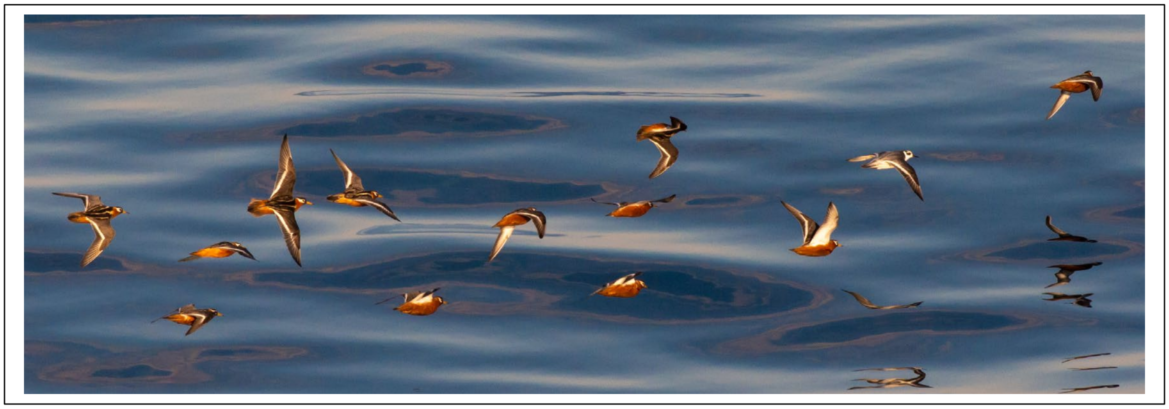
OCS Study
BOEM 2022-067

Marine Bird Distribution and Abundance in Offshore Waters



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

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September 2022

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Bureau of Ocean Energy Management

DISCLAIMER

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ABOUT THE COVER

Top: An immature short-tailed albatross on the Bering Sea taking flight. Photo by K. Kuletz.

Middle: The University of Alaska Fairbanks' R/V *Sikuliaq* in offshore waters of Alaska. Photo by Jennifer Johnson, NOAA.

Bottom: Flock of red phalaropes over calm seas. Photo by C. Wright.

Inset: Black-legged Kittiwake. Photo by K. Kuletz.

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List of Abbreviations and Acronyms

ACC	Alaska Coastal Current
ACCAP	Alaska Center for Climate Assessment and Policy
AIERP	Arctic Integrated Ecosystem Research Program
AIS	Automatic Information Systems
AMBON	Arctic Marine Biodiversity Observing Network
AOOS	Alaska Ocean Observing System
Arctic IES	Arctic Integrated Ecosystem Survey
Arctic NCIS	Arctic Chukchi Integrated Study
ARCCS	Arctic Systems Science Program
ASGARD	Arctic Shelf Growth Advection Respiration Deposition Rate
BOEM	Bureau of Ocean Energy Management
C3O	Canada Three Oceans
CAFF-CBMP	Conservation of Arctic Flora and Fauna-Circumpolar Biodiversity Monitoring Program
CCGS	Canadian Coast Guard Service
Cbird	Circumpolar Seabird Group
COASST	Coastal Observation and Seabird Survey Team
DBO	Distributed Biological Observatory
ESA	Endangered Species Act
ESM	Environmental Science Management
FOCI	Fisheries Oceanographic Coordinated Investigations
GIS	Geographic Information System
IAA	Intra-agency Agreement
IARPC	Arctic Research Policy Committee
JDSDM	Joint Dynamic Species Distribution Models
LME	Large Marine Ecosystem
NBS	Northern Bering Sea Fisheries Survey
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
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VAST	Vector Autoregressive Spatiotemporal modeling
WGICA	Working Group on Integrated Ecosystem Assessment for the Central Arctic Ocean

Acknowledgments

This project was funded by an Intra-agency Agreement from the Bureau of Ocean Energy Management (Project BOEM AK-17-03). The US Fish and Wildlife Service, Office of Migratory Bird Management, provided in-kind support for K. Kuletz (Principal Investigator) and E. Labunski (Biologist), as well as community outreach conducted by T. Zeller. Dan Cushing (Pole Star Ecological Research LLC, Anchorage, AK) processed the original data and participated in analyses and production of associated publications. We depended on the hospitality and expert seamanship of the vessel crews of the *Sikuliaq* (University of Alaska Fairbanks), *Healy* (U.S. Coast Guard), *Sir Wilfrid Laurier* (Canadian Coast Guard), *Oscar Dyson* (NOAA), *Northwest Explorer* (NOAA Charter Vessel), *Tiglax* (U.S. Fish and Wildlife Service), *Oshoro Maru* (University of Hokkaido), and *Noresman II* (UAF charter vessel). We thank the captains and crew for their seamanship, safe operations, hospitality, and exceptional efforts in support of our studies. Chief Scientists and Principal Investigators that contributed logistic and scientific support, as well as data, during this project included: Carin Ashjian, Jackie Grebmeier, Toro Hirawake, Katrin Iken, Franz Mueter, Jim Murphy, John Nelson, and Bob Pickart. K. Kuletz and E. Labunski periodically served as observers, as did Brendan Higgins, Zachary Pohlen, Martin Reedy, Charlie Wright, Linnaea Wright, and Tamara Zeller. We thank them all for their dedication and professionalism at sea.

List of Presentations and Outreach Efforts

Presentations at Professional Meetings

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 through 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 entitled "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.

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

Saalfeld S, Valcu M , Lanctot R, Krietsch J, McGuire R, Robards M, Schulte S, Brown S, Latty C, Harrison A-L, Scarpignato A, Kempenaers B. 2020. Migratory movements of Red Phalarope in the Beaufort, Chukchi and Bering Seas, and their association with oceanographic conditions. Alaska Shorebird Group Meeting. Anchorage, Alaska, December 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. Oral presentation.

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.
- 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's 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. The WGICA will provide an ecosystem assessment and recommendations regarding shipping and potential fishery and resource extraction impacts in the Central Arctic Ocean Large Marine Ecosystem and adjacent slope and shelf regions (i.e., the Bering Strait and Chukchi Sea). K. Kuletz is a team member of WG-39.
- 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.
- Integrated Environmental Assessment of the Northern Bering-Chukchi Sea Large Marine Ecosystem. This is a working group (WG44, formalized in September 2020) under the ICES/PICES Secretariat. K. Kuletz is a team member of WG 44.

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
- 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 meeting, 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.
- NOAA's Alaska Seabird Bycatch Working Group meeting, Juneau, Alaska, March 2018.

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.

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 meeting in La Jolla, California, May 2018.

Websites and Press Articles

A series of seabird mortality events ("die-offs") occurred along the coastlines and islands of the 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 all cruises. Several of our 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, USFWS seabird observers and biologists 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, https://www.fws.gov/alaska/pdf/BeringSea_DieOff_Info_Ver3_DEC2017_Final.pdf

- 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 website: https://blog.arctic.nprb.org/blog/2019/8/5/the-sound-of-science
- 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
- 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
- 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

List of Publications

The following publications were based in part on seabird data collected during this project, or used some component of those 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. 2022. Influence of water masses on the summer structure of the seabird community in the northeastern Chukchi Sea. Plos One 17: e0266182 (Appendix 1).

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. (Appendix 2)

Nishizawa, Bungo, Nodoka Yamada, Haruka Hayashi, Charlie Wright, Kathy J. Kuletz, Hiromichi Ueno, Tohru Mukai, Toru Hirawake, and Yutaka Watanuki. 2020. At-Sea Associations between seabirds and their prey in the northern Bering Sea during summer of 2017 and 2018. *Deep Sea Research II.* vol 181–182, https://doi.org/10.1016/j.dsr2.2020.104898.

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.

Publications in Prep

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

Saalfeld ST, Valcu M, Brown S, English W, Giroux M-A, Harrison A-L, Krietsch J, Kuletz K, Lamarre J-F, Latty C, Lecomte N, McGuire R, Robards M, Scarpignato A, Schulte S, Smith P, Kempenaers B, Lanctot, R. In Prep. Variability in the southward migration of the North American Red Phalarope. Marine Ecology Progress Series.

List of Reports

This project relied on collaboration with multiple vessel-based projects and programs operating in Alaska. Long-term and continuing projects which we collaborated with included the Distributed Biological Observatory, the Arctic Marine Biodiversity Observing Network, NOAA's fisheries surveys, and the Canadian 3-Oceans (C3O) program, among others. K. Kuletz and the USFWS team provided annual project reports (Appendix 3). 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. In addition, quarterly reports were made to the Bureau of Ocean Energy Management (BOEM). Because this report is required to be comprehensive and stand alone, components of previous reports have been incorporated into this report.

Study Objectives

The goal of this project (AK-17-03) was to conduct at-sea surveys to provide pertinent information on the seasonal distribution and abundance of marine birds in the Chukchi and Beaufort seas and oceanographically and biologically connected waters of the northern Bering Sea. A secondary goal was to support a pilot program to investigate nearshore and marine habitat use by the red phalarope (*Phalaropus fulicarius*), a terrestrial-breeding shorebird, using recently developed GPS tags. This information will provide the U.S. Fish and Wildlife Service (USFWS), the North Pacific Research Board (NPRB), and Bureau of Ocean Energy Management (BOEM) with current data and improved knowledge for ongoing and proposed marine planning activities, particularly oil and gas exploration, development, and production in the Chukchi and Beaufort Sea Planning Areas. The USFWS conducted marine bird surveys by collaborating with vessel-based projects conducting research in these geographic regions. Results provided the spatial distribution and seasonal changes in marine bird communities within and near the Planning Areas. The seabird data were processed, submitted, and archived in the North Pacific Pelagic Seabird Database (NPPSD), and were submitted to the BOEM Environmental Sciences Management Section (ESM).

Specific study objectives under Intra-agency Agreement M17PG00039 were:

1. Coordinate with vessel-based research programs conducting operations in the Bering, Chukchi or Beaufort seas, and place marine observers on vessels during research cruises. Conduct seabird surveys from vessel platforms and obtain at-sea density estimates of all marine birds.
2. Determine the spatial distribution, species composition, and seasonal changes in species and abundances for marine birds in designated and potential BOEM Planning Areas.
3. Process data for entry into the NPPSD for future accessibility to facilitate management decisions and to develop a geodatabase for BOEM use.

4. Coordinate with project Principal Investigators of the associated research cruises to integrate marine bird data with oceanographic and prey data.
5. Determine migratory movements and nearshore and marine habitat use of red phalaropes, in conjunction with associated at-sea surveys and oceanographic and prey data.

Study Chronology

This OCS Study (BOEM Project AK-17-03) was proposed in March 2017 and initiated through an Intra-agency Agreement (IAA) between the USFWS and BOEM in April 2017. The original Principal Investigator, Kathy Kuletz, retired in February 2022, and Elizabeth Labunski took over as PI. The original period of performance was designated from July 18, 2017 to September 20, 2021. Modifications to the IAA were made annually to provide funds to continue the at-sea surveys through fall 2022. 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 December 20, 2022 (Modification 8). During all years of this study, 2017–2021, the USFWS conducted marine bird surveys in collaboration with a variety of vessel-based research projects. All data collected during this project has been submitted to the BOEM Anchorage office and to the North Pacific Pelagic Seabird Database (NPPSD). The NPPSD, managed by the U.S. Geological Survey (USGS), consolidates and archives marine bird and mammal survey data and the most recent version includes data collected by USFWS, 2006–2020 (Drew and Piatt 2015). Using the remaining AK-17-03 funds, five surveys were conducted with collaborators in summer and fall 2022; these data will be contributed to the NPPSD and the BOEM ESM, but are not included in this report.

Survey data from the Arctic Marine Biodiversity Observing Network cruise in 2017 also have been archived on the Alaska Ocean Observing System Arctic Integrated Ecosystem Survey (Arctic IES) Workspace at https://www.sciencebase.gov/catalog/item/5e0e2aeee4b0b207aa137840

During the BOEM AK-17-03 project, (IAA M17PG00039) the USFWS also conducted surveys in the same study region as part of BOEM AK-16-07c (IAA MP17PG00017). The data from these two projects were complementary and thus were typically combined for analyses used in publications and presentations. Publications that incorporated data from both of these recent BOEM projects also typically included data from previous USFWS offshore seabird surveys, which were funded by grants and other 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 2015), 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 Intra-agency Agreement with the Bureau of Ocean Energy Management (BOEM M17PG00039) to conduct at-sea seabird surveys in the Bering, Chukchi and Beaufort seas. Results provide BOEM with current data, as well as seasonal comparisons, of 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 ESM. We conducted surveys during 2017–2022, although results presented here do not include data collected in 2022. Survey coverage extended from May to December of each year, with most surveys occurring between June and September. During 2017–2021, we surveyed a total of 43,443 km including 32,779 km within the focal study area comprising six BOEM Planning Areas. We observed 43 marine bird species and three non-marine bird species. For all Planning Areas combined, 10 species accounted for 90% of total birds recorded on transect and species composition was similar between summer (June–August) and fall (September–November). Short-tailed shearwater (*Ardenna tenuirostris*) was the numerically dominant species throughout the study area, accounting for 43% of all seabird observations, followed by crested auklets (*Aethia cristatella*; 9%), northern fulmars (*Fulmarus glacialis*; 9%) and least auklets (*Aethia pusilla;* 8%). Seabird density was highest in Hope Basin (0.31 birds/km^2 ± 0.13), followed by Navarin Basin (0.22 birds/km^2 ± 0.05) and Norton Sound (0.19 birds/km^2 ± 0.04). Densities were much lower in St. Matthew-Hall (0.10 birds/km^2 ± 0.02), and the Chukchi (0.07 birds/km^2 ± 0.01) and Beaufort Planning Areas (0.05 birds/km^2 ± 0.02). On- and off-transect, we recorded 18 marine mammal species and 4,580 individuals, of which 743 were on-transect. Gray whales (*Eschrichtius robustus*) were the most frequently recorded cetacean, mainly in the Hope and Norton basins. Walruses (*Odobenus rosmarus*) were the most numerous marine mammal recorded, and were almost entirely in the Chukchi Sea. We tagged 92 red phalaropes (*Phalaropus fulicarius*) at Arctic-breeding sites in Alaska (2017–2020). Most individuals migrated west and then south through the Bering Strait, after which, individual routes tended to diverge as individuals migrated along both the Russian and Alaskan coastlines. Important areas for red phalaropes included: 1) onshore and nearshore areas of the Beaufort and Chukchi seas (including Barrow Canyon); 2) the Bering Strait; 3) the Gulf of Anadyr; and 4) Unimak Island. The high abundance of seabirds and marine mammals in the Bering Strait region, including Hope Basin, necessitates 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 developments.

1 Introduction

1.1 Need for information on seabirds in planning 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. Seabirds are wide-ranging upper trophic level predators and good indicators of changes in marine ecosystems. They spend most of the year offshore, yet our data gaps are greatest for the pelagic aspect of their lives. 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 (spectacled eider [*Somateria fischeri*], Steller's eider [*Polysticta stelleri*], short-tailed albatross [*Diomedea albatrus*]) as well as Priority Species identified by the U.S. Fish and Wildlife Service (USFWS) (11 Tier-I species and 14 Tier-2 species).

BOEM Environmental Studies Program funds numerous studies involving acquisition and analysis of data on marine birds and other environmental data. The BOEM AK-17-03 project was funded via an Intra-agency Agreement between BOEM and the USFWS to provide basic information on distribution, abundance, and habitat requirements of marine birds necessary to assess potential effects of oil and gas exploration in the northern Bering, Chukchi and Beaufort Seas Planning Areas. This project comprises two components: marine bird surveys (Part I) and red-phalarope (*Phalaropus fulicarius)* tracking (Part II). 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 sea ducks (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).

Basic information on timing and duration of use within designated BOEM Planning Areas is necessary to better define the impacts of perturbations and ultimately population effects. Breeding seabirds are generally monitored at colonies, yet they spend most of the year dispersed offshore. Additionally, one half or more of all marine birds do not breed in a given year, thus management requires knowledge of spatial and temporal patterns of marine bird distribution at sea. By comparing the historical (1970s–1990s) marine bird data from the NPPSD) to recent surveys by the USFWS (2006–2015) we have documented decadal changes in their distribution and relative abundance (Renner et al. 2013; Kuletz et al. 2014; Renner et al. 2016), and in species composition (Day et al. 2013; Gall et al. 2017). More recently, we have shown how the Pacific Arctic marine heatwave of 2017–2019 altered seabird distribution and abundance in the northern Bering and Chukchi seas (Kuletz et al. 2020). During the period of this project (2017–2022), changes have occurred in ocean ecosystems (Grebmeier and Maslowski 2014, Moore et al. 2014) which may have affected the foraging patterns of seabirds. Further changes due to predicted Arctic climate change are anticipated (Comiso et al. 2008) and the Bering Strait region is predicted to have among the greatest overlap of shipping traffic and seabird abundances in Arctic regions (Humphries and Huettmann 2014).

The projected increase in extent and seasonal duration of open water will affect all aspects of sub-Arctic and Arctic marine ecosystems, as well as the subsistence-based cultures of local indigenous communities. In addition, the increase in open water (spatially and temporally) is anticipated to lead to increases in vessel traffic, oil and gas extraction, and commercial fishing (NRC 2014), all of which have potential to impact marine birds. The combination of the vessel-based projects (AK-16-07c and AK-17-03) and tracking of individual birds increases our understanding of the mechanisms and processes that structure the ecosystem of the northern Bering, Chukchi, and Beaufort seas and provides greater seasonal and spatial coverage for seabirds in Alaska's BOEM Planning Areas.

1.2 Project collaborations and partnerships

Species composition of marine birds varies tremendously by season, with species-specific responses to environmental conditions and habitats (Gall et al. 2013; Kuletz et al. 2015). Rapid seasonal changes (Gall et al. 2013; Kuletz et al. 2015; Gall et al. 2017) and spatial variation of seabird communities in Alaska's northern oceans (Kuletz and Labunski 2017; Kuletz et al. 2020) requires broad survey coverage to fully describe and quantify seabird abundance throughout the open-water season. Collaborative efforts with multiple studies over 5 years were critical to collecting a dataset with extensive temporal and spatial coverage.

An important development in Pacific Arctic research was the establishment of the Distributed Biological Observatory (DBO) in 2010. This system of internationally accepted sampling sites allows a project such as our marine bird surveys to contribute data to multidisciplinary programs that track biological responses to the changing conditions in the Arctic. Most vessel-based programs operating in the Bering, Chukchi, and Beaufort seas have agreed to cover these DBO sites. Thus, we were able to place observers on multiple vessels to obtain seabird data across various seasonal and annual time frames within a consistent study area. This expanded temporal coverage increases our understanding of marine bird distribution and community composition. The DBO also provides complementary oceanographic data from our survey areas collected by other research programs to explore mechanisms that drive seabird distributions in this dynamic and rapidly changing marine system.

One of our long-term collaborations that samples the DBO array has been the 'Canada's Three Oceans' (C3O) program conducted by Fisheries and Oceans Canada, Institute of Ocean Sciences. We deployed a seabird observer on the annual cruises conducted by the CCGS *Sir Wilfrid Laurier* that traveled from Victoria, BC, Canada through the Gulf of Alaska, Bering, Chukchi, and Beaufort seas and into Canadian Arctic waters. Other programs have more intensive regional purviews that together broaden the coverage beyond what the long, single transits can provide. The Arctic Marine Biodiversity Observation Network (AMBON), operated by the University of Alaska Fairbanks, combines year-round monitoring using a moored instrument array, with vessel-based sampling focused on the Chukchi Sea. The Fisheries Oceanography Coordinated Investigations (FOCI), established by the National Oceanic and Atmospheric Administration (NOAA) in 1984, studies the ecosystems of the North Pacific Ocean and Bering Sea. The fishery and oceanographic survey in the northeastern Bering Sea, also operated by NOAA, conducts surface trawls to collect indices on fish size, relative abundance, energetic status, distribution, and diet. Concurrent collection of seabird data on these cruises is especially powerful because it facilitates studies of predator-prey dynamics. In addition to these long-term, annual programs, we collaborated with several shorter-term projects to deploy seabird observers and maximize our coverage within the focal area.

This program (BOEM AK-17-03) supported a portion of the study that tracked the migratory movements of male and female red phalaropes from their breeding sites in Alaska and northern Canada using satellite transmitters (Saalfeld et al. *In prep*; Appendix 5). The tracking component provides migration information on an individual level, which complements the population-level data provided by the at-sea surveys. Additionally, it provides information on the use of nearshore and onshore habitats by migratory phalaropes, providing a more comprehensive look at habitat use during migration. Red phalaropes nest in coastal tundra habitat but spend the remainder of the year in the pelagic environment (Tracy et al. 2020).

During the nonbreeding season, they functionally act like surface-feeding planktivorous seabirds, feeding opportunistically on zooplankton such as copepods, as well as amphipods and fish eggs and larvae at the surface (Dodson and Egger 1980; Briggs et al. 1984; Craig et al. 1984; Brown and Gaskin 1988). Recent evidence suggests population declines (Gratto-Trevor et al. 1998; Alaska Shorebird Group 2019; Smith et al. 2020), likely due to factors on the non-breeding grounds (Weiser et al. 2018). Their small size and pelagic behavior have made investigations during the non-breeding season difficult. Contemporary information on non-breeding distributions comes from anecdotal (e.g., eBird; Sullivan et al. 2009) and vessel-based at-sea surveys (e.g., Smith et al. 2014; Kuletz et al. 2015, 2019). However, little is known about the species' migratory routes, stopover sites, or connectivity between breeding and wintering areas (Tracy et al. 2020). By examining results from the tracking study and the at-sea surveys, this project provides information on habitat use during the post-breeding period in the Beaufort, Chukchi, and Bering seas at both individual and population-level scales.

1.3 Study area

1.3.1 Physical properties

The primary marine bird study area was the northern Bering, Chukchi and Beaufort seas. We focused the analysis of trends in distribution and abundance on six BOEM Planning Areas: the Navarin Basin, St. Matthew-Hall, Norton Sound/Chirikov Basin (hereafter, Norton), Hope Basin, the Chukchi Sea, and the Beaufort Sea (Figure 1.1). We also collected data in the southern Bering Sea and the Gulf of Alaska, and these data are summarized where relevant (the data are available in the NPPSD and with BOEM).

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 (Figure 1.2; Coachman et al. 1975; Weingartner et al. 1999). 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 and Shigaev 1992; Weingartner 1997). The Alaska Coastal Water originates in the Gulf of Alaska (Figure 1.2), carries river input into the eastern Bering Sea, and is relatively warm, fresh, and nutrient-poor (Springer et al. 1984; Coachman and 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 1.2), 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 1.2). 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 the Bering Strait blocked by ice until mid-June, although 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.

Overall, zooplankton densities are greatest just north of Bering Strait and in high salinity Bering Sea waters, although their distribution and abundance vary 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 (Piatt and Springer 2003; Hopcroft et al. 2010; Eisner et al. 2013). 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 (Piatt and Springer 2003; Hopcroft et al. 2010; Eisner et al. 2013). Seabirds that feed primarily on zooplankton (i.e., planktivorous seabirds) include auklets (*Ptychoramphus* or *Aethia* spp), fork-tailed storm-petrels (*Hydrobates furcatus*), and shearwaters (*Ardenna* spp.). Planktivorous seabirds in the Bering and Chukchi seas 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 (Cephalopoda), and larval stages of fish and decapods. Benthic feeding birds such as sea ducks primarily consume bivalves (*Bivalvia* molluscs; Ouellet and Guillemette 2013).

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 and sometimes juvenile crustacea (Hunt et al. 2000). 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 (Piatt and Springer 2003; Eisner et al. 2013). However, in the years just preceding and during this project, large predatory fish species, primarily walleye pollock, shifted their distribution 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 sea ducks), Stercorariidae (jaegers), and phalaropes 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 1.3). 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. Except for 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).

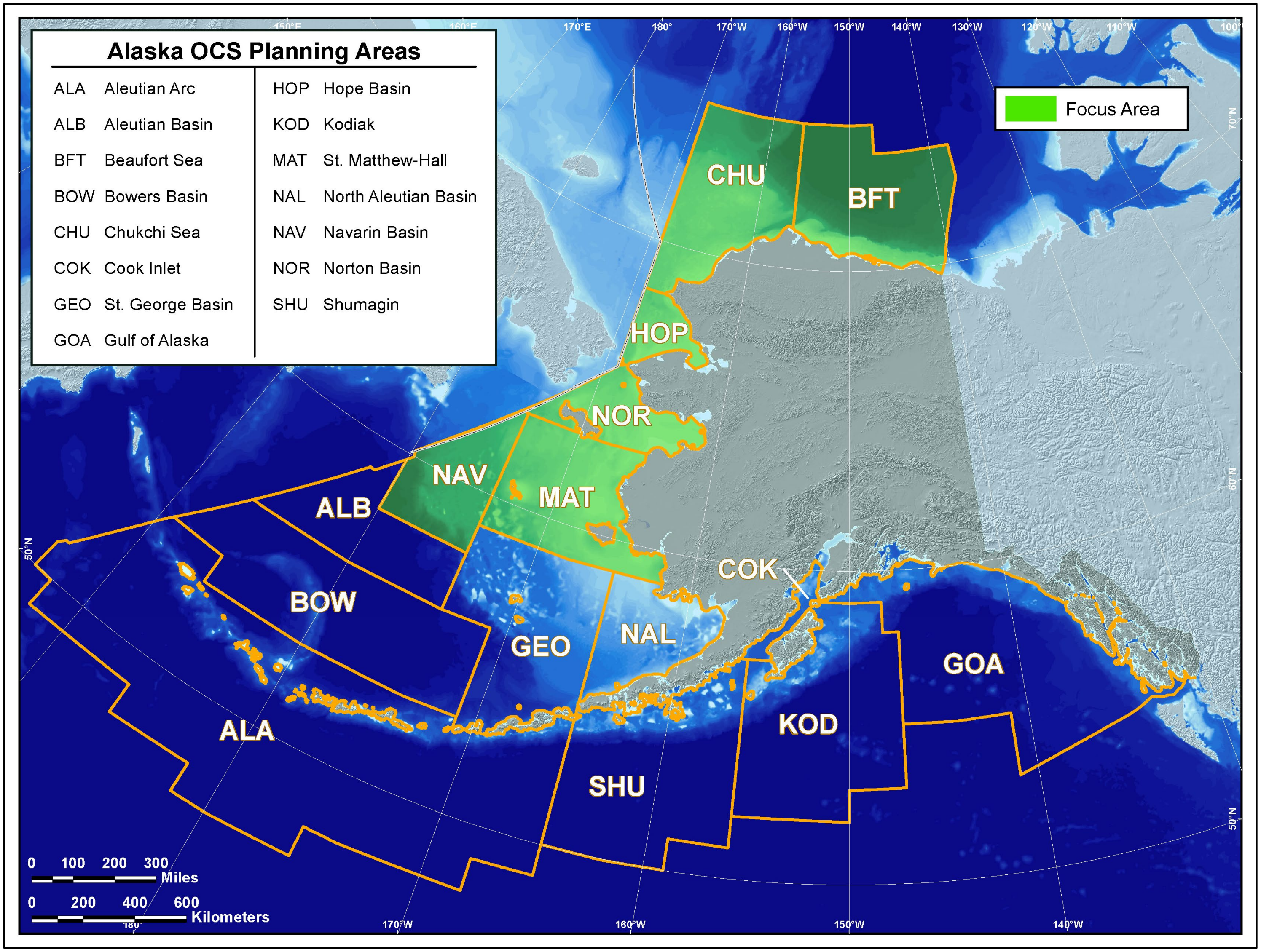

Figure 1.1. Study area for seabird surveys conducted during BOEM AK-17-03 (Marine Bird Distribution and Abundance in Offshore Waters), 2017–2021.
OCS Planning Areas in green are the focus of this project report.

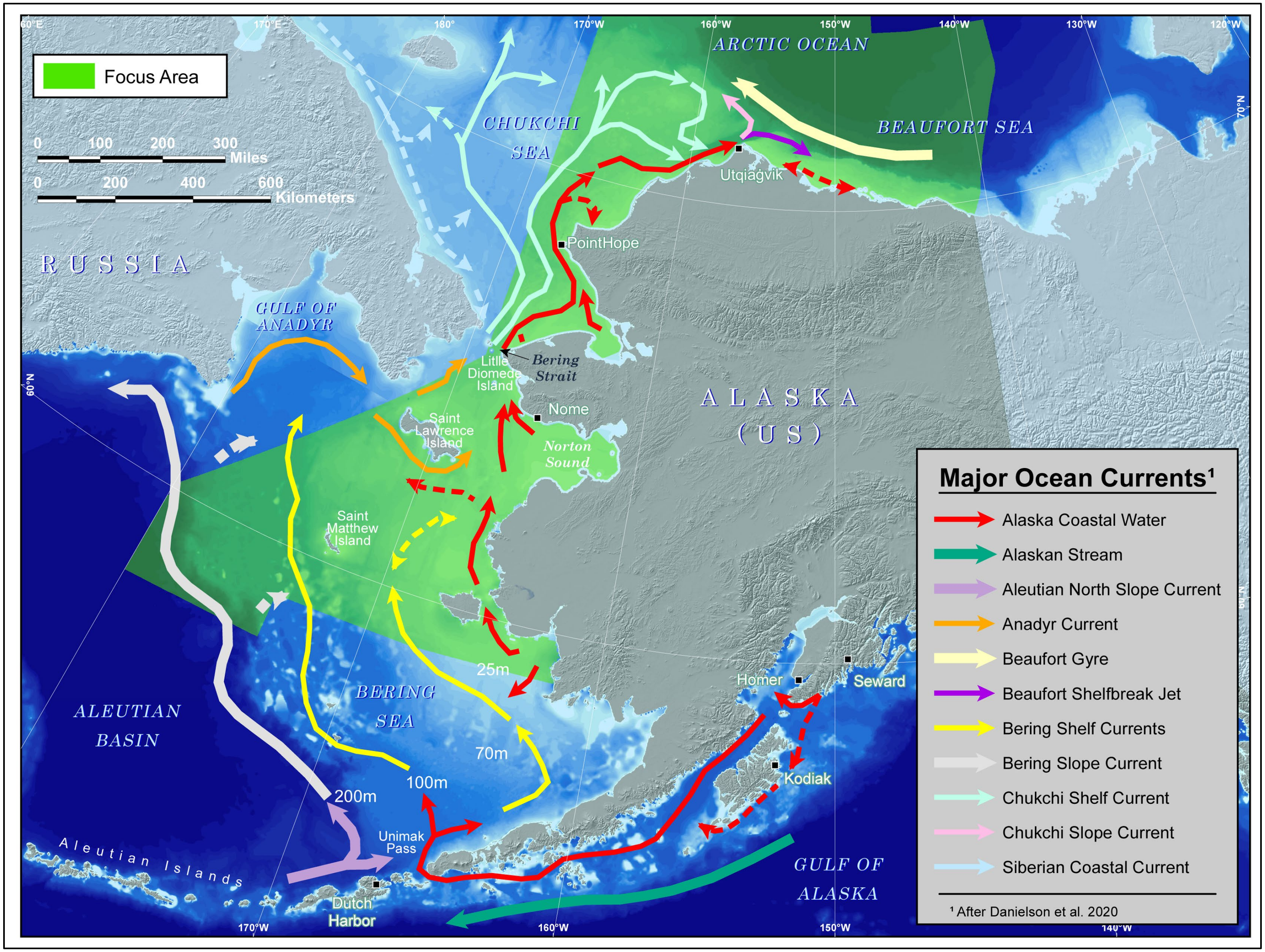

Figure 1.2. Major circulation currents in the Bering, Chukchi, and Beaufort seas.

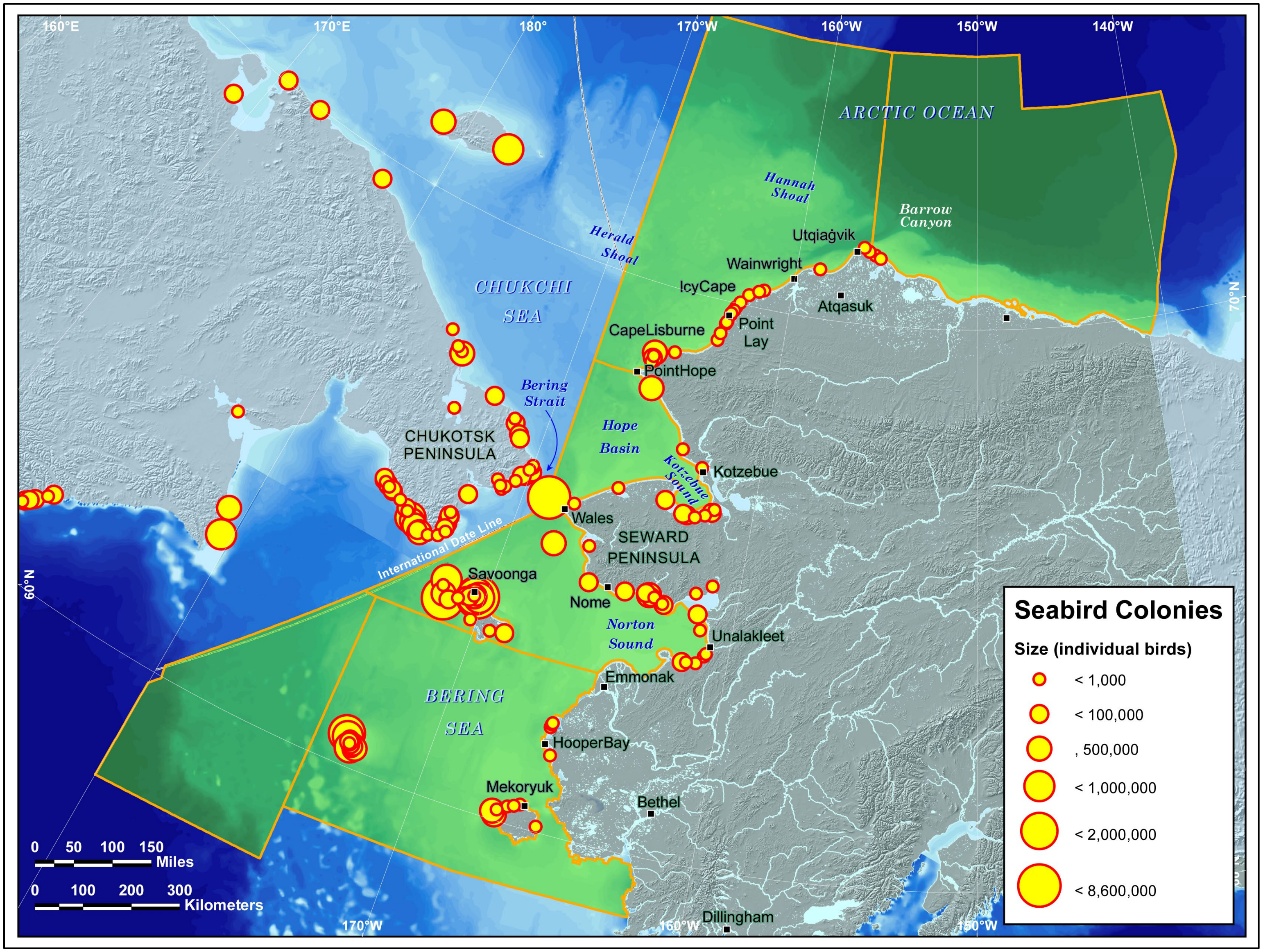

Figure 1.3. Location of known seabird colonies north of 60°N latitude in the United States of America and Russia.

Yellow dots indicate colony size.

2 Data Collection and Processing

2.1 Coordination with research programs and vessels

Principal Investigator K. Kuletz coordinated with Chief Scientists and Project Leads to include seabird surveys in their projects and cruise plans. Seabird observers were placed on 22 research cruises associated with 11 different research projects (Table 2.1). Portions of the Distributed Biological Observatory (DBO; https://www.pmel.noaa.gov/dbo/) sampling scheme were incorporated into many of the project cruises (fulfilling Objectives 1 and facilitating Objective 5). Although most projects were focused on sampling stations in the northern Bering and Chukchi seas, the ports of call often began or ended in Seward, Homer, Kodiak, Dutch Harbor, or Nome, Alaska, with one cruise in 2021 starting from Victoria, British Columbia (Table 2.1). During the vessel's transit between ports and the sampling sites, we conducted additional surveys while underway (Figure 2.1); these transect data from outside the focal area were also submitted to the NPPSD (https://data.usgs.gov/datacatalog/data/USGS:ASC29) and to the BOEM ESM.

2.2 At-sea survey protocols

Observers were trained on land and at sea in the protocol and data entry. Prior to 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 from the centerline in 50 m increments (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).

2.3 Data processing and analysis

We reviewed data 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. We processed, summarized, and analyzed all data 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, we binned all daily sequential transect lines 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). We calculated densities (birds/km^2) 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 2021.

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) to produce data summaries using Program R (R Core Team 2020) and mapped results using geographic information systems (GIS; PostGIS and ArcGIS 10.8, Redland, CA). Marine bird distributions were mapped using a polar stereographic projection.

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 and species richness, which used all transects. We assigned 3-km transects to cells in a hexagonal grid overlaid on the study area based on the location of the transect centroid. Each grid cell measured 60 km from vertex to vertex. Hexagons have lower sampling bias at edges than do rectangular cells (Birch et al. 2007). For each cell, we calculated the density of seabirds as the total of birds observed on those transects within the cell divided by the total area surveyed. To avoid bias from over-inflated densities in hexagons with little surveyed area, we limited analysis of abundance and distribution to cells that had a minimum of 5 km^2 of transect area sampled during a given season or year. There were 208 hexagons with adequate samples of transect data to include in density summaries. These hexagons were surveyed between 1 and 5 years each (Figure 2.2) for a total of 554 cell-years.

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), marine species of Anatidae (eiders and other sea ducks), and phalaropes. These species were grouped by foraging guild based on their preferred prey (planktivores, piscivores, benthivores). Short-tailed shearwaters (hereafter, shearwaters) feed primarily on zooplankton, but consume a variety of other invertebrates and fish, and forage by both surface-seizing and diving (Hunt et al. 2002; Berlincourt et al. 2015). We placed shearwaters in their own foraging guild because of the flexibility of their diet and foraging behavior, and because they can occur in such large numbers that they would numerically eclipse any other species within the same foraging guild.

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.

We summarized the distributions of foraging guilds and individual species that were most abundant by pooling data from all years and using cell-year as the sampling unit. First, we calculated the density by adding the counts within a cell and year and dividing by the area surveyed within that cell and year. We then calculated means and standard errors from all cell-years within a Planning Area. We explored seasonal changes in distribution by comparing observations collected in June, July, and August (summer) to those collected in September, October, and November (fall).

Funds from the BOEM AK-17-03 project supported the deployment of 92 two-gram solar-powered Argos Platform Transmitter Terminal tags on red phalaropes at Arctic-breeding sites located in Alaska (2017–2020). Detailed methods for analyzing the location data for red phalaropes are presented in Appendix 5.

Table 2.1. Research cruises conducted in the Gulf of Alaska, Bering, Chukchi, and Beaufort seas that included seabird observers, 2017–2021.

Year	Cruise Name	Project	Start Date	End Date	Survey Days	Total Distance Surveyed (km)	Planning Areas[1]
2017	AMBON 2017	Arctic Marine Biodiversity Monitoring Network	5 Aug	25 Aug	20	1,918	CHU, HOP, NOR
	Arctic NCIS 2017	Northern Chukchi Integrated Study Distributed Biological Observatory (DBO)	26 Aug	14 Sep	19	2,961	CHU, HOP, NOR, NAV, MAT, GEO
	NBS FISH 2017	Northern Bering Sea Fisheries Survey	25 Aug	12 Sep	18	1,827	NOR, MAT, GEO
	Sikuliaq ARCSS 2017	Arctic Systems Science Program	25 Aug	17 Sep	23	2,050	CHU, BFT, HOP, NOR
	SWL 2017	Canadian 3 Oceans Survey DBO	12 Jul	18 Jul	6	1,077	HOP, NOR, NAV, MAT, GEO
	Total					9,833	CHU, BFT, HOP, NOR, NAV, MAT,
2018	ARCSS 2018	Arctic Systems Science Program	3 Aug	26 Aug	23	2,032	CHU, BFT, HOP, NOR
	C3O DBO 2018	Canadian 3 Oceans Survey DBO	14 Jul	23 Jul	9	1,175	CHU, HOP, NOR, NAV, MAT, GEO
	HLY1801	Northern Chukchi Integrated Study DBO	7 Aug	23 Aug	16	1,989	CHU, BFT, HOP, NOR
	HLY1803	Monitoring Western Arctic Boundary Current	25 Oct	18 Nov	24	1,980	CHU, BFT, HOP, NOR, MAT, GEO
	MACE III 2018	Midwater Assessment and Conservation Engineering Program Fishery Survey	14 Aug	25 Aug	11	1,613	NAV, GEO, SHU, KOD
	NBS 2018	Northern Bering Sea Fisheries Survey	29 Aug	18 Sep	20	2,642	HOP, NOR, MAT, GEO
	Oshoro Maru 2018	Research cruise of T/S *Oshoro Maru IV* in the northern Bering Sea and Arctic Ocean, 2018	29 Jun	15 Jul	16	2,205	HOP, NOR, NAV, MAT, GEO
	Tiglax 2018	U.S. Fish and Wildlife Service	22 May	5 Jun	14	439	MAT, GEO, BOW, ALA, SHU, KOD
	Total					14,076	
2019	FOCI Fall 2019	Fisheries Oceanography Coordinated Investigations	19 Sep	1 Oct	12	1,443	NAV, MAT, GEO, SHU, KOD
	GOWEST 2019	Go West: Sea ice association of Polar cod and its prey in the western Arctic Ocean	7 Nov	30 Nov	23	895	CHU, BFT, HOP, NOR, MAT, GEO
	HLY 1901	Northern Chukchi Integrated Study DBO	4 Aug	22 Aug	18	2,499	CHU, BFT, HOP, NOR, NAV, MAT, GEO

Year	Cruise Name	Project	Start Date	End Date	Survey Days	Total Distance Surveyed (km)	Planning Areas[1]
2019	NBS 2019	Northern Bering Sea Fisheries Survey	28 Aug	19 Sep	22	2,518	HOP, NOR, MAT, GEO
	SWL 2019	Canadian 3 Oceans Survey DBO	11 Jul	22 Jul	11	1,251	HOP, NOR, NAV, MAT, GEO
	Total					8,604	
2020	OD2001	Fisheries Oceanography Coordinated Investigations	28 Aug	24 Sep	27	2,661	CHU, BFT, HOP, NOR, NAV, MAT, GEO, ALB, SHU, KOD
	Total					2,661	
2021	FOCI Spring 2021	Fisheries Oceanography Coordinated	1 May	19 May	18	2,587	NAV, MAT, ALB, GEO, SHU, KOD
	NBS 2021	Northern Bering Sea Fisheries Survey	28 Aug	18 Sep	21	2,882	NOR, MAT, GEO
	SWL 2021	Canadian 3 Oceans Survey DBO	11 Jul	24 Jul	13	1,319	CHU, HOP, NOR, NAV, MAT, GEO,
	Total					6,787	

[1] ALB = North Aleutian Basin; BFT = Beaufort Sea; CHU = Chukchi Sea; GEO = St. George Basin; HOP = Hope Basin; KOD = Kodiak; MAT= St. Matthew-Hall; NAV = Navarin Basin; NOR = Norton Basin; SHU = Shumagin

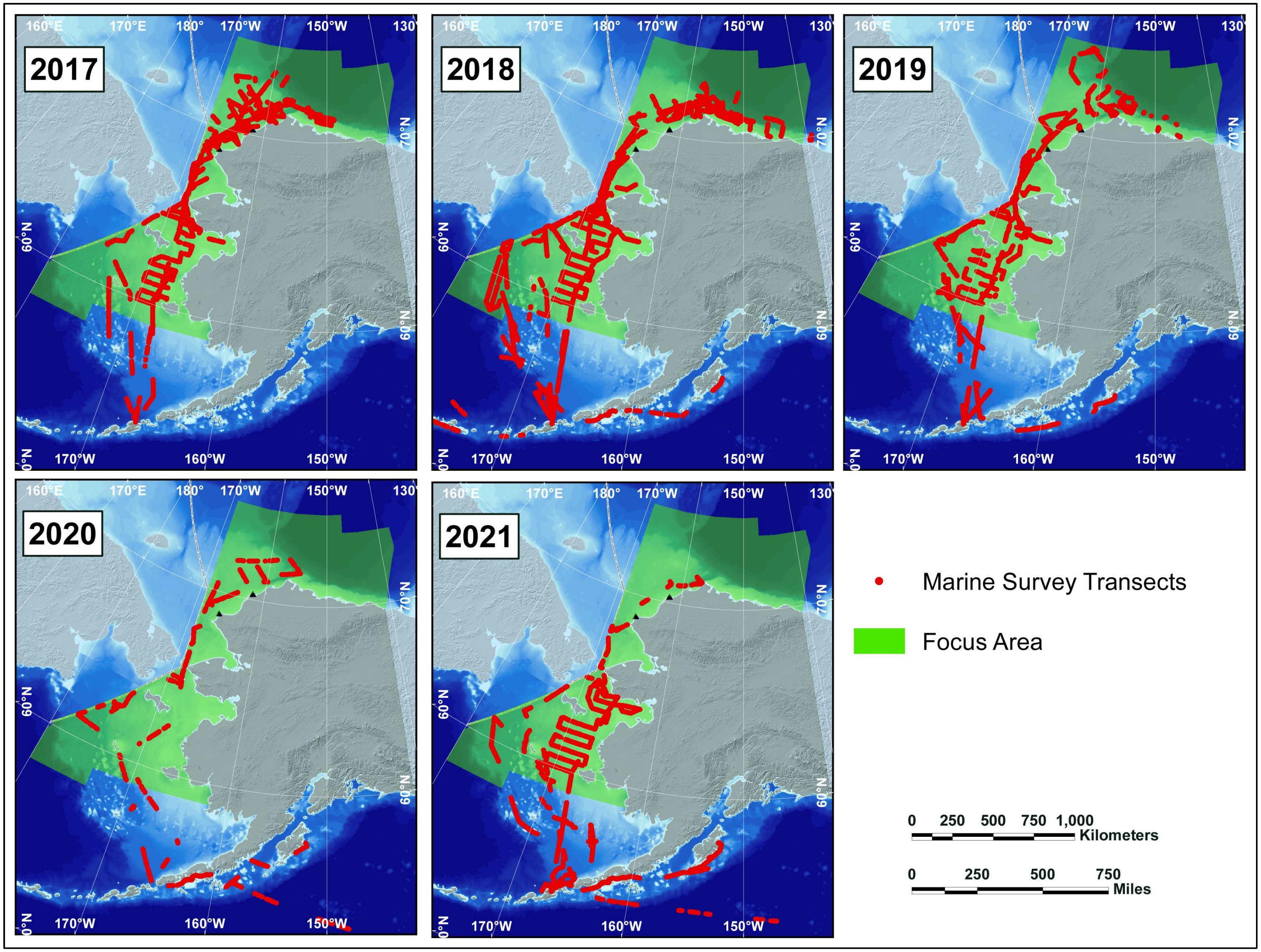

Figure 2.1. Transects surveyed for seabirds by USFWS, 2017–2021.
Funded as part of BOEM AK-17-03.

