Eisner et al. 2013; Hopcroft et al. 2010; Piatt and Springer 2003). There is also a latitudinal gradient, with sub-arctic species most abundant in the northern Bering and southern Chukchi seas, and Arctic species abundant in the Chukchi Sea (Eisner et al. 2013; Hopcroft et al. 2010; Piatt and Springer 2003). Seabirds that feed primarily on zooplankton (i.e., planktivorous seabirds) include auklets, storm-petrels, and shearwaters. In the AIERP study area, planktivorous seabirds rely primarily on large copepods (e.g., *Neocalanus* spp, *Calanus* spp) and euphausiids (or krill; *Thysanoessa* spp), but may also consume hyperiids (amphipods; *Themisto* spp), cephalopods, and larval stages of fish and decapods. Benthic feeding birds such as sea ducks primarily consume bivalves (Bivalvia molluscs).

Seabirds that feed primarily on fish (i.e., piscivorous seabirds) consume juveniles of a variety of pelagic and demersal fish, and juveniles and adults of small-bodied forage fish, as well as cephalopods, squid, and sometimes krill and juvenile crustacea. In the AIERP study area, marine fishes are structured primarily along a latitudinal gradient and secondarily with water masses (Eisner et al. 2013). Prey species include juvenile saffron cod (*Eleginus gracilis*), juvenile Arctic cod (*Boreogadus glacialis*), and adult Pacific sand lance (*Ammodytes hexapterus*), which are most abundant in the central and northern Chukchi Sea, while adult Pacific herring (*Clupea pallasii*), walleye pollock (*Theragra chalcogramma*), and capelin (*Mallotus villosus*) are most abundant in the northern Bering and southern Chukchi seas (DeRobertis et al. 2017; Stevenson and Lauth 2019). Both diversity and biomass decrease with latitude, and high diversity and biomass are associated with Alaska Coastal Water (Eisner et al. 2013; Piatt & Springer 2003). However, in the years just preceding and during the AIERP, large predatory fish species, primarily walleye pollock, shifted northward (Stevenson and Lauth 2019), and in 2018, the northern Bering and Chukchi sea region had an unprecedented influx of these species.

1.3.3 Marine birds

The offshore waters of Alaska support a diversity of marine birds, including taxa that use marine areas only during migration or for portions of their annual cycle. Members of the families Gaviidae (loons), Anatidae (in particular eiders and other seaducks), Stercorariidae (jaegers), and phalaropes (*Phalaropus* spp.) are considered marine birds, but for portions of the year they depend on inland habitats and prey, particularly during the breeding season. In contrast, 'seabirds' generally refers to species that feed primarily in marine environments, spend most of the year at sea, and typically nest near the water on coastal cliffs or islands, often in colonies; these families include the Procellariidae (albatross, fulmars, shearwaters, storm-petrels), Phalacrocoracidae (cormorants), Laridae (gulls and terns), and Alcidae (murres, puffins, murrelets, auklets, guillemots). Our surveys recorded all marine birds, but where relevant we refer to seabirds, which are the most abundant category of marine birds in Alaska's offshore waters.

The Bering and Chukchi seas have some of the largest seabird breeding populations in the world (Stephensen and Irons 2003), and seabird colonies extend throughout most of the coastline of the northern Bering and southern Chukchi seas (Figure 1.4). An estimated 12 million seabirds nest at colonies on either side of the Bering Strait, with at least 5 colonies of >1 million birds and another 8 colonies with >125,000 birds (USFWS 2014). The largest colonies along the Chukchi sea coast are between Cape Thompson and Cape Lisburne. With the exception of a few small colonies east of Pt. Barrow and scattered larids, jaegers, and phalaropes, seabirds do not nest along the Beaufort coast. Seabird densities at sea in the study area range from very low to high, depending on location and date (Gall et al. 2013, Kuletz et al. 2015), with areas near Bering Strait among the highest recorded in the North Pacific and Atlantic (Humphries and Huettmann 2014; Wong et al. 2014). Offshore seabird densities are augmented by an influx of millions of migrants from the Bering Sea and the southern hemisphere, with the latter primarily consisting of short-tailed shearwaters (*Ardenna tenuirostris*) (Gall et al. 2013, Kuletz et al. 2015).

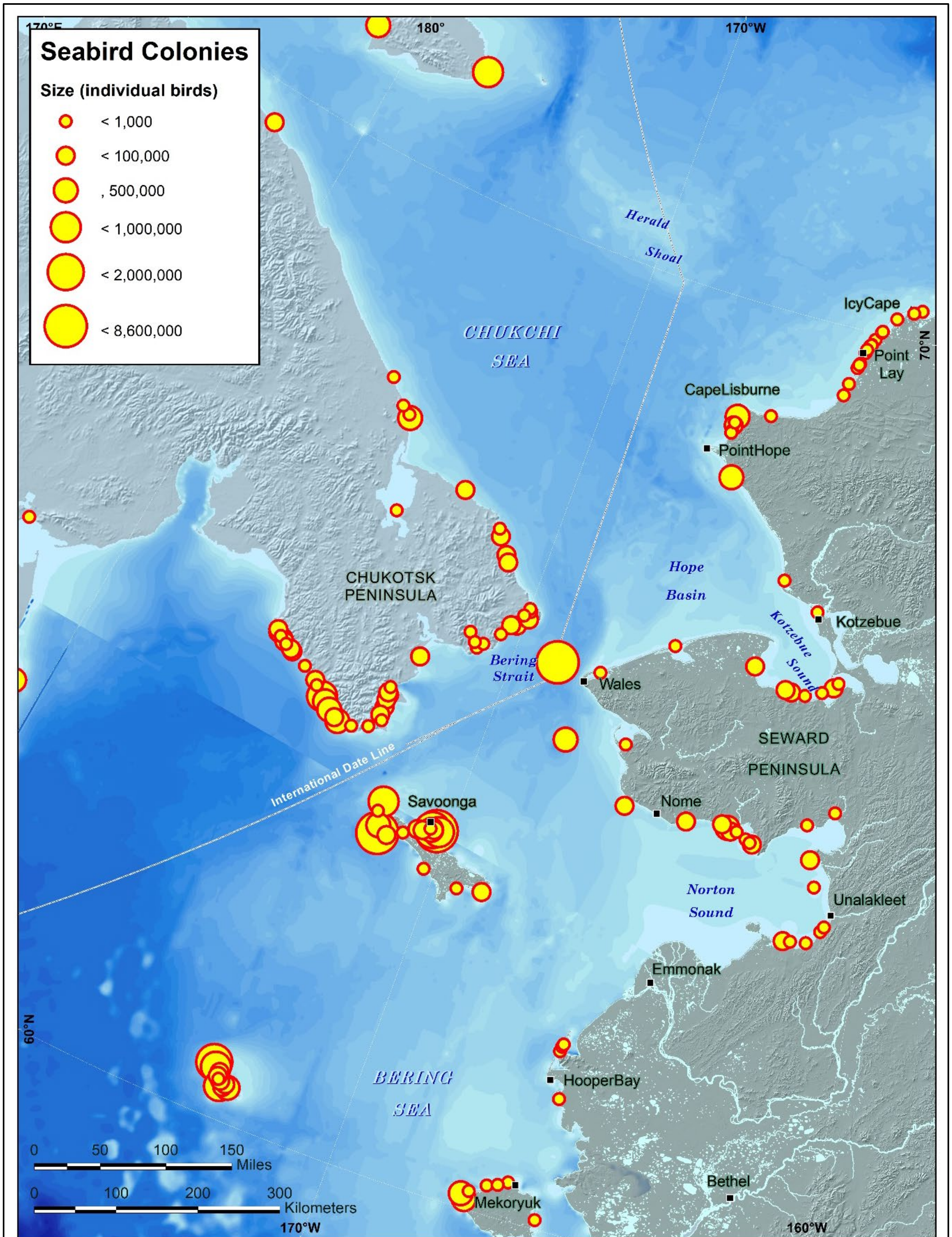

Figure 1.4. Size and location of seabird colonies within the AIERP study area.
Data were obtained from the North Pacific Seabird Colony Database, maintained by the U.S. Fish and Wildlife Service, and accessible via the North Pacific Seabird Data Portal.

2 Data Collection and Processing

2.1 Marine bird surveys

2.1.1 Coordination with research programs and vessels

Principal Investigator K. Kuletz coordinated with ASGARD and Arctic IES Chief Scientists and Project Leads to include seabird surveys in their projects and cruise plans. Seabird observers were placed on two ASGARD and two Arctic IES research cruises (Table 2.1). Portions of the Distributed Biological Observatory (DBO; http://www.pmel.noaa.gov/dbo/) sampling scheme were incorporated into most of the AIERP project cruises, thus fulfilling Objective 4 of the ASGARD study proposal. Although the projects were focused on the Chukchi Sea sampling stations, the ports of call often began or ended in Seward, Nome, or Dutch Harbor, Alaska (Table 2.1). During the vessel's transit between ports and the sampling sites (Figure 2.1) we conducted additional surveys while underway (Figure 2.2); these extra transect data were also submitted to the NPPSD (https://data.usgs.gov/datacatalog/data/USGS:ASC29) and to the BOEM, Environmental Sciences, Alaska Region Seabird Database

Table 2.1. Survey cruise dates, research vessel used, and ports of call during AIERP 2017–2019.

Year	Project	Survey leg	Ship	Dates	Ports
2017	ASGARD	SKQ201709S	Sikuliaq	9 June–28 June	Dutch - Nome
2017	Arctic IES	OS1701	Ocean Starr	2 Aug–24 Aug	Dutch - Nome
2017	Arctic IES	OS1702	Ocean Starr	25 Aug–16 Sep	Nome - Nome
2017	Arctic IES	OS1703	Ocean Starr	16 Sep–27 Sep	Nome - Nome
2018	ASGARD	SKQ201813S	Sikuliaq	31 May–24 June	Seward - Nome
2019	Arctic IES	OS1901	Ocean Starr	1 Aug–24 Aug	Dutch - Nome
2019	Arctic IES	OS1902	Ocean Starr	24 Aug–14 Sep	Nome - Nome
2019	Arctic IES	OS1903	Ocean Starr	14 Sep–30 Sep	Nome - Nome

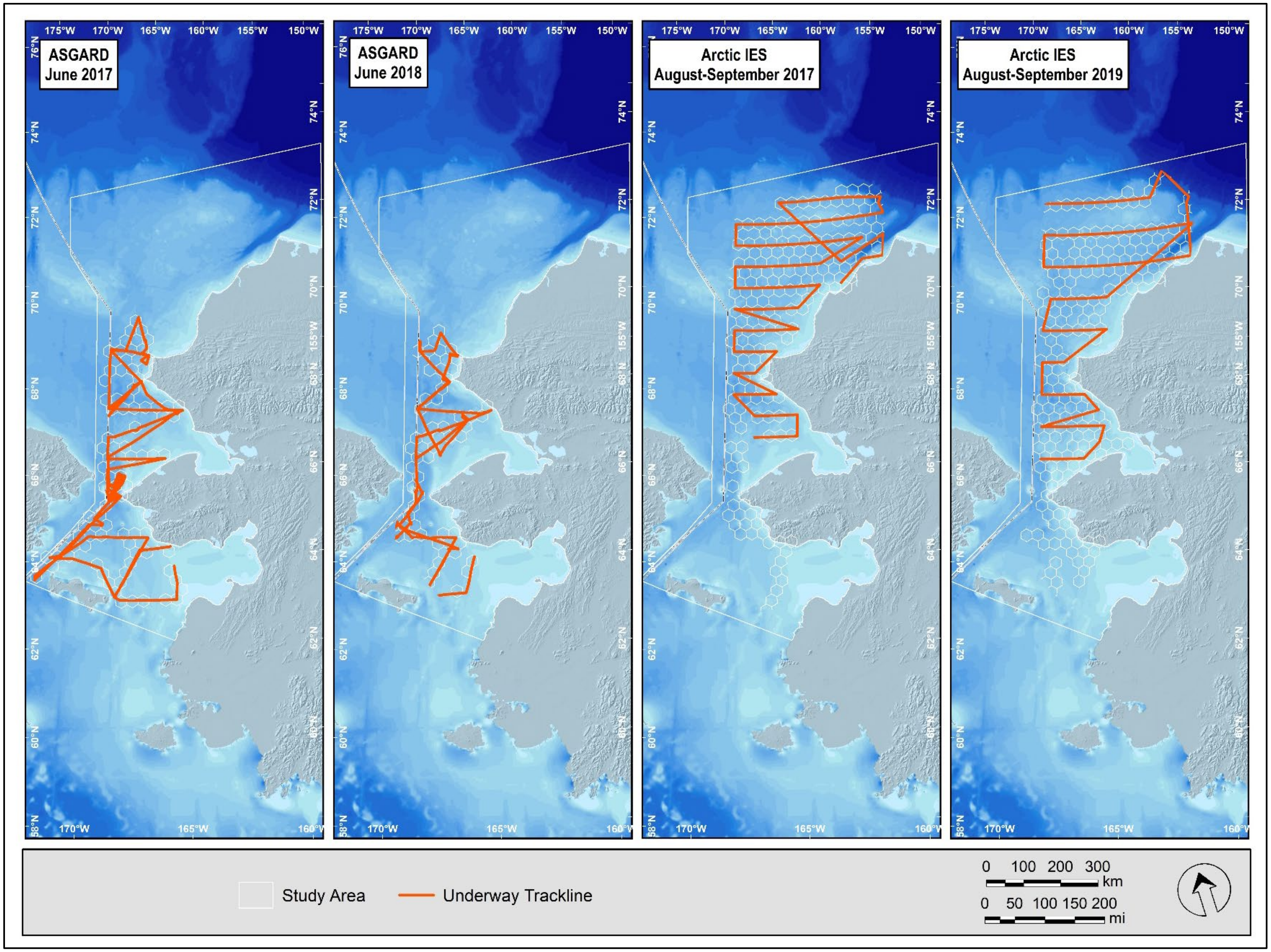

Figure 2.1. Research vessel track lines (ASGARD 2017, 2018 and Arctic IES 2017, 2019).
Lines show the path of travel between oceanographic stations for each survey.

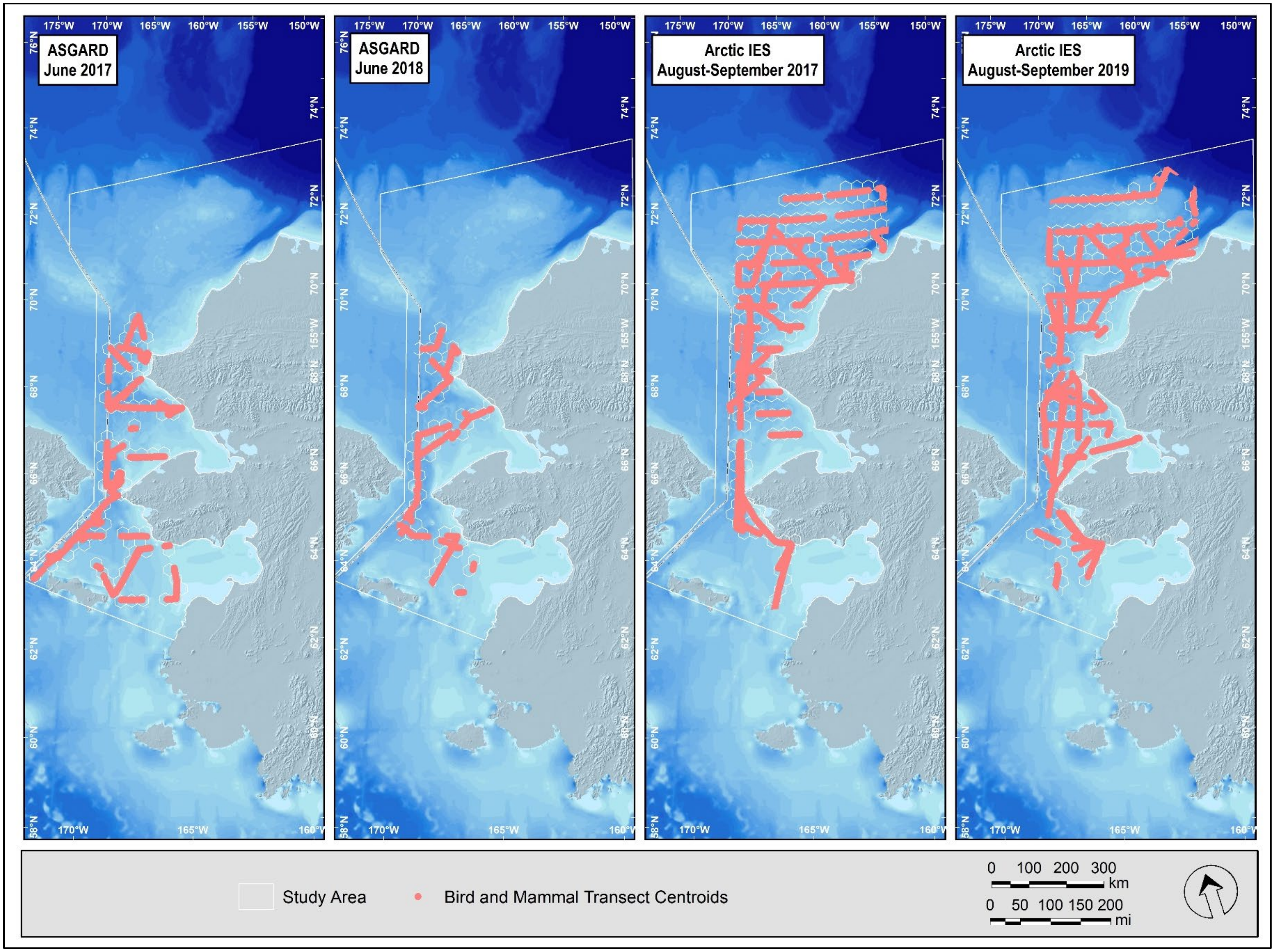

Figure 2.2. Locations of transects used for seabird density and distribution analysis during each of the four AIERP surveys.

2.1.2 At-sea survey protocols

Observers were trained on land and at sea in the protocol and data entry. Prior to AIERP cruises, training sessions were conducted at USFWS offices, and occasionally during research cruises on other large vessels. Marine bird surveys were conducted using visual observations and modified strip transects (Tasker et al. 1984; Kuletz et al. 2008) during daylight hours while transiting between ports or sample stations. A single observer recorded all marine bird and mammal sightings within 300 m and a 90° arc to port or to starboard from the centerline of travel, depending on the side of the ship where the observer was located. Transect width was occasionally reduced to 200-m or 100 m depending on visibility conditions, and surveys were discontinued if visibility was <100 m (i.e., due to fog or high seas), or if seas were Beaufort Scale >6. Birds and marine mammals on or in the water were recorded continuously, while flying birds were recorded during quick 'scans' of the transect window at intervals of approximately 1/min (depending on vessel speed) to avoid double-counting flying birds. Birds actively foraging from the air, such as surface plunging or touching the water surface were recorded as if 'on water' (i.e., continuously). Although we recorded marine mammals on and off transect, we maintained the seabird protocol and focused on the 300-m transect width, thus the densities for marine mammals are not to be used for other than distributional inference.

Surveying was generally conducted from the port side of the bridge but transferred to the starboard side if glare or weather conditions were more favorable. Data were entered directly into a computer using survey software DLog3 (A.G. Ford, Inc., Portland, OR) and connected to the ship's global positioning system. Latitude and longitude were continuously recorded (at 20-sec intervals). Binoculars (10 × 42) were used to aid in species identification, and a digital camera was occasionally used to confirm identification. A geometrically marked wooden dowel was used to estimate distance to the bird or mammal, and verified when possible with a laser rangefinder. Observers also regularly practiced estimating distances using the rangefinder.

The observer recorded species, number of individuals, behavior (on water, in air, on ice), and distance bin from the centerline (0–50 m, 51–100 m, 101–200 m, 201–300 m). Birds were identified to the lowest taxonomic level possible. Environmental variables such as sea state (Beaufort Scale), glare, weather, and sea ice cover (proportion in tenths) were recorded at first entry and automatically thereafter unless updated as necessary. For details, see Kuletz et al. 2008.

2.1.3 Marine bird data processing and analysis

Data were reviewed for accuracy on-site, typically within a day or two of collection. Final data review and quality checks were conducted at the USFWS office in Anchorage, AK. All data were processed, summarized, and analyzed using program R (R Core Team 2021) unless otherwise noted. Cleaned data were post-processed by Dan Cushing, Pole Star Ecological Consulting, LLC (Anchorage, AK). During post-processing, all daily sequential transect lines were binned into approximately 3-km segments. The total area surveyed for a segment was adjusted by transect width assigned at 100-m intervals.(i.e., transect width used at time of survey, in 100-m increments to 300 m). Densities (birds/km^2) were calculated for each species in each 3-km segment based on the adjusted area of their respective segments. The original data files (in csv format), cleaned and edited data (csv format), and processed data (csv format, with no environmental attributes) are archived at Migratory Bird Management, USFWS, Anchorage, AK, and were transferred to BOEM annually, with the final submission made in 2020.

Data summaries and mapping of distribution were done using geographic information systems (GIS; PostGIS and ArcGIS 10.8, Redland, CA). We used raw numbers (counts of birds or mammals, each with latitude and longitude) or processed data (densities in ~3-km segments, with a centroid latitude and longitude). For most mapping products and publications, the sample unit was marine bird density for each

~3-km segment. For this report, to avoid the over-influence of small segments, we only included transect segments >2.5 km in length for analysis, except for the total bird densities, which used all transects. Detectability of marine birds is affected by the bird's size and behavior and by sea conditions (Spear et al. 2004). We did not correct for detection because our primary goal was to describe distribution and seasonal patterns of abundance indices, rather than estimate absolute abundance. For our statistical summaries, we did not include observations of dabbling ducks, shorebirds (with exception of phalaropes) or land birds, thus the seven taxa of marine bird families included: Stercorariidae (jaegers), Alcidae (auks), Laridae (gulls, terns), Gaviidae (loons), Hydrobatidae (storm-petrels), Procellariidae (fulmars, shearwaters), Phalacrocoracidae (cormorants) plus marine species of Anatidae (eiders and other seaducks) and phalaropes (genus *Phalaropus*).

Marine bird distributions were mapped using a polar stereographic projection, and the average of 3-km segment densities aggregated to hexagonal grid cells that measured 30 km side-to-side. Individual foraging guilds and common species distributions were mapped for each of the four surveys.

We used the Shannon and Simpson diversity indices to compare species diversity between seasons and years (the June ASGARD and August–September Arctic IES surveys). Both indices estimate diversity by accounting for both the number of species and the relative abundance of each species. We created rarefaction curves by plotting the diversity indices and species richness for a randomized selection of 3-km segments from each project and year. The size of the randomized selection increased in 25-segment intervals. We made 200 random draws at each interval and then used quantiles to calculate 95% confidence intervals. When calculating the number of species present, we only included unidentified species groups in the total when none of the lower-order taxa was identified in any of the segments within a cruise.

2.2 Oceanographic conditions

Data on oceanographic conditions were collected by other components of the ASGARD (Danielson et al. 2022) and Arctic IES projects (Farley et al. 2022). For this report, we summarized the data that were relevant to the AK-16-07c seabird component at the scale of the 30-km hexagonal grid cells. Processed original data were provided by Seth Danielson (University of Alaska, Fairbanks; UAF), Dean Stockwell (UAF), Lisa Eisner (NOAA, Alaska Fisheries Science Center, Seattle WA), and their colleagues. These data will be incorporated into subsequent analyses and publications. Note that due to equipment issues or lack of sampling, we do not have temperature, salinity, or chlorophyll-a (Chl-a) measurements for the Northern Chukchi subregion during either ASGARD cruise, nor for the Northern Bering subregion during Arctic IES 2017.

2.2.1 Sea ice coverage

Daily sea ice extent for the entire study area was downloaded from the National Snow and Ice Data Center (ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/north/daily/geotiff). These data are part of the Sea Ice Index, Version 3 dataset which is derived from the DMSP F16, F17, and F18 satellite images that are collated in the Near-Real-Time DMSP SSMIS Daily Polar Gridded Brightness Temperatures dataset. The Sea Ice Index is available on a daily temporal scale. Each geotiff image consists of 25-km^2 grid cells with a binary assignment of whether or not ice was present within the grid cell on the date of data collection. We used a spatial overlay of all three study subregions with daily ice extent to calculate the percentage of grid cells that were ice free within the boundaries of each subregion. We determined and recorded the first dates for which the percentage of grid cells were without ice within a subregion and within the entire study as: 51–74% ice-free, 75–99% ice free, and 100% ice free. We also report the number of days (for each subregion and the entire study area) when 100% of all grid cells were without ice.

2.2.2 Water temperature and salinity

Average water column temperature and salinity were collected using a Conductivity-Temperature-Depth datalogger (CTD; Fast Cat Sea-bird SBE49) at oceanographic sampling stations (Figure 1.2; see Danielson et al. 2022; Farley et al. 2022). The average water column temperature and salinity were calculated for and visually displayed using the same 30-km hexagonal grid used for the seabird analyses. In most cases, a single CTD cast fell within a grid cell, with exception of two cells, for which we used the average of the two stations' values. We then used the cell-averaged values to calculate the water column temperature (°C) and salinity (practical salinity units, psu) for a given cruise. We also calculated average water column temperature and salinity for each of the three subregions during each survey, using the mean grid cell values.

2.2.3 Chlorophyll-a

Average water column Chl-a density (mg/m^3) was collected at oceanographic sampling stations (see Danielson et al. 2022; Farley et al. 2022). As with temperature and salinity, we averaged water column Chl-a using the 30-km hexagonal grid, thus for all but two cells a single CTD collection site was used, otherwise we used the average of two CTD casts within a grid cell. We then used the cell-averaged values to derive the mean Chl-a density for a given cruise. We also calculated average Chl-a density for each of the three subregions during each survey, using the mean grid cell values.

2.3 Distribution of prey

2.3.1 Zooplankton

During Arctic IES surveys (2017, 2019) average water column zooplankton density (individuals/m^3) was collected at oceanographic sampling stations (for details see: Kimmel and Spear 2022; in Farley et al. 2022). To ascertain relationships between seabird distributions and their prey we summarized data for euphausiids and copepods (primarily *Calanus* spp, and *Pseudocalanus* spp), which are known to be key prey species for seabirds (Hunt et al. 2000).

Zooplankton abundance was estimated from samples collected via bongo net and preserved in formalin. Zooplankton were sorted, identified to lowest taxonomic resolution possible, and enumerated. The zooplankton were identified by the staff at the Poland Plankton Sorting and Identification Center in Szczecin, Poland (see details in Kimmel and Spear 2022). For each cruise, average zooplankton density was calculated for each 30-km hexagonal grid cell where sampling occurred, thus for all but two of those cells, a single collection site was used, otherwise we used the average of two plankton tow stations within a grid cell. We then used the cell-averaged values to derive the mean zooplankton density for a given cruise. We also calculated average zooplankton density for each of the three subregions during each survey, using mean grid cell values.

2.3.2 Fish

Information on fish abundance was collected using acoustic-trawl sampling while in transit between oceanographic stations during the Arctic IES surveys (2017, 2019). Acoustic backscatter was measured at 38 and 120 kHz, at 3.7 m depth, as the ship transited at ~3.3 m/s along survey transects during daylight. Species composition was determined from targeted midwater trawls (33 sites in 2017 and 43 sites in 2019) in areas of high backscatter; for details see DeRobertis et al. (2017), Levine et al. (in review). Data were binned by species, depth (6.5–20 m, 20–40 m, 40-60 m, 60–80 m, >80 m) and fish size class (<-5.5 cm, 5.6–10.5 cm, >10.5 cm). To focus on fish sizes most relevant to seabirds we only considered fish in the two smaller size classes, <5.5 cm and 5.6–10.5 cm. Average fish density (fish/m^2) for these two size classes were aggregated to each 30 km hexagonal grid cell where sampling occurred, by taking the average value measured at each measurement point within a grid cell. The average value of all measurements was also calculated for each sub-region and cruise.

2.3.3 Seabird-biological oceanography correlations

We used Spearman rank correlations as a preliminary exploration of the relationship between prey resources and density of seabirds by foraging guild. Spearman rank correlation does not require the assumption of parameter normality, thus was suited for preliminary analysis of seabird density parameters, which contain an inflated number of 0s. We compared cell-averaged values of Chl-a, small copepods (< 2mm), *Calanus* (the predominate large copepod), Euphausiids, and small and large fish densities to seabird foraging guild density for each grid cell. Data for all cruises were pooled. Chl-a was the only parameter available for all 4 cruises. The remaining prey parameters were available for Arctic IES 2017 and 2019. The rho statistic, number of sample grid cells, and *P* value are presented for each prey parameter and foraging guild combination.

3 Results

3.1 Survey effort (temporal and spatial coverage)

From June 2017 through September 2019 we surveyed a total of 16,870 km (Table 3.1) including 14,247 km within the AIERP study area (Figure 2.2). The Arctic IES project consisted of three legs, and had roughly 3 times the survey length as the single-leg ASGARD project. Within the AIERP study area, ASGARD (in June) had 690 3-km transect segments, while Arctic IES (August-September) had 1,700 3-km transect segments (Table 3.1). ASGARD surveys were concentrated in the Northern Bering and Southern Chukchi subregions, with no coverage in the Northern Chukchi subregion (Figure 3.1). Arctic IES surveys had limited coverage of the Northern Bering subregion and extensive coverage of the Chukchi Sea, although the 2017 cruise mainly covered the Northern Chukchi subregion, with little coverage of the Southern Chukchi subregion (Figure 3.1).

3.2 Marine birds and mammals

3.2.1 Species richness and diversity

3.2.1.1 Marine birds

Across all transects within the AIERP study area, we observed 38 marine bird species and 4 non-marine bird species (Table 3.2). For both projects, 5–9 species accounted for 90% of total birds recorded on transect. Thick-billed murre (*Uria lomvia*), crested auklet (*Aethia cristatella*), and black-legged kittiwake (*Rissa tridactyla*) were among the numerically dominant species across all cruises. Least auklet (*A. pusilla*) and short-tailed shearwater were also within the numerically dominant taxa in 3 out of 4 cruises. For both years of the ASGARD project, least auklet was the numerically dominant species representing ~22–34% of total birds recorded on transect (Table 3.2), and together, least and crested auklets were the most abundant birds in both the Northern Bering and Southern Chukchi subregions (Figure 3.2). Species composition shifted from the June ASGARD surveys to the August–September Arctic IES surveys, when short-tailed shearwaters represented 64–69% of total birds; they were numerically dominant in all 3 subregions, with the notable exception of the Northern Bering Sea in 2019 (Figure 3.2). Shearwaters composed an increasing proportion of total birds moving from south to north, and represented the highest proportion of total seabirds in the Northern Chukchi subregion (Figure 3.2).

Species richness (the estimated number of species) was similar among cruises, but slightly higher during August–September Arctic IES, with an estimated 34 species (Figure 3.3A,B). Rarefaction curves also showed similar patterns in richness across cruises, and indicated that our sample sizes (Table 3.1; 3-km segments) were more than adequate to capture the species richness inflection point (at approximately 30 species), with the possible exception of ASGARD in 2018 (507 segments). Annual differences in rarefaction curves for estimated richness within a season were minor and often had overlapping 95% confidence intervals.

Based on the Simpson Diversity Index, which is weighted by the number of dominant species, the ASGARD surveys were different between years, with 2017 showing a higher diversity than 2018 (Figure 3.3C), but that 2018 value was still slightly higher than either of the Arctic IES surveys. During both years of Arctic IES, diversity was very low, indicating numerical dominance by 1–3 species (Figure 3.3D). The Shannon Diversity Index, which is weighted by the number of common species, also differed between the two ASGARD surveys, with 2017 again showing higher diversity (Figure 3.3E). During both years of Arctic IES, diversity was low and similar between years (Figure 3.3F). In summary, compared to

June (ASGARD), we recorded more species but the community was dominated by a few species in August–September, and more consistent between years.

3.2.1.2 Marine mammals

Ten species of marine mammals were identified within the AIERP study area and 8 species of marine mammals were recorded on seabird transects (Table 3.3). Gray whales were the most frequently recorded marine mammal, and were observed on- and off-transect on every cruise (Table 3.3). Humpback whales were also recorded on every cruise, both within the AIERP study area and in transit (Appendix 3), and fin and minke whales were rare within the study area. Northern fur seal, bowhead whale and killer whale were only observed in the study area during Arctic IES 2019 and harbor porpoise during Arctic IES 2017. Walruses were recorded on all cruises except ASGARD 2018 and were most numerous during Arctic IES 2019. Only one seal was identified to species, a ringed seal during Arctic IES 2019, although unidentified seals were recorded on every cruise (Table 3.3).

3.2.2 Distribution, abundance and seasonal changes

3.2.2.1 Total seabirds

Total marine bird density was lowest during ASGARD 2017 (9.3 birds/km^2) and highest during ASGARD 2018 (22.2 birds/km^2). During Arctic IES, total bird densities were similar between years, with 18.2 birds/km^2 in 2017 and 13.1 birds/km^2 in 2019. Both years of the ASGARD project showed similar overall distribution patterns, with abundance highest in a few cells in the Chirikov Basin and Bering Strait (Figure 3.4), wherein average densities within cells were up to 100 birds/km^2. These high density areas tended to be near large seabird colonies on St. Lawrence and Diomede islands (Figure 1.4). In June 2018, total bird densities were also high offshore of Cape Thompson, another seabird colony. Otherwise, total bird densities were generally <10 birds/km^2 (Figure 3.4).

During both Arctic IES cruises, high-density cells were mostly farther north, with lower total bird densities in Bering Strait (Figure 3.4). However, total densities were also high in Hope Basin in 2019 (when there was better coverage in the Southern Chukchi subregion). In both years, high bird densities occurred near Herald and Hanna shoals, but appeared to be more dispersed throughout the Northern Chukchi subregion in 2017, whereas in 2019 birds were concentrated over the two shoals and Barrow Canyon (Figure 3.4).

3.2.2.2 Seabird foraging guilds

Planktivores outnumbered piscivores during 3 of the 4 cruises, with only ASGARD 2017 having a higher density of piscivores, primarily diving foragers (Table 3.4). Mean densities of both planktivores and piscivores ranged 1.8–4.7 birds/km^2, with notable exception of ASGARD 2018, which had an average of 17.9 planktivores/km^2, nearly all of them diving foragers. The exceptionally high density of diving planktivores in June 2018 was due to auklets, primarily least auklets (Table 3.2), in offshore waters of the Northern Bering subregion (Figure 3.2). During both August–September Arctic IES cruises, shearwaters (which we considered a single-species foraging guild) numerically dominated all other categories (Table 3.4). Benthivores (seaducks) had the lowest densities among foraging guilds during all cruises.

Both planktivores and piscivores were distributed throughout the study area, but planktivores appeared to have more high-density clusters (Figures 3.5–3.8). We observed high densities of planktivores near Bering Strait and in Chirikov Basin during June 2018 (Figure 3.7), and during August–September in Hope Basin, Hanna Shoal, and Barrow Canyon in the Chukchi Sea (Figure 3.5, 3.7).

Although piscivores were generally more dispersed at low densities, we observed high densities of this group near Bering Strait and offshore of Cape Thompson to Cape Lisburne (Figures 3.6, 3.8), where there are large colonies. In the Bering Strait region, diving piscivores were more abundant during June surveys (Figure 3.8), and surface piscivores were more abundant during August–September surveys (Figure 3.6). This was also evident in the decline in mean density of diving piscivores from 3.6 ± 0.3 birds/km^2 during June (ASGARD) to 0.7 ± 0.1 birds/km^2 during August–September (Arctic IES), while the mean densities of surface piscivores remained stable (1.2–1.9 birds/km^2) across all four cruises.

Shearwaters were nearly absent during June (ASGARD) surveys, although there were low numbers in June 2017 in the Northern Bering subregion and a few sightings just north of Bering Strait (Figure 3.9). By August–September (Arctic IES) surveys, shearwater densities had increased dramatically in both years, with slightly higher mean density in 2017 (Table 3.4). Arctic IES cruises had shearwater densities of >50 birds/km^2 near Herald and Hanna shoals and Barrow Canyon in 2017, and additionally, in Hope Basin and the Northern Chukchi shelf in 2019 (Figure 3.9).

Benthivorous marine birds were generally scarce and widely scattered, with more sightings (if not highest densities) during Arctic IES surveys (Figure 3.10). In general, benthivore sightings were within 100 km of land, and nearly all were flying over the area, not directly associated with the water.

3.2.2.3 Key seabird species

Thick-billed murres were slightly more abundant than common murres on every cruise and both species had higher densities during June (ASGARD) than August–September (Arctic IES) (Table 3.2). Highest densities for both species occurred near Bering Strait and Hope Basin (Figure 3.11), with thick-billed murres having a more northerly distribution (Figure 3.12). Thick-billed murres also had high densities around Point Hope and adjacent coastline 2017 and June 2018, but less so in August–September 2019.

All three *Aethia* auklets had lower densities during June (ASGARD) 2017 than in June 2018 with less extreme differences in August–September (Arctic IES) between 2017 and 2019 (Table 3.2). During June, all three auklet species were aggregated in the Chirikov Basin and near Bering Strait, near the large breeding colonies, but during August–September they varied in their distribution in the Chukchi Sea. Parakeet auklet was the least abundant auklet, with means of 0.69 birds/km^2 in June to 0.12 birds/km^2 in August–September. During August–September, there were few parakeet auklets in the Chukchi Sea in 2017, but in 2019 they were abundant in Hope Basin and the waters west of Point Lay (Figure 3.13).

Least auklet was the most numerous auklet during ASGARD surveys (Table 3.2; mean = 4.9 birds/km^2), particularly in 2018 when they composed 22% of total birds. Least auklet densities were much lower in August–September (mean = 0.25 birds/km^2) although in 2017, they occurred widely along the western edge of the Chukchi study area and there were moderate densities near Hanna Shoal (Figure 3.14). In August–September 2019, only low densities of least auklets occurred over Hanna Shoal, and they were otherwise clustered in one location in northwestern Hope Basin, in Bering Strait, and primarily in western Chirikov Basin (Figure 3.14). Crested auklet abundance was similar between June (mean = 1.66 birds/km^2) and August–September (1.45 birds/km^2), but their distribution differed between seasons. Crested auklets were highly aggregated in Chirikov Basin and Bering Strait in June (similar to least auklets), but they dispersed north into the Chukchi Sea in August–September (Figure 3.15). Crested auklets occurred in high densities in both the Southern and Northern Chukchi subregions in 2017, but only in the Northern Chukchi in 2019 (Figure 3.15), and they composed a high proportion of total birds in the Northern Chukchi during both years (Figure 3.2).

Both horned and tufted puffins had similar abundances during each cruise, with slightly higher densities during June (Table 3.2). Horned puffins ranged from 0.24 birds/km^2 in June to 0.04 birds/km^2 in August–September, and were dispersed at low densities throughout Northern Bering and Southern Chukchi seas (Figure 3.16). Tufted puffin density ranged from 0.27 birds/km^2 in June to 0.08 birds/km^2 in August–

September, and had a distribution (Figure 3.17) similar to horned puffin; for both puffin species, there were few sightings north of Cape Lisburne.

Black-legged kittiwakes densities were similar across all cruises, ranging 0.85–1.18 birds/km² and with similar distribution across seasons (Figure 3.18). Kittiwakes occurred throughout the Northern Bering and Southern Chukchi subregions, with highest densities in August–September off the Cape Thompson to Cape Lisburne coast. They were also widely dispersed in low densities throughout the Northern Chukchi in August–September. Northern fulmar densities were also similar across cruises, with means of 0.12–0.65 birds/km². As with kittiwakes, fulmars were widely dispersed at low densities, with a few exceptions in Hope Basin, but during August–September, they had higher densities in the Northern Chukchi subregion (Figure 3.19).

Phalarope (primarily red phalarope) densities were very low in June, but increased in August–September, as migrating birds headed south after nesting on coastal tundra. Their densities never averaged more than 0.19 birds/km² but sightings were common throughout the Chukchi Sea in August–September, especially in 2019 (Figure 3.20).

3.2.2.4 Marine mammals

Across all surveys within the AIERP study area, we recorded 733 marine mammals, of which only 184 individuals were on transect (within 300 m of the transect centerline) (Table 3.3). Walruses were the most numerous (286 individuals), and were encountered more frequently during Arctic IES cruises, particularly in the Northern Chukchi subregion near Barrow Canyon and Hanna Shoal (Figure 3.21). During the 2019 Arctic IES cruise there were also low numbers of walruses dispersed across the Chukchi Sea and one sighting near St. Lawrence Island. Gray whale was the most numerous cetacean identified (168 whales), with highest numbers (110 whales) observed in June 2017 (Table 3.3), all in northwestern Hope Basin and 48 whales recorded in June 2018 in western Hope Basin and southern Bering Strait (Figure 3.22). There were fewer gray whales recorded during August–September, primarily near Barrow Canyon (Figure 3.22). Of the four species of baleen whales, few were recorded in the Northern Bering subregion except in June 2018, and most (primarily humpback whales) were observed in August–September in Hope Basin or near Barrow Canyon (Figure 3.23). The one killer whale sighting was during Arctic IES 2019, near Icy Cape (Figure 3.24).

3.3 Oceanographic conditions

3.3.1 Sea ice coverage

During our study, the Northern Bering subregion was already at least 50% ice-free by January or February, and the percentage of open water generally increased northward from May to August (Table 3.5). Sea ice was absent from the Northern Bering subregion and 75% ice-free in the Southern Chukchi subregion before the June (ASGARD) surveys in both 2017 and 2019. The entire study area was ice-free by mid-July in 2017 and 2019, but in 2018, ice persisted in the Northern Chukchi subregion until 15 August (Table 3.5). For the entire study area, 2017 stayed ice-free the longest (105 days), followed by 2019 (91 days), and 2018 had the fewest ice-free days (66 days), but each subregion had a differing interannual pattern. In the Northern Bering, 2018 was ice-free the longest, followed by 2019 and 2017. In the Southern Chukchi, 2017 and 2018 were similar and 2019 had the fewest days ice-free. In the Northern Chukchi, 2019 was ice-free the longest, followed by 2017, and ice was most persistent in 2018 (Table 3.5).

3.3.2 Water temperature and salinity

Average water column temperature varied throughout the study area and by season and ranged 0.33–9.9 °C. As expected, water temperatures tended to be cooler during June (ASGARD) surveys (Table 3.6) and progressively cooler from south to north (Table 3.6, Figure 3.1). The coldest temperature was recorded during ASGARD 2018 in the Southern Chukchi subregion and the warmest during Arctic IES 2019 in the Northern Bering subregion. Average June (ASGARD) temperatures were warmer in 2017 than in 2018 and during August–September (Arctic IES) were cooler in 2017 than 2019 (Table 3.6). During August–September 2017, the warmer temperatures were restricted to coastal waters (i.e., the ACC), but in 2019, temperatures were both warmer and extended to the western boundary of the Southern Chukchi subregion (Figure 3.25).

Average water column salinity within subregions did not vary much within or among years, ranging from 30 to 32 psu, but individual sampling stations ranged 25.3–32.9 psu. In general, salinity increased from the coast westward (reflecting the influence of the fresher ACC along the coast), and the highest values occurred along the western eastern edge of the Northern Bering subregion in June (reflecting the influence of the saline Anadyr current), particularly in 2018. In August–September 2017, high salinity waters extended throughout the Southern Chukchi and into the Northern Chukchi (Figure 3.26), whereas in 2019 the Southern Chukchi had the lowest salinity of any sub-region or year (Table 3.6). In both 2017 and 2019, August–September salinity remained low along the Northern Chukchi shelf edge (Figure 3.26).

3.3.3 Chlorophyll-A

Chl-a values were highly variable, and ranged 0.96–15.9 mg/m^{3}at individual sampling stations. Higher values were recorded during June (ASGARD) surveys, with 2018 having the highest Chl-a values (Table 3.6). In both years of June sampling, the high values occurred primarily along the western edge of the Northern Bering and Southern Chukchi subregions (Figure 3.27). In August–September, Chl-a values were generally lower than in June and mixed with areas of very low Chl-a, but tended to be higher in Hope Basin and along the coast and near Hanna Shoal in the Northern Chukchi (Figure 3.27). During both Arctic IES surveys, the Northern Chukchi subregion had the lowest average Chl-a values compared to the other subregion(s) (Table 3.6).

3.4 Prey abundance and distribution

3.4.1 Zooplankton

At this time, we only have zooplankton results for the August–September Arctic IES surveys in the Southern and Northern Chukchi subregions. Small copepods (<2 mm) were the most abundant zooplankton taxon, and were composed primarily of *Acartia* spp., *Pseudocalanus* spp., and *Oithona* spp. Zooplankton samples were highly variable; grid cell averages ranged 0–39,456 small copepod/m^3. While small copepod densities were similar between 2017 and 2019 (Table 3.6), their distributions differed between years. In 2017, small copepod densities were high in the Southern Chukchi and almost uniformly low or absent in the Northern Chukchi, whereas they were widely dispersed at moderately high densities throughout most of the Chukchi Sea in 2019 (Figure 3.28).

Nearly all copepods >2mm size were *Calanus* spp.; this taxon is larger and more energy-rich than other genera of copepods, and thus an important prey for many seabirds. Abundance of *Calanus* was marginally higher in August–September 2019 (Table 3.6), but was more widely dispersed that year. In 2017, *Calanus* was concentrated in the eastern portion of the Southern Chukchi subregion (Figure 3.29), where the highest density (470 *Calanus*/m^3) was recorded in Hope Basin. In contrast, cells with high *Calanus* densities were scattered throughout the Chukchi in 2019, primarily along the western edges and in the northwest corner of the Northern Chukchi subregion (Figure 3.29).

Euphausiids in August–September 2017 were found in central Hope Basin in the Southern Chukchi subregion, and waters northwest of Icy Cape, near the boundary between Southern and Northern Chukchi subregions, and a few cells near the Northern Chukchi shelf edge (Figure 3.30). Euphausiid densities were higher overall in August–September 2019, with substantially higher average density in the Southern Chukchi subregion (Table 3.6). In 2019, euphausiid densities were high in Hope Basin and along the western edge of the Chukchi Sea study area, but otherwise nearly absent (Figure 3.30).

In summary, important zooplankton prey taxa were overall less abundant and tended to be more spatially aggregated in 2017 compared to 2019. Smaller copepods were concentrated in the Southern Chukchi subregion in 2017 and more dispersed throughout the Chukchi Sea in 2019. Large *Calanus* copepods were highly aggregated in the Northern Chukchi subregion in 2017 and more dispersed in 2019. Euphausiids had low densities and were concentrated near the boundary between southern and northern Chukchi subregions in 201, and in 2019 had higher densities in the Southern Chukchi subregion and along the northwestern boundary of the study area.

3.4.2 Fish

We summarized hydroacoustic data on fish collected in the Southern and Northern Chukchi subregions during Arctic IES surveys in 2017 and 2019. The highest densities for both small fish (<5.5 cm) and large fish (5.6–10.5 cm) were recorded in 2017, with large fish more abundant in the Southern Chukchi than the Northern Chukchi and small fish more abundant in the Northern Chukchi than the Southern Chukchi (Table 3.6). Large fish were widely distributed in 2017, with high densities from Icy Cape to offshore of Ledyard Bay and moderate to high densities in most of the Northern Chukchi (Figure 3.32). Fish abundance was much lower in 2019 overall, with small fish nearly absent from the Southern Chukchi and densities an order of magnitude lower in the Northern Chukchi than in 2017 (Figure 3.31). Large fish were also an order of magnitude less abundant in 2019 and more restricted in spatial distribution. They were located almost entirely in the Northern Chukchi subregion along the southwestern flank of Hanna Shoal and did not extend to the shelf break (Figure 3.32).

3.5 Correlations between seabirds and lower trophic levels

A preliminary examination of seabird associations with Chl-a, zooplankton, and fish revealed weak correlations (rho <0.4), few of which were statistically significant (Table 3.7). Shearwaters had a weak negative correlation with small copepods (rho = -0.20, $P = 0.04$). Among foraging guilds, diving piscivores had weak, positive correlations with Chl-a (rho = 0.14, $P = 0.05$) and small copepods (rho = 0.24, $P = 0.01$) and a negative correlation with small fish (rho = -0.20, $P < 0.01$). Diving planktivores were negatively correlated to small copepods (rho = -0.28, $P < 0.01$) and large fish (rho = -0.17, $P = 0.02$). Surface piscivores had the strongest correlations with prey, with a positive correlation to small copepods (rho = 0.34, $P < 0.01$) and a negative correlation to small fish (rho = -0.36, $P < 0.01$). Surface planktivores had a weak negative correlation with small fish (rho = -0.19, $P = 0.01$). None of the foraging guilds had statistically significant relationships with *Calanus* copepods or euphausiids, and no strong (>0.2) correlation to Chl-a or large fish.

Table 3.1. Summary of total kilometers surveyed and birds and mammals observed on-transect within the study area, during each study period for AIERP 2017–2019.

Summaries for Entire Cruise			Individuals on Transect		Count of Species		Number of transect Segments	
Year	Project	Total km surveyed	Total Marine Birds	Total Marine Mammals	Marine Bird Species	Marine Mammal Species	Total	Segments >2.5 km
2017	ASGARD	2,183	5,302	28	27	6		
2017	Arctic IES	6,301	28,372	51	38	7		
2018	ASGARD	2,036	21,513	23	39	5		
2019	Arctic IES	6,350	22,896	110	41	8		
Summaries for AIERP study area								
2017	ASGARD	2,183	5,302	28	27	6	847	690
2017	Arctic IES	5,345	23,786	39	30	5	2,019	1,695
2018	ASGARD	1,210	6,448	21	24	4	468	377
2019	Arctic IES	5,509	20,248	96	34	5	2,099	1,741

Table 3.2. Density for all species of marine birds observed during AIERP 2017–2019.