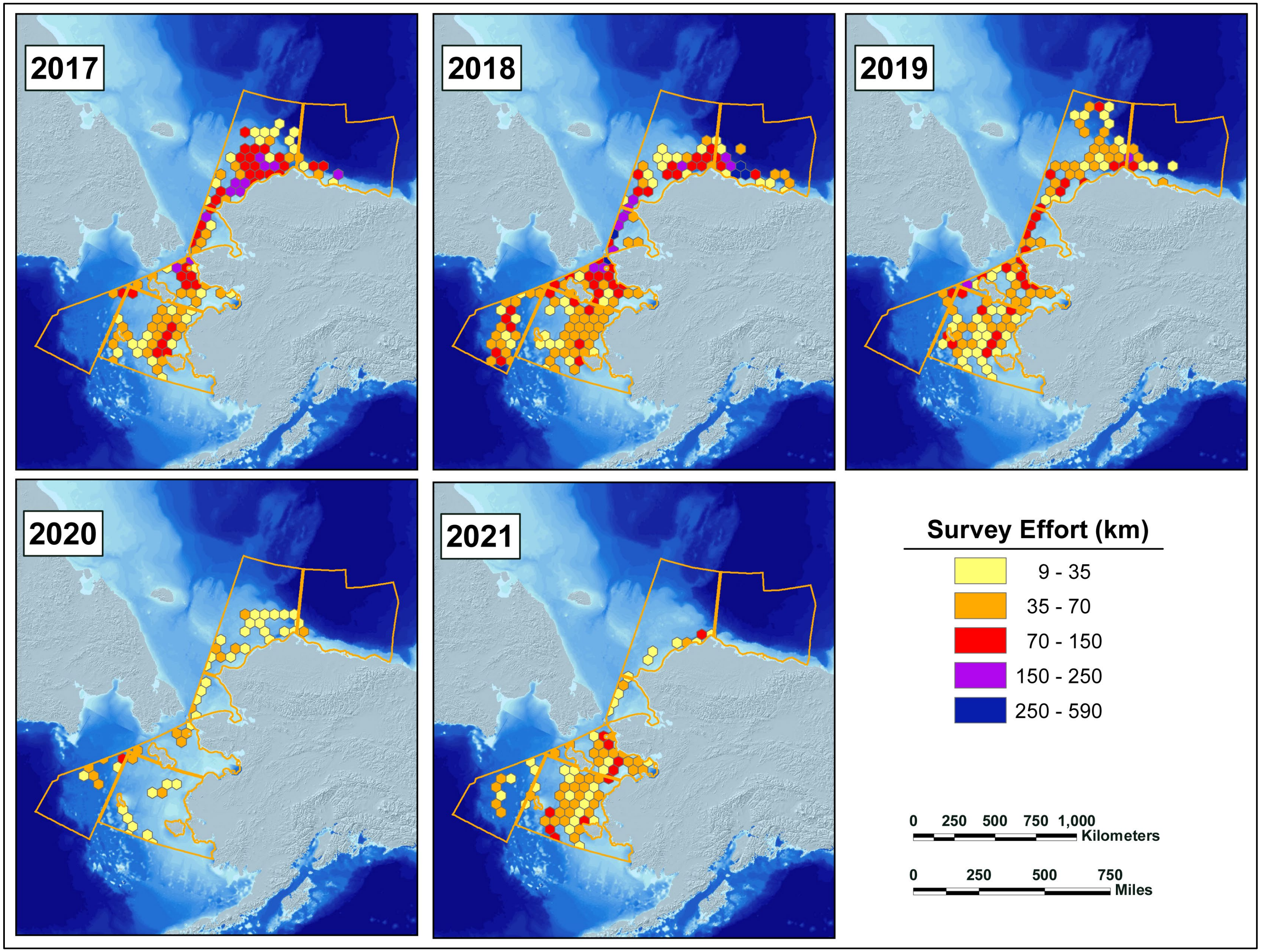

Figure 2.2. At-sea survey effort represented in 60-km hexagons within 6 focal BOEM Planning Areas.

3 Results

3.1 Survey effort

From July 2017 through September 2021, we surveyed a total of 43,443 km (Table 3.1) throughout the Gulf of Alaska, Bering, Chukchi, and Beaufort seas (Figure 2.1). Within the focal study area, we surveyed a total of 32,779 km of transects among the 6 Planning Areas, with the most coverage in the Chukchi Sea, followed by St. Matthew-Hall and Norton Basin (Figure 2.2). Survey effort varied across years; we surveyed 9,896 km in 2017, 14,230 km in 2018, 8,701 km in 2019, 3,289 km in 2020 and 7,327 km in 2021 (Table 3.1). The onset of the COVID-19 pandemic forced the cancellation of several research cruises in 2020 and yet even in that year, all 6 focal Planning Areas were surveyed. The Navarin Basin had the least survey effort of all Planning Areas while the Beaufort Planning Area was the only area surveyed in 4 of 5 years (it was not surveyed in 2021). Additional surveys are being conducted in 2022 with funds that were budgeted and not used in 2020. Those data are not included in this report.

3.2 Seabirds

3.2.1 Seabird community

We recorded a total of 145,747 birds on transect during the project, of which 78,403 birds were within the focal area. We observed 43 marine bird species and 3 non-marine bird species (harlequin duck [*Histrionicus histrionicus*] red-necked grebe [*Podiceps grisegena*], and common loon [*Gavia immer*]; Table 3.2). The highest number of species was recorded in Norton Basin (39 species), followed by St Matthew-Hall (37 species); the lowest number of species was recorded in the Beaufort Sea (22 species; Table 3.3). For all Planning Areas combined, 10 species accounted for 90% of total birds recorded on transect and species composition was similar between summer and fall.

Short-tailed shearwaters were the numerically dominant species throughout the focal area, accounting for 43% of all seabird observations, followed by crested auklets (*Aethia cristatella*; 9%), northern fulmars (*Fulmarus glacialis;* 9%) and least auklets (*Aethia pusilla;* 8%). Short-tailed shearwaters were the most abundant species in 5 of 6 Planning Areas. In Norton Basin, however, least auklets were the most abundant species, composing 30% of all records, followed by crested auklets (22%) and short-tailed shearwaters (14%). Other species that contributed to 90% of the total were black-legged kittiwakes (*Rissa tridactyla*), thick-billed (*Uria lomvia*) and common murres (*U. aalge*), fork-tailed storm-petrels, red phalaropes, and parakeet auklets (*Aethia psittacula*). Rare species with fewer than 5 records included 4 ivory gulls (*Pagophila eburnea*), 4 white-winged scoters (*Melanitta deglandi*), 2 dovekies (*Alle alle*), 1 Aleutian tern (*Onychoprion aleuticus*), 1 red-throated loon (*G. stellata*), and 1 common loon.

3.2.2 Distribution, abundance, and seasonal changes

3.2.2.1 Total seabirds

Total marine bird density was 0.13 birds/km^2 and was highest in the Planning Areas closest to the Bering Strait. Seabird density was highest in Hope Basin (0.31 birds/km^2 ± 0.13), followed by Navarin (0.22 birds/km^2 ± 0.05) and Norton basins (0.19 birds/km^2 ± 0.04). Densities were much lower in St. Matthew-Hall (0.10 birds/km^2 ± 0.02), and the Chukchi (0.07 birds/km^2 ± 0.01) and Beaufort seas (0.05 birds/km^2 ± 0.02; Figure 3.1). Survey effort varied between Planning Areas (Figure 2.2), resulting in no estimates of spatial variance in some areas, as no standard deviation could be estimated for areas surveyed only once over 5 years (Figure 3.1). Spatial variance was generally higher in areas with higher average density (Figure 3.1).

The highest densities of surface planktivores were observed in cells within Hope (5.76 birds/km^2) and Navarin (2.80 birds/km^2) basins (Table 3.4, Figures 3.2 and 3.8). The high density of surface planktivores in Hope Basin was primarily composed of phalaropes, while those in Navarin Basin were largely fork-tailed storm petrels, both of which had a very low density in all other Planning Areas (Table 3.2). The highest densities of diving planktivores were observed within cells in Norton Basin (9.60 birds/km^2), followed by Hope Basin (2.49 birds/km^2; Table 3.4, Figures 3.2 and 3.8), and these were primarily least and crested auklets (Table 3.2). Hope, Navarin, and Norton basins had the highest densities of diving piscivores (1.63–1.96 birds/km^2), primarily common and thick-billed murres (Table 3.2), while Navarin Basin had the highest densities of surface piscivores (4.44 birds/km^2; Figures 3.2 and 3.8), primarily northern fulmars and black-legged kittiwakes (Table 3.2). Shearwaters occurred across the study area in high numbers, with the highest densities in cells in Navarin Basin (5.28 birds/km^2; Table 3.4, Figures 3.2 and 3.8), although these high densities in Navarin Basin may be biased because of limited sampling there compared to the other Planning Areas. Densities of benthivores were low across the focal area, however, the highest density was found in the Beaufort Sea (0.11 birds/km^2; Table 3.4, Figures 3.2 and 3.8), primarily due to high densities of long-tailed ducks (*Clangula hyemalis*; 0.07 birds/km^2; Table 3.2).

With the exception of benthivores and shearwaters, the lowest densities of all foraging guilds were found in the Beaufort Sea (surface planktivores, 0.06 birds/km^2; surface piscivores, 0.38 birds/km^2; diving planktivores 0.01 birds/km^2, diving piscivores 0.04 birds/km^2; Table 3.4). The lowest densities of benthivores were found in Navarin Basin, and St. Matthew Hall (<0.01 birds/km^2; Table 3.4), and the lowest density of shearwaters was in Norton Basin (1.23 birds/km^2; Table 3.4). Compared with the other Planning Areas that had high densities of seabirds (Hope and Norton basins), few diving planktivores were observed in Navarin Basin (Figure 3.2).

Average marine bird density was very similar between the summer (0.14 birds/km^2 ± 0.02) and fall surveys (0.13 birds/km^2 ± 0.02) across all regions. However, species densities by species or guilds varied throughout the focal area between seasons (detailed below).

In addition to live birds, we recorded a total of 81 bird carcasses during surveys within the focal Planning Areas (Table 3.5). Carcasses were recorded in 5 of 6 Planning Areas, with no carcasses found in the Beaufort (Figure 3.4). Most (30) carcasses were of procellariids, followed by alcids (23) and ducks (2; Table 3.5).

3.2.2.2 Planktivores

The most common planktivores across the study area were least and crested auklets, and phalaropes (Table 3.2). Least auklets, which feed by diving, were primarily observed in Norton (5.15 birds/km^2) and Hope (1.09 birds/km^2) basins, however, they were widely distributed across the study area as far north as the Chukchi Sea (Table 3.2, Figure 3.5). Crested auklets were most numerous in Norton Basin (2.97 birds/km^2) and the Chukchi Sea (1.10 birds/km^2), primarily north of Icy Cape and south of Peard Bay (Figure 3.5). They were widely distributed across the study area, including occurring in the Beaufort Planning Area (0.01 birds/km^2, Figure 3.5). Crested auklet densities were lower in the fall than the summer, particularly in Norton Basin (Figure 3.6).

Phalaropes (red-necked [*P. lobatus*], red, and unidentified phalaropes), which feed at the surface, were observed in low densities (<0.1 birds/km^2) across the study area, with higher densities reported in Hope (5.69 birds/km^2) and Norton basins (0.65 birds/km^2; Table 3.2, Figure 3.5). Phalarope observations were concentrated in Norton and Hope basins in the summer season, and more widely distributed in the fall during the migratory period (Figure 3.6). Phalaropes were concentrated within Hope Basin in a small area; one 60 km grid cell had a 70.34 birds/km^2 density (Figure 3.5). The only other surface-feeding planktivore, fork-tailed storm petrels, were also observed in fairly low densities (<0.1 birds/km^2) across the study area, with high densities observed in Navarin Basin (2.75 birds/km^2; Table 3.2, Figure 3.3), where one grid cell had a 15.36 birds/km^2 density.

3.2.2.3 Piscivores

The most common piscivores were thick-billed murres, common murres, black-legged kittiwakes, and northern fulmars (Table 3.2). The highest densities of thick-billed and common murres were found in Navarin Basin, and the lowest in the Beaufort Sea (Table 3.2). Thick-billed murres had a more northerly distribution than common murres (Figure 3.7). The highest densities of thick-billed murres were in Navarin Basin (0.89 birds/km^2), and the lowest in the Beaufort Sea (0.002 birds/km^2; Figure 3.7). Higher densities of thick-billed murres were observed in the southern Norton and southern Chukchi Sea (Figure 3.7), however average densities across the Norton (0.27 birds/km^2) and Chukchi Sea (0.35 birds/km^2) Planning Areas were similar to those found in Hope Basin (0.36 birds/km^2) and St. Matthew-Hall (0.22 birds/km^2; Table 3.2). Common murres were distributed fairly uniformly across the study area as far north as Point Hope (0.2–0.33 birds/km^2), with lower densities observed in the Chukchi (0.05 birds/km^2) and Beaufort seas (0.001 birds/km^2; Table 3.2, Figure 3.7). The highest densities of common murres were in St. Matthew-Hall (0.33 birds/km^2), and the lowest in the Beaufort Sea (0.001 birds/km^2; Figure 3.7). Thick-billed murres were more abundant than common murres in the Chukchi Sea, Hope Basin, and Navarin Basin, and lower, or equal, density in the Beaufort Sea, Norton Basin, and St. Matthew-Hall (Table 3.2, Figure 3.7). Murres were more abundant across the study area in summer than fall, but their distribution was similar (Figure 3.8).

Black-legged kittiwake densities were similar across the northern Bering and Chukchi seas, ranging 0.0.40–0.58 birds/km^2, but were lower in the Beaufort Sea (0.21 birds/km^2; Table 3.2, Figure 3.7). Kittiwakes had a similar distribution in the summer and fall seasons, occurring throughout the study area with the highest densities in the southern Chukchi Planning Area (Figure 3.8).

Northern fulmar densities were the highest in Navarin Basin (3.08 birds/km^2), and lowest in the Beaufort Sea (0.02 birds/km^2; Table 3.2, Figure 3.7). As with kittiwakes, fulmars were widely dispersed at low densities in both the summer and fall, with a few exceptions in the Navarin Basin (Figure 3.8).

3.2.2.4 Shearwaters

Short-tailed shearwater were the most abundant species in 5 (Chukchi and Beaufort seas, and Hope, Navarin and St. Matthew-Hall Basins) of the 6 Planning Areas, with average densities ranging from 1.55–9.67 birds/km^2 (Table 3.2). The highest densities of shearwaters were found in Navarin Basin (9.67 birds/km^2; Table 3.4, Figure 3.5). Norton had the lowest densities of shearwaters (1.89 birds/km^2; including unidentified shearwaters). Shearwaters were widely distributed in both the summer and fall across the entire study area, including the Beaufort Sea (Figure 3.6).

3.2.3 Phalarope movements

Of 93 red phalaropes tagged in Alaska, 67 birds provided post-breeding movements (61 tagged at Utqiaġvik, 2 at Qupałuk in the north central portion of the Teshekpuk Lake Special Area, 1 at the Colville River Delta, and 3 at the Canning River Delta). Most individuals migrated west and then south through the Bering Strait, after which, individual routes tended to diverge as individuals migrated along both the Russian and Alaskan coastlines (Appendix 5). While individuals generally moved southwest in the Beaufort/Chukchi seas, south in the Bering Strait and South Bering, and southeast in the Aleutians, we observed movements in all directions, many over considerable distances (e.g., >250 km) and in directions not consistent with the expected migration route (Appendix 5). Foraging red phalaropes were often associated with areas of greater food availability, such as in highly productive ocean currents, or near ocean fronts or upwellings, within the marginal ice zone, and in areas known to be frequented by foraging whales. Stopover locations occurred on land and at sea and were concentrated along the Alaska coastline of the Beaufort and Chukchi seas; in the Chukchi Sea north of the Chukotka Peninsula, along the coastline of the Chukotka Peninsula, throughout the Bering Strait, around St. Lawrence and St. Paul islands; and along the Aleutian Islands, especially near Unimak Island (Appendix 5). Kernel utilization distributions revealed four high-use areas, including the Alaska coastline of the Beaufort and Chukchi seas, along the Russian side of the Bering Strait, in the Gulf of Anadyr, and along the Aleutian Islands near Unimak Island (Appendix 5). Foraging red phalaropes were also found on land and in nearshore areas more than was expected. More detailed analysis and discussion is presented in Appendix 5.

3.3 Marine mammals

Over the five years of the study, we recorded 4,580 marine mammals in the six BOEM Planning Areas, of which 743 were observed on transect (Table 3.6). Walruses (*Odobenus rosmarus*) were the most numerous species with 3,231 individuals observed, of which 275 walruses were on transect (Table 3.6), primarily in the Chukchi Sea north of Icy Cape (Figure 3.9). The next most abundant species were gray whales (*Eschrichtius robustus*; 287 whales total) and humpback whales (*Megaptera novaeangliae*; 118 whales total; Table 3.6). In transit to the focal study area, we recorded an additional 578 marine mammals, primarily cetaceans (458), and almost all in St. George Basin (Appendix 4).

Gray whales were primarily observed in Hope and Norton basins, and humpback whales were observed in Hope Basin (Figure 3.9). We observed 768 cetaceans (whales and porpoises not identified to species) both on and off transect (Table 3.6). The highest number of whales were observed in Hope Basin (393), including those observed both on and off transect. Similar numbers of whales were observed in the Chukchi Sea (102) and Norton Basin (117), while fewer than 29 whales were observed within each of the remaining Planning Areas (Table 3.6). Killer whales were observed in low and sporadic numbers across the study area as far north as Barrow Canyon, with the highest numbers observed in St. Matthew-Hall and Norton basins (Table 3.6; Figure 3.10). Bowhead whales were observed in the northern Chukchi Sea and Beaufort Sea areas in 2017 and 2018 (Table 3.6; Figure 3.10).

We observed a total of 541 seals on and off transect, with most (469 seals) recorded in the Beaufort Sea, followed by the Chukchi Sea (173 seals). Fewer than 16 seals were observed within each of the remaining Planning Areas (Table 3.6). Polar bears were only observed in the northern Beaufort and Chukchi seas, primarily in the Hanna Shoal area and east of Barrow Canyon (Table 3.6; Figure 3.10).

In addition to live mammals, we recorded a total of 15 mammal carcasses during surveys within the focal Planning Areas (Table 3.5). Carcasses were recorded in 5 of 6 Planning Areas, with no carcasses of marine mammals found in the Navarin Basin (Table 3.5). Most (12) carcasses were seals, with two whales and one walrus also recorded (Table 3.5).

Table 3.1. Survey effort (km/year) within the 6 focal BOEM Planning Areas in the Gulf of Alaska, Bering, Chukchi, and Beaufort seas 2017–2021.

Transit effort to and from the focal area is shown for additional BOEM Planning Areas. Focal Planning Areas are noted in bold type.

	Year (km surveyed)					
Planning Area[1]	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**
Chukchi Sea	**3,574**	**2,232**	**1,915**	**622**	**252**	**8,595**
Beaufort Sea	**1,158**	**1,945**	**430**	**76**	**0**	**3,609**
Hope Basin	**938**	**1,541**	**861**	**164**	**246**	**3,749**
Norton Basin	**1,432**	**2,649**	**1,433**	**204**	**1,299**	**7,018**
Navarin Basin	**105**	**1,097**	**217**	**273**	**329**	**2,021**
St. Matthew-Hall	**1,767**	**1,960**	**1,961**	**286**	**1,815**	**7,789**
North Aleutian Basin	0	0	0	64	348	412
St. George Basin	859	2,022	1,430	275	1,435	6,021
Bowers Basin	0	56	0	0	0	56
Aleutian Arc	0	207	0	0	0	207
Shumagin	0	247	215	398	514	1,373
Kodiak	0	121	142	299	550	1,112
Non-lease area	64	155	97	628	540	1,483
Total	9,896	14,230	8,701	3,289	7,327	43,443

Table 3.2. Mean density (birds/km^2; mean ± standard error) of birds recorded at sea in 6 Planning Areas in the Bering, Chukchi, and Beaufort seas, 2017–2021.

Grid cell density is calculated as the average transect density for all transects within a grid cell in each year. Planning Area means and standard errors are calculated from all cell-years within a Planning Area.

Foraging guild	English Name	Scientific Name	Chukchi Sea	Beaufort Sea	Hope Basin	Norton Basin	Navarin Basin	St. Matthew-Hall
Surface Planktivore	Red-necked Phalarope	*Phalaropus lobatus*	0.005 ± 0.002	0	0.005 ± 0.005	0.028 ± 0.022	0.004 ± 0.004	0.019 ± 0.013
	Red Phalarope	*Phalaropus fulicarius*	0.131 ± 0.043	0.045 ± 0.037	1.142 ± 0.723	0.515 ± 0.257	0.022 ± 0.011	0.044 ± 0.015
	Unidentified phalarope	*Phalaropus* sp.	0.031 ± 0.012	0.001 ± 0.001	4.542 ± 3.935	0.116 ± 0.045	0.010 ± 0.006	0.083 ± 0.029
	Fork-tailed Storm-Petrel	*Hydrobates furcatus*	0.001 ± 0.001	0	0.007 ± 0.004	0.079 ± 0.039	2.745 ± 0.790	0.024 ± 0.009
Surface Piscivore	Pomarine Jaeger	*Stercorarius pomarinus*	0.024 ± 0.005	0.013 ± 0.006	0.028 ± 0.009	0.035 ± 0.010	0.012 ± 0.007	0.021 ± 0.005
	Parasitic Jaeger	*Stercorarius parasiticus*	0.012 ± 0.004	0.007 ± 0.003	0.020 ± 0.009	0.003 ± 0.001	0.004 ± 0.004	0.005 ± 0.003
	Long-tailed Jaeger	*Stercorarius longicaudus*	0.002 ± 0.001	0.001 ± 0.001	0.002 ± 0.001	0.001 ± 0.001	0.011 ± 0.009	0.001 ± 0
	Unidentified jaeger	*Stercorarius* sp.	0.001 ± 0.001	0	0.007 ± 0.005	0.005 ± 0.002	0	0.002 ± 0.001
	Black-legged Kittiwake	*Rissa tridactyla*	0.396 ± 0.073	0.206 ± 0.084	0.528 ± 0.145	0.394 ± 0.065	0.580 ± 0.112	0.454 ± 0.043
	Red-legged Kittiwake	*Rissa brevirostris*	0	0	0	0	0.012 ± 0.006	0.006 ± 0.003
	Unidentified kittiwake	*Rissa* sp.	0	0	0	0	0	0.001 ± 0.001
	Ivory Gull	*Pagophila eburnea*	0	0.002 ± 0.002	0	0	0	0
	Sabine's Gull	*Xema sabini*	0.035 ± 0.019	0.010 ± 0.005	0	0.003 ± 0.002	0.005 ± 0.003	0.036 ± 0.015
	Herring Gull	*Larus argentatus*	0	0	0	0.005 ± 0.003	0.006 ± 0.004	0.007 ± 0.002
	Slaty-backed Gull	*Larus schistisagus*	0	0	0	0.001 ± 0.001	0.001 ± 0.001	0.001 ± 0.001
	Glaucous-winged Gull	*Larus glaucescens*	0	0.001 ± 0.001	0.002 ± 0.001	0.008 ± 0.003	0.010 ± 0.007	0.034 ± 0.009
	Glaucous Gull	*Larus hyperboreus*	0.045 ± 0.009	0.038 ± 0.012	0.074 ± 0.025	0.036 ± 0.010	0.057 ± 0.040	0.050 ± 0.017
	Unidentified gull	*Larid* sp.	0.002 ± 0.001	0.003 ± 0.002	0.009 ± 0.005	0.004 ± 0.002	0.001 ± 0.001	0.010 ± 0.003
	Aleutian Tern	*Onychoprion aleuticus*	0	0	0	0.001 ± 0.001	0	0
	Arctic Tern	*Sterna paradisaea*	0.025 ± 0.010	0.019 ± 0.015	0.023 ± 0.015	0.003 ± 0.001	0	0.006 ± 0.003

Foraging guild	**English Name**	**Scientific Name**	**Chukchi Sea**	**Beaufort Sea**	**Hope Basin**	**Norton Basin**	**Navarin Basin**	**St. Matthew-Hall**
Surface Piscivore	Laysan Albatross	*Phoebastria immutabilis*	0	0	0	0	0.084 ± 0.028	0.001 ± 0.001
	Short-tailed Albatross	*Phoebastria albatrus*	0	0	0	0	0.015 ± 0.007	0.001 ± 0.001
	Northern Fulmar	*Fulmarus glacialis*	0.258 ± 0.071	0.018 ± 0.009	0.317 ± 0.083	0.947 ± 0.252	3.124 ± 0.605	0.813 ± 0.153
Diving Planktivore	Dovekie	*Alle*	0	0	0	0.001 ± 0	0	0
	Cassin's Auklet	*Ptychoramphus aleuticus*	0	0	0	0.001 ± 0.001	0	0.005 ± 0.002
	Parakeet Auklet	*Aethia psittacula*	0.008 ± 0.004	0	0.191 ± 0.061	0.57 ± 0.1894	0.183 ± 0.060	0.272 ± 0.103
	Least Auklet	*Aethia pusilla*	0.095 ± 0.027	0	1.091 ± 0.454	5.152 ± 1.609	0.085 ± 0.036	0.079 ± 0.030
	Crested Auklet	*Aethia cristatella*	1.103 ± 0.293	0.006 ± 0.005	0.492 ± 0.227	2.970 ± 1.106	0.215 ± 0.073	0.162 ± 0.106
	Unidentified auklet	*Ptychoramphus or Aethia* sp.	0.011 ± 0.005	0	0.100 ± 0.054	0.091 ± 0.045	0.032 ± 0.014	0.023 ± 0.005
Diving Piscivore	Red-necked Grebe	*Podiceps grisegena*	0.001 ± 0.001	0	0	0.001 ± 0.001	0	0
	Common Murre	*Uria aalge*	0.054 ± 0.014	0.001 ± 0.001	0.201 ± 0.055	0.245 ± 0.068	0.268 ± 0.085	0.327 ± 0.057
	Thick-billed Murre	*Uria lomvia*	0.349 ± 0.125	0.002 ± 0.001	0.363 ± 0.110	0.270 ± 0.058	0.887 ± 0.171	0.222 ± 0.036
	Unidentified murre	*Uria* sp.	0.197 ± 0.095	0.001 ± 0.001	0.285 ± 0.070	0.265 ± 0.076	0.181 ± 0.034	0.129 ± 0.030
	Black Guillemot	*Cepphus grylle*	0.001 ± 0	0.010 ± 0.005	0.002 ± 0.001	0.001 ± 0.001	0	0
	Pigeon Guillemot	*Cepphus columba*	0	0	0	0.002 ± 0.001	0	0
	Unidentified guillemot	*Cepphus* sp.	0	0	0	0.001 ± 0.001	0	0
	Marbled Murrelet	*Brachyramphus marmoratus*	0	0	0	0.002 ± 0.002	0	0.001 ± 0.001
	Kittlitz's Murrelet	*Brachyramphus brevirostris*	0.002 ± 0.002	0.001 ± 0.001	0.001 ± 0.001	0	0	0
	Unidentified murrelet	*Brachyramphus* sp.	0	0	0.001 ± 0.001	0	0	0.001 ± 0.001
	Ancient Murrelet	*Synthliboramphus antiquus*	0.035 ± 0.017	0	0.014 ± 0.007	0.096 ± 0.043	0.076 ± 0.040	0.088 ± 0.027
	Horned Puffin	*Fratercula corniculata*	0.009 ± 0.003	0.001 ± 0.001	0.138 ± 0.054	0.148 ± 0.036	0.042 ± 0.027	0.073 ± 0.022

Foraging guild	**English Name**	**Scientific Name**	**Chukchi Sea**	**Beaufort Sea**	**Hope Basin**	**Norton Basin**	**Navarin Basin**	**St. Matthew-Hall**
Diving Piscivore	Tufted Puffin	*Fratercula cirrhata*	0.004 ± 0.001	0	0.196 ± 0.062	0.311 ± 0.093	0.101 ± 0.022	0.134 ± 0.046
	Unidentified puffin	*Fratercula or Cerorhinca* sp.	0	0	0.004 ± 0.002	0.001 ± 0	0	0.001 ± 0.001
	Unidentified alcid		0.003 ± 0.001	0	0.013 ± 0.006	0.063 ± 0.028	0.009 ± 0.005	0.027 ± 0.006
	Red-throated Loon	*Gavia stellata*	0	0	0.002 ± 0.002	0	0	0
	Pacific Loon	*Gavia pacifica*	0.021 ± 0.005	0.015 ± 0.005	0.010 ± 0.005	0.005 ± 0.002	0	0.009 ± 0.004
	Common Loon	*Gavia immer*	0	0	0	0	0	0
	Yellow-billed Loon	*Gavia adamsii*	0.001 ± 0.001	0	0.006 ± 0.005	0.001 ± 0.001	0	0
	Unidentified loon	*Gavia* sp.	0.001 ± 0	0.001 ± 0.001	0.021 ± 0.011	0.002 ± 0.001	0	0.003 ± 0.002
	Pelagic Cormorant	*Urile pelagicus*	0	0	0.003 ± 0.003	0.003 ± 0.001	0	0.004 ± 0.002
	Unidentified cormorant	*Urile* sp.	0	0	0	0.002 ± 0.002	0	0
Benthivore	Spectacled Eider	*Somateria fischeri*	0.001 ± 0.001	0	0	0.006 ± 0.004	0	0
	King Eider	*Somateria spectabilis*	0.015 ± 0.013	0.003 ± 0.002	0.022 ± 0.022	0.010 ± 0.009	0	0.002 ± 0.001
	Common Eider	*Somateria mollissima*	0	0.008 ± 0.004	0.010 ± 0.006	0	0	0
	Unidentified eider	*Polysticta* or *Somateria* sp.	0.002 ± 0.001	0	0.046 ± 0.032	0.008 ± 0.006	0	0.001 ± 0.001
	Harlequin Duck	*Histrionicus*	0	0	0	0.002 ± 0.002	0.004 ± 0.004	0.005 ± 0.002
	White-winged Scoter	*Melanitta deglandi*	0	0	0	0	0	0.001 ± 0.001
	Long-tailed Duck	*Clangula hyemalis*	0.072 ± 0.054	0.065 ± 0.036	0.001 ± 0.001	0	0	0.003 ± 0.002
Shearwater	Short-tailed Shearwater	*Ardenna tenuirostris*	2.942 ± 0.713	1.550 ± 0.688	4.369 ± 1.592	1.858 ± 0.611	9.672 ± 3.775	3.905 ± 1.359
	Unidentified dark shearwater	*Ardenna* sp.	0.152 ± 0.101	0.735 ± 0.535	0.140 ± 0.122	0.034 ± 0.021	0	0.015 ± 0.013
	Unidentified procellarid	*Procellariidae* sp.	0	0	0	0	0	0.001 ± 0.001

Table 3.3. Number of seabird species recorded during at-sea surveys in 6 BOEM Planning Areas in the Bering, Chukchi, and Beaufort seas, 2017–2021.

Planning Area	2017	2018	2019	2020	2021
Beaufort Sea	12	13	15	7	
Chukchi Sea	29	24	22	15	12
Hope Basin	20	30	21	14	18
Navarin Basin	7	20	15	17	15
Norton Basin	27	34	30	15	22
St. Matthew-Hall	30	28	29	23	27

Table 3.4. Mean densities (birds/km^2; mean ± standard error) of seabirds by foraging guild and BOEM Planning Areas, 2017–2021.

Density is calculated as the sum of counts within each cell and year, divided by the area surveyed within that cell and year. Means and standard errors are calculated from all cell-years within a Planning Area. Values for the Beaufort Sea in 2021 are calculated from a single cell and therefore have no standard error.

Foraging Guild	Planning Area	2017	2018	2019	2020	2021	All Years
Surface Planktivore	Chukchi Sea	0.349 ± 0.114	0.154 ± 0.075	0.049 ± 0.043	0.003 ± 0.003	0	0.174 ± 0.045
	Beaufort Sea	0.031 ± 0.024	0.066 ± 0.057	0.242 ± 0.242	0	0	0.055 ± 0.040
	Hope Basin	0.270 ± 0.121	14.545 ± 11.493	0.696 ± 0.382	0.991 ± 0.789	7.198 ± 5.342	5.761 ± 4.627
	Norton Basin	0.474 ± 0.150	0.921 ± 0488	1.945 ± 0.924	0.626 ± 0.626	0.005 ± 0.005	0.836 ± 0.316
	Navarin Basin	0	4.473 ± 1.363	0.204 ± 0.106	0.950 ± 0.498	0.036 ± 0.031	2.804 ± 0.784
	St. Matthew-Hall	0.349 ± 0.148	0.087 ± 0.032	0.410 ± 0.186	0.400 ± 0.242	0.262 ± 0.146	0.215 ± 0.052
Surface Piscivore	Chukchi Sea	1.744 ± 0.381	0.748 ± 0.313	0.775 ± 0.147	0.591 ± 0.133	0.486 ± 0.119	0.840 ± 0.111
	Beaufort Sea	1.732 ± 0.490	0.197 ± 0.072	0.635 ± 0.239	0.563 ± 0.232	0.473	0.378 ± 0.128
	Hope Basin	1.235 ± 0.417	1.198 ± 0.281	1.601 ± 0.482	0.784 ± 0.428	4.433 ± 1.564	1.199 ± 0.261
	Norton Basin	2.163 ± 0.762	1.912 ± 0.449	1.829 ± 0.356	3.492 ± 0.422	0.839 ± 0.226	1.980 ± 0.356
	Navarin Basin	2.931 ± 2.210	4.408 ± 0.654	3.420 ± 0.960	10.634 ± 4.336	1.853 ± 0.643	4.442 ± 0.602
	St. Matthew-Hall	1.223 ± 0.279	1.024 ± 0.227	2.826 ± 0.445	2.945 ± 0.755	0.896 ± 0.207	1.845 ± 0.222
Diving Planktivore	Chukchi Sea	2.002 ± 0.550	0.226 ± 0.070	0.432 ± 0.142	0.941 ± 0.308	0	1.224 ± 0.311
	Beaufort Sea	0	0.017 ± 0.017	0.007 ± 0.007	0.138 ± 0.138	0	0.011 ± 0.010
	Hope Basin	1.260 ± 0.330	4.025 ± 2.253	1.016 ± 0.326	0.587 ± 0.261	26.368 ± 20.796	2.488 ± 1.166
	Norton Basin	9.567 ± 6.277	11.392 ± 3.006	7.514 ± 3.704	0.536 ± 0.341	6.047 ± 5.138	9.603 ± 2.253
	Navarin Basin	0.320 ± 0.320	0.675 ± 0.147	0.505 ± 0.138	0.162 ± 0.115	0.152 ± 0.113	0.551 ± 0.110
	St. Matthew-Hall	0.175 ± 0.048	0.977 ± 0.634	0.443 ± 0.154	0.471 ± 0.265	0.296 ± 0.074	0.856 ± 0.445
Diving Piscivore	Chukchi Sea	0.571 ± 0.182	0.969 ± 0.366	1.521 ± 0.696	0.180 ± 0.045	2.065 ± 0.936	0.711 ± 0.233
	Beaufort Sea	0.068 ± 0.021	0.022 ± 0.009	0.174 ± 0.111	0.160 ± 0.099	0	0.039 ± 0.010
	Hope Basin	1.760 ± 0.815	1.632 ± 0.564	2.341 ± 1.011	0.961 ± 0.438	5.050 ± 1.785	1.633 ± 0.509
	Norton Basin	1.264 ± 0.418	2.347 ± 0.592	1.473 ± 0.459	1.050 ± 0.373	0.978 ± 0.536	1.957 ± 0.507
	Navarin Basin	2.262 ± 1.974	1.643 ± 0.226	1.667 ± 0.606	1.803 ± 0.743	1.853 ± 0.620	1.896 ± 0.256

Foraging Guild	Planning Area	2017	2018	2019	2020	2021	All Years
Diving Piscivore	St. Matthew-Hall	1.024 ± 0.240	1.234 ± 0.373	0.941 ± 0.219	2.119 ± 1.532	0.766 ± 0.179	1.375 ± 0.270
Benthivore	Chukchi Sea	0.113 ± 0.083	0.002 ± 0.002	0.088 ± 0.084	0.053 ± 0.039	0.186 ± 0.151	0.102 ± 0.059
	Beaufort Sea	0.103 ± 0.071	0	0.323 ± 0.314	0.682 ± 0.682	1.367	0.105 ± 0.063
	Hope Basin	0	0.238 ± 0.115	0.038 ± 0.038	0	0	0.096 ± 0.049
	Norton Basin	0.003 ± 0.003	0.039 ± 0.026	0.070 ± 0.039	0	0.015 ± 0.015	0.035 ± 0.016
	Navarin Basin	0	0	0	0	0.036 ± 0.036	0.009 ± 0.009
	St. Matthew-Hall	0.009 ± 0.008	0.012 ± 0.009	0.016 ± 0.011	0	0.023 ± 0.012	0.014 ± 0.005
Shearwater	Chukchi Sea	2.657 ± 1.389	0.230 ± 0.093	2.562 ± 0.828	4.009 ± 2.504	0.087 ± 0.052	1.697 ± 0.432
	Beaufort Sea	1.493 ± 0.980	0	6.481 ± 3.231	14.754 ± 12.921	0.227 ± 0.227	1.492 ± 0.620
	Hope Basin	0.658 ± 0.377	22.124 ± 18.492	0.795 ± 0.319	4.242 ± 2.421	0.390 ± 0.196	2.410 ± 0.893
	Norton Basin	0.882 ± 0.339	1.389 ± 0.545	0.801 ± 0.265	1.865 ± 0.891	0.301 ± 0.109	1.229 ± 0.377
	Navarin Basin	0.190 ± 0.156	5.768 ± 2.448	2.407 ± 1.464	15.321 ± 12.239	0.041 ± 0.038	5.277 ± 2.062
	St. Matthew-Hall	0.561 ± 0.312	0.463 ± 0.178	0.778 ± 0.246	15.040 ± 7.461	1.891 ± 1.091	2.258 ± 0.748

Table 3.5. Count of seabird carcasses by species-group, year, and Planning Area in the Bering, Chukchi, and Beaufort seas, 2017–2021.

Family	Species	Planning Area	2017	2018	2019	2020	2021	All Years
Anatidae	Long-tailed Duck	Norton Basin		2				2
Alcidae	Thick-billed Murre	Hope Basin			1			1
	Unidentified murre	Chukchi Sea	1					1
		Hope Basin	3					3
		Norton Basin		2				2
		Navarin Basin		1				1
		St. Matthew-Hall	2	2				4
		St. George Basin		2				2
	Least Auklet	Norton Basin			1			1
		St. Matthew-Hall			1			1
	Crested Auklet	Hope Basin			2			2
		Norton Basin			1			1
	Unidentified auklet	St. Matthew-Hall			1			1
		Shumagin			1			1
	Horned Puffin	Hope Basin		2	1			3
		Norton Basin	1					1
		Kodiak				1		1
		Shumagin			1			1
	Unidentified alcid	St. Matthew-Hall			1			1
Laridae	Red-legged Kittiwake	St. George Basin		2				2
Procellariidae	Northern Fulmar	Hope Basin	1		1			2
		Navarin Basin		4				4
		St. Matthew-Hall		1				1
		St. George Basin			1			1
	Short-tailed Shearwater	Chukchi Sea	8		1			9
		Hope Basin			4			4
		Norton Basin	1	3	1			5
		St. Matthew-Hall	1	2	1		1	5

Family	Species	Planning Area	2017	2018	2019	2020	2021	All Years
Odobenidae	Walrus	Hope Basin			1			1
Phocidae	Bearded Seal	Chukchi Sea		2				2
	Ringed Seal	Chukchi Sea		2				2
		Beaufort Sea	1					1
	unidentified seal	Chukchi Sea		2				2
		Beaufort Sea		4				4
		Norton Basin			1			1
Other	unidentified whale	Norton Basin			1			1
		St. Matthew-Hall	1					1
	unidentified bird	Chukchi Sea	1	2			2	5
		Hope Basin		2	1		2	5
		Norton Basin	1	2	2		2	7
		St. Matthew-Hall	1	1	5		2	9

Table 3.6. Counts of marine mammals recorded in 6 focal BOEM Planning Areas in the Bering, Chukchi, and Beaufort seas, 2017–2021.

The fields on/off indicate if an observation was on or off transect.

Years	Common Name	Scientific Name	Chukchi Sea		Beaufort Sea		Hope Basin		Norton Basin		Navarin Basin		St. Matthew Hall		Total
			on	off	on	off	on	off	on	off	on	off	on	off	
2017	Northern Fur Seal	*Callorhinus ursinus*	0	0	0	0	0	0	0	0	0	0	0	1	1
	Walrus	*Odobenus rosmarus*	106	150	0	2	0	0	0	0	0	0	0	0	258
	Bearded Seal	*Erignathus barbatus*	10	4	12	9	0	0	0	0	0	0	0	0	35
	Spotted Seal	*Phoca largha*	12	4	0	0	1	1	0	0	0	0	1	1	20
	Ringed Seal	*Pusa hispida*	6	0	22	2	0	0	0	0	0	0	0	0	30
	unidentified seal		9	10	24	22	0	0	1	0	0	0	2	1	69
	unidentified pinniped		3	3	0	0	0	0	0	0	0	0	0	0	6
	Bowhead Whale	*Balaena mysticetus*	0	7	0	4	0	0	0	0	0	0	0	0	11
	Minke Whale	*Balaenoptera acutorostrata*	0	1	0	0	0	0	0	0	0	0	4	-3	4
	Fin Whale	*Balaenoptera physalus*	0	0	0	0	0	3	0	1	0	0	0	0	4
	Humpback Whale	*Megaptera novaeangliae*	0	0	0	0	0	70	0	0	0	0	0	3	73
	Gray Whale	*Eschrichtius robustus*	4	39	0	0	11	21	0	18	0	0	0	2	95
	Killer Whale	*Orcinus orca*	0	0	0	0	0	0	0	0	0	0	2	0	2
	Harbor Porpoise	*Phocoena phocoena*	0	3	0	0	0	0	0	4	0	0	0	0	7
	Dall's Porpoise	*Phocoenoides dalli*	0	0	0	0	0	0	5	0	3	5	8	3	24
	unidentified whale		1	5	0	0	0	11	0	15	0	0	1	4	37
2018	Polar Bear	*Ursus maritimus*	0	7		1	17		0	0		0	0		0
	Northern Fur Seal	*Callorhinus ursinus*	0	0		0	0		0	0		0	0		0
	Steller's Sea Lion	*Eumetopias jubatus*	0	0	0	0	0	0	0	0	0	0	0	1	1
	Walrus	*Odobenus rosmarus*	106	150	0	2	0	0	0	0	0	0	0	0	258
	Bearded Seal	*Erignathus barbatus*	10	4	12	9	0	0	0	0	0	0	0	0	35

Years	Common Name	Scientific Name	Chukchi Sea		Beaufort Sea		Hope Basin		Norton Basin		Navarin Basin		St. Matthew Hall		Total
			on	off	on	off	on	off	on	off	on	off	on	off	
2018	Ribbon Seal	*Histriophoca fasciata*	12	4	0	0	1	1	0	0	0	0	1	1	20
	Spotted Seal	*Phoca largha*	6	0	22	2	0	0	0	0	0	0	0	0	30
	Ringed Seal	*Pusa hispida*	9	10	24	22	0	0	1	0	0	0	2	1	69
	unidentified seal		3	3	0	0	0	0	0	0	0	0	0	0	6
	unidentified pinniped		0	0	0	0	0	0	0	0	0	0	0	1	1
	Bowhead Whale	*Balaena mysticetus*	0	7	0	4	0	0	0	0	0	0	0	0	11
	Minke Whale	*Balaenoptera acutorostrata*	0	1	0	0	0	0	0	0	0	0	4	0	4
	Fin Whale	*Balaenoptera physalus*	0	0	0	0	0	3	0	1	0	0	0	0	4
	Humpback Whale	*Megaptera novaeangliae*	0	0	0	0	0	70	0	0	0	0	0	3	73
	Gray Whale	*Eschrichtius robustus*	4	39	0	0	11	21	0	18	0	0	0	2	95
	Killer Whale	*Orcinus orca*	0	0	0	0	0	0	0	0	0	0	2	0	2
	Harbor Porpoise	*Phocoena phocoena*	0	3	0	0	0	0	0	4	0	0	0	0	7
	Dall's Porpoise	*Phocoenoides dalli*	0	0	0	0	0	0	5	0	3	5	8	3	24
	unidentified whale		1	5	0	0	0	11	0	15	0	0	1	4	37
2019	Polar Bear	*Ursus maritimus*	0	0	0	1	0	0	0	0	0	0	0	0	1
	Northern Fur Seal	*Callorhinus ursinus*	0	0	0	0	0	0	0	2	0	0	3	2	7
	Walrus	*Odobenus rosmarus*	16	35	0	0	0	0	0	0	0	0	0	0	51
	Bearded Seal	*Erignathus barbatus*	5	0	0	0	0	0	0	0	0	0	0	0	5
	Spotted Seal	*Phoca largha*	6	0	0	0	2	0	1	0	0	0	0	0	9
	Harbor Seal	*Phoca vitulina*	0	0	0	0	0	0	0	1	0	0	0	0	1
	Ringed Seal	*Pusa hispida*	1	0	1	0	0	0	0	0	0	0	0	0	2
	unidentified seal		6	5	10	1	1	0	1	0	0	0	1	0	25
	unidentified pinniped		4	0	0	0	1	0	0	0	0	0	0	0	5

Years	Common Name	Scientific Name	Chukchi Sea		Beaufort Sea		Hope Basin		Norton Basin		Navarin Basin		St. Matthew Hall		Total
			on	off	on	off	on	off	on	off	on	off	on	off	
2019	Minke Whale	*Balaenoptera acutorostrata*	1	0	0	0	0	0	0	0	0	0	0	0	1
	Fin Whale	*Balaenoptera physalus*	0	0	0	0	0	6	0	0	0	3	2	3	14
	Humpback Whale	*Megaptera novaeangliae*	0	8	0	0	3	2	0	0	0	0	0	0	13
	Gray Whale	*Eschrichtius robustus*	0	0	0	0	4	9	2	7	0	0	0	0	22
	Killer Whale	*Orcinus orca*	0	0	0	4	3	0	4	4	0	0	4	14	33
	Harbor Porpoise	*Phocoena phocoena*	0	0	0	0	1	2	4	0	0	0	1	0	8
	Dall's Porpoise	*Phocoenoides dalli*	0	0	0	0	0	0	0	0	0	0	4	0	4
	unidentified whale		0	3	0	0	3	44	1	5	1	2	1	4	64
2020	Northern Fur Seal	*Callorhinus ursinus*	0	0	0	0	0	0	0	0	0	1	0	0	1
	Walrus	*Odobenus rosmarus*	7	18	0	0	0	0	0	0	0	0	0	0	25
	unidentified seal		1	1	0	0	0	0	0	0	0	0	0	0	2
	Minke Whale	*Balaenoptera acutorostrata*	2	0	0	0	0	0	0	0	0	0	0	0	2
	Fin Whale	*Balaenoptera physalus*	0	0	0	0	0	1	0	0	0	1	0	0	2
	Gray Whale	*Eschrichtius robustus*	0	0	0	0	0	36	0	0	0	0	0	0	36
	Beluga	*Delphinapterus leucas*	1	0	0	0	0	0	0	0	0	0	0	0	1
	unidentified whale		0	0	0	0	0	3	0	1	0	5	0	1	10
2021	Northern Fur Seal	*Callorhinus ursinus*	0	0	0	0	0	0	0	0	0	0	1	1	2
	Steller's Sea Lion	*Eumetopias jubatus*	0	0	0	0	0	0	0	0	0	0	1	0	1
	Walrus	*Odobenus rosmarus*	8	0	0	0	0	0	0	0	0	0	0	0	8
	Bearded Seal	*Erignathus barbatus*	1	0	0	0	0	0	0	0	0	0	0	0	1
	unidentified seal		4	1	0	0	2	0	0	0	1	0	0	0	8
	unidentified pinniped		0	0	0	0	0	0	0	2	0	0	0	0	2

Years	Common Name	Scientific Name	Chukchi Sea		Beaufort Sea		Hope Basin		Norton Basin		Navarin Basin		St. Matthew Hall		Total
			on	off	on	off	on	off	on	off	on	off	on	off	
2021	Minke Whale	*Balaenoptera acutorostrata*	0	0	0	0	0	0	0	1	0	0	0	0	1
	Gray Whale	*Eschrichtius robustus*	1	1	0	0	8	14	0	0	0	0	0	0	24
	Killer Whale	*Orcinus orca*	0	0	0	0	0	0	0	0	4	0	0	0	4
	Dall's Porpoise	*Phocoenoides dalli*	0	0	0	0	0	0	0	0	6	0	0	0	6
	unidentified whale		0	1	0	0	0	2	0	1	0	1	0	0	5

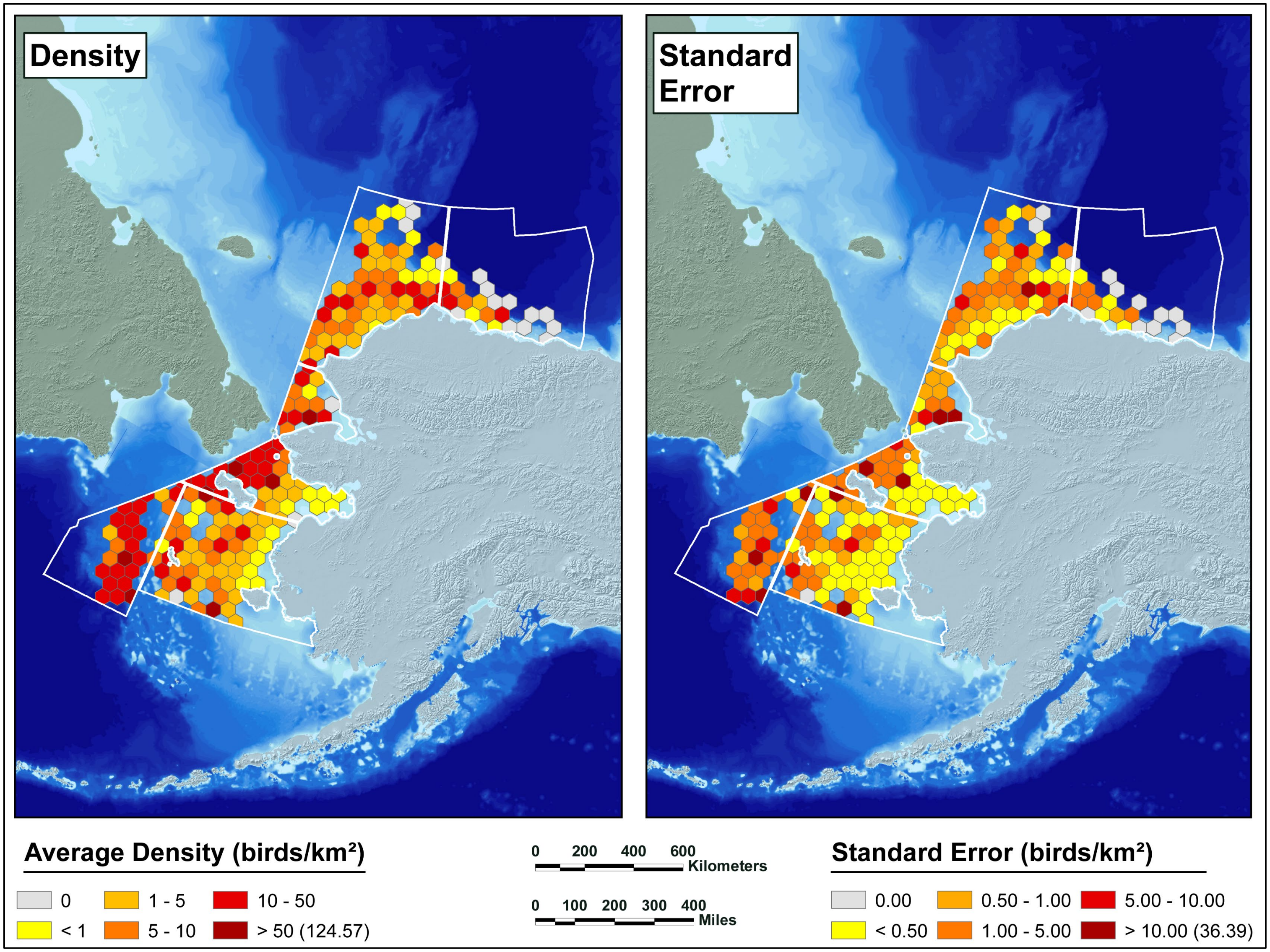

Figure 3.1. Distribution of seabirds (birds/km^2) and associated standard error within each 60-km hexagon across the Bering, Chukchi, and Beaufort seas, 2017–2021.
The highest density is shown in parentheses.

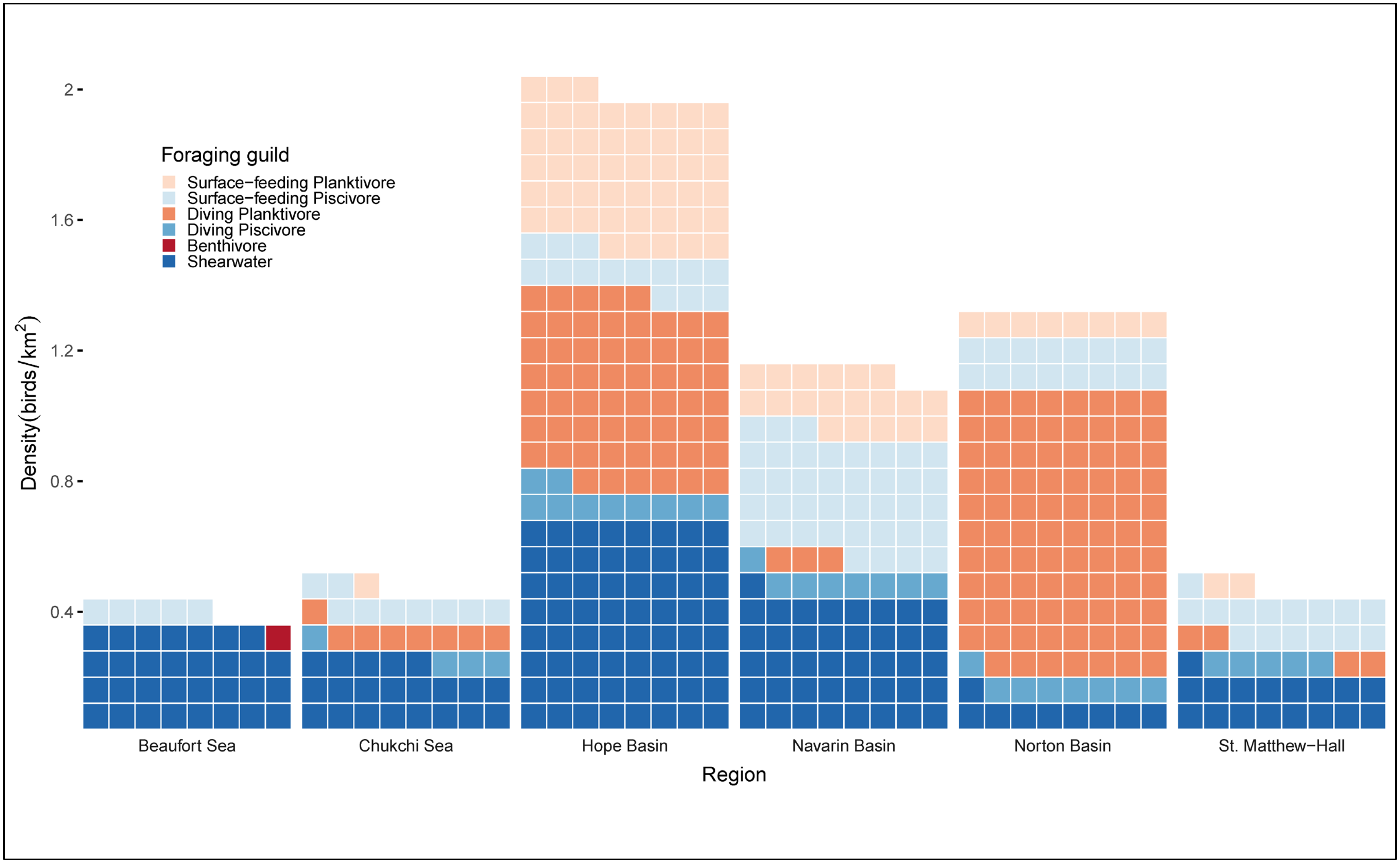

Figure 3.2. Composition of the seabird community in 6 BOEM Planning Areas in the Bering, Chukchi, and Beaufort seas, 2017–2021.

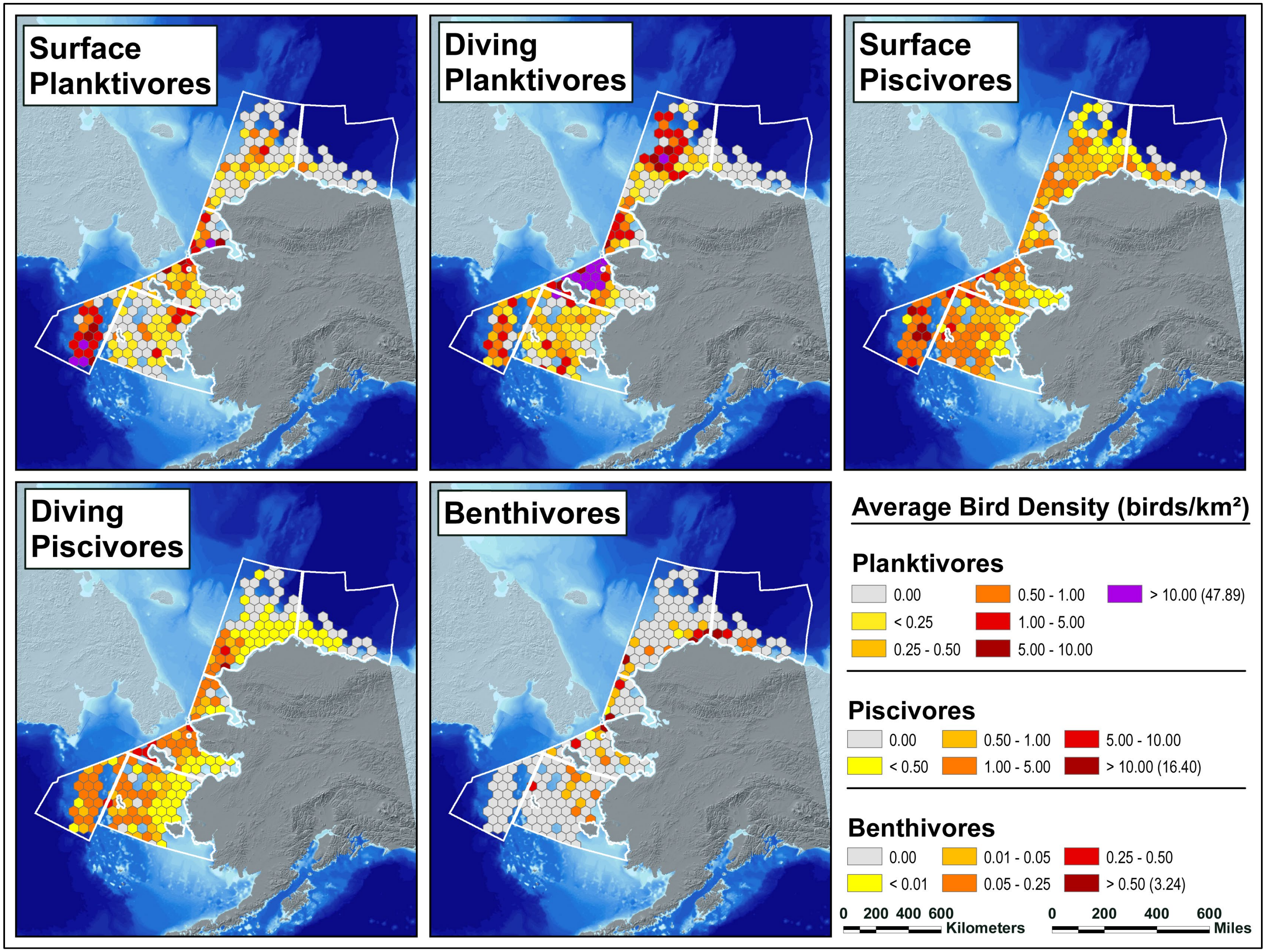

Figure 3.3. Density (birds/km^2) of seabirds by foraging guild in the Bering, Chukchi, and Beaufort seas, 2017–2021. The highest density is shown in parentheses for each guild.

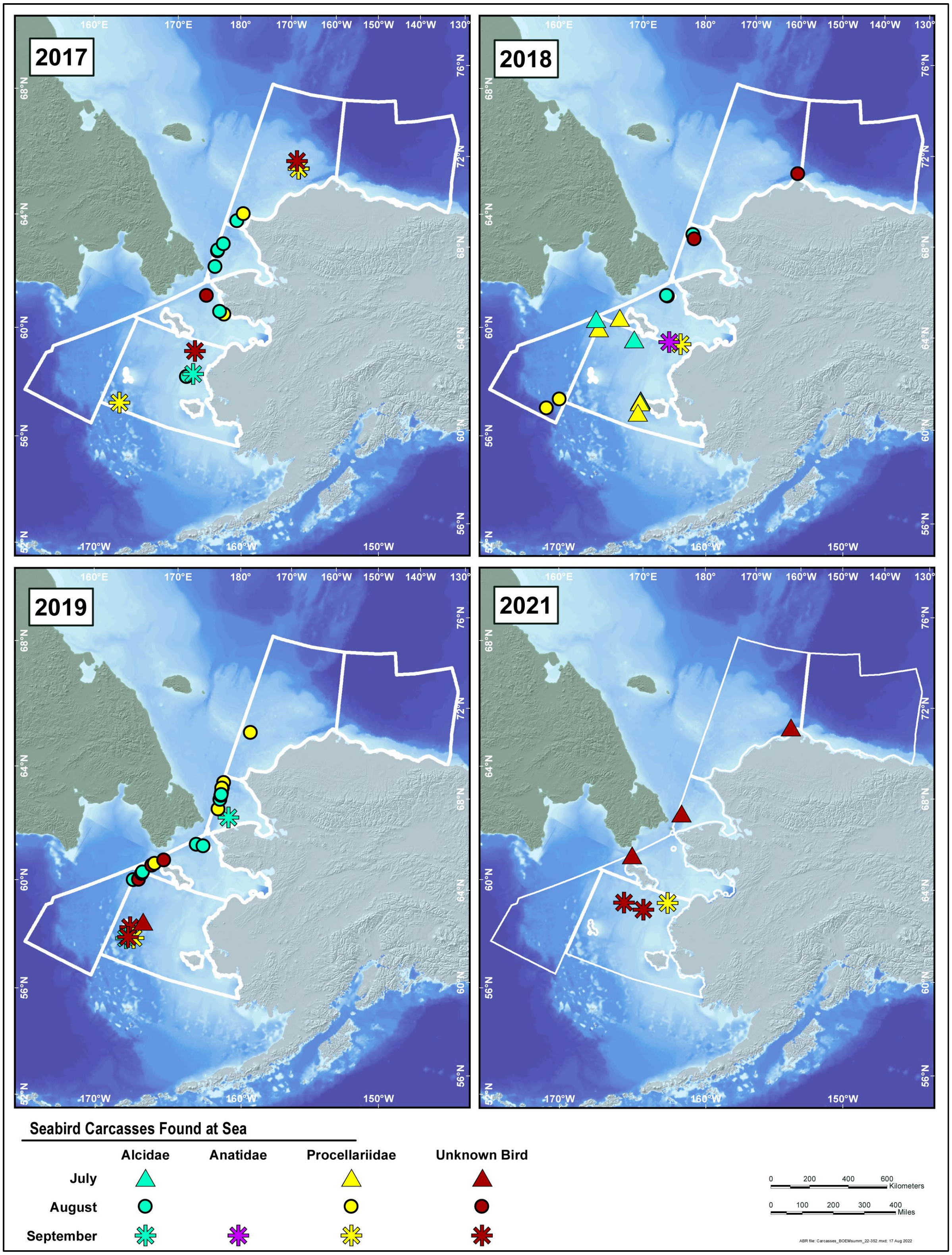

Figure 3.4. Distribution of observations of seabird carcasses recorded in the Bering, Chukchi, and Beaufort seas, 2017–2021, by family.
No carcasses were observed in 2020.

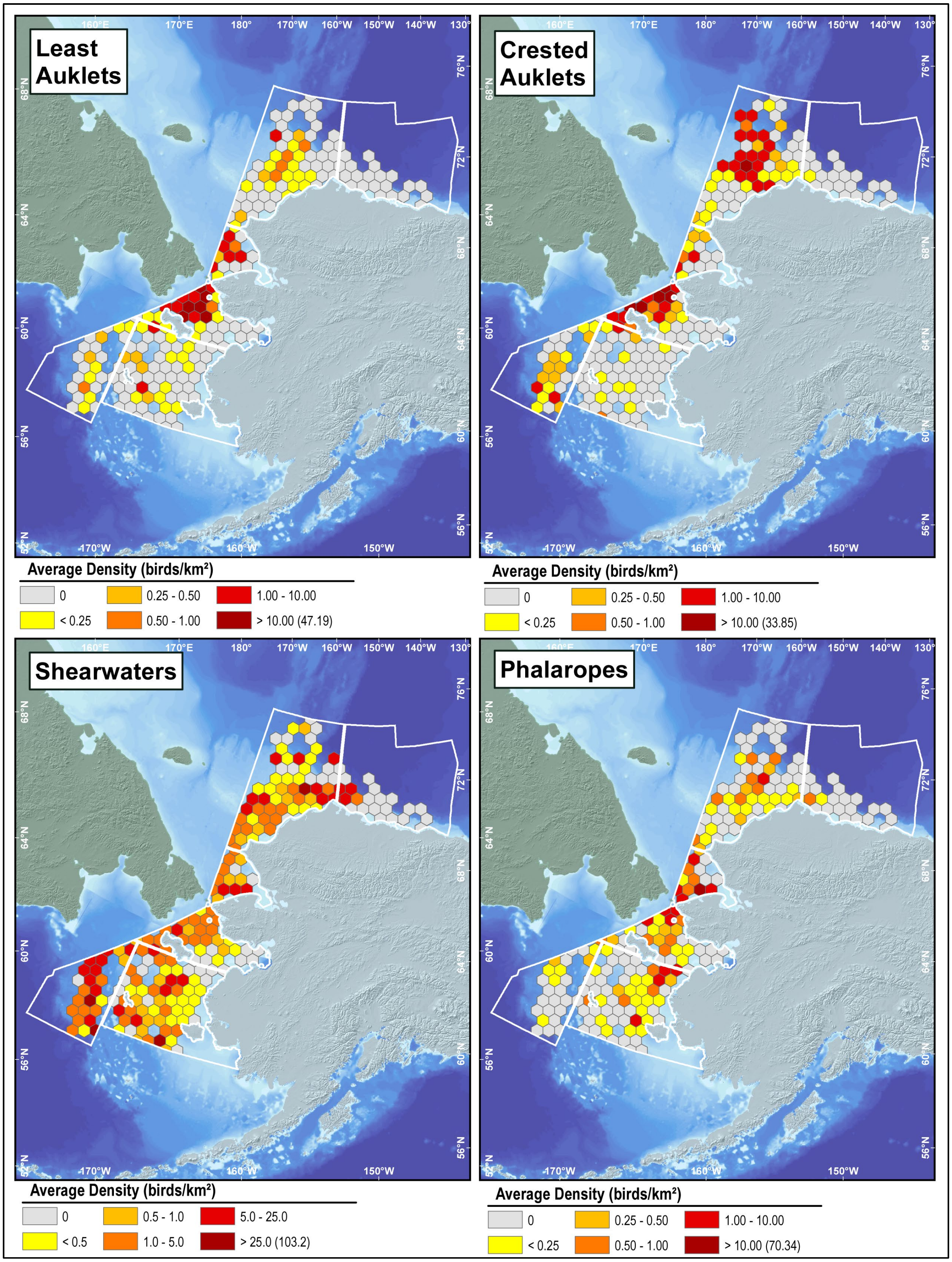

Figure 3.5. Density (birds/km^2) of planktivorous seabirds (least and crested auklets and phalaropes) and short-tailed shearwaters across the Bering, Chukchi, and Beaufort seas, 2017–2021.
The highest density is shown in parentheses for each species.

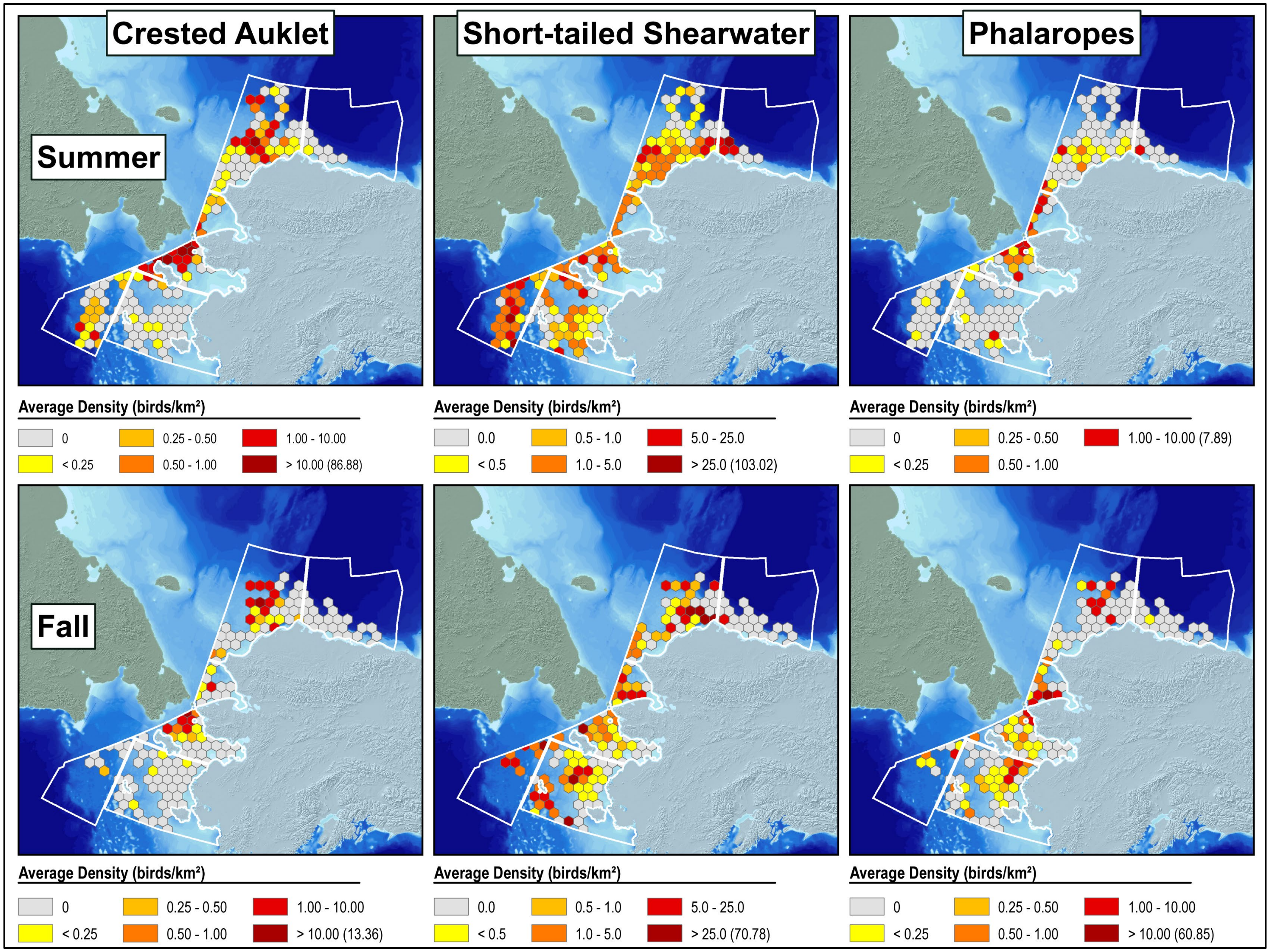

Figure 3.6. Seasonal density (birds/km^2) distribution of planktivorous seabirds (crested auklets and phalaropes) and short-tailed shearwaters in summer (June, July, and August) and fall (September, October, November) in the Bering, Chukchi, and Beaufort seas, 2017–2021.

The highest density is shown in parentheses for each species.

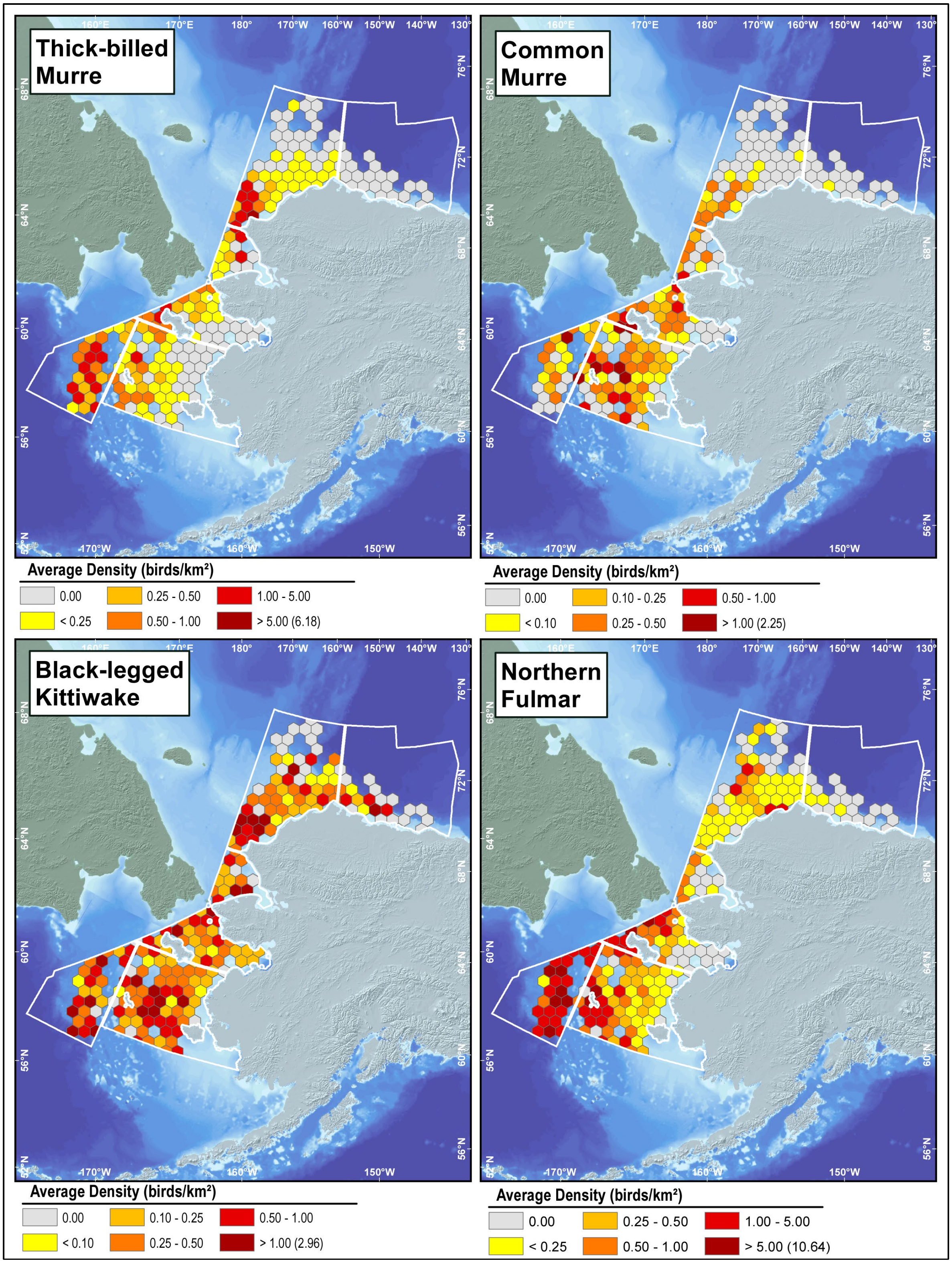

Figure 3.7. Density (birds/km^2) of piscivorous seabirds (thick-billed murres, common murres, black-legged kittiwakes and northern fulmars) in the Bering, Chukchi, and Beaufort seas, 2017–2021.

The highest density is shown in parentheses for each species.

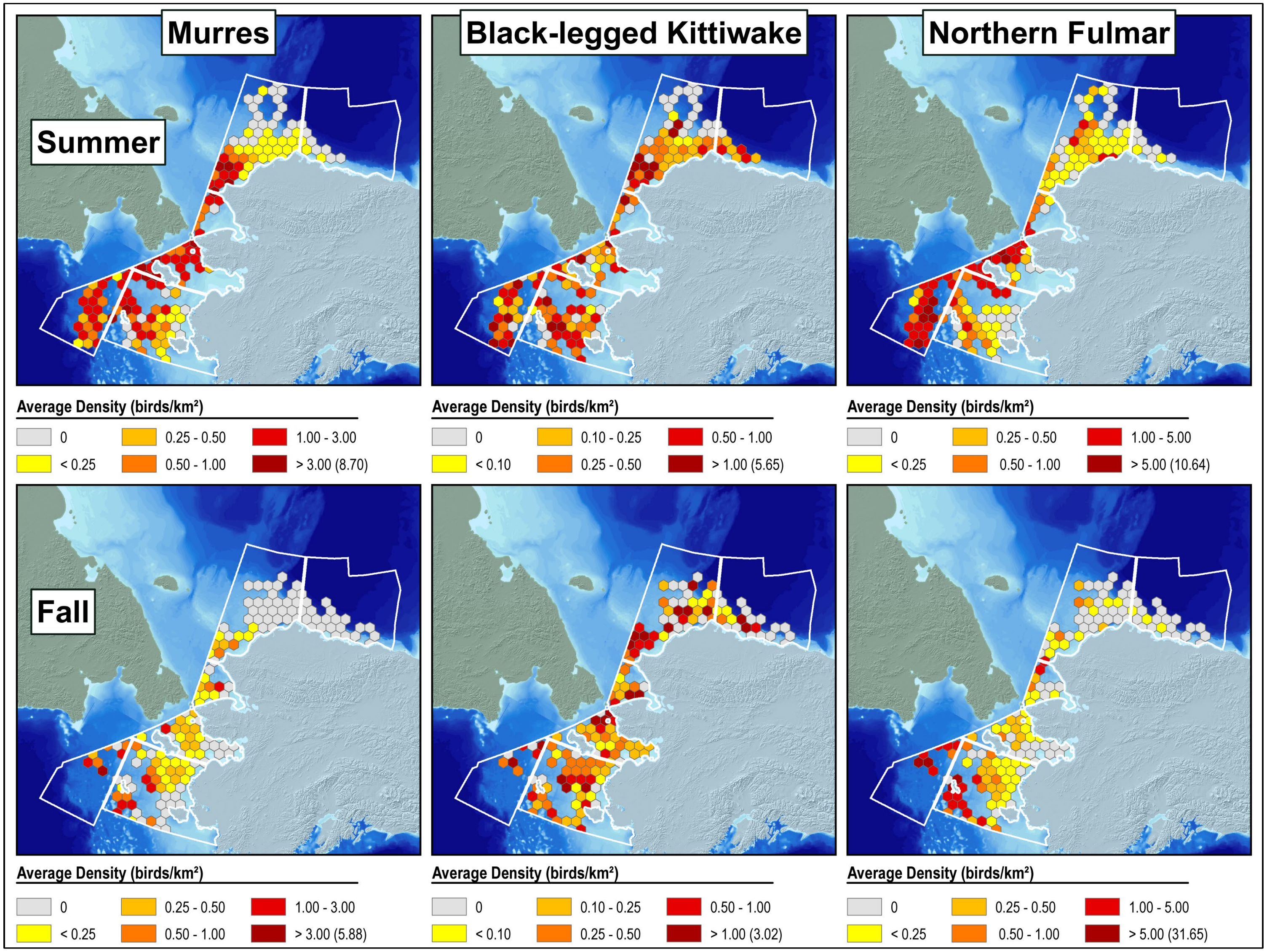

Figure 3.8. Seasonal density (birds/km^2) distribution of piscivorous seabirds (murres, black-legged kittiwakes and northern fulmars) in summer (June, July, and August) and fall (September, October, November) in the Bering, Chukchi, and Beaufort seas, 2017–2021. The highest density is shown in parentheses for each species.

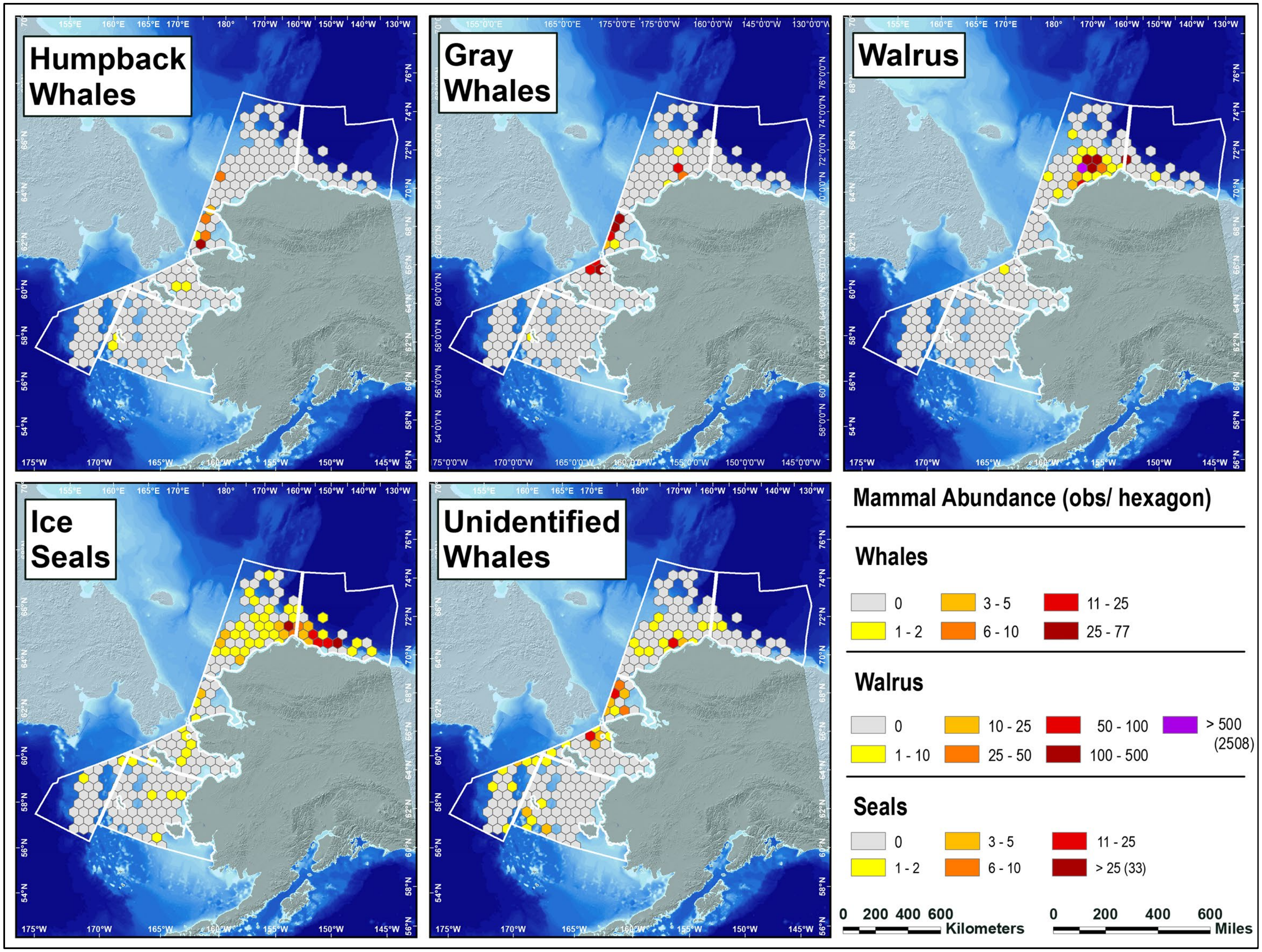

Figure 3.9. Distribution of marine mammals (observations/hexagon) in 6 BOEM Planning Areas in the Bering, Chukchi, and Beaufort seas, 2017–2021.
The highest count of marine mammals is shown in parentheses for each species.

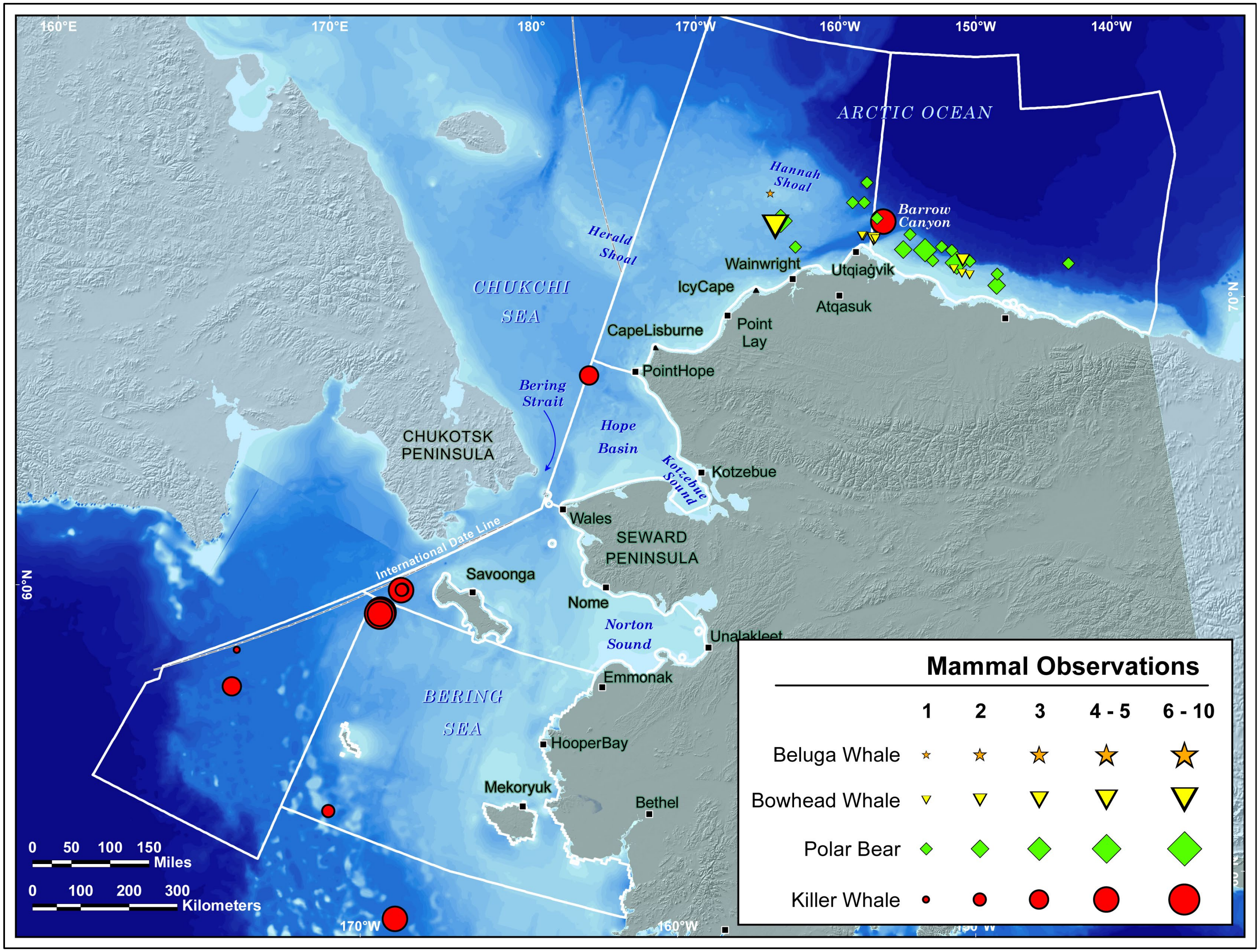

Figure 3.10. Observations of beluga, bowhead and killer whales, and polar bears in 6 BOEM Planning Areas in the Bering, Chukchi, and Beaufort seas, 2017–2021.

4 Discussion

The USFWS successfully collaborated with 12 projects operated by investigators at 9 different agencies and organizations, including researchers from Canada and Japan, to deploy seabird observers on research vessels. These collaborations resulted in a broadscale dataset that described the distribution and composition of the seabird community in US waters of the northern Bering, Chukchi, and Beaufort seas during the open-water season (June–November), 2017–2021. In addition, support for a satellite tracking study of phalaropes highlighted the importance of combining methods to obtain more complete information on habitat use for species of conservation concern.

4.1 Seabird abundance and distribution

Short-tailed shearwaters composed nearly half of the offshore bird community throughout the focal area. These results are consistent with findings of the Seabird Offshore Project funded by BOEM, conducted in 2010–2016 (Kuletz and Labunski 2017), and the seabird component of the Arctic Integrated Ecosystem Research Project (AIERP) conducted in 2017 and 2019 (Kuletz et al. 2022). When summarizing the results by Planning Area, however, several patterns emerged that revealed the latitudinal variation in the seabird community and how the distribution and abundance of seabirds has shifted as oceanographic conditions have changed over the past decade.

In the southern Planning Areas, surface-feeding birds (both planktivores and piscivores) composed a higher proportion of the community than did diving birds. These findings are consistent with other studies that found an increase in the abundance of surface foragers over the middle and outer shelf domains of the Bering Sea (Sigler et al. 2011; Hunt et al. 2014; Santora et al. 2018). The planktivorous guild in Navarin Basin was composed primarily of fork-tailed storm-petrels, rather than the auklets and phalaropes found farther north. Fork-tailed storm-petrels breed as far north as the Aleutian Islands and the birds seen in Navarin Basin were foraging at the northern extent of their range (Boersma and Silva 2012). The piscivorous community in Navarin Basin and St. Matthew-Hall had higher proportions of surface-feeding northern fulmars and black-legged kittiwakes than of diving murres. Northern fulmars only breed as far north as St. Matthew Island whereas black-legged kittiwakes breed throughout the Bering Sea and into the southern Chukchi Sea. In the Bering Sea, both species rely on hydrographic fronts that concentrate zooplankton and forage fish to feed themselves and obtain food for their chicks (Hunt et al. 2008; Jahncke et al. 2008; Eisner et al. 2014).

The seabird community in and near Bering Strait had high proportions of least and crested auklets that outnumbered short-tailed shearwaters in the Norton Planning Area (Norton Sound and Chirikov Basin) and rivaled the numbers of short-tailed shearwaters in Hope Basin. Hope Basin also supported the highest average density of surface-feeding planktivores, although that value was driven by extremely high phalarope numbers in single grid cells in Hope Basin in 2018 and 2021. The physical constriction at Bering Strait creates a turbulent flow where three water masses interact (Coachman 1975; Coachman and Shigaev 1992) and create a rich foraging environment for seabirds in Chirikov and Hope basins (Piatt and Springer 2003; Santora et al. 2018).