Family	Species	Scientific Name	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
Anatidae	Snow Goose	*Anser caerulescens*				*
	Greater White-fronted Goose	*Anser albifrons*	*			
	Canada Goose	*Branta canadensis*				*
	Northern Pintail	*Anas acuta*	0.001 ± 0.001			
	Steller's Eider	*Polysticta stelleri*	*		*	
	Spectacled Eider	*Somateria fischeri*		0.010 ± 0.010	0.009 ± 0.006	0.006 ± 0.003
	King Eider	*Somateria spectabilis*	0.019 ± 0.015	*	*	0.013 ± 0.008
	Common Eider	*Somateria mollissima*	*	0.026 ± 0.019	0.003 ± 0.003	0.006 ± 0.006
	Unidentified eider	*Polysticta* or *Somateria* sp.	0.043 ± 0.031	0.102 ± 0.078	0.016 ± 0.008	0.003 ± 0.002
	Harlequin Duck	*Histrionicus histrionicus*	*			
	White-winged Scoter	*Melanitta deglandi*	*		*	0.002 ± 0.002
	Long-tailed Duck	*Clangula hyemalis*	0.001 ± 0.001	0.003 ± 0.003	0.011 ± 0.008	0.006 ± 0.004
	Unidentified goldeneye	*Bucephala* sp.	*			
	Unidentified duck	*Anatidae* sp.		0.010 ± 0.010	0.002 ± 0.002	0.002 ± 0.002
Podicipedidae	Red-necked Grebe	*Podiceps grisegena*				*
Charadriidae	Pacific Golden-Plover	*Pluvialis fulva*				*
Scolopacidae	Marbled Godwit	*Limosa fedoa*			*	
	Ruddy Turnstone	*Arenaria interpres*				*
	Black Turnstone	*Arenaria melanocephala*		*		
	Unidentified turnstone	*Arenaria* sp.				0.002 ± 0.001
	Pectoral Sandpiper	*Calidris melanotos*				*
	Semipalmated Sandpiper	*Calidris pusilla*			*	
	Unidentified sandpiper	*Calidris* sp.			0.001 ± 0.001	

Family	Species	Scientific Name	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
	Unidentified (*Charadrius*)	*Charadrius* sp.	0.003 ± 0.003	0.009 ± 0.006	0.002 ± 0.001	0.009 ± 0.005
	Red-necked Phalarope	*Phalaropus lobatus*	0.052 ± 0.036			0.001 ± 0.001
	Red Phalarope	*Phalaropus fulicarius*	0.063 ± 0.055	0.054 ± 0.020	0.194 ± 0.163	0.545 ± 0.134
	Unidentified phalarope	*Phalaropus* sp.		0.015 ± 0.010	0.847 ± 0.420	0.372 ± 0.098
Stercorariidae	Pomarine Jaeger	*Stercorarius pomarinus*	0.025 ± 0.010	0.020 ± 0.008	0.025 ± 0.006	0.034 ± 0.008
	Parasitic Jaeger	*Stercorarius parasiticus*	0.019 ± 0.007	0.017 ± 0.009	0.008 ± 0.003	0.014 ± 0.005
	Long-tailed Jaeger	*Stercorarius longicaudus*	0.003 ± 0.002	0.010 ± 0.005	0.003 ± 0.001	0.001 ± 0.001
	Unidentified jaeger	*Stercorarius* sp.	0.001 ± 0.001	0.010 ± 0.006	0.005 ± 0.002	0.007 ± 0.002
Alcidae	Dovekie	*Alle alle*	0.005 ± 0.004	0.007 ± 0.007		
	Common Murre	*Uria aalge*	0.424 ± 0.046	0.115 ± 0.028	0.113 ± 0.021	0.125 ± 0.023
	Thick-billed Murre	*Uria lomvia*	1.182 ± 0.097	1.187 ± 0.157	0.571 ± 0.202	0.224 ± 0.047
	Unidentified murre	*Uria* sp.	1.234 ± 0.180	1.168 ± 0.243	0.062 ± 0.009	0.060 ± 0.011
	Black Guillemot	*Cepphus grylle*		0.018 ± 0.011	*	*
	Pigeon Guillemot	*Cepphus columba*	0.038 ± 0.014		0.002 ± 0.002	
	Kittlitz's Murrelet	*Brachyramphus brevirostris*	0.002 ± 0.002		0.001 ± 0.001	0.001 ± 0.001
	Unidentified murrelet	*Brachyramphus* sp.	0.003 ± 0.003			0.002 ± 0.001
	Ancient Murrelet	*Synthliboramphus antiquus*	0.001 ± 0.001		0.037 ± 0.011	0.024 ± 0.011
	Parakeet Auklet	*Aethia psittacula*	0.562 ± 0.164	0.822 ± 0.135	0.073 ± 0.018	0.159 ± 0.028
	Least Auklet	*Aethia pusilla*	1.912 ± 0.345	7.947 ± 1.853	0.166 ± 0.028	0.370 ± 0.083
	Crested Auklet	*Aethia cristatella*	0.821 ± 0.141	2.497 ± 0.662	2.428 ± 0.538	0.475 ± 0.101
	Unidentified auklet	*Ptychoramphus* or *Aethia* sp.	0.077 ± 0.022	2.996 ± 0.795	0.051 ± 0.012	0.036 ± 0.011
	Horned Puffin	*Fratercula corniculata*	0.186 ± 0.031	0.214 ± 0.054	0.059 ± 0.013	0.037 ± 0.009
	Tufted Puffin	*Fratercula cirrhata*	0.209 ± 0.043	0.252 ± 0.069	0.076 ± 0.015	0.025 ± 0.006

Family	Species	Scientific Name	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
	Unidentified puffin	*Fratercula* sp.	0.001 ± 0.001		0.001 ± 0.001	
	Unidentified alcid	*Alcidae* sp.	0.030 ± 0.013	2.955 ± 1.851	0.046 ± 0.011	0.051 ± 0.012
Laridae	Black-legged Kittiwake	*Rissa tridactyla*	0.937 ± 0.098	0.861 ± 0.220	1.180 ± 0.129	0.850 ± 0.064
	Sabine's Gull	*Xema sabini*	0.004 ± 0.003	0.002 ± 0.002	0.005 ± 0.003	0.029 ± 0.014
	Herring Gull	*Larus argentatus*	*	*	0.001 ± 0.001	0.002 ± 0.002
	Slaty-backed Gull	*Larus schistisagus*	0.002 ± 0.002		*	
	Glaucous-winged Gull	*Larus glaucescens*	0.009 ± 0.004	*	0.001 ± 0.001	0.006 ± 0.004
	Glaucous Gull	*Larus hyperboreus*	0.041 ± 0.011	0.104 ± 0.033	0.042 ± 0.006	0.073 ± 0.011
	Unidentified gull	*Larus* sp.	0.004 ± 0.003	0.012 ± 0.012	0.007 ± 0.002	0.003 ± 0.002
	Arctic Tern	*Sterna paradisaea*			0.009 ± 0.004	0.074 ± 0.026
	Unidentified tern	*Sterna/Onychoprion* sp.			0.017 ± 0.013	
Gaviidae	Red-throated Loon	*Gavia stellata*			0.001 ± 0.001	0.001 ± 0.001
	Arctic Loon	*Gavia arctica*				0.001 ± 0.001
	Pacific Loon	*Gavia pacifica*	0.007 ± 0.004	0.080 ± 0.046	0.005 ± 0.003	0.046 ± 0.010
	Common Loon	*Gavia immer*			0.001 ± 0.001	0.002 ± 0.001
	Yellow-billed Loon	*Gavia adamsii*	*		*	0.008 ± 0.006
	Unidentified loon	*Gavia* sp.		0.002 ± 0.002	0.011 ± 0.003	0.010 ± 0.003
Hydrobatidae	Fork-tailed Storm-Petrel	*Hydrobates furcatus*		0.032 ± 0.017	0.008 ± 0.004	0.002 ± 0.001
Procellariidae	Northern Fulmar	*Fulmarus glacialis*	0.250 ± 0.063	0.652 ± 0.335	0.351 ± 0.038	0.124 ± 0.026
	Short-tailed Shearwater	*Ardenna tenuirostris*	1.059 ± 0.398	0.002 ± 0.002	11.711 ± 1.630	9.242 ± 1.308
	Unidentified dark shearwater	*Ardenna* sp.			0.003 ± 0.002	0.005 ± 0.004
	Unidentified procellarid	*Procellariidae* sp.			0.001 ± 0.001	

Family	Species	Scientific Name	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
Phalacrocoracidae	Pelagic Cormorant	*Phalacrocorax pelagicus*	0.008 ± 0.005	0.009 ± 0.005	0.011 ± 0.007	*
	Pelagic/Red-faced Cormorant	*Phalacrocorax* sp.				0.001 ± 0.001
Accipitridae	Bald Eagle	*Haliaeetus leucocephalus*				*
Falconidae	Peregrine Falcon	*Falco peregrinus*				*
	Unidentified passerine	*Passeriformes* sp.	0.012 ± 0.008		0.001 ± 0.001	0.001 ± 0.001
	Unidentified bird	*Aves* sp.		0.007 ± 0.004	0.002 ± 0.001	0.003 ± 0.001
	Total Birds		9.251 ± 0.72	22.234 ± 3.814	18.18 ± 1.78	13.095 ± 1.334

Note: Density includes all marine birds observed on-transect and is the mean of all transects within the study area during each study period.
* Species seen only off-transect during a cruise.

Table 3.3. Total count of each marine mammal species observed both on and off transect during AIERP 2017–2019.

Family	Species	Scientific name	2017		2018		2017		2019	
			ASGARD		ASGARD		Arctic IES		Arctic IES	
			On Transect	Off Transect	On Transect	Off Transect	On Transect	Off Transect	On Transect	Off Transect
Otariidae	Northern Fur Seal	*Callorhinus ursinus*								1
Odobenidae	Walrus	*Odobenus rosmarus*	2	23			15	27	78	141
Phocidae	Ringed Seal	*Pusa hispida*							1	
	unidentified seal		3	1	3		6	3	4	7
	unidentified pinniped		1		1		6	1	4	5
Balaenidae	Bowhead Whale	*Balaena mysticetus*								2
Balaenopteridae	Minke Whale	*Balaenoptera acutorostrata*	3	1	1					5
	Fin Whale	*Balaenoptera physalus*	1			3			3	3
	Humpback Whale	*Megaptera novaeangliae*	4	8	1	1	1	6		28
Eschrichtiidae	Gray Whale	*Eschrichtius robustus*	14	76	14	34	3	16	3	8
Delphinidae	Pacific White-sided Dolphin	*Lagenorhynchus obliquidens*								
	Killer Whale	*Orcinus orca*							2	2
Phocoenidae	Harbor Porpoise	*Phocoena phocoena*					3			3
	Dall's Porpoise	*Phocoenoides dalli*								
	unidentified whale			3	1	1	5	68	1	72
	Total		28	112	21	39	39	121	96	277

Table 3.4. Densities of seabirds (birds/km^2) by foraging guild recorded on ASGARD cruises (June 2017 and 2018) and AIERP cruises (August–October 2017 and 2019) in the northern Bering and Chukchi seas.

Foraging Guild	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
Diving Planktivore	3.102 ± 0.405	17.792 ± 3.993	2.951 ± 0.632	1.124 ± 0.154
Surface Planktivore	0.141 ± 0.080	0.125 ± 0.035	0.528 ± 0.109	1.073 ± 0.200
Diving Piscivore	3.290 ± 0.275	3.878 ± 0.791	0.825 ± 0.114	0.557 ± 0.065
Surface Piscivore	1.365 ± 0.145	1.889 ± 0.521	1.670 ± 0.142	1.210 ± 0.076
Shearwater	1.193 ± 0.485	0.003 ± 0.003	12.084 ± 1.807	10.300 ± 1.566
Benthivore	0.078 ± 0.043	0.152 ± 0.096	0.049 ± 0.015	0.033 ± 0.012
Planktivore	3.243 ± 0.412	17.917 ± 3.993	3.479 ± 0.641	2.197 ± 0.255
Piscivore	4.655 ± 0.312	5.767 ± 0.993	2.495 ± 0.180	1.768 ± 0.102
Diving Forager	6.392 ± 0.551	21.670 ± 4.461	3.776 ± 0.641	1.682 ± 0.171
Surface Forager	1.506 ± 0.167	2.013 ± 0.522	2.197 ± 0.180	2.283 ± 0.214

Note: Densities are the mean density of all transects within the study area during each study period.

Table 3.5. Dates of ice retreat and the total number of days ice-free for 3 regions of the Bering and Chukchi seas, Alaska, 2017–2019.

Year	Percent area ice-free	Region			Entire Study Area
		Northern Bering	Southern Chukchi	Northern Chukchi	
2017	50	Jan 1	May 10	Jun 4	Jun 4
	75	May 9	May 19	Jun 24	Jun 24
	100	May 26	Jun 27	Jul 18	Jul 19
	Last date ice-free	Nov 17	Nov 1	Nov 4	Nov 1
2018	50	Jan 1	Apr 27	May 25	May 25
	75	Apr 18	May 11	Jul 18	Jul 18
	100	May 9	Jun 19	Aug 15	Aug 15
	Last date ice free	Nov 22	Oct 22	Oct 20	Oct 20
2019	50	Feb 27	May 4	May 22	May 22
	75	Mar 1	May 9	Jun 25	Jun 25
	100	May 13	Jun 20	Jul 10	Jul 14
	Last date ice free	Nov 12	Oct 13	Nov 11	Oct 13

Table 3.6. Average temperature (°C), salinity (psu), and densities of chlorophyll-A, zooplankton, and fish for 3 regions of the Bering and Chukchi seas, Alaska, 2017–2019.

Survey	Region	Temperature °C	Salinity	Chlorophyll mg/m^3	Euphausiids ind/m^3	Copopods log(ind/m^3)	Calanus log(ind/m^3)	Fish (<5.5 cm) ind/km^2	Fish (5.5–10.5 cm) ind/km^2
ASGARD 2017	Bering/Chirikov	6.12 ± 0.36	31.58 ± 0.22	1.74 ± 0.22					
	Southern Chukchi	4.25 ± 0.18	32.00 ± 0.11	2.79 ± 0.47					
	Northern Chukchi								
Arctic IES 2017	Bering/Chirikov								
	Southern Chukchi	6.88 ± 0.31	31.25 ± 0.14	1.62 ± 0.11	0.42 ± 0.10	4.05 ± 0.06	0.43 ± 0.07	58,822 ± 3,370	67,732 ± 2,694
	Northern Chukchi	5.89 ± 0.17	30.87 ± 0.18	1.13 ± 0.07	0.47 ± 0.11	3.15 ± 0.05	0.62 ± 0.10	199,469 ± 3,282	15,066 + 385
ASGARD 2018	Bering/Chirikov	4.35 ± 0.51	31.68 ± 0.21	4.02 ± 0.62					
	Southern Chukchi	3.69 ± 0.26	31.15 ± 0.18	3.19 ± 0.43					
	Northern Chukchi								
Arctic IES 2019	Bering/Chirikov	8.64 ± 1.23	31.42 ± 0.42	2.66 ± 0.54					
	Southern Chukchi	9.10 ± 0.33	30.02 ± 0.32	1.53 ± 0.21	3.39 ± 1.10	3.96 ± 0.05	0.60 ± 0.11	666 ± 60	867 ± 63
	Northern Chukchi	7.85 ± 0.26	30.05 ± 0.13	1.26 ± 0.19	0.58 ± 0.21	3.51 ± 0.05	0.88 ± 0.09	21,479 ± 574	6,028 ± 162

Table 3.7. Spearman rank correlation between foraging guilds and prey for during AIERP cruises 2017–2019.

Foraging Guild	Chlorophyll (mg/m^3)			Small Copepod (<2 mm) / m3			Calanus / m^3			Euphausiid / m^3			Small Fish / km^2			Large Fish / km		
	n	rho	*P*	n	rho	*P*	n	rho	*P*	n	rho	*P*	n	rho	*P*	n	rho	*P*
Shearwater	210	-0.05	0.46	105	**-0.20**	**0.04**	105	0.14	0.16	105	-0.02	0.83	202	0.09	0.20	202	0.03	0.66
Diving Piscivore	210	**0.14**	**0.05**	105	**0.24**	**0.01**	105	-0.17	0.08	105	-0.04	0.66	202	**-0.20**	**0.00**	202	0.10	0.16
Diving Planktivore	210	0.05	0.46	105	**-0.28**	**0.00**	105	0.09	0.36	105	0.04	0.68	202	-0.01	0.91	202	**-0.17**	**0.02**
Surface Piscivore	210	0.10	0.14	105	**0.34**	**0.00**	105	-0.10	0.31	105	0.16	0.10	202	**-0.36**	**0.00**	202	0.08	0.25
Surface Planktivore	210	0.00	0.98	105	0.12	0.24	105	-0.03	0.76	105	0.02	0.84	202	**-0.19**	**0.01**	202	-0.05	0.50

Note: Bold type indicates correlations that were statistically significant with a threshold of $\alpha = 0.05$

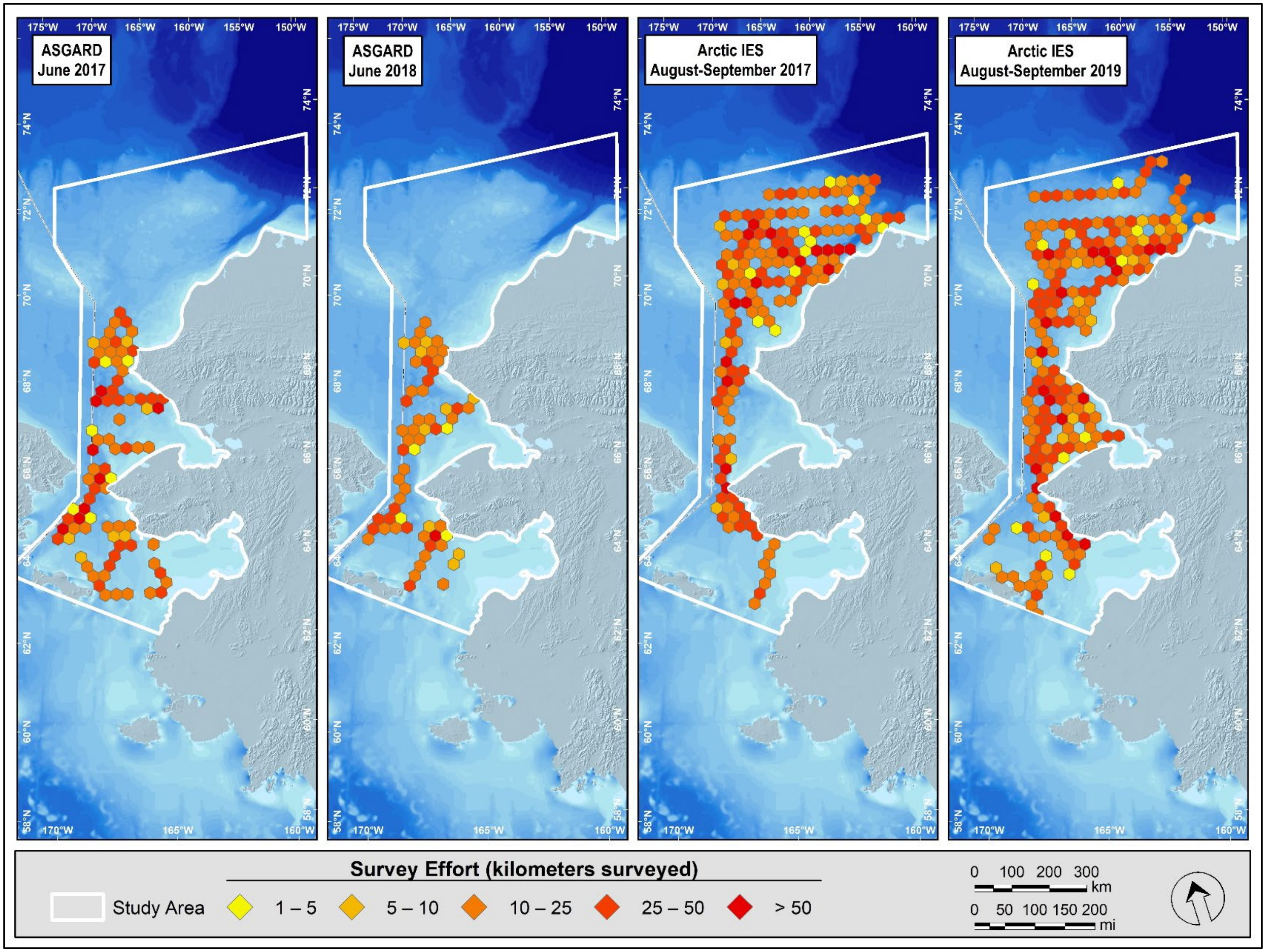

Figure 3.1. AIERP seabird survey sampling effort, 2017–2019.
Grid cells are 30 km side-to-side and effort was calculated as the total kilometer surveyed per cell for each of the 4 cruises. Empty grid cells indicate no sampling occurred within that cell during that cruise.

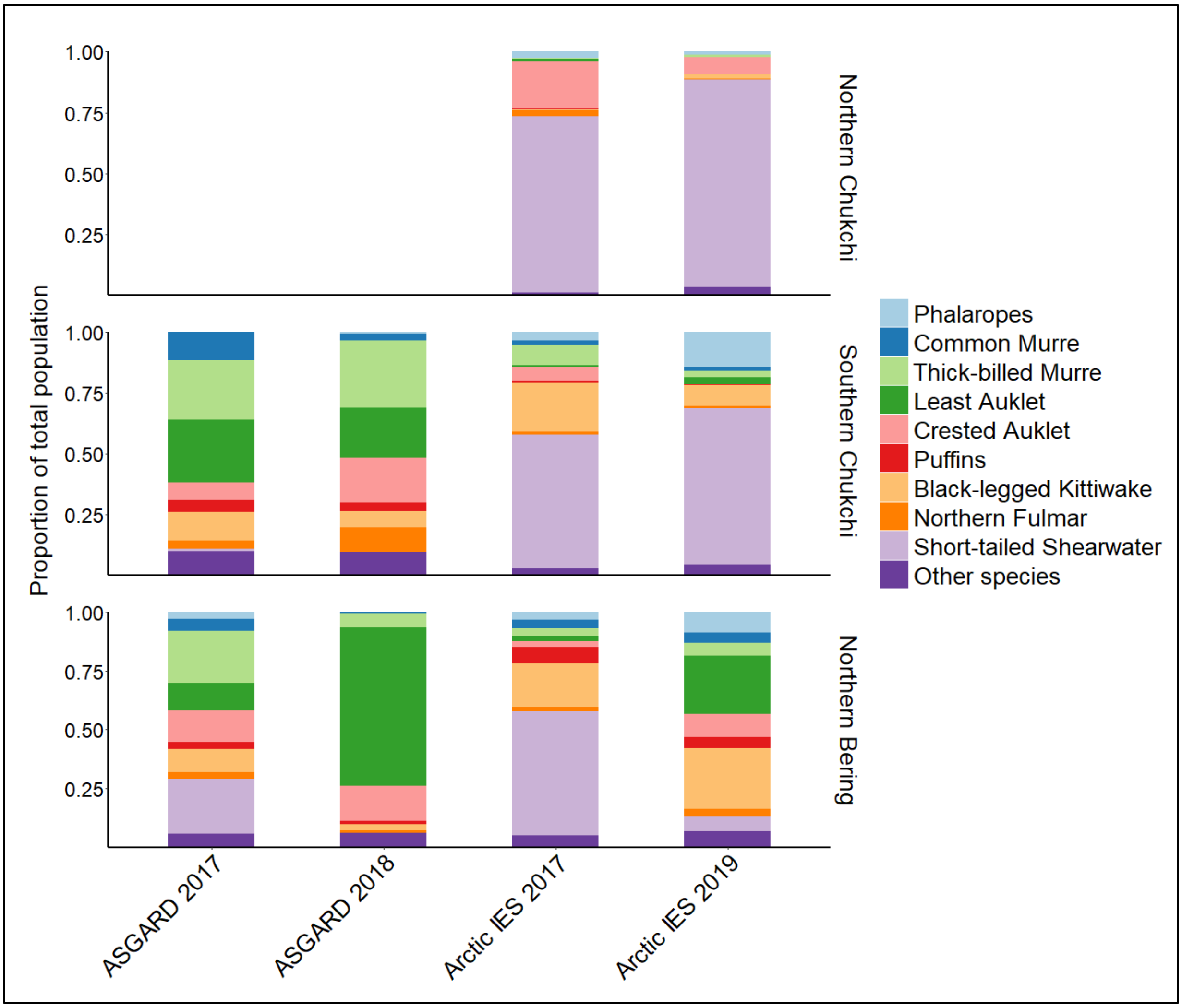

Figure 3.2. Species composition of seabirds observed during each AIERP cruise, 2017–2019. Seabirds recorded on transect in the Northern Bering, Southern Chukchi, and Northern Chukchi subregions. The Northern Chukchi was not sampled during ASGARD.

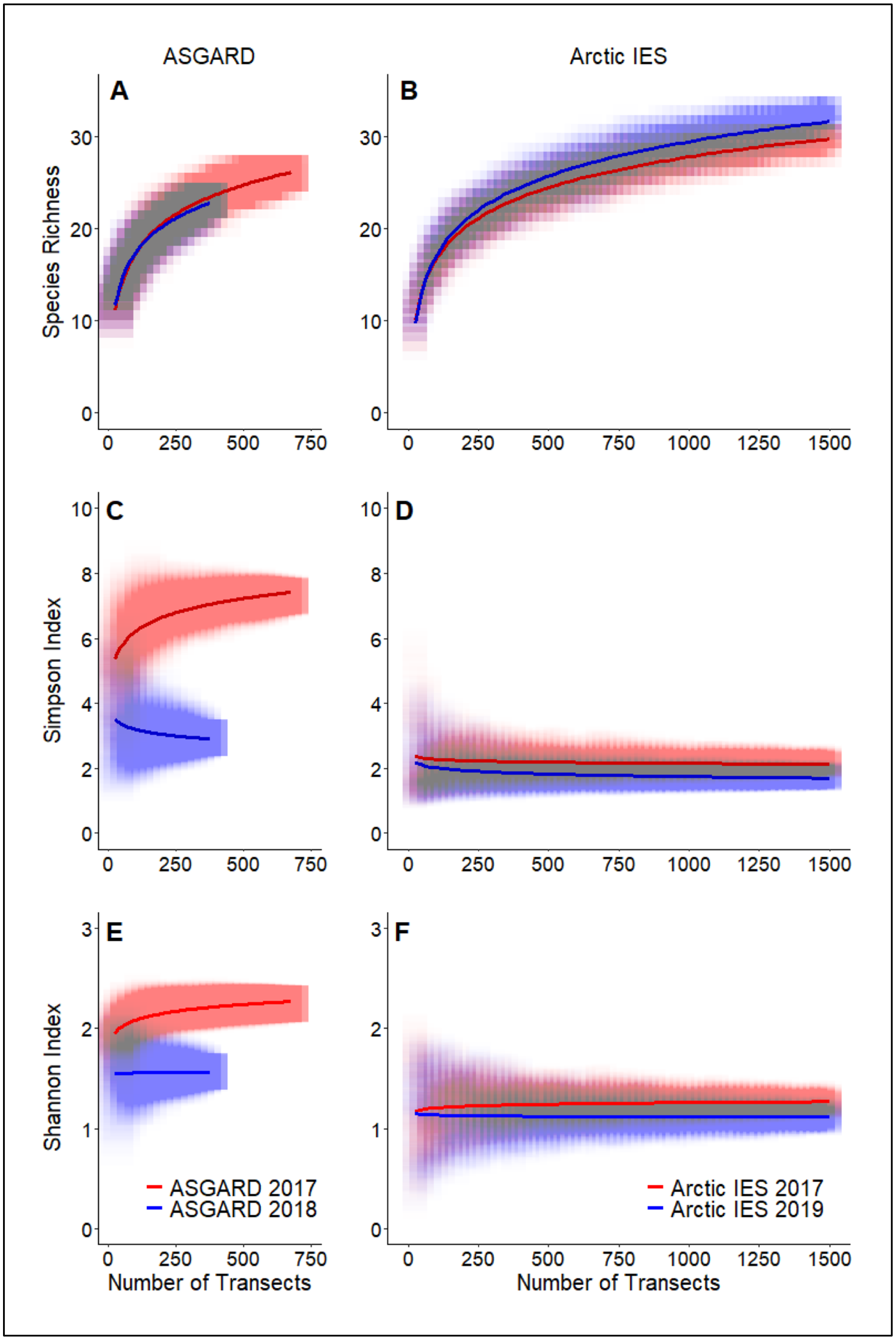

Figure 3.3. Estimated species richness and diversity (rarefaction curves) during each AIERP cruise.

Diversity was estimated using the Simpson and Shannon diversity indices. Mean (solid lines) and 95% confidence intervals (shading) were derived from random selection of 3-km transect segments from surveys conducted during each cruise.

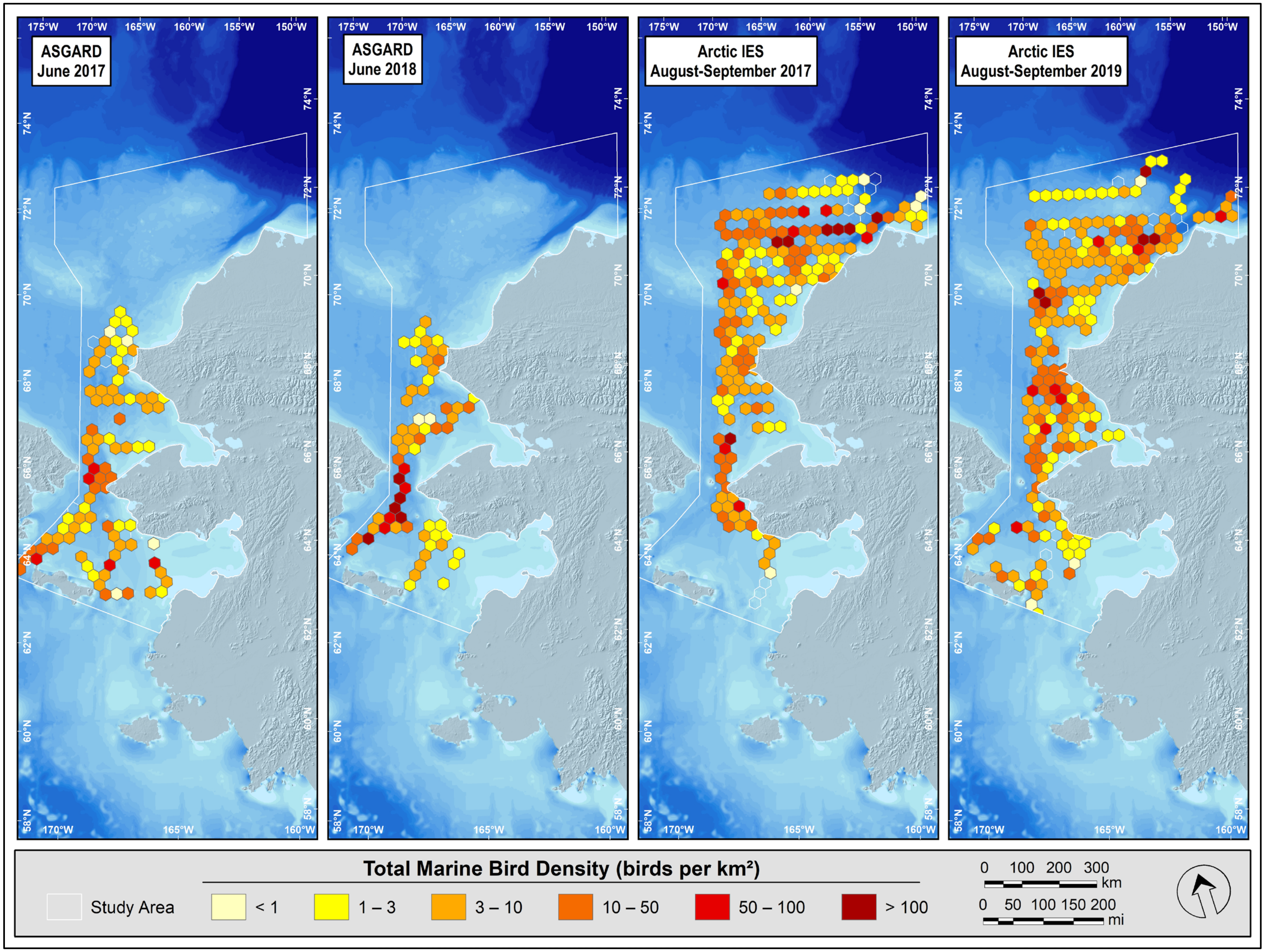

Figure 3.4. Density (birds/km^2) of total seabirds observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys. Density is the mean of all 3-km transect segments within each 30-km grid cell.

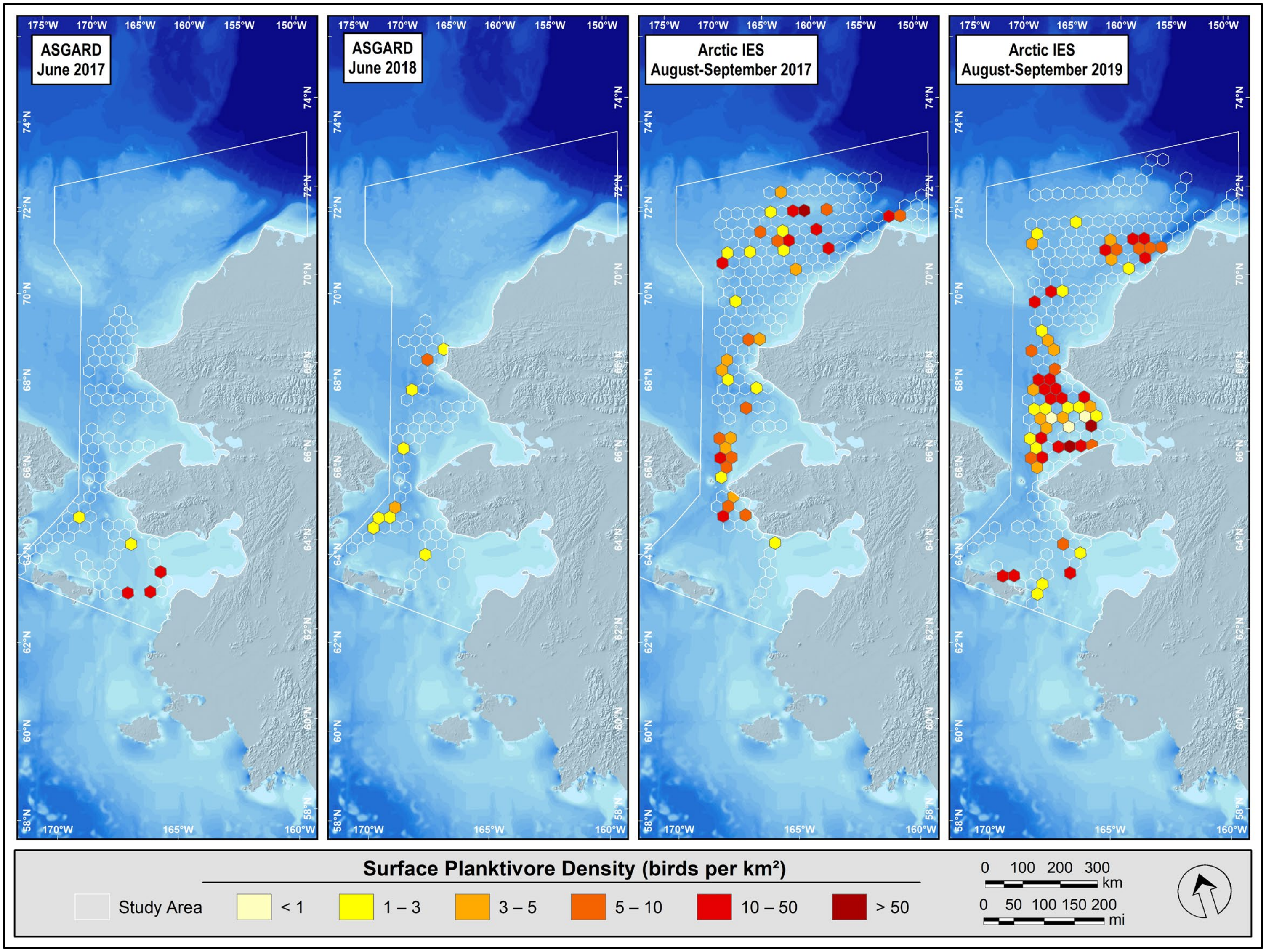

Figure 3.5. Density (birds/km^2) of total surface-feeding planktivorous seabirds observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.
Density is the mean of all 3-km transect segments within each 30-km grid cell. Shearwaters were not included in the planktivorous foraging guilds.

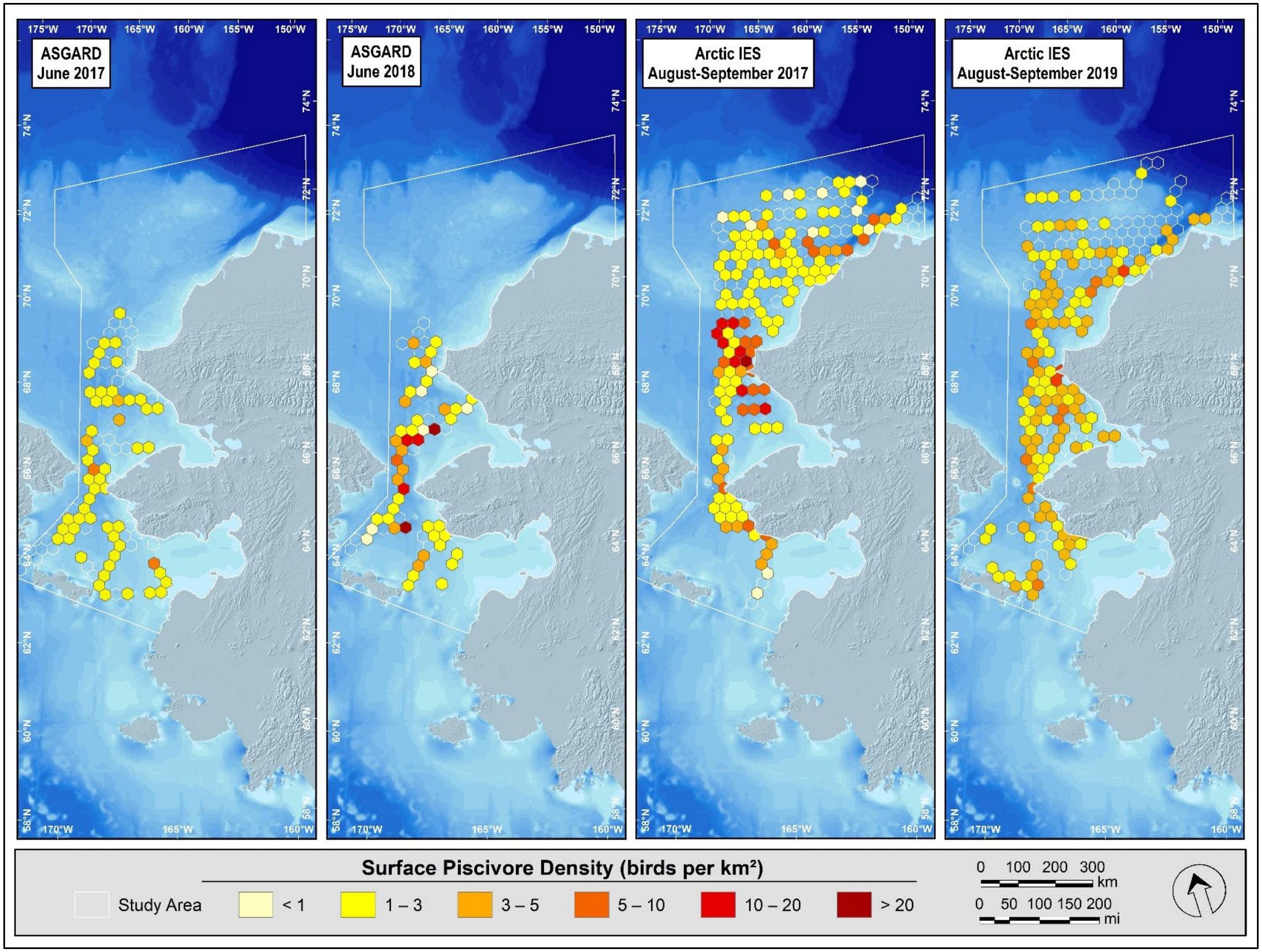

Figure 3.6. Density (birds/km^2) of total surface-feeding piscivorous seabirds observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.
Density is the mean of all 3-km transect segments within each 30-km grid cell.

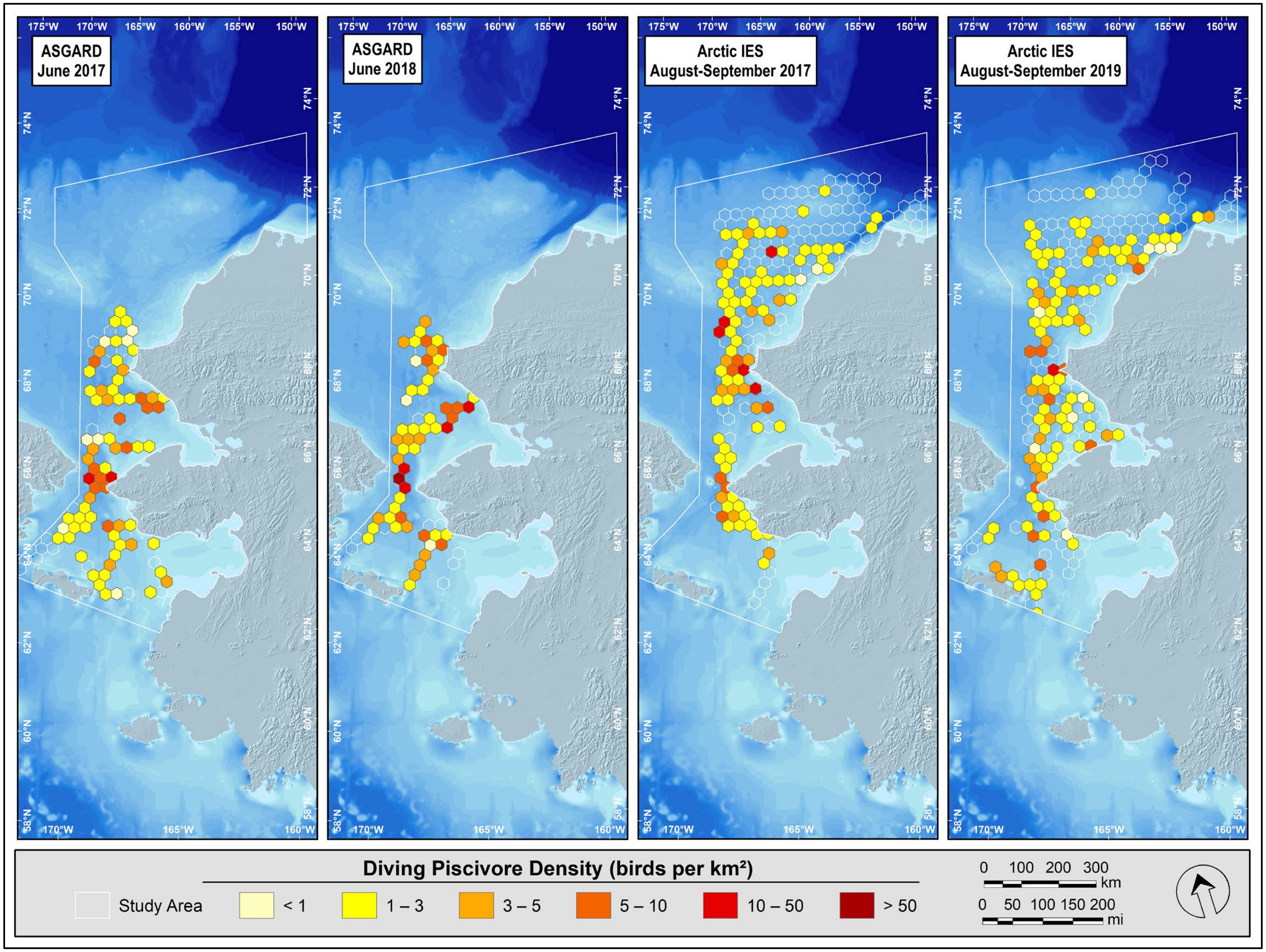

Figure 3.7. Density (birds/km^2) of total diving piscivorous seabirds observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.
Density is the mean of all 3-km transect segments within each 30-km grid cell.

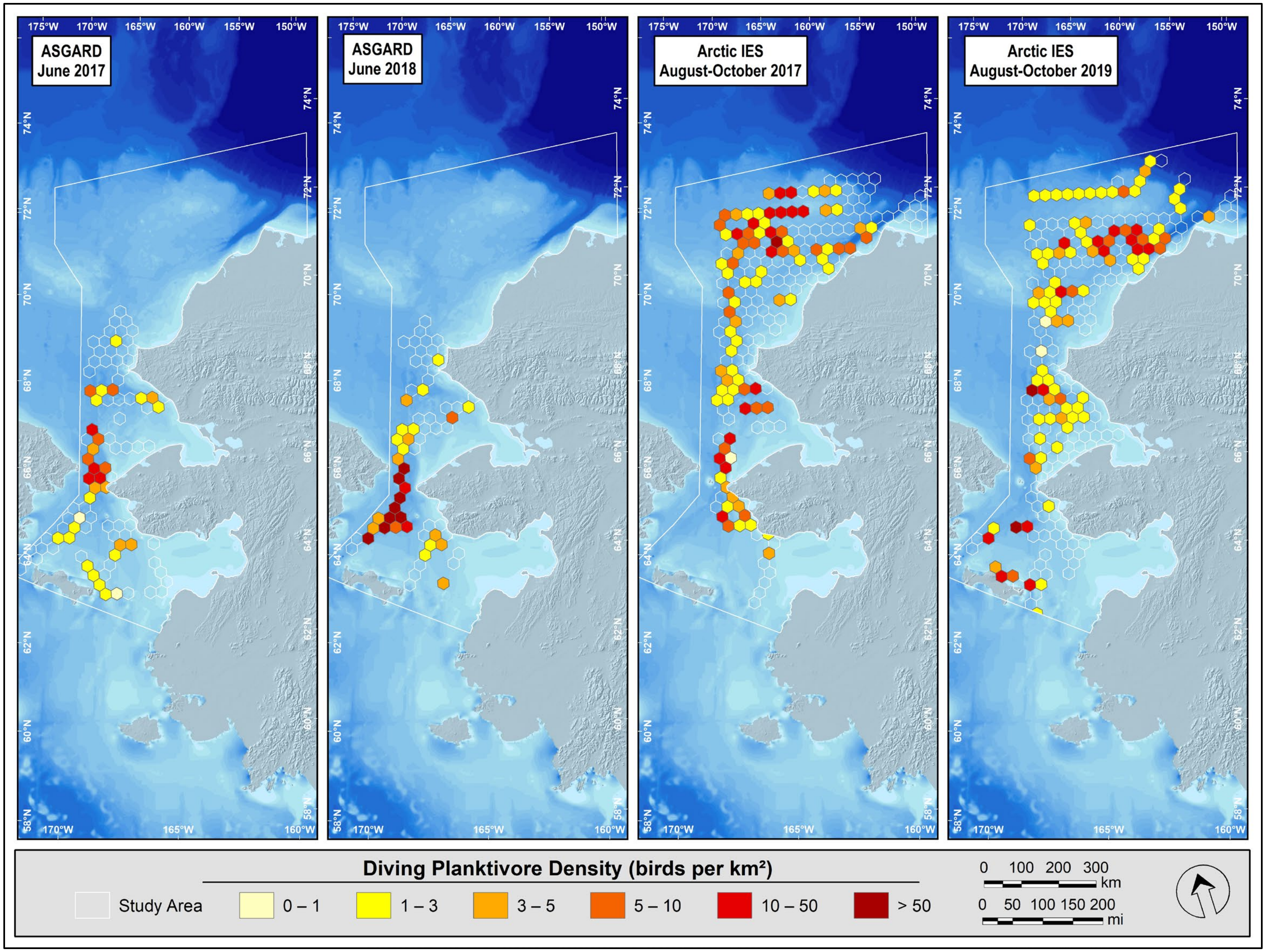

Figure 3.8. Density (birds/km^2) of total diving planktivorous seabirds observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.
Density is the mean of all 3-km transect segments within each 30-km grid cell. Shearwaters were not included in the planktivorous foraging guilds.

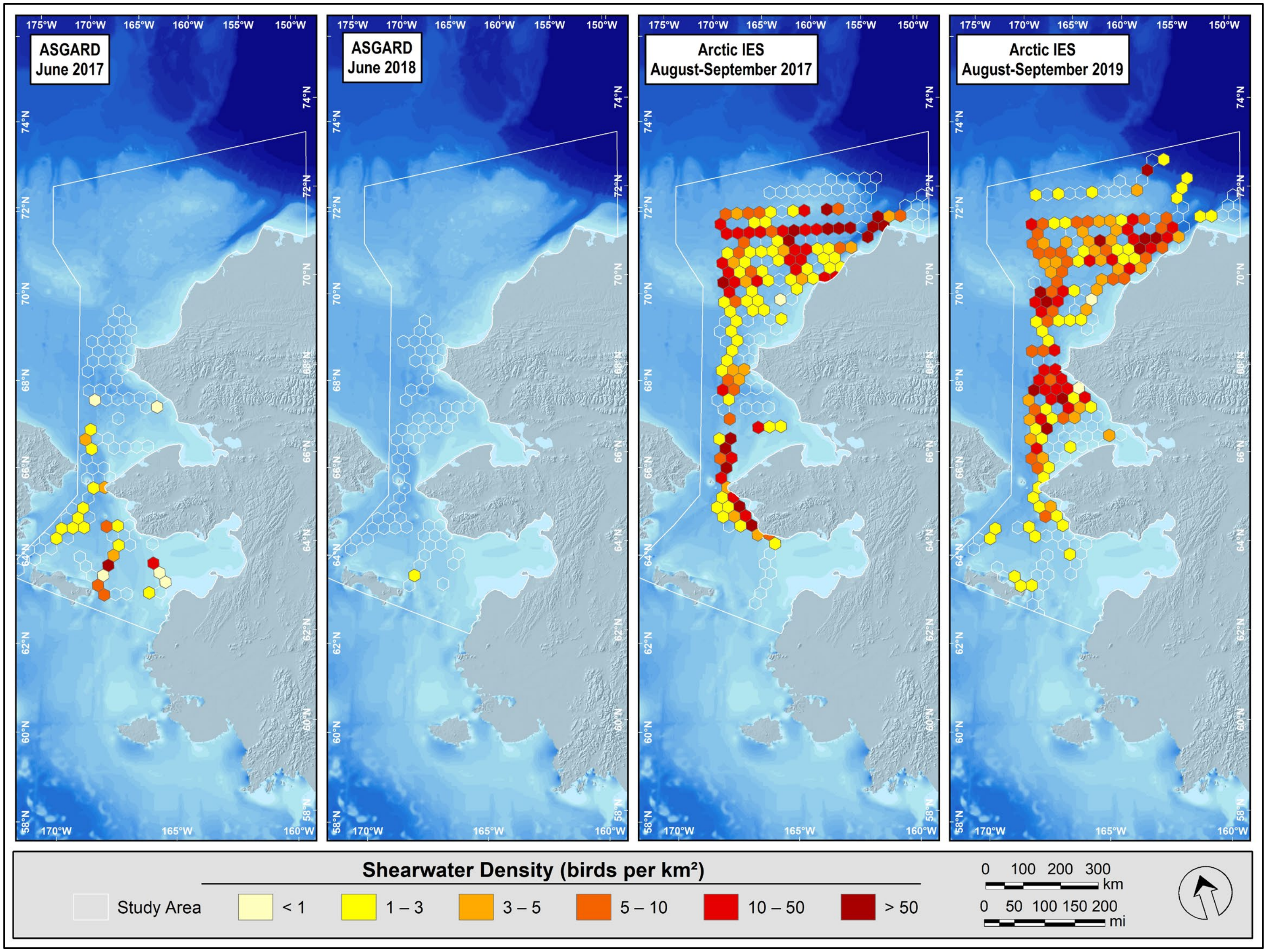

Figure 3.9. Density (birds/km^2) of total shearwaters observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.

Density is the mean of all 3-km transect segments within each 30-km grid cell.

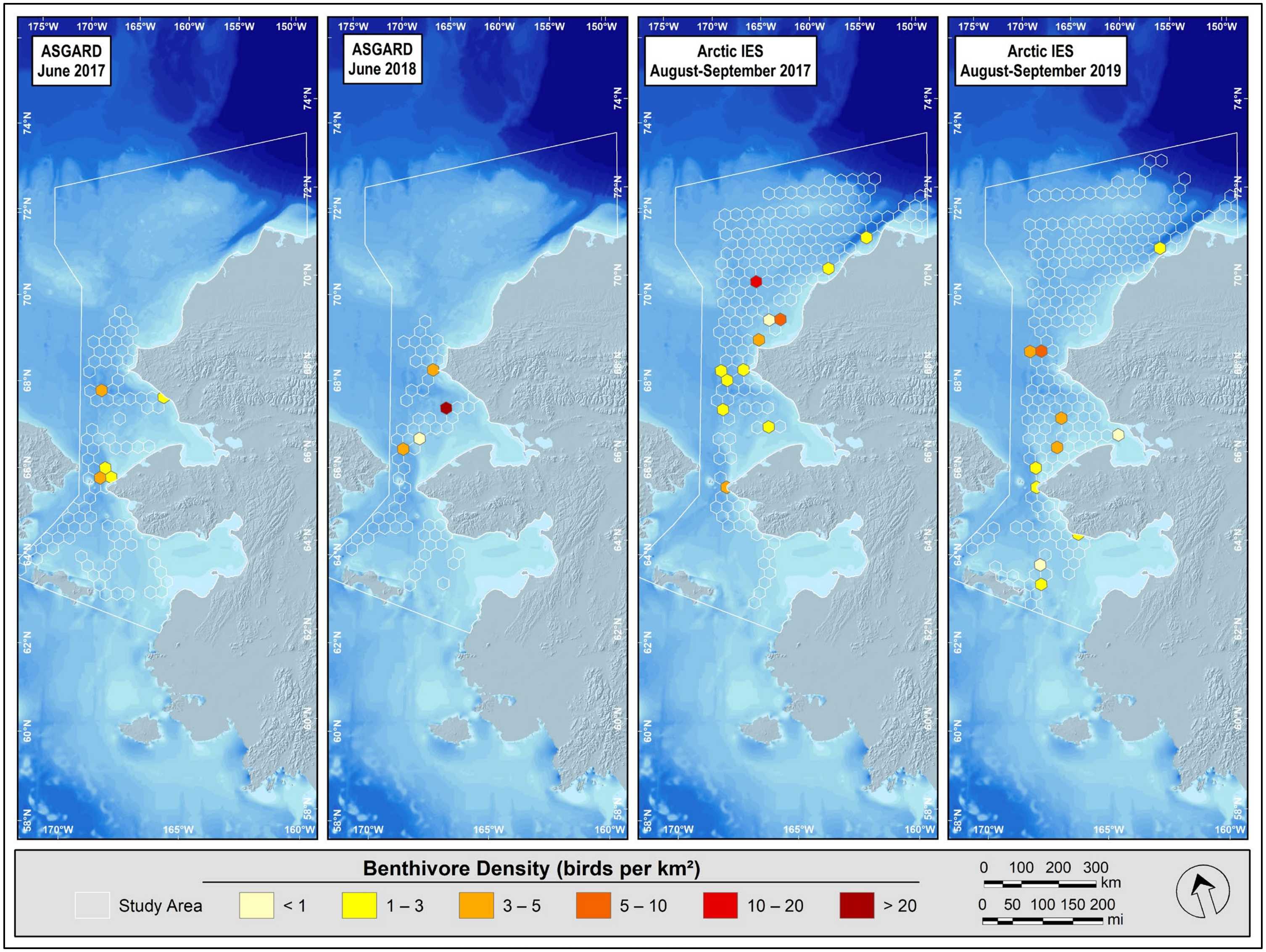

Figure 3.10. Density (birds/km^2) of total benthivorous seabirds observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.
Density is the mean of all 3-km transect segments within each 30-km grid cell.

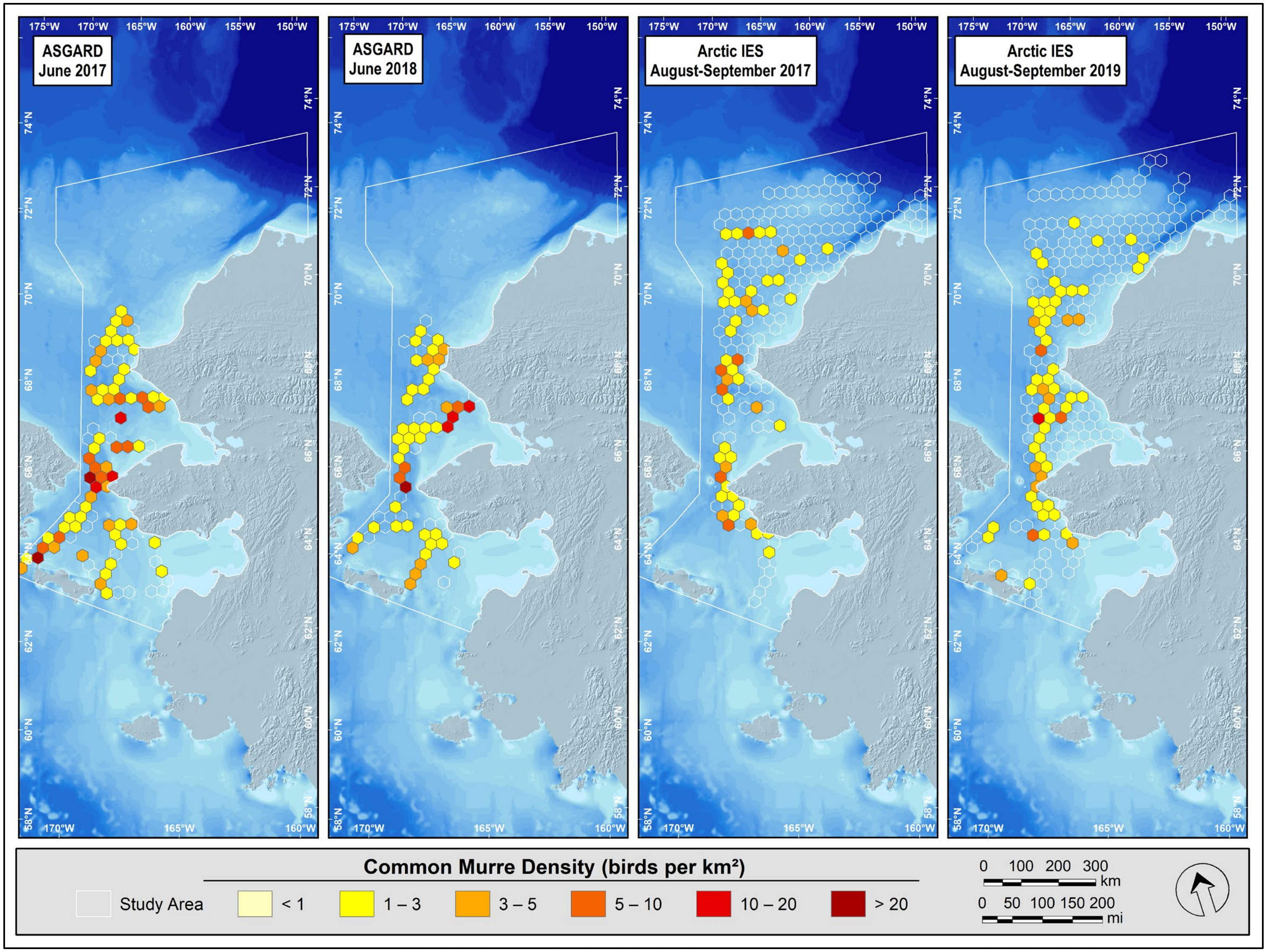

Figure 3.11. Density (birds/km²) of common murre observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.

Density is the mean of all 3-km transect segments within each 30-km grid cell.

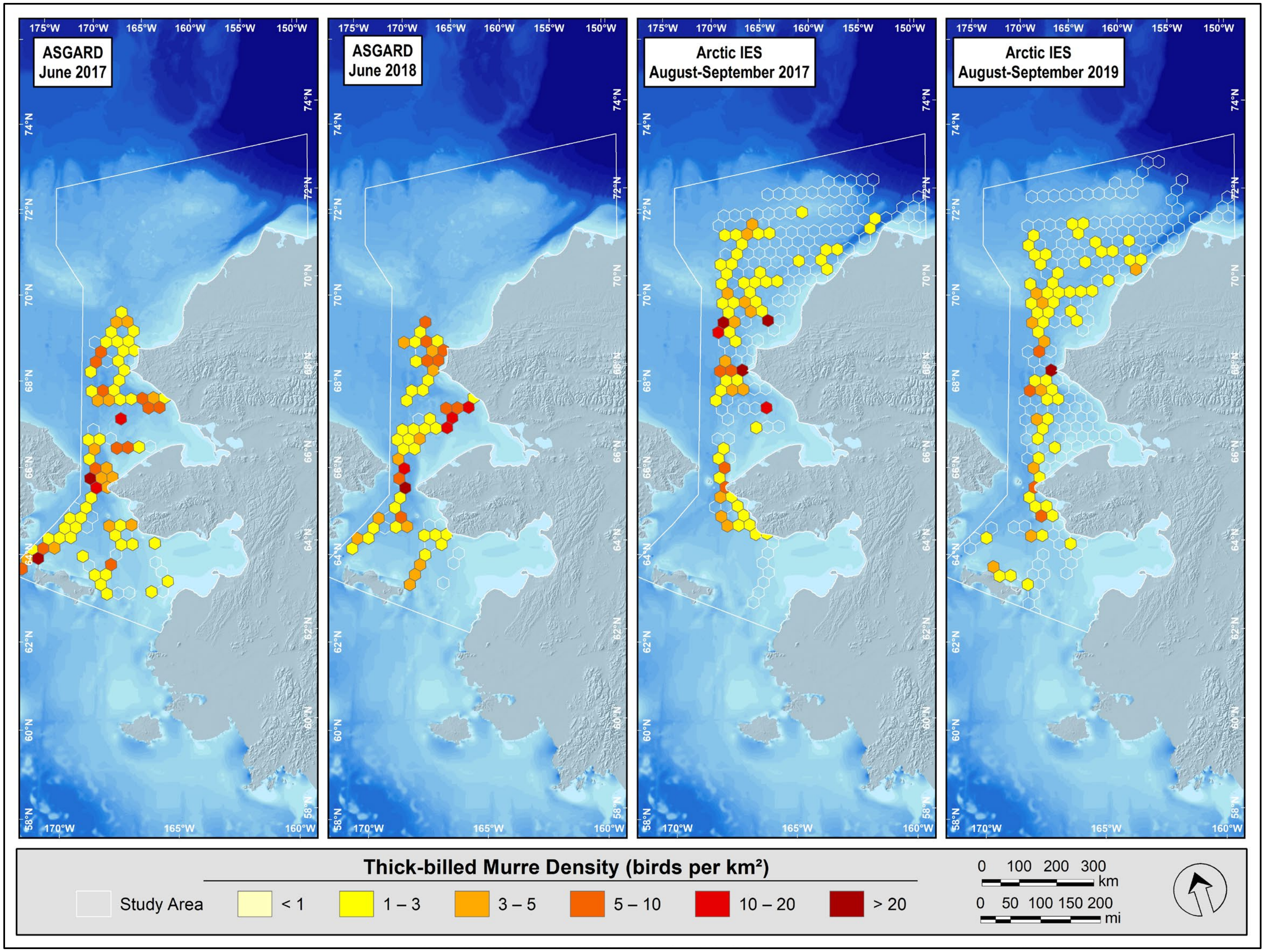

Figure 3.12. Density (birds/km²) of thick-billed murre observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.

Density is the mean of all 3-km transect segments within each 30-km grid cell.

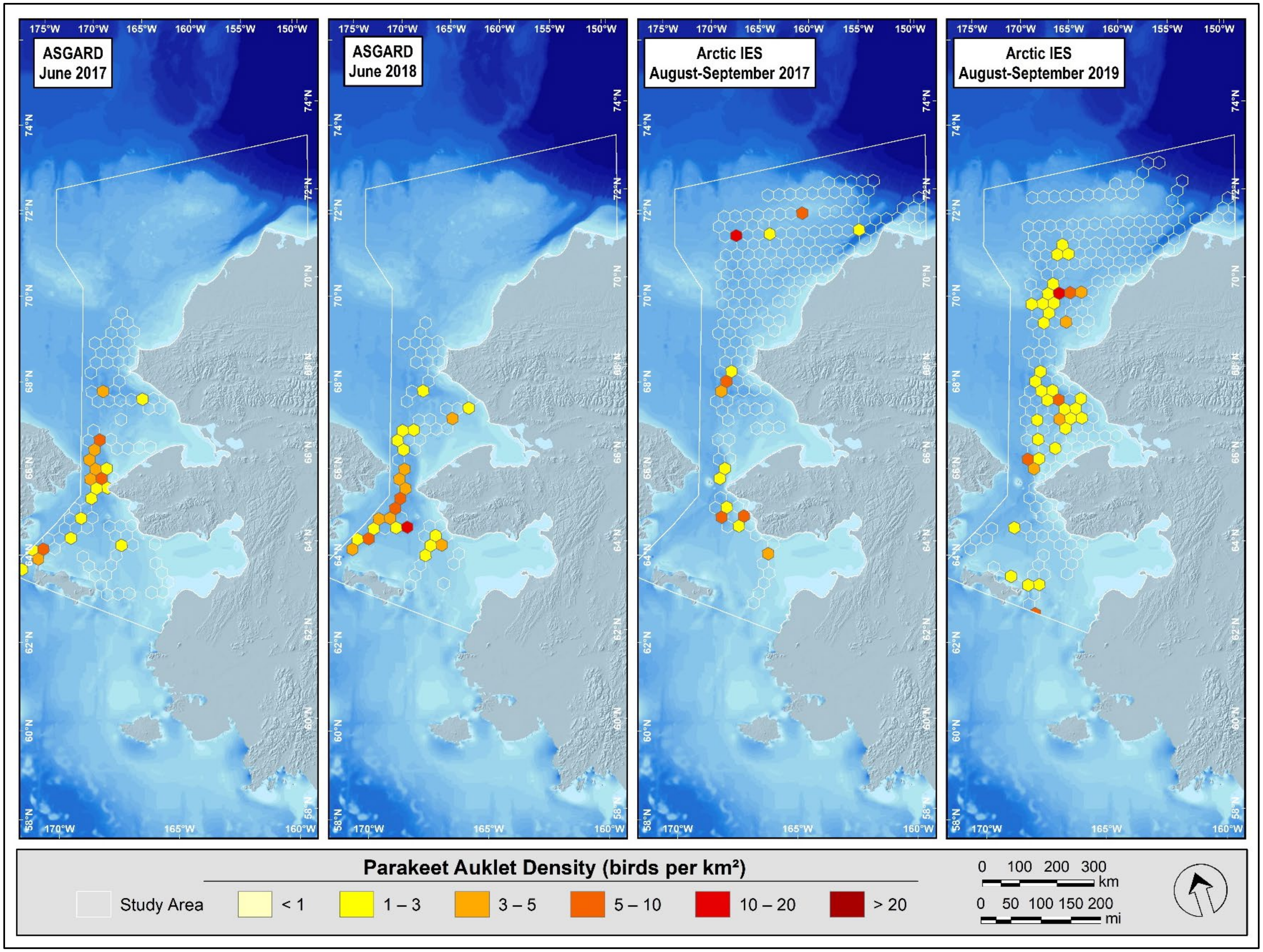

Figure 3.13. Density (birds/km^2) of parakeet auklet observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.
Density is the mean of all 3-km transect segments within each 30-km grid cell.

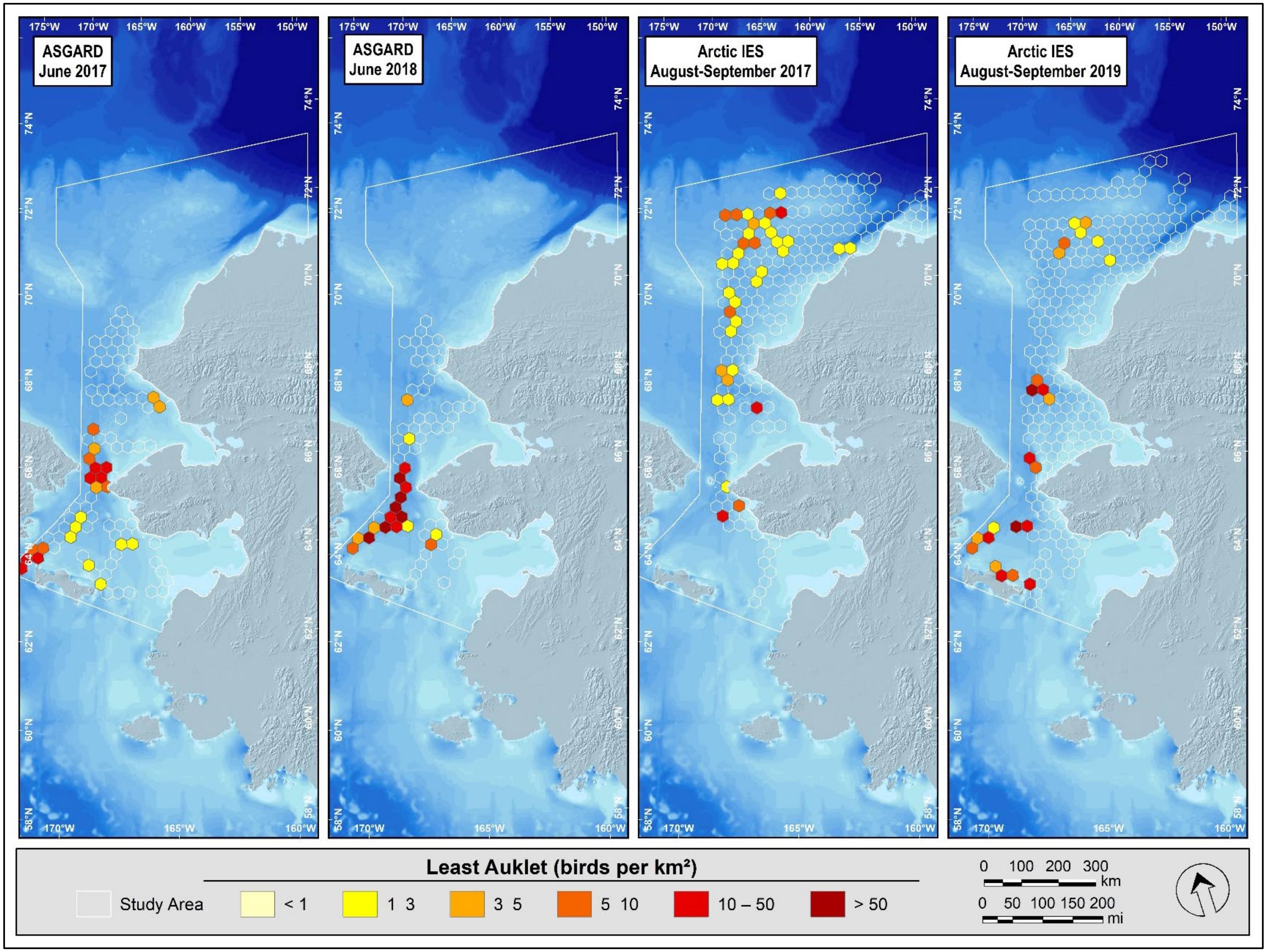

Figure 3.14. Density (birds/km^2) of least auklet observed on transect in the Bering and Chukchi seas, during each of 4 AIERP surveys. Density is the mean of all 3-km transect segments within each 30-km grid cell.

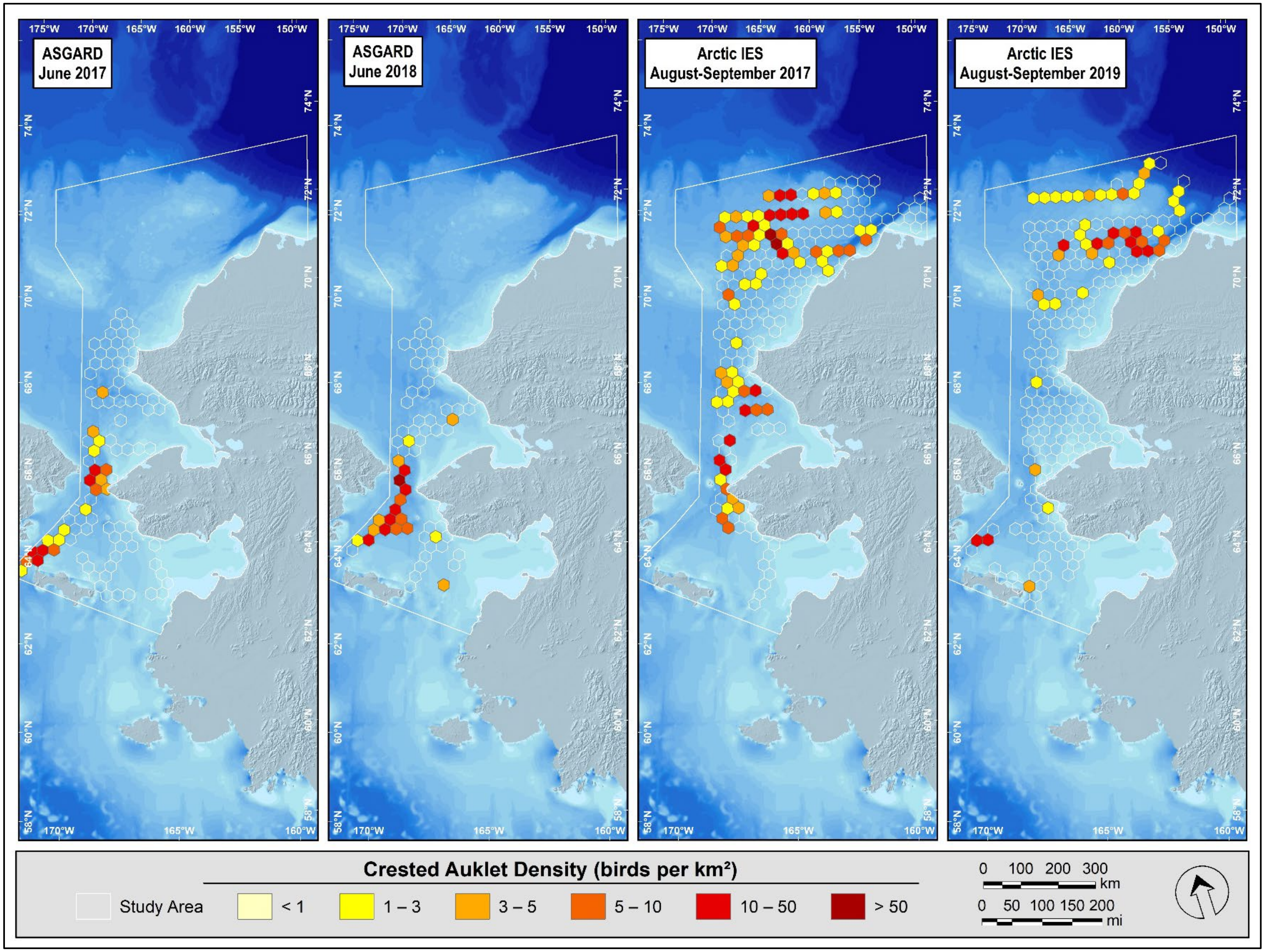

Figure 3.15. Density (birds/km^2) of crested auklet observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys. Density is the mean of all 3-km transect segments within each 30-km grid cell.

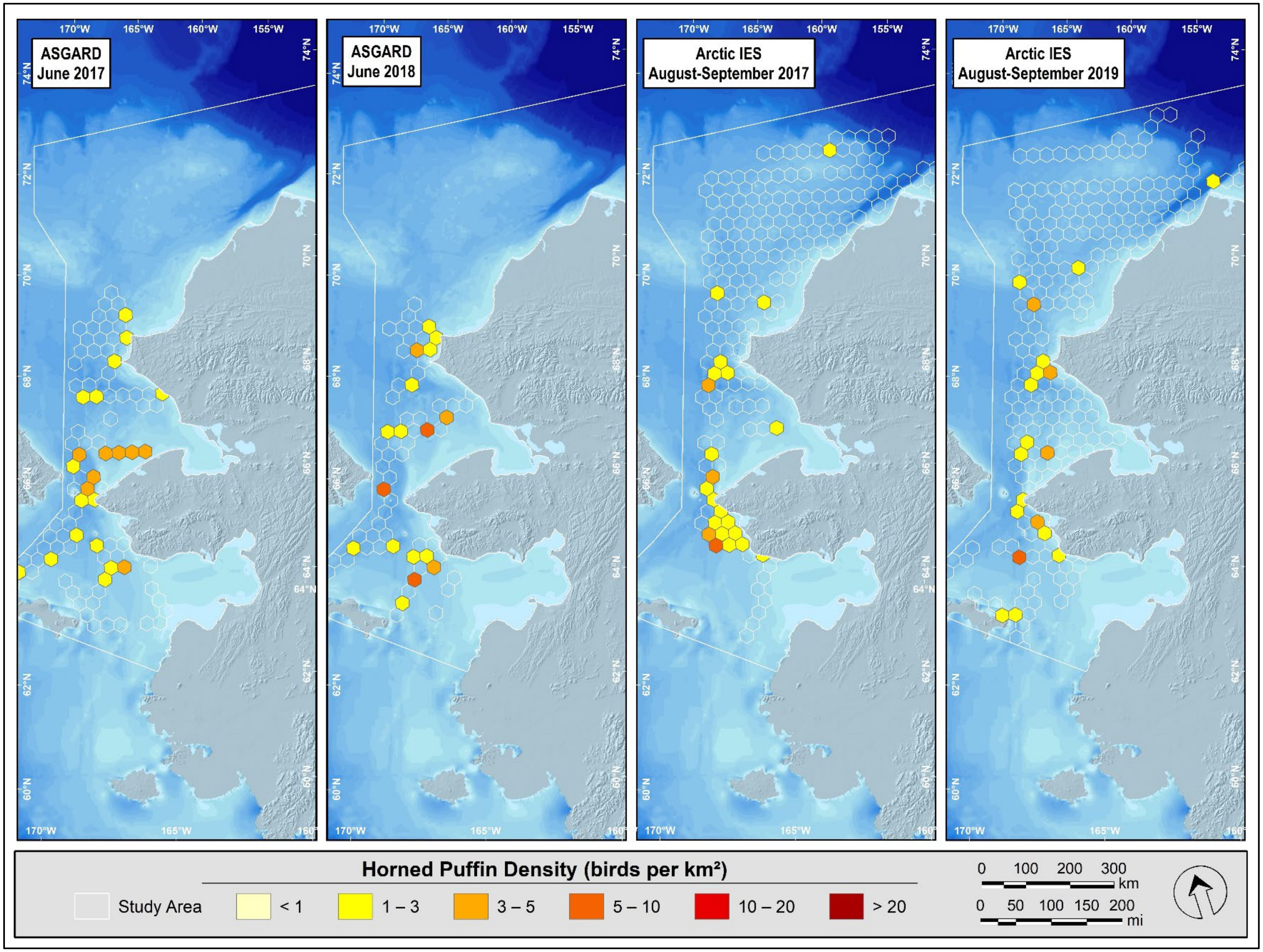

Figure 3.16. Density (birds/km²) of horned puffin observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys. Density is the mean of all 3-km transect segments within each 30-km grid cell.

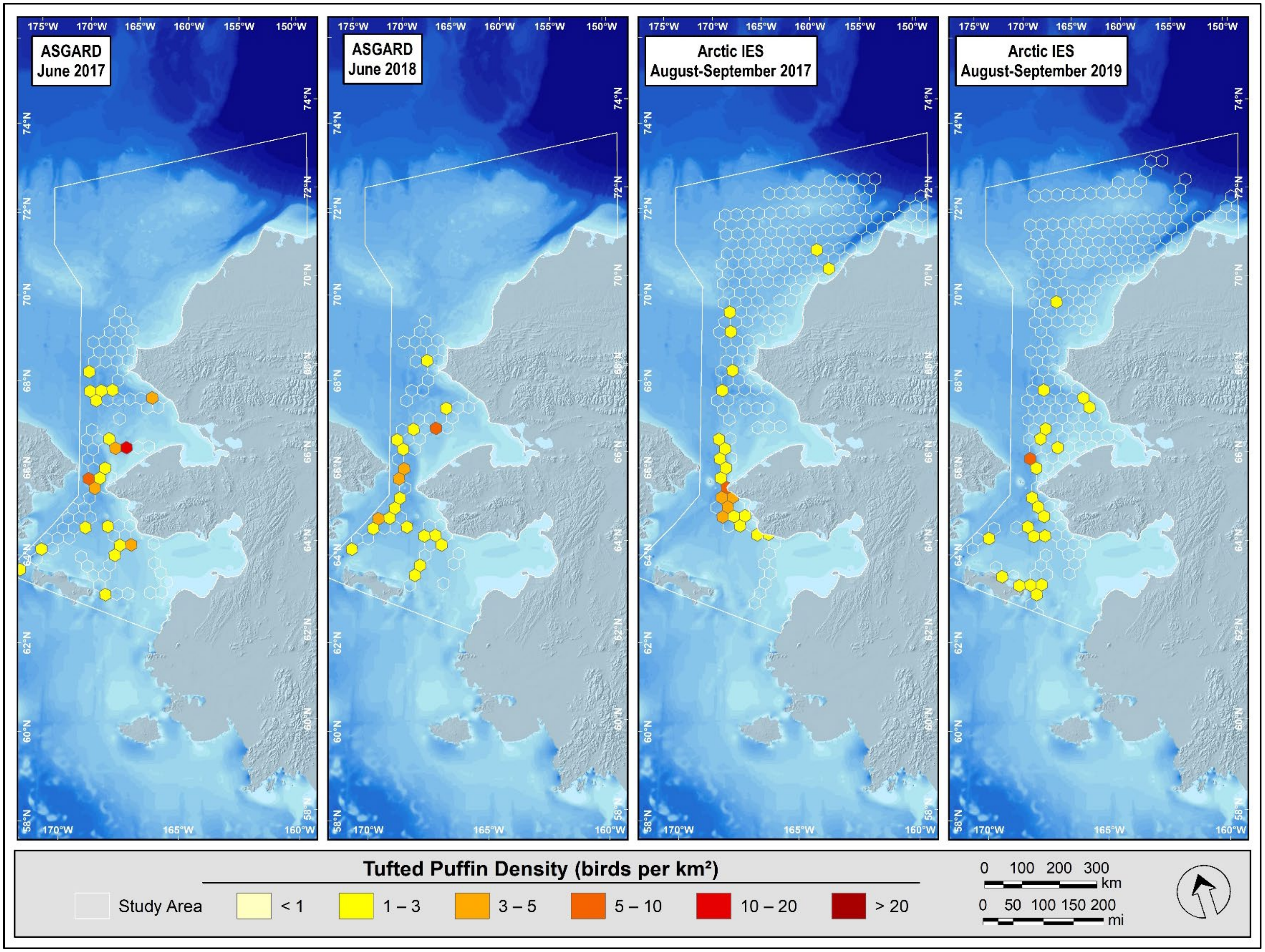

Figure 3.17. Density (birds/km^2) of tufted puffin observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys. Density is the mean of all 3-km transect segments within each 30-km grid cell.

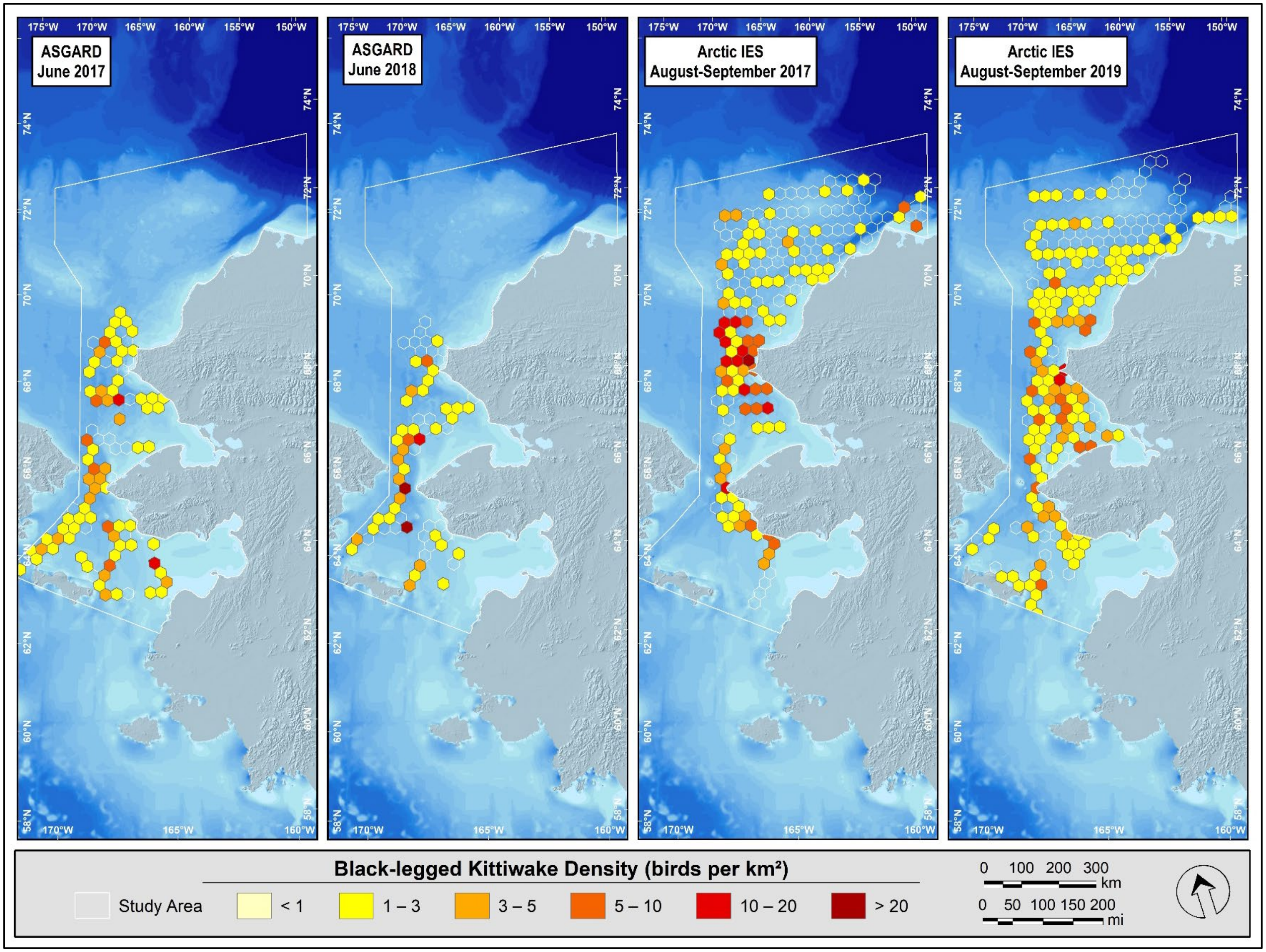

Figure 3.18. Density (birds/km²) of black-legged kittiwake observed on transect in the Bering and Chukchi seas, during each of 4 AIERP surveys.

Density is the mean of all 3-km transect segments within each 30-km grid cell.

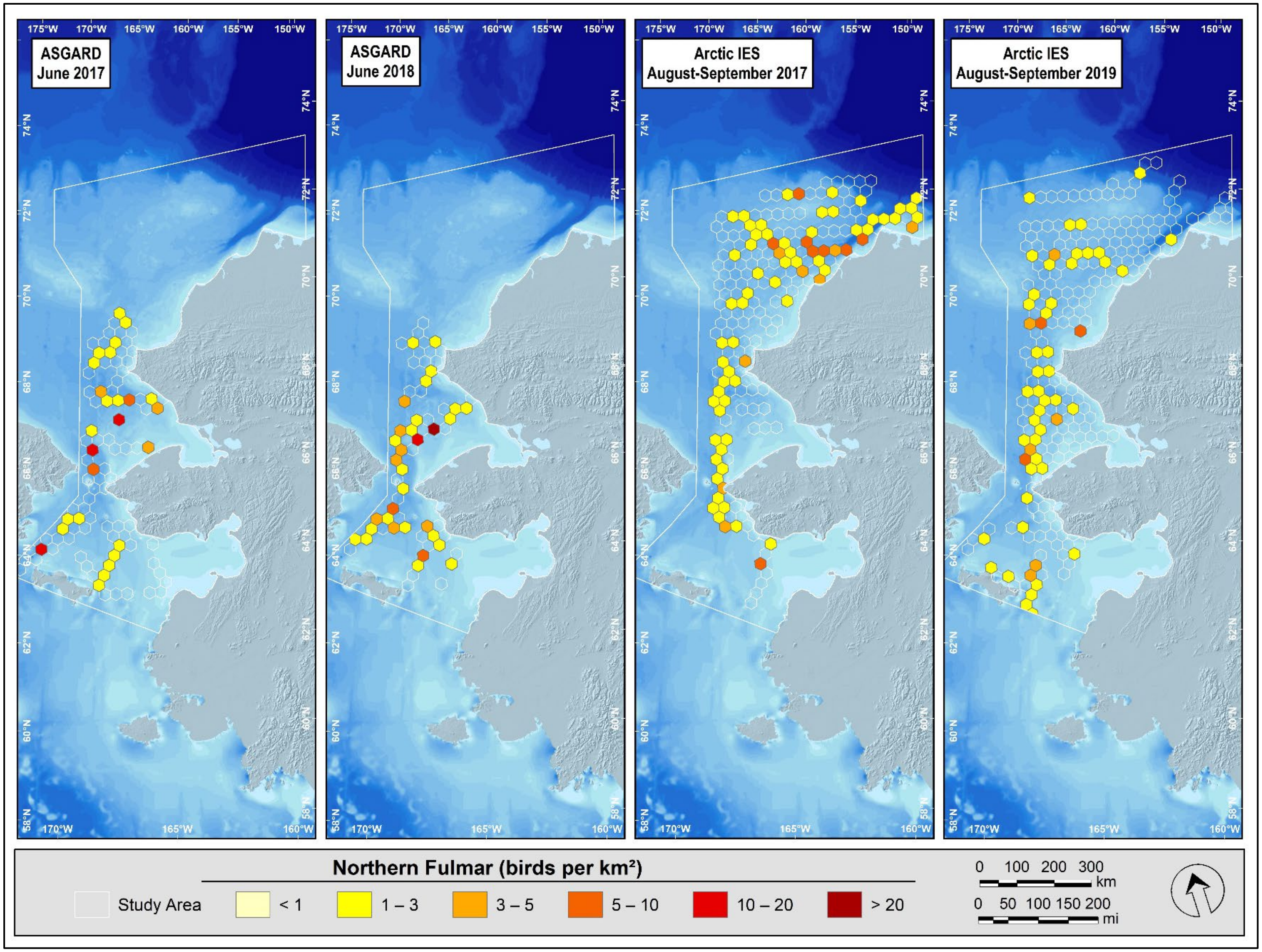

Figure 3.19. Density (birds/km^2) of northern fulmar observed on transect in the Bering and Chukchi seas during each of 4 AIERP surveys.
Density is the mean of all 3-km transect segments within each 30-km grid cell.

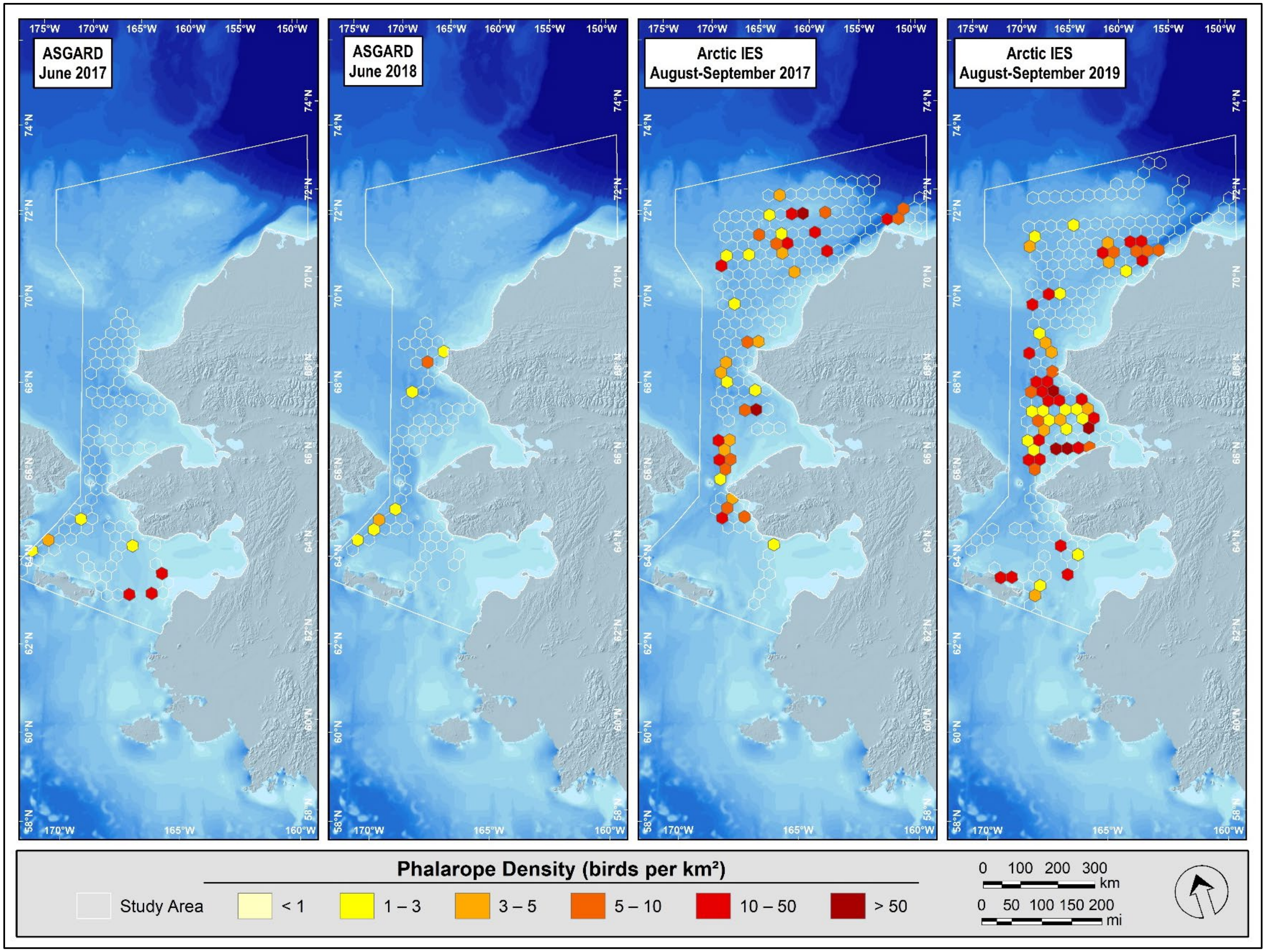

Figure 3.20. Density (birds/km^2) of phalaropes (red-necked phalarope and red phalarope) observed on transect in the Bering and Chukchi seas, during each of 4 AIERP surveys.
Density is the mean of all 3-km transect segments within each 30-km grid cell.

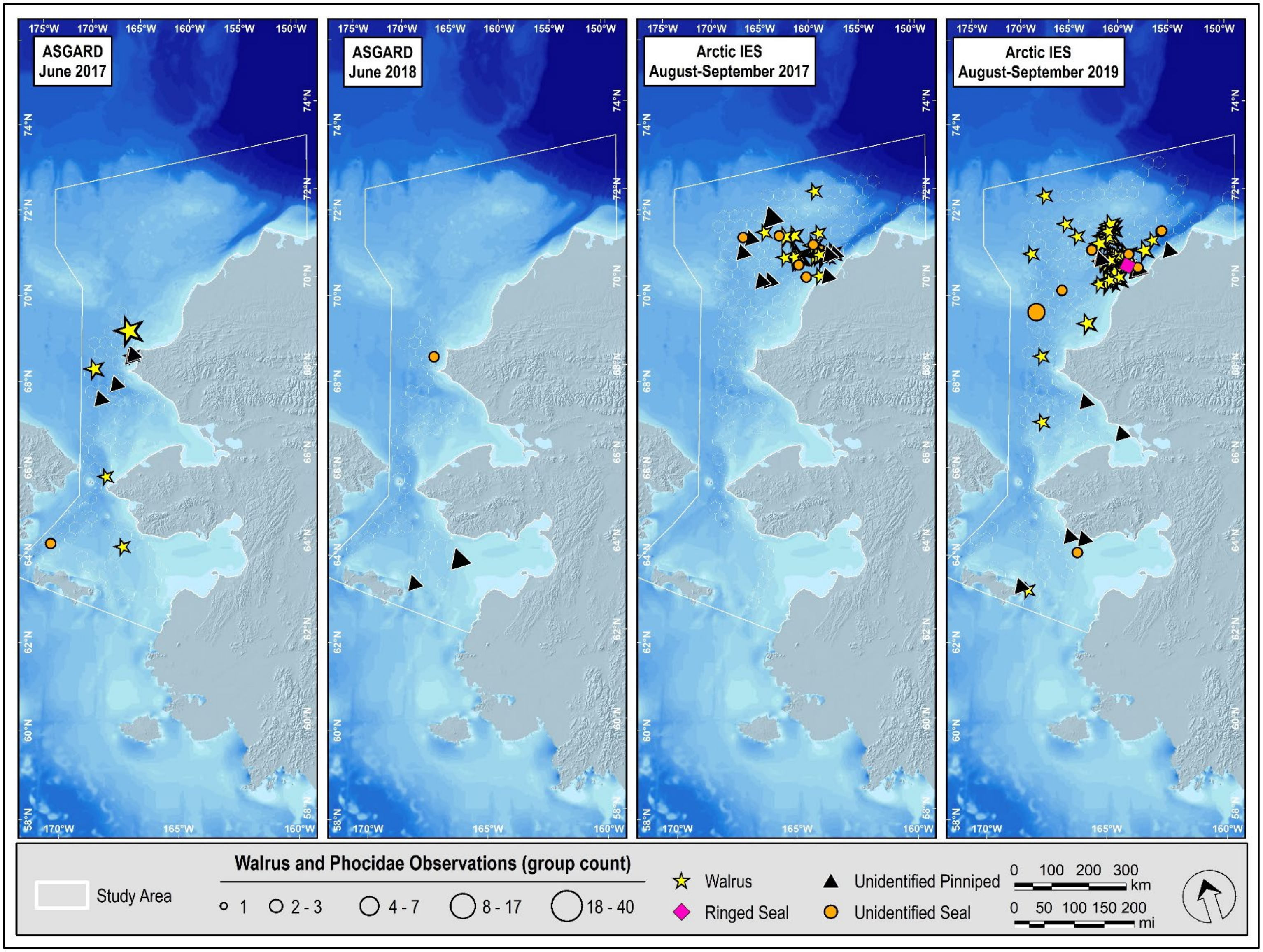

Figure 3.21. Distribution of walruses and other Phocidae observed during seabird surveys during the 4 AIERP cruises, 2017–2019. Each symbol represents the total count per sighting for a species or species group observed both on and off transect.

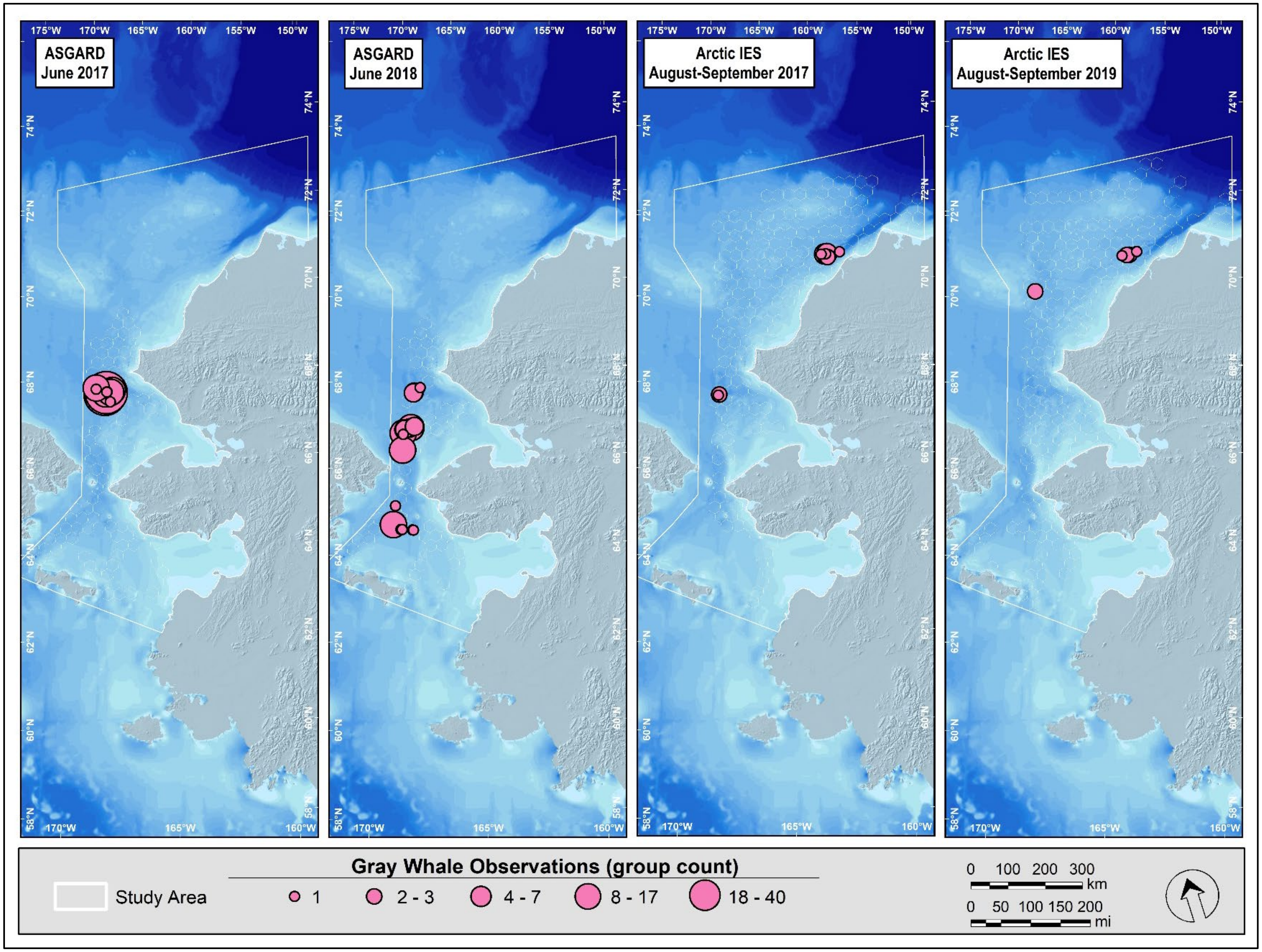

Figure 3.22. Distribution of gray whales observed during seabird surveys during the 4 AIERP cruises, 2017–2019. Each symbol represents the total count per sighting of gray whales, both on and off transect.

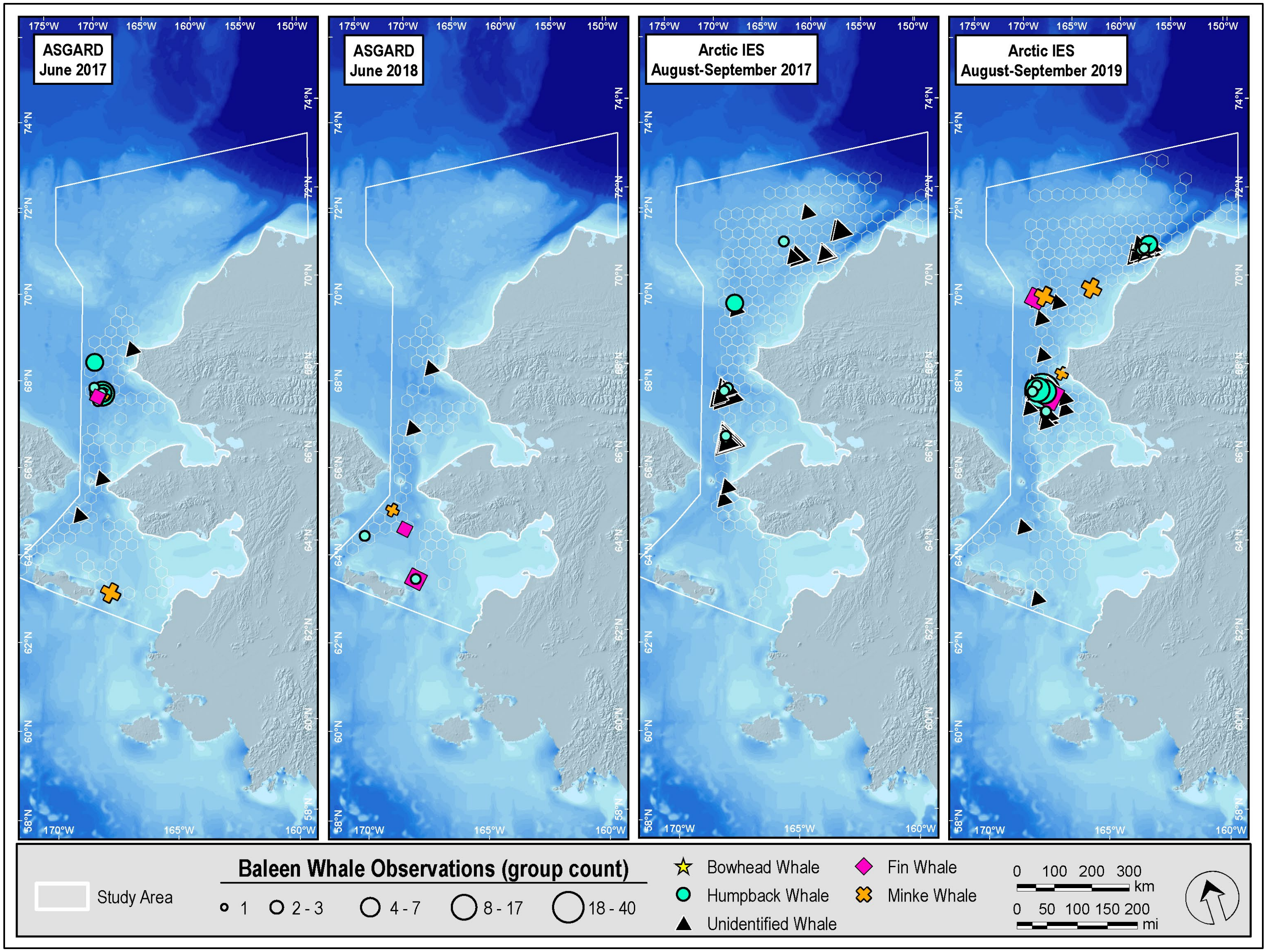

Figure 3.23. Distribution of baleen whales observed during seabird surveys during the 4 AIERP cruises, 2017–2019. Each symbol represents the total count per sighting of each species or group, both on and off transect.