North of Bering Strait, short-tailed shearwaters composed more than half of the seabird community, with fewer surface-feeding birds and more diving birds represented. The northernmost and some of the largest breeding colonies of auklets are located on the Diomede islands, within Bering Strait, because of the availability of both marine foraging and terrestrial breeding habitat. The northernmost major seabird colony is located at Cape Lisburne in the southern Chukchi Sea, and consists mainly of ~500,000 murres and ~30,000 kittiwakes (Dragoo and Dragoo 2019). Auklets, murres, and kittiwakes disperse northward into the Chukchi Sea after the breeding season to join the many short-tailed shearwaters that feed on late summer productivity before the ice begins to form again (Gall et al. 2013; Kuletz et al. 2019; Gall et al. 2022 [Appendix 1]). Over the past 5 years, however, that distribution pattern has been disrupted, possibly in response to the reductions in sea ice cover and the rapid and sustained increases in water temperatures (Carvalho et al. 2021; Mueter et al. 2021).

During our study, auklets concentrated in the Norton and Hope Planning Area in high numbers, whereas short-tailed shearwaters continued to disperse northward into the northern Chukchi and Beaufort seas, which was a distinct difference compared to the northward dispersal of alcids in 2007–2016 (Kuletz et al. 2020 [Appendix 2]). These changes in seabird distribution coincided with the onset of a marine heatwave that began affecting the focal area in 2017 (Duffy-Anderson et al. 2019; Basyuk and Zuenko 2020; Carvalho et al. 2021). The marine heatwave also affected trends of diving birds at breeding colonies. Notably, the colony at Cape Lisburne increased in size from 1987 to 2013, but the number of murres on annual monitoring plots declined from 2016 to 2019, whereas the number of black-legged kittiwakes continued to increase (Dragoo and Dragoo 2019). In 2018 and 2019, the reproductive success of seabirds in the northern Bering Sea was poor (Romano et al. 2020; Will et al. 2020), and seabird die-offs occurred throughout the Bering Sea and southern Chukchi Sea, with short-tailed shearwaters accounting for over half of all recorded mortality (Kaler and Kuletz 2022). The extreme and unprecedented environmental conditions that occurred during our project likely affected annual patterns of seabird distribution and it remains to be seen whether these changes persist.

Seasonal changes in seabird distributions may also be affected by increasing water temperatures and changes in extent and timing of sea ice cover. For example, crested auklet densities generally decline in the Norton Planning Area in the fall as post-breeding birds move northward into the Chukchi Sea to feed and molt near Hanna Shoal, where zooplankton prey are reliably available (Gall et al. 2013, 2017, 2022; Kuletz et al. 2015, 2019). Phalaropes also are less concentrated in Norton and Hope basins and distributed farther north in the fall than the summer. Individually tracked phalaropes indicated that they were moving to areas with greater food availability (Appendix 5). These post-breeding movements of planktivorous species northward into the Chukchi Sea are a 21st century phenomenon (Gall et al. 2017) facilitated by increases in the length of the open-water season that are transforming the physical and biological aspects of the Pacific Arctic region (Huntington et al. 2020, Mueter et al. 2021). There has been an increase in the distribution and abundance of zooplankton of Pacific origin across the eastern Chukchi shelf (Ershova et al. 2015; Spear et al. 2020). During the years influenced by the heatwave, however, there was an increase in small zooplankton and a decline in the abundance of large zooplankton in the northern Chukchi Sea (Lalande et al. 2021). Many auklets appeared to abandon their post-breeding migration northward from the Bering Sea and instead, remained in the Chirikov Basin (Kuletz et al. 2020). Auklets and phalaropes that did move northward aggregated near Hanna Shoal (Kuletz et al. 2022, this study), highlighting the important role that bathymetric features play in aggregating prey, especially in years of poor prey availability.

4.2 Phalarope movements

Through a combination of tracked individuals and at-sea surveys, we identified four important areas within Beringia for red phalaropes: 1) onshore and nearshore areas of the Beaufort and Chukchi seas (including Barrow Canyon); 2) the Bering Strait, especially along the Russian coast and Hope Basin; 3) the Gulf of Anadyr; and 4) Unimak Island and surrounding areas. Individuals exhibited notable variation in the timing, routes, and habitat selected. Unlike other shorebirds, migration of red phalaropes was characterized by indirect, circuitous routes with numerous stops over a long period of time, suggesting individuals are not time-limited during southward migration. Foraging red phalaropes were often associated with areas of greater food availability, such as in highly productive ocean currents, near ocean fronts or upwellings, and within the marginal ice zone. Red phalaropes were also found foraging on land during migration, which was unexpected. Males commonly used onshore sites in both the Beaufort/Chukchi and South Bering regions, and both sexes used nearshore (i.e., littoral habitats) habitats along the coasts of Russia and Alaska. Such extensive use of onshore and nearshore habitats suggests that these areas may provide alternative foraging opportunities for individuals during migration, especially in areas or at times when pelagic environments have lower ocean productivity (see Drever et al. 2018).

The combination of migration tracks from individuals and population-scale surveys conducted offshore allowed us to more fully examine important areas for migratory phalaropes. High-use areas identified by tracking red phalaropes, such as the Beaufort/Chukchi region and the Aleutian Islands, were also identified as being used by red phalaropes during the at-sea surveys, and both methods identified the Bering Strait region as having particularly high use (Appendix 5). The at-sea surveys did not detect other high-use areas found by tracking individuals, such as onshore and nearshore habitats, nor areas along the Russian coastline, such as the Gulf of Anadyr, because either no or few vessel-based surveys occurred there.

The discrepancies in areas identified as important to phalaropes identify the biases inherent in each method. At-sea survey data are limited to areas traveled by large offshore vessels and are often restricted by geopolitical boundaries, seasons, weather conditions, and other logistical constraints (particularly in nearshore waters), and provide no data on movements between areas by individuals. In the tracking study, the sample size of tracked males was small and individuals were tracked only briefly, potentially biasing the results to areas selected earlier in the season. Additionally, the sample of tagged individuals has a potential to bias the determination of habitat use, particularly if there is high migratory connectivity, or highly variable migration patterns where a small sample will not capture all, or even most of the variation. For example, at-sea surveys indicated fairly high use of several areas on the Bering Sea Shelf, particularly near the 50 m and 70 m isobaths, none of which were indicated by individually tracked phalaropes (Appendix 5). There may also be a behavioral bias if tagged individuals behave differently than individuals without tags. These methodological biases indicate that models to assist management decisions could be improved by combining data sources.

4.3 Marine mammals

Most marine mammal observations were recorded north of Bering Strait in the Chukchi Sea, where seals, whales, and walruses were recorded in all years of the program. These marine mammal observations are incidental to observations of marine birds and therefore, 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’ for a variety of cetaceans in Hope Basin, walruses near Hanna Shoal, and seals in the Beaufort Sea (Kuletz et al. 2015, 2022). Gray whales were recorded in Hope Basin and the Chukchi Sea, with no observations near Barrow Canyon or in the Beaufort Sea, in contrast to the observations recorded over Barrow Canyon and in the western Beaufort Sea during 2010–2016 (Kuletz and Labunski 2017, Appendix 1), and over the canyon during AIERP surveys in 2017 and 2019 (Kuletz et al. 2022). The numbers of walruses observed during this project were considerably lower than what was observed during 2010–2016 (Kuletz and Labunski 2017), which likely reflects the lower amount of sea ice in the Chukchi Sea in recent years.

4.4 Leveraging collaborative programs

During this project we participated in several collaborative ecosystem-based studies that provided an opportunity to collect seabird data concurrently with a suite of biological and physical oceanographic data (Table 2.1). The longest (and continuing) time series of collaborative projects included the C3O, NOAA’s

Northern Bering Sea Fisheries Survey (NBS), and the NOAA Fisheries Oceanographic Coordinated Investigations Survey (FOCI). In addition, we participated in the Arctic Marine Biodiversity Observing Network (AMBON), with which we collaborated prior to AK-17-03 and anticipate continuing in the future. These projects were largely focused in the BOEM Planning Areas in the northern Bering and Chukchi seas, and along with other collaborations, typically included sampling among stations of the DBO, which extends into the Beaufort Sea. Inclusion of seabird surveys with these on-going projects will depend on funding.

Our coordination with these projects provided an opportunity to take part in multidisciplinary research projects that were used to inform ecosystem-based resource management questions and provided timely information to the public. Annually we contributed seabird information to NOAA's Ecosystem Status Report (https://www.fisheries.noaa.gov/alaska/ecosystems/ecosystem-status-reports-gulf-alaska-bering-sea-and-aleutian-islands), which consolidates regional research information to inform fishery management decisions. Furthermore, the seabird data collected during these surveys was used to assess the scope of ongoing seabird die-off events in northwestern Alaska. At-sea seabird mortality data was shared with our partner agencies, including Alaska Sea Grant, the USGS National Wildlife Health Center, and the Coastal Observation and Seabird Survey Team. We presented information at meetings and public events, including the Alaska Migratory Bird Co-Management Council, the North Pacific Fisheries Management Council, and various Arctic Council workshops. Public presentations were also given at community events like the University of Alaska-Nome "Strait Science Series", and the University of Alaska "Opportunities for Lifelong Education (OLLE) Series" (see List of Presentations and Workshops, this report).

4.5 Management applications

In remote offshore marine areas, obtaining useful and current information on resources is difficult, both fiscally and logistically, necessitating collaborative efforts (Danielson et al. 2022) like the one supported by this project. However, the seasonal variation in the presence of seabirds in the focal area, coupled with the spatial autocorrelation inherent in continuous vessel-based transect data, creates challenges to providing reliable information on seabird distribution and abundance. These statistical challenges can be addressed with new modeling techniques that use the strong correlations inherent in seabird communities to improve predictions of seabird distribution. Vector Autoregressive Spatiotemporal modeling (VAST; Thorson 2019) was first developed for fisheries (Thorson et al. 2015, 2016) and is now being adapted for seabirds (Appendix 6). Joint Dynamic Species Distribution Models (JDSDMs), as implemented in VAST v.3.9.0, have greater predictive power than simple univariate models of seabird transect data. Gridded density estimates that span seasonal time-scales provide a means of understanding when and where the greatest risk from energy development may occur. Importantly, the models also can identify where more data are required to reduce uncertainty, and thereby guide future research efforts. As more data are collected, they can be incorporated easily into the existing framework to inform adaptive management strategies.

Increases in shipping activity have amplified multiple risk factors to seabirds, particularly in the Bering Strait region (Huntington et al. 2015). Risks include increased mortality from seabird-vessel strikes, disruption of migratory patterns due to light pollution, displacement from foraging areas, interactions with fishing gear, and oiling from vessel accidents. At-sea survey data can be used to assess the risks posed to seabirds by this increased vessel activity (Appendix 7). These risk assessments are relevant to BOEM because any oil and gas development that occurs in these Planning Areas will necessarily further increase vessel traffic, particularly through Bering Strait. Environmental assessments and documentation required by NEPA for any federal action need these data to conduct robust quantitative analyses. For example, vessel traffic can be quantified from Automatic Information Systems (AIS) deployed on commercial vessels and compared to distributions of seabirds to estimate the risk of collisions or fouling in the event of an oil spill (Appendix 7). By sampling throughout the open-water season, seabird surveys provide the temporal resolution to account for seasonal variation in risk that is important in developing risk reduction and mitigation strategies.

When evaluating the possible impacts of anthropogenic activity, assessments must also account for environmental stressors that are occurring independently, but can have cumulative effects. Marine heatwaves, or prolonged increases in ocean temperatures, have become more prevalent and intense in the past several decades (Oliver et al. 2018) and one consequence has been widespread die-offs of seabirds in Alaskan waters (Piatt et al. 2020, Romano et al. 2020, Suryan et al. 2021). These die-offs are primarily detected and documented by the Coastal Observation and Seabird Survey Team (COASST), a citizen science program that collects and compiles data from effort-standardized surveys for seabird carcasses on beaches. Although finding carcasses at sea is rare, the observations collected during this program (Table 3.5, Figure 3.4) helped further describe the magnitude and spatial extent of seabird die-offs that occurred in 2019 (Kaler and Kuletz 2022).

5 Conclusions

To better understand and anticipate the impact of environmental change on marine birds, this project built on an established at-sea survey program to collect distribution data on marine birds via partnership and collaboration among the USFWS, BOEM, the North Pacific Research Board (NPRB), and NOAA Fisheries. The data from these collaborative vessel-based projects contributed 43,443 km of transects to the North Pacific Pelagic Seabird Database, from the northern Gulf of Alaska to the Arctic. We determined the current species composition, distribution, and abundance of seabirds during the open water seasons of 2017–2021. We examined synoptic distributions by foraging guild and selected species, focusing on the northern Bering, Chukchi, and Beaufort seas. We also explored seasonal changes by comparing summer (June–August) to fall (September–November) patterns of seabird distribution. Finally, we presented results from a study we facilitated that examined migratory movements and nearshore and marine habitat use of red phalaropes in concert with at-sea surveys.

Collaborations with other at-sea projects create robust datasets that maximize efficiency and our ability to make inferences about potential risk in ecologically important regions. We identified offshore waters of importance to a variety of marine bird and mammal species in the context of oil and gas Planning Areas. Clearly, the Norton and Hope Planning Areas will require care and diligence to protect the birds and mammals that breed near, forage, and migrate through these areas. Included within these two Planning Areas are: (1) the Chirikov Basin, which is important breeding and foraging habitat for millions of auklets and other seabirds, as well as foraging and migrating cetaceans; (2) Hope Basin, which hosts high densities and diversity of marine birds and marine mammals; and (3) Bering Strait, the bottleneck through which most species belonging to the upper trophic levels of this region pass during some stage of the open-water season.

The Chukchi Planning Area is also seasonally important to a variety of birds and mammals that use this area, particularly walruses and short-tailed shearwaters. Shearwaters, although they nest in the southern hemisphere, are an important component of the seabird community and increasingly, they numerically dominate the offshore seabird community in the Chukchi Sea during summer and fall. The changing feeding conditions and risks that shearwaters encounter in the northern Bering and Chukchi seas will ultimately impact the breeding populations in Australia. The red phalarope project illustrates how combining population-level surveys with tracking information will provide more complete pictures of the timing and duration of habitat use for species of conservation concern in this changing region.

Seabirds that nest in Beringia have also shown shifts in distribution and abundance and may be vulnerable to on-going changes in prey and ocean conditions. They have recently been exposed to potentially harmful algal blooms, as well as increased anthropogenic activity. Since 2017 this region has experienced annual multi-species marine bird die-off events that include important local subsistence food resources for coastal communities and thus a food security issue in western Alaska. With Arctic marine ecosystems warming at twice the global average (Hoegh-Gulberg and Bruno 2010), consistent, annual data collection such as the effort supported by this project will be critical to assessing the status and trends of marine resources in BOEM’s Arctic Planning Areas.

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Appendix 1: Influence of water masses on the summer structure of the seabird community in the Northeastern Chukchi Sea

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Abstract

We used data collected during a variety of research cruises in the northeastern Chukchi Sea and contributed to the Distributed Biological Observatory to explore the influence of the seasonal change in water masses on the development of the seabird community during the summer. Surveys that included seabird observations and hydrographic sampling were conducted from Alaska's northwestern coast to ~220 km offshore during 2008–2018. Species composition varied geographically, shifting from a nearshore community that included short-tailed shearwaters, loons, and seaducks to an offshore community dominated by crested auklets. Crested auklets were remarkably consistent in their occupation of Hanna Shoal among years and remained in the area throughout the summer. Short-tailed shearwaters exhibited the greatest seasonal and interannual variation in abundance and distribution of the 35 species recorded. They were concentrated south of 71 °N and within 50 km of shore in August and tended to spread throughout the region in September. Surface-feeding species like gulls, fulmars, and phalaropes were 1–2 orders of magnitude less abundant and had wider distributions than birds that feed by diving. Including information about hydrography improved the fit of models of seabird density. Seabirds, especially those that breed in the Bering Sea, generally were more abundant in areas dominated by moderate-salinity Bering Sea Water than nearshore in low-salinity Alaska Coastal Water. The distribution of seabirds across the northeastern Chukchi Sea reflected the heterogeneity of oceanic habitats and prey availability over the shallow shelf. Our results will inform efforts to develop ecosystem models that incorporate oceanographic conditions to predict ongoing consequences of climate change.

Introduction

Seabird distribution across a seascape can reflect oceanographic conditions at lower trophic levels, serving as visible indicators of marine ecosystems that are otherwise obscured under water [1–3]. The northeastern Chukchi Sea is being altered by fundamental changes in the regional climate that are restructuring the marine food web by creating an environment that is warmer, fresher, and more ice-free than in the previous three decades [4]. The rate of warming has been accelerating in recent years and decades (5). These changes are affecting processes that influence the distribution, life history, and interactions of biological communities [6–9]. Declining seasonal ice cover also is increasing access to the Chukchi Sea, providing new opportunities for human activities such as recreational boating, commercial shipping and fishing, and oil and gas exploration. The seabird community offers benchmarks for evaluating both the short-term effects of catastrophic events such as oil spills and the long-term responses to climate change.

The eastern Chukchi shelf sustains a diverse seabird community during the July–October open-water season [10–12]. A few species of piscivorous seabirds such as murres (*Uria* spp.), puffins (*Fratercula* spp.), and black-legged kittiwakes (*Rissa tridactyla*) nest in large colonies (~500,000 birds) at Cape Thompson and Cape Lisburne to take advantage of the fish available in nearshore waters [13–15]. Other species-groups such as jaegers (*Stercorarius* spp.), gulls (*Larus* spp.), and loons (*Gavia* spp.), nest on the tundra and forage in the marine environment during or after the breeding season [16]. In addition to breeding seabirds, non-breeding and post-breeding seabirds move into the northern Chukchi Sea as the ice recedes to feed on both fish and zooplankton (10–12). This community of >40 species of seabirds depends on a variety of habitats created when warm water masses move northward from the Bering Sea (17) and interact with cold water masses of the northern shelf formed during winter [18,19] and modified by nearshore warming during spring and summer. Together, these physical processes form four major water masses that drive the environmental gradients of the Chukchi Sea.

The four water masses within the study area in the summer differ in temperature, salinity, and stratification, which are key determinants of foraging habitat [20]. The Alaska Coastal Current (ACC) lies adjacent to the Alaska coastline and flows northward, carrying Alaskan Coastal Water (ACW), a warm (>7 °C), low-salinity (<30.8) water-mass [5] that originates south of Bering Strait and is additionally supplied by fresh river outflows as it progresses northward. The currents farther offshore move Bering Sea Water (BSW; [17,21]), a moderately warm (0–7 °C) and moderate-salinity (30.8–33.4) water mass [5], northward through the Central Channel and Herald Valley (Fig. 1; [22]). One branch of the BSW pathway is an eastward flow south of Hanna Shoal [23,24]. BSW is often a mixture of Anadyr Water and Bering Shelf Water from south of Bering Strait; it has an elevated nutrient content and transports more and larger oceanic zooplankton than do the ACW flows [25,26]. Water masses are modified on the Chukchi shelf in the winter when ice formation produces cold (~- 2–0°C) and brine-enriched, Winter Water (WW). Ice melts and leaves cool (0–3 °C), low-salinity (<30.8) Meltwater (MW) at the surface [5; 27] that helps regulate the exchange of heat between the BSW and the pack ice [28]. These four water masses (ACW, BSW, WW, and MW) provide habitat for a seasonally diverse assemblage of seabirds. Dynamic fronts and flow instabilities occur at the boundaries between the Chukchi water masses [28], which can concentrate plankton and increase foraging opportunities for surface-feeding and near-surface-feeding seabirds.

Seabird prey communities associated with these water masses also differ substantially and likely contribute to determining the distribution and composition of seabird communities. Prey species associated with ACW include small neritic copepods and a variety of forage fishes that include 5 species of salmon (*Oncorhynchus* spp.), rainbow smelt (*Osmerus mordax*), Pacific sandlance (*Ammodytes hexapterus*), and Arctic cod (*Boreogadus saida*; [29,30]. Salmonids are found almost exclusively in the surface waters of the shelf [30,31], whereas other forage fish are found throughout the water column. The low temperatures of two-layered MW/WW near Hanna Shoal preclude the development of a diverse fish community [8,32]. In contrast, the pelagic community is characterized primarily by cold-tolerant Arctic cod and the seasonal development of a zooplankton community that includes the large arctic copepod *Calanus glacialis* [33]. BSW is intermediate in temperature and salinity between WW and ACW and transports energy-rich Pacific zooplankton prey, including *Neocalanus* copepods and euphausiids, into the study area [34].

The biological communities found on the broad shelf of the northeastern Chukchi Sea are structured by the northward flow of Pacific water and the seasonal advance and retreat of sea ice [35–38]. These simple food webs are now being disrupted by increases in advection through Bering Strait and changes in sea ice regimes [36]. The Distributed Biological Observatory was established in 2010 as a change detection array to develop consistent time series for exploring the ecological consequences of climate change [39–41]. One of the strengths of the framework is a holistic approach that seeks to link measurements of oceanography with data on species composition and distribution. We leveraged data collected on hydrography and seabirds in the northeastern Chukchi Sea to explore the influence of the seasonal change in water masses on the development of the seabird community during the open-water season.

We examined the distribution, abundance, and community composition of seabirds in the Chukchi Sea from Alaska's northwestern coast to ~220 km offshore during 2008–2018. Herein we describe temporal and spatial changes in seabird species-composition along the nearshore–offshore oceanographic gradient and with respect to hydrographic conditions. By relating the temporal response of the seabird community to the intrusion and distribution of BSW, models that predict future oceanographic conditions may be applied to predict possible changes in the timing and composition of seabird communities as the Arctic continues to warm.

Methods

Study area

This study was conducted in the northeastern Chukchi Sea in an area bounded near the village of Point Lay in the south (69.922 °N 162.578 °W) and the Chukchi shelf break in the north (72.866 °N 156.648 °W), with data collection focused in an area extending from Alaska's northwestern coastline westward to the U.S.–Russia maritime boundary (168.976 °W, Fig. 1). For comparisons of community composition, we divided the study area into four geographical/ecological strata to account for the effects of latitude, water masses, currents, and bathymetry on determining oceanic habitat [38]. First, we divided the area along the 40-m isobath running roughly parallel to shore. Although the exact location of the front between ACW and the offshore water-masses (BSW, MW, WW) may change within and among years [19], the 40-m isobath approximates the composite location of this front over time. Next, we divided the area by latitude along 71 °N, an area of persistent eastward flow from the Central Channel to Barrow Canyon [22,24]. The resulting strata have distinct hydrographic characteristics, which we expected would influence and differentiate seabird communities within each one.

The Southern Offshore stratum has an area of 35,059 km^2 and is characterized by northward flow of BSW through the Central Channel that then splits as it approaches Hanna Shoal, with some flow turning east toward the head of Barrow Canyon. The Southern Nearshore stratum has an area of 25,405 km^2 and is influenced by northward coastal flows that carry predominantly ACW, although episodic flow reversals can transport slope waters southward from Barrow Canyon [43,44]. The Northern Offshore stratum has an area of 67,625 km^2 and is influenced by the anticyclonic flow around Hanna Shoal [45] and resident MW/WW over the shoal that drains into Barrow Canyon from the shelf throughout the summer [27]. The Northern Nearshore stratum includes the head of Barrow Canyon and the eastern end of the Chukchi continental slope, an area of high biological productivity that supports feeding aggregations of seabirds and marine mammals [12].

Data collection

Oceanographic data and data from systematic seabird surveys were pooled across various research programs conducted during 2008–2018 (Table 1). We surveyed a total of 35,680 km across years (11,893 3-km transects), with all surveys conducted from 13 August to 2 October. Seabird surveys followed protocols established and refined by the U.S. Fish and Wildlife Service [46,47] using vessels 35–128 m long and in waters at least 6 m deep. The closest approach to shore was 1.3 km and no permits were required to operate in Federal or State waters. A small number of transects extended into the Ledyard Bay Critical Habitat Unit, an area managed by the U.S. Fish and Wildlife Service (USFWS) for the protection of molting spectacled eiders. We engaged in an informal consultation with the USFWS to confirm best practices while operating in the bay; no special permits were required.

We conducted seabird surveys as continuous sampling when the ship was moving along a straight-line course at a minimum speed of 9.3 km/h [46,48]. These survey lines subsequently were split into 3-km sampling units (transects) for analysis using GIS because seabird communities are considered spatially independent at scales ≥ 3 km [49–51].

We collected data 9–12 h/day during daylight hours, weather and ice conditions permitting. Surveys generally were stopped when sea state was Beaufort 6 (seas ~2–3 m) or higher. One observer stationed on the bridge of the ship recorded all birds seen within a radius of 300 m in a 90° arc from the bow to the beam on the port side of the ship (the count zone) and located and identified seabirds with 10× binoculars. For each bird or group of birds, we recorded species (or identity to lowest possible taxon); total number of individuals; distance from the centerline (in categories; 0–50 m, 51–100 m, 101–150 m, 151–200 m, 201–300 m); location (air, water, flotsam/jetsam, ice); and behavior (flying, sitting, swimming, feeding, comfort behavior, courtship behavior, other).

We counted all birds on the water within the count zone, taking care to avoid recounting the same individuals. For flying birds, however, we conducted scans ~1 time/min (the exact frequency varied with ship's speed) and recorded an instantaneous count ("snapshot") of all birds flying within the count zone. This snapshot method reduces the bias of overestimating the abundance of flying birds [46,48]. We counted only those flying birds that entered the count zone from the sides or front and did not count those that entered from behind the ship (i.e., an area that already had been surveyed) to avoid the possibility of counting ship-following birds. We recorded observations of all birds directly into a computer connected to a global positioning system (GPS) with TigerObserver software (TigerSoft, Las Vegas, NV) or DLog (Glenn Ford, Seattle, WA). These programs time-stamped and georeferenced every observation entered in real time and provided a trackline of sampling effort.

Hydrographic data came from stations spaced 25–50 km apart, depending on the cruise. Conductivity-temperature-depth (CTD) measurements were made with a Sea-bird (SBE) 911 or SBE 25 CTD sampling at 24 and 4 Hz, respectively, that was lowered through the water-column at a rate of ~0.5 m s^{-1} to within 5 m of the seafloor. We measured pressure, temperature (± 0.005 °C), and conductivity (S/m) and then computed depth and salinity (±0.02). Data collected with the CTD were processed according to the manufacturer's recommendations and screened for anomalous spikes, dropouts and density inversions. We averaged the station data to 1-decibar (~1-m) vertical profiles that were then used to calculate the summary values for temperature, salinity, and density gradient.

Data analysis

We selected transects that were conducted within a study area covering 140,582 km^2, during days of year 225–275 (13 August–2 October), and had associated oceanographic data collected in situ within 2 days and at stations within 20 km of the respective transect centroid. To explore the influence of seasonal changes in water masses on the distribution of seabirds, we divided the study period into two 25-day periods: early summer (13 August–6 September) and late summer (7 September–2 October). In August, waters are typically the warmest and most ice-free and in September, waters tend to cool as days get shorter.

We limited the analysis to species that forage in the marine environment, and specifically in the Chukchi Sea. These included Scolopacidae (phalaropes), Stercorariidae (jaegers), Alcidae (auks), Laridae (gulls, terns), Gaviidae (loons), Procellariidae (fulmars, shearwaters), and marine species of Anatidae (eiders, scoters, other seaducks) (Table 2). All data processing, analysis, and statistical tests were performed in program R version 4.0.3 [52], with significance of $p<0.05$. Means are presented ± standard error (SE). Maps were created using ArcGIS v. 10.8 and other results figures were produced using package 'ggplot2' in R [53].

Community analyses

We used descriptive statistics and multivariate analyses to explore spatial and temporal variation in the seabird community. We first calculated sample-based rarefaction curves to evaluate species richness between seasons. This approach accounts for variation in sampling effort by resampling 3-km segments without replacement to estimate the rate at which species are detected [54,55]. For individual observations not identified to species, we retained the higher-order taxon only if no individuals of that group were identified to species [56].

For multivariate community analyses, we included only bird observations that were identified to species. Species that occurred in < 5% of groups or had fewer than 10 records were excluded from the analysis; these were short-billed gulls, ivory gulls, common loons, dovekies, and red-throated loons. We grouped data by geographic stratum, season, and year for ordination using non-metric multidimensional scaling (nMDS) [57]. The log-transformed species densities were used to calculate a Bray-Curtis similarity matrix [58] and then mapped those distances in two-dimensional space. The stress coefficient of the ordinations was 0.118, indicating adequate fit to the data [59]. We examined the variation in species composition among geographic strata and seasons with permutational multi- variate analysis of variance (PERMANOVA), which partitions variation and requires no assumptions about the distribution or correlations among the variables [60]. Finally, we visualized species composition by geographical stratum and season. We did not include 2017 in the species composition summary figures because in late summer 2017, short-tailed shearwaters were remarkably more abundant (by 1–2 orders of magnitude) and widespread than in other years, swamping all other species. We used package 'vegan' v.2.5-7 [61] for community analyses and packages 'vegan' and 'ggplot2' [53] for visualizations.

Abundance and distribution

We assigned 3-km transects to cells in a hexagonal grid overlaid on the study area based on the location of the transect centroid. Each grid cell measured 30 km from vertex to vertex. Hexagons have lower sampling bias at edges than do rectangular cells [62]. For each cell, we calculated the density of seabirds for each season and year as the total of birds observed on those transects within the cell divided by the total area surveyed.

To avoid bias from over-inflated densities in hexagons with little surveyed area, we limited analysis of abundance and distribution to cells that had a minimum of 5 km^2 of transect area sampled during a given season and year. There were 320 hexagons in early summer and 236 hexagons in late summer with adequate samples of transect data to include in density models. These hexagons were surveyed between 1 and 7 years each (Fig. 2).

We selected 8 focal taxa for statistical analyses that together represent 95% of the seabird community: crested auklet (*Aethia cristatella*), least auklet (*A. pusilla*), phalaropes (*Phalaropus* spp.), short-tailed shearwater (*Puffinus tenuirostris*), black-legged kittiwake (*Rissa tridactyla*), thick-billed murre (*Uria lomvia*), glaucous gull (*Larus hyperboreus*), and northern fulmar (*Fulmarus glacialis*). Because red-necked and red phalaropes often occur in mixed-species flocks and are difficult to distinguish at a distance, especially during molt, we combined observations of these 2 species with those of unidentified phalaropes and treated them collectively as phalaropes. These 8 focal taxa represented a variety of foraging methods (e.g., diving, surface feeding, shallow plunging) and prey preferences (e.g., planktivores, piscivores, omnivores), thereby providing an overview of the main functional ecological groups of the seabird community.

We considered 5 explanatory oceanographic variables to model the occurrence and abundance of the 8 focal taxa of seabirds. Hydrographic variables included temperature and salinity in the upper 10 m of the water-column, temperature and salinity in the lower 10 m of the water-column, and the density gradient from the surface to the bottom of the water column. Salinity and temperature are characteristics that define water masses in this region [19,42]. The density gradient is a characteristic of the water-column that we considered to be a proxy for foraging conditions. A strong density gradient indicates water column stratification that can enhance prey availability by concentrating prey at the pycnocline, whereas a weak density gradient can indicate a well-mixed water column that enhances prey availability at the surface [63–65]. These 5 variables were derived from measurements at fixed oceanographic stations throughout the study area. We assigned physical-oceanographic values to each transect based on the nearest station sampled to avoid artifacts inherent in using interpolated values. Values for each 30-km cell were calculated as the mean of values for each transect within a cell-season-year.

We also considered two time-related variables (year and season), and two geographic variables (latitude and distance from shore) calculated from the centroid of each grid cell in the models. We used distance to shore to account for the possible effect of proximity of terrestrial breeding habitat (coastal islands, cliffs, or tundra) that can influence foraging distributions of nesting marine birds. We did not include longitude because it was strongly correlated with distance from shore.

There were strong correlations ($r > 0.6$) among many combinations of the 5 water mass variables (temperature, salinity, and gradient). We therefore used principal component analysis (PCA) run on the scaled variables for variable reduction. The first component of the PCA analysis (PCA1) explained 69.7% of the variability in the 5 water mass variables. The PCA1 score increased with higher values of upper temperature, upper salinity, and bottom temperature, and decreased with higher values of density gradient and bottom salinity (Table 3).

We used generalized additive models (GAM; [66]) to compare seabird counts to the two geographic factors (latitude and distance to shore) and the PCA1 score as an indicator of hydrographic conditions, hereafter, "hydrography." We included year as a factor to account for variations in density among years. The count of each species of seabird within a hexagon was modeled with a negative binomial distribution and the natural log of transect area was included as an offset term to account for differing survey effort in different hexagons by year and season. GAM models were fit with the default smoother, a penalized thin plate regression spline [67].

We compared four different models containing the geographic variables (latitude and distance from shore) and hydrography: 1) a model with the geographic variables and hydrography varying by season; 2) a model with just the geographic variables varying by season; 3) a model with just hydrography varying by season, and 4) a model with no variables varying by seasons. We used the model with the lowest AIC score and highest model weight for inference [68].

Results

Oceanographic conditions

Denser near-bottom water (Fig. 3) was generally cool (mean: 0.83 °C, range: -1.72 to 9.82 °C) and salty (mean: 32.4, range: 28.7 to 34.8) relative to the less dense surface water (Fig. 4) that tended to be warmer (mean: 4.33 °C, range: -1.12 to 10.06 °C) and fresher (mean: 30.4, range: 25.5 to 32.4). In most years with sampling throughout the open-water period, surface water noticeably cooled from August to September (Fig. 4), whereas in 2010 and 2017 temperatures in the upper 10 m of the water column remained relatively unchanged from the early to late season sampling.

Seabird community

We recorded a total of 90,985 individuals and identified 35 species of seabirds during these surveys. Of these, crested auklets were the most abundant (49% of total), followed by short-tailed shearwaters (31%) and least auklets (5%). Species richness was similar between seasons but slightly higher in late summer (Fig. 5), with 33 and 35 species recorded in early and late summer, respectively. Ivory and Ross's gulls were recorded only in late summer, all other species were recorded in both seasons.

Species composition varied geographically (Table 4), shifting from a community that included short-tailed shearwaters, loons, and seaducks nearshore to one dominated by crested auklets offshore (Fig. 6). The nMDS ordination showed a weak separation between the nearshore and offshore strata (Fig. 7), with offshore areas having higher values along MDS1 and MDS2 than nearshore areas. Two season-year combinations were outliers from the predominant pattern. In early summer 2012, the species composition in the Northern Nearshore stratum included Least Auklets, phalaropes, and other alcids that are generally more abundant in the offshore areas. In late summer 2017, the first year of a 3-year heatwave, the species composition of the Northern Nearshore stratum clustered with the offshore samples because Short-tailed Shearwaters were more abundant and widespread than in other years, swamping out all other species in the Northern Nearshore, Northern Offshore, and Southern Offshore strata.

Seabird abundance and distribution

Seabirds were more abundant offshore than nearshore, especially in early summer when short-tailed shearwaters were present in highest numbers. Least and crested auklets were more abundant offshore than nearshore in both seasons (Fig. 8, 9). Black-legged kittiwakes, short-tailed shearwaters, and phalaropes had areas of high abundance near Barrow Canyon in early summer. There was insufficient sampling in the nearshore area from Peard Bay north to Utqiaġvik to quantify patterns in seabird density near Barrow Canyon in late summer.

For 4 of 8 species, the best predictive model for abundance included the geographic variables (latitude, distance to shore), hydrography, and interactions with season. The model with hydrography and interactions between season and the geographic variables was the best model for 3 species, and the model with geographic variables and an interaction between season and hydrography was the best model for thick-billed murre (Table 5). There was model uncertainty for phalaropes and glaucous gulls, with two models nearly equal in performance (Table 5), although parameter estimates did not support a strong seasonal difference in the effect of hydrography (Fig. 10).

Hydrography was a significant predictor of seabird distribution in most cases, with the exceptions of glaucous gull in early season ($p = 0.085$) and thick-billed murre in late season ($p = 0.062$; Table 6). After accounting for latitude and distance to shore, black-legged kittiwakes, crested auklets, least auklets, northern fulmars, and thick-billed murres were all positively associated with areas that had warmer, saltier water in the upper layer and weaker density gradients in early summer (Fig. 10). These conditions were typical of BSW in the Central Channel and other offshore areas. For auklets, northern fulmars, and phalaropes, the effect of hydrography was consistent among seasons. In contrast, densities of short-tailed shearwaters in early summer were positively associated with water that was cooler, fresher, and more stratified, suggesting an association with ACW. In late summer, short-tailed shearwaters were positively associated with waters that warmer and saltier in the upper layer (Fig. 10), which was indicative of BSW.

The distance to shore variable was significant for all species except black-legged kittiwakes ($p = 0.201$) and northern fulmars during early summer ($p = 0.067$), and phalaropes during both the early summer ($p = 0.578$) and late summer ($p = 0.238$; Table 6). Crested and least auklets and thick-billed murres were more abundant farther offshore in both seasons whereas glaucous gulls and short-tailed shearwaters were more abundant nearshore in early summer and distributed throughout the study area in late summer (Fig. 11).

The latitude variable was significant for all species except black-legged kittiwakes ($p = 0.136$), northern fulmars during the early season ($p = 0.061$) and late season ($p = 0.654$), and short-tailed shearwaters during the late season ($p = 0.634$; Table 6). Least Auklets, phalaropes, and thick-billed murres were more abundant south of 71 °N in late summer whereas black-legged kittiwakes, crested auklets, glaucous gulls, and northern fulmars had similar or higher abundance north of 71 °N in late summer as well as in early summer (Fig. 12). Short-tailed Shearwaters were generally more abundant south of 71 °N in both seasons (Fig. 8 and 9). The widespread distribution of Short-tailed Shearwaters in late summer 2017 may have influenced the estimate of the effect of latitude in the models (Fig. 12).

Discussion

We show that the distribution of seabirds throughout the northeastern Chukchi Sea reflects the heterogeneity of oceanic habitats over the shallow shelf. Auklets, murres, and northern fulmars generally were more abundant in offshore areas of the Chukchi Sea dominated by moderate-salinity Bering Sea Water than nearshore in low-salinity Alaska Coastal Water. The seabird community within 50 km of the coast had low densities compared to areas farther offshore. Although auklets and other alcids were found in these nearshore waters, the community was composed primarily of short-tailed shearwaters and also included diving piscivores such as loons and benthic feeders such as eiders and long-tailed ducks.

With a maximum depth of only ~ 100m and most of the shelf < 50m deep, variations in bathymetry of only a few meters help steer water masses of varying temperature and salinity, and their associated prey species [24]. High salinity surface currents flowing northward through the Central Channel from the Bering Sea carry copepods and euphausiids to the Chukchi Sea [15,34]. Auklets (*Aethia* spp) and short-tailed shearwaters that forage in the Bering Sea from May through July were found in the Central Channel stream in August and September, presumably following their prey [11,12,69].

As with other studies of seabird distribution [70], GAMs were effective at revealing the factors that caused observed variance in seabird abundance. The GAMs revealed that most seabird-habitat relationships were species-specific, non-linear, and in some cases, varied by season. In general, auklets and murres, species that feed almost exclusively by diving, had distributions that were well-predicted by latitude and distance to shore. Thick-billed murres and least auklets were more abundant south of 71 °N whereas crested auklets were distributed primarily 71–72 °N throughout the summer. In contrast, short-tailed shearwaters were more abundant south of 71 °N in early summer and at all latitudes in late summer. Although short-tailed shearwaters are capable divers [71], they are also stronger fliers than are alcids.

Surface-feeding species like gulls, fulmars, and phalaropes had wider distributions than birds that feed by diving. Glaucous gulls nest on the Arctic Coastal Plain and may have been more abundant nearshore in August because they were still tending to chicks. By September, most glaucous gull young have left the nest and are independent [72], allowing both adults and young to disperse widely. The distributions of black-legged kittiwakes and phalaropes were not influenced by distance to shore.

Including information about hydrography improved the fit of the models describing seabird density, despite the challenges of quantifying oceanographic conditions at scales that match the decisions made by foraging seabirds. The relationship to hydrography was strongest and most consistent between seasons for northern fulmars, phalaropes, and least auklets. Thick-billed murres, however, were associated with BSW in early summer but showed no relationship to hydrography in late summer. The relationship of surface-feeding species to hydrography was more challenging to characterize, partly because they had low abundance overall and perhaps because they may make decisions about foraging at spatial and temporal scales that are shorter than those at which hydrography was sampled in this study [51,73,74].

Influence of foraging conditions

We assumed that foraging conditions were the most important factor in determining the distribution of seabirds. During the early summer (which was primarily August in this study), we observed consistent associations of planktivorous seabirds with offshore waters that are typically saltier than waters found along the coast. In late summer (primarily September in this study), we observed southward movements in species such as phalaropes and thick-billed murres, while auklets and gulls remained widespread throughout the study area. This southward movement was consistent with a southward shift during fall that was described for seabirds using the Chukchi Sea in 2007–2012 [12]. The timing of departure from the northeastern Chukchi Sea precedes the formation of ice by several weeks, suggesting that the availability of preferred prey for these southbound species changes sooner than it does for auklets.

Crested auklets numerically dominated the seabird community in the northeastern Chukchi Sea throughout the open-water season in most years, even though their nearest nesting areas were at least 550 km to the south. Our study area closely overlapped the 'crested auklet-dominated' community identified within a larger study area encompassing the northern Bering and Chukchi seas [69]. This was one of five communities defined for the Pacific Arctic overall, and one of the most spatially well defined, indicating specific habitat preferences, or with prey associated with that habitat. Crested auklets are widespread across the Chukchi shelf and least abundant nearshore. They are remarkably consistent in their occupation of Hanna Shoal and remain in the area until ice starts to form in October [12,69]. Observations during surveys suggest that crested auklets are flightless and likely undergoing molt during August and early September, which limits their mobility and makes it even more important that prey be reliably accessible. Other diving species that rely heavily on planktonic prey, such as short-tailed shearwaters and thick-billed murres, are also common offshore but do not aggregate as far north as do crested auklets. What is it about Hanna Shoal that attracts such high numbers of crested auklets?

The zooplankton community around and south of Hanna Shoal is dominated by *Calanus glacialis* and *Pseudocalanus* spp. [34,75,76], prey that are essential to crested auklets [77,78]. Hanna Shoal is encircled by clockwise circulation that brings BSW northward along the western flank and then east towards Barrow Canyon [22,79,80]. To the east, water from the Shoal mixes with northward flowing coastal currents [75]. These general patterns of circulation can vary in their persistence and strength among years, leading to variable mixing of water masses and their entrained zooplankton [34,75]. The combination of shallow bathymetry, weak surface flow, and reliable aggregations of zooplankton advected from the Bering Sea make the eastern Chukchi Sea ideal habitat for non-breeding and post-breeding crested auklets.

Together with crested auklets, short-tailed shearwaters drive community structure in the northeastern Chukchi Sea. In contrast to crested auklets, short-tailed shearwaters were less consistent in distribution and abundance among years. This greater inter-annual variance compared to location was also evident at a larger geographic scale study that included all DBO sites [69]. In most years, short-tailed shearwaters are strongly associated with nearshore waters south of 71 °N. The exceptions were occasional years (2009, 2017) when shearwaters were extremely abundant and dispersed widely, occupying more northerly and/or offshore regions. In the Chukchi Sea, shearwaters appear to forage primarily on euphausiids [81], although they also consume large zooplankton, invertebrates and small fish [82]. Seabird surveys of the northern Bering and Chukchi seas showed a trend of northward movement of short-tailed shearwaters beginning around 2013, with peak numbers in 2015 [69], thus a pattern of greater occupation of the Chukchi Sea by shearwaters began prior to the large influx we observed in 2017. However, 2017 was the first of a 3-year period with exceptionally warm ocean waters in the northern Bering-Chukchi large marine area (5,56). During this period, seabird die offs occurred, breeding seabirds failed, and some species showed declines in abundance at sea [83,84]. Concurrently, small copepods predominated in place of large-bodied copepods, and they occurred farther north in the Chukchi Sea. In a study focused on the Barrow Canyon area of the northern Chukchi Sea, krill abundance showed a positive correlation between late spring ice melt and ice extent, with those conditions occurring in 2006, 2009, 2012-2014, and the opposite occurring other years through 2015 [85]. Although 2017 was outside the time periods examined, these results suggest that years of shearwater irruptions in the Chukchi Sea (2009, 2013) may coincide with high krill abundance driven by spring ice conditions.

Geographic patterns

Effective marine conservation relies on the predictability of locating resources that require protection. One of the essential assumptions of the DBO is that the sites selected for monitoring are in areas of high biomass, high species biodiversity, representative of the Pacific Arctic ecosystem, and will remain so over time [40,86]. This study focused on DBO sites 4 and 5, where hotspots of seabird aggregation have been identified in nearshore waters near the village of Wainwright, in an offshore area on the southern flank of

Hanna Shoal, and at the mouth of Barrow Canyon [12,69]. These hotspots were also apparent in our analysis in early summer. In late summer, however, we did not include data from near Barrow Canyon because none of the transects in that area had oceanographic data available from within 2 days and 20 km of when the birds were recorded. Our study emphasizes the importance of collecting data on seabird occurrence concurrently with oceanographic data on water column properties, currents, and perhaps most importantly, thermohaline fronts that affect prey availability. Doing so will improve our ability to predict possible future shifts in the distribution and abundance of seabirds as the Artic warms. Our results can inform efforts to develop ecosystem models that incorporate oceanographic conditions, nutrients, prey species, and top predators to predict ongoing consequences of climate change [87].

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Table 1. **S**ampling effort by year, northeastern Chukchi Sea, 2008–2018.