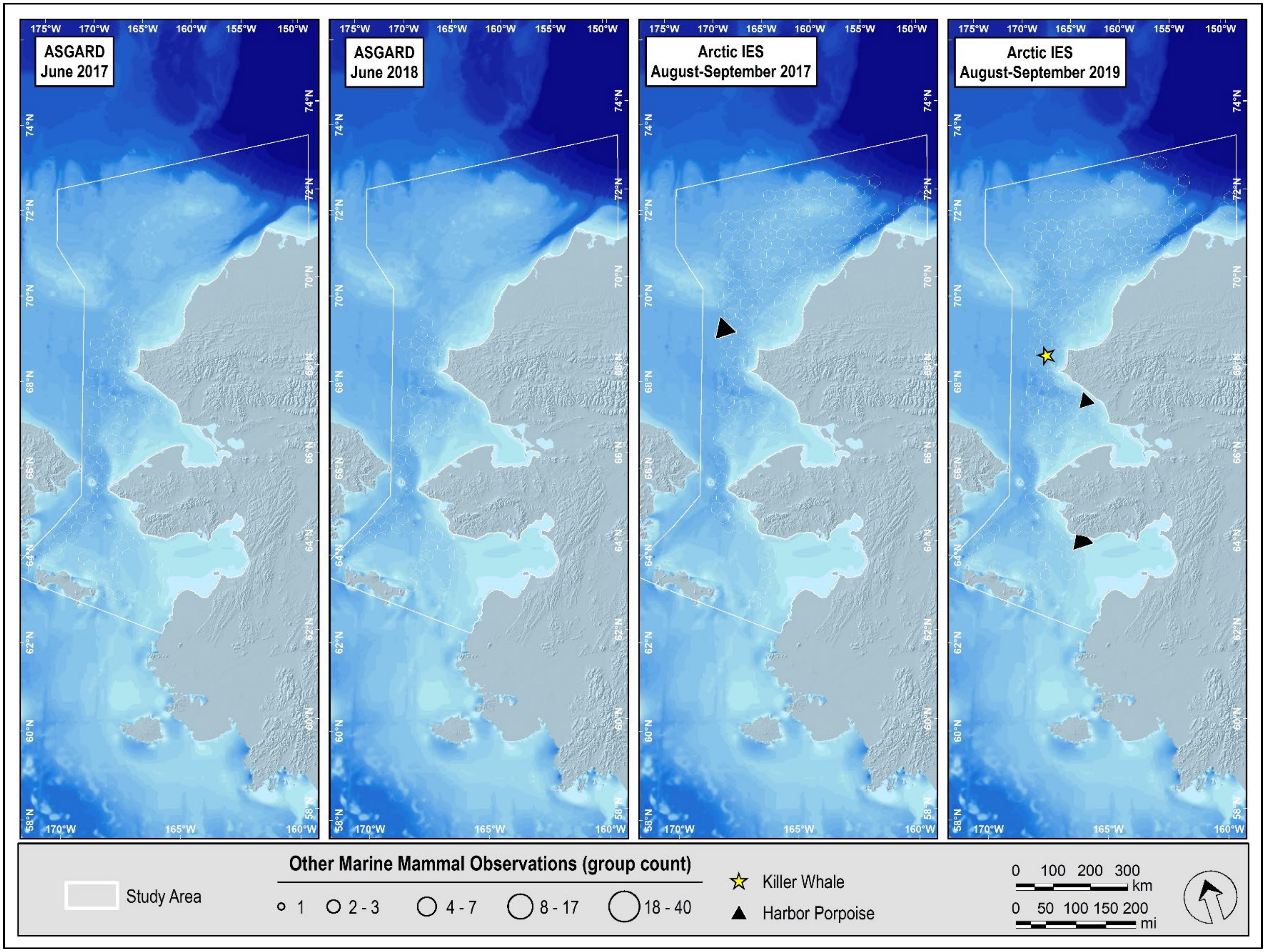

Figure 3.24. Distribution of killer whales and harbor porpoises observed during seabird surveys during the 4 AIERP cruises, 2017–2019. Symbols for each species represent each sighting, both on and off transect.

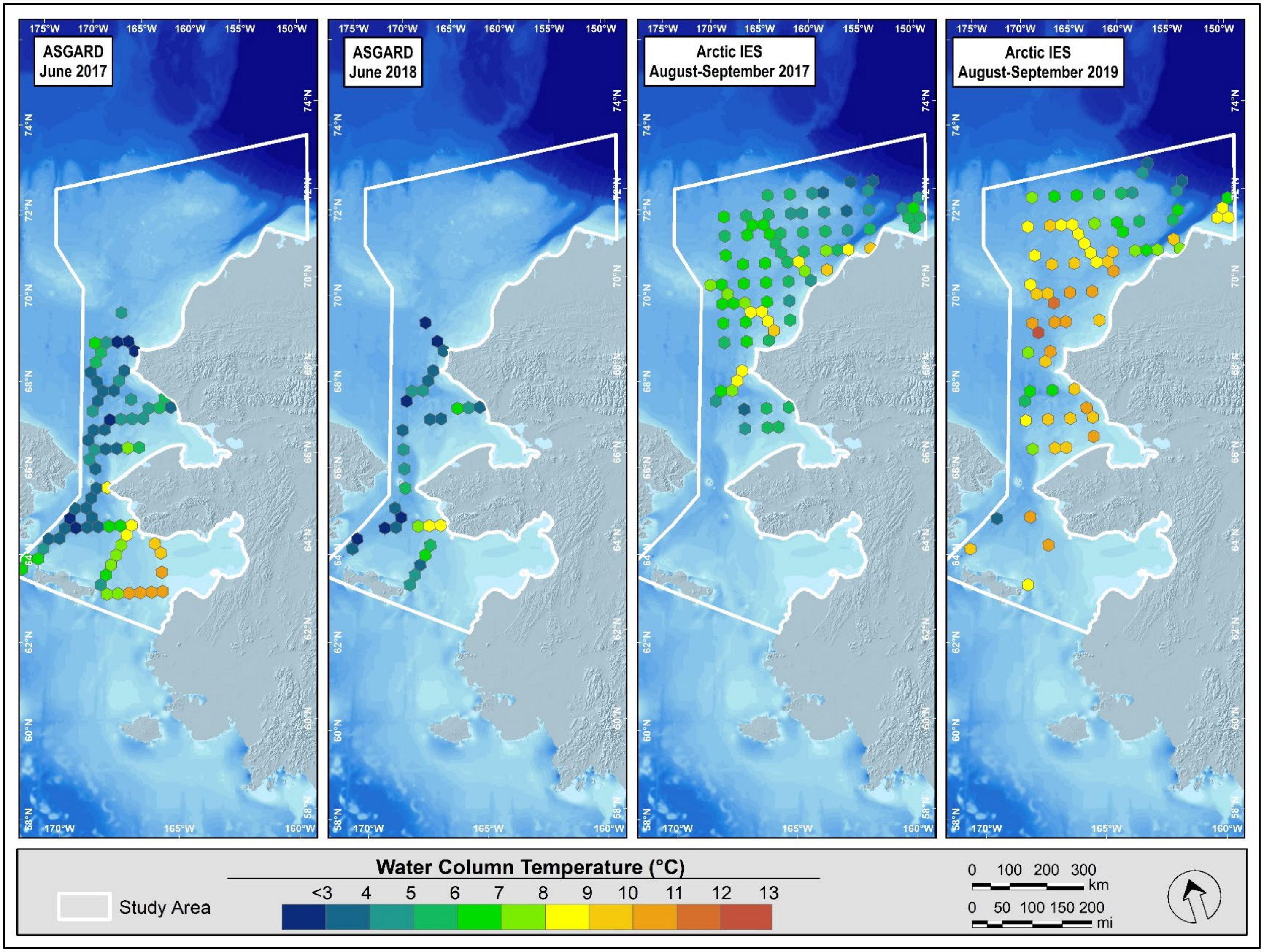

Figure 3.25. Averaged water column temperature (°C) for each 30-km grid cell sampled during each of 4 AIERP surveys. Most cells had a single oceanographic station. For the two cells with two oceanographic stations, we show the mean of the two stations within the cell. Grid cells that did not contain an oceanographic sampling station are not shown.

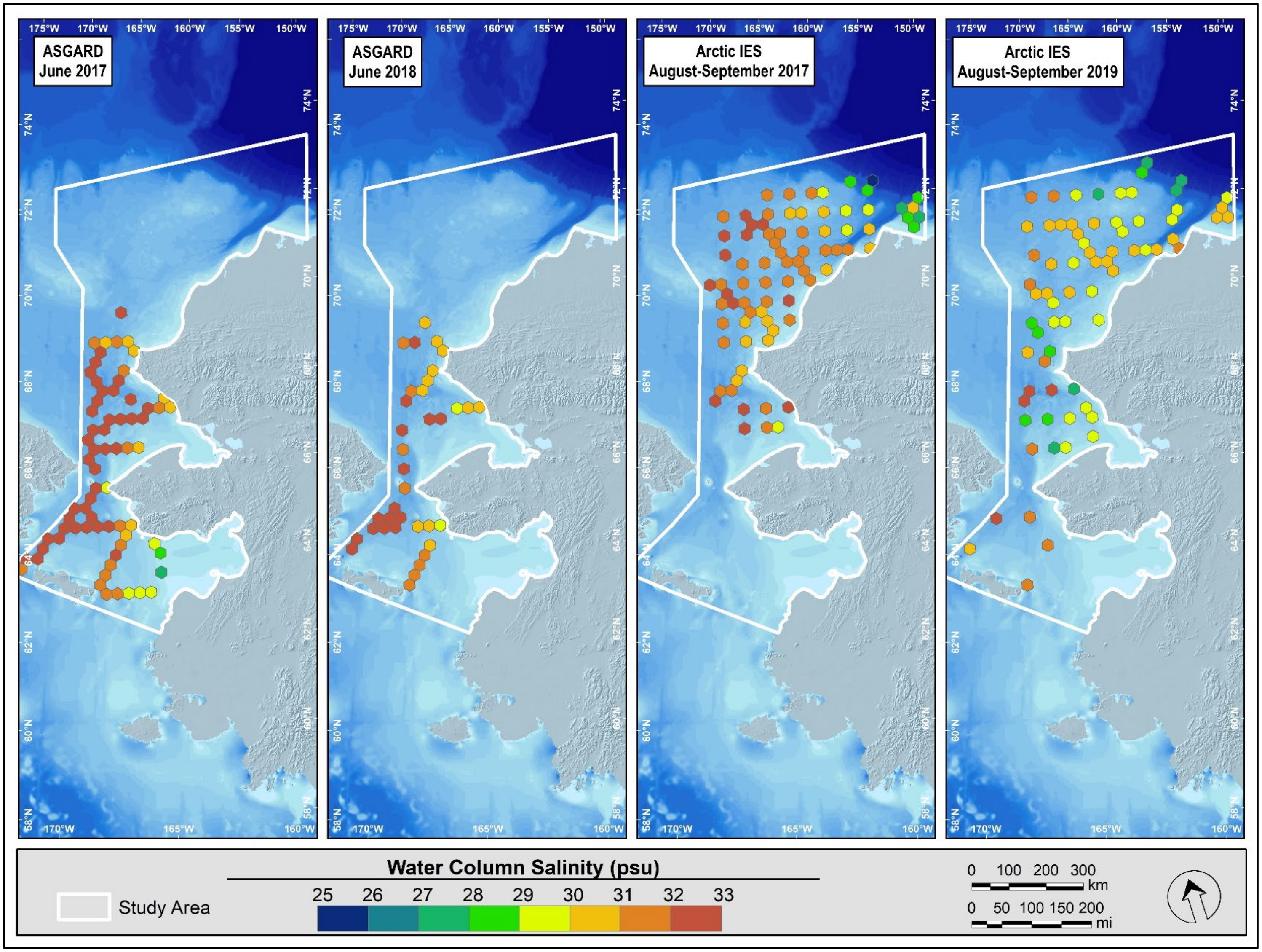

Figure 3.26. Averaged water column salinity for each 30-km grid cell sampled during each of 4 AIERP surveys.
Most cells had a single oceanographic station. For the two cells with two oceanographic stations, we show the mean of the two stations within the cell. Grid cells that did not contain an oceanographic sampling station are not shown.

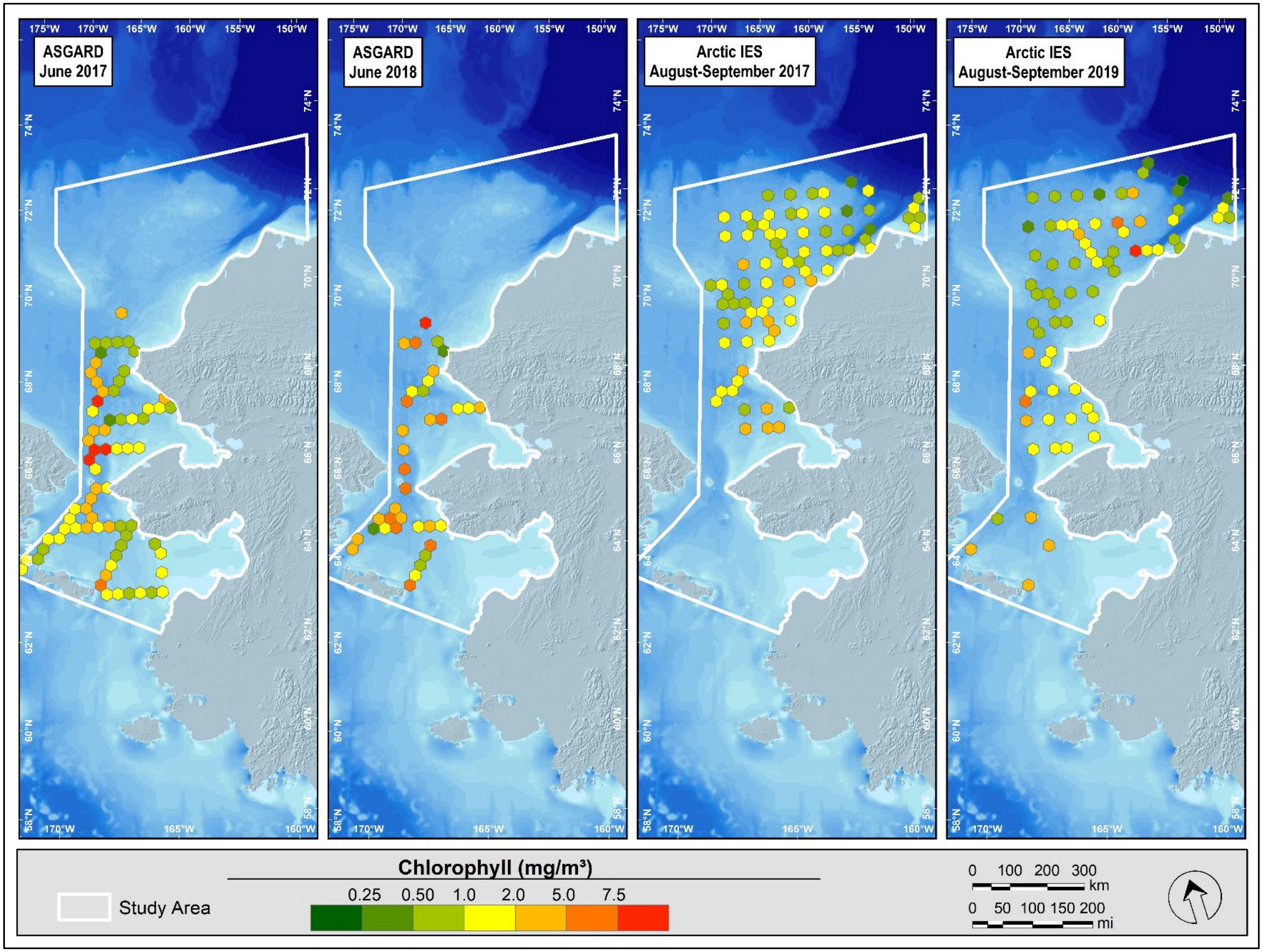

Figure 3.27. Averaged water column Chlorophyll-A (mg/m^3) for each 30-km grid cell sampled during the 4 AIERP surveys. Grid cells that did not contain an oceanographic sampling station are not shown.

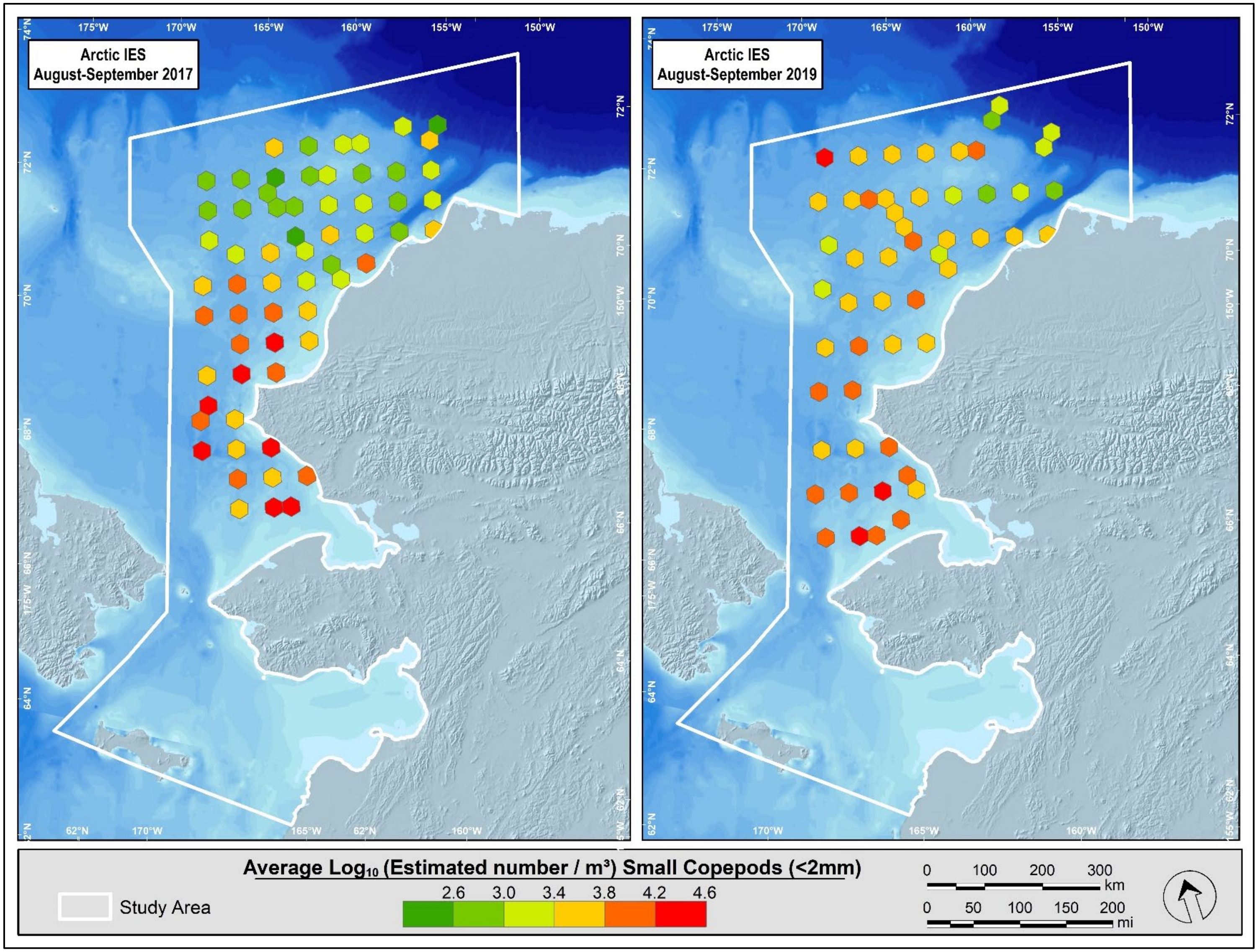

Figure 3.28. Average Small Copepod density (log_{10} individuals/m^3) for each 30-km grid cell sampled during each of 2 Arctic IES surveys, 2017 and 2019.

Grid cells that did not contain a zooplankton sampling station are not shown.

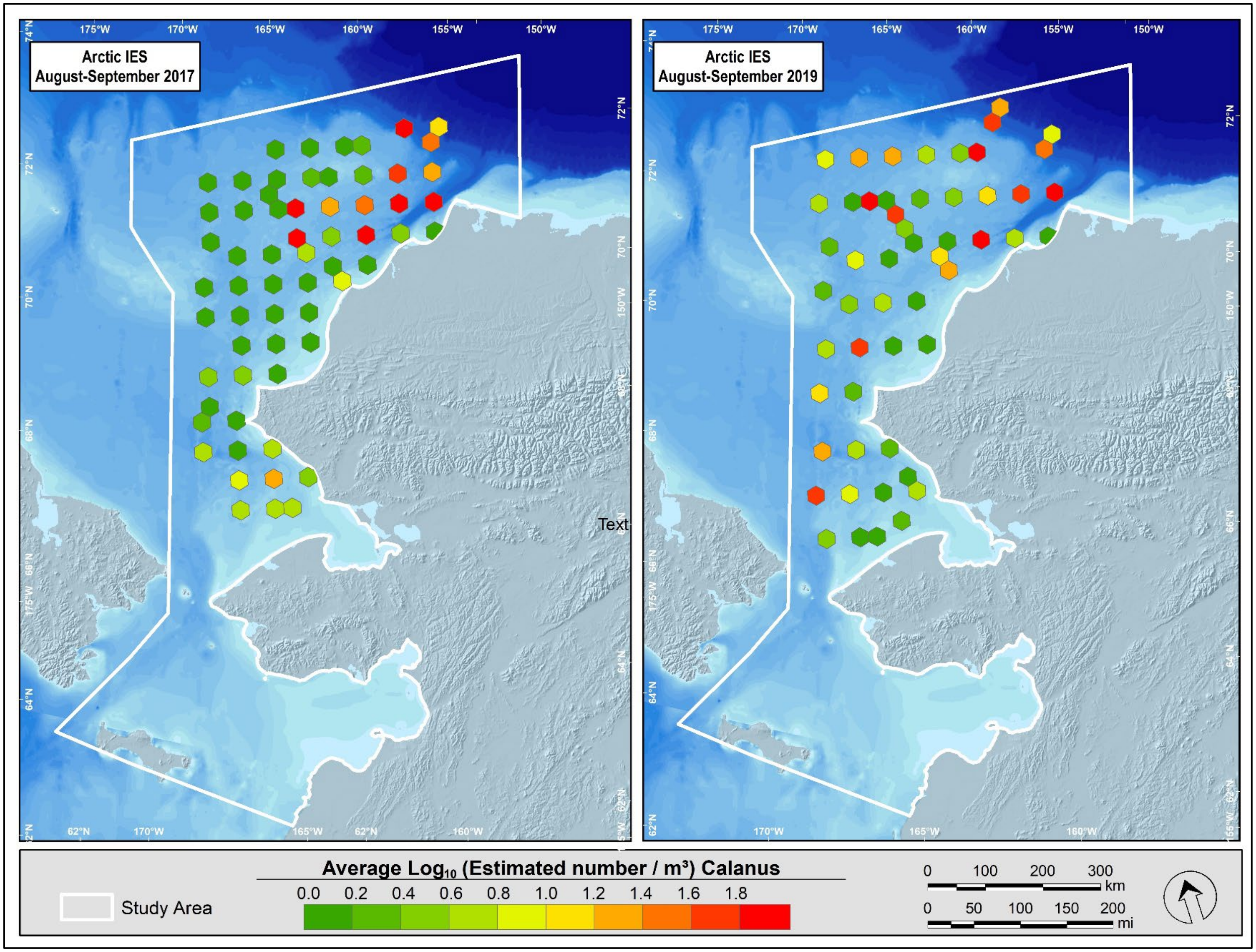

Figure 3.29. Average *Calanus* copepod density (log_{10} individuals/m^3) for each 30-km grid cell sampled during each of 2 Arctic IES surveys, 2017 and 2019.
Grid cells that did not contain a **zooplankton** sampling station are not shown.

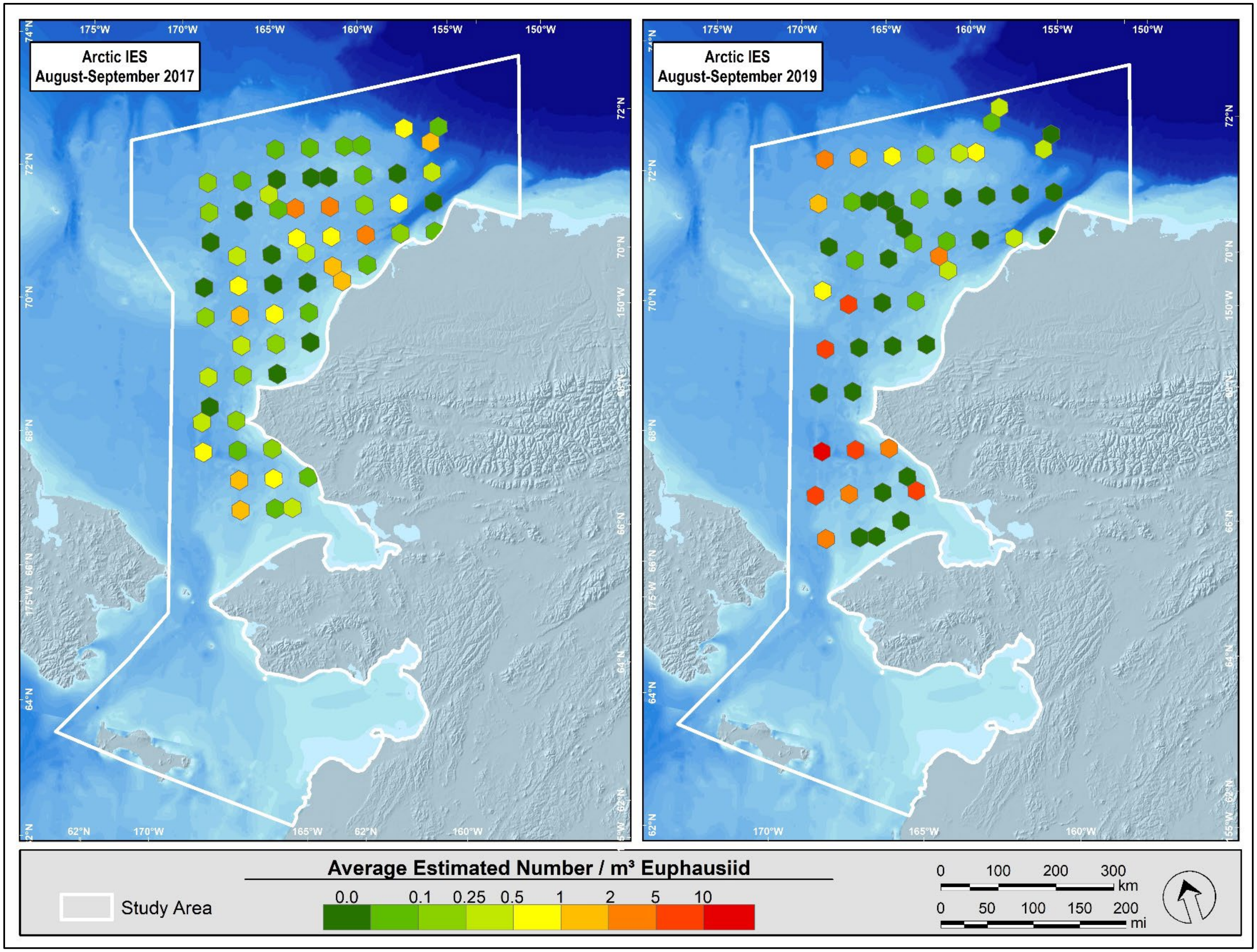

Figure 3.30. Average Euphausiid density (individuals/m^3) for each 30-km grid cell sampled during each of 2 Arctic IES surveys, 2017 and 2019.
Grid cells that did not contain a **zooplankton** sampling station are not shown.

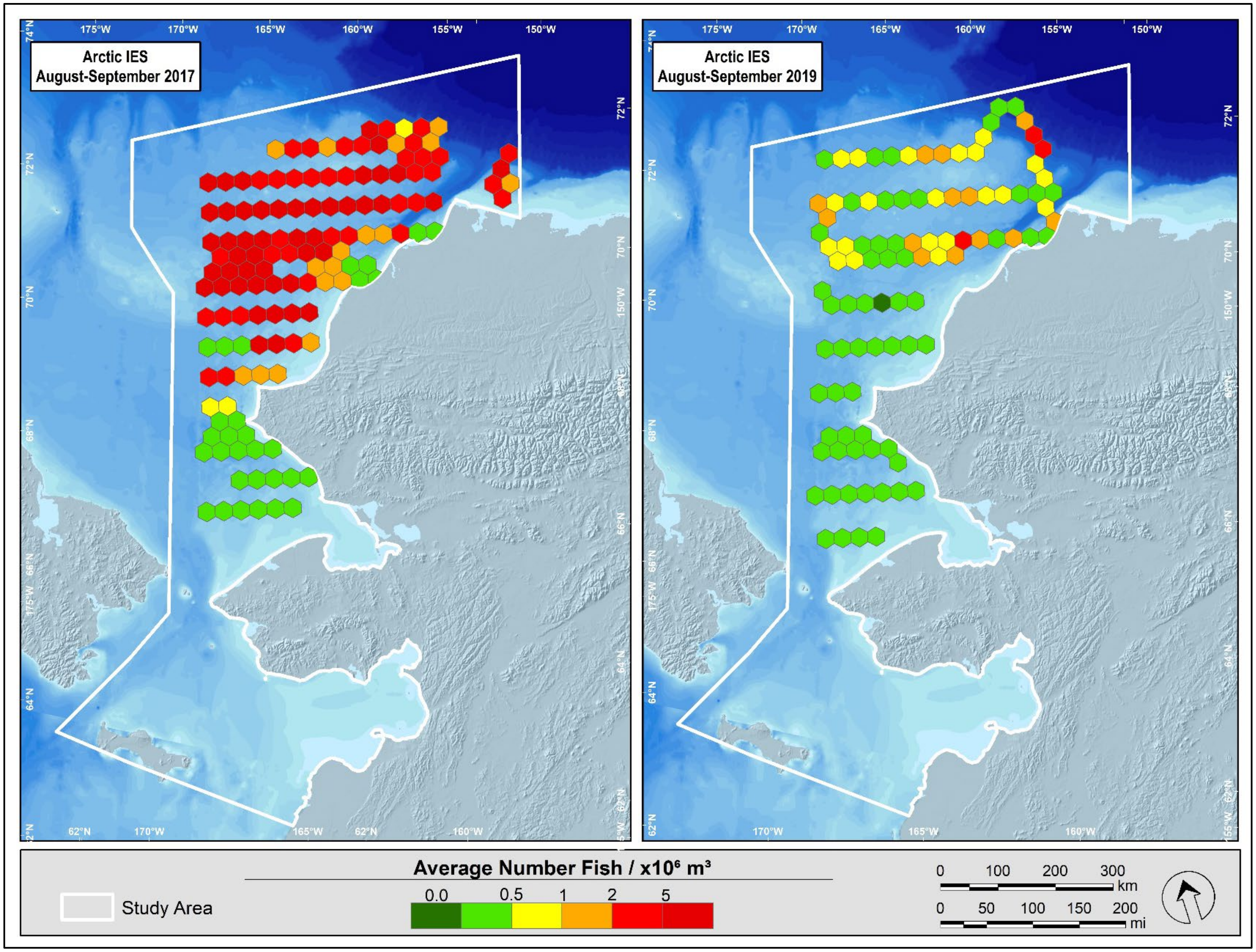

Figure 3.31. Density (fish/km^2) of small fish (0–5.5 cm) for each 30-km grid cell sampled during each of 2 Arctic IES surveys, 2017 and 2019.

For each cell, average fish density was calculated from hydroacoustic sampling, with all depths and species pooled. Grid cells that did not contain hydroacoustic sampling data are not shown.[

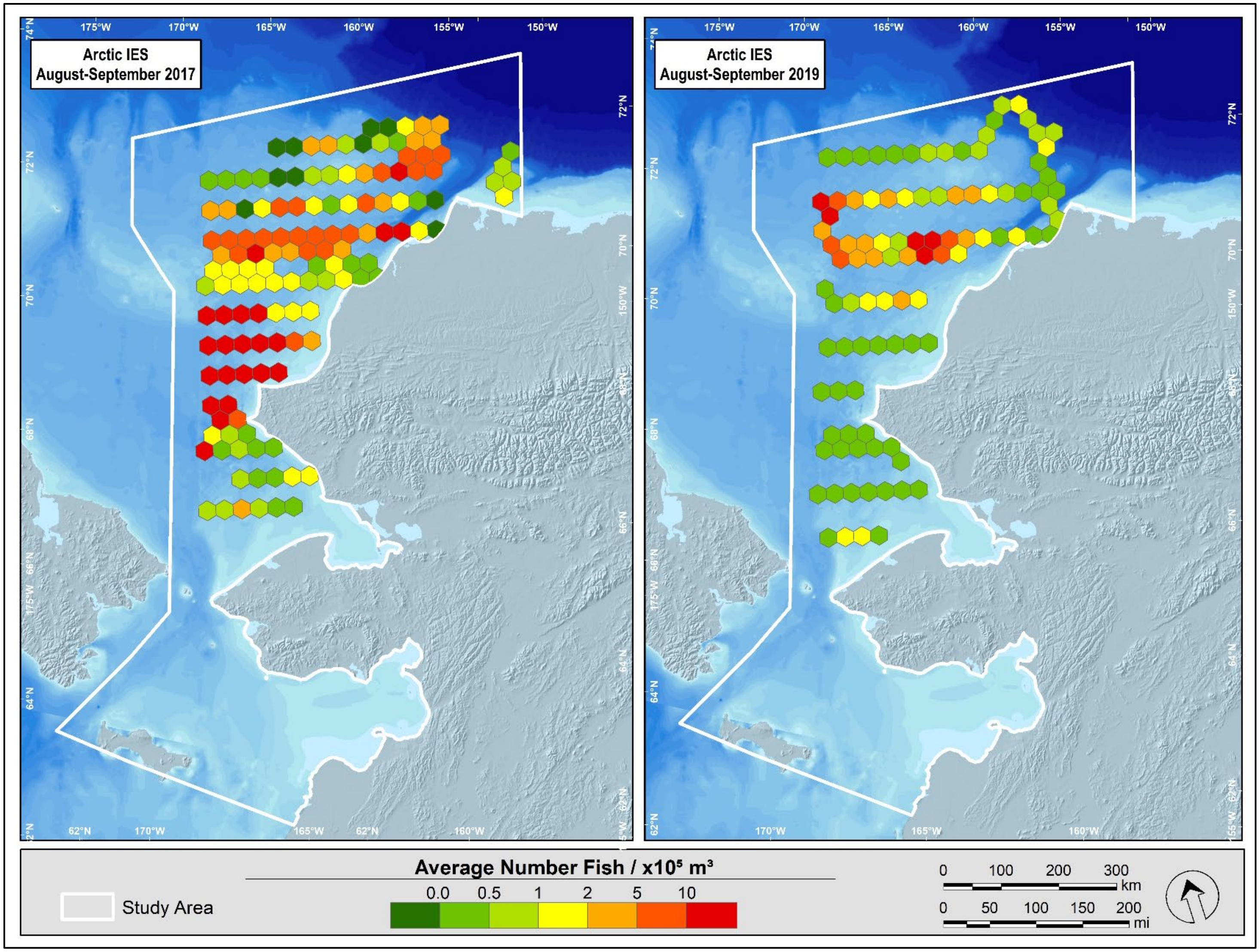

Figure 3.32. Density (fish/km^2) of large fish (5.6–10.5 cm) for each 30-km grid cell sampled during each of 2 Arctic IES surveys, 2017 and 2019.
For each cell, average fish density was calculated from hydroacoustic sampling, with all depths and species pooled. Grid cells that did not contain hydroacoustic sampling data are not shown.

4 Discussion

4.1 Availability of data for seasonal comparisons

Participating in the ASGARD surveys provided a unique opportunity to obtain data on seabirds in the northern Bering and southern Chukchi subregions during early summer. The ASGARD surveys allowed us to examine changes in seabird distribution, abundance, and species composition between early (June) and late summer (August–September, Arctic IES). While the USFWS has conducted a small number of seabird surveys in the region during spring (March–May) and early summer (June), these were the first comprehensive surveys during this seasonal period. Only one previous study incorporated a small number of late June surveys into a summer analysis of hotspots, which combined data from June 15 to August 31 (Kuletz et al. 2015). Otherwise, earlier studies in the 1980s (Divoky 1987) focused on the mid- to late-summer seasonal period (July to October) because that was the period when open water allowed research vessels access to the region, or more recently, there was adequate sample size (kilometers of transect) and sufficient spatial coverage during that period. Both Gall et al. (2017) and Kuletz et al. (2019) used surveys conducted July to early-October, with a focus on 1975–2012 (Gall et al. 2017) or 2007–2015 (Kuletz et al. 2019). A later analysis (Kuletz et al. 2020) included years 2007–2019, during months of July through September; that study included Arctic IES data and is presented in Appendix 5. Thus, there is little historic comparison available for our June (ASGARD) surveys, whereas August–September has long-term and more recent analyses available for comparison.

4.2 Species richness and diversity

Species richness was only slightly lower in June compared to August–September but that difference could have been influenced by the greater spatial coverage and higher number of transect segments during Arctic IES. Within a season, species richness did not differ substantially between years, with an estimated 24–27 species in early summer (actual observations were up to 34 species recorded when including off-transect observations, for the Northern Bering and Southern Chukchi subregions). Estimated species richness increased slightly in August–September, to approximately 30–34 species (up to 37 species actually recorded including off-transect observations, extending to the northern Chukchi Sea shelf edge). The modeled estimates indicated that we had adequate coverage to examine species richness, and that was evident in the slightly higher numbers of species actually observed. Our results are similar to or slightly lower than previous August–September studies, which had 40 to 50 species in the northern Bering and 30 to 40 species in the Chukchi Sea (Kuletz et al. 2019, 2020). The higher richness in earlier studies is likely due to the larger areas covered and substantially higher number of transect segments, because they included more years of surveys.

Accounts of seabirds in June in offshore waters of the northern Bering and southeastern Chukchi seas are sparse, but historic species richness was likely lower than what we recorded in June 2017 and 2018. Prior to 2017, sea ice covered most of the ASGARD study area until mid- to late June, with exception of open water leads and polynyas, which were mostly near the coasts (Stringer and Groves 1991; Stabeno and Bell 2019). Murres (2 species), puffins (2 species), auklets (3 species), kittiwake (1 species), and large gulls (2–4 species) would be attending breeding colonies or migrating and could possibly forage in offshore waters. Spectacled eiders aggregate in polynyas near St. Lawrence Island in spring (Petersen et al. 1999) and king eiders use the coastal waters of the southeastern Chukchi Sea in June during spring migration (Oppel et al. 2009). Common eiders and long-tailed ducks might still be passing through the area in June. Black guillemots follow the ice edge in the Bering and Chukchi seas from fall to spring (April) (Divoky et al. 2016); they were observed in open leads in the northern Bering Sea in March 2009 (Kuletz, pers. obs) and likely to be present in early summer. While Kittlitz's murrelets were also observed in these open leads in March 2009, they would have migrated to coastal or southern Alaska breeding areas before June. Together, the birds most likely to be present in the AIERP study area in early summer would number ~18–20 species, approximately 60% of the number of species we observed in 2017 and 2018, although a careful accounting of historical anecdotal records might find other species that were present in earlier years.

The diversity of marine birds was more variable between years in early summer than it was in late summer. Diversity was higher in June 2017 than it was in June 2018, whereas diversity indices were nearly identical between years in August–September. Concurrently, seabird abundance was much lower in June 2017 than June 2018 or the two August–September surveys. The lower abundance and greater diversity that occurred in June 2017 may be attributed to the low densities of 'core' species, including *Aethia* auklets, both species of murres, and black-legged kittiwakes, and the presence (in low numbers) of short-tailed shearwaters. In addition, the extremely high abundance of least auklets in the Northern Bering subregion in June 2018 contributed to the low diversity in that year. In August–September of both years, the preponderance of short-tailed shearwaters was an important contributor to the low species diversity, despite many post-breeding birds of other species migrating through the region at that time of year (Divoky 1987; Kuletz et al. 2015; Gall et al. 2017).

The greater interannual contrast in seabird diversity and abundance between years during June may be indicative of the sensitivity of the avian community to timing of sea ice retreat in the study area in early summer. The retreat of sea ice in early June is both a recent occurrence and subject to changes in short periods of time. Ice remained in the Northern Bering subregion 2–3 weeks longer in 2017 (based on 75% or 100% open water), and in the Southern Chukchi for about a week longer in 2017 than in 2018 (Table 3.5). Thus the earlier retreat of ice in 2018 did not alter species richness in June, but corresponded to lower diversity and higher abundance of birds, due to large numbers of locally breeding birds (primarily auklets and to lesser degree, murres) present in offshore waters.

4.3 Abundance and distribution

The high density of least auklets in offshore waters in June 2018 coincided with reports of low colony attendance, low nesting attempts, and high breeding failure at auklet colonies on St. Lawrence Island that year (Will et al. 2020a). Because our surveys were generally >50 km from any coastline (partly to avoid disturbance to local hunters), densities of breeding species may be low offshore when birds are attending colony nest sites or incubating eggs. Consequently, high occupation of offshore waters may be indicative of low colony attendance. In subsequent studies, we will examine the possibility that an inverse relationship occurs in the study area between at-sea densities of locally breeding birds and ocean conditions that facilitate breeding success.

Although non-breeding birds may forage farther offshore from colonies, there is still a 'halo effect' in adjacent waters, where seabird densities are typically higher near colonies during the breeding season (Sigler et al. 2012; Kuletz et al. 2015, 2019). We observed such a colony influence in June near St Lawrence Island and the Diomede islands, as well as in waters near Cape Thompson to Cape Lisburne (the locations of the largest and most northerly colonies in the eastern Chukchi Sea). Our August–September surveys (Arctic IES) spanned the period of chick-rearing and post-breeding, as chronology varies among species. In September, as birds complete breeding attempts (successfully or not), seabirds typically disperse; a study in the southeastern Bering Sea showed that birds were more dispersed at lower densities in fall (Suryan et al. 2016). Our results were consistent with this pattern, with locally breeding species having lower densities in August–September (compared to June) and being more widely dispersed. For auklets, this post-breeding dispersal can be fairly well synchronized, with birds migrating hundreds of kilometers to the Chukchi Sea. The late summer migration of auklets into the Chukchi Sea was noted in historical studies, but only as far as the central Chukchi (Divoky 1987). Since the mid-

2000s, auklets, particularly crested auklets, have been regularly occurring in the northeastern Chukchi Sea, and especially near Hanna Shoal (Kuletz et al. 2015, 2019; Gall et al. 2017).

4.3.1 Shearwaters as a foraging guild

In contrast to locally breeding species, the influx of short-tailed shearwaters into the study area greatly increased their densities during late summer, making the two-year average for total density of seabirds higher than during June, despite the high abundance of local breeders (especially least auklets) in June 2018. Short-tailed shearwaters breed on Australian islands from November to March/April, after which they begin migrating north to summer foraging grounds (Carboneras et al. 2020; Price et al. 2020). The species has long been recognized as one of the most abundant birds in the Bering Sea during summer (Hunt et al. 1981) and is abundant in late summer at least into the nearshore waters of the central Chukchi Sea (Divoky 1987). Most shearwaters enter the Bering Sea around late June or early July, and have rarely been observed in the northern Bering Sea before July (although there were low numbers in June 2017). Based on AIERP and other USFWS at-sea surveys, large numbers of shearwaters enter the Chukchi Sea around early August and peak in the region by late August to early September (Kuletz, unpubl. data), thus coinciding with the Arctic IES surveys.

During August–September, short-tailed shearwaters composed 64–69% of total seabird observations and were numerically dominant in both years and in all subregions, with exception of the Northern Bering subregion in 2019. Although short-tailed shearwaters were common in offshore waters of the northeastern Chukchi Sea during 1975–1981, by the early 2000s their density had increased, and they occurred farther north in the northernmost waters of the central and eastern Chukchi Sea (Gall et al. 2017). An examination of the DBO array from 2007–2015 (July through early October) identified the shearwater-dominated seabird community as the dominant community in five of eight DBO sites extending from the northern Bering Sea to the western Beaufort Sea (Kuletz et al. 2019). During the years of the AIERP study (2017–2019), short-tailed shearwaters shifted even farther north to the northern Chukchi Sea and shelf edge. However, the northward shift from the northern Bering to the Chukchi Sea actually began in 2013 (Kuletz et al. 2020; Appendix 5, with Arctic IES seabird data included in this study). Notably, during Arctic IES surveys, shearwater distribution also expanded westward across the Chukchi Sea shelf, particularly in 2019 (Figure 3.9).

4.3.2 Other foraging guilds

Other foraging guilds that did not include short-tailed shearwaters showed different patterns. Diving foragers (alcids, both piscivorous and planktivorous) were numerically dominant during June, and in June 2018 diving planktivores swamped all other groups, primarily because of the extremely high abundance of least auklets concentrated in the Chirikov Basin and Bering Strait. By August–September, both diving and surface-feeding planktivores were numerically dominant in the Northern Chukchi subregion but were highly aggregated, compared to diving and surface-feeding piscivores, which were more widely dispersed. These patterns suggest that prey availability was more highly aggregated for planktivores, and more dispersed for piscivores. Piscivores (primarily murres, puffins, kittiwakes), which breed along sections of the eastern Chukchi coast, had higher densities near their colony sites in August–September 2017, when many individuals of these species were still likely tied to colonies throughout August to raise chicks. However, there was no such aggregation near colonies by piscivorous seabirds in August–September 2019, consistent with reports of low nesting attempts and failed nesting attempts reported for seabirds in the Northern Bering subregion (Will et al. 2020a).

4.3.3 Marine mammals

While our records of marine mammal observations are informative, they are limited in their inference about abundance and species composition compared to data collected using marine mammal protocols.

Nonetheless, our observations were consistent with previous studies which showed 'hotspots' in the Chirikov Basin for gray whales, and for a variety of cetaceans in Hope Basin and the head of Barrow Canyon, and walrus near Hanna Shoal (Kuletz et al. 2015).

4.4 Influences of oceanographic and prey conditions on offshore seabird communities

During AIERP studies, water temperatures were warmer in 2019 throughout the Southern Chukchi and extending into the Northern Chukchi (Figure 3.25), with greater freshwater influence on the shelf (Figure 3.26). Findings from Gall et al. (in review) found that hydrography was a significant predictor of seabird distribution. Kittiwakes, auklets, northern fulmars, and thick-billed murres were all positively associated with waters that were warmer and saltier in the upper layer, typical of Bering Sea Water. In contrast, short-tailed shearwaters shifted from an association with cooler, fresher, stratified waters (indicative of Alaska Coastal Water) in early summer, to warmer, saltier water indicative of Bering Sea Water in late summer. Presumably, these water mass associations reflect prey distributions.

Peak densities of short-tailed shearwaters occurred in the northern Bering and Chukchi seas in 2015, and have generally declined since then (Kuletz et al. 2020; Appendix 5), although their abundance has been highly variable in the region over time (Kuletz et al. 2015; Gall et al. 2017). Years with shearwater 'irruptions' in the Chukchi Sea (2009, 2013, 2017) may be linked to years of high krill abundance driven by spring sea ice conditions (Gall et al. in review; includes Arctic IES seabird data). Preliminary results (Kuletz et al. in prep) suggest that conditions in March, primarily winds and heat transport through Bering Strait, were the best predictors of shearwater abundance during late summer in the Chukchi Sea. Winter and spring conditions influence summer krill abundance and distribution (Ashjian et al. 2021), and thus lag effects may need to be incorporated into exploration of the relationships between shearwaters, their prey, and hydrography. Additionally, although short-tailed shearwaters may feed primarily on euphausiids, they can dive as well as surface-feed, and have an omnivorous diet. Notably, the northward shift in distribution observed in shearwaters in 2017, and again in 2019, coincided with high abundance of large *Calanus* copepods, euphausiids, and forage fish in the Chukchi Sea, particularly the Northern Chukchi subregion.

The low abundance of short-tailed shearwaters during August–September of 2019 coincided with a series of shearwater mortality events that occurred in Alaska, with over 10,000 birds found on beaches, emaciated and starved (USFWS 2019). The shearwater die-off occurred from June to September throughout the Bering and southern Chukchi seas, but roughly half of the dead shearwaters were found in the southeastern Bering Sea during July, and the rest were primarily in the Northern Bering and Southern Chukchi seas during August (USFWS 2019). Thus, shearwater numbers may have been depressed by the inability of shearwaters to migrate farther north, and many may not have made it into the Chukchi Sea in August–September 2019.

Compared to 2017, during August–September 2019, smaller copepods were numerically dominant throughout the Chukchi Sea, and large *Calanus* copepods were mainly in the northernmost Chukchi Shelf during both years. Compared to years preceding Arctic IES, the Chukchi Sea during 2017–2019 was dominated by smaller species of copepod, with larger *Calanus* copepods shifting to the northern Chukchi shelf (Kimmel and Spear 2022). Euphausiids, which were widely distributed in August–September 2017, had high densities in 2019 but were concentrated in the Southern Chukchi or western edges of the study area.

The AIERP studies coincided with a massive influx of juvenile walleye pollock into the Chukchi Sea in 2017, with large numbers still prevalent in the Northern Chukchi subregion in 2019 (Levine et al., in review). During 2017, juvenile pollock and other forage fish would have been within foraging range of piscivorous birds raising chicks, but they were hundreds of km too far north in 2019; this may have been one reason densities of piscivorous birds (mainly, kittiwakes and murres) were low near colonies in the southern Chukchi in 2019. In contrast, planktivorous seabirds (primarily least and crested auklets), of which large numbers appeared to forego nesting in 2018, remained in the Northern Bering Sea, where several major colony sites are located. During August–September of 2019, auklets were less abundant in the Chukchi Sea, indicating fewer had migrated north, as they had in previous years (Kuletz et al. 2020).

During 2007–2015, crested auklets were the primary species forming one of six seabird communities in the northern Bering-Chukchi Sea region (Kuletz et al. 2019). The crested-auklet community was centered over and near Hanna Shoal, where sea ice remains into late summer and surrounding currents provide abundant copepod biomass (Dunton et al. 2017). Crested auklets also appear to molt in this area in late summer/early fall, during which birds are temporarily flightless and thus dependent on predictable and abundant prey (Gall et al. 2017, Kuletz et al. 2015). However, the spatial extent of the crested auklet-dominated community contracted during the anomalously warm years of 2017–2019, as did the least auklet-dominated community in the Bering Strait region (Kuletz et al. 2020 [Appendix 5]).

If prey was of lower abundance or of lower nutrient value than previous years, it may not have been profitable for birds to fly 600 km north in late summer, particularly if they did not breed those years. When raising chicks, local availability of prey, and the quality of prey (i.e., size and fat content of copepods) is critical (Sheffield-Guy et al. 2009). As part of AK-16-07c, Pinchuk et al. (Appendix 4) examined chick diet samples for least and crested auklets nesting on St. Lawrence Island. During 2016–2019, the diets of least and crested auklet also overlapped in species composition more than they had in earlier years. Diet composition shifted from mesoplankton (e.g., copepods and hyperiids) in 2000–2004 (Gall et al. 2006; Sheffield-Guy et al. 2009) and 2016 (this study), to micronekton (juvenile euphausiids) during 2017–2019. The change in prey species coincided with changes in oceanographic conditions, which appeared to affect distribution and abundance of large-bodied zooplankton in the Chukchi Sea.

5 Conclusions and Management Applications

The AIERP seabird studies provide evidence of rapid changes in seabird distribution and species composition throughout the northern Bering and Chukchi seas in response to changes in physical oceanography, prey species, and the influx of large predatory fish. During the Arctic Marine Biodiversity Observing Network (AMBON) study in the eastern Chukchi Sea, the seabird community was highly correlated with communities of LTL taxa in late summer of 2015, including zooplankton and fish communities. However, in 2017, at the beginning of a heat wave in the region, seabirds had no significant correlations with any LTL taxa or prey communities, suggesting that seabirds (at least as a group) were not able to respond to the rapid changes in prey that occurred that year (Mueter et al. 2021). Our preliminary analyses of spatial correlations between seabirds and prey were consistent with these results.

The AIERP was conducted during several years of anomalously warm ocean temperatures (Danielson et al. 2022, Farley et al. 2022), changes in the zooplankton community (Kimmel and Spear 2022), and a massive influx of large predatory fish into the northern Bering Sea (Farley et al. 2022), with repercussions throughout the food web (Duffy-Andersen et al. 2019; Huntington et al. 2020). Die-offs of seabirds were recorded in the Bering Strait region in 2017 and 2018 throughout the Bering Sea (Duffy-Anderson et al. 2019, Romano et al. 2020). The seabird die-offs were concurrent with changes in oceanography, zooplankton, and fish, following the absence of winter sea ice and subsequent loss of the deep cold pool that formed a thermal barrier to large predatory fish such as walleye pollock and Pacific cod (Duffy-Andersen et al. 2019). Murres breeding in the northern Bering Sea failed to nest or failed to fledge chicks (Romano et al. 2020) and both planktivores and piscivores showed detrimental response to the conditions associated with the heat wave (Will et al. 2020b).

One of the Arctic IES hypotheses was that warmer seas would lead to smaller zooplankton and thus less suitable prey to support high densities of planktivorous seabirds, resulting in a shift back towards a predominantly piscivorous seabird community. Piscivorous seabirds had always been, and remain, the numerically dominant species at Chukchi colonies, and there is evidence that murres and kittiwakes have even been increasing at the Lisburne colony over the past decade (Dragoo et al. 2020). While changes in environmental conditions and prey undoubtedly affect breeding birds, our study focused on offshore waters, which includes both breeding and non-breeding populations. The planktivorous birds that have predominated in offshore waters of the Chukchi over the past two decades nest in the Bering Sea (or travel from Australia during their non-breeding season) and only forage in the Chukchi Sea during late summer. Although limited to two years of August–September surveys, the Arctic IES results were consistent with the proposed hypothesis. We found spatial contraction of the two auklet-dominated seabird communities, and lower abundance of planktivorous birds in general (including short-tailed shearwater) during the warmer year, when there was a lack of large copepods or restriction of large zooplankton to northern edges of the Chukchi Sea shelf. Whether this reduced use of the Chukchi Sea offshore waters continues, or was a temporary response to extremely warm conditions, remains to be seen.

The numerical dominance of a few species in the northern Bering and Chukchi seas may shift to a more diverse seabird community, but the variability in conditions, particularly during early summer, indicates that the timing of seabird abundance will be difficult to predict in the future. However, locations of important areas within the region have been fairly consistent (Kuletz et al. 2015, 2019). The increased use of the Bering Strait region by a greater variety and abundance of seabirds during early summer has implications to evaluation of risk to seabird populations. More birds will be present as the open water period expands in both early summer and fall. During fall, migration southward through the southern Chukchi Sea and Bering Strait will occur when seasonal darkness returns to the region, but without the presence of ice. The concurrent increase in shipping traffic will present risks to seabirds (Humphries and Huettmann 2014; Wong et al. 2014).

Vessel traffic may increase incidents of light attraction causing vessel strikes (Gjerdrum et al. 2021; Merkel and Johansen 2011), disturbance to prey and foraging, and potential oiling from vessel accidents. Waters near breeding sites have consistently high seabird densities and are thus inherently sensitive areas, although birds may be more dispersed when breeding is interrupted, as occurred during the 2018–2019 heatwave. The high abundance of both seabirds and marine mammals in the Bering Strait region, including Hope Basin, highlights once again, the importance of careful mitigation of human activities in this region. Possible mitigation methods to address these risks include reduction in amount of radiance, downward-directed lighting, slower vessel speeds, and avoiding high-use areas during sensitive seasonal periods (Gjerdrum et al. 2021; Merkel and Johansen 2011; Rodriguez et al. 2014). At-sea seabird survey data could be combined with vessel traffic data (e.g., Automated Identification System ship identifiers) to model temporal and spatial high-risk situations. The cumulative effects on seabirds of changes in oceanographic conditions, prey types and distribution, and human activities will need to be considered when assessing potential impacts of proposed developments.

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Appendix 1: Density for all species of birds observed on-transect during each AIERP cruise 2017–2019.

Family	Species	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
Anatidae	Snow Goose				*
	Greater White-fronted Goose	*			
	Cackling Goose			<0.001	
	Canada Goose				*
	Northern Pintail	0.001 ± 0.001			
	Steller's Eider	*		*	
	Spectacled Eider		0.006 ± 0.006	0.008 ± 0.005	0.005 ± 0.003
	King Eider	0.019 ± 0.015	*	*	0.012 ± 0.007
	Common Eider	*	0.016 ± 0.011	0.003 ± 0.002	0.005 ± 0.005
	Unidentified eider	0.043 ± 0.031	0.061 ± 0.047	0.013 ± 0.006	0.003 ± 0.002
	Harlequin Duck	*		0.003 ± 0.002	0.003 ± 0.002
	White-winged Scoter	*		0.011 ± 0.011	0.001 ± 0.001
	Long-tailed Duck	0.001 ± 0.001	0.002 ± 0.002	0.010 ± 0.007	0.005 ± 0.004
	Unidentified goldeneye	*			
	Unidentified duck		0.006 ± 0.006	0.001 ± 0.001	0.002 ± 0.001
Podicipedidae	Red-necked Grebe				*
Charadriidae	Pacific Golden-Plover				*
Scolopacidae	Marbled Godwit			*	
	Ruddy Turnstone				0.001 ± 0.001
	Black Turnstone		*		
	Unidentified turnstone				0.002 ± 0.001
	Sharp-tailed Sandpiper				*
	Pectoral Sandpiper				*
	Semipalmated Sandpiper			*	
	Unidentified sandpiper			0.001 ± 0.001	

Family	Species	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
	Unidentified (Charadrius)	0.003 ± 0.003	0.016 ± 0.009	0.002 ± 0.001	0.008 ± 0.004
	Red-necked Phalarope	0.052 ± 0.036	0.015 ± 0.015		0.001 ± 0.001
	Red Phalarope	0.063 ± 0.055	0.296 ± 0.208	0.165 ± 0.138	0.477 ± 0.116
	Unidentified phalarope		0.294 ± 0.165	0.727 ± 0.357	0.328 ± 0.086
Stercorariidae	Pomarine Jaeger	0.025 ± 0.010	0.021 ± 0.007	0.025 ± 0.005	0.032 ± 0.007
	Parasitic Jaeger	0.019 ± 0.007	0.016 ± 0.008	0.007 ± 0.002	0.014 ± 0.005
	Long-tailed Jaeger	0.003 ± 0.002	0.006 ± 0.003	0.002 ± 0.001	0.001 ± 0.001
	Unidentified jaeger	0.001 ± 0.001	0.006 ± 0.004	0.004 ± 0.002	0.010 ± 0.003
Alcidae	Dovekie	0.005 ± 0.004	0.004 ± 0.004		0.001 ± 0.001
	Common Murre	0.424 ± 0.046	0.189 ± 0.034	0.122 ± 0.019	0.199 ± 0.025
	Thick-billed Murre	1.182 ± 0.097	0.748 ± 0.098	0.489 ± 0.172	0.294 ± 0.046
	Unidentified murre	1.234 ± 0.180	0.771 ± 0.149	0.065 ± 0.010	0.100 ± 0.021
	Black Guillemot		0.011 ± 0.006	*	*
	Pigeon Guillemot	0.038 ± 0.014	0.004 ± 0.004	0.008 ± 0.005	
	Marbled Murrelet			0.002 ± 0.002	
	Kittlitz's Murrelet	0.002 ± 0.002		0.001 ± 0.001	0.001 ± 0.001
	Unidentified (Brachyramphus) murrelet	0.003 ± 0.003			0.002 ± 0.001
	Ancient Murrelet	0.001 ± 0.001	0.062 ± 0.024	0.036 ± 0.010	0.048 ± 0.013
	Cassin's Auklet		0.003 ± 0.003	0.018 ± 0.007	0.029 ± 0.008
	Parakeet Auklet	0.562 ± 0.164	0.528 ± 0.084	0.067 ± 0.016	0.147 ± 0.025
	Least Auklet	1.912 ± 0.345	4.774 ± 1.119	0.141 ± 0.024	0.324 ± 0.072
	Crested Auklet	0.821 ± 0.141	1.510 ± 0.399	2.066 ± 0.457	0.412 ± 0.087
	Rhinoceros Auklet		0.002 ± 0.002		
	Unidentified auklet	0.077 ± 0.022	1.799 ± 0.479	0.044 ± 0.010	0.049 ± 0.011
	Horned Puffin	0.186 ± 0.031	0.214 ± 0.038	0.052 ± 0.011	0.059 ± 0.012
	Tufted Puffin	0.209 ± 0.043	0.772 ± 0.092	0.078 ± 0.013	0.087 ± 0.020
	Unidentified puffin	0.001 ± 0.001		0.001 ± 0.001	0.001 ± 0.001

Family	Species	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
	Unidentified alcid	0.030 ± 0.013	1.786 ± 1.110	0.046 ± 0.011	0.048 ± 0.011
Laridae	Black-legged Kittiwake	0.937 ± 0.098	0.636 ± 0.135	1.299 ± 0.125	0.914 ± 0.061
	Red-legged Kittiwake		0.001 ± 0.001	0.004 ± 0.002	0.024 ± 0.007
	Unidentified kittiwake			0.001 ± 0.001	
	Sabine's Gull	0.004 ± 0.003	0.001 ± 0.001	0.005 ± 0.002	0.025 ± 0.012
	Bonaparte's Gull		0.003 ± 0.003		
	Herring Gull	*	*	0.001 ± 0.001	0.002 ± 0.002
	Slaty-backed Gull	0.002 ± 0.002		*	
	Glaucous-winged Gull	0.009 ± 0.004	0.119 ± 0.062	0.032 ± 0.015	0.057 ± 0.018
	Glaucous Gull	0.041 ± 0.011	0.064 ± 0.020	0.037 ± 0.005	0.065 ± 0.010
	Unidentified gull	0.004 ± 0.003	0.007 ± 0.007	0.006 ± 0.002	0.002 ± 0.002
	Arctic Tern			0.007 ± 0.004	0.064 ± 0.023
	Unidentified tern			0.014 ± 0.011	
Gaviidae	Red-throated Loon			0.001 ± 0.001	0.001 ± 0.001
	Arctic Loon				<0.001
	Pacific Loon	0.007 ± 0.004	0.048 ± 0.028	0.005 ± 0.002	0.041 ± 0.008
	Common Loon		0.001 ± 0.001	0.001 ± 0.001	0.001 ± 0.001
	Yellow-billed Loon	*	0.003 ± 0.003	*	0.007 ± 0.005
	Unidentified loon		0.001 ± 0.001	0.011 ± 0.003	0.008 ± 0.003
Diomedeidae	Laysan Albatross		0.081 ± 0.020	0.007 ± 0.003	0.008 ± 0.003
	Black-footed Albatross		0.056 ± 0.015	0.002 ± 0.002	0.001 ± 0.001
	Short-tailed Albatross		0.003 ± 0.002		*
Hydrobatidae	Fork-tailed Storm-Petrel		0.282 ± 0.069	0.072 ± 0.013	0.084 ± 0.014
	Leach's Storm-Petrel		0.190 ± 0.051		
Procellariidae	Northern Fulmar	0.250 ± 0.063	9.075 ± 4.708	0.755 ± 0.108	0.804 ± 0.227
	Short-tailed Shearwater	1.059 ± 0.398	1.713 ± 0.925	9.996 ± 1.386	8.577 ± 1.149
	Sooty Shearwater		0.043 ± 0.031		<0.001

Family	Species	ASGARD 2017	ASGARD 2018	Arctic IES 2017	Arctic IES 2019
	Unidentified dark shearwater		9.790 ± 3.485	1.651 ± 1.464	0.082 ± 0.038
	Unidentified procellarid			0.005 ± 0.002	
Phalacrocoracidae	Pelagic Cormorant	0.008 ± 0.005	0.030 ± 0.015	0.009 ± 0.006	*
	Pelagic/Red-faced Cormorant				<0.001
Accipitridae	Bald Eagle			<0.001	*
Falconidae	Peregrine Falcon				*
	Unidentified passerine	0.012 ± 0.008		0.001 ± 0.001	0.001 ± 0.001
	Unidentified bird		0.004 ± 0.003	0.001 ± 0.001	0.003 ± 0.001
	Total Birds	9.251 ± 0.72	36.093 ± 7.563	18.141 ± 2.112	13.488 ± 1.196

Notes: Overall density is the mean density of all transects across the entire cruise.
* Species seen only off-transect during a cruise.

Appendix 2: Densities of birds for each cruise within each subregion of the AIERP study area.

		ASGARD 2017		ASGARD 2018			Arctic IES 2017				Arctic IES 2019			
Family	Species	Northern Bering	Southern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Northern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Northern Chukchi
Anatidae	Snow Goose												*	
	Greater White-fronted Goose		*											
	Cackling Goose						0.012 ± 0.012							
	Canada Goose												*	
	Northern Pintail	0.003 ± 0.003												
	Steller's Eider	*	*						*					
	Spectacled Eider					0.017 ± 0.017			0.028 ± 0.019			0.010 ± 0.010	0.009 ± 0.007	0.001 ± 0.001
	King Eider		0.034 ± 0.027		*	*				*		0.026 ± 0.021	0.026 ± 0.020	
	Common Eider	*	*		*	0.047 ± 0.033			0.002 ± 0.002	0.005 ± 0.005		*	0.017 ± 0.017	
	Unidentified eider	0.067 ± 0.067	0.024 ± 0.020		0.057 ± 0.057	0.136 ± 0.132		0.015 ± 0.015	0.039 ± 0.022	0.002 ± 0.002		0.005 ± 0.005	0.005 ± 0.005	0.001 ± 0.001
	Harlequin Duck	*												
	White-winged Scoter	*					0.258 ± 0.258	*					0.005 ± 0.005	
	Long-tailed Duck	*	0.002 ± 0.002		0.007 ± 0.007			0.004 ± 0.004	0.010 ± 0.006	0.015 ± 0.015		*	0.016 ± 0.012	
	Unidentified goldeneye	*												
	Unidentified duck				0.022 ± 0.022				0.005 ± 0.005				0.006 ± 0.005	
Podicipedidae	Red-necked Grebe											*		
Charadriidae	Pacific Golden-Plover												*	
Scolopacidae	Marbled Godwit							*						
	Ruddy Turnstone													*
	Black Turnstone					*								
	Unidentified turnstone												0.002 ± 0.002	0.002 ± 0.002
	Pectoral Sandpiper													*
	Semipalmated Sandpiper									*				
	Unidentified sandpiper									0.002 ± 0.002				
	Unidentified (Charadrius)	0.006 ± 0.006		0.112 ± 0.112	0.020 ± 0.014			0.006 ± 0.006		0.002 ± 0.002			0.006 ± 0.006	0.014 ± 0.009
	Red-necked Phalarope	0.117 ± 0.081	*									0.007 ± 0.007		
	Red Phalarope	0.143 ± 0.125	*		0.057 ± 0.027	0.052 ± 0.029		0.006 ± 0.006	0.507 ± 0.495	0.053 ± 0.034	*	0.226 ± 0.136	1.325 ± 0.370	0.086 ± 0.042
	Unidentified phalarope				0.016 ± 0.016	0.013 ± 0.013	0.051 ± 0.051	0.306 ± 0.161	1.702 ± 1.265	0.467 ± 0.137	0.031 ± 0.031	0.158 ± 0.099	0.865 ± 0.273	0.087 ± 0.028
Stercorariidae	Pomarine Jaeger	*	0.044 ± 0.017	0.100 ± 0.072	0.019 ± 0.011	0.022 ± 0.011	0.057 ± 0.033	0.046 ± 0.027	0.013 ± 0.005	0.027 ± 0.007	0.057 ± 0.036	0.066 ± 0.034	0.037 ± 0.012	0.021 ± 0.007
	Parasitic Jaeger	0.019 ± 0.008	0.019 ± 0.010		0.017 ± 0.017	0.017 ± 0.010			0.007 ± 0.004	0.011 ± 0.004		0.010 ± 0.007	0.017 ± 0.014	0.013 ± 0.004
	Long-tailed Jaeger	*	0.005 ± 0.003		0.017 ± 0.010	0.004 ± 0.004		0.013 ± 0.008	*	0.001 ± 0.001		0.003 ± 0.003	0.002 ± 0.002	*
	Unidentified jaeger		0.002 ± 0.002		0.006 ± 0.006	0.013 ± 0.010		0.004 ± 0.004		0.009 ± 0.003		0.007 ± 0.005	0.005 ± 0.003	0.008 ± 0.003
Alcidae	Dovekie	0.012 ± 0.010			0.016 ± 0.016									
	Common Murre	0.246 ± 0.038	0.564 ± 0.077	0.544 ± 0.223	0.119 ± 0.034	0.112 ± 0.043	0.035 ± 0.020	0.323 ± 0.083	0.179 ± 0.049	0.013 ± 0.006	0.477 ± 0.235	0.177 ± 0.058	0.262 ± 0.058	0.009 ± 0.005
	Thick-billed Murre	1.051 ± 0.156	1.286 ± 0.122	0.448 ± 0.269	1.019 ± 0.258	1.317 ± 0.194	0.011 ± 0.011	0.300 ± 0.096	1.455 ± 0.615	0.096 ± 0.017	0.063 ± 0.063	0.278 ± 0.078	0.362 ± 0.127	0.105 ± 0.021
	Unidentified murre	1.685 ± 0.377	0.879 ± 0.125	0.244 ± 0.108	1.043 ± 0.450	1.266 ± 0.253	0.012 ± 0.012	0.068 ± 0.021	0.107 ± 0.023	0.032 ± 0.009	0.032 ± 0.032	0.093 ± 0.052	0.080 ± 0.016	0.035 ± 0.009
	Black Guillemot				0.040 ± 0.025			*		*				*
Alcidae	Pigeon Guillemot	0.025 ± 0.011	0.048 ± 0.023					0.015 ± 0.012						
	Kittlitz's Murrelet		0.004 ± 0.004					*	0.002 ± 0.002	0.001 ± 0.001			*	0.002 ± 0.002

Family	Species	ASGARD 2017		ASGARD 2018			Arctic IES 2017				Arctic IES 2019			
		Northern Bering	Southern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Northern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Northern Chukchi
	Unidentified (Brachyramphus) murrelet		0.005 ± 0.005											0.004 ± 0.002
	Ancient Murrelet	0.003 ± 0.003					0.035 ± 0.035	0.027 ± 0.024	0.071 ± 0.029	0.018 ± 0.009	0.218 ± 0.142	0.050 ± 0.050	0.037 ± 0.021	0.006 ± 0.004
	Cassin's Auklet										0.031 ± 0.031			
	Parakeet Auklet	0.689 ± 0.346	0.462 ± 0.110	0.294 ± 0.176	1.422 ± 0.255	0.355 ± 0.129	0.034 ± 0.024	0.217 ± 0.083	0.075 ± 0.029	0.030 ± 0.019	0.046 ± 0.046	0.035 ± 0.015	0.270 ± 0.055	0.122 ± 0.041
	Least Auklet	1.124 ± 0.220	2.532 ± 0.590	0.145 ± 0.145	16.117 ± 4.091	1.578 ± 0.617		0.227 ± 0.127	0.061 ± 0.021	0.215 ± 0.037	0.031 ± 0.031	1.366 ± 0.387	0.373 ± 0.150	0.032 ± 0.016
	Crested Auklet	1.307 ± 0.264	0.438 ± 0.138		4.082 ± 1.319	1.262 ± 0.567		0.235 ± 0.074	0.510 ± 0.151	4.244 ± 1.017		0.378 ± 0.223	0.017 ± 0.008	0.839 ± 0.192
	Unidentified auklet	0.084 ± 0.024	0.071 ± 0.034	0.074 ± 0.074	5.016 ± 1.549	1.421 ± 0.727		0.008 ± 0.005	0.048 ± 0.018	0.065 ± 0.019			0.040 ± 0.014	0.044 ± 0.021
	Horned Puffin	0.140 ± 0.046	0.223 ± 0.043	0.432 ± 0.193	0.290 ± 0.103	0.155 ± 0.054	0.011 ± 0.011	0.260 ± 0.074	0.061 ± 0.017	0.001 ± 0.001	*	0.133 ± 0.049	0.037 ± 0.011	0.004 ± 0.002
	Tufted Puffin	0.229 ± 0.067	0.193 ± 0.055	0.482 ± 0.223	0.429 ± 0.149	0.113 ± 0.039		0.422 ± 0.094	0.035 ± 0.010	0.003 ± 0.002		0.083 ± 0.029	0.030 ± 0.012	0.002 ± 0.002
	Unidentified puffin	0.003 ± 0.003						0.006 ± 0.006						
	Unidentified alcid	0.058 ± 0.028	0.007 ± 0.004		4.401 ± 4.011	1.828 ± 1.045		0.074 ± 0.039	0.057 ± 0.018	0.031 ± 0.013			0.026 ± 0.010	0.087 ± 0.024
Laridae	Black-legged Kittiwake	1.017 ± 0.169	0.874 ± 0.114	0.486 ± 0.193	1.039 ± 0.452	0.721 ± 0.173	2.342 ± 0.818	2.166 ± 0.592	2.319 ± 0.260	0.191 ± 0.068	1.011 ± 0.263	1.353 ± 0.206	1.398 ± 0.148	0.284 ± 0.027
	Red-legged Kittiwake						*							
	Sabine's Gull	0.006 ± 0.006	0.003 ± 0.003			0.004 ± 0.004			*	0.010 ± 0.005			0.005 ± 0.003	0.056 ± 0.028
	Herring Gull	*	*		*			0.006 ± 0.006		*		0.014 ± 0.011		
	Slaty-backed Gull	0.004 ± 0.004	*							*				
	Glaucous-winged Gull	0.021 ± 0.009	*		*		0.023 ± 0.016			0.002 ± 0.002	0.648 ± 0.312	0.036 ± 0.022	*	
	Glaucous Gull	0.050 ± 0.021	0.034 ± 0.012	*	0.099 ± 0.038	0.108 ± 0.050	0.017 ± 0.017	0.040 ± 0.013	0.028 ± 0.010	0.052 ± 0.009	0.042 ± 0.033	0.057 ± 0.021	0.124 ± 0.025	0.041 ± 0.012
	Unidentified gull	0.009 ± 0.007				0.022 ± 0.022		0.019 ± 0.008	0.004 ± 0.003	0.006 ± 0.003		0.003 ± 0.003		0.004 ± 0.004
	Arctic Tern							0.004 ± 0.004	0.003 ± 0.003	0.014 ± 0.008		0.003 ± 0.003	0.015 ± 0.009	0.140 ± 0.054
	Unidentified tern								0.002 ± 0.002	0.031 ± 0.025				
Gaviidae	Red-throated Loon							0.006 ± 0.006				0.005 ± 0.005	*	
	Arctic Loon													0.001 ± 0.001
	Pacific Loon	0.003 ± 0.003	0.010 ± 0.006		0.023 ± 0.018	0.125 ± 0.081		0.017 ± 0.013	0.003 ± 0.003	0.003 ± 0.002	0.016 ± 0.016	0.013 ± 0.010	0.097 ± 0.025	0.020 ± 0.007
	Common Loon									0.002 ± 0.002				0.003 ± 0.002
	Yellow-billed Loon		*	0.056 ± 0.056						*			0.022 ± 0.018	*
	Unidentified loon				0.006 ± 0.006		0.058 ± 0.048	0.023 ± 0.011		0.014 ± 0.005			0.013 ± 0.007	0.010 ± 0.003
Hydrobatidae	Fork-tailed Storm-Petrel				0.067 ± 0.039	0.004 ± 0.004		0.023 ± 0.019	0.016 ± 0.009		0.032 ± 0.032	0.010 ± 0.006	0.002 ± 0.002	
	Leach's Storm-Petrel													
Procellariidae	Northern Fulmar	0.289 ± 0.122	0.220 ± 0.060	0.262 ± 0.108	0.327 ± 0.089	0.905 ± 0.591	0.249 ± 0.104	0.163 ± 0.050	0.179 ± 0.032	0.511 ± 0.068	1.004 ± 0.225	0.134 ± 0.035	0.229 ± 0.069	0.045 ± 0.012
	Short-tailed Shearwater	2.308 ± 0.900	0.076 ± 0.025		0.006 ± 0.006		0.011 ± 0.011	5.406 ± 2.532	7.812 ± 2.170	15.927 ± [illegible]	0.452 ± 0.122	0.268 ± 0.059	10.134 ± 1.535	11.620 ± 2.452
	Sooty Shearwater													
	Unidentified dark shearwater						0.012 ± 0.012		0.004 ± 0.003	0.003 ± 0.003	0.094 ± 0.070		0.014 ± 0.011	
	Unidentified procellarid								0.002 ± 0.002	0.001 ± 0.001				
Phalacrocoracidae	Pelagic Cormorant	0.010 ± 0.008	0.007 ± 0.007	0.413 ± 0.239	0.021 ± 0.012			0.026 ± 0.019	0.021 ± 0.019			*		
	Pelagic/Red-faced Cormorant											0.003 ± 0.003		
Accipitridae	Bald Eagle											*		

Family	Species	ASGARD 2017		ASGARD 2018			Arctic IES 2017				Arctic IES 2019			
		Northern Bering	Southern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Northern Chukchi	Southern Bering	Northern Bering	Southern Chukchi	Northern Chukchi
Falconidae	Peregrine Falcon											*		
	Unidentified passerine	0.003 ± 0.003	0.019 ± 0.015						0.002 ± 0.002	0.001 ± 0.001			0.002 ± 0.002	
	Unidentified bird				0.003 ± 0.003	0.010 ± 0.007			0.001 ± 0.001	0.003 ± 0.002			0.003 ± 0.002	0.004 ± 0.002
	Total Birds	10.731 ± 1.303	8.087 ± 0.774	4.091 ± 0.726	35.827 ± 7.795	11.639 ± 2.88	3.228 ± 0.843	10.479 ± 2.659	15.367 ± 2.625	22.115 ± 2.871	4.284 ± 0.738	5.01 ± 0.598	15.939 ± 1.649	13.757 ± 2.465

Note: The reported densities are the mean density of all birds seen on transects within each subregion.
* Species seen only off-transect within a subregion during a cruise.

Appendix 3: Counts of marine mammals by cruise on transect (<300m from vessel) and off transect (>300m from vessel or on starboard side).

			2017		2018		2017		2019	
			ASGARD		ASGARD		Arctic IES		Arctic IES	
Family	**Species**	**Scientific name**	**On Transect**	**Off Transect**	**On Transect**	**Off Transect**	**On Transect**	**Off Transect**	**On Transect**	**Off Transect**
Otariidae	Northern Fur Seal	*Callorhinus ursinus*			1	1	6		9	1
Odobenidae	Walrus	*Odobenus rosmarus*								
Phocidae	Ringed Seal	*Pusa hispida*								
	unidentified seal									
	unidentified pinniped									
Balaenidae	Bowhead Whale	*Balaena mysticetus*								
Balaenopteridae	Minke Whale	*Balaenoptera acutorostrata*				2				
	Fin Whale	*Balaenoptera physalus*							3	7
	Humpback Whale	*Megaptera novaeangliae*			1	5	1	2	1	6
Eschrichtiidae	Gray Whale	*Eschrichtius robustus*								
Delphinidae	Pacific White-sided Dolphin	*Lagenorhynchus obliquidens*				50				
	Killer Whale	*Orcinus orca*				4				
Phocoenidae	Harbor Porpoise	*Phocoena phocoena*							1	
	Dall's Porpoise	*Phocoenoides dalli*					5			
	unidentified whale					1				20
	Total		0	0	2	63	12	2	14	34

Appendix 4: Diets of Breeding Auklets in the Northern Bering Sea: Consequences of Recent Oceanographic Changes in the Alaskan Subarctic.

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Introduction

The Pacific Arctic marine ecosystem is undergoing rapid changes manifested by retreating sea ice and increasing influx of warmer Pacific water. These changes influence primary productivity and zooplankton distribution, which, in turn, affect many anadromous and forage fish, migratory seabirds, waterfowl, and marine mammals. The northern Bering – southern Chukchi seas shelf serves as a gateway of the Pacific inflow into the Arctic, and it is experiencing rapid environmental changes associated with warming, which have implications at all trophic levels (Duffy-Anderson et. al. 2019). St Lawrence Island is in the middle of the northern Bering Sea Shelf, a dynamic area influenced by water masses of different origins (Coachman et al. 1975, Danielson et al. 2006); it also hosts one of the largest seabird breeding colonies in the Bering Sea (Stephensen and Irons 2003). Two planktivorous species of auklets, crested auklet (*Aethia cristatella*) and least auklet (*A. pusilla*), rely on locally available meso-zooplankton prey to feed their chicks during the short breeding season.

The goal of this component of the seabird project is to first, analyze the diets of zooplanktivorous auklets nesting on St. Lawrence Island, and second, interpret the dietary data in relation to changing oceanographic conditions in the northern Bering Sea. We hypothesize that the recent oceanographic changes marked by the disappearance of ice from the northern Bering Sea shelf act as environmental drivers that affect auklet prey, thereby impacting breeding planktivorous seabirds. Specifically, we propose that on-shelf advection of prey, driven by spring winds and summer temperatures, affected advection patterns and distribution of water masses and thus availability of auklet prey. Subsequent changes in auklet prey can be determined by shifts in prey composition brought to chicks. To address this hypothesis, we: (1) analyze diet composition of two planktivorous species of auklets from St Lawrence Island during summer 2016-2019; (2) compare our data to historical records from 2000-2004 (Gall et al 2004; Sheffield Guy et al 2009) to examine long-term patterns in auklet feeding habits; (3) analyze interannual changes in wind fields promoting on-shelf advection of prey in spring, and; (4) analyze sea surface temperatures during sampling periods, to describe thermal conditions and to detect potential replacement of water masses in the study area.

Methods

Least and crested auklet chick meals were collected at both the Kitnik and Myaughee colonies east of the village of Savoonga on the St. Lawrence Island in July-August 2016-2019 (Fig.1, Table 1). Adult auklets returning to nests after foraging and carrying chick meals in their throat pouches were captured with mist nets. Chick meals were collected from throat pouches and from rock surfaces, where adults sometimes regurgitated contents of the throat pouch during handling. Regurgitation samples were transferred to individual plastic bags and frozen for later analysis. All auklets were released after collection of their chick meal.

A total of 356 samples were collected with most (73%) collected during 2016 and 2017 (Table 1). In the lab, each diet sample was thawed and poured into a sorting tray for visual inspection. Large samples were sequentially split using a Folsom splitter until the smallest subsample contained 100-200 specimens. All taxa in the smallest subsamples were counted and identified to lowest taxa possible and categorized by developmental stage. Each larger subsample was examined to identify and count the less abundant taxa. Blotted wet weights for undamaged specimens of each taxon and developmental stage were measured to nearest 0.1 mg. Wet weights of damaged specimens were estimated from their lengths using established allometric equations. Zooplankton wet weights obtained during previous research in the Bering Sea (e.g., Coyle and Pinchuk 2002, Pinchuk and Eisner 2017) were applied when prey items were severely damaged.

Auklet diet data were uploaded into a Microsoft Access database. We calculated aggregate percent biomass (APB) represented by each prey taxa to give equal weight to each sampled chick meal (Swanson et al. 1974, Gall et al. 2006, Sheffield Guy et al. 2009). Analyses were performed on transformed data, including abundance of prey, using either log10 (for diet diversity) or fourth root (power of 0.25) (for diet similarity) transformation. Diversity of the diets was assessed with Shannon's index using PRIMER (v7) (Clarke et al. 2014). Since the majority (~90%) of the samples were collected at the Kitnik colony, and no differences in diets between the colonies were detected in previous studies (Gall et al. 2006, Sheffield Guy et al. 2009), we pooled samples across sites for interannual comparisons. Since 2019 only had 3% of the total samples, we presented the data for illustrative purpose only and excluded it from statistical analyses.

To examine potential changes in on-shelf advection patterns, wind fields (10 m above the sea level) were constructed for spring and summer months of 2016-2018 in the northern Bering Sea, using 1 h ERA5 atmospheric reanalysis with 0.25° spatial resolution. The ERA5 reanalysis data were downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) website https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. To analyze thermal conditions during the sampling period we used the NOAA 1/4° daily Optimum Interpolation Sea Surface Temperature (or daily OISST), obtained from https://www.ncdc.noaa.gov/oisst.

We analyzed the 4-year time series of chick diet samples from least and crested auklets from the northern shore of St. Lawrence Island during July-August of 2016 – 2019. We compared the taxonomic composition, abundance, and biomass of zooplankton prey with those in the 5-year time-series collected at the same location during 2000-2004 (Figure 1). The observation period included sequences of cold (2000-2004) and warm (2016-2019) years, the 2016-2017 heat wave, and the period of record low winter sea ice coverage in the Bering Sea (2018-2019), allowing examination of contrasting scenarios in auklet foraging habits under changing environmental conditions.

Results

We found substantial differences in prey diversity and composition between auklet species and across years (Fig. 2). Crested auklet diets almost entirely consisted of large (>10 mm) juvenile euphausiids *Thysanoessa raschii* and *Thysanoessa inermis*, equally represented in 2017-2019 samples. In contrast, 2016 samples lacked euphausiids, but consisted of a diverse diet which included small fish (presumably flatfish), hyperiids *Temisto pacifica* and *T. libellula*, copepods *Neocalanus flemingeri* and *N. cristatus*, and a variety of decapod larvae (Paguridae, Caridea, and Brachyura). A similar dietary shift occurred in least auklets which consumed large juvenile *Thysanoessa* spp. almost exclusively in 2017-2019, while in 2016 their diets comprised mainly large calanoid copepods *Neocalanus* spp (Fig. 2).

The diversity of the diets in both auklet species significantly decreased compared to the 2000-2004 study (Figure 3). In least auklets, diet diversity was initially high in 2000-2001, but plummeted in 2002 and remained low throughout the remaining years of observation (Figure 3A). In crested auklets, diet diversity continuously decreased from 2000 through 2019, with a single spike in diversity in 2016 (Figure 3B). The decrease in diversity was due to apparent lack of copepod and hyperiid prey in the diets of both species, which was especially noticeable in 2017-2019 (Fig. 2).

Discussion

Our results confirm the importance of copepods and euphausiids in the diet of auklets in the northern Bering Sea. As with the earlier 2000–2004 studies, we saw differences between auklet species and among years (Fig. 2). However, during 2016–2019, we found more overlap in diet between species and among years compared to earlier years, particularly during the warmer 2017–2019 seasons. In 2016, auklet diet was more similar in species composition to the earlier years than it was to the latter three years. The shift in auklet diet composition from mesoplankton (e.g., copepods and hyperiids) to micronekton (euphausiids) between 2000–2004/2016 and 2017–2019, coincided with changes in oceanographic conditions, which may have affected larger-bodied zooplankton in the study area.

The oceanographic circulation in the northwestern Bering Sea is defined by the Bering Slope Current flowing from the southeast. In vicinity of underwater Navarin canyon, this flow forks with one branch flowing westward and then southwestward following the continental slope, while the other branch (Navarin Current) enters the shelf and flows toward the Bering Strait crossing the Gulf of Anadyr and bringing so called Anadyr Water to St Lawrence Island (Basyuk and Zuenko, 2020). Before 2017, sea ice extent in the northern Bering Sea in mid-March reached 60° N, while in 2017 and 2018 in the northwestern Bering Sea (south of Cape Olyutorsky and north of Cape Navarin) it receded to ~65° N (Baker et al. 2020). The retreat of sea ice resulted in substantial redistribution of water properties, which considerably weakened the Navarin Current in the fall of 2018, such that the northward water transport originated from the eastern Bering Sea shelf instead of deep Aleutian Basin and Vityaz Sea Valley, and comprised mainly the Alaskan Coastal Water (Basyuk and Zuenko, 2020).

We hypothesized that the change in zooplankton prey used by auklets was also influenced by changes in local advection patterns preventing transport of oceanic *Neocalanus* copepods onto the shelf near St. Lawrence Island. *Neocalanus* copepods undergo ontogenetic seasonal migration when later stage V copepodites descend from the subsurface layer to 400-600 m depth in early summer where they mature and enter dormancy until their spawning in late winter (Tsuda et al. 1999; Tsuda et al. 2004). Young copepodites appear in the subsurface layer in early spring where they quickly develop and grow taking advantage of seasonal phytoplankton and microzooplankton blooms (Kobari and Ikeda, 2001a, 2001b). During this time, they are advected onto the shelf where they become a preferred prey for many zooplanktivores. While deep Pacific water from the Aleutian Basin enters the southeastern shelf via Bering, Pribilof, and Zhemchug canyons, carrying oceanic zooplankton into the shallow water areas, it takes from 1 to 3 years for the water parcels to reach the Bering Strait area (Panteleev et al. 2016). Therefore, the majority of *Neocalanus* that reaches St. Lawrence Island enter the northern Bering Sea shelf via the on-shelf flow through the Navarin Canyon (Gibson et al. 2013, Zimmermann et al. 2018). Thus, a steady on-shelf flow in the northwestern Bering Sea (Navarin Current) during early spring appears a prerequisite for an abundant *Neocalanus* population near St Lawrence Island during auklet chick feeding season in late summer.

Our retrospective analysis of mean monthly wind speed and direction for the northern Bering Sea (60-66° N) for the spring and early summer months (March – July) indicated that in March and April, strong northeasterly winds persisted over the area in most years except for 2002 and 2003, when the wind shifted to the west (Fig. 4). Until recently, the northern Bering Sea has been covered with ice during early spring (Stabeno et al. 2012, Baker et al. 2020), and northerly winds might not have been able to produce enough wind stress to slow down or reverse on-shelf transport via Navarin Current. However, once the ice cover disappeared in 2017, the strong spring winds appeared to be extremely unfavorable for northward transport of subsurface water (Fig. 5), which may have resulted in lower numbers of *Neocalanus* copepodites reaching St. Lawrence Island in July, when auklets start feeding chicks.

Contrary to this hypothesis, observations conducted in the northern Bering Sea in 2017-2018 revealed that substantial numbers of *Neocalanus* were present in June-July 2017 southwest and north of St. Lawrence

Island (Kimura et al. 2020; Hopcroft pers. communication). One possible reason for the discrepancy between the lack of *Neocalanus* in auklet diets and their abundance in zooplankton surveys is that the sampling stations were located well outside of the auklet foraging range from the colony (~50 km, Obst et al 1995), thus birds may have been foraging where there were few *Neocalanus*.

An alternative explanation may be that the weakening of the Navarin Current and prevalence of southeasterly winds led to replacement of oceanic Anadyr Water, near St Lawrence Island, with Alaskan Coastal Water and Bering Sea Water from the eastern Bering Sea shelf. Both water masses are formed in the southeastern Bering Sea and transported northward with sluggish tidal driven flow (Stabeno et al 2001). Since the eastern Bering Sea shelf large zooplankton taxa are numerically dominated by *Calanus glacialis* copepods and euphausiids *Thysanoesa raschii* and *T. inermis* (Coyle et al 2008, Pinchuk & Coyle 2008, Bi et al 2015), such a replacement could result in disappearance of *Neocalanus* in auklet diets. While comparison of wind fields and surface sea temperatures indicate such a possibility (Fig. 6), the lack of local in situ oceanographic observations directly within the actual auklet forage range (vertical CTD profiles in particular) preclude a definitive answer.

There are two other potential reasons for the observed dietary shift by auklets. First, a major biological change was the expansion of large, predatory southern fish species into the northern Bering Sea starting in 2017. For instance, Pacific Cod and Walleye Pollock became prominent and could have competed with planktivorous seabirds for Neocalanus copepods (Spies et al 2019, Eisner et al 2020). In addition, while no observational data is available on productivity of the overwintering source *Neocalanus* populations in the Bering Sea Basin, it might have decreased due to the North Pacific heat wave effects.

The general decline in diversity of auklet diet since 2000 may reflect changes in the zooplankton community, but might also be an artifact of sampling size, since sample sizes can affect estimates of species richness. Nonetheless, the abrupt change in auklet diet during 2017–2019, when both auklet species consumed primarily euphausiids, coincided with the warmest ocean temperatures recorded for the region. Simultaneously, auklet distribution during 2017-2019 shifted in late summer from the Chukchi Sea to the northern Bering Sea (Kuletz et al. 2020). During the previous decade, *Aethia* auklets tended to move into the Chukchi Sea post-breeding (Kuletz et al. 2015), but during the three warm years more of them remained near breeding sites in the Chirikov Basin, and many did not attempt to breed or were unsuccessful (Will et al. 2020). During 2017-2019, least auklets were less abundant in the Chukchi Sea, whereas the crested auklet population split into two factions, with one moving into the far northern Chukchi Sea and the other remaining in the Chirikov Basin (Kuletz et al. 2020).

When comparing reproductive success and stress levels for auklets nesting on St. Lawrence Island during 2016-2019, Will et al. (2020) found that both species experienced severe nutritional stress (measured by blood and stable isotope analysis) in 2018. The lowest stress levels in birds were recorded in 2016, when auklet diets were more diverse and comprised of more copepods (this study). Both auklet species also demonstrated colony-wide reproductive failure in 2018 and 2019 (Will et al. 2020). Thus, the dietary shift we demonstrated during 2017-2019 may have been indicative of lack of suitable prey for raising chicks, particularly for the smaller bodied least auklet, which typically feeds almost entirely on copepod species. The shift in diet to euphausiids (and absence of copepods), together with reproductive failures and changes in at-sea distribution, suggest that planktivorous auklets are struggling with adapting to rapidly changing ocean and prey conditions.

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Table 1. Number of the processed auklet diet samples by year for least auklets (LEAU) and crested auklets (CRAU).

	2016		2017		2018		2019	
Date	LEAU	CRAU	LEAU	CRAU	LEAU	CRAU	LEAU	CRAU
July 23								3
July 26					1			2
July 28			1					
July 29					1	1		
July 30			7		2		1	
July 31			6	1			1	
August 01	1		1			1		1
August 02	4	1	1		1	1		
August 03	1			1	6	2		
August 04	1	2	6	6	2	2		
August 05	12		7	2	32	7		
August 06	17		2	1				
August 07					11	1		1
August 08					6			
August 09			19	1			1	1
August 10	8	1	12	4				
August 11	6	1				1		
August 12	2							
August 15			2					
August 16			7	12	3			
August 17			1	1				
August 18	11	1			1			
August 20	11	5	22	2		1		
August 22			1	2				
August 23	19	4						
August 24	17	5						
August 27	1	2						
August 28							1	
TOTAL	**111**	**22**	**95**	**33**	**66**	**17**	**4**	**8**

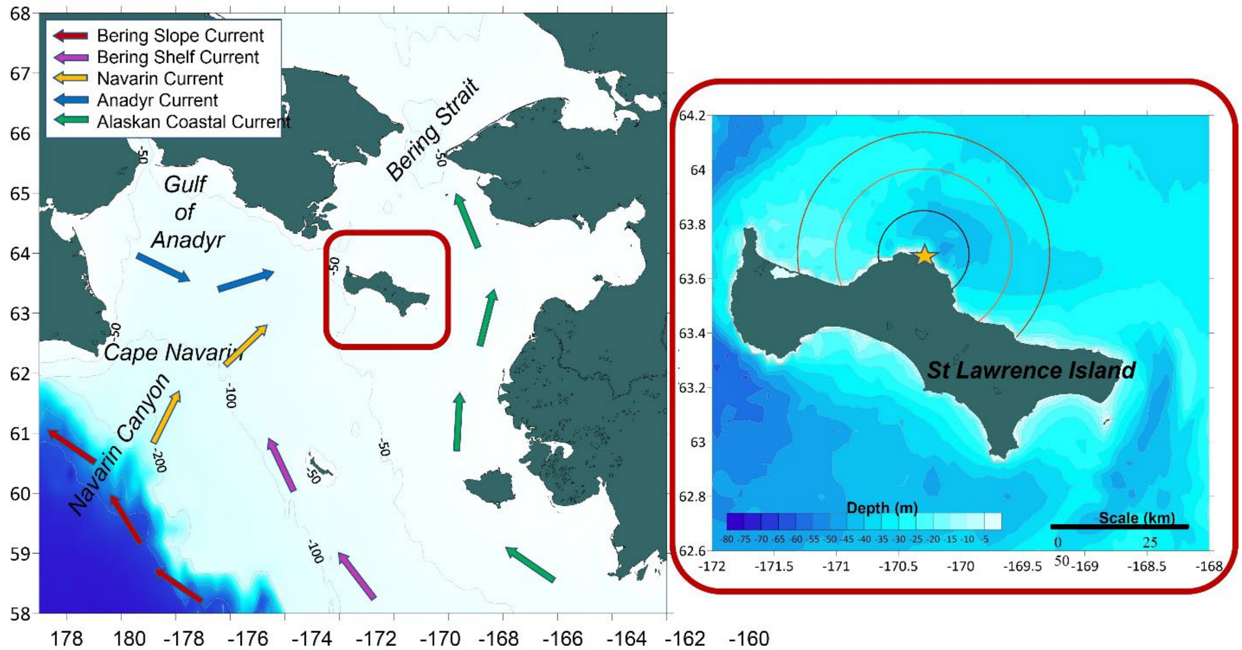

Figure 1. Map of St. Lawrence Island, showing the study colony (star) and prevailing currents (from Basyk and Zuenko 2020, modified), and auklet maximal feeding ranges during incubation (outer ring) and chick-rearing (inner rings) periods. Feeding ranges data obtained from GPS loggered crested auklets (A. Kitaysky, pers. comm.).

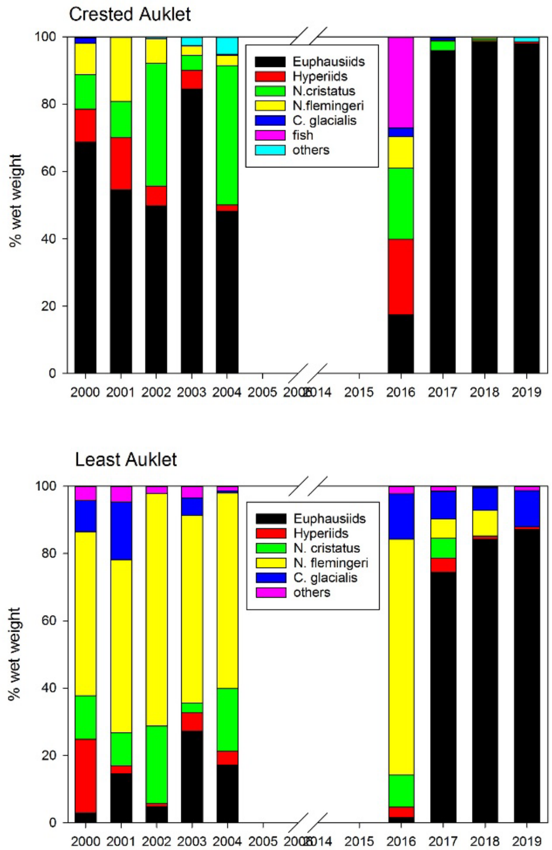

Figure 2. Taxonomic composition of crested and least auklet chick meals in 2000–2004 (from Sheffield Guy et al 2006) and in 2016–2019 (this study).

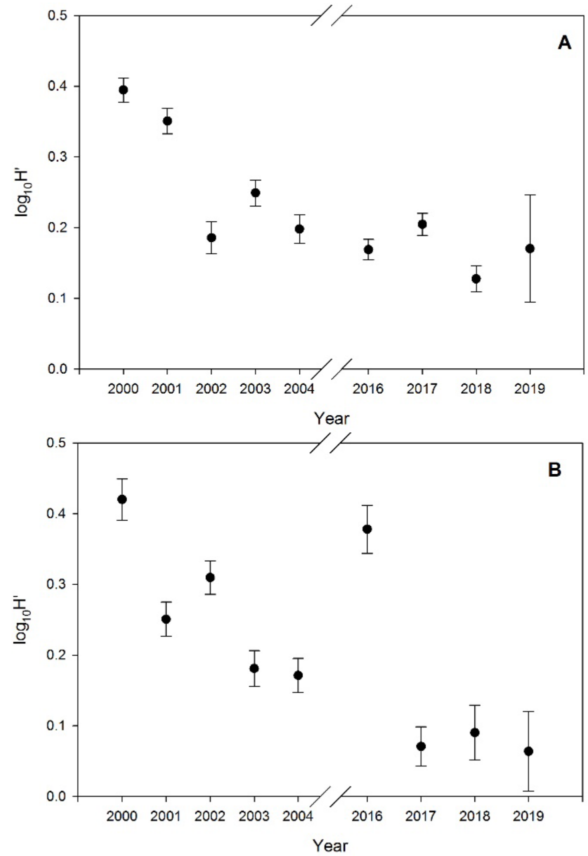

Figure 3. Interannual changes in the mean diversity of least auklet (A) and crested auklet (B) chick diets, as measured with Shannon's diversity index. Vertical bars are standard deviation.

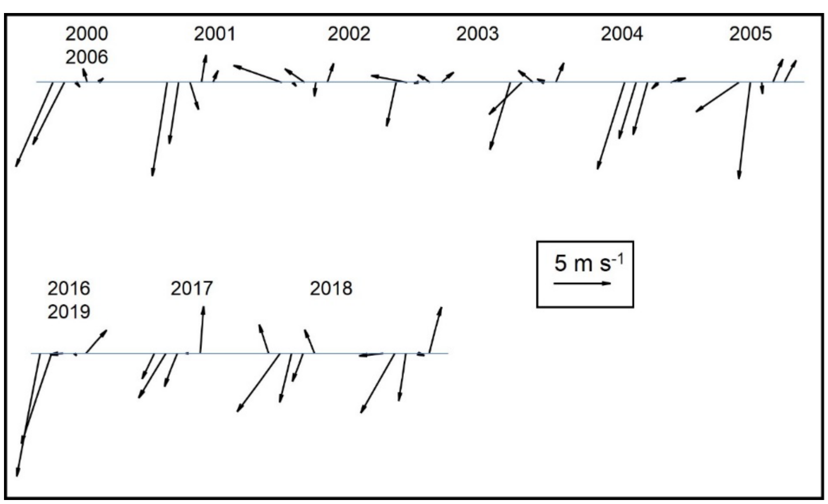

Figure 4. Monthly (March–July) mean wind vectors in the northern Bering Sea (60-66° N) during years of this study. Wind data is from the European Centre for Medium-Range Weather Forecasts (ECMWF) website (https://www. ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5).

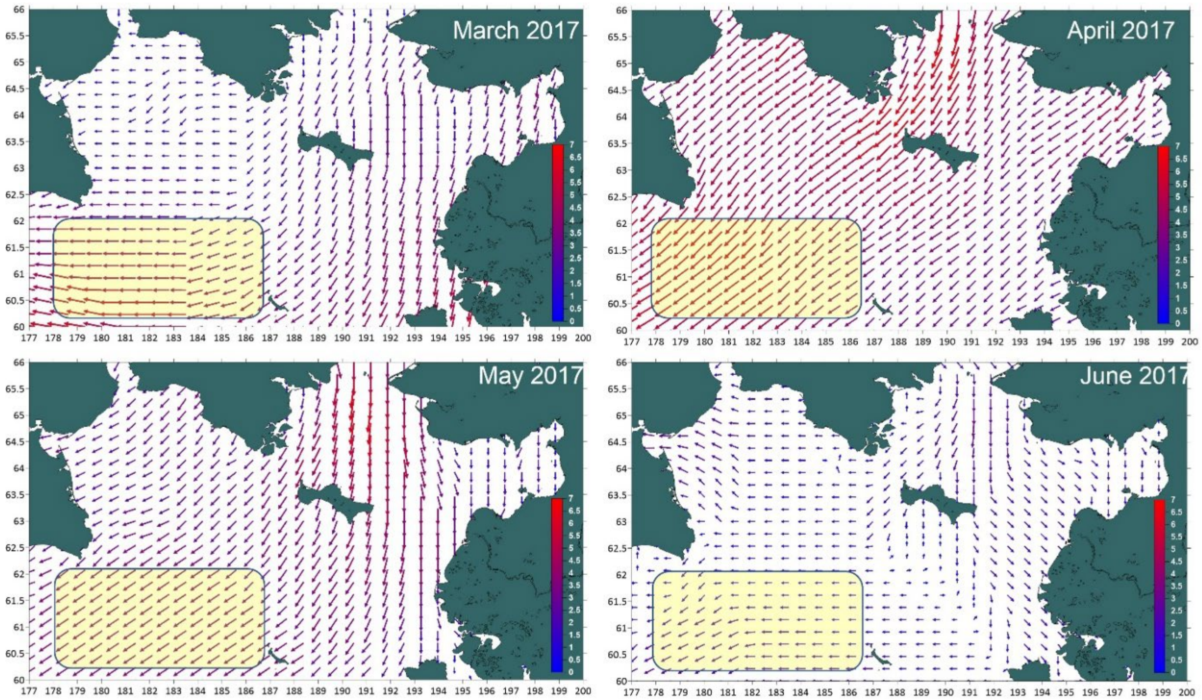

Figure 5. Monthly mean winds in the northern Bering Sea in spring and early summer 2017. Yellow polygon is the area of advection of the deep water onto the shelf.

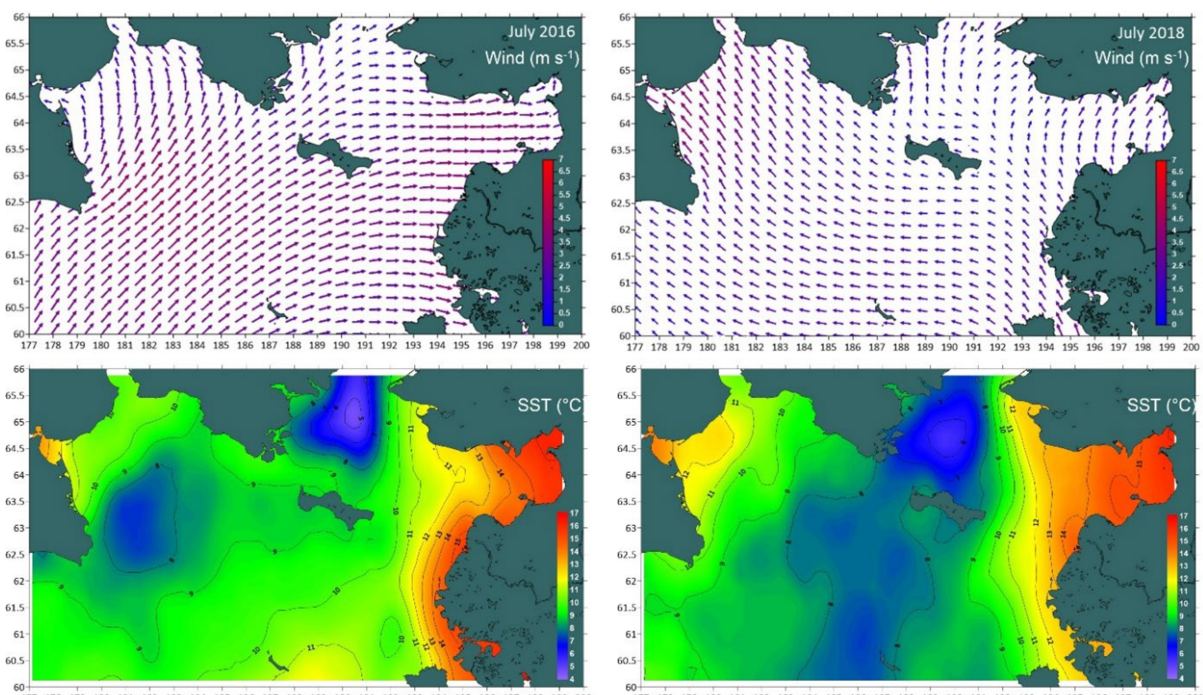

Figure 6. Monthly mean wind (top row) and surface sea temperatures (bottom row) in July 2016 (left column) and 2018 (right column), indicating potential advection of Alaskan Coastal Water into the vicinity of St. Lawrence Island.