Year	**Date start**	**Date end**	**Number of 3-km transects**	**Area surveyed (km^2)**
2008	16-Aug-2008	28-Sep-2008	838	623
2009	13-Aug-2009	2-Oct-2009	1,484	1,172
2010	13-Aug-2010	2-Oct-2010	1,749	1,374
2011	13-Aug-2011	2-Oct-2011	1,633	1,188
2012	15-Aug-2012	1-Oct-2012	2,368	1,784
2013	13-Aug-2013	2-Oct-2013	1,329	989
2014	20-Aug-2014	23-Sep-2014	348	682
2015	13-Aug-2015	3-Sep-2015	1,014	823
2016	12-Sep-2016	13-Sep-2016	45	37
2017	13-Aug-2017	21-Sep-2017	979	739
2018	13-Aug-2018	25-Aug-2018	106	75
Total			11,893	9,485

Table 2. Species of seabirds recorded during ship-based surveys in the northeastern Chukchi Sea, 2008–2018.

Family	**Scientific name**	**English name**	**Code**	**Total count**	
				Early summer	**Late summer**
Sea ducks	*Somateria fischeri*	Spectacled Eider	SPEI	21	17
	Somateria spectabilis	King Eider	KIEI	3	45
	Somateria mollissima	Common Eider	COEI	59	51
	Clangula hyemalis	Long-tailed Duck	LTDU	137	300
Phalaropes	*Phalaropus lobatus*	Red-necked Phalarope	RNPH	655	591
	Phalaropus fulicarius	Red Phalarope	REPH	529	180
Jaegers	*Stercorarius pomarinus*	Pomarine Jaeger	POJA	105	22
	Stercorarius parasiticus	Parasitic Jaeger	PAJA	26	4
	Stercorarius longicaudus	Long-tailed Jaeger	LTJA	10	2
Alcids	*Alle alle*	Dovekie	DOVE	13	3
	Uria aalge	Common Murre	COMU	283	92
	Uria lomvia	Thick-billed Murre	TBMU	1,892	1,102
	Cepphus grille	Black Guillemot	BLGU	7	10
	Brachyramphus brevirostris	Kittlitz's Murrelet	KIMU	95	79
	Synthliboramphus antiquus	Ancient Murrelet	ANMU	50	441
	Aethia psittacula	Parakeet Auklet	PAAU	81	89
	Aethia pusilla	Least Auklet	LEAU	2,735	2,184
	Aethia cristatella	Crested Auklet	CRAU	25,642	18,885
	Fratercula corniculate	Horned Puffin	HOPU	66	5
	Fratercula cirrhata	Tufted Puffin	TUPU	24	2
Gulls	*Rissa tridactyla*	Black-legged Kittiwake	BLKI	1,021	1,931
	Pagophila eburnea	Ivory Gull	IVGU	0	3
	Xema sabini	Sabine's Gull	SAGU	167	12
	Rhodostethia rosea	Ross's Gull	ROGU	0	314
	Larus brachyrhynchus	Short-billed Gull	SBGU	1	0
	Larus argentatus	Herring Gull	HEGU	9	26
	Larus hyperboreus	Glaucous Gull	GLGU	174	499
	Sterna paradisaea	Arctic Tern	ARTE	75	3
Loons	*Gavia stellata*	Red-throated Loon	RTLO	1	8
	Gavia pacifica	Pacific Loon	PALO	50	492
	Gavia immer	Common Loon	COLO	1	4
	Gavia adamsii	Yellow-billed Loon	YBLO	4	48
Procellariiids	*Fulmarus glacialis*	Northern Fulmar	NOFU	906	246
	Ardenna tenuirostris	Short-tailed Shearwater	STSH	17,282	11,171

Table 3. Factor loading output from principal component analysis of 5 oceanographic variables calculated over survey transects within hexagon shaped grid cells.

Variable	**Comp.1**	**Comp.2**	**Comp.3**	**Comp.4**	**Comp.5**
Temperature (upper 10 m)	0.464	–	0.882	–	–
Salinity (upper 10 m)	0.440	0.553	0.152	–	-0.684
Density gradient	-0.472	0.411	0.280	0.130	-0.717
Salinity (bottom 10 m)	-0.398	-0.622	0.224	0.627	0.106
Temperature (bottom 10 m)	0.458	0.369	-0.265	0.762	–
Proportion of variance explained	0.697	0.180	0.064	0.042	0.017

Table 4. PERMANOVA of species composition of the seabird community in the northeastern Chukchi Sea, 2008–2018. Analysis was based on Bray-Curtis dissimilarities from log-transformed data. Each term was tested using 1,000 random permutations of the stratum-season-year samples.

Source	**Degrees freedom**	**Mean squares**	***F***	***R*²**	***P***
Season	1	0.467	2.083	0.035	0.046
Region	3	0.676	3.018	0.15	<0.001
Residuals	49	0.224		0.815	
Total	53			1.000	

Table 5. Generalized additive models that best explained variation in abundance and distribution of seabirds in the northeastern Chukchi Sea, 2008–2018 (n=256 hexagonal cells, 30-km from vertex to vertex). Values are the Akaike's Information Criterion score (AIC), difference in AIC score (ΔAIC) from the the model with the best fit, and Akaike weights (ω_i). DistShore is the distance to shore from the centroid of each cell in the sampling grid.

Model	**AIC**	**ΔAIC**	**ω_i**
Phalaropes			
Hydrography; DistShore (seasons), Latitude (seasons)	2248.0	0.0	0.53
Hydrography (seasons); DistShore (seasons), Latitude (seasons)	2248.9	0.9	0.34
Hydrography, DistShore, Latitude	2251.4	3.4	0.10
Hydrography (seasons); DistShore, Latitude	2254.0	6.0	0.03
Thick-billed Murres			
Hydrography (seasons); DistShore, Latitude	1902.7	0.0	0.87
Hydrography (seasons); DistShore (seasons), Latitude (seasons)	1906.5	3.8	0.13
Hydrography, DistShore, Latitude	1914.6	11.9	0.00
Hydrography; DistShore (seasons), Latitude (seasons)	1918.5	15.8	0.00
Least Auklets			
Hydrography; DistShore (seasons), Latitude (seasons)	2523.2	0.0	0.94
Hydrography (seasons); DistShore, Latitude	2530.1	6.9	0.03
Hydrography, DistShore, Latitude	2531.4	8.1	0.02
Hydrography (seasons); DistShore (seasons), Latitude (seasons)	2532.4	9.2	0.01
Crested Auklets			
Hydrography (seasons); DistShore (seasons), Latitude (seasons)	4912.3	0.0	1.00
Hydrography; DistShore (seasons), Latitude (seasons)	4928.2	15.9	0.00
Hydrography (seasons); DistShore, Latitude	4930.3	18.0	0.00
Hydrography, DistShore, Latitude	4943.5	31.2	0.00
Black-legged Kittiwakes			
Hydrography (seasons); DistShore, Latitude	2485.6	0.0	1.00
Hydrography (seasons); DistShore (seasons), Latitude (seasons)	2504.3	18.7	0.00
Hydrography; DistShore (seasons), Latitude (seasons)	2562.6	77.1	0.00
Hydrography, DistShore, Latitude	2562.9	77.4	0.00
Glaucous Gulls			
Hydrography (seasons); DistShore (seasons), Latitude (seasons)	1358.1	0.0	0.53
Hydrography (seasons); DistShore, Latitude	1358.4	0.3	0.47
Hydrography; DistShore (seasons), Latitude (seasons)	1433.9	75.8	0.00
Hydrography, DistShore, Latitude	1443.0	84.9	0.00
Northern Fulmars			
Hydrography; DistShore (seasons), Latitude (seasons)	1777.5	0.0	0.69
Hydrography, DistShore, Latitude	1779.4	1.8	0.28
Hydrography (seasons); DistShore (seasons), Latitude (seasons)	1784.6	7.1	0.02
Hydrography (seasons); DistShore, Latitude	1786.5	9.0	0.01
Short-tailed Shearwaters			
Hydrography (seasons); DistShore (seasons), Latitude (seasons)	3852.9	0.0	1.00
Hydrography; DistShore (seasons), Latitude (seasons)	3872.0	19.1	0.00
Hydrography (seasons); DistShore, Latitude	3875.5	22.6	0.00
Hydrography, DistShore, Latitude	3888.2	35.3	0.00

Table 6. Variables that best described the variation in distribution and abundance of 8 species of seabirds in the northeastern Chukchi Sea, 2008–2018. P-values indicate statistical significance from generalized additive models (GAM). Dist. Shore is the distance to shore from the centroid of each cell in the sampling grid.

Variable	**Phalaropes**	**Thick-billed Murres**	**Least Auklets**	**Crested Auklets**	**Black-legged Kittiwakes**	**Glaucous Gulls**	**Northern Fulmars**	**Short-tailed Shearwaters**
Hydrography	**<0.001**		**<0.001**				**0.001**	
Hydrography: Early summer		**<0.001**		**<0.001**	**<0.001**	0.085		**0.021**
Hydrography: Late summer		0.692		**<0.001**	**<0.001**	**<0.001**		**<0.001**
Dist. Shore		**0.001**			0.403			
Dist. Shore: early	0.578		**<0.001**	**<0.001**		**<0.001**	0.067	**<0.001**
Dist. Shore: Late	0.238		**<0.001**	**<0.001**		**0.050**	**0.039**	**0.009**
Latitude		**<0.001**			0.271			
Latitude: Early	**0.045**		**0.034**	**<0.001**		**0.003**	0.061	**<0.001**
Latitude: Late	**0.035**		**<0.001**	**<0.001**		**0.050**	0.654	0.634
Deviance Explained	**19.10%**	**54.18%**	**47.77%**	**35.33%**	23.48%	28.68%	21.60%	30.23%

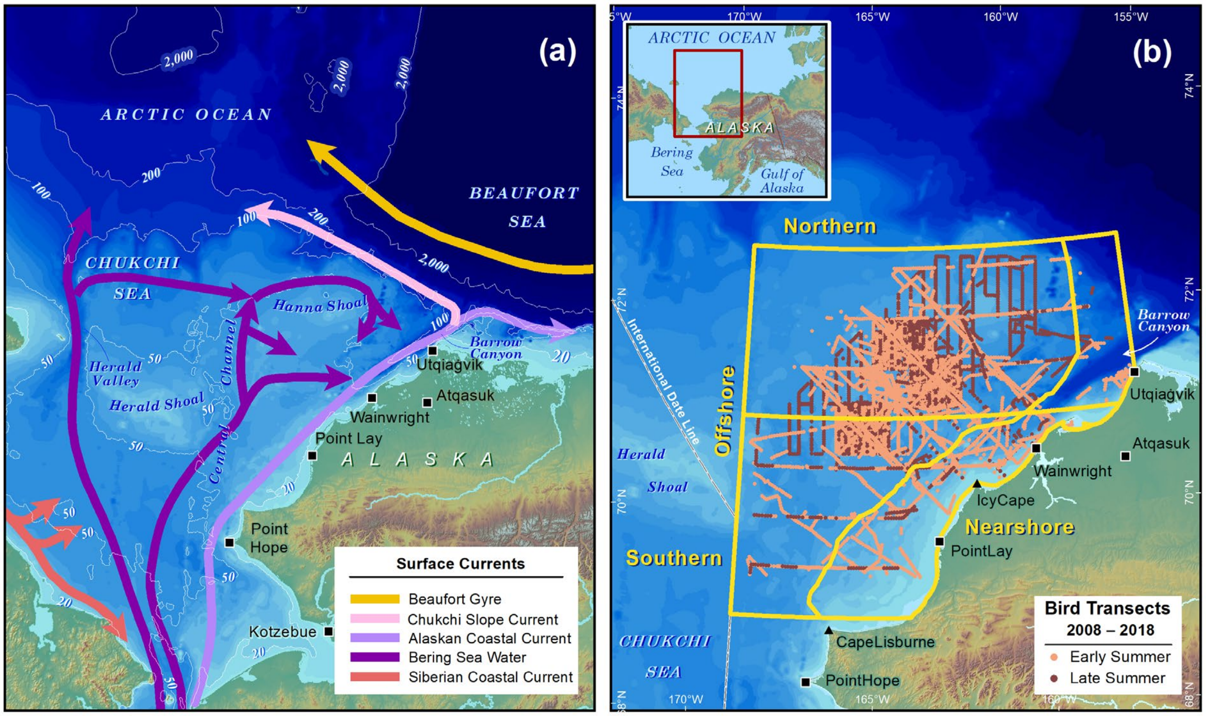

Fig 1. The Chukchi Sea, showing (a) current locations; and (b) geographic strata and survey effort. Bathymetry data are from the International Bathymetric Chart of the Arctic Ocean www.ibcao.org.

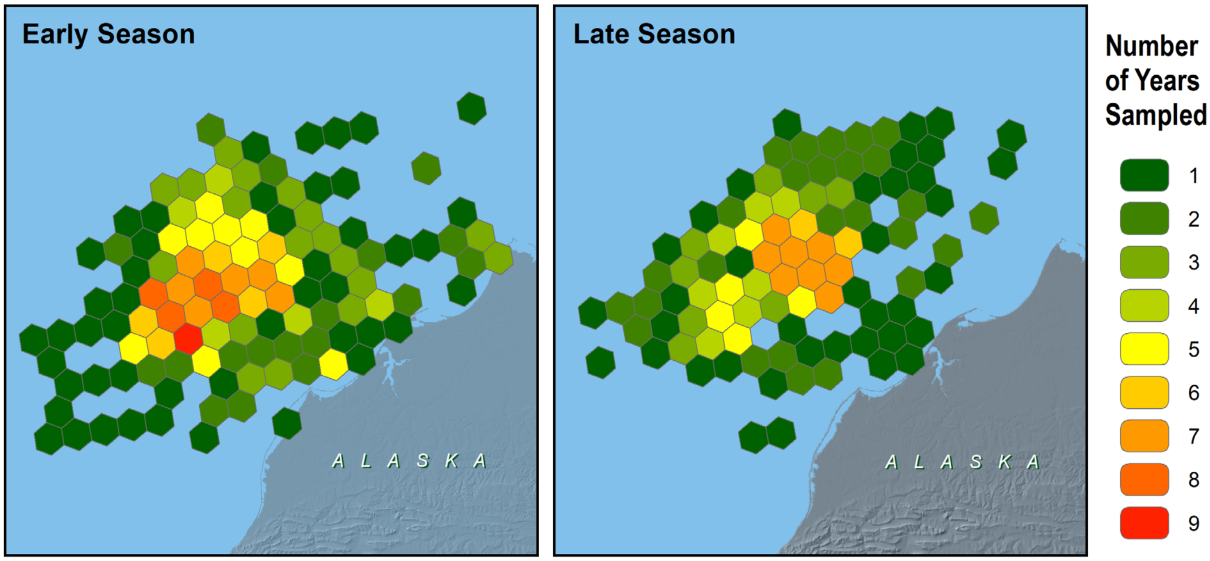

Fig 2. Seasonal and interannual differences in sampling effort in the northeastern Chukchi Sea, 2008–2018.

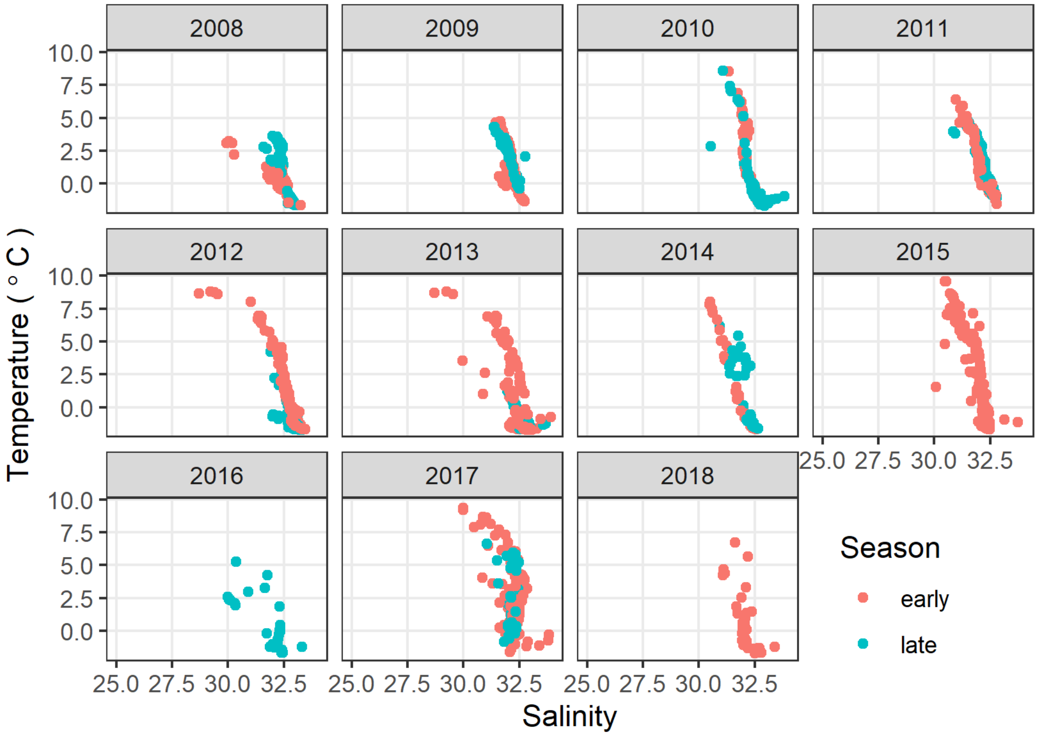

Fig 3. Temperature and salinity of water in bottom 10 m of water column, northeastern Chukchi Sea. Early summer was 13 Aug–6 September and late summer was 7 September–2 October.

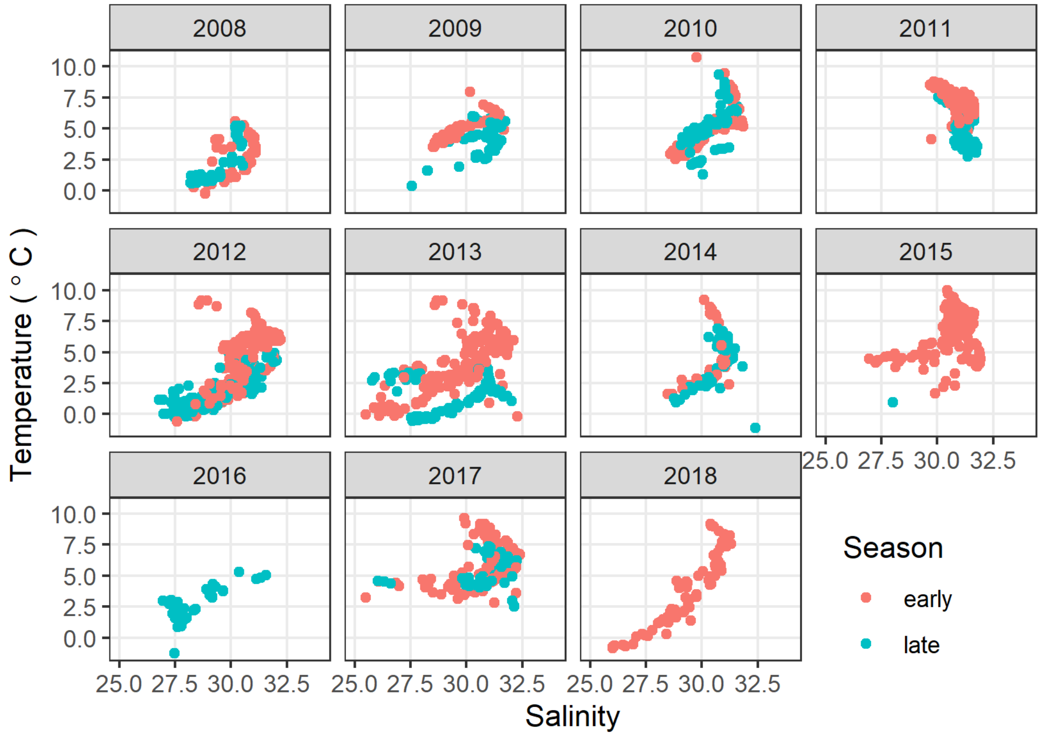

Fig 4. Temperature and salinity of water in upper 10 m of water column, northeastern Chukchi Sea. Early summer was 13 Aug–6 September and late summer was 7 September–2 October.

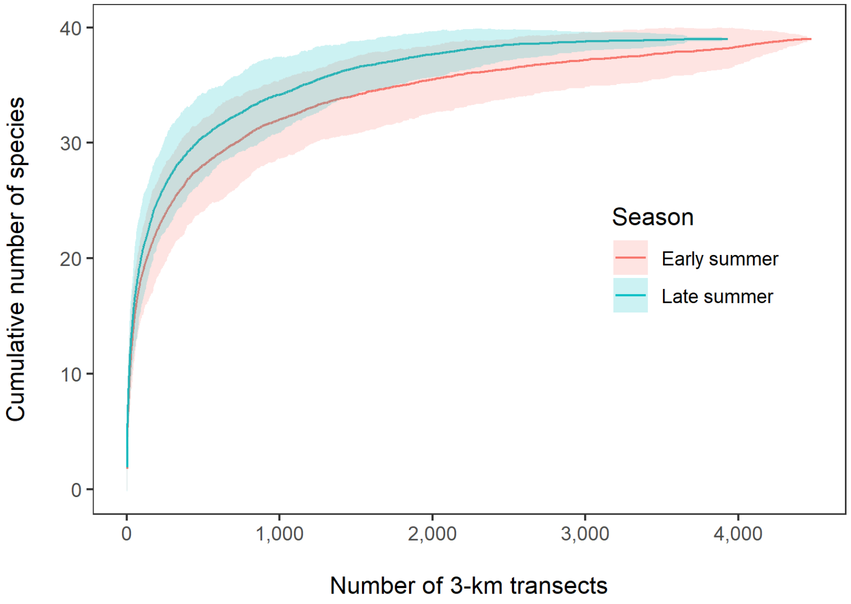

Fig 5. Seabird species rarefaction curves from surveys conducted in the northeastern Chukchi Sea in early and late summer, 2008–2018. Early summer (pink) was 13 August–6 September and late summer (aqua) was 7 September–2 October. Shading indicates 95% confidence intervals based on resampling transects without replacement.

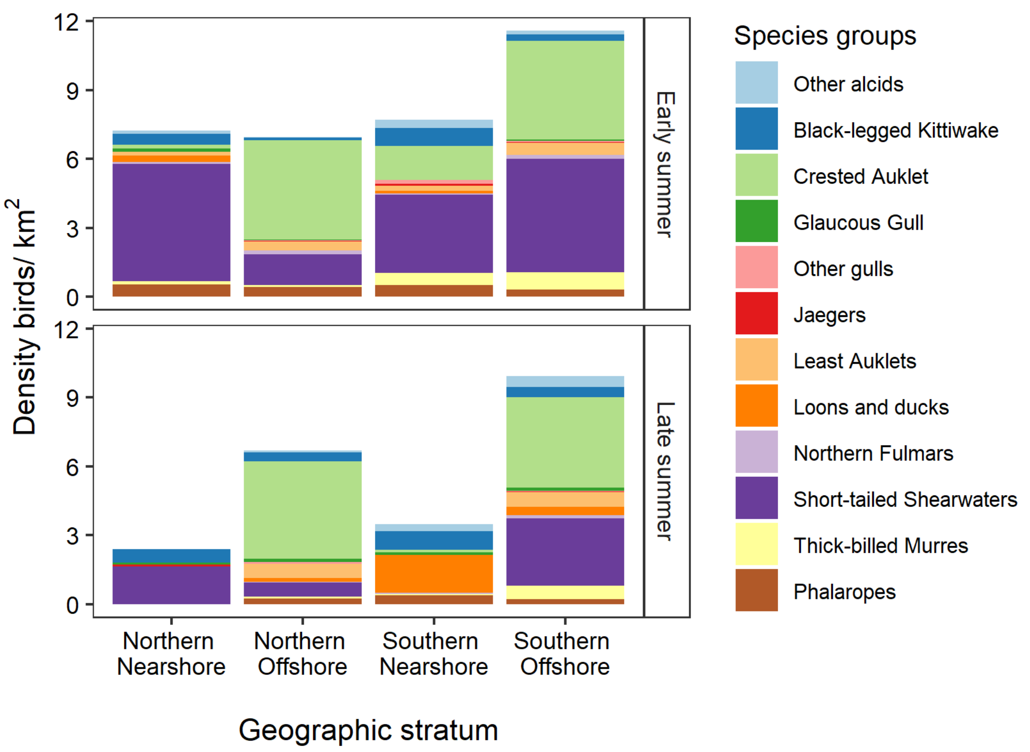

Fig 6. Species composition of seabird community in geographic strata of the northeastern Chukchi Sea, 2008–2018.

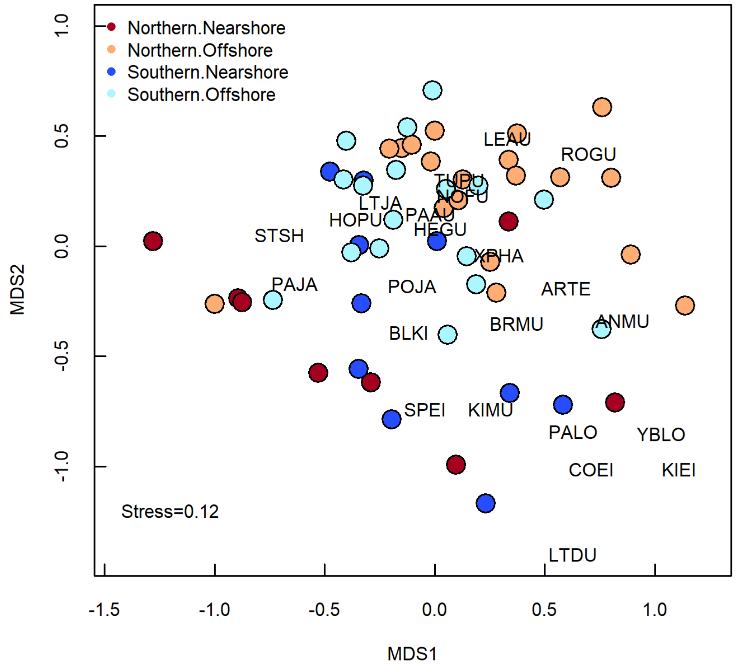

Fig 7. Non-metric multidimensional scaling (nMDS) of the seabird community in the northeastern Chukchi Sea, 2008–2018.

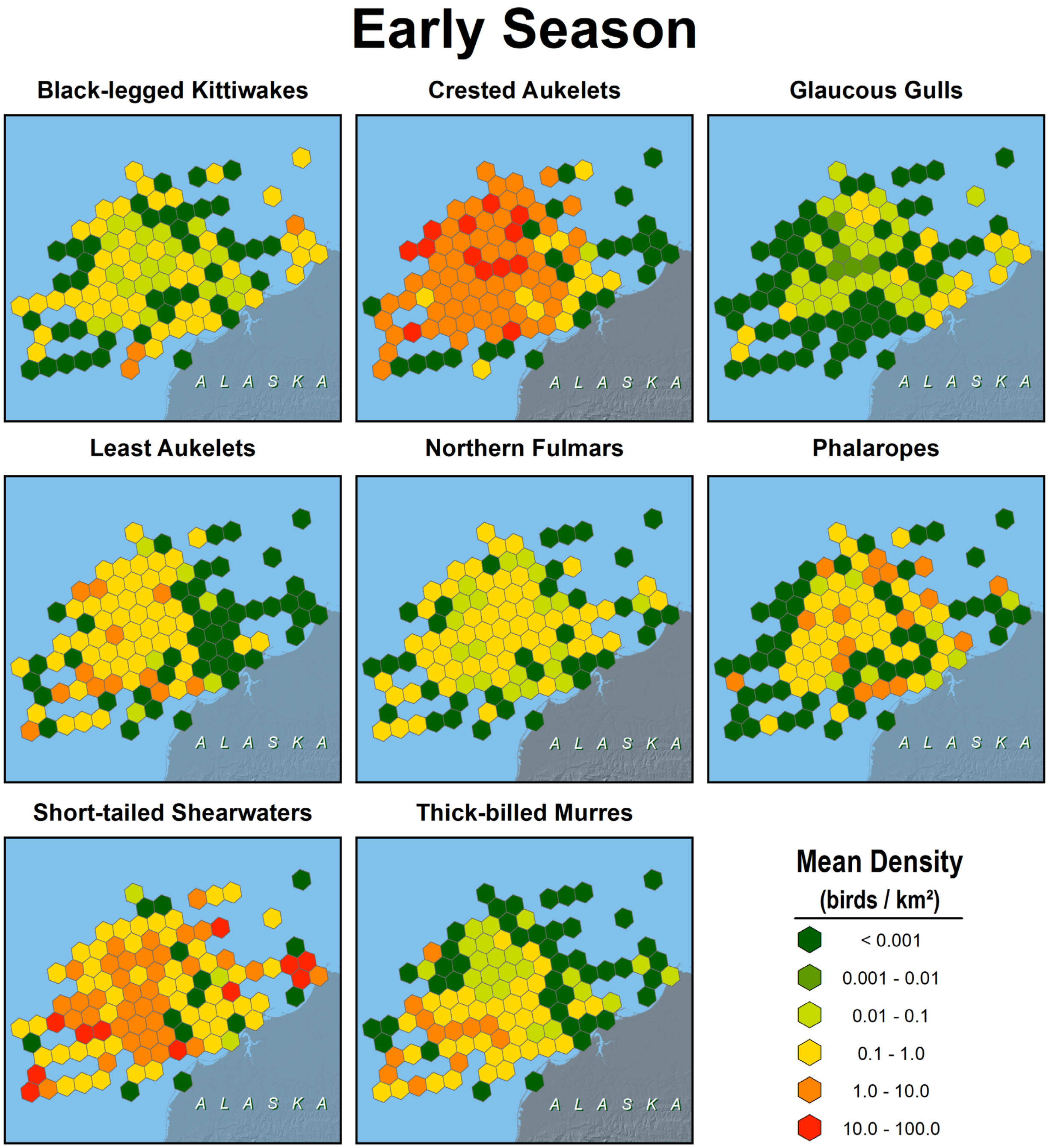

Fig 8. Distribution of 8 species of seabirds in the northeastern Chukchi Sea, early summer 2008–2018. Values in cells are means of transects from surveys conducted during 13 August–6 September.

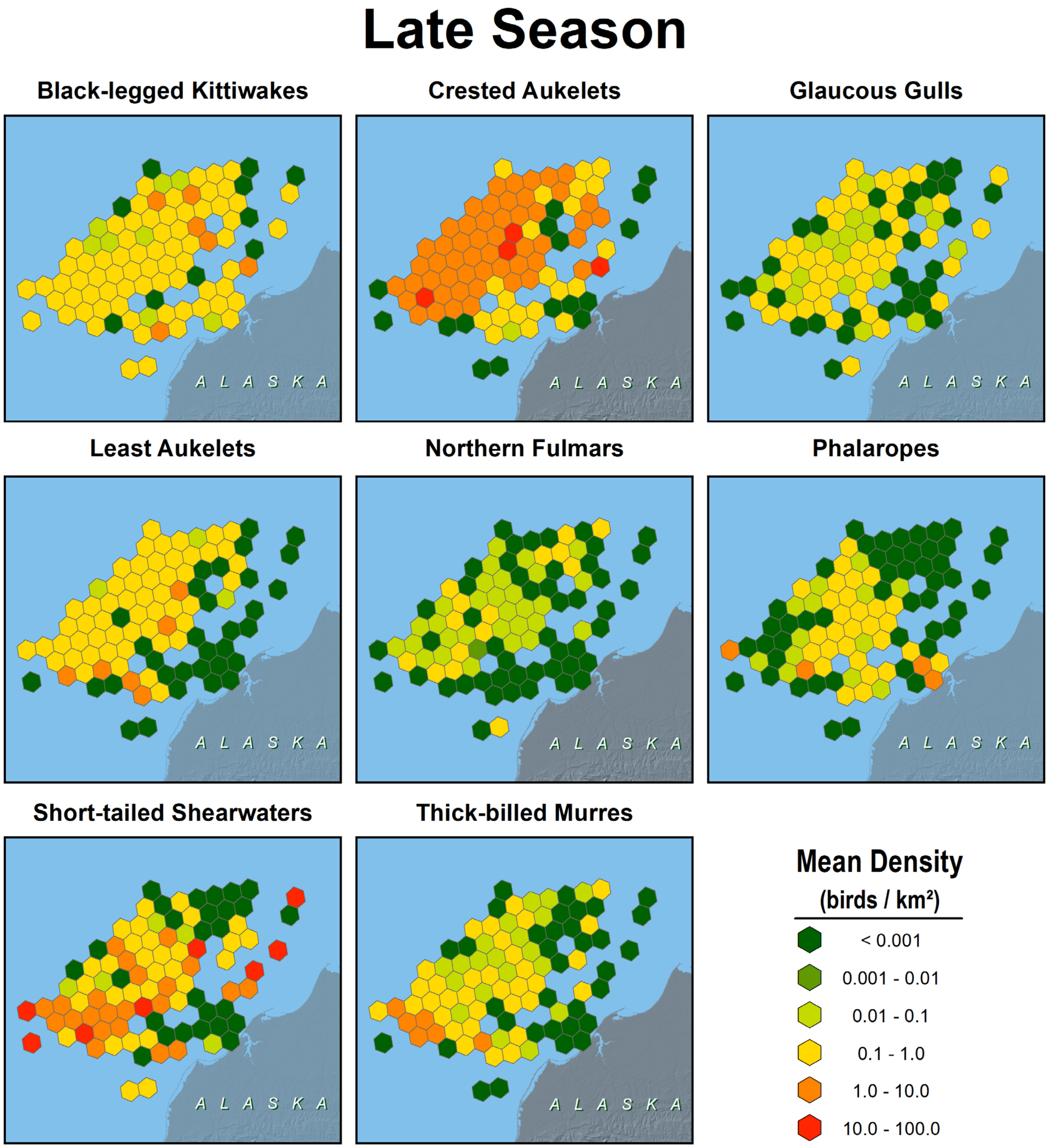

Fig 9. Distribution of 8 species of seabirds in the northeastern Chukchi Sea, late summer 2008–2018. Values in cells are means of transects from surveys conducted during 7 September–2 October.

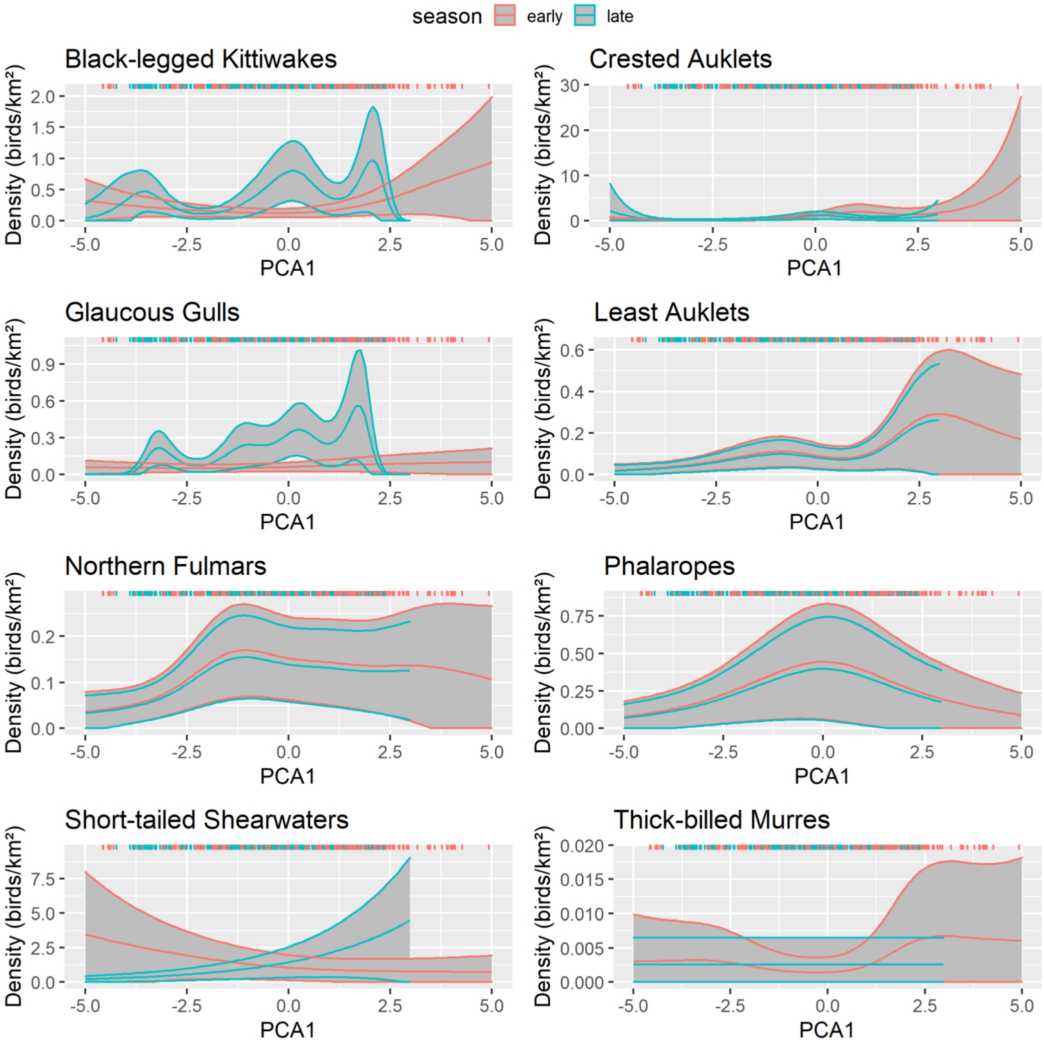

Fig. 10. Effect of hydrography on seabird density, northeastern Chukchi Sea, 2008–2018. Response curves are from the best-fitting generalized additive model. Solid lines represent the smooth function and 95% confidence limits for early summer (pink) and late summer (aqua). Gray shading indicates the 95% confidence intervals. Colored ticks indicate the distribution of observations.

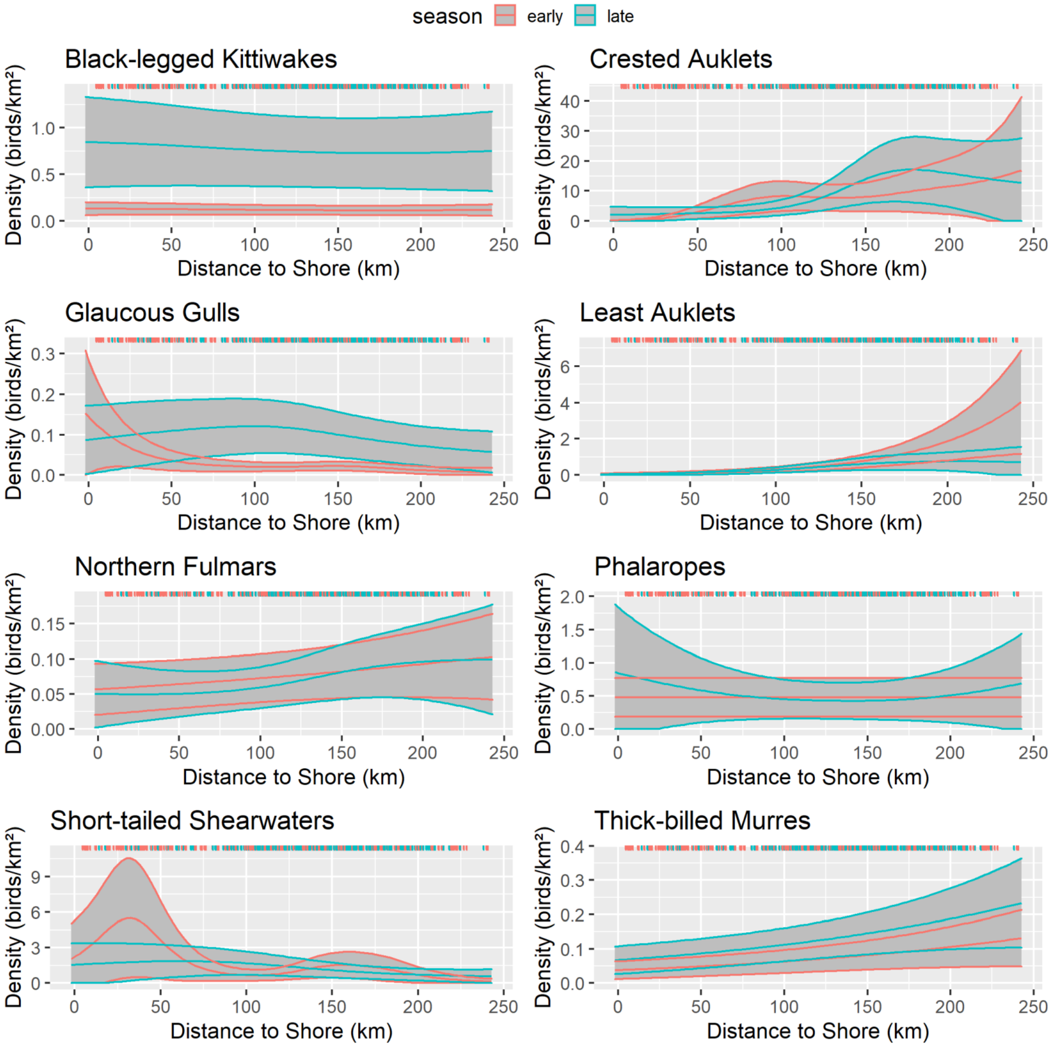

Fig. 11. Effect of distance to shore on seabird density, northeastern Chukchi Sea, 2008–2018. Response curves are from the best-fitting generalized additive model. Solid lines represent the smooth function and 95% confidence limits for early summer(pink) and late summer(aqua). Gray shading indicates the 95% confidence intervals. Colored ticks indicate the distribution of observations.

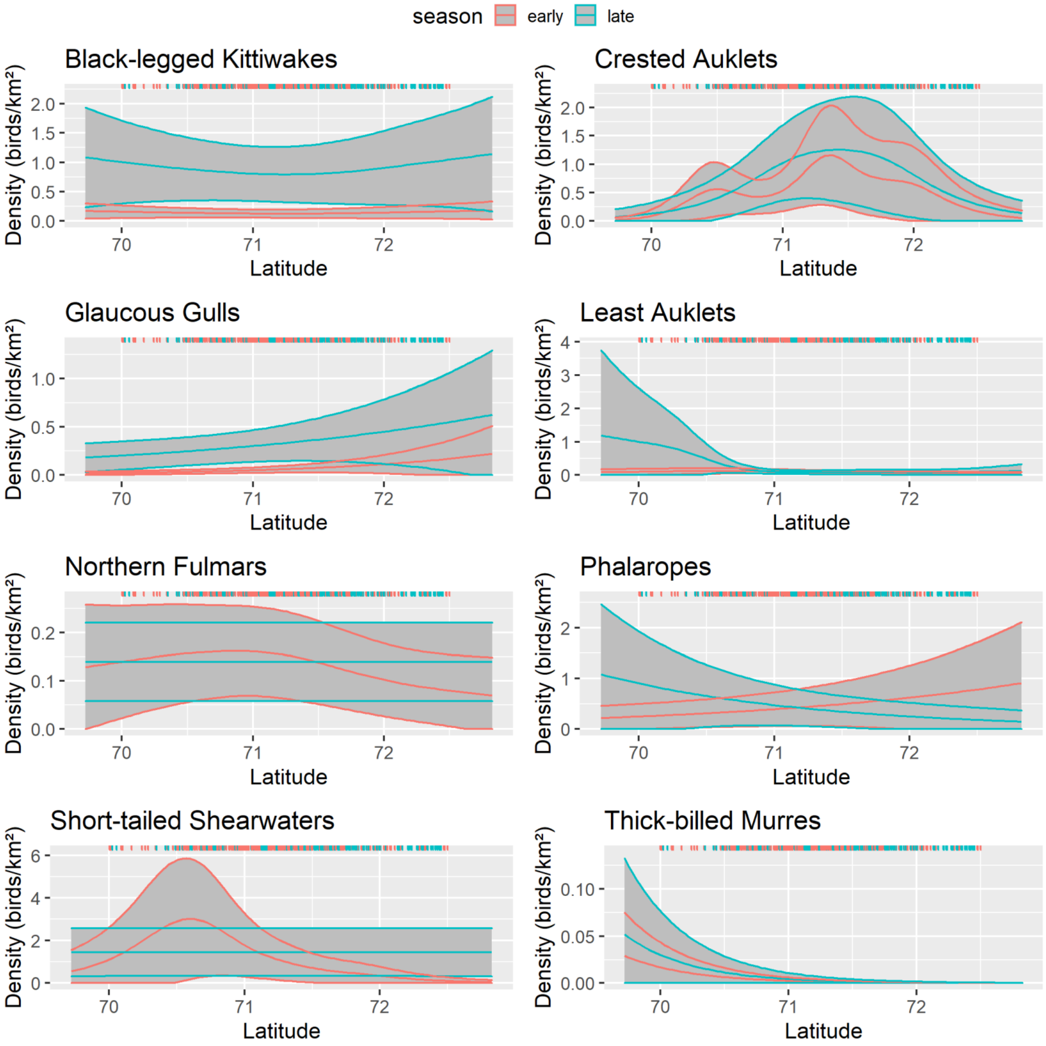

Fig. 12. Effect of latitude on seabird density, northeastern Chukchi Sea, 2008–2018. Response curves are from the best-fitting generalized additive model. Solid lines represent the smooth function and 95% confidence limits for early summer(pink) and late summer(aqua). Gray shading indicates the 95% confidence intervals. Colored ticks indicate the distribution of observations.