Appendix 5: Kuletz et al. manuscript: Changes in distribution.

Distributional shifts among seabird communities of the Northern Bering and Chukchi seas in response to ocean warming during 2017–2019

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ABSTRACT

In the northern Bering Sea and eastern Chukchi Sea, 2017-2019 were record-breaking years for warm ocean temperatures and lack of sea ice. The region supports millions of seabirds that could be affected by shifts in prey distribution and availability caused by changing environmental drivers. However, seabirds are highly mobile and often flexible in diet, and might alter their foraging distributions accordingly. To determine if there was evidence of long-term changes in abundance of seabirds, or if seabirds used the offshore habitat differently during recent warm years, we compared species richness, community composition, and distribution and abundance of selected species and Total seabirds (all species combined) between two periods, 2007–2016 and 2017–2019. We also evaluated annual changes in abundance during 2007–2019. We used 79,426 km of transects from vessel-based surveys conducted July through September. Total seabird density for the entire study area increased by ~20% during 2017-2019, but changes were not consistent across the study area, nor among species, and species richness declined except for a slight increase in the northern Chukchi Sea. Total seabird density declined most in the northern Bering Sea (-27%), although it increased in the Chirikov Basin by 73%. During 2017–2019, abundance of piscivorous murres (*Uria* spp.) decreased everywhere, whereas planktivorous Aethia auklet density increased by 70% in Chirikov Basin; auklets apparently abandoned their post-breeding migration to the Chukchi Sea. Short-tailed shearwaters (*Ardenna tenuirostris*) expanded farther into the northern Chukchi Sea, with nearly twice the density of the previous decade. We identified five seabird community types, three of which (all dominated by an alcid species) contracted spatially in the later period, and shifted south or near colonies. In contrast, a short-tailed shearwater dominated community expanded northward, and a community defined by low seabird density expanded throughout the eastern portion of both the northern Bering and Chukchi seas, suggesting higher-density communities had shifted westward. The variable responses among species correspond to documented changes in the environment as well as their natural history.

1. Introduction

The Bering and Chukchi seas have been undergoing warming events and subsequent alteration of biological ecosystem components over the last 20 years (Grebmeier et al., 2006; Stabeno and Bell, 2019). However, events during 2017–2019 appear to have been distinctively disruptive of long term physical and biological patterns. Sea ice plays a critical role in primary productivity of these marine ecosystems. The formation of ice algae feeds phytoplankton blooms as the ice retreats (Brown and Arrigo, 2013), supporting zooplankton production (Campbell et al., 2016; Stabeno et al., 2010), and ultimately upper trophic levels. Early ice retreat, or lack of sea-ice formation, impacts these mechanisms with repercussions throughout the food web (Hunt et al., 2011). In the northern Bering Sea, warm conditions lead to early ice retreat, resulting in early and high primary productivity, particularly near the ice edge (Brown et al., 2011; Brown and Arrigo, 2013).

During 2017, sea ice formed over the eastern Bering Sea shelf, but there was an unusual and early retraction of ice over the northwestern Bering Shelf, attributed to persistent southerly winds. As a result, the northern Bering Sea was characterized by ice conditions similar to those of a 'warm' year, despite ice coverage farther south (Siddon and Zador, 2018). In 2018 and again in 2019, ocean temperatures were above normal in winter, and ice extent in the Bering Sea was the lowest recorded in four decades. In both years, sea ice retreated north of Bering Strait before spring (Siddon and Zador, 2018, 2019; Cornwall, 2019). The extremely low ice cover during 2017–2019 in the northern Bering Sea and Chukchi Sea resulted in altered oceanographic and biological conditions; these were most evident in 2018, and included impacts to lower and upper trophic levels (Duffy-Anderson et al., 2019).

Seabirds are indicators of ocean conditions (Murphy, 1936; Piatt et al., 2007 and references therein; Velarde et al., 2019). By understanding responses of seabirds to broad-scale ecological shifts we may better predict impacts to upper trophic-level taxa in a rapidly changing environment. In the Bering Sea, recent responses of seabirds to ocean warming have included mass mortality (Jones et al., 2019), failed nesting attempts and low reproductive success (Dragoo et al., 2020; Romano et al., this issue). Since 2015, seabird mass mortality events have occurred almost annually in the Bering Strait region (Duffy-Anderson et al., 2019). Species-specific mortality events and seabird reproductive success at monitored colonies can be indicative of food web changes (Abraham and Sydeman, 2004; Jones et al. 2019; Piatt et al., 2020). However, these metrics do not necessarily provide insight into how the broader seabird community has responded to an altered ecosystem.

Seabirds are long-lived, with adaptations to buffer variability in their environment. Forgoing a breeding season or undergoing a few years of low breeding success may not necessarily lead to substantial population-level repercussions (Cairns, 1992; Velarde and Ezcurra, 2018). Seabirds are also highly mobile, and can search for prey over a large area, particularly when not attending a colony. Further, seabirds spend most of their lives at sea, and their temporal and spatial distribution across the seascape often reflects the productivity and foraging conditions of large marine areas (Ballance et al., 1997; Gall et al. 2013; Suryan et al., 2012; Yen et al., 2006). Here, we examine broad-scale responses of seabirds to a warm period (2017–2019) in the Northern Bering and Chukchi Sea Large Marine Ecosystem (LME) relative to the preceding decade (2007–2016). Specifically, we use vessel-based surveys to assess how seabirds differed in species-specific and community-level abundance and distribution between these two time periods.

2. Methods

2.1. Study area

Our study area encompassed offshore waters of two regions, the northern Bering Sea (hereafter, Bering Sea) and eastern Chukchi Sea (hereafter, Chukchi Sea) (Fig. 1), and we considered southern and northern subregions within each region. We refer to the subregions (Fig. 2) as the Northern Bering (59.5°N to St. Lawrence Island; distinct from the general northern Bering Sea), the Chirikov Basin (St. Lawrence Island to Bering Strait at ~65.8°N, including Little Diomede Island), the Southern Chukchi (Bering Strait to 70°N) and Northern Chukchi (70°N to 72.5°N). The western boundary of all regions followed the U.S. Exclusive

Economic Zone to 175°W and the eastern boundary followed an offshore buffer bordering coastal Alaska, to include only waters where our surveys occurred in most years (Fig. 2).

The northern Bering Sea is hydrographically and biologically distinct from the southern Bering Sea, separated at approximately 60°N (Stabeno et al., 2010; Sigler et al., 2011, 2017). The shallow continental shelf of the northern Bering Sea includes the Inner Shelf domain (<50 m deep) and Middle Shelf domain (50-100 m deep), with some influence from the more dynamic Outer Shelf and slope domains, which are beyond our study area. The Inner Shelf is bordered by the Alaska Coastal Current on the east side and the more saline, colder and nutrient rich waters of the Anadyr Current in the west (Fig. 1). Both of these water masses pass through Bering Strait and, as Bering Sea Water, facilitate structure of the Chukchi Sea. The Chukchi Sea is also structured by the Siberian Current, which flows eastward along the northern coast of Russia. The Chukchi Sea, particularly in the north, is also heavily influenced by fresh, cold winter water, derived from sea-ice melt (Coachman et al., 1975; Weingartner et al., 2005, 2013). North of Bering Strait, the Bering Sea waters split and branch westward and eastward, encircling the bathymetrically complex, shallow, and nutrient rich Hanna Shoal in the northern Chukchi Sea (Coachman et al., 1975; Dunton et al., 2017; Fig. 1).

Sea-ice is a primary driver of both Bering and Chukchi ecosystems. The extent of ice coverage and the timing of ice retreat in the spring drives annual primary productivity by affecting sea surface temperatures and light availability for photosynthesis, and by providing a platform for epontic algal growth (Arrigo, 2003). Ultimately, the effects of spring conditions cascade to lower and upper trophic levels (Stabeno et al., 2010; Hunt et al., 2011, 2018). Sea ice generally retreats north of Bering Strait throughout late spring and summer, with the ice minimum occurring between September and October. However, ice extent and duration was minimal overall during 2017–2019 (Siddon and Zador, 2018, 2019).

The study area includes large seabird colonies (Stephensen et al., 2003) with an estimated 12 million birds nesting in the Northern Bering and Southern Chukchi subregions (USFWS, 2014). The largest colonies are on St. Matthew and St. Lawrence islands in the Northern Bering, the two Diomede islands in the Bering Strait, and Cape Thompson and Cape Lisburne in the Southern Chukchi (Fig. 1). In late summer and early fall this LME is also used by equal numbers of migratory birds (Kuletz et al., 2015, 2019), particularly short-tailed shearwaters (*Ardenna tenuirostris*), which nest in the southern hemisphere. Other seasonal visitors that nest south of the study area include members of the Alcidae and Laridae families, as well as waterfowl (Anatidae), phalaropes (Scolopacidae), and loons (Gaviidae), which pass through from Alaska's North Slope after breeding.

2.2. Data collection

At-sea distribution and abundance of seabirds were obtained from surveys conducted from research vessels using U.S. Fish and Wildlife Service protocols (Kuletz et al., 2008). A single observer recorded all birds on one side of the vessel, within 300 m and a 90° arc from the centerline of travel. The observer recorded species, number of individuals, and behavior (on water, on ice, foraging, in air) and perpendicular distance from the centerline (using distance bins). Birds were identified to the lowest taxonomic level possible, using 10x binoculars, and sometimes a digital camera, to assist with species identification. Birds on water or actively foraging were recorded continuously, whereas birds in the air (not actively foraging by touching the water surface) were recorded during quick scans within the transect window, at approximately $1 \cdot min^{-1}$ (varying with respect to vessel speed), and avoiding double counting. Surveys were conducted with seas of Beaufort scale $\leq$ 6 and were discontinued when dense fog or precipitation impeded visibility. Observations were entered into a laptop computer connected to a Global Positioning System (GPS), using software DLog3 (R.G. Ford, Portland, OR). Every record entry was stamped with time, latitude and longitude, and environmental conditions, and automatically updated at 20 sec intervals to record effort. We divided survey transect lines into ~3 km segments, with the segment centroid serving as sample location, and calculated density of birds ($birds \cdot km^{-2}$) for each transect segment. Transect widths were narrowed from 300 m to 200 m or based on observation conditions.

2.3. Data treatment and analysis

Survey effort (Table 1, Fig. 2) within the study area during 2007–2019 totaled 79,426 km, using only surveys conducted 1 July to 30 September; these months reflect peak breeding season for seabirds in the study area, and omit June, when we had little survey effort. We compared species richness, community composition, and abundance of key species within the subregions between two time periods, 2007–2016 and 2017–2019. The latter years were characterized by anomalously low sea-ice coverage in the study region, with the warmest year (2018) exhibiting the highest record of seabird mortalities and reproductive failure (Duffy-Anderson et al., 2019; Romano et al., this issue). We also examined annual differences in abundance of key species and Total seabirds (all species combined, including phalaropes and seaducks but excluding other shorebirds, waterfowl, land birds, and birds of prey; Appendix A).

2.3.1. Species richness

Because sampling effort was not consistent among the four subregions and two time periods, we used rarefaction curves to examine species richness during each time period and within each subregion. We randomly resampled 3-km segments (without replacement) and generated plots of number of species observed vs. number of segments sampled, with 95% confidence intervals calculated using quantiles from 2000 random draws for each sample size. During surveys, it was not always possible to identify sightings to the species level, for example due to a brief or inadequate view. In the rarefaction analysis, a higher-order taxon was counted as a unique species if and only if a corresponding lower-order taxon was not present in the sample. For example, an unidentified murre (*Uria* spp.) would be counted as a species if and only if no common murres (*U. aalge*) or thick-billed murres (*U. lomvia*) occurred in a sample.

For the remaining analyses, we applied a 30-km hexagonal cell grid to the study area, and derived density of each species by cell using the mean of 3-km segments within each cell. Birds that had not been identified to species were apportioned from higher-order taxa to species based on the ratio of identified birds within a cell and year. If there were no identified species within a higher-order taxon in a given cell and year (ranging from 0-7% of cells, with an average of 1%, depending on taxon), unidentified birds were prorated to species based on spatial interpolation of species ratios derived from kriging surrounding cells; kriging applied a cutoff distance of 60 km (~ 2 grid cells).

The number of sampled cells within a subregion varied among years, ranging from 98 to 371 cells for a given year. Because spatial differences in sampling among years could bias comparisons, we imputed species densities for grid cells missing years using methods described in Renner et al. (2013) and Kuletz et al. (2014). Species densities of grid cells not surveyed in a given year were interpolated through time (not space). Within each grid cell, densities in any missing years were imputed using linear interpolation. Any missing values at the beginning or end of the time-series were imputed by replacing missing values with the closest neighbor in time (rather than projecting trends).

2.3.2. Abundance and distribution

During preliminary analyses, we examined the distribution and abundance of four foraging guilds (surface planktivore, diving planktivore, surface piscivore, diving piscivore) along with individual species. Because the foraging guild patterns were largely driven by the most abundant species within each guild, here we present results for Total seabirds and seven focal species: thick-billed murre, common murre, crested auklet (*Aethia cristatella*), least auklet (*A. pusilla*), northern fulmar (*Fulmarus glacialis*), black-legged kittiwake (*Rissa tridactyla*), and short-tailed shearwater. We selected these focal species because they were widespread in the study area (Appendix B) and relatively abundant during all years (Appendix A). Five of them were the predominate species for seabird communities identified in this LME during 2007-2015 (Kuletz et al., 2019).

We used two methods to evaluate distribution and abundance of these species and groups. First, we calculated annual density estimates for species or species groups from the cell means within a subregion and year. The grid cell means for each species were used to plot standardized mean anomalies for each subregion and time period (2007–2016 and 2017–2019). Near the coastline, some cells were truncated, thus we used weighted averages based on the area of each hexagon cell; this avoided over-representation in the overall average due to the presence of large flocks in small cells. Second, we examined the spatial distribution of increases or decreases in seabird densities (by species) by subtracting mean densities (by cell) for 2007–2016 from mean densities for 2017–2019, and mapping these differences.

2.3.3. Community composition

To identify seabird communities in the study area and compare their distribution between the two time periods, we used K-Means Cluster analysis (Hartigan and Wong, 1979). In the first step, we grouped the 30-km hexagon grid cells based on similarity in densities of birds, using log-transformed densities. Clustering was based on species densities, not geographic coordinates, and performed on all years combined, 2007–2019. Five communities were identified in the study area, based on the inflection point of within-group sum of squares vs. the number of clusters (Hartigan and Wong, 1979). In the second step, the clusters were then redistributed to their respective time-period maps (2007–2016 or 2017–2019).

We used R functions and scripts for analyses (R Core Team, 2015), with kriging for species' ratios applying function *krige* in package gstat (Pebesma, 2004). Cluster analysis used the R function *kmeans* (Hartigan and Wong, 1979).

3. Results

3.1. Species richness

Estimated species richness was higher in the Bering Sea (~40 species) than in the Chukchi Sea (~30 species) during both time periods. Within the two Bering subregions, species richness was slightly lower during 2017–2019, whereas it remained similar overall in the two Chukchi subregions (Fig. 3). However, in both the Bering and Chukchi regions, there was a reversal in richness between subregions; i.e. during the later period the Chirikov Basin had slightly higher species richness than the Northern Bering, and the Northern Chukchi had higher richness than the Southern Chukchi (Fig. 3).

3.2. Spatial changes in density

Compared to 2007–2016, Total seabird density was higher in 2017–2019 (Table 2), but the direction of changes in density were not equal across the study area, nor among species. Mean densities indicated both murre species declined in the later period, whereas both auklet species and black-legged kittiwakes increased slightly, and short-tailed shearwaters nearly doubled in density (Table 2). During the later time period, Total seabird density increased along the Anadyr Current, and in the northern Hope Basin, the western portion of the Northern Chukchi, and over Barrow Canyon (Fig. 4a). Decreases occurred in most of the Northern Bering, but also in the eastern Chirikov Basin to southern Hope Basin and the eastern coastal waters of the Northern Chukchi. This pattern largely reflects that of short-tailed shearwaters, a numerically dominate species, although shearwaters also showed large increases in 2017–2019 northwest of Cape Lisburne and over the Hanna Shoal and Barrow Canyon areas (Fig. 4b). Northern fulmars did not have a clear pattern of spatial change, with both increases and decreases scattered throughout the study area and large areas with no change (Fig. 4c). Black-legged kittiwakes also showed little evidence of a clear pattern, although there were more increases in Hope Basin and northwest of Cape Lisburne (Fig. 4d).

Common murres showed few increases in abundance, with those mainly in the Northern Bering, and they otherwise decreased, particularly in the Southern Chukchi (Fig. 4e). Thick-billed murres increased in later years northwest of Cape Lisburne, but primarily decreased throughout the study area, including near the St. Matthew colony (Fig. 4f). Least auklets had large increases in the Chirikov Basin, but mainly decreased throughout the Chukchi Sea (Fig. 4g). Crested auklets increased near the Anadyr Current in the Chirikov Basin and in the northern edge of the Northern Chukchi, but declined in other areas of the Northern and Southern Chukchi (Fig. 4h).

3.3. Annual trends in abundance

For Total seabirds, the annual trends in abundance indicated a general northward shift in distribution. This shift began around 2014 in the Bering Sea, 2015 in the Southern Chukchi, and 2016 in the Northern Chukchi, although relative abundance was below the long-term mean in 2019 for all but the Northern Chukchi (Fig. 5a). In contrast, abundance in the Northern Bering was below the long-term mean for most years after 2013. This general pattern reflected the influence of the most abundant avian species in the study area, the short-tailed shearwater, the least auklet, and the crested auklet (Table 2). Short-tailed shearwaters differed from Total seabirds in having extremely high abundance in the Chirikov Basin and the Southern Chukchi in 2015 (Fig. 5b). Trends of northern fulmars were mixed, with fluctuations between subregions of the Bering and in the Southern Chukchi, but generally lower use of the Northern Chukchi after 2010 (Fig. 5c). Abundance of black-legged kittiwakes shifted from the Northern Bering during 2007-2011 to the Chirikov Basin during 2012-2015, and to the Chukchi subregions from 2014-2019 (Fig. 5d).

In general, the diving alcids declined in recent years in the Chukchi, with the *Aethia* auklets increasing in the Chirikov Basin and Northern Bering, and the murres mostly decreasing throughout the study area after 2013. Starting in 2014 both common murres (Fig. 5e) and thick-billed murres (Fig. 5f) showed steadily declining trends in the Northern Bering and below average abundance (common murre) or very low abundance (thick-billed murre) in the Chirikov Basin. Abundances of both murre species were below the long term mean in the Chukchi subregions for most years after 2013. In contrast, least auklets, which were highly abundant in the Chukchi during 2010 to 2012, increased abruptly in the Chirikov Basin and Northern Bering during 2017–2019 (Fig. 5g). Crested auklets showed a similar pattern, although they were sporadically abundant in the Northern Chukchi and did not substantially increase in the Chirikov Basin until 2018 (Fig. 5h).

3.4. Seabird communities

Within our study area we identified five clusters of grid cells that differed from each other in seabird community composition and densities (Appendix C). Four of the clusters had the same primary species as the community types identified by Kuletz et al. (2019); these clusters were dominated by thick-billed murres, least auklets, crested auklets, and short-tailed shearwaters, plus a ‘Low Density’ cluster type defined by low total densities and no definitive predominant species (no species had a mean density of >0.54 birds$\cdot$km^{-2}). A sixth community type identified by Kuletz et al. (2019), dominated by northern fulmars, was not distinguished in this new analysis, reflecting the omission of more southerly waters of the outer Bering Sea shelf that were part of the previous study.

The distribution maps for the five community clusters in each time period depicted a spatial contraction of the thick-billed murre, crested auklet, and least auklet-dominated clusters during 2017–2019 (Fig. 6). During the late period the thick-billed murre cluster was less extensive throughout the study area and was located primarily near St Matthew Island in the Northern Bering and the Cape Thompson and Cape Lisburne colonies in the Southern Chukchi. The crested auklet cluster covered a much smaller area and was concentrated in the northeastern portion of its previous range in the Chukchi Sea, although there were also isolated, scattered cells between Chirikov Basin and Hope Basin (Fig. 6). The least auklet cluster also covered less area in 2017–2019, and was found primarily south of Bering Strait, abandoning its earlier occupation of Hope Basin.

In contrast to the three alcid-dominated clusters, the short-tailed shearwater-dominated cluster expanded during 2017–2019, and was located primarily in the Chukchi Sea. Its increase was greatest in Hope Basin and contiguously along the western edge of the study area and in a band from Hanna Shoal to Wainwright and Point Barrow – the Barrow Canyon area (Fig. 6). The Low-Density cluster also expanded in the later period. During 2017–2019, this cluster covered more area (compared to 2007–2016) throughout the Bering Sea shelf, particularly in the Northern Bering subregion. Its distribution in the Southern Chukchi did not change much between time- periods, but in the eastern half of the Northern Chukchi, it greatly expanded during 2017–2019 (Fig. 6).

4. Discussion

During the exceptionally warm, low-ice years of 2017–2019, we found evidence of broad-scale shifts in distribution of individual species and of identified seabird communities compared to the previous decade. Sea-ice extent in the northern portion of the Bering Sea was the lowest on record during the late period of our study. In 2017, sea ice failed to form over the northwestern Bering Shelf due to atypical southerly wind patterns. Unprecedented open water predominated throughout the Northern Bering and Southern Chukchi subregions in 2018 and 2019 as well (Siddon and Zador, 2018, 2019). Nonetheless, density of Total seabirds increased approximately 20% during this period, with the increase largely due to short-tailed shearwaters in the Chukchi Sea, and least and crested auklets in the Chirikov Basin.

Short-tailed shearwaters breed on islands off Australia's southern coast during the austral summer. After breeding they migrate to Alaska for the boreal summer, and reach the northernmost extent of their migrations in the Chukchi Sea. Untethered from nesting colonies during their non-breeding season, shearwaters can readily respond to shifts in prey distribution. In contrast, the two species of auklet nest during summer in dense colonies on islands in the Chirikov Basin and Northern Bering, although some auklets in the offshore waters could have originated from colonies in the Aleutian Archipelago (Will et al., 2017) or the Siberian coast (USFWS, 2014). What all three species have in common is a diet primarily composed of zooplankton. The short-tailed shearwater is considered an omnivore, with a varied diet that includes euphausiids, copepods, cephalopods, amphipods, and larval and juvenile fish (Hunt et al., 2002; Ogi et al., 1980), but recent studies suggest it primarily feeds on euphausiids while in Alaska (Nishizawa et al., 2017, this issue). Both auklet species are planktivorous, with the smaller-bodied least auklet feeding mainly on *Neocalanus* copepods, and the larger crested auklet feeding on a variety of large copepod taxa, euphausiids, and occasionally, larval fish (Sheffield-Guy et al., 2009; Gall et al., 2006).

The Chukchi Sea has a late seasonal plankton bloom tied to the timing of ice retreat, long daylight hours, and stratification, which makes copepods available into late summer (Weingartner et al., 2013, 2017; Danielson et al., 2017). In comparison to historic patterns (1940s to 1990s), seasonally early ice retreat in the 2000s was associated with higher primary productivity and larger biomasses of lipid-rich copepods (such as *Calanus glacialis*), euphausiids (*Thysanoessa* spp.) and amphipods (*Themisto* spp.) (Ershova et al., 2015; Matsuno et al., 2011). This may be why Gall et al. (2017) found higher predicted abundance of short-tailed shearwaters and crested auklets with earlier ice retreat, based on survey data from the Chukchi Sea during 1975–2012. Our shearwater observations during 2017–2019 are consistent with that model. However, planktivorous seabirds, primarily short-tailed shearwaters and crested auklets, did not predominate in the offshore waters of the Chukchi Sea until sometime between the 1980s and 2007 (Gall et al., 2017). The late summer and fall presence of crested and least auklets far from breeding colonies were presumed to be post-breeding birds replenishing body reserves before migrating back to the Bering Sea for winter (Kuletz et al., 2019; Will et al., 2017).

During the current decade, sea ice has further diminished. Zooplankton communities in the Chukchi Sea have shown highly localized influences of shifting water masses, resulting in high interannual variability (Pinchuk and Eisner, 2017; Spear et al., 2019). The irregular pattern of abundance exhibited by crested auklets in the Northern Chukchi may reflect these localized fluctuations (Fig. 5h). Preliminary examination of zooplankton samples from the Northern Chukchi found that large copepods were more abundant in 2017 than in 2019, albeit both years had lower copepod abundance than during cooler years of 2012–2015 (D. Kimmel, unpubl. data). Our observations suggest that crested auklets and short-tailed shearwaters took advantage of aggregations of large copepods and euphausiids in the Northern Chukchi, particularly in 2017 (Fig. 5 b, h).

The abundance of crested auklets in the Northern Chukchi suggests that a portion of the Alaska-wide metapopulation rely on the prey in these cooler waters. However, the dynamics of sea ice, water temperature, primary productivity, and zooplankton are complex. Longer periods of open water and thinner sea ice have been linked to increased open water primary productivity in the Arctic (Arrigo et al., 2008; Brown et al., 2011) and an increase in advected Pacific-Bering zooplankton (Ershova et al., 2015). At the same time, warm, low-ice conditions have been associated with a decrease in production by ice algae, which are rich in long-chain omega-3 fatty acids (Søreide et al., 2010), and also with potentially lower local production of Arctic zooplankton fauna, including *C. glacialis* (Spear et al., 2019). In studies during the relatively cool years of 2010–2012, Spear et al. (2019) found highest concentrations of *C. glacialis* along the eastern waters of the Northern Chukchi, from Icy Cape to Barrow Canyon. Indeed, during those years the crested auklet community cluster extended well into these waters (Kuletz et al., 2019), whereas during the warmer period of 2017–2019 (this study), the Low Density seabird community predominated in this area (Fig. 6).

Although least auklets also appear to move into the Chukchi Sea in summer and fall, they primarily occur in the Southern Chukchi (Kuletz et al., 2015, 2019). Small copepods, which least auklets consume, are often abundant in Hope Basin and remained available there in 2017 and 2019 (no data are available for 2018; Kimmel, unpubl. data). Small copepod taxa (*Acartia* spp., *Pseudocalanus* spp., and *Oithona* spp.), were also abundant in the Northern Bering and Chirikov Basin in 2018 (Kimmel et al., 2018), when least auklets shifted to those subregions (Fig. 5g).

Concurrent with decreases in sea ice, northward flow from the Bering Sea has been increasing (Woodgate et al., 2012), which could increase advection of zooplankton and larval fish from the Bering shelf to Hope Basin and Hanna Shoal in the Chukchi Sea (Grebmeier et al., 2006; Dunton et al., 2017). Since the 2000s, zooplankton biomass has also increased along the Chukchi shelf break (Lane et al., 2008). Despite unusually high densities of least and crested auklets in the Chirikov Basin during 2017–2019, the Chukchi Sea will likely remain important post-breeding foraging habitat for these species, as evident in their overall distributions (Appendix B) and observed increases in some locations of the Northern Chukchi (Fig. 4 g, h).

An important feature of the Northern Chukchi is Barrow Canyon, which is a recognized hotspot of seabird activity (Kuletz et al., 2015), and where we found increased densities of several species in 2017–2019. Abundance of short-tailed shearwaters, and to lesser extent black-legged kittiwakes and northern fulmars, increased in the Barrow Canyon area during the late period. These surface feeders may forage over the canyon and adjacent waters because of the associated upwelling and concentration of euphausiids (Okkonen et al., 2011), as well as a variety of forage fishes attracted to large biomasses of copepods there (Logerwell et al., 2018).

The northward distributional shift observed for seabirds during this study was most evident for short-tailed shearwaters; higher densities began in the Chirikov Basin in 2014, the Southern Chukchi in 2015, and the Northern Chukchi in 2016, although shearwater abundance was near the long-term mean in 2018 and 2019 (Fig. 5b). This pattern coincides with seabird mortality events that included shearwaters in the Bering Strait region in summers of 2017–2019. The short-tailed shearwater was the main species impacted by the largest die off in the Bering Sea in recent years, in the southeast Bering Sea in 2019 (Siddon and Zador, 2019; USFWS, unpubl. data). Necropsies revealed birds were emaciated and starved, thus the large increases in shearwaters observed in the Chukchi Sea suggest foraging conditions were forcing ever-farther migration north to obtain energy stores for the migration back to breeding grounds. The extra distance may have contributed to the late arrival of shearwaters to breeding sites in Australia recorded in October–November of 2019 (Liao 2019).

Piscivorous seabirds could also have been impacted by changes in their prey. A variety of forage fish are available in the study area, with the lipid-rich Arctic cod (*Boreogadus saida*) the most abundant (De Robertis et al., 2017; Logerwell et al., 2018). Age-0 Arctic cod were particularly abundant in the Northern Chukchi during 2012 and 2013, suggesting it is an important nursery ground for the species (De Robertis et al., 2017). In the northern Bering Sea, forage fish biomass in summer 2019 was low compared to previous years, indicating poor conditions for fish growth and survival, or alternatively, that the fish migrated north for better foraging (Yasumiishi et al., 2019). Arctic cod prefer cold, high salinity water masses, where there tends to be high biomass of large copepods (De Robertis et al, 2017; Logerwell et al., 2020). While the effects of warm conditions during 2017–2019 are not yet fully understood, evidence suggests that key seabird prey species, at least in the Bering Sea, were either low in abundance or shifted distribution (Duffy-Anderson et al., 2019; Siddon and Zador, 2018, 2019). These changes in prey availability could have differentially affected breeding seabirds, or birds that have restricted foraging ranges. Murres, which have high wing loading, tend to forage where prey patches are persistent and highly aggregated, or forage closer to their colony (Decker and Hunt, 1996; Sigler et al., 2012).

Both species of murres also experienced mass mortality events in the Bering Sea during 2017–2019, with evidence of starvation (Romano et al., this issue; Siddon and Zador, 2018, 2019) and potentially avian disease (A. Will et al., this issue). The low numbers of murres at colonies in 2018 (Romano et al., this issue; Will et al., this issue), together with broad-scale reductions in offshore densities (this study) concurrent with the mortality events, suggest major reductions in murre populations have probably occurred. Notably, Piatt et al. (2020) speculated that based on satellite-tagged murres, the huge mass mortality of common murres in the Gulf of Alaska during the winter of 2015–2016 could have included birds from the Bering Sea. This would be consistent with the trend of lower abundance in offshore waters of our study area, although we show a decline in abundance of murres starting in 2014 (Fig. 5e, f). In addition, euphausiids make up a high proportion of the diets of adult thick-billed murres, but not common murres. The greater dietary diversity of thick-billed murres may be one reason their densities were more stable than that of common murres, particularly in the Chukchi Sea.

Despite broad-scale declines in abundance at sea, murre (and kittiwake) plot counts at the Cape Lisburne colony in the Southern Chukchi increased at a rate of 6-7% in 2019, with an average increase of ~ 4% per annum over the past decade (Dragoo et al., 2020). The unusually high rate of growth would likely require immigration (D. Dragoo, pers. comm.), perhaps an indication of better foraging conditions near Cape Lisburne. In contrast, the murre colony at Cape Thompson (~100 km over water to the south) has decreased since the 1960s (Dragoo et al. 2000), indicating that murre breeding population trends have not been consistent among Chukchi Sea colonies. Nonetheless, it is noteworthy that at least the northernmost large colony in the Chukchi Sea shows increases in murres and kittiwakes, while the four colonies monitored by the Alaska Maritime National Wildlife Refuge in the southern Bering Sea show evidence of declines in murres, particularly common murre, and three of these colonies show declines in kittiwakes (Dragoo et al. 2000). The decrease in abundance of murres that we detected in offshore waters may reflect population declines in murres throughout the Bering Sea. Black-legged kittiwakes show a similar but less conclusive pattern of convergence between colony and offshore trends.

During 2017–2019, seabird species richness of the Northern Chukchi increased, while richness of other subregions converged at a slightly lower level than during the prior decade. This suggests that less-abundant seabird species were occurring in the Northern Chukchi with increasing frequency during the later period. The convergence of species richness estimates between the Bering and Chukchi regions was mainly due to a decrease in species richness in the Bering Sea, and was concurrent with the expansion of the Low Density community cluster. Notably, the expansion of the Low Density community during the three warmest years (2017–2019) was nearly entirely along the eastern side of the study area. This expansion occurred in the Northern Bering and Chirikov Basin throughout the Inner Shelf, including areas east and south of St. Lawrence Island, which has large seabird colonies (Fig. 6). The Low Density community primarily displaced the short-tailed shearwater and thick-billed murre community clusters in the Bering Sea, and in the Northern Chukchi it displaced the short-tailed shearwater, thick-billed murre, and crested auklet communities. Thus, multiple foraging guilds appear to have been affected by conditions that concurrently led to the expansion of the Low Density community type.

The Inner Shelf waters of the Bering Sea, influenced by the fresher, warmer waters of the Alaska Coastal Current, have long been recognized as being nutrient-poor. These waters tend to have smaller zooplankton species, lower fish biomass (Eisner et al., 2013) and fewer seabirds compared to Anydyr waters to the west (Piatt and Springer, 2003; Sigler et al., 2017). The expansion of a Low Density seabird community in recent years suggests that large-scale ecosystem changes are altering the Inner Shelf, and to some degree the Middle Shelf and associated currents, thereby expanding the area of low productivity. In contrast, seabird density remained high near the Anadyr Current and western portions of the northern Bering and Chukchi seas. However, we lack sufficient data on seabird distribution west of the International Dateline to determine how far west those conditions exist. A long-term examination of marine fish from the Bering and Chukchi seas found that taxa respond to climate-related changes at different spatial and temporal scales (Alabia et al., 2018); similarly, we show that seabird species demonstrate a diversity of distributional responses, which may provide some level of resilience to their long-term prospects in the Pacific Arctic.

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Table 1. Survey effort during two time periods, 2007–2016 and 2017–2019.

Subregion	**2007–2016**	**2017–2019**	**Total**
Number of km surveyed			
Northern Chukchi	16969	9096	26065
Southern Chukchi	11393	7335	18728
Chirikov Basin	7212	5110	12322
Northern Bering	16268	6043	22311
Number of 30-km grid cells			
Northern Chukchi	608	299	907
Southern Chukchi	425	197	622
Chirikov Basin	306	164	470
Northern Bering	820	295	1115

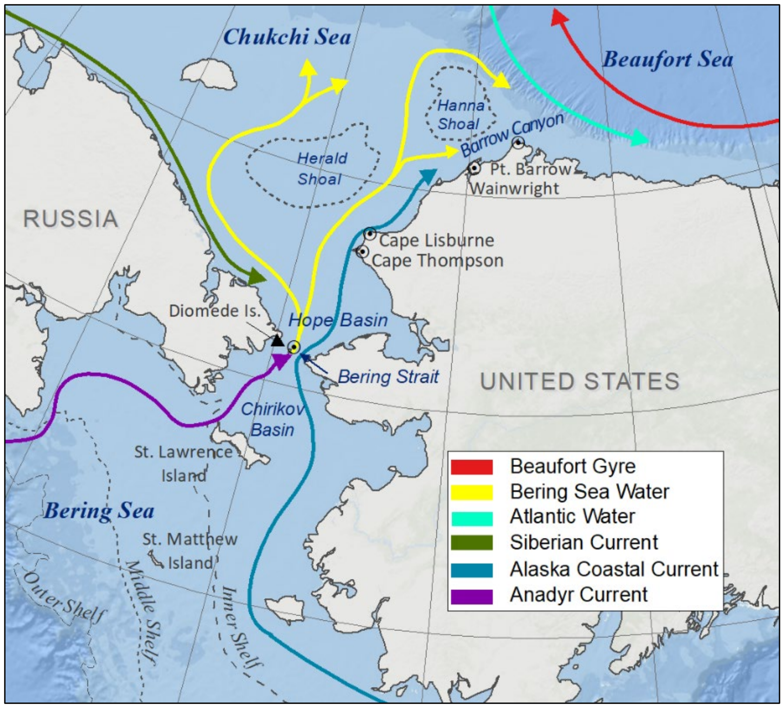


Figure 1. The Bering Sea and Chukchi Sea study area, showing generalized trajectories of major water masses. Map by EAL, based on Dunton et al. (2017).

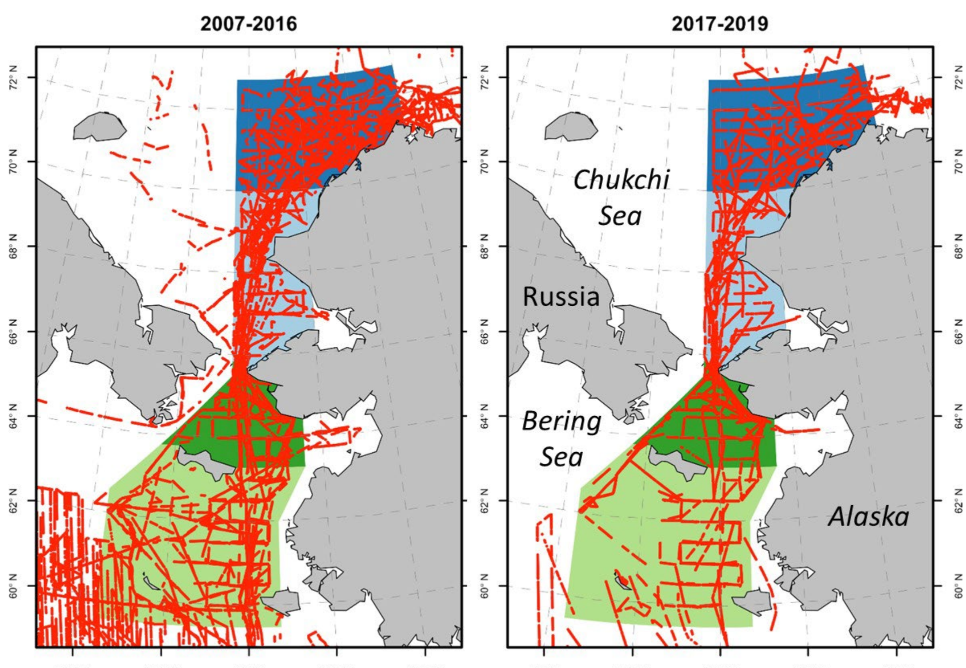


Figure 2. Four subregions of the study area: Northern Bering (light green), Chirkov Basin (dark green), Southern Chukchi (light blue) and Northern Chukchi (dark blue), with seabird survey transects overlaid for each time period.

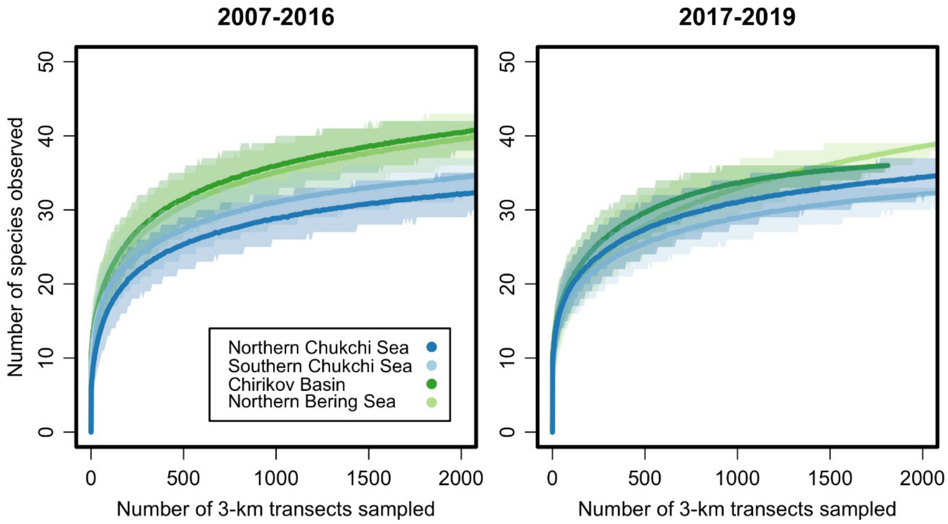


Figure 3. Species richness (rarefaction curves) in 4 subregions of the study area, for 2007–2016 and 2017–2019. Mean (solid lines) and 95% confidence intervals (shading) were derived from random selection of 3-km transect segments from surveys conducted during each time period and subregion.

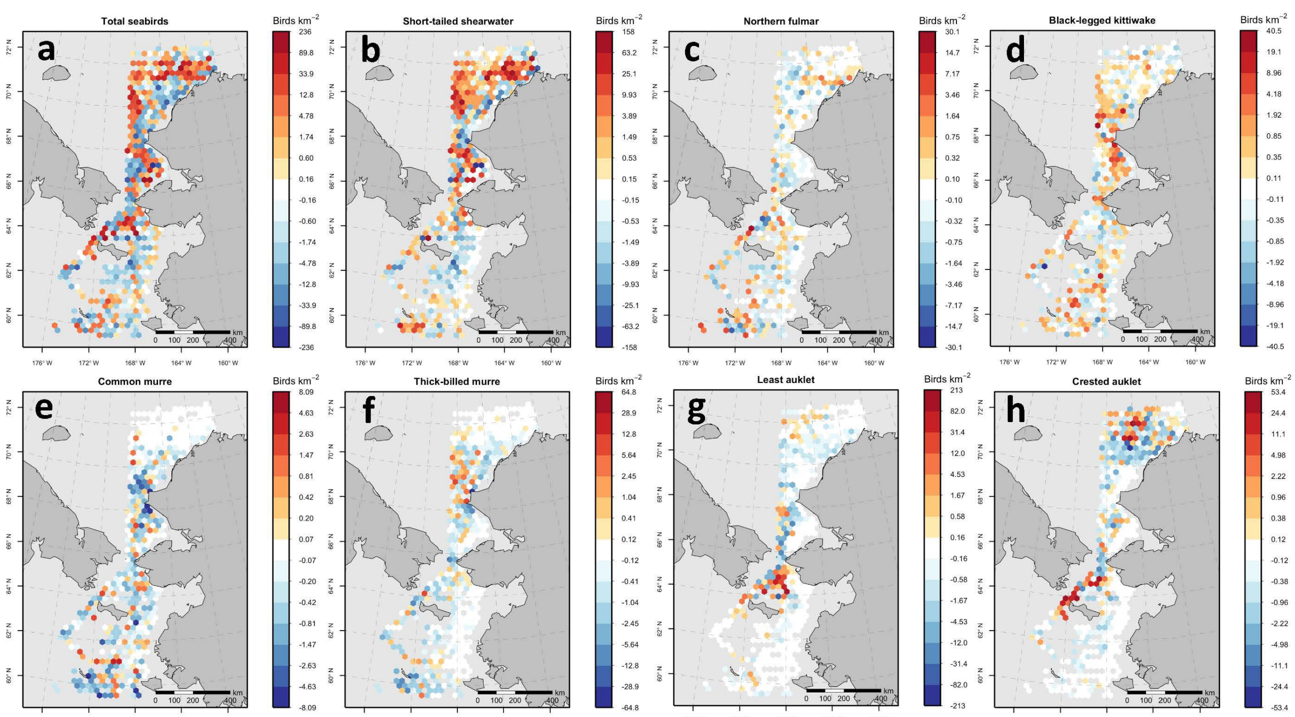


Figure 4. Distribution of increases (oranges) and decreases (blues) in densities of Total Seabirds and seven focal species in 2017–2019, compared to 2007–2016. Mean densities were calculated per 30-km grid cell within each time period for cells surveyed in both time periods.

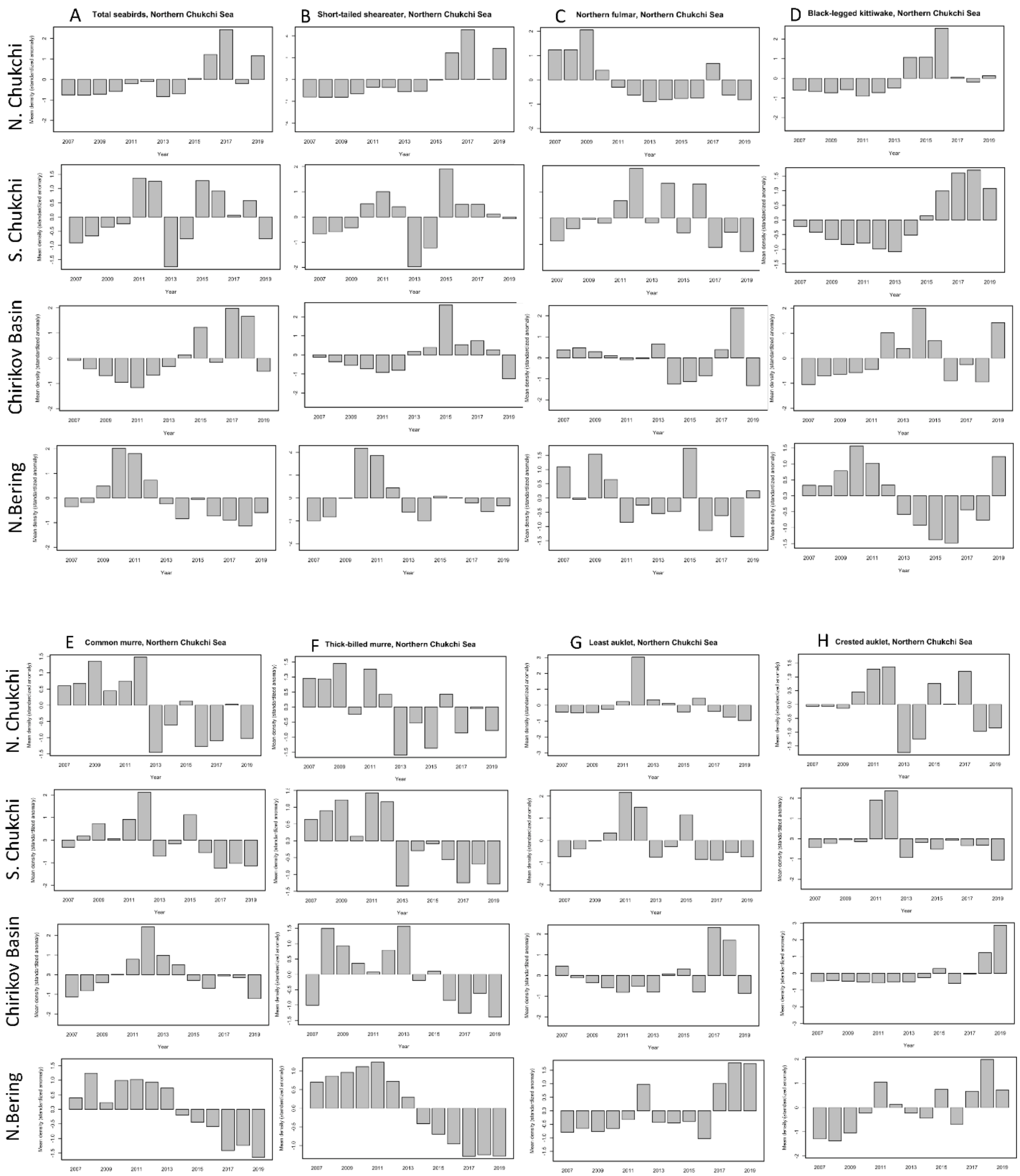


Figure 5. Standardized mean anomalies for total seabirds and seven focal species, for each subregion across all years, 2007–2019.

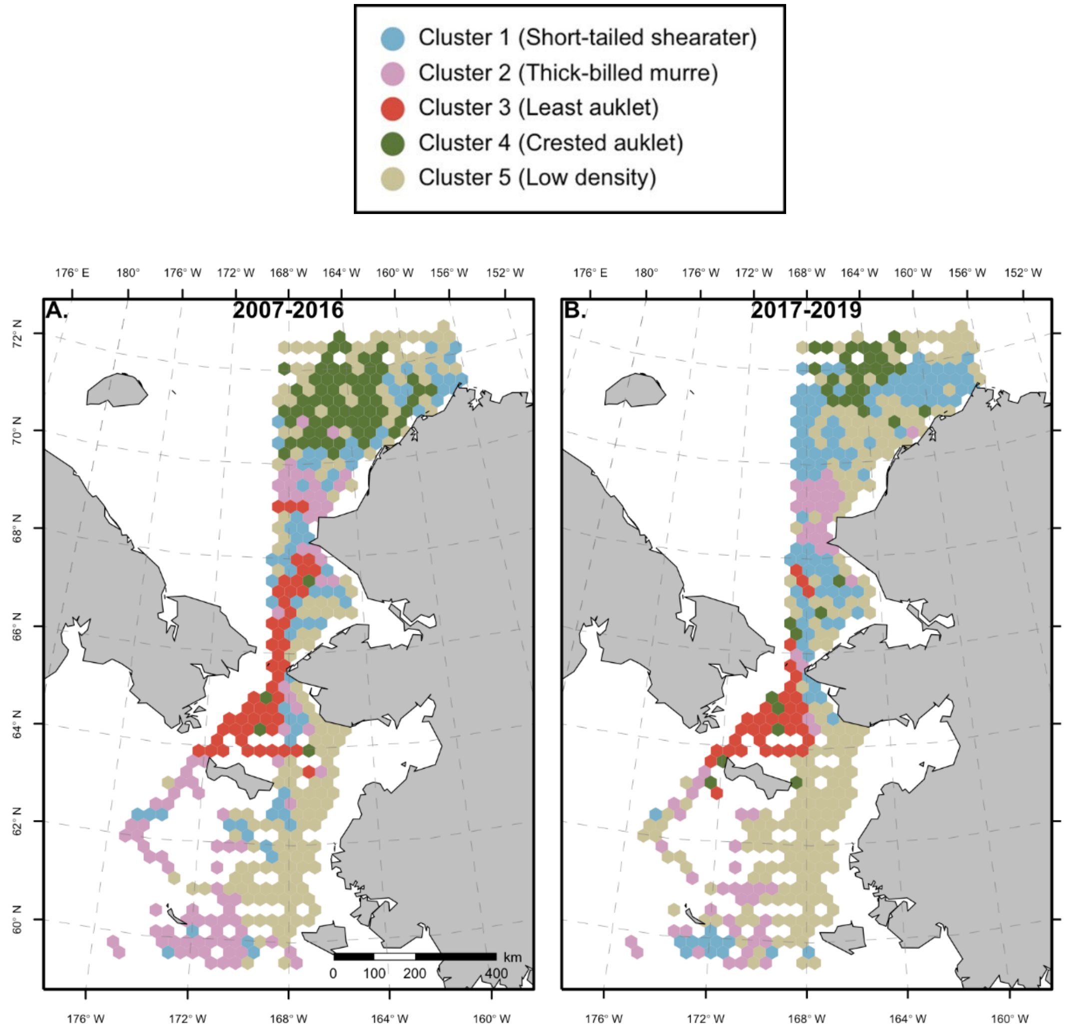
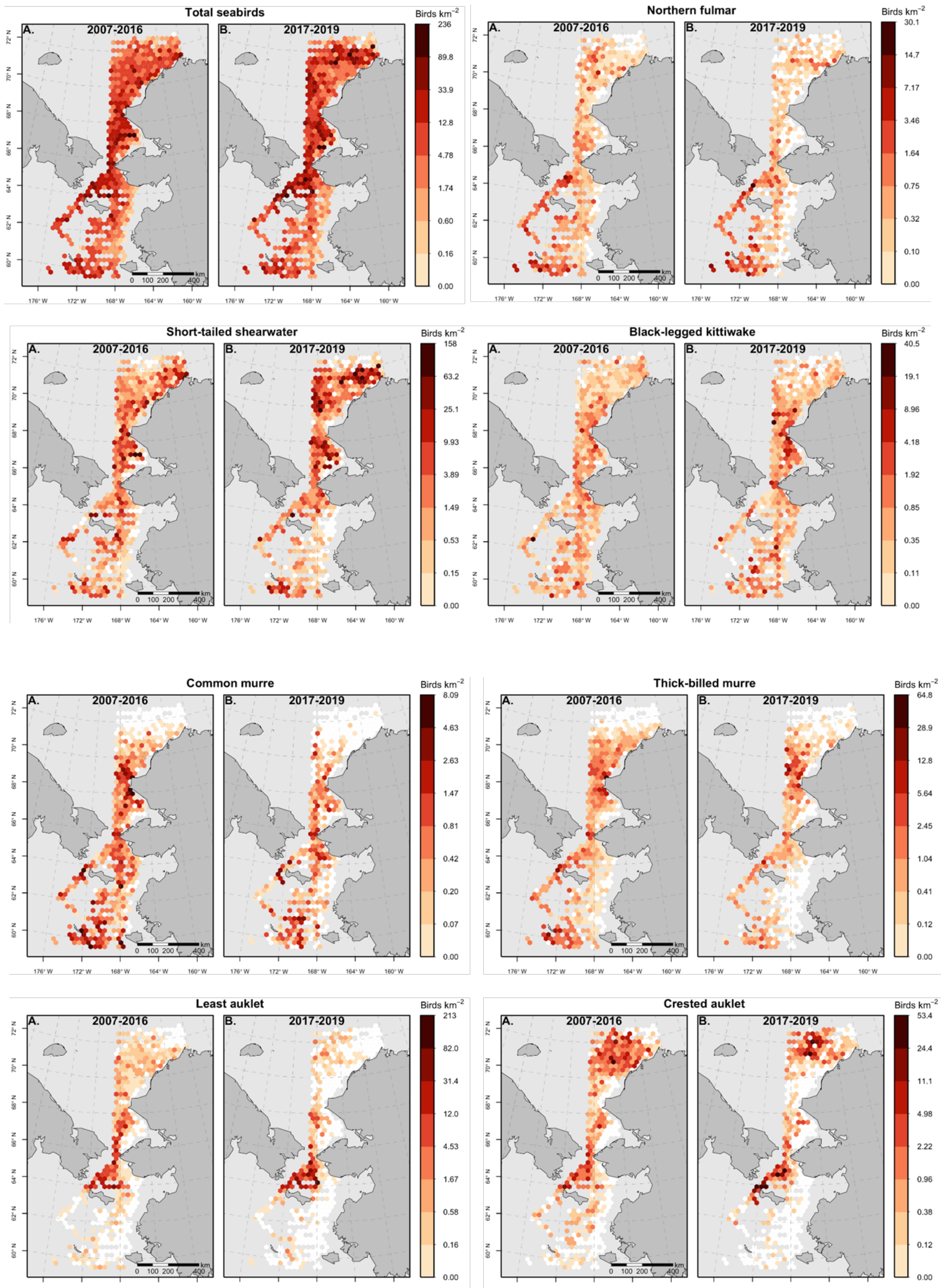


Figure 6. Distribution of five identified seabird community types (clusters) during two time periods, based on K-means cluster analysis. Colors represent community types referred to by the most abundant species (Clusters 1–4), or by low density and lack of a dominant species (Cluster 5).