Appendix 2: Distributional shifts among seabird communities of the Northern Bering and Chukchi seas in response to ocean warming during 2017–2019

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Citation: Kuletz et al. 2020. North Bering and Chukchi Seabirds. Deep-Sea Research II

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 $1 \cdot \text{min}^{-1}$ (varying with respect to vessel speed), and avoiding double counting. Surveys were conducted with seas of Beaufort scale ≤ 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 ($\text{birds} \cdot \text{km}^{-2}$) 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 (Figure 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·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

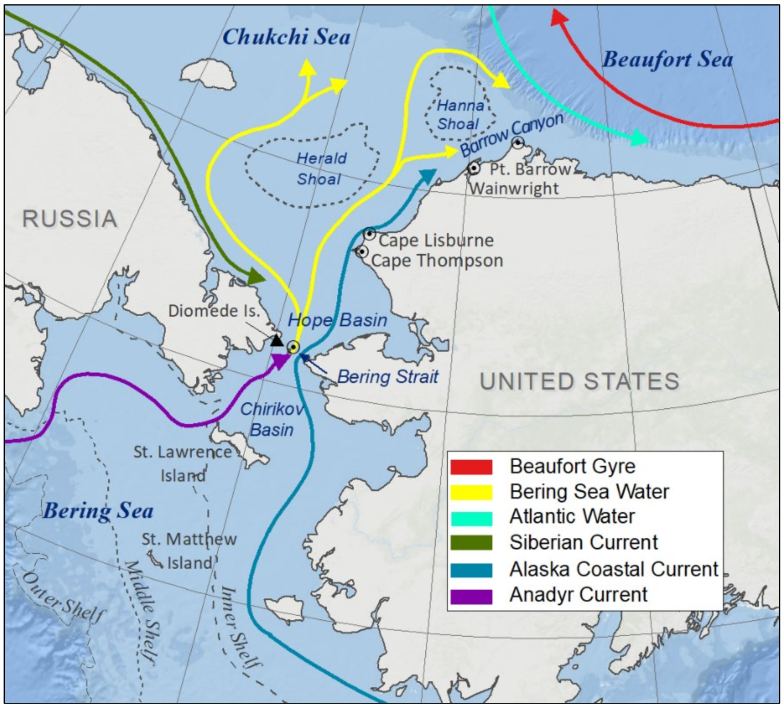

Fig. 1. The Bering Sea and Chukchi Sea study area, showing generalized trajectories of major water masses. Map by EAL, based on Dunton et al. (2017).

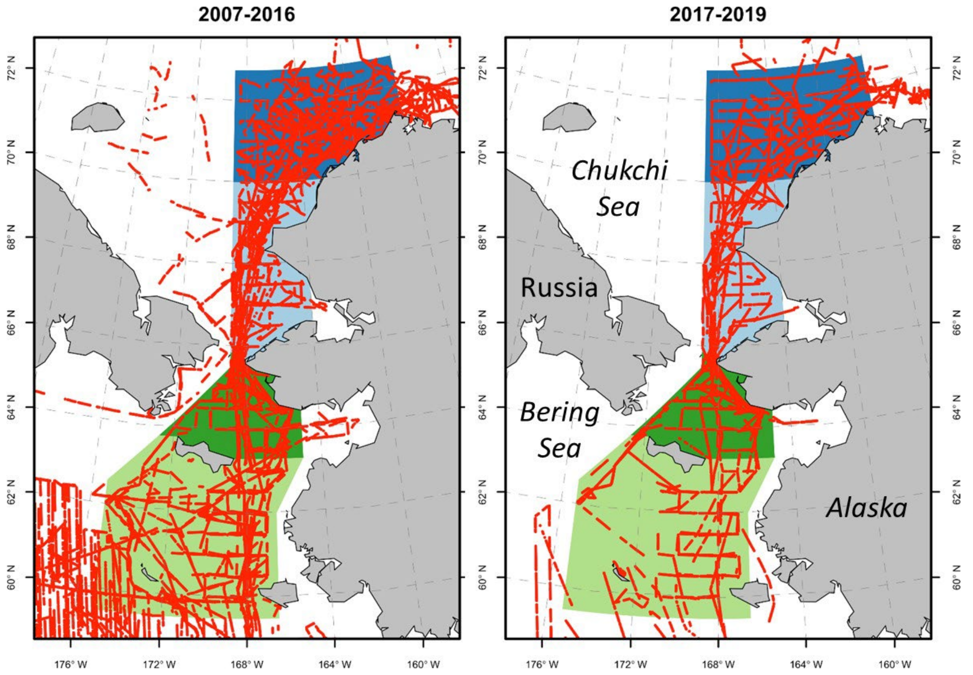

Fig. 2. Four subregions of the study area: Northern Bering (light green), Chirkov Basin (dark green), Southern Chukchi (light blue) and Northern Chukchi (dark blue), with seabird survey transects overlaid for each time period.

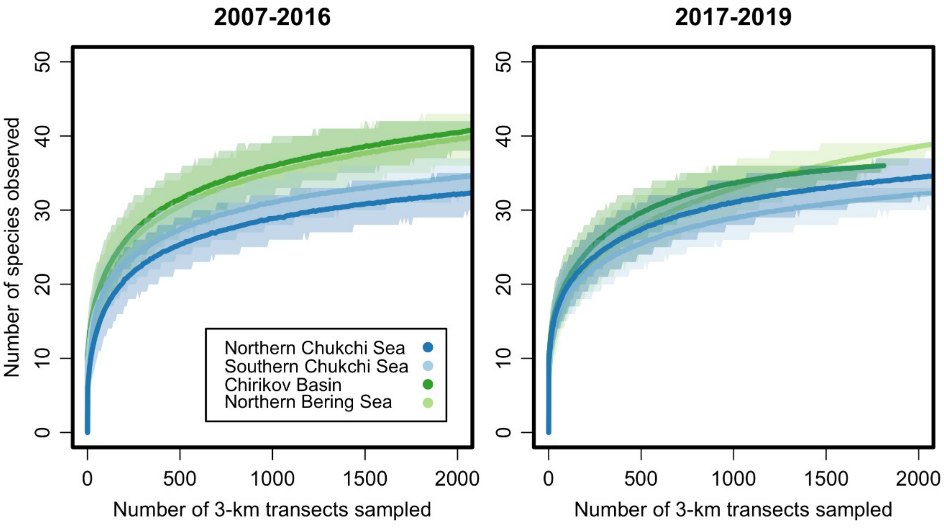

Fig. 3. Species richness (rarefaction curves) in four subregions of the study area, for 2007-2016 and 2017-2019. Mean (solid lines) and 95% confidence intervals (shading) were derived from random selection of 3-km transect segments from surveys conducted during each time period and subregion.

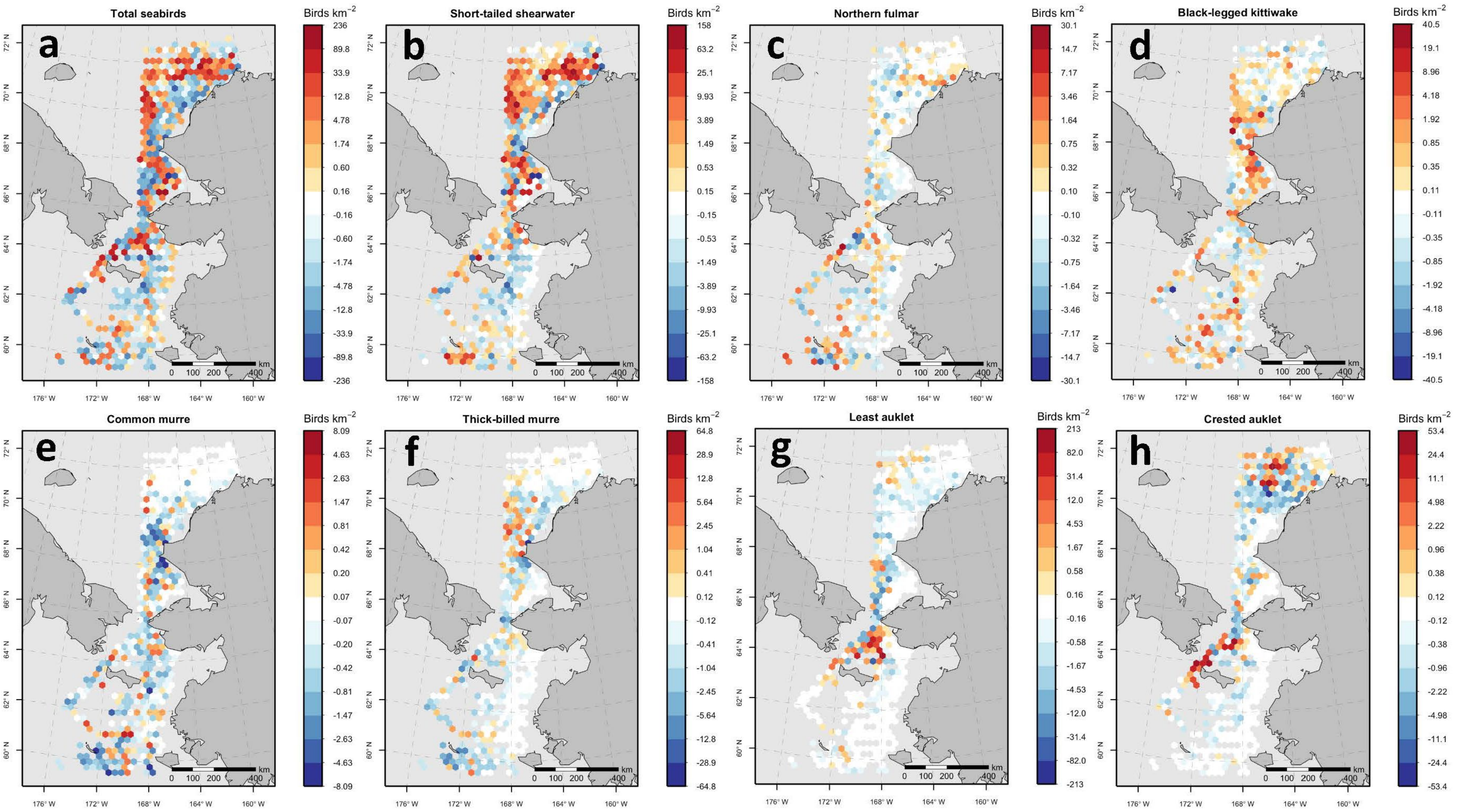

Fig.4. Distribution of increases (oranges) and decreases (blues) in densities of Total seabirds and seven focal species in 2017-2019, compared to 2007-2016. Mean densities were calculated per 30-km grid cell within each time period for cells surveyed in both time periods.

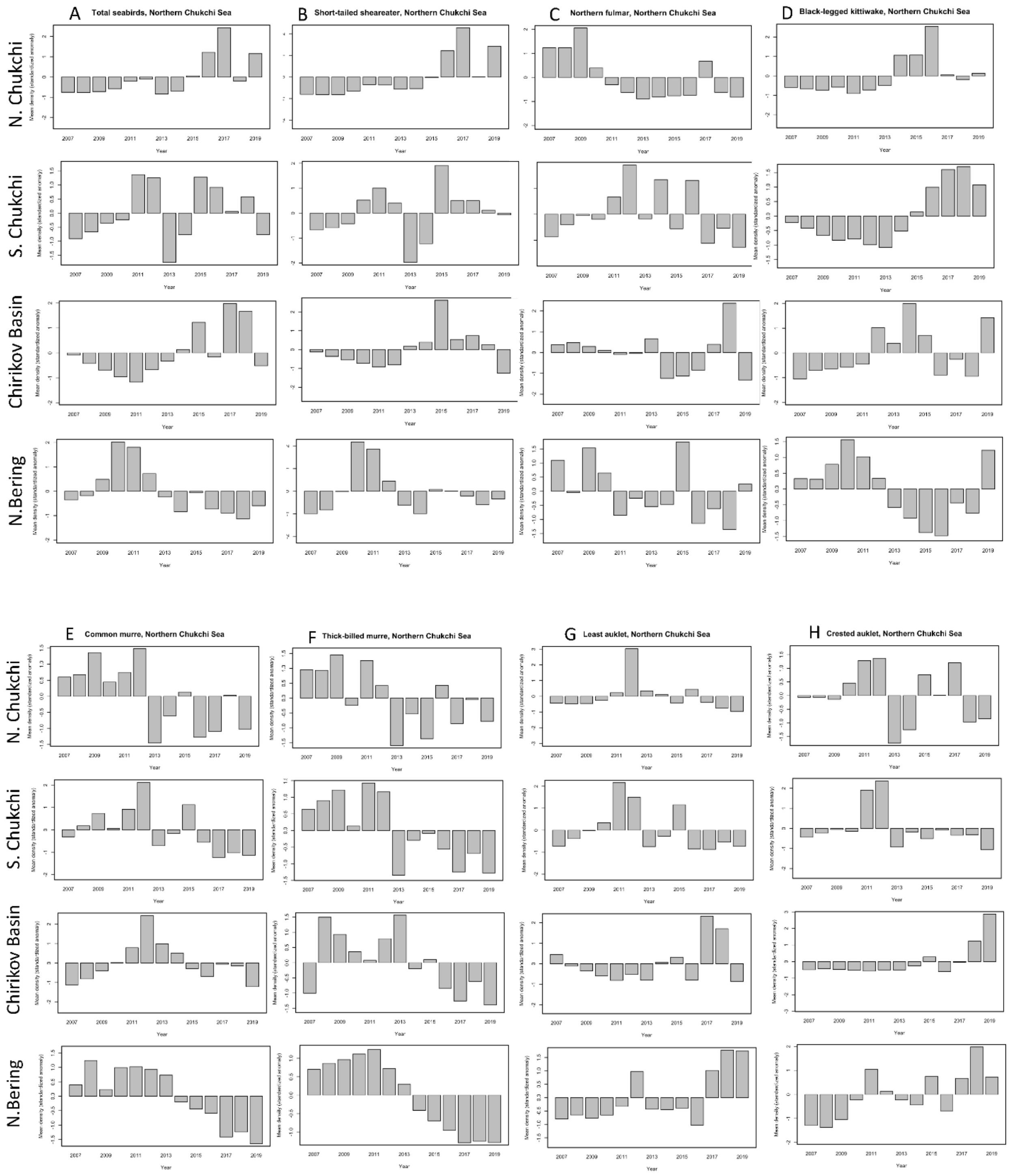

Fig. 5. Standardized mean anomalies for Total seabirds and seven focal species, for each subregion across all years, 2007-2019.

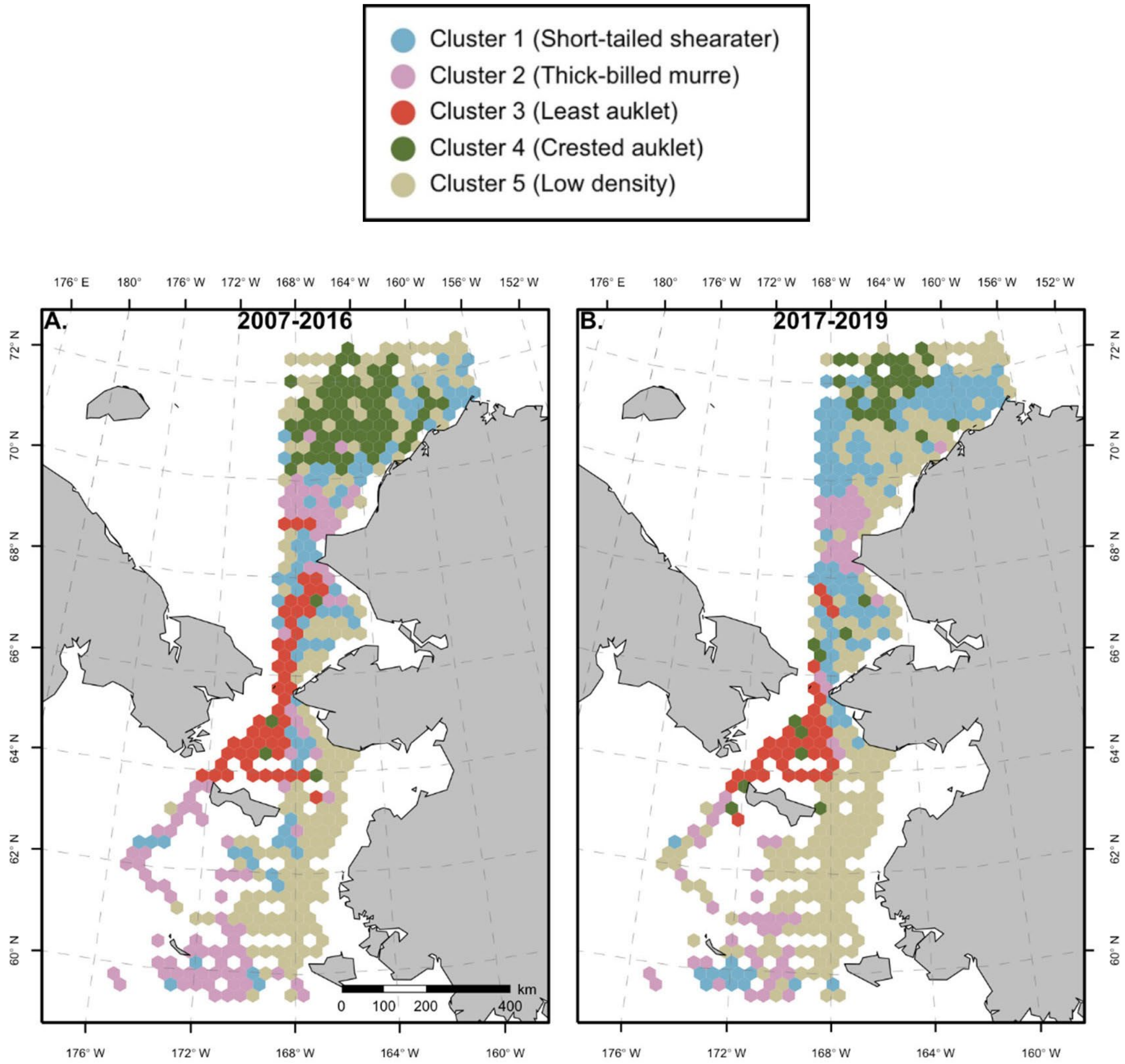

Fig. 6. Distribution of five identified seabird community types (clusters) during two time periods, based on K-means Cluster Analysis. Colors represent community types referred to by the most abundant species (Clusters 1 – 4), or by low density and lack of a dominant species (Cluster 5).

Appendix 3: Project cruise reports

Date submitted	Report Title
15 January 2018	Marine Bird Distribution and Abundance in Offshore Waters—Annual Progress Report for 18 July 2017—31 December 2017
9 April 2019	Marine Bird Distribution and Abundance in Offshore Waters—Annual Progress Report for 15 January 2018—31 December 2018
11 February 2020	Marine Bird Distribution and Abundance in Offshore Waters—Annual Progress Report for 1 January 2019—31 December 2019
15 January 2021	Marine Bird Distribution and Abundance in Offshore Waters—Annual Progress Report for 1 January 2020—31 December 2020
3 February 2022	Marine Bird Distribution and Abundance in Offshore Waters—Annual Progress Report for 1 January 2021—31 December 2021

Appendix 4: Counts of marine mammals recorded in transit to and from focal BOEM Planning Areas, 2017–2021.

The fields on/off indicate if an observation was on or off transect.

Year	English Name	Scientific Name	St. George Basin		North Aleutian Basin		Kodiak		Shumagin		Bowers Basin		Aleutian Arc		Total
			on	off	on	off	on	off	on	off	on	off	on	off	
2017	Northern Fur Seal	*Callorhinus ursinus*	18	0	0	0	0	0	0	0	0	0	0	0	18
	Spotted Seal	*Phoca largha*	0	2	0	0	0	0	0	0	0	0	0	0	2
	unidentified seal		1	0	0	0	0	0	0	0	0	0	0	0	1
	unidentified pinniped		1	0	0	0	0	0	0	0	0	0	0	0	1
	Fin Whale	*Balaenoptera physalus*	0	4	0	0	0	0	0	0	0	0	0	0	4
	Humpback Whale	*Megaptera novaeangliae*	1	41	0	0	0	0	0	0	0	0	0	0	42
	Killer Whale	*Orcinus orca*	0	2	0	0	0	0	0	0	0	0	0	0	2
	Dall's Porpoise	*Phocoenoides dalli*	17	58	0	0	0	0	0	0	0	0	0	0	75
	unidentified whale		0	8	0	0	0	0	0	0	0	0	0	0	8
2018	Northern Fur Seal	*Callorhinus ursinus*	6	6	0	0	0	0	0	0	0	0	0	0	12
	unidentified pinniped		0	0	0	0	0	0	1	0	0	0	0	0	1
	Humpback Whale	*Megaptera novaeangliae*	1	0	0	0	0	0	0	0	0	0	0	0	1
	Killer Whale	*Orcinus orca*	0	4	0	0	0	1	0	0	0	0	0	0	5
	Dall's Porpoise	*Phocoenoides dalli*	18	0	0	0	0	7	0	0	0	0	0	0	25
	unidentified whale		3	11	0	0	0	7	0	3	0	0	0	3	27

			St. George Basin		North Aleutian Basin		Kodiak		Shumagin		Bowers Basin		Aleutian Arc		
Year	**English Name**	**Scientific Name**	**on**	**off**	**on**	**off**	**on**	**off**	**on**	**off**	**on**	**off**	**on**	**off**	**Total**
2019	Northern Fur Seal	*Callorhinus ursinus*	44	7	0	0	0	0	0	0	0	0	0	0	51
	unidentified seal		1	0	0	0	0	0	0	0	0	0	0	0	1
	unidentified pinniped		4	5	0	0	0	0	0	0	0	0	0	0	9
	Minke Whale	*Balaenoptera acutorostrata*	1	0	0	0	0	0	0	0	0	0	0	0	1
	Fin Whale	*Balaenoptera physalus*	1	2	0	0	0	0	0	5	0	0	0	0	8
	Humpback Whale	*Megaptera novaeangliae*	0	4	0	0	0	0	0	0	0	0	0	0	4
	Killer Whale	*Orcinus orca*	4	4	0	0	0	0	0	0	0	0	0	0	8
	Harbor Porpoise	*Phocoena phocoena*	5	0	0	0	0	0	0	0	0	0	0	0	5
	Dall's Porpoise	*Phocoenoides dalli*	13	13	0	0	0	0	0	0	0	0	0	0	26
	unidentified whale		2	9	0	0	0	0	0	10	0	0	0	0	21
2020	Northern Fur Seal	*Callorhinus ursinus*	0	1	3	0	0	0	1	0	0	0	0	0	4
	Harbor Seal	*Phoca vitulina*	0	0	0	0	1	0	0	0	0	0	0	0	1
	Fin Whale	*Balaenoptera physalus*	1	0	0	0	0	0	6	9	0	0	0	0	16
	Humpback Whale	*Megaptera novaeangliae*	10	27	0	0	1	0	9	25	0	0	0	0	72
	Killer Whale	*Orcinus orca*	0	0	0	0	0	1	0	0	0	0	0	0	1
	Harbor Porpoise	*Phocoena phocoena*	0	0	0	0	0	3	0	1	0	0	0	0	4
	Dall's Porpoise	*Phocoenoides dalli*	4	5	0	0	3	0	9	0	0	0	0	0	21
	unidentified whale		0	2	0	0	0	1	0	11	0	0	0	0	14

			St. George Basin		North Aleutian Basin		Kodiak		Shumagin		Bowers Basin		Aleutian Arc		
Year	English Name	Scientific Name	on	off	on	off	on	off	on	off	on	off	on	off	Total
2021	Northern Fur Seal	*Callorhinus ursinus*	11	5	0	0	0	0	1	0	0	0	0	0	17
	Steller's Sea Lion	*Eumetopias jubatus*	1	0	0	0	0	0	0	0	0	0	0	0	1
	unidentified seal		1	0	0	0	0	0	0	0	0	0	0	0	1
	Minke Whale	*Balaenoptera acutorostrata*	0	0	1	0	0	0	0	0	0	0	0	0	1
	Fin Whale	*Balaenoptera physalus*	0	0	0	0	1	1	0	0	0	0	0	0	2
	Humpback Whale	*Megaptera novaeangliae*	0	2	0	0	0	6	1	14	0	0	0	0	23
	Killer Whale	*Orcinus orca*	0	4	0	0	0	0	0	0	0	0	0	0	4
	Dall's Porpoise	*Phocoenoides dalli*	7	6	0	0	0	0	1	6	0	0	0	0	20
	unidentified whale		0	3	0	0	1	10	1	3	0	0	0	0	18

Appendix 5: Variability in the southward migration of the North American Red Phalarope

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Abstract

Many shorebird populations have experienced dramatic population declines, with those breeding in the Arctic some of the most highly impacted. Studies of the migration movements of Arctic-breeding shorebirds play a crucial role in our ability to ascertain causes of these declines and identify areas of conservation importance. Red Phalaropes (*Phalaropus fulicarius*) nest in coastal tundra habitat throughout the Holarctic, but for much of their annual cycle they functionally act like seabirds in the pelagic environment, where they consume zooplankton. As a result, migratory movements and threats experienced by Red Phalaropes during the nonbreeding season are likely to be vastly different than those experienced by their land-based conspecific relatives. Between 2017 and 2020, we tagged 102 (71 females and 31 males) Red Phalaropes with 2-gram solar-powered Argos Platform Transmitter Terminal tags at 7 Arctic-breeding sites located in Alaska and the Central Canadian Arctic to identify their migratory routes, stopover areas, and areas of concentrated use. In general, we observed two distinct migration routes taken by Red Phalaropes, with most birds breeding in Alaska traveling toward the Pacific Ocean to winter off the coast of South America, and birds breeding in the Central Canadian Arctic traveling toward the Atlantic Ocean. Individuals exhibited notable variation in the timing, routes, and habitat selected. Unlike other shorebirds, migration of Red Phalaropes was characterized by indirect, circuitous routes with numerous stops over a long period of time, suggesting individuals are not time-limited during southward migration. As expected from independently conducted at-sea observations, foraging Red Phalaropes were often associated with areas of greater food availability, such as in highly productive ocean currents, near ocean fronts or upwellings, and within the marginal ice zone. Red Phalaropes were also found foraging on land and in nearshore areas. Within the Beringia region, we identified four important areas for Red Phalarope conservation: 1) onshore and nearshore habitats of the Beaufort and Chukchi seas; 2) the western edge of the Bering Strait; 3) the Gulf of Anadyr in the western Bering Sea; and 4) Unimak Island in the Aleutian Archipelago. Our study indicates that Red Phalaropes are likely to be exposed to multiple anthropogenic threats throughout their annual cycle, including oil and gas exploration and development, commercial fishing, vessel traffic, wind farm development, and plastic ingestion. In addition, climate change impacts such as the increase in ocean temperatures and reduction in sea ice extent will likely impact Red Phalarope prey and foraging opportunities, as well as movement patterns.

Keywords: Arctic, animal tracking, Bering Sea, Beringia, Chukchi Sea, marine bird foraging, migratory, pelagic, *Phalaropus fulicarius*, PTT tags, seabirds, shorebirds

Introduction

Many shorebird populations have experienced dramatic population declines, with those breeding in the Arctic some of the most highly impacted. Recent estimates suggest North American shorebird populations have experienced a 37% decline in numbers since 1970 (Rosenberg et al. 2019), with over half (51%) of the Arctic-breeding shorebird taxa in decline (Smith et al. 2020). As most Arctic-breeding shorebirds are long-distance migrants, individuals face a variety of threats at numerous locations while going through their annual cycle. Previous studies suggest that population declines are likely the result of issues occurring during migration (Thomas et al. 2006) or reduced survival during winter (Weiser et al. 2018, Weiser et al. 2020). Studies of the migration of Arctic-breeding shorebirds thus plays a crucial role in our ability to ascertain the causes of these declines, as key information can be obtained on population subdivisions; patterns of migratory connectivity; migration routes; and breeding, stopover, and wintering areas. This information can be used to assess potential threats throughout the annual cycle, which can help focus conservation actions on the most important issues and areas.

The Red Phalarope (*Phalaropus fulicarius*) could benefit from such information, as recent evidence suggests population declines (Gratto-Trevor et al. 1998, Alaska Shorebird Group 2019, B.J. McCaffery, unpubl. data, Smith et al. 2020), likely due to threats in nonbreeding (i.e., migrating and wintering) areas (Weiser et al. 2018). Large population declines of Red-necked Phalaropes were attributed to ENSO events that lead to low food levels on their wintering grounds (Nisbet and Veit 2015). Red Phalaropes are small Holarctic-breeding shorebirds with a unique life-history. During the breeding season, they spend 1–2 months nesting in coastal tundra habitat exhibiting social polyandry, sex-role reversal in which only males incubate eggs and care for offspring (van Bemmelen 2019, Tracy et al. 2020, Krietsch et al. 2022). During the nonbreeding season, they functionally act like surface-feeding planktivorous seabirds in the pelagic environment, feeding opportunistically on zooplankton such as copepods (e.g., *Calanus* spp.), amphipods, fish eggs, and fish larvae near the surface (Tracy et al. 2020).

Given the pelagic nature of this species, migratory movements and ecological factors experienced by Red Phalaropes during the nonbreeding season are likely fundamentally different from those of other shorebird species that stage and winter on land. For example, foraging locations within the pelagic environment can be highly dynamic within and across seasons, as zooplankton availability is controlled by numerous climatic (e.g., temperature and wind), oceanographic (e.g., salinity, sea surface temperature, chlorophyll concentrations, currents, upwellings, and extent and timing of sea ice retreat) and biological (e.g., foraging whales) processes (reviewed in Hopcroft et al. 2008, Smith et al. 2017). Similarly, anthropogenic threats Red Phalaropes experience while at sea will differ from those experienced by their land-based conspecific relatives. For example, marine birds are likely to encounter and ingest plastics that accumulate in marine areas, especially microplastics that float on the surface (Moser and Lee 1992, Drever et al. 2018, Baak et al. 2021, Flemming et al. 2022). In addition, vessel traffic is also increasing, resulting in increased disturbance and collisions with marine birds (CAFF 2017). Potentially exacerbating these impacts, marine birds are often disoriented and fatally attracted to lights produced by vessels, as well as nearshore and offshore developments (Merkel 2010, Gjerdrum et al. 2021). Oil and gas development and associated activities have also led to the release of contaminants in the pelagic environment (Tyler et al. 1993, Wahl et al. 1993, O'Hara and Morandin 2010). Finally, offshore wind farms are expanding dramatically in the United States (U.S. Department of Energy 2022). Such developments increase the risk of disturbance, displacement, and collisions for marine birds, depending on numerous factors such as location of structures as well as the birds' migratory patterns and behaviors (Garthe and Hüppop 2004, Stienen et al. 2007, Furness et al. 2013, Dierschke et al. 2016).

The physical and biological conditions of the pelagic environment used by Red Phalaropes are also changing rapidly and dramatically. Increases in sea surface temperatures and reduction in sea ice extent have accelerated (Wadhams and Davis 2000, Overland and Stabeno 2004, Arrigo et al. 2008, Danielson et al. 2020), with projections that the Arctic Ocean is likely to become predominately ice-free during the summer by the end of the twenty-first century (Johannessen et al. 2004, Zhang and Walsh 2006) or as early as 2040 (Holland et al. 2006, Wang and Overland 2009, Overland and Wang 2013). These oceanographic changes are predicted to result in a cascade of events, from seasonal changes in primary production (e.g., amount of phytoplankton produced, as well as timing of phytoplankton blooms) to changes in the distribution and composition of species (e.g., zooplankton, fish, seabirds, and marine mammals) across the food web (Overland and Stabeno 2004, Grebmeier et al. 2006, Cusset et al. 2019, Duffy-Anderson et al. 2019, Stevenson and Lauth 2019, Huntington et al. 2020). Collectively, these changes are likely to impact prey availability for Red Phalaropes. In addition, warmer sea surface temperatures are predicted to lead to a higher frequency of toxic algae blooms (Glibert et al. 2014, Gibble and Hoover 2018, Huntington et al. 2020), which, when combined with changes in food-web dynamics, has been associated with seabird mortality events (Van Hemert et al. 2020, Van Hemert et al. 2021). Thus, understanding how and where Red Phalaropes migrate is critical to assess their exposure to anthropogenic factors, their likely response to changes in oceanographic conditions, and to identify important areas for conservation protection.

Although well-studied during the breeding season, little is known about Red Phalarope migratory routes, stopover areas, or connectivity between breeding and wintering areas (Tracy et al. 2020). Currently, it is thought that several populations of Red Phalaropes occur throughout the species' North American range, with individuals wintering in both the Pacific and Atlantic oceans (Tracy et al. 2020). General observations have shown that Red Phalaropes, especially juveniles, are common fall migrants in littoral habitats within the Arctic, with females generally arriving in these habitats earlier than males (Connors et al. 1981, Smith and Connors 1993, Andres 1994, Taylor et al. 2010, Taylor et al. 2011). After departing these coastal areas, Red Phalaropes often utilize pelagic areas far from the coast (Briggs et al. 1984, Brown and Gaskin 1988, Vermeer et al. 1993), where prey concentrates near the surface such as at ocean fronts (i.e., convergent water masses where temperature and salinity change abruptly) or upwellings (Briggs et al. 1984, Brown and Gaskin 1988, DiGiacomo et al. 2002). Red Phalaropes have also been observed foraging near grounded sea ice or in areas of low (e.g., < 40%) sea-ice concentration (Divoky 1979, Connors et al. 1981, Orr et al. 1982), as well as near whales whose foraging behavior brings zooplankton to the surface (Nelson 1883, Obst and Hunt 1990, Grebmeier and Harrison 1992, Elphick and Hunt 1993).

Taylor et al. (2011) first tracked Red Phalaropes using VHF radio transmitters and land- and aerial-based detection platforms, but despite tremendous effort, relocated only 5 of 69 tagged individuals, each only once at nearby (<150 km from capture site) coastal sites. Van Bemmelen (2019) tracked 16 individuals from breeding areas in Greenland and Svalbard to wintering areas in the Atlantic Ocean using geolocators. However, no studies have tracked the annual movements of Red Phalaropes breeding in North America. In this study, we used satellite transmitters to track the migratory movements of male and female Red Phalaropes from their breeding sites in Alaska and northern Canada. We describe migration routes, stopover areas, and areas of concentrated use during fall migration, and relate this information to oceanographic conditions. Based on prior studies summarized above, we made the following predictions: 1) Red Phalaropes would migrate along two distinct migration routes, with birds breeding in Alaska traveling toward the Pacific Ocean to winter off the coast of Central and South America, and birds breeding in Canada traveling toward the Atlantic Ocean to winter off the coast of the eastern United States or Africa; 2) females would leave Arctic-breeding locations earlier than males, as only males incubate eggs and care for offspring; 3) adults from both populations would utilize coastal areas post-breeding before migrating into the pelagic environment; and 4) once in the pelagic environment, individuals would occur mainly offshore, far from the coast in association with areas of greater food availability such as in highly productive ocean currents, near ocean fronts or upwellings, or in association with the ice edge.

Materials and Methods

Capture and nest monitoring

We captured 71 female Red Phalaropes during pre-breeding by dropping a mist net on them while they foraged in or along the edges of shallow ponds in late May–early June at one Arctic site (Utqiaġvik) in 2017 and 2018 (Table 1, Figure 1). Most of these females were paired (i.e., observed with a male). We captured 31 males on their nest while incubating using a modified luchock trap (or bow-net; Priklonsky 1960) in late June–early July at 7 sites across the Arctic in 2019 and 2020 (Table 1, Figure 1). We found nests by opportunistically flushing adults, or by following adults back to their nests after spotting them during systematic area searches or while dragging a rope across the tundra (see Saalfeld and Lanctot 2015). Upon capture, we marked all individuals with a U.S. Geological Survey metal leg band, recorded body mass and morphometrics, and in some instances, collected the 10th secondary feather from both wings. We attached 2-gram solar-powered Argos Platform Transmitter Terminal (PTT) tags (Microwave Telemetry, Inc., Maryland, US) on females and males with a full-body harness made of 1 mm (outer diameter) silicone surgical tubing (Chan et al. 2015) or by gluing the tag on the back approximately 1 cm above the uropygial gland after feather clipping (only at East Bay field site; Warnock and Warnock 1993). Tags weighed, on average, 3.4% (range = 2.7–4.1%) of female's and 4.0% (range = 3.4–5.0%) of male's weights.

We revisited nests of most tagged males to ensure tags remained attached and to determine nest attendance and fate. We visited nests found with fewer than four eggs (modal clutch size) daily until the clutch was completed, or until clutch size remained unchanged for two consecutive days. We estimated nest initiation dates (i.e., date first egg laid) assuming one egg was laid per day. For nests found during incubation, we used egg flotation to estimate the start of incubation (i.e., date 4th egg was laid; Liebezeit et al. 2007). We predicted hatch date by adding 19 days (incubation period for this species; Weiser et al. 2017) to the estimated incubation start date (day 0 = date last egg laid). We checked nests every 3–5 days until 3–4 days prior to the estimated hatch date; at which time we checked nests every 2 days until eggs were starred (i.e., hatching was initiated), and daily thereafter. We defined a nest as successful when at least one egg hatched (Mayfield 1975). See Saalfeld and Lanctot (2015) for evidence used to determine hatching or failure. When evidence at the nest was not conclusive, we classified the nest fate as unknown.

Tracking movements

Location data from PTT tags are based on calculations by measuring the Doppler effect on transmission frequency as recorded by Argos receivers (Lopez et al. 2014). This process can result in multiple locations per day, but at varying time intervals and with varying accuracy and precision (Douglas et al. 2012, Lopez et al. 2014). To standardize location data, we estimated 1 location every 8 hours by fitting a continuous-time random walk state-space model to each individual's locations using the foieGras package (Jonsen et al. 2019, Jonsen and Patterson 2020, Jonsen et al. 2020) in R (R Core Team 2021). This approach accounts for the error associated with each location (as estimated by the location quality class) while predicting locations at regular intervals. We chose an 8-hour time interval, as ~75% of raw locations were obtained within 8 hours of each other. This allowed us to estimate several locations per day while avoiding model overfit (i.e., predicting locations in large temporal data gaps). To estimate distance between 8-hr predicted post-breeding locations, we used straight-line geodesic distances between consecutive locations, recognizing that this represents the minimum distance traveled.

Prior to using the state-space models, we first excluded two types of data. First, as the purpose of this paper was to investigate post-breeding movements, we excluded all locations at breeding sites that were initially occupied on or before July 4, the latest date Red Phalaropes have been documented to initiate nests in the North American Arctic (Lanctot and Saalfeld, unpublished data). Data from later dates were also excluded if an individual remained at the presumed breeding site past July 4. These data included all locations from sites within the breeding range of the species (area defined in the Birds of the World; Tracy et al. 2020). Second, we excluded all locations from individuals when we suspected the tag fell off or the individual died as indicated by a lack of directional movement (i.e., a shotgun pattern of locations due to the inherent inaccuracy of PTT tags) usually accompanied by an inconsistent transmission rate (i.e., temporal gaps in locations greater than a day). We used the location prior to the lack of movement or when data were inconsistently received as the last known location of a bird. Lastly, we offset locations with the same date and time (e.g., when two location solutions were given for a transmission) for a given individual by 1 sec to allow inclusion of all locations into the model and removed outlier locations that had a speed > 25 m/s from the previous location, reflecting an unrealistic movement (Duijns et al. 2019).

Predicting activity states

We predicted the activity state for each 8-hr predicted post-breeding location by fitting hidden Markov models using the package moveHMM (Michelot et al. 2016) in R. We estimated two states of activity within this post-breeding model based on step lengths (i.e., distance traveled between points) and turning angles (i.e., change in direction of travel from prior movement) using the gamma distribution (Michelot et al. 2016). Here, foraging locations (state 1) were characterized by relatively short steps and many turns between locations, while migrating locations (state 2) were characterized by longer steps and fewer turns between locations. As initial parameter values were required for model estimation, we verified that the model had identified the maximum-likelihood estimates of the parameters by refitting the model 50 times with random initial parameter values (Michelot and Langrock 2019). We used the Viterbi algorithm to estimate the most likely sequence of movement states to have generated the observations based on the fitted model (Michelot et al. 2016).

While the above post-breeding model predicted activity states for all locations during the post-breeding period, we reran the models using only locations within Beringia (i.e., Beaufort, Chukchi, and Bering seas; see Figure 1) and refer to this as the Beringia-only model. We did this to improve the accuracy of activity state classifications within this region, as the bulk of locations (78%) were from this region, and distance and angle of movements used to define states were likely more consistent due to similar environmental conditions experienced by individuals in this region. For the Beringia-only model, we also added distance to coast (NASA Ocean Biology Processing Group and R.P. Stumpf 2012) downloaded using the Env-DATA System (Dodge et al. 2013) on Movebank (movebank.org) to the intercept-only model to relate to transition probabilities (i.e., probability of switching between or staying within an activity state) within Beringia. We did not include distance to coast in the post-breeding model because the availability of coastlines varied throughout the migration route (e.g., pelagic areas far from the coast in the Pacific Ocean), and therefore, likely would not result in a consistent selection pattern (i.e., variable relationship between distance to coast and activity state transition probabilities based on coastline availability). The best supported model was identified as having the lowest Akaike's information criterion (AIC) value (Burnham and Anderson 2002). Final activity states were obtained from the post-breeding model for locations outside of Beringia and from the Beringia-only model for locations within Beringia.

Identifying stopover and high-use areas

To identify stopover areas, we first formed clusters of all consecutive foraging locations (i.e., all foraging locations before and after switching from a migrating state) for each individual. We then calculated the mean center of all points within each cluster in ArcGIS 10.8.1 (Environmental Systems Research Institute, Redlands, CA) and the number of days a bird was at a stopover area by subtracting the latest date from the earliest date an individual was at each area. Stopovers represented areas ranging from less than 1 to ~ 54,000 km^2 (mean = 1,880 km^2) that were occupied for less than 1 to 86 days (mean = 6 days; $n = 489$), with the size of the stopover area generally increasing with the time an individual remained at an area ($r = 0.64$; $P < 0.001$).

For the Beringia region (see Figure 1), we identified high-use areas by estimating kernel utilization distributions of foraging locations for all individuals combined using the adehabitatHR package (Calenge 2006) in R. Because tags failed at different locations throughout Beringia (e.g., most stopped transmitting prior to 49°N), we estimated separate kernel utilization distributions within four regions (i.e., Beaufort/Chukchi: north of 69°N, Bering Strait: between 63°N and 69°N, South Bering: between 58°N and 63°N, and Aleutians: between 49°N and 58°N; Figure 1). For each region, we restricted our analyses to individuals with complete tracks through a region regardless of whether they stopped. We then standardized each regional utilization distribution by dividing by the number of individuals with complete tracks within each region using the Raster Calculator in ArcGIS 10.8.1 (Environmental Systems Research Institute, Redlands, CA).

Oceanographic conditions

To better understand the oceanographic conditions present at high use areas within Beringia, we obtained satellite-derived monthly composites (i.e., average value across the month for a given variable) from July to October during each year of the study (2017–2020) for the following oceanographic variables: sea surface temperature (JPL MUR MEaSUREs Project 2015, Chin et al. 2017), sea surface salinity (Meissner et al. 2018, Meissner et al. 2019), and chlorophyll-a (Hu et al. 2012, NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group 2018). In addition, we obtained daily estimates of sea ice concentration (Spreen et al. 2008; obtained from https://www.seaice.uni-bremen.de) and the marginal ice zone (U.S. National Ice Center 2020) from late June to early August within each year to relate to Red Phalarope locations while in the Beaufort/Chukchi region. Here, the sea ice concentration index depicted the location of the pack ice while the daily marginal ice zone identified areas of sparse or broken sea ice.

Statistical analyses

When appropriate, we compared tag performance (i.e., number of days individuals were tracked) and migration metrics (i.e., departure date from breeding grounds, residency time, number of stopover areas, foraging probability, and probability of being on land) among or between sexes, regions, and/or years using an analysis of variance (ANOVA) in R. We calculated departure dates from breeding grounds as the date an individual left its last breeding site (i.e., a site within the species' breeding range that was initially occupied on or before July 4). Residency times for each individual within each Beringia region was defined as the total number of 8-hour locations regardless of activity state within a region divided by 3 (such that the unit of measure is the number of days). We calculated foraging probability and probability of being on land within regions for each individual as the number of foraging locations or locations on land within a region divided by the total number of locations within a region. We restricted calculations of residency time and number of stopover areas to individuals with complete tracks for a given region. For calculations of foraging probability and probability of being on land, we used individuals with both complete and incomplete tracks for each region. We used an ANOVA to compare departure dates from breeding grounds between males with successful and failed nests. Finally, we used a linear mixed effects model (with individual included as a random effect) to compare dates females were present within each region between years using the package lme (Bates et al. 2015) in R.

Comparison with at-sea data

To compare to high-use areas identified by the satellite tracking data, we estimated Red Phalarope densities (birds/km^2, based on means of 3-km segments within each 30-km hexagonal cell) and survey effort (km surveyed within cells) from U.S. Fish and Wildlife vessel-based surveys (see Kuletz et al. 2019 for details). We used transects surveyed within Beringia between June and October 2017–2020 (years corresponding to tagging studies) and in 2006–2021 (all available years of data).

Results

Tracking success

Of the 102 Red Phalaropes tagged, we successfully tracked 72 individuals (50 females, 22 males) after breeding; 67 (out of 92) in Alaska and 5 (out of 9) in Canada (Table 1). The number of days an individual was tracked ranged from 5–275 (mean = 58), with females transmitting, on average, 28 days longer than males ($F_{1,70} = 6.23$; $P = 0.015$; Table 2). One individual migrated over 33,000 km, which included its travel to the wintering grounds and part of its return north. However, the average individual traveled ~5,000 km (range: 206–33,364 km) before the tags stopped transmitting. Females, on average, were tracked >4,000 km more than males (Table 2, Figure 2). We did not acquire post-breeding locations for 29 individuals (20 females, 9 males; see Table 1). In most cases, we were unable to determine cause of tag failures, but presume it was due to individuals losing their tags (for tags attached with glue), mortality of the individual (one female tagged in Barrow was attacked and killed by a pair of Parasitic Jaegers; *Stercorarius parasiticus*), another was killed by a hunter, or tag transmission failure.

General migration patterns

Departure date from breeding grounds.–Red Phalaropes exhibited large individual variability in when they began their post-breeding migration. In general, individuals left their last breeding site between late June and mid-August, with females, on average, leaving 17 days earlier than males ($F_{1,70} = 80.67$; $P < 0.001$; Table 2; Figure 3). Within a sex, departure dates varied by 33 (females) to 40 days (males). Some of the variability in female departure dates was explained by annual differences, with average departures dates 7 days earlier in 2017 compared to 2018 ($F_{1,48} = 22.72$; $P < 0.001$; Table 2). Males tended to leave later in 2019 as compared to 2020, but the differences were not significant ($F_{1,20} = 1.13$; $P = 0.301$; Table 2). Surprisingly, males with successful nests tended to depart at similar dates (mean: 24 Jul; range: 11 Jul–14 Aug; $n = 9$) as males with unsuccessful nests (mean: 18 Jul; range = 6 Jul–13 Aug; $n = 9$; $F_{1,16} = 1.40$; $P = 0.254$). We found similar results when analyses were restricted to males captured in Alaska.

Identification of behavioral states.–Using location information throughout the Western Hemisphere, we used the post-breeding model to identify foraging sites outside of the Beringia region. In this model, the foraging state had a mean step length of 12.4 km (SD = 11.5 km) and a mean turning angle of -0.13° (concentration = 0.04), compared to the migrating state with a mean step length of 81.2 km (SD = 71.6 km) and mean turning angle of 0.02° (concentration = 1.39). The concentration measure indicates how clustered the turning angles are around the mean, with large values indicative of directional movements and values close to zero indicative of undirected movements (Michelot and Langrock 2019).

Migration patterns and stopover areas across the Western Hemisphere.–In general, Red Phalaropes tagged in Alaska migrated west into the Pacific Ocean while those tagged in the Central Canadian Arctic migrated east into the Atlantic Ocean (Figure 2). However, there were two females and one male tagged in Alaska that migrated east into Canada. One female and one male turned around after stopping on Banks Island and within the Mackenzie River Delta area, respectively. The other female continued to migrate across the Canadian Arctic, stopped briefly at Banks Island for 2 days, then made numerous 1–6 day stops around Baffin and Prince Charles Islands, and in Baffin Bay before the tag stopped transmitting (Figure 2). Of the

5 birds tagged in Canada that provided post-breeding locations, only 2 were tracked away from the breeding grounds, stopping on and around Baffin and Prince Charles Islands from late July to early October (Figure 2). Only one individual provided locations farther south; this bird traveled non-stop (i.e., no foraging locations) for over 6 days following the Labrador Current in early October, with its last transmission occurring in the Atlantic Ocean off the east coast of the United States on October 11 (Figure 2).

Of the 67 birds tagged in Alaska that provided post-breeding movements, most individuals migrated west and then south through the Bering Strait, after which, individual routes tended to diverge as individuals migrated along both the Russian and Alaskan coastlines (Figure 2; see below for more detailed information within Beringia). Only 10 female Red Phalaropes were tracked south of the Bering Sea, where most locations tended to occur along the North Pacific Current (38°–46°N latitude and 129°–179°W longitude; Figure 2). This area was used for foraging by all 10 individuals, with each stopping often multiple times between 1–24 days from late July to early January (Figure 2). After spending 21–107 days (mean = 49 days) within this region, 5 individuals traveled southeast toward California (Figure 2). After reaching the California coastline, these individuals migrated south along the California Current on average 250 km from the coast (range: ~ 0–527 km), stopping to forage at sites along the Baja California coast, in both the Pacific Ocean and the Gulf of California (Figure 2). Only one female was successfully tracked farther south, where it stopped at sites off the coast of Ecuador and Peru (Figure 2). This female then traveled along the Peru Current to reach its wintering area off the coast of Chile in early December (Figure 2), traveling a total of 24,253 km from its breeding location. This female remained ~ 0–129 km (mean ~ 46 km) in a relatively small area (28,340 km^2) off the coast from Concepción, Chile (Figure 2). On 25 March, this female began its northward migration, staying farther from the coast (~300–1200 km) than during its southward migration, traveling > 4,000 km (~29° latitude) before transmission was lost (Figure 2).

Migration patterns through Beringia

Identification of behavioral states.–The best supported Beringia-only model predicting foraging and migrating states included distance to coast as a covariate (AIC = 115,978; $w_i = 1.0$; for reference, the AIC for intercept-only model = 116,085, $w_i = 0.0$). Individuals closer to the coast were more likely to transition to and remain in a foraging state compared to individuals farther from the coast (Figures 4 and 5). In the Beringia-only model, the foraging state had a mean step length of 11.5 km (SD = 10.8 km) and a mean turning angle of 3.11° (concentration = 0.04), compared to the migrating state with a mean step length of 69.7 km (SD = 61.32 km) and a mean turning angle of 0.03° (concentration = 1.09).

Migration variability in Beringia.–Red Phalaropes that migrated through the four Beringia regions, showed large variability in migration patterns and behaviors. While individuals generally moved southwest in the Beaufort/Chukchi seas, south in the Bering Strait and South Bering, and southeast in the Aleutians, movements in all directions were observed, many over considerable distances (e.g., >250 km) in directions not consistent with the expected migration route (Figure 6). Individuals meandered in all directions and even backtracked as they made their way through Beringia toward their wintering range (see Figure 2). Individuals often foraged in these regions and traveled shorter distances (e.g., < 25 km) between consecutive foraging sites, with no directional movement (Figure 6).

On average, individuals occurred progressively later the farther south they migrated through the regions, with males generally migrating later than females (Figure 7). However, there was considerable variability in when individuals migrated through each region. For example, females were present in all regions as early as July and as late as October (Figure 7). This variability in timing among females was generally not due to different annual conditions. The one exception was the Beaufort/Chukchi region where females were present later in 2018 (mean = 1 Aug; range = 2 Jul–8 Oct; $n = 28$) compared to 2017 (mean = 14 Jul, range = 25 Jun–14 Aug; $n = 22$; $t_{1,48} = 2.06$; P=0.045). The number of days present, the number of stopover areas, the probability of foraging, and the probability of being on land within each region were similar for females in 2017 and 2018. The only exception was that females had a greater probability of being on land within the Beaufort/Chukchi region in 2018 (mean = 0.53; SE= 0.04) than in 2017 (mean = 0.19; SE = 0.06; $F_{1,48} = 24.14$; *P*<0.001).

The amount of time individuals spent within a region varied with foraging probability. Female Red Phalaropes spent more time ($F_{3,107} = 17.72$; *P*<0.001), had more stops ($F_{3,107} = 16.73$; *P*<0.001), and a higher foraging probability ($F_{3,145} = 17.61$; *P*<0.001) in the Bering Strait and Aleutian regions than in the Beaufort/Chukchi and South Bering regions (Figure 7). Males, however, had greater foraging probabilities in the Beaufort/Chukchi and Bering Strait regions as compared to the South Bering region ($F_{2,25} = 6.16$; *P*=0.007), consistent with relatively long residencies and numerous stops within the former regions. However, we do not have data on residency times and number of stopover areas in the South Bering region for comparison (Figure 7).

Both females ($F_{3,145}$=7.64; *P*<0.001) and males ($F_{2,25}$=14.48, *P*<0.001) had a greater probability of being on land in the Beaufort/Chukchi region as compared to all other regions (Figure 7). As compared to females, males also made more stops and spent more time foraging on land in the Beaufort/Chukchi region (stopovers: $F_{1,55} = 10.15$; *P*=0.002; residency: $F_{1,55} = 37.48$; *P*<0.001; foraging probability: $F_{1,65} = 48.81$; *P*<0.001; probability of being on land $F_{1,65} = 24.81$; *P*<0.001; Figure 7). Males also spent more time foraging in the Bering Strait region compared to females ($F_{1,54}$=6.776; *P*=0.012; Figure 7).

Characteristics of stopover and high-use areas

Within Beringia, Red Phalarope stopover areas occurred both on land and at sea and were concentrated along the Alaska coastline of the Beaufort and Chukchi seas; in the Chukchi Sea north of the Chukotka Peninsula, along the coastline of the Chukotka Peninsula, throughout the Bering Strait, around St. Lawrence and St. Paul islands, and along the Aleutian Islands, especially near Unimak Island (Figure 2). Kernel utilization distributions revealed four high-use areas, including the Alaska coastline of the Beaufort and Chukchi seas, along the Russian side of the Bering Strait, in the Gulf of Anadyr, and along the Aleutian Islands near Unimak Island (Figure 8).

Red Phalaropes used land and marine areas (including Barrow Canyon) within the Beaufort/Chukchi high-use area (Figure 8) from late June to early September, with most occurrences in July and August (Figure 9). Pack ice was present in the Beaufort/Chukchi high-use area throughout much of July in 2018 and 2020, but had retreated to the north, outside this region by early July in 2017 and 2019 (Figure 10). Occasionally, we observed individuals migrating over the pack ice, but none ever stopped to forage (Figure 10). In contrast, females frequently foraged within the marginal ice zone, which is characterized by broken sea ice intermixed with open water, whereas males stayed on land or in open water (Figure 10). Red Phalaropes were present in the Beaufort/Chukchi high-use area when sea surface temperatures were relatively cold (i.e., monthly averages typically between 1–5°C; Figures 9 and 11). Within the western portion of the Beaufort/Chukchi high-use area, higher salinity (> 30 PSU) was observed due to the northward-flowing currents through the Bering Strait (Figures 9 and 11). Chlorophyll-a concentrations were consistently high (>3 mg/m^3) nearshore but declined farther from the coast (<1.5 mg/m^3, Figures 9 and 11).

Red Phalaropes were present from late June to October within the Bering Strait high-use area, with most locations occurring at sea, although a few locations were present along the coast of the Chukotka and Seward peninsulas, as well as on St. Lawrence Island (Figure 9). This area showed relatively low sea surface temperatures (i.e., monthly averages typically between 4–9°C) but high salinity (>30 PSU) due to the Anadyr Current (Figures 9 and 11). Chlorophyll-a concentrations within the Bering Strait high-use area were relatively high (many areas >4 mg/m^3), especially in August and September (Figures 9 and 11).

Red Phalaropes were present from mid-July to October within the Gulf of Anadyr high-use area, but in smaller numbers compared to the Beaufort/Chukchi and Bering Strait high-use areas (Figure 9). When Red

Phalaropes were present, this area had relatively low sea surface temperatures (i.e., monthly averages typically between 4–11°C) and high variability in saline levels (Figures 9 and 11); although salinity data were not available for many (especially nearshore) locations. Chlorophyll-a concentrations within the Gulf of Anadyr high use area were relatively high (many areas >4 mg/m^3), especially from July to September (Figures 9 and 11).

Red Phalaropes were present from mid-July to late September within the Aleutian Islands high-use area, but only a few females still provided location data this far south (Figure 9). This area was characterized by the highest sea surface temperatures (i.e., monthly averages typically between 9–11°C) and salinity (>32 PSU; Figures 9 and 11). Overall, chlorophyll-a concentrations were the lowest within this region (i.e., most areas <2 mg/m^3), although patchy areas of high concentrations were present, especially near shore (Figures 9 and 11).

Comparison with at-sea data

The vessel-based at-sea surveys which overlapped the tagging studies (2017-2020) identified the Bering Strait region, including Hope Basin in the Chukchi Sea, as having the highest densities of migrating Red Phalaropes (Figure 12A). During this period, Red Phalaropes were also widespread throughout the northern Chukchi, particularly near Point Barrow and over Hanna Shoal. South of the Bering Strait, high densities occurred in the Chirikov Basin, especially near St. Lawrence Island and in the Anadyr Current. Densities were sparse throughout the southern Bering Sea, but high density cells occurred in Unimak Pass and east of Kodiak in the Gulf of Alaska. Over the longer time series of at-sea surveys (Figure 12B), the Bering Strait region from Hope Basin in the Chukchi to St. Lawrence Island in the northern Bering, remained the region with highest densities. However, this longer time series also shows widespread phalarope observations throughout Beringia, including high density cells near the 50m or 70m isobaths, which structure fronts paralleling the coast along the inner shelf of the southern Bering Sea (Stabeno et al. 2016). Other areas with moderate to high densities occurred in the Aleutian Islands and Gulf of Alaska continental shelf (Figure 12B).

Discussion

Temporal and spatial variability in fall migration behavior

We documented post-breeding movements of Red Phalaropes across the North American Arctic using satellite tracking data. As predicted, we generally observed two distinct migration routes in Red Phalaropes, with most birds breeding in Alaska traveling toward the Pacific Ocean to winter off the coast of South America, and birds breeding in Canada traveling toward the Atlantic Ocean. However, two females and one male that bred in Alaska migrated toward the Atlantic Ocean; two of the three backtracked to the Pacific Ocean, but the third was still traveling southeast when the tag stopped transmitting. Taylor et al. (2011) also noted several Red Phalaropes making small-scale movements toward the east along the coasts of the Chukchi and Beaufort seas; however, the final migratory pathway of these individuals was not determined. Similar migratory movements have been documented in other long-distance migratory seabirds such as Short-tailed Shearwaters (*Ardenna tenuirostris*) with individuals following prey into the western Beaufort Sea before returning west and south to migrate to southern breeding grounds (Kuletz et al. 2015, Kuletz et al. 2019). Nevertheless, these exceptions to the primary migration paths we documented suggest that migratory connectivity may be lower than originally assumed, with wintering populations in the Pacific and Atlantic oceans likely not isolated from one another.

Red Phalaropes showed variation in the timing, routes, and habitat selected during their southward migration. While we predicted that females would leave Arctic-breeding locations earlier than males due to the species' male-only incubation behavior, this effect was small and both sexes left the breeding grounds over an extended period (33- to 40-day period for females and males, respectively). The large variability in departure dates was not explained by variation in annual conditions or by a male's breeding success; some individuals stayed in the breeding area well after mating opportunities (females) or parental duties (males) were over. Individual Red Phalaropes (especially males) commonly used the lagoons and associated tundra near their breeding sites as a post-breeding site, instead of relocating to the pelagic environment (see Figures 2 and 9). This was apparent at Utqiaġvik, a previously identified important post-breeding area for Red Phalaropes (Connors et al. 1981, Smith and Connors 1993, Andres 1994, Taylor et al. 2010, Taylor et al. 2011), where post-breeding densities in littoral habitats were often higher than breeding densities on the nearby tundra (Connors et al. 1979). Post-breeding sites in the Beaufort/Chukchi region likely allow birds to replenish energy reserves prior to migrating to the pelagic environment, as previous studies have noted individuals feeding heavily on marine zooplankton, as they forage along gravel beaches in these areas (Connors et al. 1981). In addition, these post-breeding sites could be molting areas, as Red Phalaropes may begin their molt at or near breeding sites prior to their southward migration (A. Taylor and R. Lanctot, unpubl. data). While our study indicated that these Beaufort/Chukchi post-breeding locations appeared to be more important for males than females, we cannot rule out the possibility that females used some of these areas as post-breeding sites prior to 4 July (the date after which we classified newly occupied sites as post-breeding), as many females were documented moving among sites on the breeding grounds (unpublished data). Alternatively, the locations for acquiring energy or molting may differ between the sexes, with females, as the non-incubating sex, requiring less time to replenish energy reserves or molt prior to entering the pelagic environment.

Male and female Red Phalaropes exhibited tremendous variability in the route used to travel south towards their wintering areas, even when captured in the same breeding area. For example, individuals breeding in Utqiaġvik followed westward routes along the coasts of both Alaska and Russia, as well as east through the Canadian Arctic. Van Bemmelen (2019) found similar spatial variability in Red Phalaropes migrating in the Atlantic Ocean with individuals utilizing three separate migration pathways and wintering areas. Furthermore, while migrating along common routes, individuals did not always utilize the same stopover areas, although we did identify several large areas (often in highly productive regions) where multiple individuals stopped to forage (e.g., within the Anadyr Current). Individuals also exhibited extreme deviations from a direct route to their wintering grounds, often traveling in all directions, with much backtracking and meandering. For example, the one individual female tracked to its wintering area traveled nearly 9,000 km (>35% of its >24,000 km journey) more than a direct route (see Figure S1). Such non-direct movements could indicate active foraging in the dynamic nature of the pelagic environment where food resources are often patchy, ephemeral, or unpredictable, especially at small spatial scales (Hyrenbach et al. 2000, Palacios et al. 2006, Weimerskirch 2007).

Van Bemmelen (2019) showed that Red Phalaropes migrating in the Atlantic Ocean used different migration routes and stopover areas depending on their wintering area. Unfortunately, our inability to identify wintering areas for most individuals precluded us from assessing whether a similar pattern existed in our study. However, observations of birds in December using a broad geographical area (between 46°N off the coast of Washington State and 37°S off the coast of Chile) suggests that individuals breeding in northern Alaska use different wintering areas along the Pacific coast, including areas farther north than previously described (Figure 2). Alternatively, individuals might still have migrated farther south after we lost their position in December. The Atlantic coast population of Red Phalaropes is also thought to winter farther north than previously described, with individuals observed north of 40°N off the east coast of North America (van Bemmelen 2019). Such northward shifts in wintering areas may be the result of changing climate conditions, as has been documented during summer in the Chukchi Sea (Mueter et al. 2021) and throughout the Pacific Arctic for higher trophic levels (Stafford et al. 2022). Alternatively, it is possible that no discrete overwintering areas exist, but rather, birds are roaming over vast oceanic areas to track variable food resources (van Bemmelen 2019).

In addition to high spatial variability, Red Phalaropes also exhibited large temporal variation in their departure dates and timing of their southward migrations. Our results suggest that Red Phalaropes do not appear to be time limited. This lack of urgency was especially apparent in males, who did not speed up their migration despite leaving breeding areas about two weeks later than females. Instead, they made more stops and spent more time foraging in the Beaufort/Chukchi region. Such patterns may suggest that additional energy requirements needed by males (see above) may carry over into the pelagic environment, necessitating the need for males to forage longer in highly productive areas before migrating further south. In addition, we observed birds remaining in the Arctic into October, well past the expected date on which individuals should begin migrating to reach nonbreeding areas by late November (Tracy et al. 2020). These observations are in contrast to optimal migration theory predicting that long-distance migrants use a time-minimizing migration strategy, with fewer stops and faster speeds (Alerstam and Lindström 1990, Alerstam 2011), as has been shown in other land-based shorebirds (Anderson et al. 2019). Red Phalaropes may opt for an energy-minimizing strategy during fall migration, taking indirect routes with numerous stops over a long period of time. Red Phalaropes traveling in a highly ephemeral, unpredictable pelagic environment may not benefit from a time-minimizing strategy, presumably because finding adequate foraging opportunities has a higher priority than minimizing time or total distance traveled. Alternatively, we cannot rule out the possibility that individuals have recently extended their stay in northern areas concurrent with warmer waters, a longer open water season, and late plankton blooms, as has been shown in other migratory seabirds such as shearwaters (Kuletz et al. 2020).

Distributions in relation to oceanographic conditions

As with previous studies (Divoky 1979, Connors et al. 1981, Orr et al. 1982), we found that Red Phalaropes, especially females earlier in the year, were often associated with the marginal ice zone. Foraging in areas with broken sea ice and open water leads may allow individuals to exploit ice-associated prey (Divoky 1979, Connors et al. 1981, Orr et al. 1982). For example, zooplankton, amphipods, and larval fish aggregate in the marginal ice zone as a result of high primary productivity associated with ice algae (Gradinger 2009). In contrast, solid pack ice, especially shore-fast ice, appears to constrain migratory movements, preventing individuals from foraging in pelagic waters altogether. Indeed, satellite-tracked Red Phalarope in our study were frequently found on land or near the coast, more than expected based on prior at-sea observations (Briggs et al. 1984, Brown and Gaskin 1988, Tyler et al. 1993, Wahl et al. 1993). Males commonly used onshore sites in both the Beaufort/Chukchi and South Bering regions, and both sexes used nearshore (i.e., littoral habitats) habitats along the coasts of Russia and Alaska. Such extensive use of onshore and nearshore habitats suggests that these areas may provide alternative foraging opportunities for individuals during migration, especially in areas or at times when pelagic environments have lower ocean productivity (see Drever et al. 2018). Thus, males may be maximizing energy accumulation by greater use of onshore areas in the Beaufort/Chukchi, Bering Strait, and South Bering in fall, when ocean conditions are less favorable.

Foraging Red Phalaropes were often associated, as expected, with areas of greater food availability, such as highly productive ocean currents, ocean fronts, or upwellings (as per Orr et al. 1982, Briggs et al. 1984, Haney 1985, Brown and Gaskin 1988, Day 1992, Tyler et al. 1993, Wahl et al. 1993, DiGiacomo et al. 2002). For example, in the Beaufort/Chukchi region, Red Phalaropes foraged within the Barrow Canyon (Figures 2 and 9), an area which extends from the Chukchi shelf into the western edge of the Beaufort Sea where upwelling periodically results in high productivity, especially when compared to surrounding areas (Pickart et al. 2013, Pisareva et al. 2019). Based on at-sea surveys (Figure 12), Barrow Canyon, and Hannah Shoal to the west, were identified as significant marine hotspots for phalaropes, as they were during more extensive surveys for phalaropes and other marine birds during summer (Kuletz et al. 2015, Kuletz et al. 2019, Gall et al. 2022). Indeed, Divoky (1984) found that Barrow Canyon was the only place in the Beaufort Sea where Red Phalaropes occurred in large numbers, as the remainder of the Beaufort Sea had low primary production and prey densities. From the southern Chukchi Sea to the Bering Sea, foraging individuals were most common along the highly productive Russian coastline. High productivity within this area is the result of the cold and highly saline, but nutrient rich, Anadyr Current that brings nutrients and zooplankton northward from the Bering Sea (Coachman et al. 1975, Sambrotto et al. 1984, Iken et al. 2009). Within the Anadyr Current, numerous eddies and upwellings bring zooplankton within foraging range of surface-feeding birds such as Red Phalaropes (Piatt and Springer 2003). In contrast, the Alaska Coastal Current that parallels the Alaskan coastline is highly influenced by river input, resulting in warm, low saline, and nutrient-poor water (Coachman et al. 1975, Sambrotto et al. 1984, Iken et al. 2009). In addition to high productivity, the Anadyr Current also contains more large-bodied copepods (a primary food item for Red Phalaropes) in comparison to the Alaska Coastal Current where smaller copepods dominate (Piatt and Springer 2003, Eisner et al. 2013). As a result, higher densities of Red Phalaropes, as well as other planktivorous avian species, have been detected within the Anadyr Current compared to the Alaska Coastal Current (Elphick and Hunt 1993, Kuletz et al. 2020). Nonetheless, the at-sea surveys from 2006-2021 indicated that phalaropes do use the southern Bering Sea inner shelf along the 50m or 70m isobaths (Figure 12B). Despite relatively low productivity within the Alaska Coastal Current, the persistent fronts along these isobaths may provide greater accessibility to prey, at least seasonally (Schneider 1982, Hunt et al. 2014). Lastly, within the South Bering region, female Red Phalaropes often foraged along the Aleutian Islands, especially near Unimak and False passes, areas that can have high productivity (especially along the northern edge) where the Alaska Coastal Current flows northward between the islands creating convergent tidal fronts (Ladd et al. 2005, Mordy et al. 2005). Previous studies have observed Red Phalaropes foraging at whale plumes (Kumlien 1879, Nelson 1883, Harrison 1979, Obst and Hunt 1990, Day 1992, Grebmeier and Harrison 1992, Elphick and Hunt 1993), and indeed, the highly productive areas selected by foraging Red Phalaropes are also important to foraging whales (Ashjian et al. 2010, Okkonen et al. 2011, Heide-Jørgensen et al. 2012, Citta et al. 2015, Citta et al. 2018). However, more information is needed to understand the degree Red Phalaropes are using whales in their selection of foraging areas.

Comparison with at-sea distributions and potential biases

Data on contemporary at-sea distributions of Red Phalaropes are primarily from vessel-based surveys conducted between 2006 and 2021 (Figure 12B). Both the at-sea surveys and our tracking data (Figure 8) identified the Bering Strait as having high densities of migrating Red Phalaropes. This region has previously been described as a “de facto” hotspot for both marine birds and mammals due to its high productivity, as well as being the only corridor between the Arctic and the Bering Sea (Kuletz et al. 2015). Other high use areas identified by tracking Red Phalaropes, such as the Beaufort/Chukchi region and the Aleutian Islands, were also identified as being used by Red Phalaropes during the at-sea surveys, but often at lower densities than the Bering Strait region (Figure 12). The at-sea surveys did not detect other high use areas found by tracking individuals (see Figures 2 and 8), such as onshore and nearshore habitats, nor areas along the Russian coastline, such as the Gulf of Anadyr, because either no or few vessel-based surveys occurred in these regions (Figure 12). At-sea survey data are limited to areas traveled by offshore vessels whose missions are unrelated to phalarope observations and are often restricted by geopolitical boundaries, season and weather conditions, and other logistical constraints. The at-sea surveys also identified the Bering Sea Shelf as having several areas of high use (Figure 12), but this area was not used by any of our tracked birds, despite high productivity within this region (Springer et al. 1996). Selection of foraging areas might vary among age classes and local populations or depending on annual conditions. Further, our sample size of tracked males was small and individuals were tracked only briefly, potentially biasing our results to areas selected earlier in the season. These methodological biases indicate that our ability to inform models to assist management decisions could be improved by combining data sources.

While our tracked Red Phalaropes provided information that is not biased by human search effort, it is important to note that individuals with PTT tags may behave differently than individuals without tags. Despite attaching one of the smallest solar-powered PTT devices available, many individuals only sent data for a relatively short duration (Table 2). This was especially true for males, the sex with the lower body mass. Thus, we cannot exclude that individuals incurred an additional stress due to tag attachment that ultimately resulted in higher mortality. Poor tracking success has also been found in other marine birds such as jaegers and skuas (Sittler et al. 2011, Thaxter et al. 2016, Seyer et al. 2021; but see Harrison et al. 2021), as tags attached to marine birds with harnesses may reduce flight performance, reduce foraging efficiency, increase energy expenditure, or compromise insulation (Thaxter et al. 2016, Seyer et al. 2021). The latter effect may be especially important in the Arctic marine environment where poor insulation and damp feathers can quickly lead to hypothermia and death, especially for species that have no opportunity to dry themselves on land (Seyer et al. 2021). However, we also cannot rule out the possibility that birds suffered a natural high mortality rate in the study years (e.g., due to low food availability; Duffy-Anderson et al. 2019, Romano et al. 2020, Will et al. 2020, Kaler and Kuletz 2022), that tags fell off or failed due to prolonged saltwater exposure, solar panels became covered with feathers or salt, or to a combination of these factors.

Conservation implications

Marine birds have often been described as bioindicators of the marine environment, as they are highly sensitive to ecosystem and environmental changes (Cairns 1987, Furness and Camphuysen 1997, Piatt et al. 2007, Mallory et al. 2010, Provencher et al. 2012, Vihtakari et al. 2018). Thus, understanding their migration routes and selection of foraging areas is critical to not only identify important areas for conservation, but also assess threats of anthropogenic and climatic changes. In this study, we identified four important areas within Beringia for Red Phalarope conservation: 1) onshore and nearshore areas of the Beaufort and Chukchi seas (including Barrow Canyon); 2) the Bering Strait, especially along the western edge; 3) the Gulf of Anadyr; and 4) Unimak Island and surrounding areas (Figure 8). These results complement studies by Kuletz et al. (2015) that identified important marine areas of the Pacific Arctic and Smith et al. (2014) that identified four globally important (i.e., containing ≥ 1% of the global population) areas for Red Phalaropes within this region: two in the Beaufort/Chukchi region, one between Seguam and Amlia islands along the Aleutian Islands, and one on the Bering Sea Shelf. However, designation of important bird areas or marine protection areas for this species must account for foraging requirements throughout the species' migratory route, as well as the ephemeral nature of the marine environment and resources used by Red Phalaropes (Hyrenbach et al. 2000, Palacios et al. 2006). Thus, larger or more dynamic areas of protection are likely needed for this species, as important foraging areas are likely to change or shift annually or seasonally as physical and biological conditions change. Red Phalaropes, however, are just one of over 60 marine bird species that utilize the Beringia region (Kuletz and Labunski 2017); therefore, to protect all species, designation of important marine bird areas should focus on areas important for multiple species across guilds (e.g., see Smith et al. 2014, Kuletz et al. 2015). This approach, however, may not be effective for all species, especially those with unique requirements. Therefore, understanding species-specific requirements and migration movements remains important for identifying threats, as well as establishing species-specific protection.

Within the pelagic environment, anthropogenic impacts from oil and gas exploration, commercial fishing, vessel traffic, and wind farm development are increasing (Tyler et al. 1993, Wahl et al. 1993, Humphries and Huettmann 2014, Silber et al. 2021). Thus, current distributions and migration pathways should be considered before any future developments occur. For example, within the Beaufort/Chukchi region, Red Phalaropes were found primarily in littoral habitats, areas that are important for numerous post-breeding and juvenile shorebirds (Taylor et al. 2010, Taylor et al. 2011, Churchwell et al. 2018), and which are likely to be first impacted if an oil spill occurs (Connors et al. 1981). Similarly, high use areas utilized by Red Phalaropes, such as the Aleutian Islands, Bering Strait, and along the Russian coastline, occur in areas with high vessel traffic, increasing the risk of vessel disturbance and collision in these regions (Humphries and Huettmann 2014, Silber and Adams 2019, Silber et al. 2021). This may be especially apparent in areas such as Bering Strait and Unmiak and False passes which are bottlenecks for both marine birds and vessels

(Humphries and Huettmann 2014, Renner and Kuletz 2015, Silber and Adams 2019, Silber et al. 2021). Finally, increasing offshore wind farm development could have profound impacts on Red Phalaropes as they migrate through nearshore waters where lease sales are likely to occur (e.g., see Bureau of Ocean Engery Management 2022, Flint et al. 2022).

Along with the direct impacts from anthropogenic development and disturbance, many marine birds are also at risk of indirect anthropogenic impacts such as the ingestion of plastics. A species' risk of plastic ingestion depends on its foraging strategy, as well as the degree of overlap with areas of high plastic concentration (Titmus and Hyrenbach 2011, Williams et al. 2011). Red Phalaropes, as surface feeders, appear to be especially vulnerable to plastic ingestion (Moser and Lee 1992, Drever et al. 2018, Baak et al. 2021, Flemming et al. 2022). This vulnerability may be enhanced due to the species' preferential selection of oceanographic features that concentrate plastics such as convergences and eddies (Moore et al. 2001). For example, foraging Red Phalaropes migrating through the Pacific Ocean were often found within the North Pacific Current, the northern boundary of the "Great Pacific Garbage Patch", a 1.6 million km^2 square region that contains ~79 thousand tonnes of plastic trapped by the North Pacific Subtropical Gyre (Lebreton et al. 2018).

Climatic changes are also altering the marine environment on which Red Phalaropes rely, especially in the Arctic. Warmer temperatures and earlier sea ice retreat are predicted to change both the timing and magnitude of spring phytoplankton and zooplankon blooms (Hunt et al. 2002, Overland and Stabeno 2004, Arrigo et al. 2008, Sigler et al. 2016, Duffy-Anderson et al. 2019, Huntington et al. 2020), potentially resulting in a phenological mismatch or lower food availability for migrating Red Phalaropes. Additionally, the composition of prey items such as zooplankton have shifted with warming temperatures. For instance, previous studies have found a shift from large- to small-bodied zooplankton taxa in warmer years and a northward shift in Arctic zooplankton species (Coyle et al. 2008, Hunt et al. 2011, Eisner et al. 2014, Duffy-Anderson et al. 2019), which may make high value prey less available to migrating phalaropes. This shift from larger to smaller prey items likely has a detrimental impact on the foraging efficiency of species such as Red Phalaropes that may preferentially select larger prey items in cold water currents such as the Anadyr Current. However, changes in ocean or climate conditions may make these high productivity areas less stable or unpredictable (Roemmich and McGowan 1995). Along with changes in prey communities, predator communities are also changing. For example, the northward expansion of several fish species occurred with warmer temperatures (Hunt et al. 2002, Overland and Stabeno 2004, Grebmeier et al. 2006, Stevenson and Lauth 2019, Huntington et al. 2020, Mueter et al. 2021) and may result in added predation pressure on the zooplankton communities used by Red Phalaropes. Other predator species such as bowhead and gray whales are also shifting their movements farther north and remaining there for longer periods of time (Moore et al. 2003, Moore 2016, Tsujii et al. 2021). The degree to which these climate-induced ecosystem changes will ultimately impact Red Phalarope populations, however, depends on the adaptability of the species. The large variability in migration timing and routes observed in this study suggests that Red Phalaropes may be capable of adapting to changing conditions if they can find areas with sufficient food during migration. However, recent evidence suggests that phalarope densities have declined as the result of fewer ice-free days in the eastern Chukchi Sea (Gall et al. 2017).

Information needs

This study provides baseline data on Red Phalarope movements throughout the Western Hemisphere. However, movement data from additional birds from additional breeding populations would improve our knowledge of migratory connectivity, as well as the degree of spatial segregation between birds wintering along the Pacific and Atlantic oceans. In addition, movement data from other Arctic-breeding areas such as Russia are important to determine global migratory patterns and high use areas. More information on male migration patterns (hampered by our low sample sizes) would improve our understanding of the extent of annual variability and habitat use. Fine-scale selection patterns of oceanographic conditions are also needed to determine which areas individuals select for foraging. Such information could be used to predict how future oceanographic changes may impact this species. Finally, we still lack information for the spring migration period where high use areas and migration routes may be vastly different than those during fall migration. Given their small size, low site fidelity, and almost exclusive use of the marine environment, understanding migratory movements of Red Phalaropes is challenging and requires innovative techniques to follow this species throughout its annual cycle.

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Table 1. Capture location, year, and number of female and male Red Phalaropes equipped with 2-gram solar-powered Argos Platform Transmitter Terminal (PTT) tags from 2017–2020.

Capture location	Location	Year	Latitude	Longitude	Females[a]	Males[a]
Utqiaġvik	Alaska	2017	71.273	-156.614	40 (28)	
Utqiaġvik	Alaska	2018	71.273	-156.614	30 (22)	
Utqiaġvik	Alaska	2019	71.273	-156.614		5 (4)
Qupaluk	Alaska	2019	70.673	-152.845		3 (2)
Colville River	Alaska	2019	70.438	-150.688		1 (1)
Canning River	Alaska	2019	70.117	-145.838		3 (3)
Cambridge Bay	Canada	2019	69.171	-105.117		1 (0)
East Bay	Canada	2019	63.979	-81.702		4 (2)
Igloolik	Canada	2019	69.392	-81.566		4 (3)
Utqiaġvik	Alaska	2020	71.273	-156.614		10 (7)

[a] Number of individuals tagged and in parentheses number of individuals that provided post-breeding locations.

Table 2. Summary of migration and tracking information obtained during southward migration for female and male Red Phalaropes fitted with 2-gram solar-powered Argos Platform Transmitter Terminal (PTT) tags from 2017–2020. All data are restricted to locations and individuals tracked during post-breeding (i.e., sites initially occupied after 4 July or after an individual left the breeding grounds). All values are mean (range) unless otherwise stated.

Category	Departure date from last breeding site[a]	Time (hr) between locations[b]	Number of locations obtained[c]	Number of days tracked[d]	Date of last location[e]	Distance (km) tracked[f]
2017 (females)	1 Jul (25 Jun-9 Jul)	2.4 (0.0-75.9)	708 (230-2,490)	69 (13-275)	9 Sep (17 Jul-29 Mar)	6,616 (1,087-33,364)
2018 (females)	8 Jul (2 Jul-28 Jul)	2.3 (0.0-84.9)	666 (24-1,571)	63 (5-172)	9 Sep (12 Jul-27 Dec)	6,970 (999-18,086)
2019 (males)	23 Jul (8 Jul-14 Aug)	1.3 (0.0-73.2)	724 (62-1,742)	38 (7-89)	31 Aug (19 Jul-23 Oct)	2,474 (288-9,981)
Alaska-only	25 Jul (8 Jul-14 Aug)	1.2 (0.0-40.8)	547 (62-1,164)	40 (13-89)	4 Sep (3 Aug-23 Oct)	2,326 (457-5,499)
Canada-only	20 Jul (11 Jul-1 Aug)	1.5 (0.0-73.2)	813 (282-1,742)	35 (7-87)	23 Aug (19 Jul-10 Oct)	2,773 (287-9,981)
2020 (males)	17 Jul (5 Jul-1 Aug)	1.0 (0.0-50.7)	922 (421-1,919)	40 (18-89)	26 Aug (27 Jul-13 Oct)	1,878 (206-5,448)
Total (females)	**4 Jul (25 Jun-28 Jul)**	**2.3 (0.0-84.9)**	**689 (24-2,490)**	**67 (5-275)**	**9 Sep (12 Jul-29 Mar)**	**6,771 (999-33,364)**
Total (males)	**21 Jul (5 Jul-14 Aug)**	**1.2 (0.0-73.2)**	**787 (62-1,919)**	**39 (7-89)**	**29 Aug (19 Jul-23 Oct)**	**2,285 (206-9,981)**
Alaska-only	**22 Jul (5 Jul-14 Aug)**	**1.1 (0.0-50.7)**	**858 (282-1,919)**	**40 (13-89)**	**31 Aug (27 Jul-23 Oct)**	**2,141(206-5,499)**
Canada-only	**20 Jul (11 Jul-1 Aug)**	**1.5 (0.0-73.2)**	**547 (62-1,164)**	**35 (7-87)**	**23 Aug (19 Jul-10 Oct)**	**2,773 (287-9,981)**
Total (all individuals)	**9 Jul (25 Jun-14 Aug)**	**1.9 (0.0-84.9)**	**719 (24-2,490)**	**58 (5-275)**	**5 Sep (12 Jul-29 Mar)**	**5,401 (206-33,364)**

[a] A breeding site was defined as a site within the species' breeding range that was initially occupied on or before July 4.

[b] Time between successive locations obtained from PTT tags from all individuals. Time = 0.0 corresponds to < 3 minutes (0.05 hr).

[c] Total number of post-breeding locations obtained per individual from PTT tags.

[d] Number of days between the date an individual left its last breeding location and the date the last location was received or the date on which the tag was presumed to have fallen off or individual died.

[e] Date of the last location received or the date on which the tag was presumed to have fallen off or individual died.

[f] Total distance traveled from an individual's last breeding location to the last transmission received or the date on which the tag was presumed to have fallen off or individual died (see Methods). Distances were calculated as cumulative straight line geodesic distances between predicted locations generated every 8 hours for individuals using continuous-time random walk state-space models.

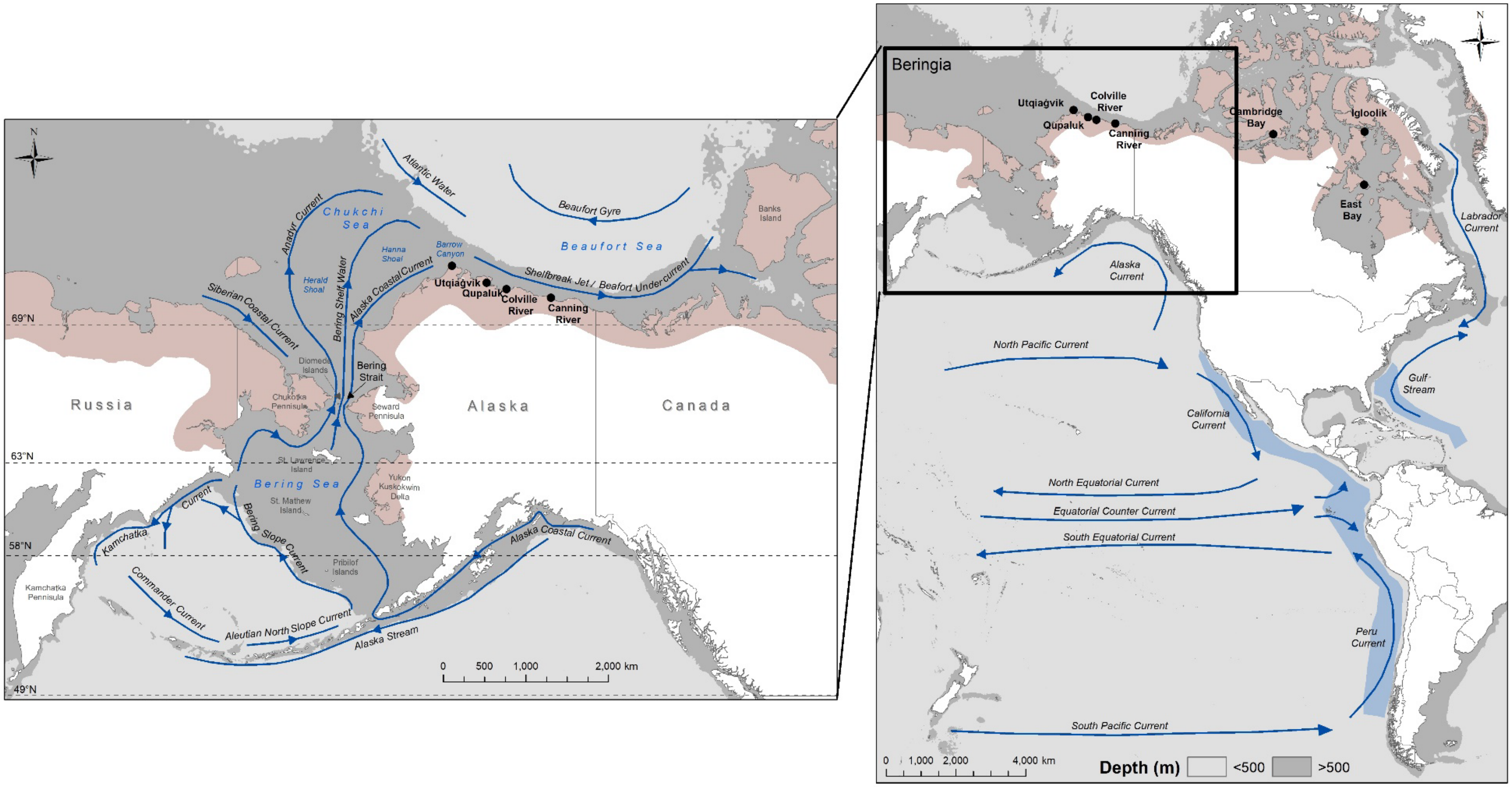

Figure 1. Major currents and geographic features along the southward migration route of Red Phalaropes in the Western Hemisphere; inset map illustrates the Beringia region in more detail. Red Phalarope breeding (pink shading) and wintering (blue shading) areas from BirdLife International and Handbook of the Birds of the World (2021). Tagging locations from 2017–2020 are indicated by black dots (see Table 1). Currents in Beringia taken from Smith et al. (2017); others from Pidwirny (2006). Bathymetry from Becker et al. (2009).

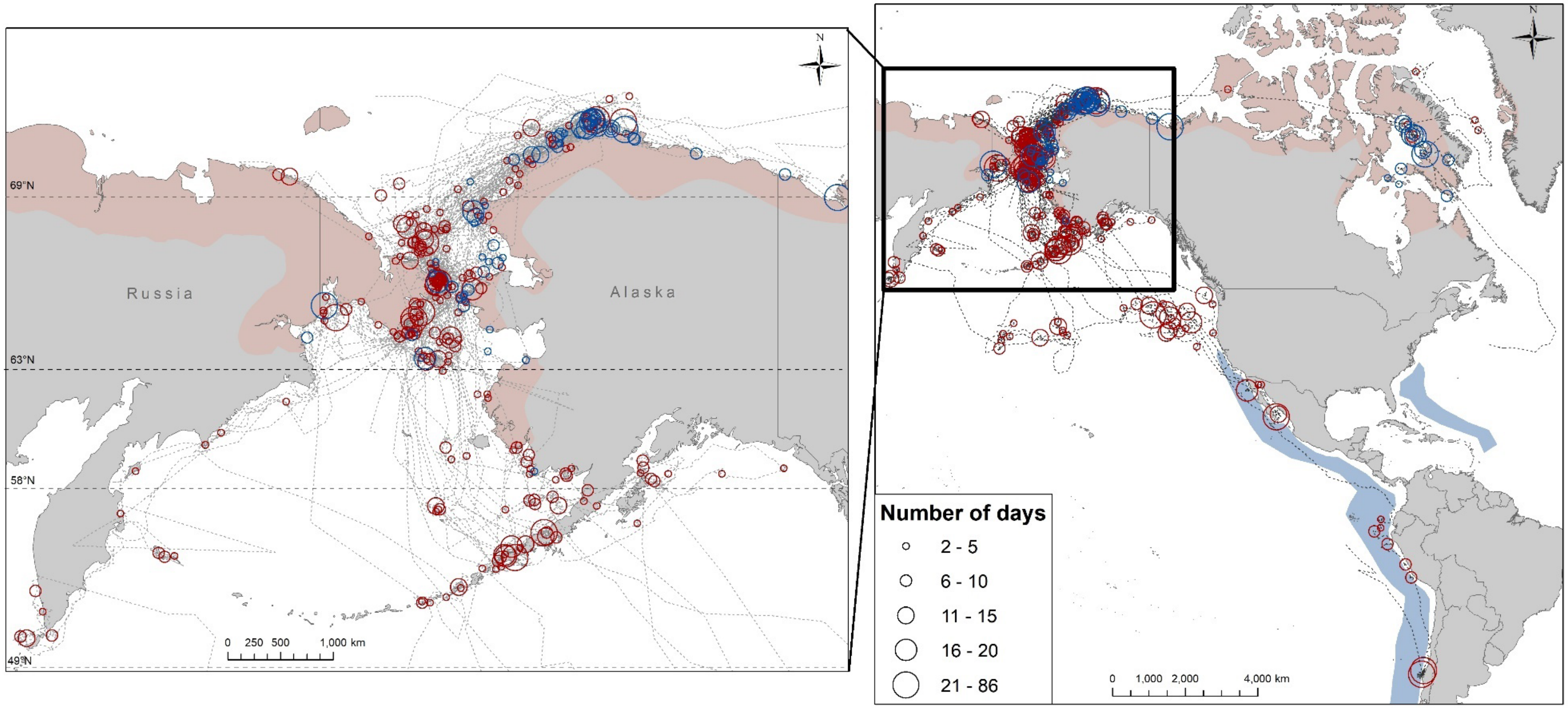

Figure 2. Migration routes and stopover areas for female (red circles) and male (blue circles) Red Phalaropes during southward migration from 2017–2020. Predicted locations were generated every 8 hours for individuals using continuous-time random walk state-space models. Stopovers were generated from foraging locations where state was classified using hidden Markov models. The size of the stopover symbol depicts the number of days an individual spent foraging before being classified as migrating. Note that starting locations for migration routes occur at the last site on the breeding grounds that was initially occupied on or before July 4. Red Phalarope breeding (pink shading) and wintering (blue shading) areas from BirdLife International and Handbook of the Birds of the World (2021).