Appendix A. Mean densities (birds km^2), by species, and subregion, during two time periods, 2007–2016 and 2017–2019. Asterisk indicates densities were <0.01.

		2007–2016					2017–2019				
		Mean density to 0.00 or <0.01 (*)					Mean density to 0.00 or <0.01 (*)				
Common Name	Latin name	Northern Bering	Chirikov Basin	Southern Chukchi	Northern Chukchi	all Regions	Northern Bering	Chirikov Basin	Southern Chukchi	Northern Chukchi	all Regions
Steller's Eider	*Polysticta stelleri*	0	*	0	0	*	*	*	0	0	*
Spectacled Eider	*Somateria fischeri*	0	0	0	*	*	0	*	*	*	*
King Eider	*Somateria spectabilis*	*	0.04	*	*	*	*	0.01	0.03	*	*
Common Eider	*Somateria mollissima*	*	*	0.04	*	0.01	0	0	0.04	*	*
Harlequin Duck	*Histrionicus histrionicus*	*	*	*	0	*	*	0	0	0	*
Surf Scoter	*Melanitta perspicillata*	0	*	*	0	*	0	0	0	0	0
White-winged Scoter	*Melanitta fusca*	0	*	0	0	*	*	*	*	0	*
Black Scoter	*Melanitta americana*	*	0	0	0	*	0	0	0	0	0
Long-tailed Duck	*Clangula hyemalis*	*	*	0.04	0.02	0.02	*	*	0.04	0.07	0.03
Red-necked Grebe	*Podiceps grisegena*	*	0	0	0	*	0	0	*	0	*
Red-necked Phalarope	*Phalaropus lobatus*	0.03	0.25	0.21	0.13	0.14	0.08	0.06	0.01	0.01	0.04
Red Phalarope	*Phalaropus fulicarius*	0.14	1.21	1.49	0.21	0.63	0.1	0.82	2.89	0.27	0.86
Pomarine Jaeger	*Stercorarius pomarinus*	0.04	0.05	0.13	0.03	0.06	0.02	0.05	0.03	0.03	0.03
Parasitic Jaeger	*Stercorarius parasiticus*	*	0.01	0.03	0.01	0.02	*	*	*	0.02	*
Long-tailed Jaeger	*Stercorarius longicaudus*	*	*	*	*	*	0	*	*	*	*
Dovekie	*Alle alle*	*	*	*	*	*	*	*	0	0	*
Common Murre	*Uria aalge*	0.91	0.78	0.92	0.08	0.62	0.37	0.48	0.37	0.05	0.28
Thick-billed Murre	*Uria lomvia*	0.88	0.87	1.79	0.35	0.91	0.29	0.53	1.29	0.23	0.52
Black Guillemot	*Cepphus grylle*	0	*	*	*	*	0	*	0	*	*
Pigeon Guillemot	*Cepphus columba*	*	*	*	*	*	*	*	0	0	*
Marbled Murrelet	*Brachyramphus marmoratus*	*	*	*	0	*	*	*	0	0	*
Kittlitz's Murrelet	*Brachyramphus brevirostris*	0	0	0.04	0.02	0.01	0	0	*	*	*
Ancient Murrelet	*Synthliboramphus antiquus*	0.18	0.11	0.08	0.05	0.1	0.06	0.08	0.07	0.05	0.06
Cassin's Auklet	*Ptychoramphus aleuticus*	*	*	*	0	*	*	*	0	*	*
Parakeet Auklet	*Aethia psittacula*	0.14	0.74	0.24	0.03	0.21	0.16	0.64	0.23	0.07	0.23
Least Auklet	*Aethia pusilla*	0.07	6.98	2.85	0.43	1.87	0.16	10.48	0.64	0.12	1.95
Whiskered Auklet	*Aethia pygmaea*	0	0	0	0	0	0	0	0	0	0
Crested Auklet	*Aethia cristatella*	0.15	1.97	0.57	2.27	1.21	0.24	4.7	0.34	1.74	1.5
Horned Puffin	*Fratercula corniculata*	0.09	0.17	0.13	*	0.08	0.03	0.23	0.12	*	0.07

Common Name	Latin name	2007–2016 Mean density to 0.00 or <0.01 (*)					2017–2019 Mean density to 0.00 or <0.01 (*)				
		Northern Bering	Chirikov Basin	Southern Chukchi	Northern Chukchi	all Regions	Northern Bering	Chirikov Basin	Southern Chukchi	Northern Chukchi	all Regions
Tufted Puffin	*Fratercula cirrhata*	0.07	0.34	0.15	*	0.11	0.11	0.34	0.09	*	0.11
Black-legged Kittiwake	*Rissa tridactyla*	0.61	0.71	0.82	0.38	0.6	0.75	0.68	1.66	0.31	0.78
Red-legged Kittiwake	*Rissa brevirostris*	*	*	*	0	*	*	0	0	0	*
Ivory Gull	*Pagophila eburnea*	0	0	0	0	0	0	0	0	0	0
Sabine's Gull	*Xema sabini*	*	0.01	*	0.02	0.01	0.02	*	*	0.04	0.02
Ross's Gull	*Rhodostethia rosea*	0	0	0	*	*	0	0	0	0	0
Mew Gull	*Larus canus*	0	0	0	0	0	0	0	0	*	*
Herring Gull	*Larus argentatus*	0.01	*	*	*	*	*	*	*	0	*
Iceland Gull	*Larus glaucoides*	*	0	*	0	*	0	0	0	0	0
Slaty-backed Gull	*Larus schistisagus*	*	*	0	0	*	*	0	0	0	*
Glaucous-winged Gull	*Larus glaucescens*	0.04	0.02	*	*	0.02	0.06	*	*	0	0.02
Glaucous Gull	*Larus hyperboreus*	0.04	0.09	0.04	0.05	0.05	0.04	0.03	0.08	0.05	0.05
Aleutian Tern	*Onychoprion aleuticus*	0	0	*	0	*	0	*	0	0	*
Arctic Tern	*Sterna paradisaea*	*	*	*	0.02	*	*	*	0.01	0.05	0.02
Red-throated Loon	*Gavia stellata*	*	*	*	*	*	0	*	*	0	*
Pacific Loon	*Gavia pacifica*	0.01	0.02	0.03	0.03	0.02	0.01	0.01	0.06	0.02	0.03
Common Loon	*Gavia immer*	*	0	0	*	*	*	0	*	*	*
Yellow-billed Loon	*Gavia adamsii*	*	*	0	*	*	*	*	*	*	*
Laysan Albatross	*Phoebastria immutabilis*	0.02	0	0	0	*	*	0	0	0	*
Short-tailed Albatross	*Phoebastria albatrus*	*	0	0	0	*	*	0	0	0	*
Northern Fulmar	*Fulmarus glacialis*	0.95	0.59	0.42	0.23	0.54	0.73	0.99	0.22	0.22	0.49
Mottled Petrel	*Pterodroma inexpectata*	*	0	0	0	*	0	0	0	0	0
Short-tailed Shearwater	*Ardenna tenuirostris*	1.79	3.71	5.74	4.22	3.76	1.27	3.06	6.46	11.48	6.05
Sooty Shearwater	*Ardenna grisea*	*	0	0	0	*	0	0	0	0	0
Fork-tailed Storm-Petrel	*Oceanodroma furcata*	0.06	0.02	*	*	0.02	0.03	0.08	*	*	0.02
Red-faced Cormorant	*Phalacrocorax urile*	*	0	*	0	*	*	0	0	0	*
Pelagic Cormorant	*Phalacrocorax pelagicus*	0.01	0.01	0	0	*	*	0.02	*	0	*
Total density		6.24	18.7	15.76	8.58	11.02	4.53	23.29	14.68	14.83	13.16



Appendix B. Distribution of total birds and key species for two time periods, 2007–2016 (A) and 2017–2019 (B). All 30-km hexagon cells surveyed during each time period are shown, including those not surveyed in both periods. White cells indicate survey effort, but the species was not observed.

Appendix C. Species composition and mean densities (birds·km2) for five cluster types identified for the Northern Bering-Chukchi Sea study area, 2007–2019 (July–September) combined. Shaded cells indicate predominate species for that cluster. Asterisks indicate density <0.01, but above zero. Clusters are named for their most abundant species or Low Density (LowDen); STSH = short-tailed shearwater, TBMU = thick-billed murre, LEAU = least auklet, CRAU = crested auklet.

			Cluster Type				
			1	**2**	**3**	**4**	**5**
Family	**Common Name**	**Latin name**	**STSH**	**TBMU**	**LEAU**	**CRAU**	**LowDen**
Anatidae	Steller's Eider	*Polysticta stelleri*	*	*	*	0	*
	Spectacled Eider	*Somateria fischeri*	0.01	*	0	0	0.01
	King Eider	*Somateria spectabilis*	0.01	*	0.01	0	0.01
	Common Eider	*Somateria mollissima*	0.01	0.01	*	*	*
	Harlequin Duck	*Histrionicus histrionicus*	*	*	*	0	*
	Surf Scoter	*Melanitta perspicillata*	*	0	*	0	0
	White-winged Scoter	*Melanitta fusca*	*	*	0.01	0	*
	Black Scoter	*Melanitta americana*	0	0	0	0	*
	Long-tailed Duck	*Clangula hyemalis*	0.07	0.01	*	0.02	0.02
Podicipedidae	Red-necked Grebe	*Podiceps grisegena*	0	*	0	0	*
Scolopacidae	Red-necked Phalarope	*Phalaropus lobatus*	0.07	0.07	0.34	0.09	0.07
	Red Phalarope	*Phalaropus fulicarius*	2.00	0.15	2.28	0.34	0.23
Stercorariidae	Pomarine Jaeger	*Stercorarius pomarinus*	0.07	0.04	0.07	0.03	0.03
	Parasitic Jaeger	*Stercorarius parasiticus*	0.02	0.02	0.01	0.01	0.01
	Long-tailed Jaeger	*Stercorarius longicaudus*	*	0.01	0.00	*	*
Alcidae	Dovekie	*Alle alle*	*	*	*	*	*
	Common Murre	*Uria aalge*	0.32	1.28	0.84	0.11	0.21
		Uria lomvia	0.53		1.49	0.30	0.12
	Black Guillemot	*Cepphus grylle*	*	*	0.01	*	*
	Pigeon Guillemot	*Cepphus columba*	0.01	*	0.01	*	*
	Marbled Murrelet	*Brachyramphus marmorc*	*	*	*	0	*
	Kittlitz's Murrelet	*Brachyramphus brevirost*	0.01	0.01	*	0.01	*
	Ancient Murrelet	*Synthliboramphus antiqu*	0.09	0.16	0.09	0.05	0.06
	Cassin's Auklet	*Ptychoramphus aleuticus*	*	*	*	*	*
	Parakeet Auklet	*Aethia psittacula*	0.21	0.20	0.91	0.11	0.10
		Aethia pusilla	0.34	0.22		0.67	0.07
		Aethia cristatella	0.50	0.21	5.42		0.11
	Horned Puffin	*Fratercula corniculata*	0.07	0.16	0.21	0.02	0.04
	Tufted Puffin	*Fratercula cirrhata*	0.07	0.13	0.50	0.04	0.04
Laridae	Black-legged Kittiwake	*Rissa tridactyla*	0.97	1.39	0.61	0.35	0.54
	Red-legged Kittiwake	*Rissa brevirostris*	*	0.01	*	0	*
	Sabine's Gull	*Xema sabini*	0.02	0.02	0.01	0.02	0.01
	Ross's Gull	*Rhodostethia rosea*	0	0	0	*	0
	Mew Gull	*Larus canus*	*	0	0	*	0
	Herring Gull	*Larus argentatus*	*	0.01	*	*	*
	Iceland Gull	*Larus glaucoides*	*	*	0	0	0
	Slaty-backed Gull	*Larus schistisagus*	*	*	*	0	*
	Glaucous-winged Gull	*Larus glaucescens*	0.02	0.05	0.01	0.00	0.02
	Glaucous Gull	*Larus hyperboreus*	0.06	0.05	0.05	0.03	0.05
	Aleutian Tern	*Onychoprion aleuticus*	0	0	*	0	*
	Arctic Tern	*Sterna paradisaea*	0.03	*	*	0.01	0.02
Gaviidae	Red-throated Loon	*Gavia stellata*	*	*	*	*	*
	Pacific Loon	*Gavia pacifica*	0.05	0.02	0.01	0.02	0.02
	Common Loon	*Gavia immer*	*	0	0	*	*
	Yellow-billed Loon	*Gavia adamsii*	*	*	*	*	*
Diomedeidae	Laysan Albatross	*Phoebastria immutabilis*	*	0.02	0	0	*
	Short-tailed Albatross	*Phoebastria albatrus*	0	*	0	0	*
Procellariidae	Northern Fulmar	*Fulmarus glacialis*	0.35	1.43	1.49	0.36	0.27
	Mottled Petrel	*Pterodroma inexpectata*	0	*	0	0	0
		Ardenna tenuirostris		1.66	5.37	1.09	0.61
	Sooty Shearwater	*Ardenna grisea*	*	*	0	0	*
Hydrobatidae	Fork-tailed Storm-Petrel	*Oceanodroma furcata*	0.01	0.14	0.06	0.01	*
Phalacrocoracidae	Red-faced Cormorant	*Phalacrocorax urile*	*	0	*	0	*
	Pelagic Cormorant	*Phalacrocorax pelagicus*	0.00	*	0.01	0	0.01
Total Density			24.43	10.28	36.96	8.85	2.65

Appendix 6: Project cruise reports.

A.6.1 ASGARD Cruise Report for Marine Bird Observations: 9–29 June 2017

Seabird Observer: A. Catherine Pham
Principal Investigator: Kathy Kuletz

The 2017 Arctic Shelf Growth, Advection, Respiration and Deposition Rate Experiments (ASGARD) cruise left on the R/V *Sikuliaq* from Nome, AK at 0800 on 9 June for surveys in the northern Bering and southern Chukchi seas. From 9 to 18 June, the ship proceeded from south to north for process stations, then returned south on 19 June for survey stations. The ship deviated from the cruise plan 11 – 13 June to assist the U.S. Coast Guard with a search and rescue mission near Wales, AK. Seabird surveys were conducted during transits between stations to document seabird distribution, abundance, and behavior. The ship arrived back in Nome on 29 June.

Methods

Seabird surveys were conducted whenever the vessel was traveling and visibility was at least 100 m. All sightings within 300m and a 90° arc forward from the line of travel were recorded. All birds, marine mammals, and debris on the water were recorded continuously, while flying birds were recorded at regular time intervals in snapshot fashion to avoid overestimating. For each sighting, the species, number of individuals, behavior (water, scan, flying), and distance bin (0-50 m, 51-100 m, 101-150 m, 151-200 m, 201-300 m, off transect) was recorded. Identification was to the most accurate taxonomic level possible. Although marine mammals were recorded, this survey was done to marine bird protocol, therefore marine mammal densities are not comparable to those conducted under marine mammal survey protocols. Environmental variables such as sea state, cloud cover, and fog conditions were recorded and updated as necessary. When time permitted, straight line distance bin and angle from the line of travel to the sighting were recorded.

All surveying was conducted from the port side, as the marine mammal observer surveyed from the starboard side. The vessel's GPS was used to obtain automated waypoints. The handheld GPS could not be used as a backup because it had difficulty holding a signal when inside the bridge.

The data were continuously entered into survey software DLog3 using a Panasonic Toughbook CF-SX2 laptop or an HP Probook 430 G1 laptop. Leica Trinovoid 10x42 binoculars were used to aid in identification, and a Panasonic Lumix DMC-ZS-8 digital camera was occasionally used to confirm identification. A marked wooden dowel was used to verify distance estimates, and a Leica Rangemaster 1200 rangefinder and Vortex Viper HD R/T 50 mm tactical binoculars were occasionally used as well.

Big seas hampered surveying on 17, and 21-24 June, and fog hampered surveying on 10, 13, and 20 June. Transect width was reduced as necessary, and surveying had to be stopped completely when sea conditions exceeded Beaufort Scale 6, or fog reduced visibility to < 100 m.

Results

During the first half of the cruise, transects were conducted primarily at night because the ship occupied a single process station for much of the day. At night, CTD casts were conducted at approximately 10 nm intervals during the transit to the next process station. During the second half of the cruise, the ship conducted short survey stations at approximately 10 nm intervals throughout the entire 24 hr period, thus transects were conducted night and day as visibility and the observer's schedule allowed.

Over the 20 days of the ASGARD cruise, 118 transects were completed for a total of 128 hr and ~2,240 km surveyed. During the first half of the cruise, 51 transects were completed for a total of 61 hr and ~1,080 km surveyed, and during the second half, 67 transects were completed for a total of 67 hr and ~1,160 km surveyed.

Thirty-five species and 14 taxa (identified to genus or family) comprising 5,402 birds were recorded on transect. An additional seven species and one taxa were recorded off transect. The ten most abundant species accounted for 80% of all birds recorded on transect (Table 1, Fig. 1). These species were Least Auklets (Fig. 2), Short-Tailed Shearwaters (Fig. 3), Thick-Billed Murres (Fig. 4), Black-Legged Kittiwakes, Crested Auklets, Parakeet Auklets, Common Murres, Northern Fulmars, Horned Puffins, and Tufted Puffins.

Species of concern that were recorded included a Yellow-Billed Loon, a Kittlitz's Murrelet, and Steller's Eiders. Additionally, nine dead birds were recorded (Fig. 5), of which four were positively identified as murres (*Uria* spp.). One of the dead birds was seen while off effort, and the approximate coordinates of the sighting were recorded.

Nearly all Short-Tailed Shearwaters were observed during the second half of the cruise, and particularly when the ship was in the northern Bering Sea (Fig. 3). The distribution of shearwaters suggests that the cruise coincided with the annual shearwater migration into the northern Bering Sea, just prior to their widespread occurrence in the Chukchi Sea. Anecdotally, many of the shearwaters appeared to be molting, based on missing wing feathers. Clear pictures of molting birds could not be obtained.

Notes on equipment failures and vessel issues

On 25 June, the ship's GPS feed experienced unknown problems for approximately 1 hour. One transect had to be aborted, and another transect was conducted while manually recording GPS coordinates approximately every 10 minutes.

The survey laptop also experienced mechanical or software problems that caused it to randomly shut down. The problems may be due to drivers or the BIOS being out of date or corrupted. That the laptop shut down when DLog was running or the GPS was plugged in may be due to coincidence. The problem was somewhat mitigated by undoing some of the most recent system updates, and by switching the power plan to "high performance." The backup laptop was used on occasion to continue surveys.

The R/V *Sikuliaq* provided a good sampling location on the port side of the bridge, with a chair for the observer, adequate ledge for the laptop, GPS and power cables, and good forward and side visibility. However, the vessel experienced major plumbing problems during the cruise, and these problems could occur again in the future, due to design problems.

Table 1. Relative abundance of bird species and taxa recorded during the 2017 ASGARD cruise. Birds recorded "off transect" are those observed outside the survey window, flying through the survey window but not during a "scan," and dead birds. Species are listed from most to least abundant. Taxa include birds unidentified to species (Unid.).

Taxa	No. on transect	Rel. abund. (%)	No. off transect
Least Auklet	847	15.68	58
Short-Tailed Shearwater	757	14.01	1253
Thick-Billed Murre	730	13.51	233
Black-Legged Kittiwake	591	10.94	217
Crested Auklet	535	9.90	209
Parakeet Auklet	245	4.54	30
Common Murre	236	4.37	47
Northern Fulmar	156	2.89	861
Horned Puffin	113	2.09	59
Tufted Puffin	104	1.93	30
Red Phalarope	46	0.85	29
Red-Necked Phalarope	38	0.70	8
Pigeon Guillemot	24	0.44	15
Glaucous Gull	23	0.43	44
King Eider	14	0.26	48
Pomarine Jaeger	13	0.24	11
Parasitic Jaeger	12	0.22	26
Glaucous-Winged Gull	7	0.13	12
Pacific Loon	5	0.09	4
Pelagic Cormorant	5	0.09	5
Dovekie	4	0.07	0
Sabine's Gull	3	0.06	1
Long-Tailed Jaeger	2	0.04	11
Ancient Murrelet	1	0.02	0
Kittlitz's Murrelet	1	0.02	0
Long-Tailed Duck	1	0.02	3
Northern Pintail	1	0.02	0
Slaty-Backed Gull	1	0.02	2
Common Eider	0	0.00	12
Greater White-Fronted Goose	0	0.00	21
Harlequin Duck	0	0.00	2
Herring Gull	0	0.00	3
Steller's Eider	0	0.00	3
White-Winged Scoter	0	0.00	1
Yellow-Billed Loon	0	0.00	1
Unid. murre	775	14.35	389
Unid. auklet	49	0.91	4
Unid. eider	32	0.59	31
Unid. alcid	15	0.28	1
Unid. passerine	7	0.13	6
Unid. gull	3	0.06	4
Unid. *Brachyramphus* murrelet	2	0.04	4
Unid. shorebird	2	0.04	0
Unid. jaeger	1	0.02	1
Unid. puffin	1	0.02	0
Unid. bird	0	0.00	2
Unid. guillemot	0	0.00	1
Unid. goldeneye	0	0.00	2
Unid. loon	0	0.00	1
TOTAL	5402		3705

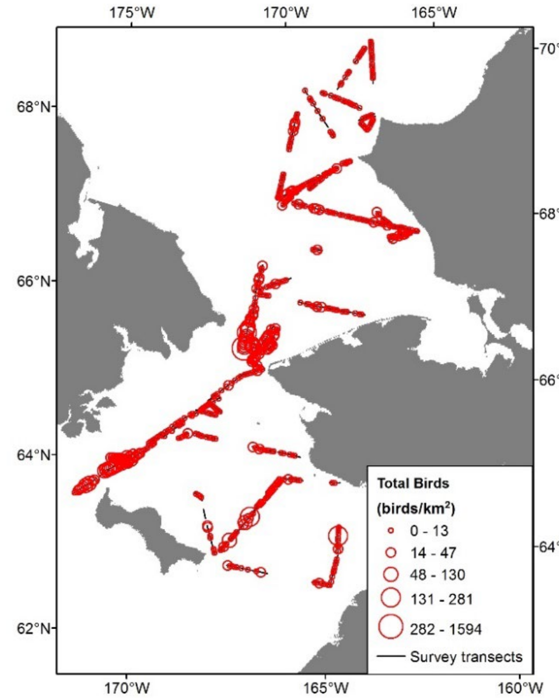


Fig. 1. Densities of total birds aggregated into 3-km bins. These densities have not been corrected for detectability, or pro-rated from unidentified taxa to species. Two transects are not included here due to GPS problems, but those track lines and sightings data will be interpolated at a later date.

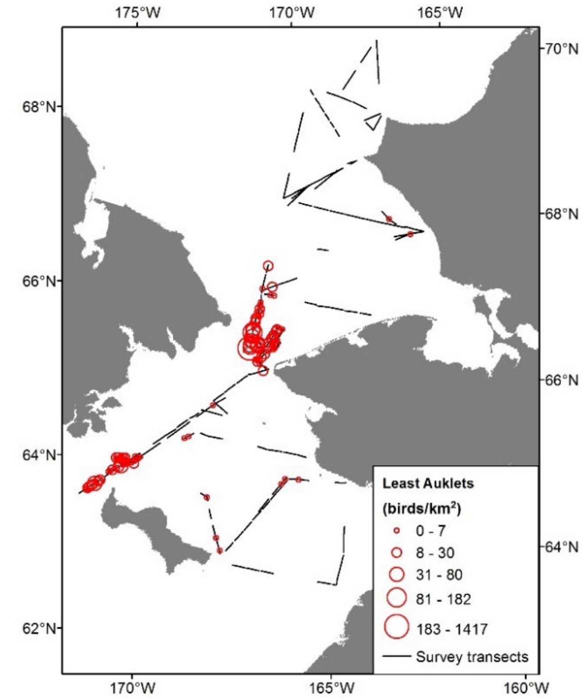


Fig. 2. Densities of Least Auklets aggregated into 3-km bins. These densities have not been corrected for detectability, or pro-rated from unidentified taxa to species. Two transects are not included here due to GPS problems, but those track lines and sightings data will be interpolated at a later date.

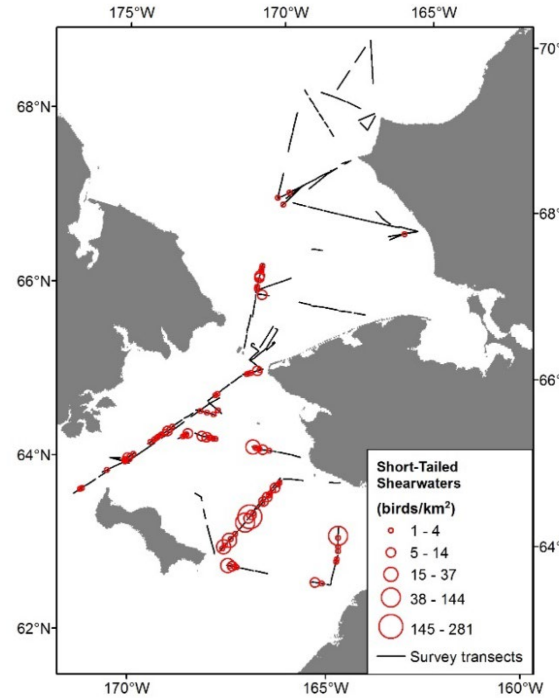


Fig. 3. Densities of Short-Tailed Shearwaters aggregated into 3-km bins. These densities have not been corrected for detectability, or pro-rated from unidentified taxa to species. Two transects are not included here due to GPS problems, but those track lines and sightings data will be interpolated at a later date.

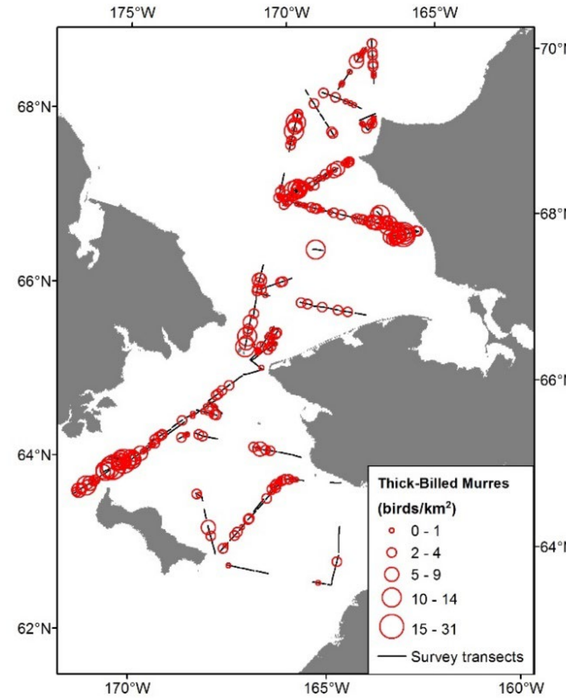


Fig. 4. Densities of Thick-Billed Murres aggregated into 3-km bins. These densities have not been corrected for detectability, or pro-rated from unidentified taxa to species. Two transects are not included here due to GPS problems, but those track lines and sightings data will be interpolated at a later date.

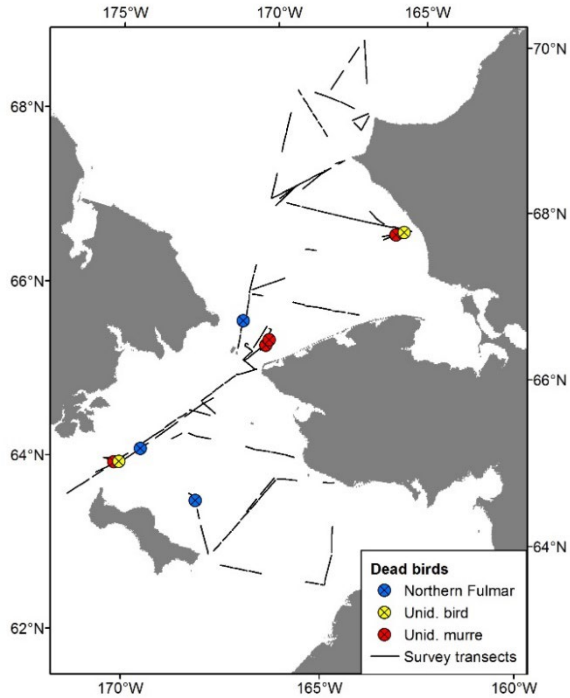


Fig. 5. Locations of the nine dead birds observed on the water during transits.

A.6.2 ASGARD Cruise Report for Marine Bird Observations: 31 May–25 June 2018

Principal Investigator and onboard observer: Kathy Kuletz

The U.S. Fish and Wildlife Service (USFWS) provided the seabird component of ASGARD, with funding from Interagency Agreement (M17PG00017) with the Bureau of Ocean Energy Management for project AK-16-07c (PI K. Kuletz). This study will combine data collected during the ASGARD cruise with data from other research cruises to examine the seasonal and interannual changes in seabird distribution relative to prey and oceanographic properties.

Methods

Seabird surveys were conducted to USFWS protocol when the vessel was traveling under acceptable survey conditions (onboard observer, K. Kuletz). All sightings within 300 m and a 90° arc forward from the line of travel were recorded. All birds, marine mammals, and debris on the water were recorded continuously, while flying birds were recorded at intervals (typically every 65 sec, depending on vessel speed). We recorded species, number of individuals, behavior (water, scan, flying), and distance bin (0-50 m, 51-100 m, 101-200 m, 201-300 m, >300 m (off transect)). Although marine mammals were recorded, this survey was done to marine bird protocol, therefore marine mammal densities are not comparable to those conducted under marine mammal protocols. Environmental variables such as Beaufort sea state, cloud cover, and fog conditions were recorded and updated as necessary. Surveys were conducted from the port side, as the marine mammal observer surveyed from the starboard side. On two occasions the seabird observer also worked from the starboard side due to excessive glare on the port side. Observations were entered into a laptop integrated with the vessel's GPS to obtain waypoints, using survey software DLog3. Binoculars (10x42) were used to aid in detection of small species and to aid species identification. A marked wooden dowel was used to verify distance estimates, with periodic checks and standardization done with a rangefinder when possible.

High winds and heavy seas restricted surveying on two days. Fog was also a problem on several days, but did not completely obstruct observations during a full transit. Surveys were temporarily halted or stopped when seas exceeded Beaufort Scale 6, or fog reduced visibility to < 100 m. During the first half of the cruise, transects were conducted primarily at night because the ship occupied a single process station for much of the day. During the second half of the cruise, the ship conducted short survey stations throughout the 24 hr period, and transects were conducted night and day as conditions allowed.

Results

I surveyed a total of 2,170 km, with 1,410 of those within the ASGARD study area through June 24. On transect I recorded 21,925 birds of 38 species, with 6,838 of those and 24 species within the ASGARD area (the northern Bering Sea and Chukchi Sea; Table 1).

During our transit from Seward in the northern Gulf of Alaska and through Unimak Pass, we observed fairly high numbers of the three North Pacific albatrosses (Fig. 1), including two immature short-tailed albatross (a listed species under the ESA). The Laysan albatross was the most abundant of the three species. Sooty shearwaters (mainly in the GOA) and short-tailed shearwaters (the main species in the Bering Sea) were abundant in the GOA and highly aggregated near Unimak Pass, but few were observed farther north (Fig. 2). Within the ASGARD study area, only two short-tailed shearwaters were recorded on 23 June in the Chirikov Basin, whereas >700 shearwaters were recorded in the northern Bering Sea during ASGARD 2017. The 2017 observations also occurred during the latter half of the ASGARD survey, which was about a week later than in 2018. Typically, short-tailed shearwaters are the most abundant species in the northern Bering and southern

Chukchi seas in mid to late summer and fall. The 2018 ASGARD survey appears to have captured the time period prior to shearwater movement into the northern Bering Sea, or, their migration north was later than observed in previous years.

Aethia auklets (the genus name) were the most abundant group of birds in the ASGARD area, but were almost entirely in the northern Bering Sea, with few birds in the Chukchi (Fig. 3). Of, the least auklet was the most abundant; it feeds on copepods. The larger crested auklet was the second most abundant and feeds on larger copepods and euphausiids. Both species are especially abundant near their colonies in the northern Bering Sea at this time of year. In previous late-summer surveys, they have also been common in the Chukchi Sea. The parakeet auklet is less abundant and includes fish in its diet. Very low numbers of parakeet auklets breed at Cape Thompson and Lisburne colonies in the Chukchi Sea, in addition to colonies in the Bering Sea, which is likely why they were the main auklet species in the Chukchi Sea during the June surveys of ASGARD 2018.

Within the ASGARD study area, thick-billed murres were ubiquitous (Fig. 4), though lower numbers were recorded compared to ASGARD 2017. Throughout the cruise, both murre species, but common murres in particular, were in much lower numbers than during previous surveys. Murres primarily eat fish, although thick-billed murres also eat krill. Other relatively abundant species in the study area in 2018 were black-legged kittiwake and northern fulmar (Table 1).

During the cruise we observed 5 dead birds on transect, including 1 murre, 1 kittiwake, 1 unidentified gull, and 2 unidentified birds), primarily in the Hope Basin area (Fig. 5). In addition, the Sikuliaq skiff crew returning from Nome salvaged a freshly dead thick-billed murre southeast of Sledge Island; the carcass was frozen and sent to the National Wildlife Health Center in Madison, WI for necropsy and testing for disease and toxin exposure. Throughout spring and early summer of 2018, seabird die offs have been reported at multiple locations in the study area, with dead birds (primarily murres, and small numbers of puffins, kittiwakes, and gulls) washing up on beaches near Nome, Shishmaref, Gambel on St. Lawrence Island, and on St. Matthew Island.

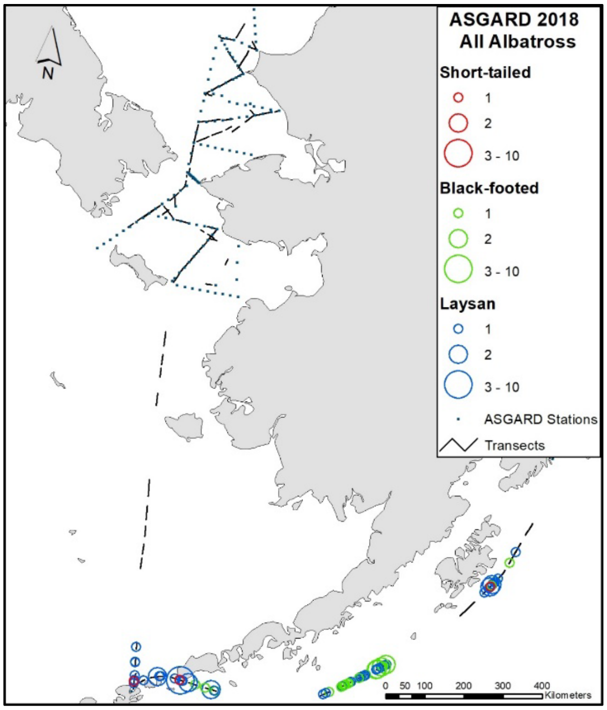


Figure 1. Sightings of albatrosses during the ASGARD 2018 cruise.

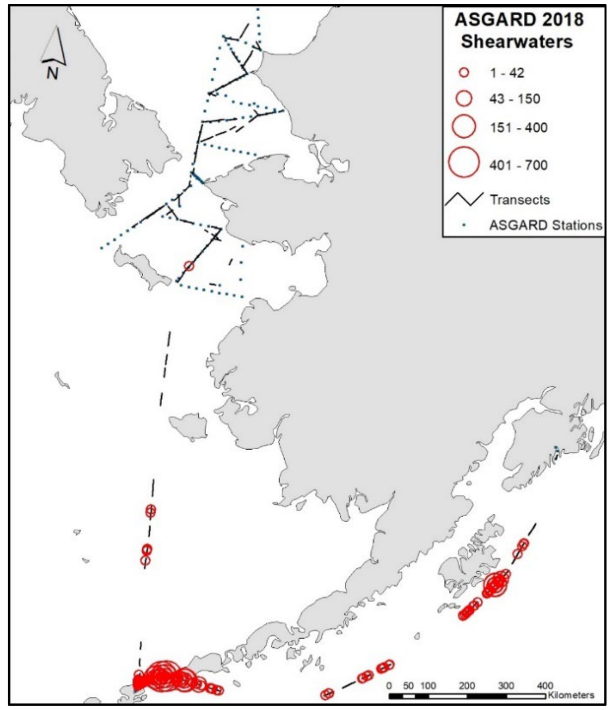


Figure 2. Sooty shearwaters (mainly in the GOA) and short-tailed shearwaters (the main species in the Bering Sea) recorded during the ASGARD 2018 cruise.

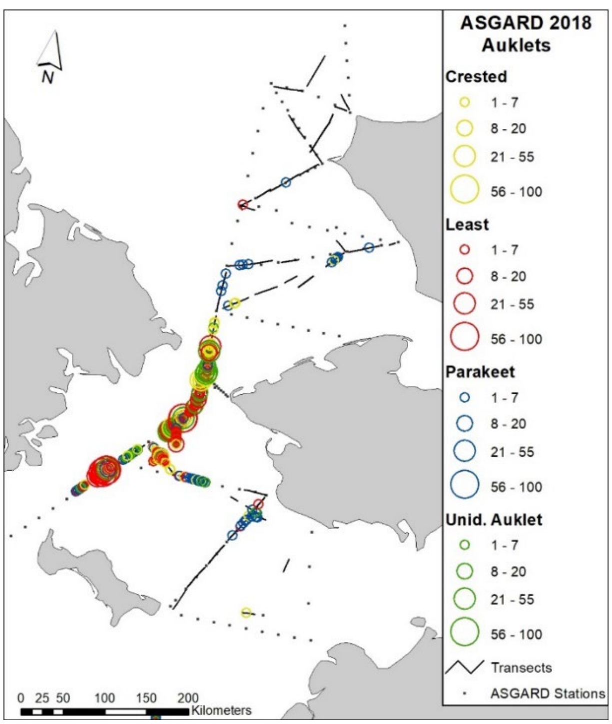


Figure 3. *Aethia* auklets observed in the ASGARD study area in 2018.

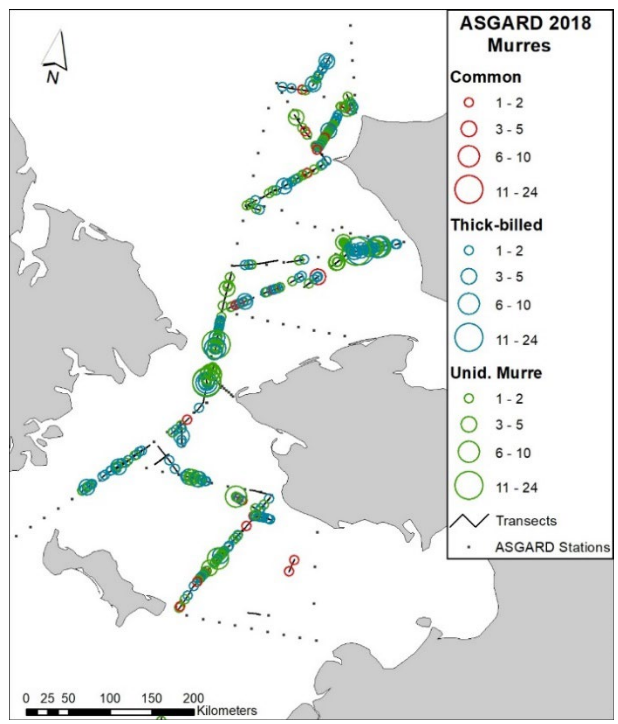


Figure 4. Records of common, thick-billed, and unidentified murres in the ASGARD study area.

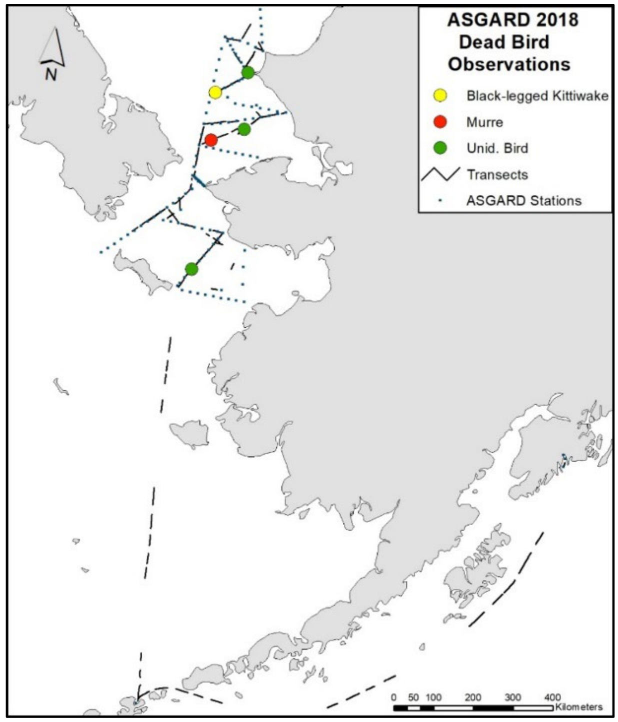


Figure 5. Dead birds recorded during surveys during ASGARD 2018.

Table 1. Counts of marine birds observed on transect during ASGARD, May 31–June 25, 2018. Highlighted cells indicate the most abundant species. Regions are Gulf of Alaska (GOA), Southern Bering Sea (SBSEA), Northern Bering Sea (NBSEA), and Chukchi Sea (Chukchi).

	GOA		SBSEA		NBSEA		Chukchi		All Regions
	No.	% Total	No.	% Total	No.	% Total	No.	% Total	Total No.
Ancient Murrelet	33	0.33	10	0.20					43
Black-footed Albatross	33	0.33							33
Black Guillemot					5	0.09			5
Black-legged Kittiwake	35	0.35	21	0.42	193	3.46	145	11.58	394
Bonaparte's Gull	1	0.01							1
Cassin's Auklet	2	0.02							2
Common Eider					4	0.07	9	0.72	13
Common Loon			1	0.02					1
Common Murre	10	0.10	36	0.72	33	0.59	16	1.28	95
Crested Auklet			9	0.18	671	12.01	80	6.39	760
Dovekie					2	0.04			2
Fork-tailed Storm-Petre	128	1.27	4	0.08	6	0.11	1	0.08	139
Glaucous Gull			1	0.02	18	0.32	22	1.76	41
Glaucous-winged Gull	76	0.75	5	0.10					81
Horned Puffin	26	0.26	7	0.14	69	1.24	22	1.76	124
Laysan Albatross	44	0.43	11	0.22					55
Least Auklet			2	0.04	2245	40.19	124	9.90	2371
Leach's Storm-Petrel	89	0.88							89
Long-tailed Duck					1	0.02			1
Long-tailed Jaeger					3	0.05	1	0.08	4
Northern Fulmar	5442	53.79	425	8.55	72	1.29	121	9.66	6060
Parakeet Auklet	8	0.08			212	3.80	29	2.32	249
Parasitic Jaeger			4	0.08	1	0.02	3	0.24	8
Pacific Loon					3	0.05	28	2.24	31
Pelagic Cormorant					14	0.25			14
Pigeon Guillemot	3	0.03							3
Pomarine Jaeger			2	0.04	5	0.09	4	0.32	11
Red Phalarope	178	1.76			7	0.13	8	0.64	193
Rhinoceros Auklet	1	0.01							1
Red-legged Kittiwake	1	0.01							1
Red-necked Phalarope	10	0.10							10
Sabine's Gull							1	0.08	1
Sooty Shearwater	20	0.20							20
Spectacled Eider							4	0.32	4
Short-tailed Albatross	1	0.01	1	0.02					2
Short-tailed Shearwate	210	2.08	965	19.42	2	0.04			1177
Thick-billed Murre			7	0.14	180	3.22	238	19.01	425
Tufted Puffin	230	2.27	125	2.52	60	1.07	20	1.60	435
Unid. Alcid	6	0.06	4	0.08	755	13.52	3	0.24	768
Unid. Auklet					790	14.14	96	7.67	886
Unid. Cormorant					2	0.04			2
Unid. Dark Shearwater	3320	32.82	3310	66.60					6630
Unid. Goose					4	0.07			4
Unid. Eider					2	0.04	31	2.48	33
Unid. Gull							5	0.40	5
Unid. Jaeger					1	0.02	4	0.32	5
Unid. Loon					2	0.04			2
Unid. Murre	18	0.18	20	0.40	205	3.67	235	18.77	478
Unid. Phalarope	190	1.88			12	0.21	2	0.16	204
Unid. Shorebird	2	0.02			6	0.11			8
Yellow-billed Loon					1	0.02			1
Total birds on transect	**10,117**		**4,970**		**5,586**		**1,252**		**21925**

A.6.3 Arctic IES Marine Bird Surveys:1 August–4 October 2017

Marine Bird Surveys: Arctic IES 2017
At-Sea Observers: Marty Reedy, Terry Doyle and Zak Pohlen
Principal Investigator: Kathy Kuletz
U.S. Fish & Wildlife Service
Migratory Bird Management
1011 E. Tudor Rd.
Anchorage, Alaska 99503

Background:

In conjunction with the 2017 Arctic IES Cruise marine bird surveys were conducted by U.S. Fish and Wildlife Service (FWS) observers aboard the R/V *Ocean Starr*. The cruise began in Dutch Harbor on August 1 and concluded in Nome on October 4, 2017. Marine bird surveys were conducted while the ship was underway through the Bering Sea and into the main survey area in the Chukchi. In this report we summarize data collected during three legs of the ArcticIERP survey. Data collated during these surveys will be uploaded to the ArcticIERP workspace and also archived in the North Pacific Pelagic Seabird Database (http://alaska.usgs.gov/science/biology/nppsd).

Methods:

Marine birds and mammals were surveyed from the starboard side of the bridge (6.78 meters/22.2 feet above the sea surface) using standard FWS protocols. Observations were conducted during daylight hours only while the vessel was underway. The observer scanned the water ahead of the ship using hand-held 10x 42 binoculars if necessary for identification and recorded all birds and mammals within a 300-m arc extending 900 from the bow to the beam. We used strip transect methodology and four distance bins extending from the vessel: 0-50 m, 51-100 m, 101-200 m, and 201-300 m and recorded the animal's behavior (flying, on water, foraging). Rare birds, large flocks, and mammals beyond 300 m or on the port side (off-transect) were also recorded but will not be included in density calculations. Birds on the water or actively foraging were counted continuously. Flying birds were recorded during quick 'Scans' of the transect window, with scan intervals based on ship speed (typically every 65 or 97 seconds). Observations were entered directly into a GPS-integrated laptop computer using the program DLOG3 (A.G. Ford Consultants, Portland, OR). Location data was also recorded automatically at 20 sec intervals, providing continuous records on weather, Beaufort Sea State, ice coverage, glare, and observation conditions. In addition, during this cruise the data management system CLAMS was used by the science crew to log of sampling events for future reference. Seabird surveys were entered into the system by recording the start end points of the survey effort while the vessel was underway.

Result:

A total of 6,565 km were surveyed during the Arctic IES cruise from Aug 1 – Oct 4, 2017 where we observed a total of 37,465 birds on-transect (Table 1) in the Bering and Chukchi Sea. Regionally we surveyed 1,670 km in the Bering Sea and recorded 9,808 birds. In the Chukchi a total of 6,565 km was surveyed and we recorded 27,657 birds on-transect. Although surveys were conducted across the Bering and Chukchi, the focus of this report will discuss the seabirds observed in the main Arctic IES study area in the Chukchi (Fig 1.)

Short-tailed shearwaters (*Ardenna tenuirostris*) were the most commonly observed species during the survey and comprised 65.6% of total observations in the Chukchi (Fig. 2). Shearwaters were widely distributed across the survey area during this time of year. Density was highest in the offshore areas north of Icy Cape. Although, shearwaters were largely absent in the study area north of 72°N.

Three species of auklets; crested auklets (*Aethia cristatella)*, least auklets (*Aethia pusilla),* and parakeet auklets (*Aethia psittacula*) comprised a total of 15.5 % of the total observations in the Chukchi (Figure 2). Crested auklets were the most prevalent auklet in the study area and comprised ~14% of the total auklet observations (Table 1). The highest density of crested auklets was observed north of 71°N in the northwestern part of the study area along with least auklets too. Parakeet auklets were mainly observed in the southern part of the Chukchi near Point Hope.

Black-legged kittiwakes (*Rissa tridactyla)* were the third most commonly observed species during the survey (Table 1). Kittiwakes were primarily observed in the southern portion of the study area extending north to ~70°N offshore of Cape Lisburne where they were seen in high densities (Fig. 4.) Glaucous gulls (*Larus hyperboreus)* were also seen across the region (Fig. 4), but were more widely distributed in the northern portion of the study area including nearshore and offshore waters. We also observed a concentration of Sabine's gulls (*Xema sabini*) and Arctic terns (*Sterna paradisaea*) along the southern portion of Barrow Canyon (Fig. 4). The majority of the Sabine's gulls and arctic terns were observed in the air when recorded during the survey. But, the birds may have also been using this area to feed. Both species are surface feeding birds that feed on similar prey items like small fish and crustaceans.

Murres (*Uria spp*.) represented 4.9% of the total observations, with thick-billed murres (*Uria lomivia*) accounted for most of the identified murres (3.5%). Thick-billed murres were recorded across the study area south of 72°N with the highest densities seen in the offshore waters northwest of Cape Lisburne (Fig. 5). Common murres (*Uria aalge*) were also distributed across the same region, but in much lower densities.

Phalaropes (*Phalaropus spp.*) were seen in patchy distribution across the study area and comprised 3.4% of the total observations (Table 1). Phalaropes were observed concentrated along Barrow Canyon and in the offshore waters northwest of Icy Cape and Wainwright (Fig. 6). In the southern Chukchi phalaropes were mainly observed near Point Hope.

Seaducks were primarily observed close to shore from Wainwright to Kivalina (Fig 7.) Long-tailed ducks (*Clangula hyemalis*) were the most commonly observed seaduck in the area. Eiders *(Somateria spp.)* were also seen in smaller groups but comprised only <.25% of the total observations.

Three species of loons (*Gavia spp*.) were recorded during the survey (Table 1). Pacific loons (*Gavia pacifica*) were the most commonly observed loon species with 54 recorded individuals. Loons were generally observed close to shore extending from Wainwright south to 67°N (Fig 8).

Marine mammal observations were also conducted during the survey using FWS survey protocols. We recorded a total of 204 marine mammals on and off transect during the survey in the Bering and Chukchi Sea (Table 2). Walrus were the most abundant marine mammal observed. The majority of walrus were concentrated in a small offshore region between Icy Cape and Wainwright (Fig. 9). Cetaceans were also seen in small numbers. High densities of gray and unidentified whales were seen in the region near Icy Cape and Wainwright (Fig. 10). Further south small groups of cetaceans were seen in the offshore waters of the DBO3 line extending off of Point Hope, and further south towards the Bering Strait. In addition, two deceased marine mammals were observed. The animals could not be positively identified, but one appeared to be a pinniped and the other a whale. A report has been submitted to the Marine

Table 1. Birds recorded on-transect during 2017 Arctic IES Surveys.

Common Name	Scientific Name	Bering		Chukchi		Total
		No.	% Total	No.	% Total	
Common Loon	*Gavia immer*			2	0.01	2
Pacific Loon	*Gavia pacifica*	34	0.35	54	0.20	88
Red-throated Loon	*Gavia stellata*	2	0.02			2
Yellow-billed Loon	*Gavia adamsii*	1	0.01	1	0.00	2
Unid. Loon	*Gavia* spp.	16	0.16	10	0.04	26
Black-footed Albatross	*Phoebastria nigripes*	6	0.06			6
Laysan Albatross	*Phoebastria immutabilis*	20	0.20			20
Northern Fulmar	*Fulmarus glacialis*	1885	19.22	507	1.83	2392
Short-tailed Shearwater	*Ardenna tenuirostri*	1564	15.95	18141	65.57	19705
Unid. Dark Shearwater	*Ardenna* spp.	3297	33.62	5	0.02	3302
Fork-tailed Storm-Petrel	*Oceanodroma furcata*	167	1.70	8	0.03	175
Unid. Procellariiformes	*Procellarid* spp.	8	0.08	2	0.01	10
Pelagic Cormorant	*Phalacrocorax pelagicus*	30	0.31	12	0.04	42
Red-faced Cormorant	*Phalacrocorax urile*	2	0.02			2
Cackling Canada Goose	*Branta hutchinsii*	1	0.01			1
Common Eider	*Somateria mollissima*			18	0.07	18
Harlequin Duck	*Histrionicus histrionicus*	4	0.04			4
King Eider	*Somateria spectabilis*	3	0.03	1	0.00	4
Long-tailed Duck	*Clangula hyemalis*	1	0.01	76	0.27	77
Spectacled Eider	*Somateria fischeri*			50	0.18	50
White-winged Scoter	*Melanitta fusca*	22	0.22			22
Unid. Eider	*Somateria* spp.	4	0.04	20	0.07	24
Unid. Duck	*Anatinae* spp.			2	0.01	2
Bald Eagle	*Haliaeetus leucocephalus*	1	0.01			1
Red Phalarope	*Phalaropus fulicarius*	41	0.42	215	0.78	256
Red-necked Phalarope	*Phalaropus lobatus*	1	0.01			1
Unid. Phalarope	*Phalaropus* spp.	102	1.04	716	2.59	818
Unid. Shorebird	*Scolopacidae* spp.	1	0.01	6	0.02	7
Long-tailed Jaeger	*Stercorarius longicaudus*	3	0.03	1	0.00	4
Parasitic Jaeger	*Stercorarius parasiticus*	4	0.04	15	0.05	19
Pomarine Jaeger	*Stercorarius pomarinus*	14	0.14	36	0.13	50
Unid. Jaeger	*Stercorarius* spp.	1	0.01	10	0.04	11
Arctic Tern	*Sterna paradisaea*	1	0.01	56	0.20	57
Unid. Tern	*Sterna* spp.			23	0.08	23
Black-legged Kittiwake	*Rissa tridactyla*	1029	10.49	1432	5.18	2461
Glaucous Gull	*Larus hyperboreus*	67	0.68	100	0.36	167
Glaucous-winged Gull	*Larus glaucescens*	149	1.52	1	0.00	150
Herring Gull	*Larus argentatus*	1	0.01			1
Red-legged Kittiwake	*Rissa brevirostris*	13	0.13			13
Unid. Kittiwake	*Rissa* spp.	6	0.06			6
Sabine's Gull	*Xema sabini*			39	0.14	39
Unid. Gull	*Larid* spp.	5	0.05	8	0.03	13
Common Murre	*Uria aalge*	136	1.39	248	0.90	384
Thick-billed Murre	*Uria lomvia*	199	2.03	973	3.52	1172

Common Name	Scientific Name	Bering		Chukchi		Total
		No.	% Total	No.	% Total	
Unidentified Murre	*Uria* spp.	57	0.58	123	0.44	180
Pigeon Guillemot	*Cepphus columba*	16	0.16			16
Ancient Murrelet	*Synthliboramphus antiquus*	88	0.90	188	0.68	276
Brachyramphus Murrelet	*Brachyramphus* spp.	4	0.04			4
Kittlitz's Murrelet	*Brachyramphus brevirostris*			22	0.08	22
Marbled Murrelet	*Brachyramphus marmoratus*	5	0.05			5
Cassin's Auklet	*Ptychoramphus aleuticus*	24	0.24			24
Crested Auklet	*Aethia cristatella*	67	0.68	3859	13.95	3926
Least Auklet	*Aethia pusilla*	88	0.90	299	1.08	387
Parakeet Auklet	*Aethia psittacula*	92	0.94	137	0.50	229
Unid. Auklet	*Aethiia* spp.	14	0.14	72	0.26	86
Horned Puffin	*Fratercula corniculata*	278	2.83	78	0.28	356
Tufted Puffin	*Fratercula cirrhata*	197	2.01	32	0.12	229
Unid. Puffin	*Fratercula* spp.	1	0.01			1
Unid. Alcid	*Alcid* spp.	36	0.37	52	0.19	88
Passerine spp.	*Passeriformes* spp.			2	0.01	2
Unid. Bird	*Aves* spp.			5	0.02	5
		9808		27657		37465

Table 2. Marine Mammals observed during 2017 Arctic IES surveys.

Common Name	Scientific Name	Bering		Chukchi		Total
		On	Off	On	Off	
Dall's Porpoise	*Phocoenoides dalli*	5				5
Harbor Porpoise	*Phocoena phocoena*			4	3	7
Harbor Seal	*Phoca vitulina*	1				1
Northern Fur Seal	*Callorhinus ursinus*	6				6
Unidentified Seal	*Phocidae* spp.	3		6	3	12
Walrus	*Odobenus rosmarus*			17	28	45
Unidentified Pinniped	*Pinnipedia* spp.			7		7
Fin Whale	*Balaenoptera physalus*		2	1	2	5
Gray Whale	*Eschrichtius robustus*			3	16	19
Humpback Whale	*Megaptera novaeangliae*	1	2	1	6	10
Killer Whale	*Orcinus orca*		5			5
Minke Whale	*Balaenoptera acutorostrata*	2	2			4
Unidentified Whale	*Cetacea* spp.		3	5	70	78

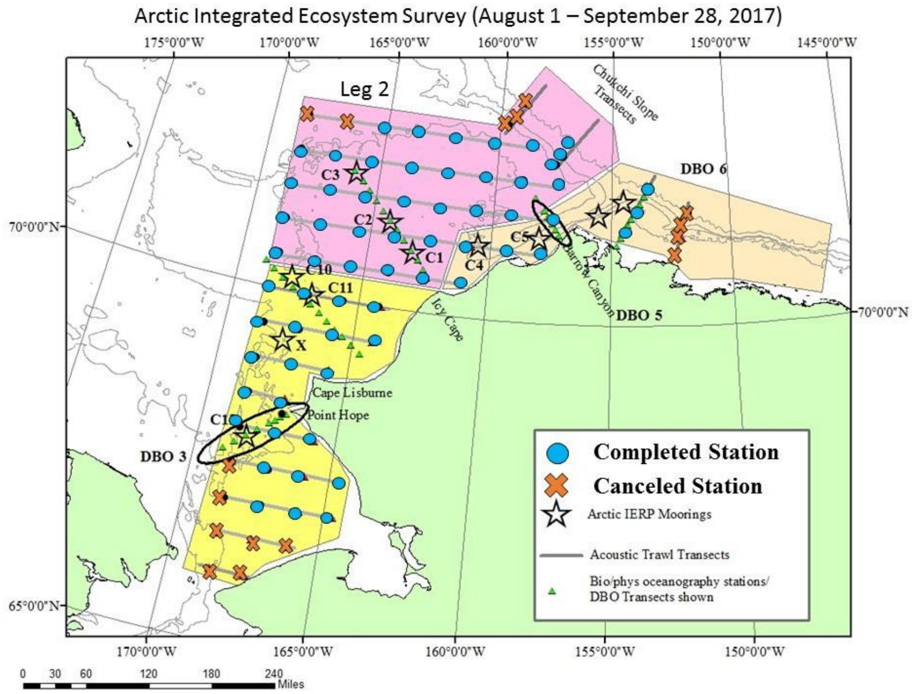


Figure 1. Study area for Arctic IES 2017: Leg 1 in tan, Leg 2 in purple, and Leg 3 in yellow. Marine Bird and Mammal Surveys were also conducted to/from ports in Nome, AK and Dutch Harbor, AK.

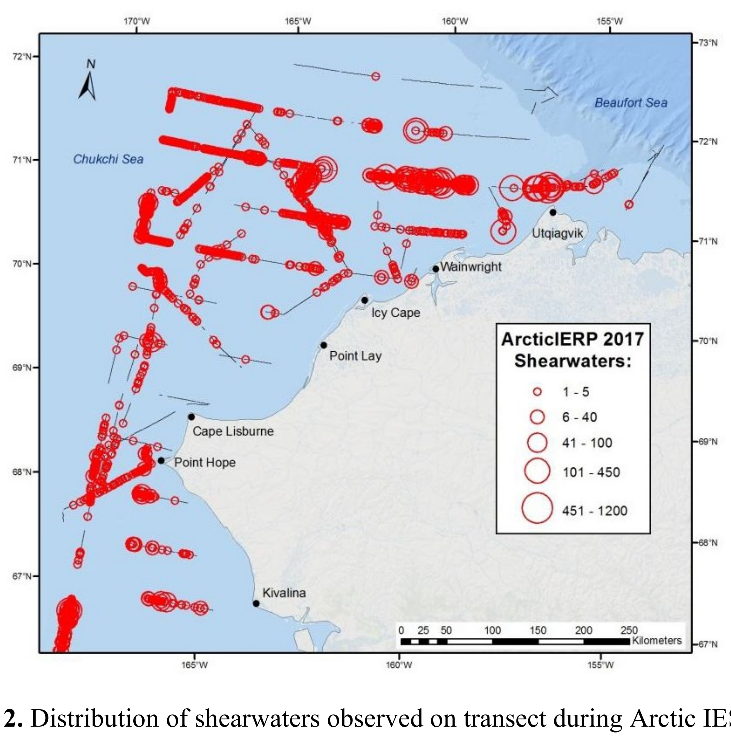


Figure 2. Distribution of shearwaters observed on transect during Arctic IES 2017.

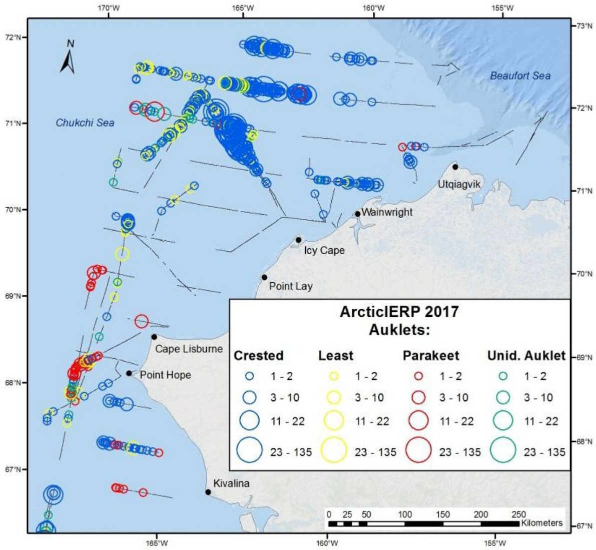


Figure 3. Distribution of auklets observed on transect during Arctic IES 2017.

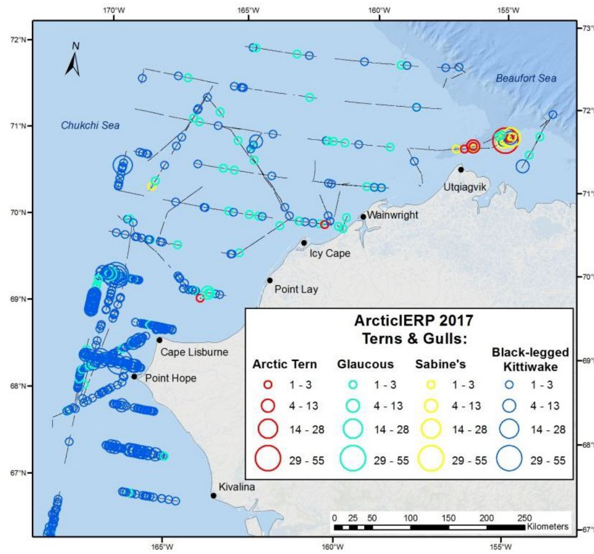


Figure 4. Distribution of terns and gulls observed on transect during Arctic IES 2017.

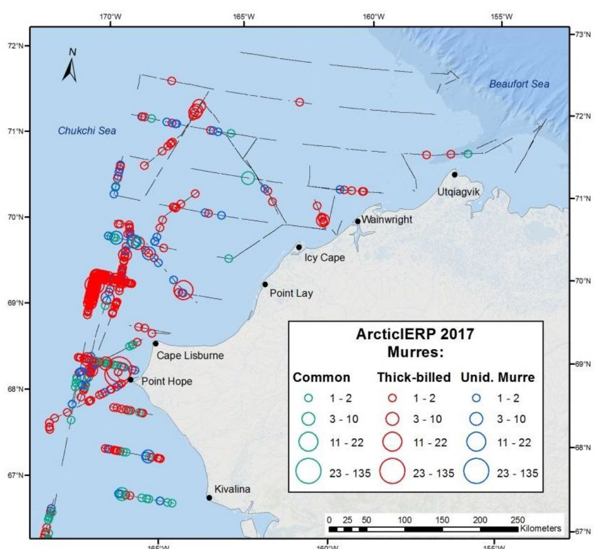


Figure 5. Distribution of murres observed on transect during Arctic IES 2017.

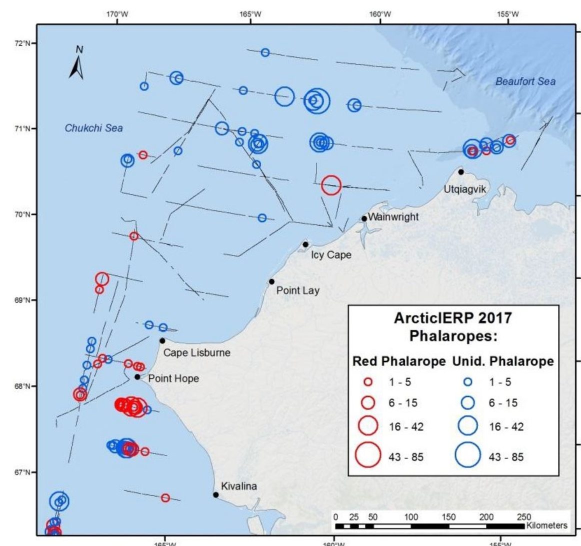


Figure 6. Distribution of phalaropes observed on transect during Arctic IES 2017.

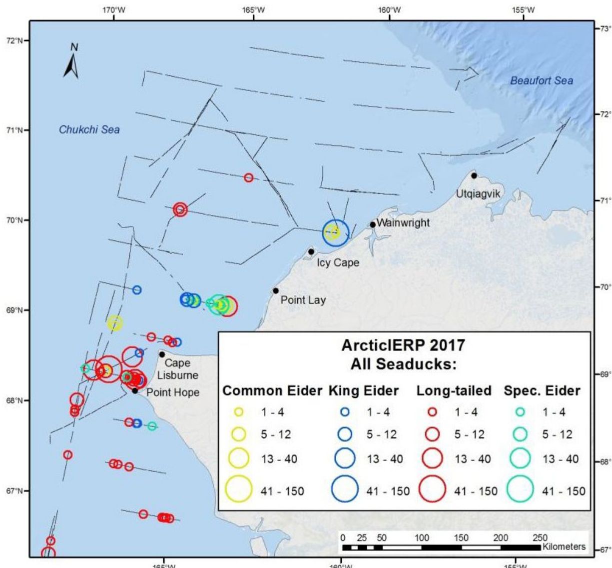


Figure 7. Distribution of all ducks observed during Arctic IES 2017.

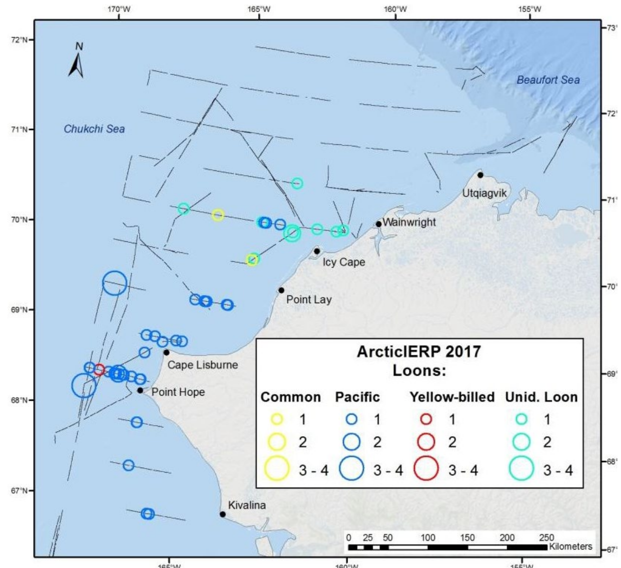


Figure 8. Distribution of loons observed on transect during Arctic IES 2017.

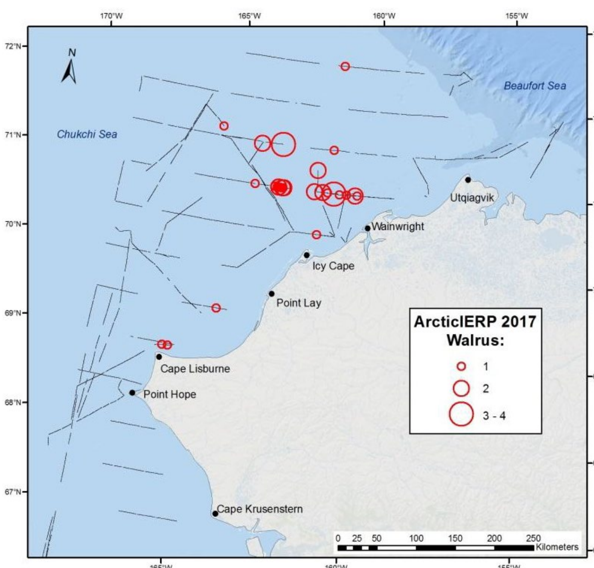


Figure 9. Distribution of walrus observed during Arctic IES 2017.

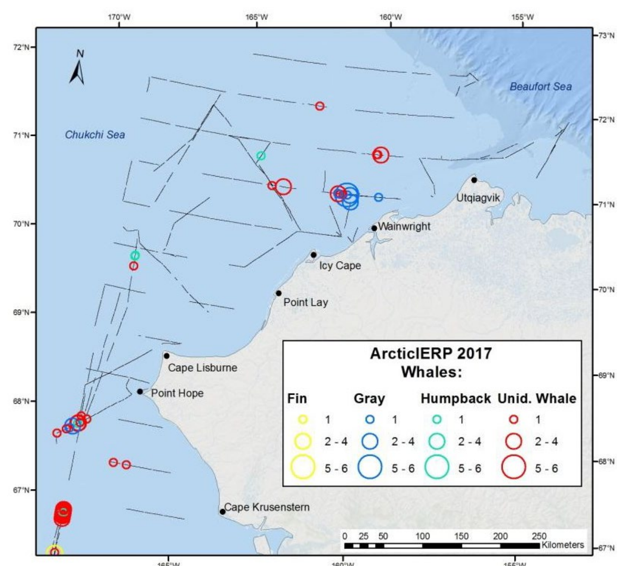


Figure 10. Distribution of whales observed during Arctic IES 2017.

A.6.4 Arctic IES 2019 Leg I-III Cruise Report for Marine Bird Surveys: 1 August–30 September 2019

Kathy Kuletz - Principal Investigator
Onboard observers: Marty Reedy, Charlie Wright, Linnaea Wright
Maps - Elizabeth Labunski
Migratory Bird Management, U.S. Fish and Wildlife Service, Anchorage, Alaska

Background:

The U.S. Fish and Wildlife Service (USFWS) conducted seabird surveys during the Arctic Integrated Ecosystem Survey (Arctic IES) Phase II, aboard the NOAA contract research vessel *Ocean Starr* from August 1-September 30, 2019. The seabird effort was funded through an Interagency Agreement (M17PG00017) with the Bureau of Ocean Energy Management (BOEM), Project AK-16-07c: Seabird Community Structure and Seabird-Prey Dynamics. The data will be integrated with Arctic IES data and will be archived in the North Pacific Pelagic Seabird Database (http://alaska.usgs.gov/science/biology/nppsd).

This report summarizes data collected during the Arctic IES portion of the cruise, in the Chukchi and Beaufort seas, although surveys were also conducted during transits to and from ports of call in the Bering Sea.

Methods:

Marine birds and mammals were surveyed from the starboard side of the bridge using standard USFWS marine bird protocols, thus mammal observations cannot be used to calculate densities. Observations were conducted during daylight hours while the vessel was underway. The observer scanned the water ahead of the ship using hand-held 10x42 binoculars as necessary for identification and recorded all birds and mammals. We used a modified strip transect methodology with four distance bins from the center line: 0-50 m, 51-100 m, 101- 200 m, 201-300 m. Rare birds, large flocks, and mammals beyond 300 m or on the port side ('off transect') were also recorded but will not be included in density calculations. We recorded the species, number of animals, and behavior (on water, in air, foraging). Birds on the water or actively foraging were counted continuously, whereas flying birds were recorded during quick 'Scans' of the transect window. Scan intervals were based on ship speed, ranging during this cruise from 49 sec to 97 sec, with the median at 65 sec.

Geometric and laser hand-held rangefinders were used to determine the distance bin to bird sightings. Observations were directly entered into a GPS-interfaced laptop computer using the DLOG3 program (Ford Ecological Consultants, Inc., Portland, OR). Location data were also automatically written to the program in 20-second intervals, which allowed us to track survey effort and simultaneously record changing weather conditions, Beaufort Sea State, glare, and ice coverage (no ice was encountered during this cruise). Other environmental variables recorded at the beginning of each transect included wind speed and direction, cloud cover, sea surface temperature, and air temperature.

Preliminary Results

We surveyed a total of 4884 km, with 4749 km in the Chukchi Sea and 135 km in the Beaufort Sea. On transect we recorded a total of 23,400 birds with the highest birds per linear km surveyed in the Chukchi Sea (4.8 birds/km) and 4 birds/km in the Beaufort Sea. We recorded 31 species on transect with species diversity highest in the Chukchi Sea (31 species). The Beaufort Sea recorded eight species (Table 1).

Marine birds

Unidentified dark shearwaters (*Ardenna spp*) and short-tailed shearwaters (*Ardenna tenuirostris*) were 81% of all recorded seabird species throughout the survey area and dominated both the Chukchi and Beaufort Sea, comprising 81% and 85%, respectively (Table 1). Survey effort was very low in the Beaufort, thus the vast majority of the shearwaters were in the Chukchi Sea, with high densities south of Point Hope, offshore of Point Lay, and north of Wainwright (Fig. 1).

The *Alcidae* family includes common murres (*Uria aalge*), thick-billed murres (*U. lomvia*), ancient murrelets (*Synthliboramphus antiquus*), crested auklets (*Aethia cristatella*), least auklets (*A. pusilla*), parakeet auklets (*A. psittacula*), horned puffins (*Fratercula corniculata*), and tufted puffins (*F. cirrhata*). This family comprised 8% of the birds throughout both regions, with a density of 8% in the Chukchi Sea and <1% in the Beaufort Sea. The three *Aethia* auklet species were 5% of birds in the Chukchi Sea, but were not observed in the Beaufort Sea. Among the auklets, crested auklets were most abundant, and were found north of 71.5ºN in the northern Chukchi Sea (Fig. 2). Parakeet auklets were recorded offshore of Point Lay and Kivalina, while least auklets were primarily south of Point Hope.

We recorded seven species of Larids in the study area: pomarine jaeger (*Stercorarius pomarinus*), parasitic jaeger (*S. parasiticus),* long-tailed jaeger (*S. longicaudus*), black-legged kittiwake (*Rissa tridactyla*)*,* glaucous gull (*Larus hyperboreus*), Sabine's gull (*Xema sabini*), and arctic tern (*Sterna paradisaea)* (Table 1). As a group, the *Laridae* family comprised 5% of total birds and were the most abundant group aside from shearwaters in the Beaufort Sea, comprising 13% of total birds in that region (Table 1). Black-legged kittiwakes were the majority of Larid species in the Chukchi Sea while the Beaufort Sea had equal numbers of kittiwakes and glaucous gulls (Table 1). Arctic tern was the second most abundant bird (10%) in the Beaufort Sea with the majority of birds recorded nearshore north of 70ºN (Fig. 1). Most of the Sabine's gulls were recorded in a single forage flock of 21 birds near Icy Cape (Fig. 3).

Phalaropus species, comprised of red phalaropes (*Phalaropus fulicarius*) and red-necked phalaropes (*P. lobatus*), have similar plumages in the fall and are difficult to distinguish at sea, thus many of the phalaropes were only identified to genus. Their relative density was 5% over both regions, although only three individuals were observed in the Beaufort Sea (Table 1). Phalarope numbers were highest in the Hope Basin along with smaller groups scattered offshore and near Wainwright (Fig. 4).

Gavia species observed during this survey were pacific loon (*Gavia pacifica*), arctic loon (*G. arctica),* common loon (*G. immer*), and yellow-billed loon (*G. adamsii*). *Gavia* species were <1% of total birds in the Chukchi Sea (Table 1). Long-tailed ducks (*Clangula hyemalis*) were the most commonly encountered waterfowl, and with king eiders (*Somateria spectabilis*), and spectacled eiders (*Somateria fischeri*), comprised <1% of total birds (Table 1).

Marine mammals

We recorded marine mammals during our surveys, but because we used seabird survey protocols our observations cannot be used to calculate densities. The USFWS observer recorded 356 marine mammals of 10 identified species, including off-transect individuals. All sightings were in the Chukchi Sea with none observed in the Beaufort Sea. There were five *Mysticeti* species with 122 individuals, of which the humpback whale was the most common with 28 individuals (Table 2).

Gray whales (*Eschrichtius robustus*) were a commonly observed whale, with 11 records (Table 2). Three individuals of this species were photographed and those observations have been sent to Sue Moore, University of Washington, Seattle. These observations are part of an assessment of gray whale body condition to further the investigation of an UME (Unusual Mortality Event) declared by NOAA for this species. Walrus (*Odobenus rosmarus*) were the most frequently observed mammal (Table 2). With no ice at their normal haul out areas, walrus were congregating along the coastal waters of Point Lay.

Observations of dead birds and mammals

During the three legs of this study we recorded 30 dead birds, all in the Chukchi Sea (Fig. 5). The majority were alcids (n = 11), followed by six shearwaters, two sandpipers (*Scolopocidae* spp.), one kittiwake, and nine unidentified birds (Table 3). Most of the dead birds were encountered south of Point Hope and offshore of Point Lay. With the able assistance of the crew and scientists we were able to collect 10 birds, which have been submitted to the USGS Wildlife Center in Madison, WI, for necropsies, testing for avian diseases, and tissue removal for toxin tests.

Additionally, three deceased walrus were observed, all of them headless. One seal, one unidentified cetacean, and two unidentified mammals were also found dead in the water in the Chukchi Sea. The majority of these animals were in advanced stages of decomposition. We submitted reports to the USFWS Marine Mammal office (Anchorage, AK) and to the NOAA Alaska Marine Mammal Stranding Network.

Table 1. Seabirds observed on transect during the 1 August–30 September 2019 Arctic IES cruise.

			CHUKCHI		BEAUFORT		ALL REGION	
Family	**Common Name**	***Latin name***	**No.**	**% Total**	**No.**	**% Total**	**No.**	**% Total**
Gaviidae	Unidentified loon	*Gavia spp.*	14	0.06	1	0.19	15	0.06
	Pacific loon	*Gavia pacifica*	56	0.24			56	0.24
	Arctic loon	*Gavia arctica*	1	<0.01			1	<0.01
	Common Loon	*Gavia immer*	3	0.01			3	0.01
	Yellow-billed loon	*Gavia adamsii*	5	0.02			5	0.02
Procellariidae	Northern fulmar	*Fulmaris glacialis*	107	0.47	1	0.19	108	0.46
	Unidentified dark shearwater	*Puffinus spp.*	3	0.01			3	0.01
	Short-tailed shearwater	*Puffinus tenuirostris*	18435	80.64	457	84.94	18892	80.74
Hydrobatidae	Fork-tailed storm-petrel	*Oceanodroma furcata*	1	<0.01			1	<0.01
Anatidae	Unidentified waterfowl	*Anatidae family*	1	<0.01			1	<0.01
	Unidentified duck	*Anatidae spp.*	3	0.01			3	0.01
	Long-tailed duck	*Clangula hyemalis*	22	0.10			22	0.09
	Unidentified eider	*Somateria spp.*	2	<0.01			2	0.01
	King eider	*Somateria spectabilis*	14	0.06			14	0.06
	Common Eider	*Somateria mollissima*	1	<0.01			1	<0.01
	Spectacled Eider	*Somateria fischeri*	3	0.01			3	0.01
	White-winged scoter	*Melanitta fusca*	2	<0.01			2	0.01
Charadriidae	Pacific golden-plover	*Pluvialis fulva*	3	0.01			3	0.01
Scolopacidae	Unidentified shorebird	*Scolopacidae family*	13	0.06	1	0.19	14	0.06
	Unidentified turnstone	*Arenaria spp.*	1	<0.01	2	0.37	3	0.01
	Unidentified phalarope	*Phalaropus spp.*	689	3.01			689	2.94
	Red phalarope	*Phalaropus fulicarius*	492	2.15			492	2.10
Laridae	Pomarine jaeger	*Stercorarius pomarinus*	28	0.12			28	0.12
	Unidentified jaeger	*Stercorarius spp.*	10	0.04			10	0.04
	Parasitic jaeger	*Stercorarius parasiticus*	12	0.05	4	0.74	16	0.07
	Long-tailed jaeger	*Stercorarius longicaudus*	1	<0.01			1	<0.01
	Unidentified gull	*Laridae family*	4	0.02			4	0.02
	Black-legged kittiwake	*Rissa tridactyla*	822	3.60	7	1.30	829	3.54
	Sabine's gull	*Xema sabini*	54	0.24	1	0.19	55	0.24
	Glaucous gull	*Larus hyperboreus*	95	0.42	7	1.30	102	0.44
	Arctic tern	*Sterna paradisaea*	78	0.34	53	9.85	131	0.56
	Unidentified alcid	*Alcidae family*	73	0.32	4	0.74	77	0.33
Alcidae	Unidentified murre	*Uria spp.*	78	0.34			78	0.33
	Common murre	*Uria aalge*	114	0.50			114	0.49
	Thick-billed murre	*Uria omvia*	313	1.37			313	1.34
	Unidentified murrelet	*Brachyramphus spp.*	3	0.01			3	0.01
	Kittlitz's murrelet	*Brachyramphus brevirostris*	3	0.01			3	0.01
	Ancient murrelet	*Synthliboramphus antiquus*	21	0.09			21	0.09
	Unidentified auklet	*Aethia spp.*	53	0.23			53	0.23
	Crested Auklet	*Aethia cristatella*	734	3.21			734	3.14
	Least auklet	*Aethia pusilla*	244	1.07			244	1.04
	Parakeet auklet	*Aethia psittacula*	199	0.87			199	0.85
	Horned puffin	*Fratercula corniculata*	26	0.11			26	0.11
	Tufted puffin	*Fratercula cirrhata*	16	0.07			16	0.07
Aves class	Passerine	*Passeriformes spp.*	1	<0.01			1	<0.01
	Unidentified bird	*Aves spp.*	9	0.04			9	0.04
			22862		**538**		**23400**	

Table 2. Marine mammals observed (on and off transect), 1 August-30 September 2019 Arctic IES. No mammals were observed in the Beaufort Sea.

Order	Suborder	Common name	*Latin name*	Chukchi
Cetacea		Unidentified Whale	*Cetacea* (Order)	70
	Mysticeti	Bowhead whale	*Balaena mysticetus*	2
		Fin Whale	*Balaenoptera physalus*	6
		Minke Whale	*Balaenoptera acutorostrata*	5
		Humpback Whale	*Megaptera novaeangliae*	28
		Gray whale	*Eschrichtius robustus*	11
	Odontoceti	Killer whale	*Orcinus orca*	1
		Harbor Porpoise	*Phocoena phocoena*	1
Carnivora	Pinnipedia	Unidentified Pinniped	*Caniformia* (Suborder)	8
		Unidentified Seal	*Phocidae* (Family)	7
		Ringed Seal	*Pusa hispida*	1
		Walrus	*Odobenus rosmarus*	216
				356

Table 3. Dead birds observed in the Chukchi Sea, 1 August-30 September 2019 during Arctic IES; all records in this table were observed in the Chukchi Sea. This table does not include dead birds found during transit between Dutch Harbor and the study area.

SPECIES Observed	No. Observed	No. Collected
Black-legged kittiwake	1	1
Crested auklet	1	1
Northern fulmar	1	
Thick-billed murre	1	1
Unidentified auklet	1	
Tufted puffin	1	1
Horned puffin	2	
Pectoral sandpiper	2	2
Unidentified murre	2	
Common murre	3	2
Short-tailed shearwater	6	2
Unidentified bird	9	
	30	**10**

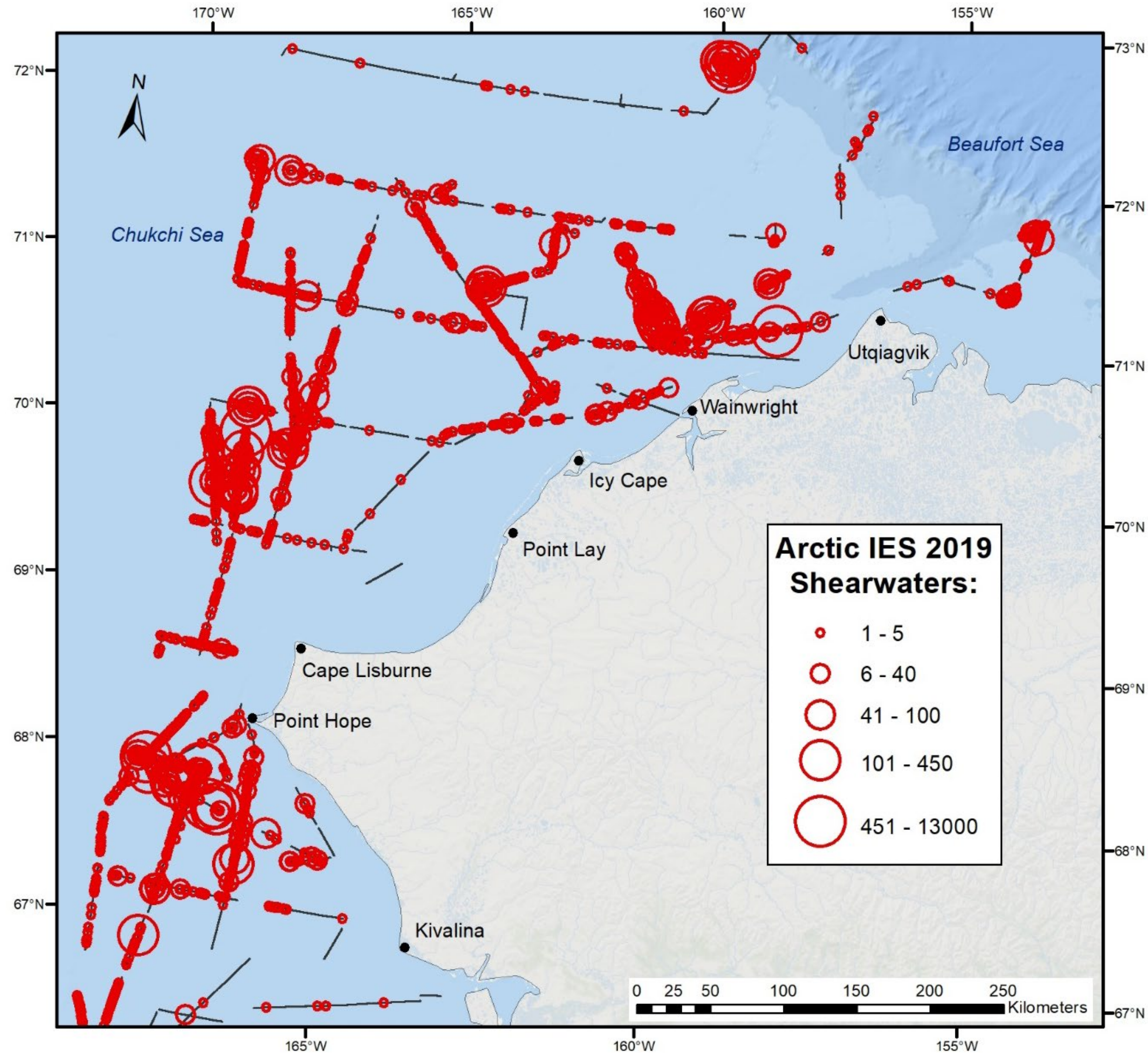


Figure 1. Distribution of shearwaters observed during the Arctic IES survey, 1 Aug–30 Sept 2019.

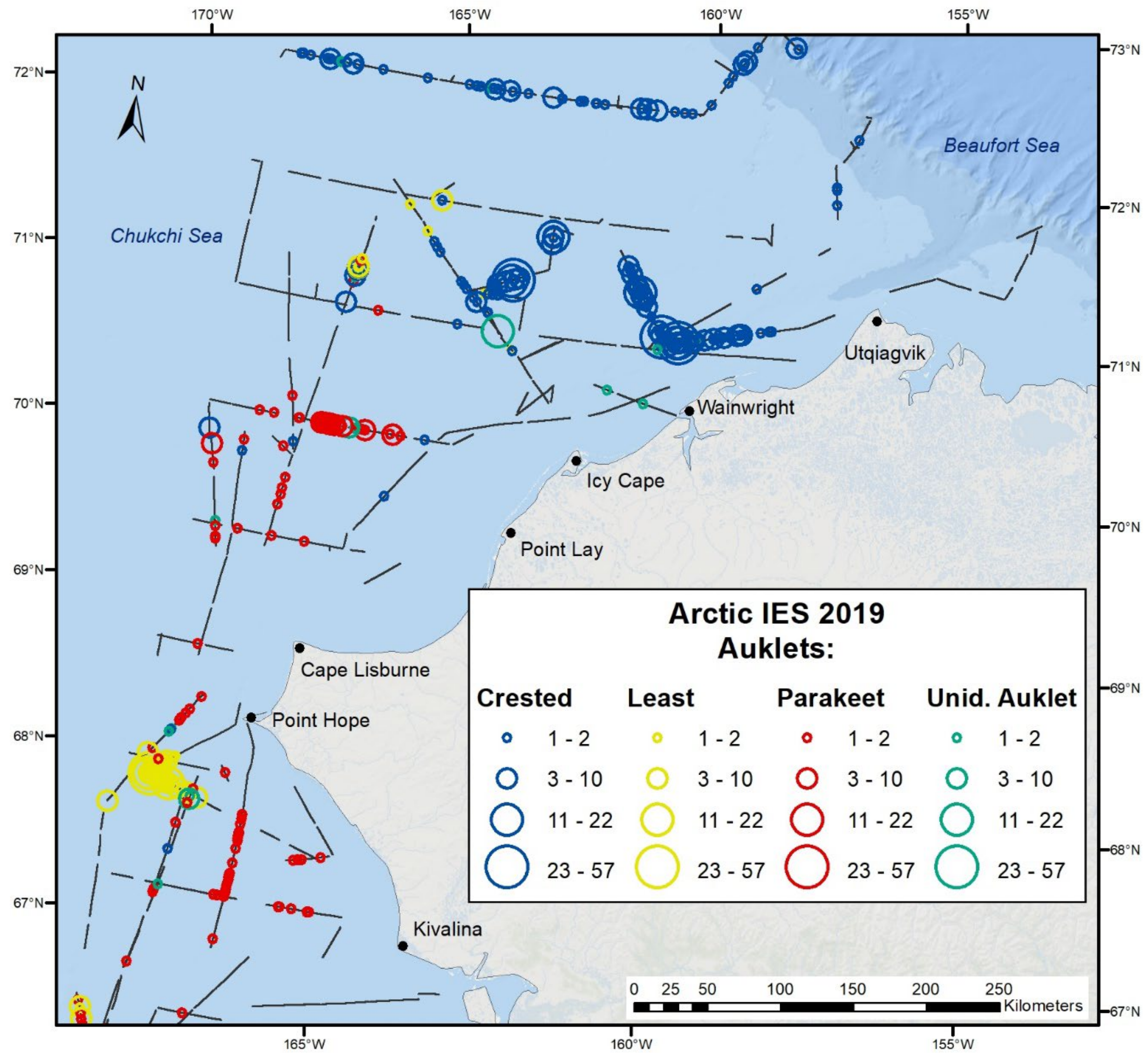


Figure 2. Distribution of auklets observed during the Arctic IES survey, 1 Aug–30 Sept 2019.

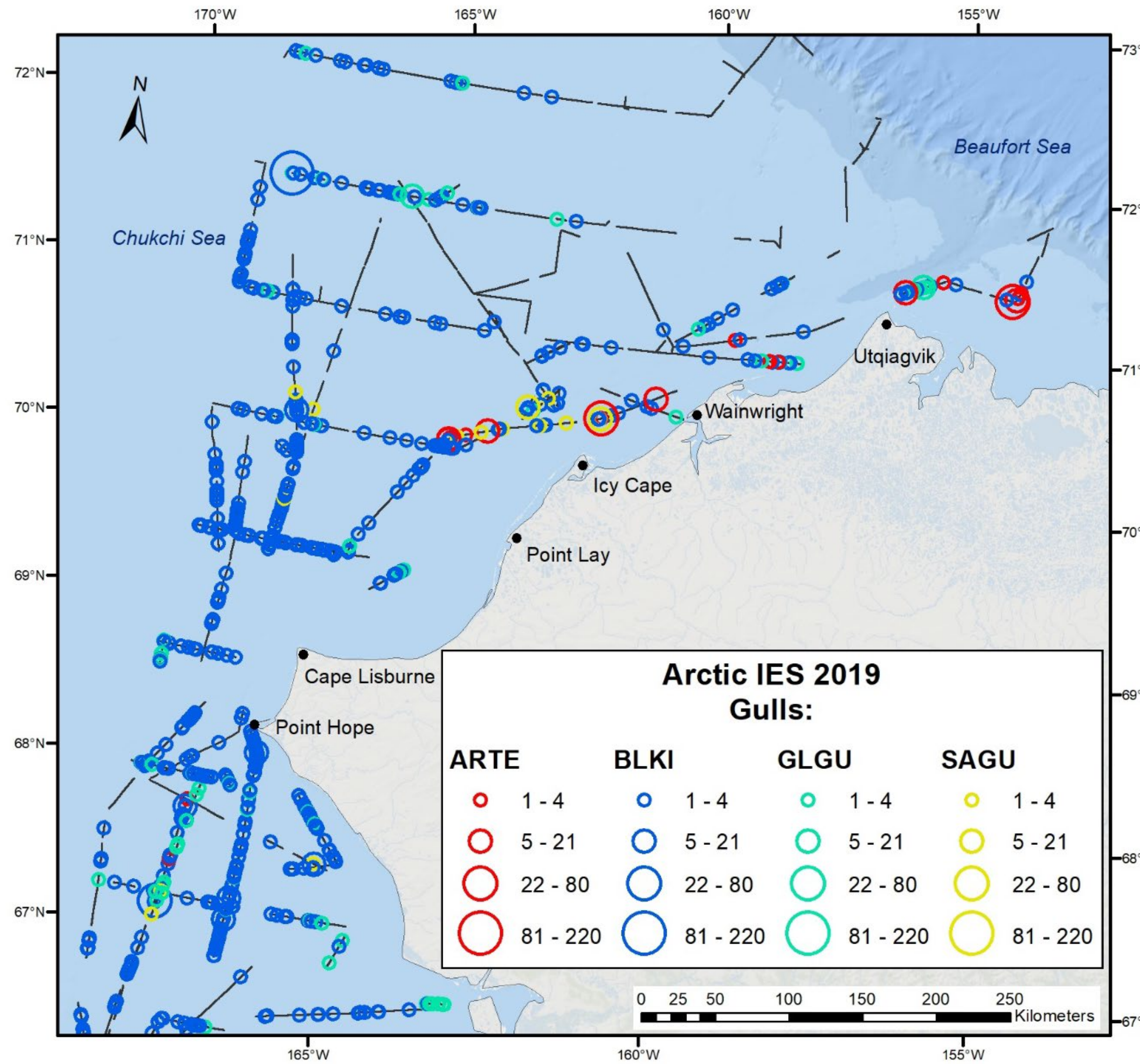


Figure 3. Distribution of Larid species observed during the Arctic IES survey, 1 Aug–30 Sept 2019. Species Codes: ARTE (Arctic Tern), BLKI (Black-legged Kittiwake), GLGU (Glaucous Gull), SAGU (Sabine's Gull).

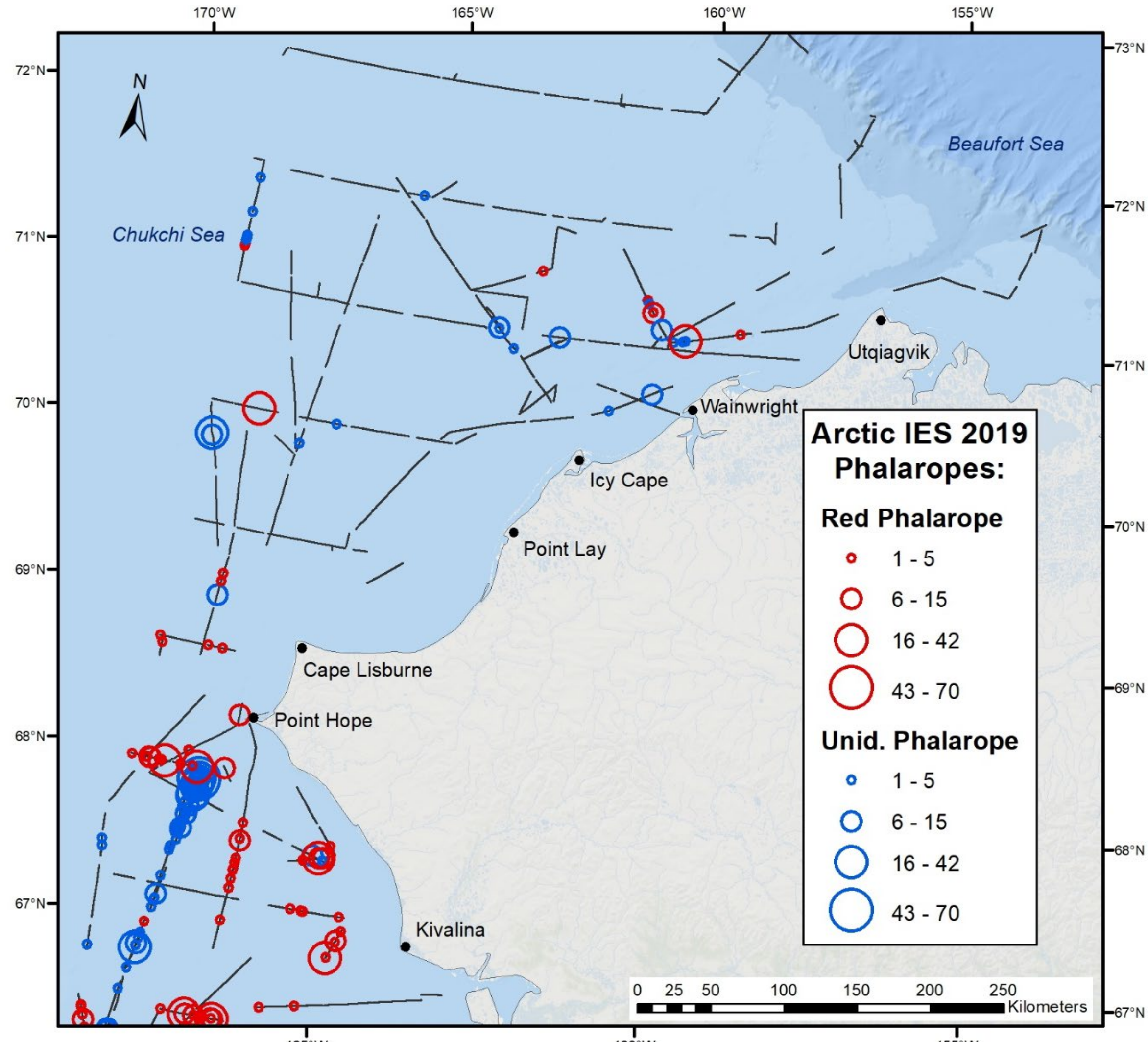


Figure 4. Distribution of phalaropes observed during the Arctic IES survey, 1 Aug–30 Sept 2019.

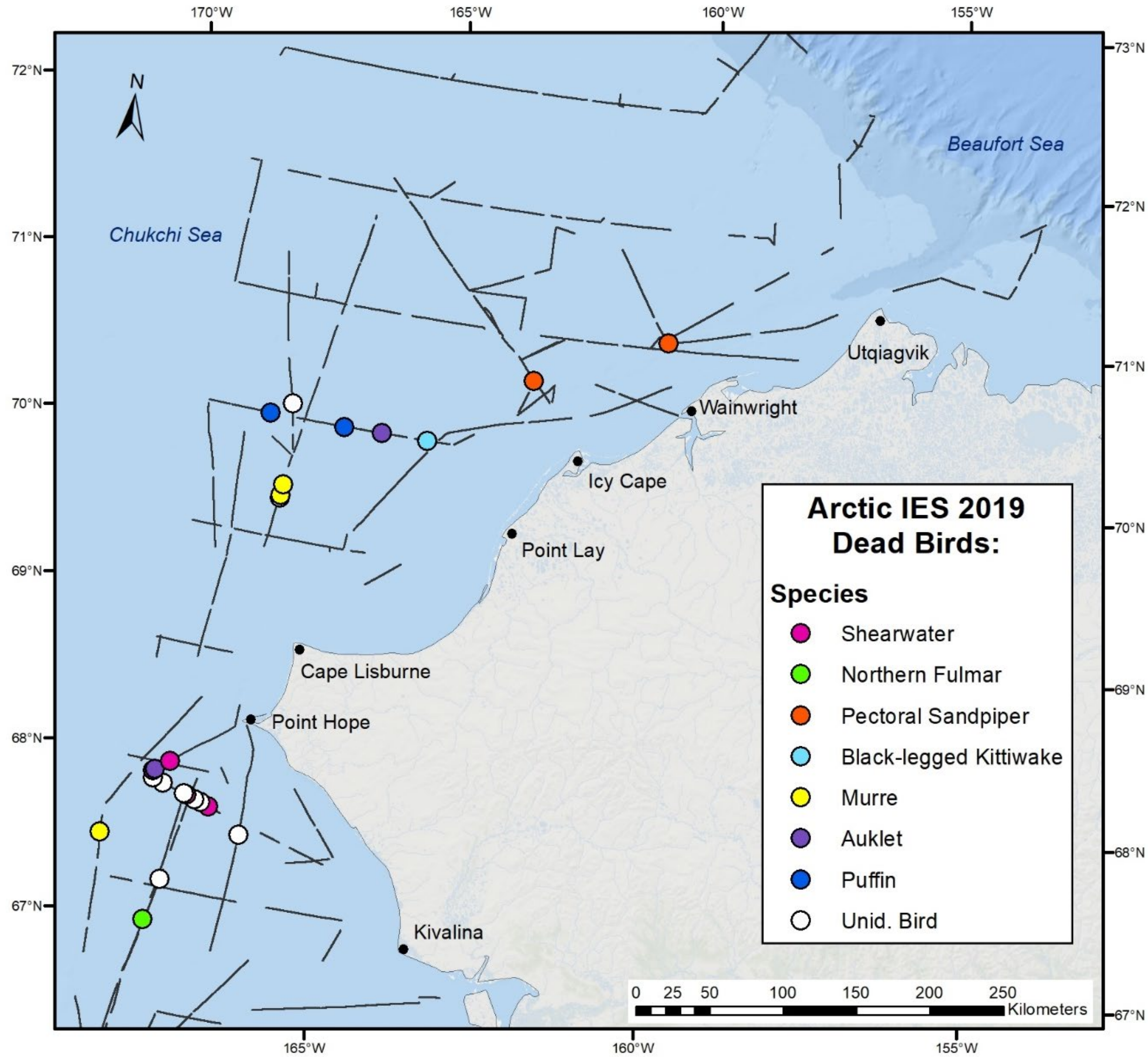


Figure 5. Distribution of dead birds observed during the Arctic IES survey, 1 Aug–30 Sept 2019.

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