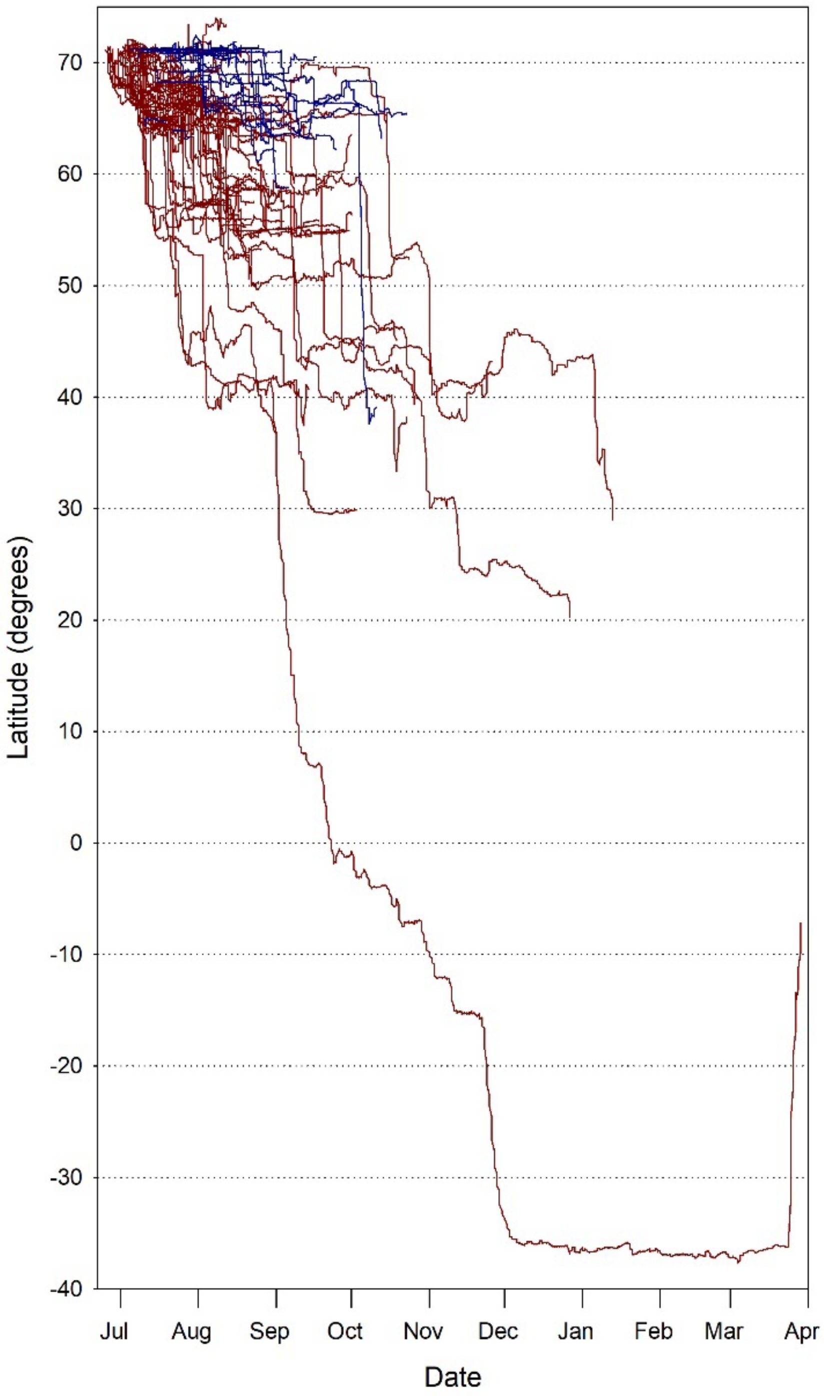

Figure 3. Latitude of female (red) and male (blue) Red Phalarope locations in relation to date (data from 2017–2020). Each line represents an individual, with predicted locations generated every 8 hours for individuals using continuous-time random walk state-space models.

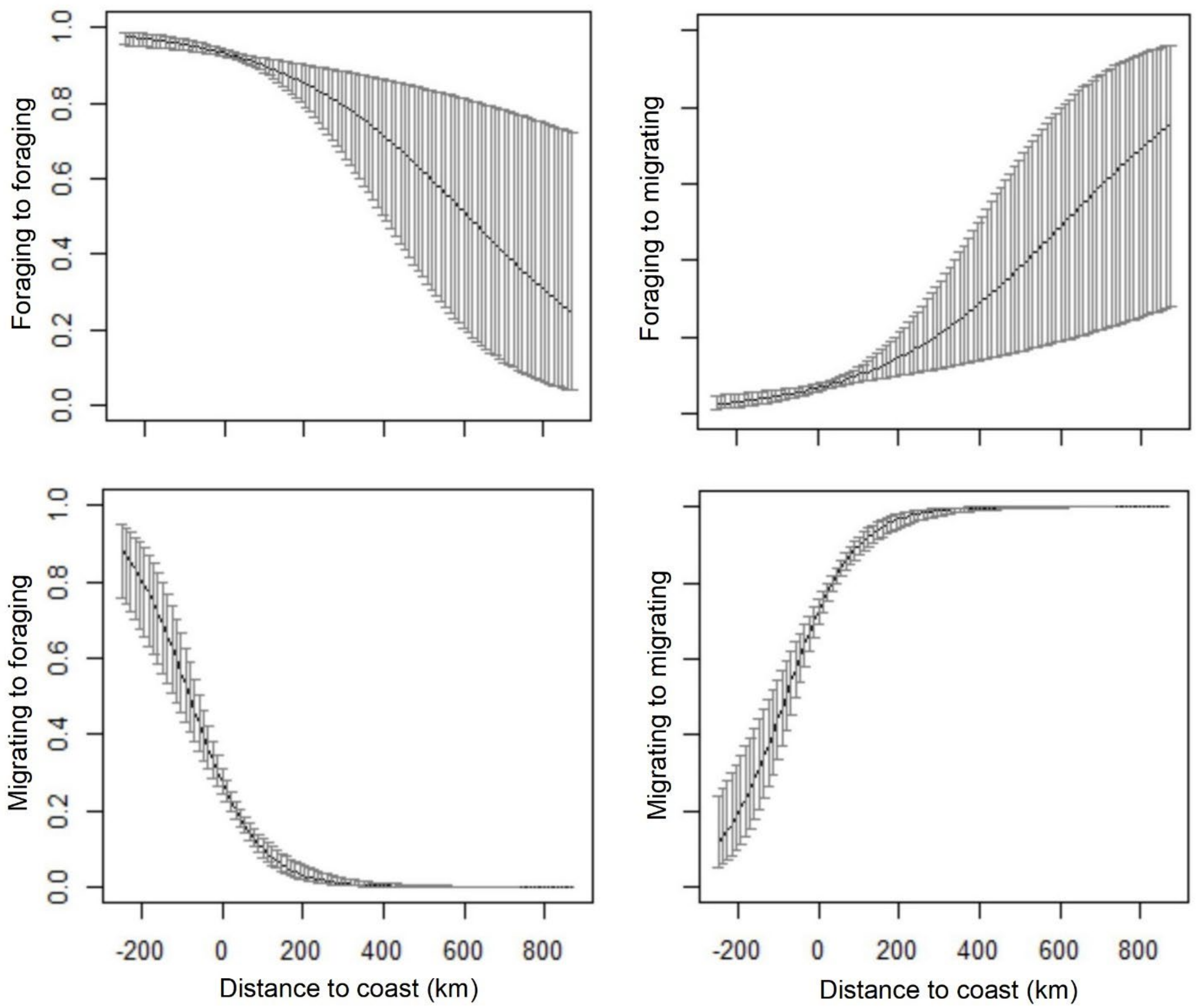

Figure 4. Transition probabilities (i.e., the probability of switching states or remaining in the same state) as a function of distance to coast (negative distance values indicate birds were on land) with 95% confidence intervals for Red Phalaropes during southward migration in Beringia based on data from 2017–2020. Predicted locations were generated every 8 hours for individuals using continuous-time random walk state-space models with foraging and migrating states classified by hidden Markov models.

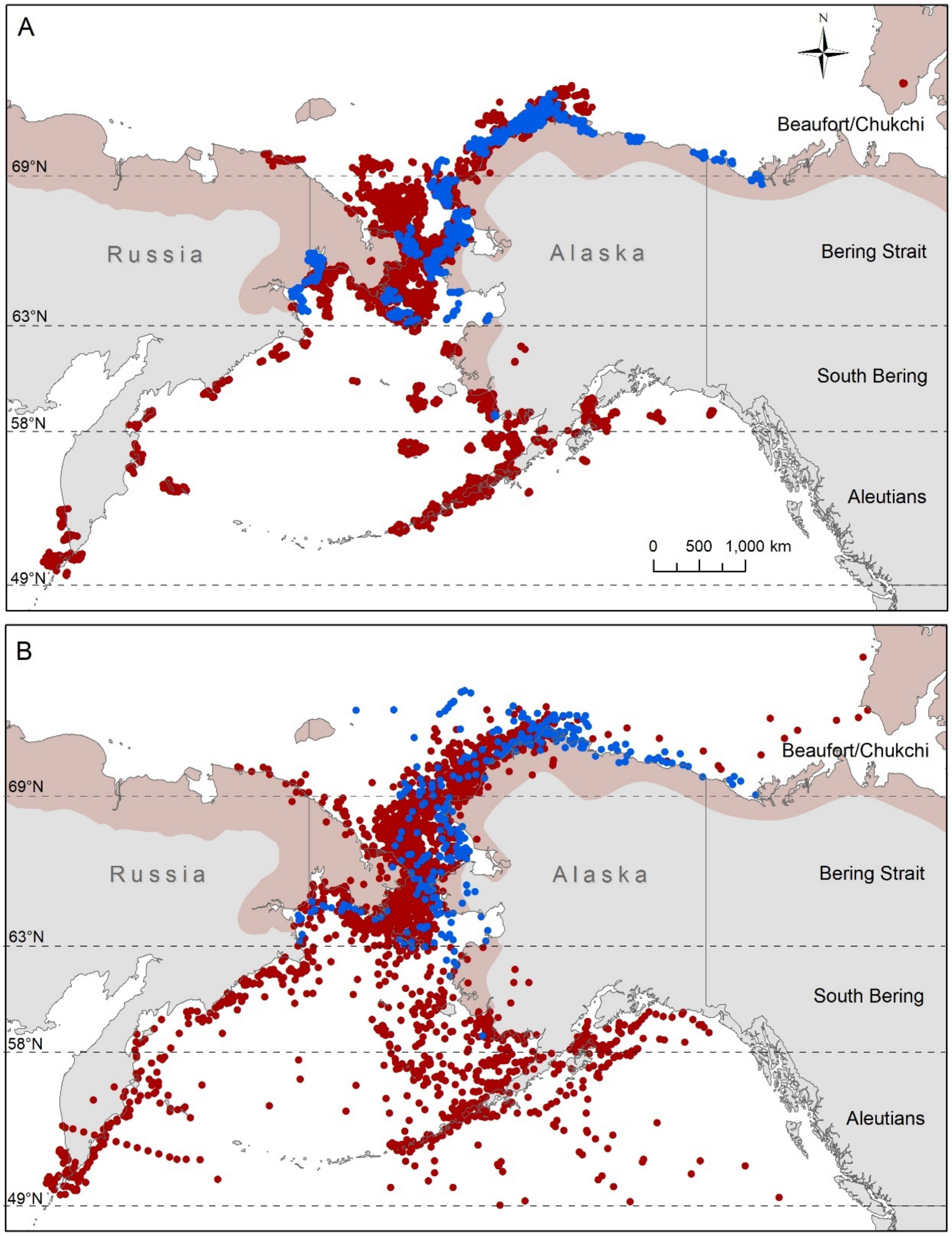

Figure 5. Foraging (A) and migrating (B) locations of 50 female (red dots) and 17 male (blue dots) Red Phalarope within four regions (separated by dashed latitudinal lines with names on the right) in Beringia as classified by hidden Markov models using predicted locations generated every 8 hours using continuous-time random walk state-space models for individuals during southward migration (data from 2017–2020). Red Phalarope breeding (pink shading) areas from BirdLife International and Handbook of the Birds of the World (2021).

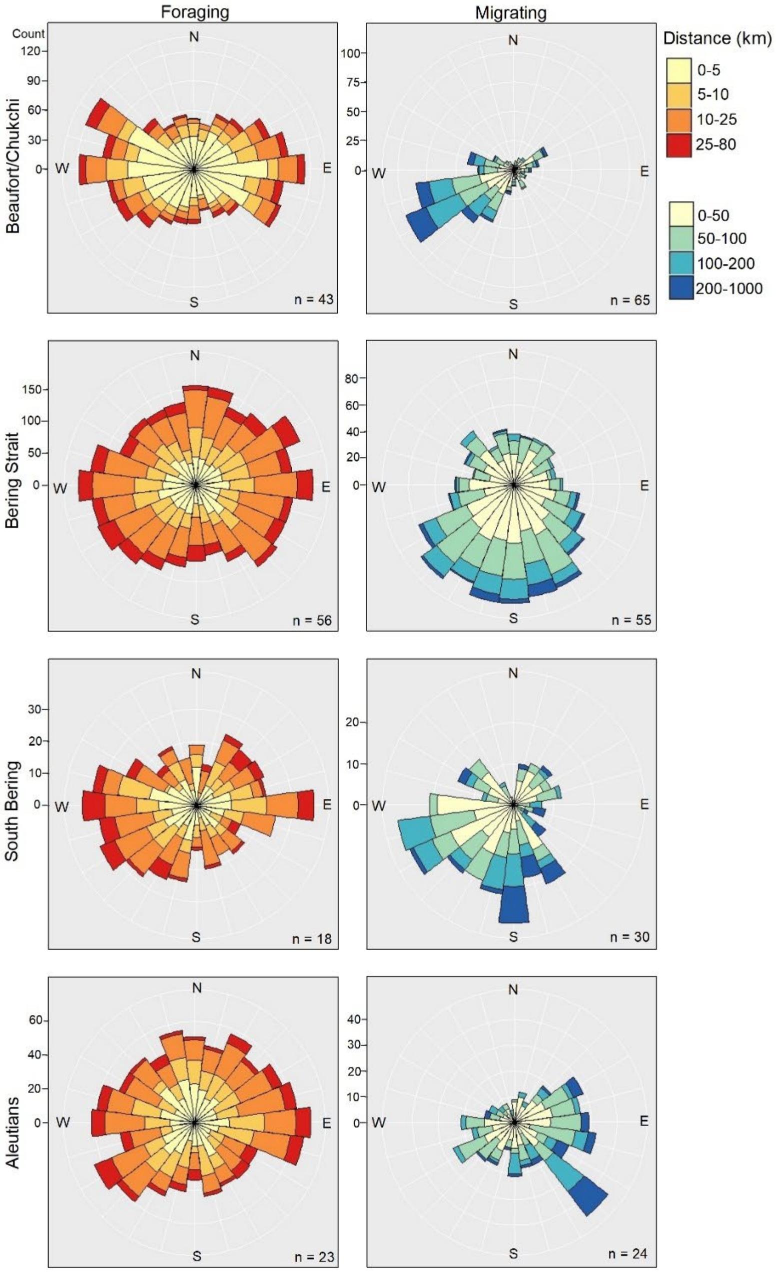

Figure 6. Counts of directional movements within distance categories between consecutive locations for foraging (left panels) and migrating (right panels) Red Phalaropes during southward migration through four regions in Beringia (see Figure 5; data from 2017–2020). n = the total number of individuals. All data presented in this figure are based on predicted locations generated every 8 hours for individuals using continuous-time random walk state-space models with foraging and migrating states classified by hidden Markov models. Directional bearings between consecutive locations were calculated using the Argosfilter package (Freitas 2013) in R (R Core Team 2021). See Figure 1 for locations of regions.

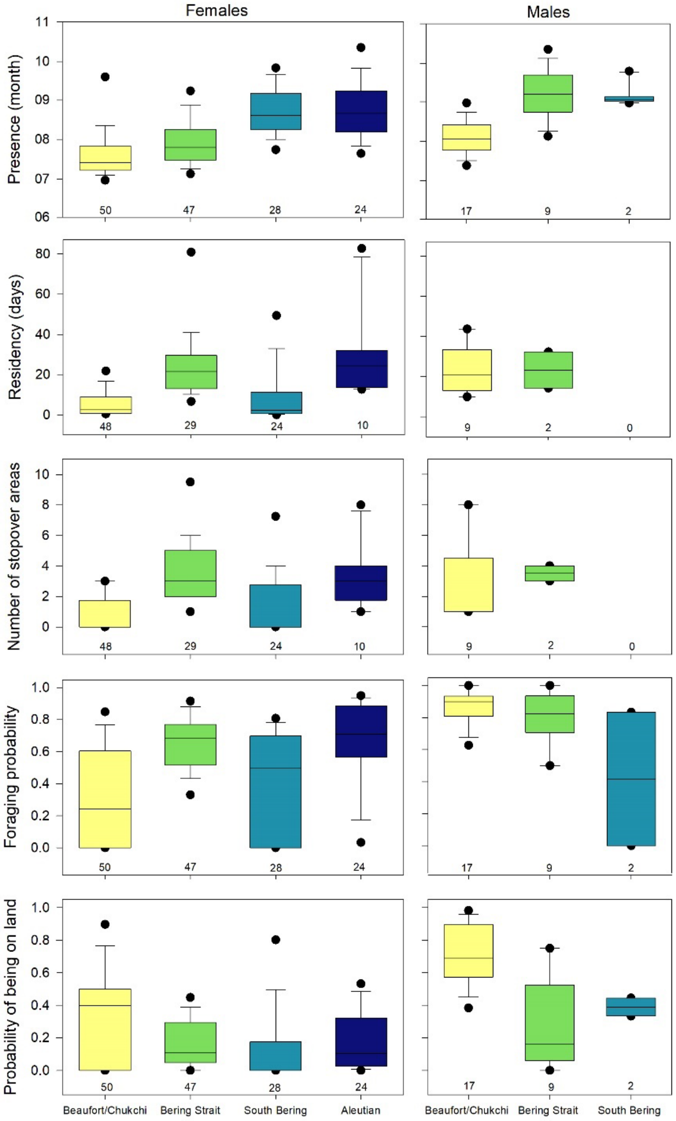

Figure 7. Spatio-temporal patterns of presence of male and female Red Phalaropes during southward migration in four regions of Beringia (see Figure 5; data from 2017–2020). Residency (in days) was calculated as the total number of 8-hour locations regardless of state within a region divided by 3. Residency and number of stopover areas were restricted to individuals with complete tracks in a given region; presence, foraging probability, and probability of being on land were calculated from all individuals in a given region (sample sizes included at the bottom of each graph). All data presented in this figure are based on predicted locations generated every 8 hours for each individual using continuous-time random walk state-space models with foraging and migrating states classified by hidden Markov models. Boundaries of the box plots represent the 25th and 75th percentile, the line within the box represents the median, error bars represent the 10th and 90th percentiles, and circles represent the 5th and 95th percentiles.

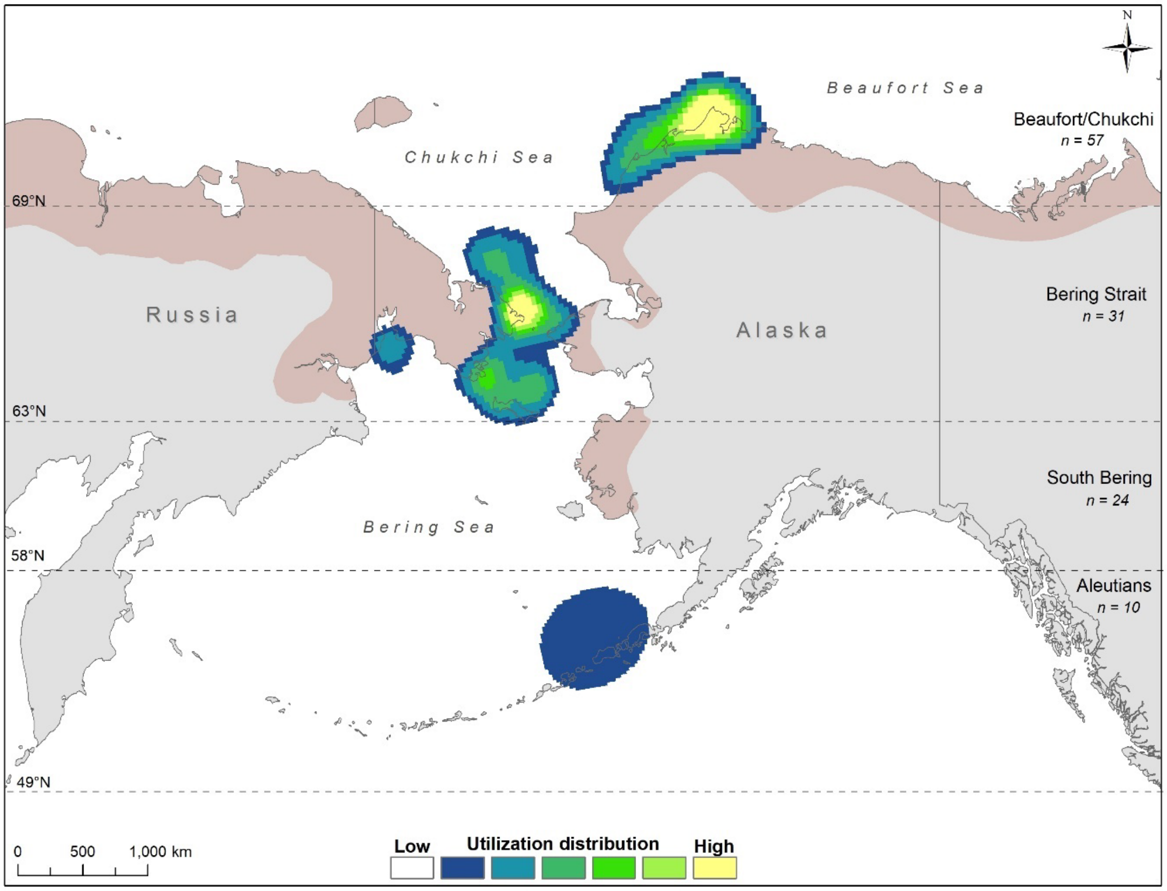

Figure 8. Kernel utilization distribution of Red Phalarope foraging locations as classified by hidden Markov models during southward migration in Beringia based on data from 2017–2020 (*n* = 48 females, 9 males). Kernel utilization distributions were estimated for each region separately (as indicated by dashed latitudinal lines; region names and sample sizes are given on the right side) using predicted locations generated every 8 hours for individuals with a complete track through a region using continuous-time random walk state-space models. All regional utilization distributions were standardized by the number of individuals with complete tracks within each region of Beringia. Red Phalarope breeding (pink shading) areas from BirdLife International and Handbook of the Birds of the World (2021).

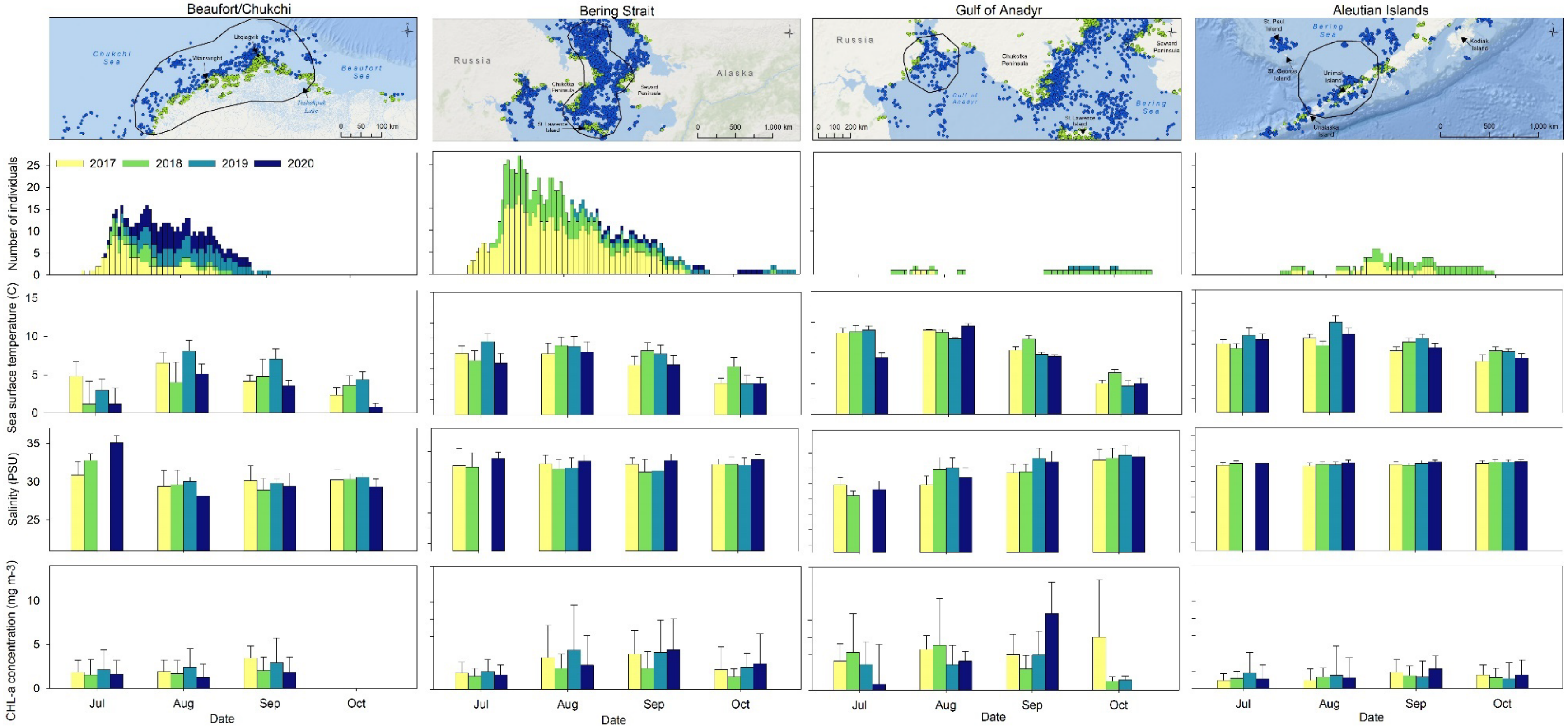

Figure 9. Characteristics of the Beaufort/Chukchi, Bering Strait, Gulf of Anadyr, and Aleutian Islands high-use areas for Red Phalaropes during southward migration in 2017–2020, including on-land (green dots) and at-sea (blue dots) foraging locations, seasonal variation in the number of foraging individuals, mean (± SD) monthly sea surface temperatures, mean (± SD) monthly sea surface salinity, and mean (± SD) monthly chlorophyll concentrations. Foraging locations were classified by hidden Markov models using predicted locations generated every 8 hours using continuous-time random walk state-space models. Maps in top panels were created using ArcGIS Online Ocean Basemap; sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors. Missing bars for sea surface temperature, sea surface salinity, or chlorophyll concentrations indicate no oceanographic data were available.

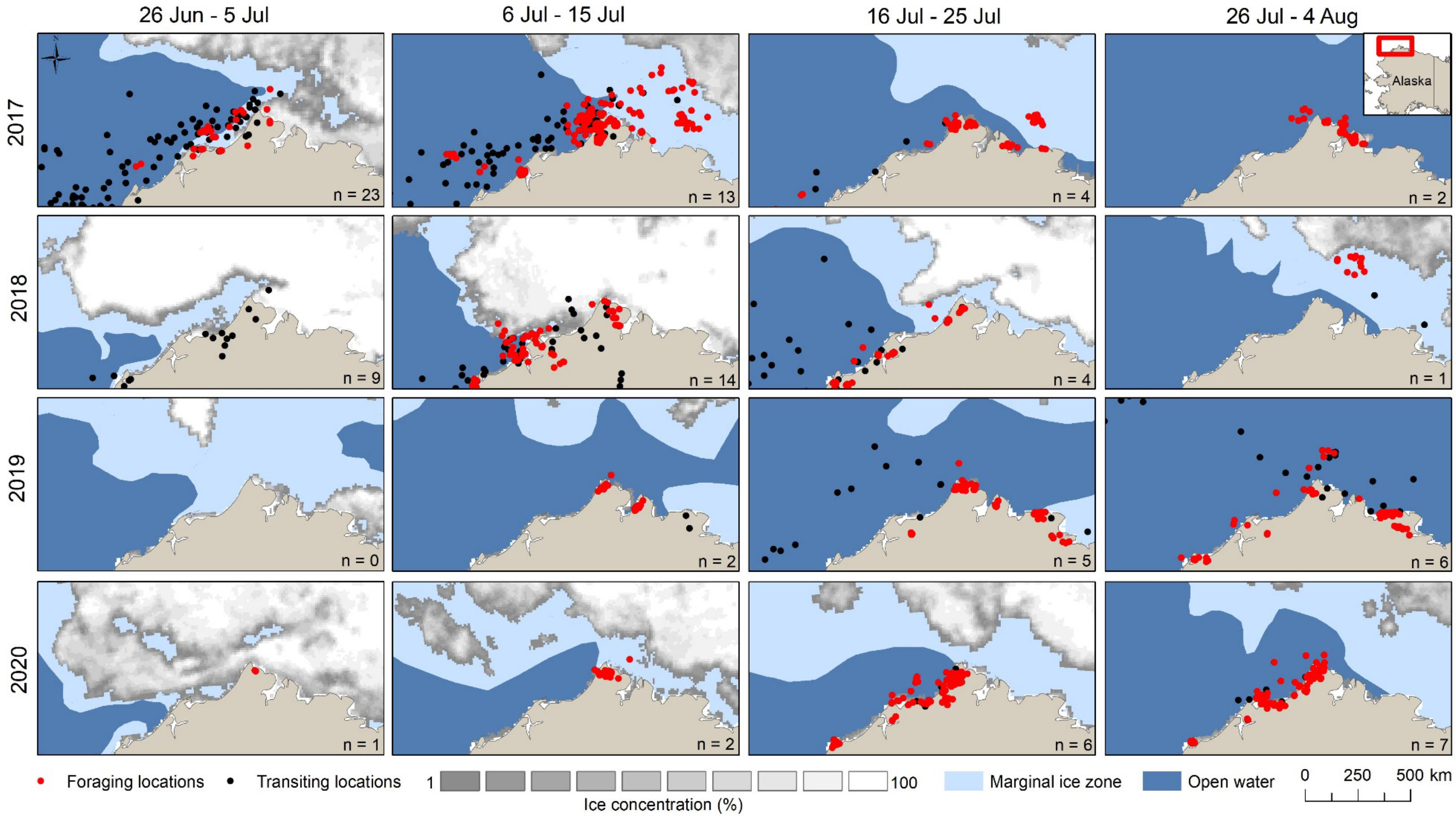

Figure 10. Estimates of daily sea ice concentration (grey-scale) and marginal ice zone (light blue) from late June to early August 2017–2020 in relation to foraging and migrating locations of female (top two series of panels) and male (bottom two series of panels) Red Phalaropes in the Beaufort and Chukchi seas as classified by hidden Markov models using predicted locations generated every 8 hours using continuous-time random walk state-space models for individuals during southward migration. Panels show Red Phalarope locations for each 10-day period, while estimates of daily sea ice concentration and the marginal ice zone are shown for only a single date in the middle of the period (e.g., 1 July for period 26 Jun–5 Jul). The number of individuals with locations displayed is shown on the bottom right of each panel.

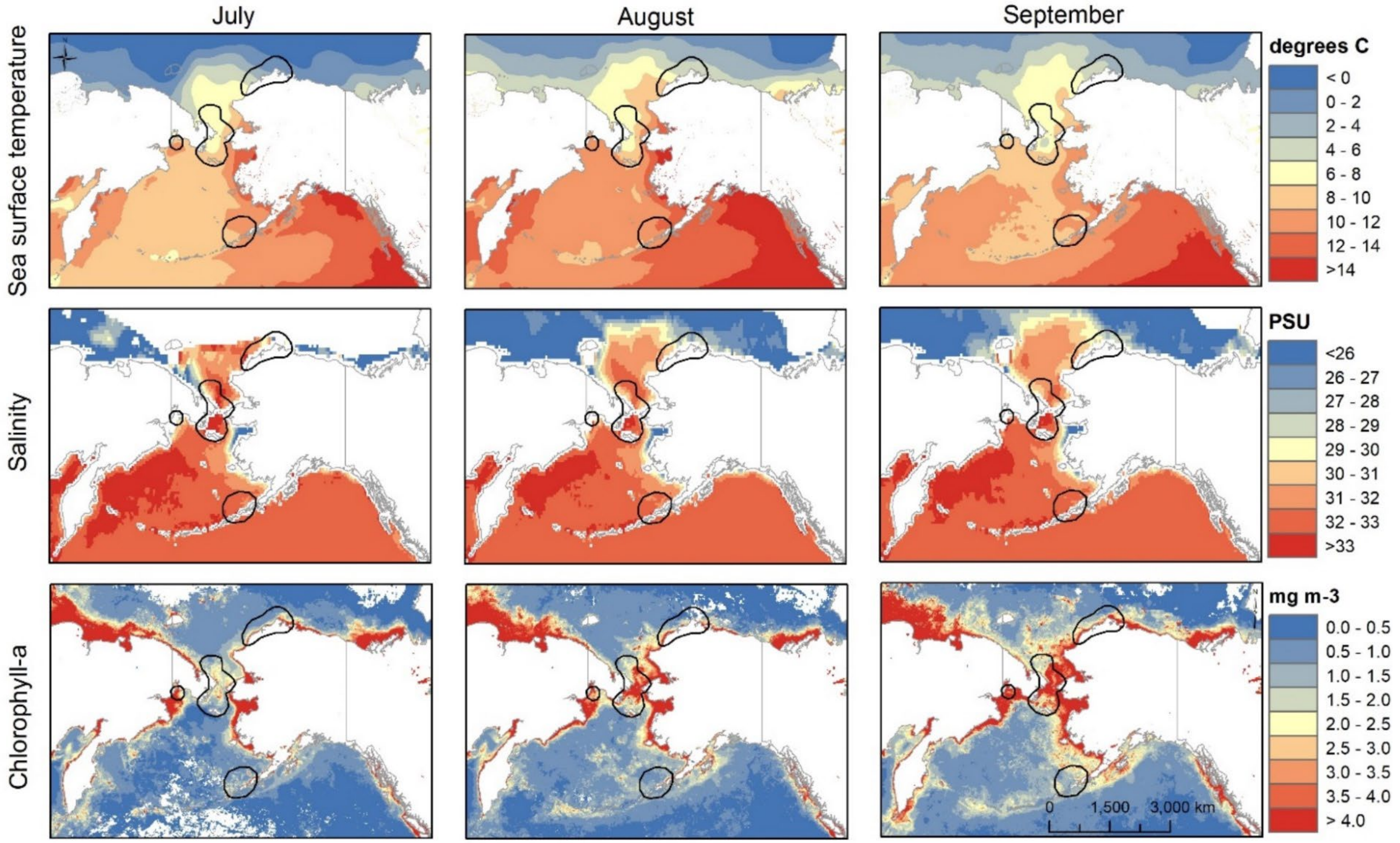

Figure 11. Average monthly oceanographic conditions for 2017–2020 in relation to high-use areas (black outlined areas) as determined from kernel utilization distributions of foraging locations (see Figure 8) of Red Phalaropes during southward migration in Beringia. Note that chlorophyll-a values (mg m^{-3}) estimated with satellite data may be upwards biased in nearshore areas, especially in areas with high turbidity from river inputs such as along the Alaska coastline (Chaves et al. 2015, Park et al. 2021).

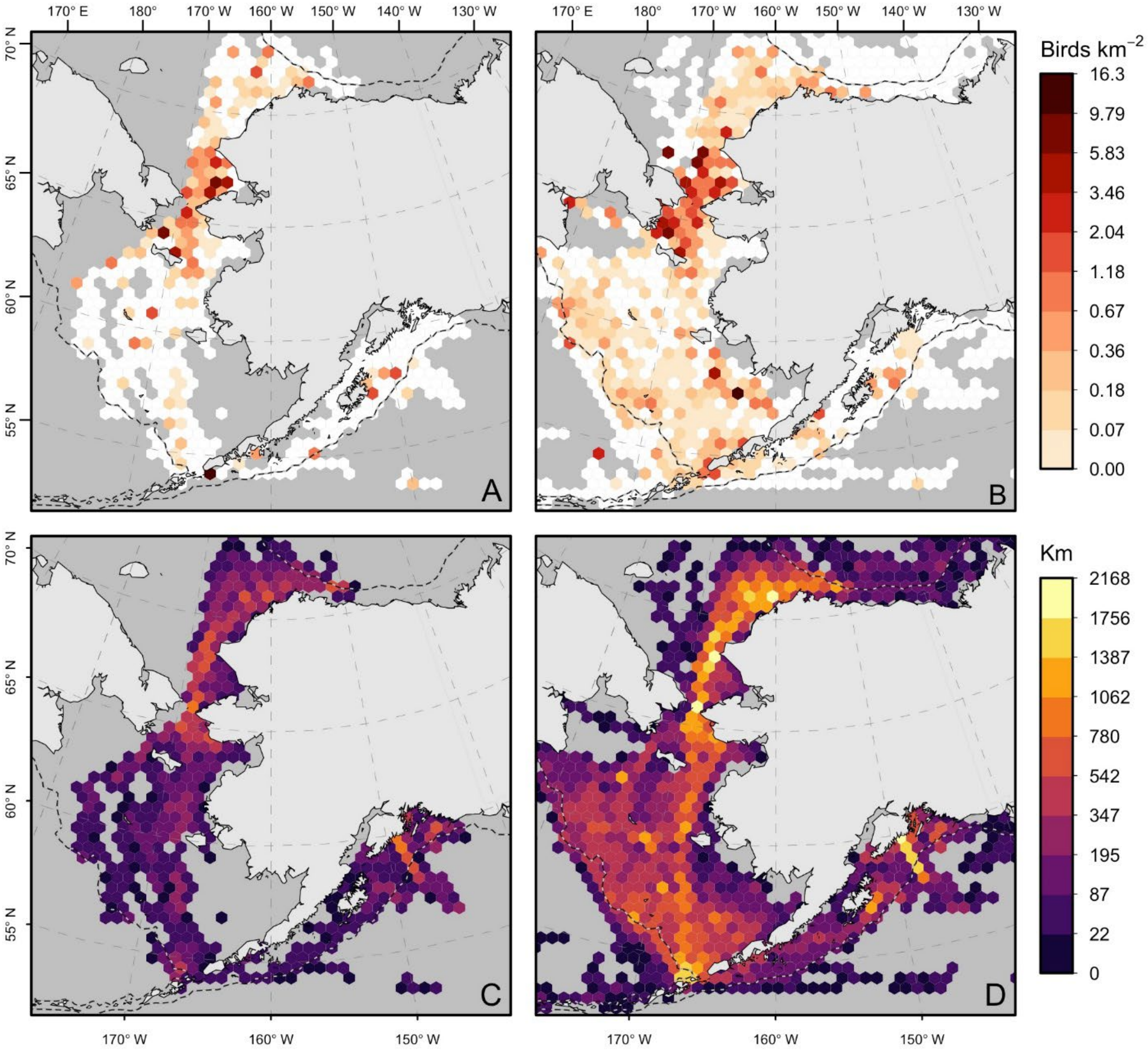

Figure 12. Red Phalarope densities (birds km^{-2}; A, B) and survey effort (km surveyed; C, D) within Beringia estimated within 30-km hexagonal cells from U.S. Fish and Wildlife vessel-based surveys (see Kuletz et al. 2019 for details) between June and October 2017–2020 (year corresponding to tagging studies; A, C) and in 2006–2021 (all available years of data; B, D). Red Phalarope densities are means of 3-km segments within each 30-km hexagonal cell; white cells indicate sampling effort, but no birds observed.

Supplemental Information

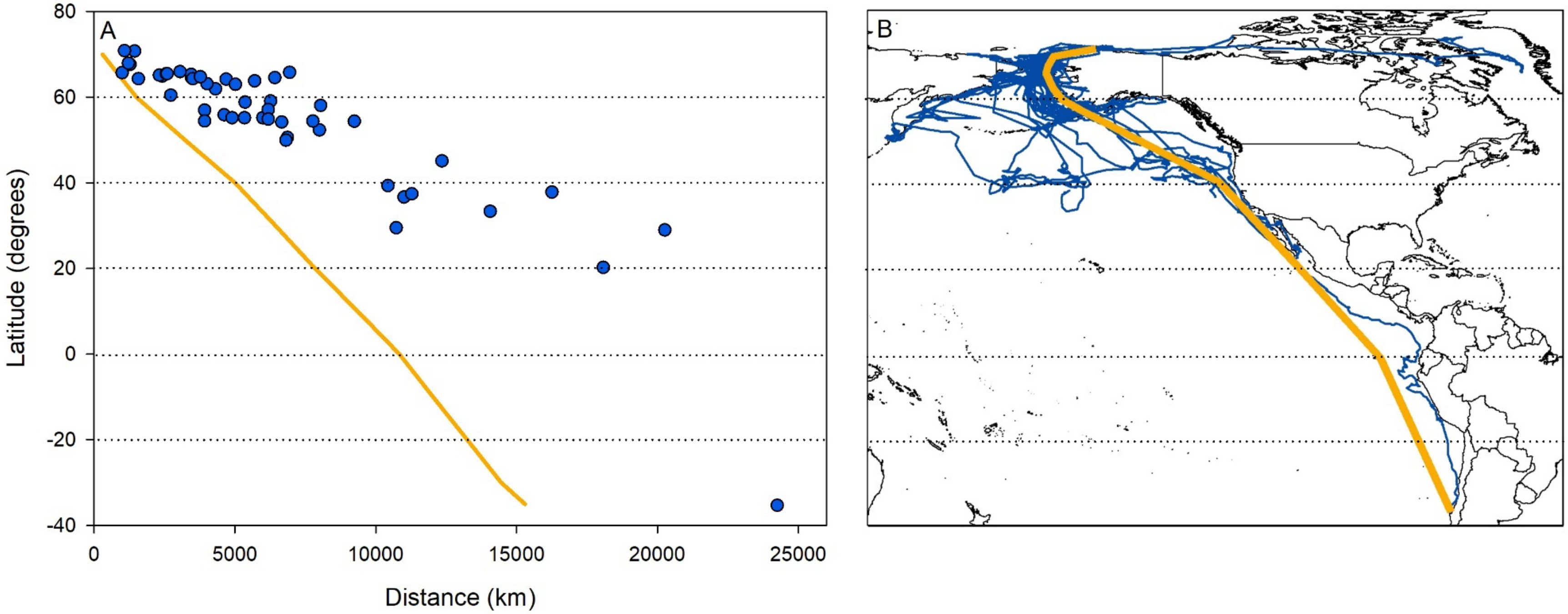

Figure S1. A) total distance traveled by post-breeding Red Phalaropes (i.e., distance from the last breeding location to the wintering grounds or to the last migration location received) from 2017–2020 in relation to an individual's most southerly latitude (i.e., minimum latitude; blue dots). For comparison, distances by latitude along a hypothetical migration route are displayed (orange line). The hypothetical migration route was created to show the minimum travel distance while maintaining the general migration pattern. B) individual migration routes of Red Phalaropes during southward migration (blue lines) and the hypothetical migration route (orange line). In both panels, predicted Red Phalarope locations (i.e., blue dots and lines) were generated every 8 hours for individuals using continuous-time random walk state-space models and were restricted to individuals captured at Utqiaġvik, Alaska, where the majority of birds were tagged.

Appendix 6: Seabird-vessel traffic risk analysis for Alaska's marine regions.

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Manuscript: Sullender Seabird-vessel Risk Analysis, draft

Introduction

The Alaskan Arctic is a nexus of wildlife migration routes as well as international maritime commerce (Arctic Council 2009, Humphries and Huettmann 2014). Globally significant populations of seabirds rely on Alaskan coastal areas and marine waters for breeding, foraging, and overwintering (Denlinger 2006). Marine waters in the sub-Arctic and Arctic oceans have historically been inaccessible to vessel traffic, but recent declines in sea ice have lengthened the duration of the shipping season and expanded the spatial coverage of large vessel routes (Arctic Council 2009, Silber and Adams 2019). In Alaska, major shipping routes run through the Aleutian Islands, and increasingly, through the Bering Strait and into the southern Chukchi Sea (https://www.pewtrusts.org/en/projects/protecting-life-in-the-arctic/priorities/shipping). As vessel traffic has increased, so too has seabird exposure to the myriad environmental risks posed by large ships, including vessel collisions, oil spills, underwater noise pollution, discharges of pollutants, and displacement from foraging grounds. Given the recent changes in both vessel traffic and potential changes in seabird distribution in the Pacific Arctic (Kuletz et al. 2020), managers, including federal, state, and tribal entities, require a more complete and current understanding of areas with elevated risk to these trust resources.

To address this information gap and management need, we conducted a pilot study to map seabird risk to vessel activity in Alaska's marine waters, with a focus on the northern Bering and Chukchi seas. This analysis integrates six years (2015-2020) of satellite vessel tracking data (Kapsar et al. 2022) with the most recent at-sea bird surveys (North Pacific Pelagic Seabird Database 3.0, 2007-2019; Drew & Piatt 2015) into an original risk assessment. We build on peer-reviewed methods (Renner & Kuletz 2015) to identify regions and seasonal periods of concern, to directly inform management measures.

Following the broad scale examination of total seabird activity throughout most of Alaska's oceans, we conducted a focused analysis for the northern Bering-Chukchi Sea region for three taxa groups: sea ducks (members of family Anatidae – eiders (*Somateria* spp), scoters (*Melanitta* spp), and long-tailed ducks (*Clangula hyemalis*); *Aethia* auklets (least (*A. pusilla*), crested (*A. cristatella*), and parakeet (*A. psittacula*) auklets; shearwaters (*Ardenna* spp, but > 99% short-tailed shearwater, *A. tenuirostris*). All three groups have been documented as being subject to collisions with vessels due to their attraction to lights (Schwemmer et al. 2011, Ryan et al. 2021, review in Rojek 2021, unpublished data, U.S Fish and Wildlife Service). Auklets and shearwaters are the two most abundant taxa in the northern Bering-Chukchi Sea region during summer and fall (Gall et al. 2017, Kuletz et al. 2015). This focal region is also a critical migration pathway for sea ducks (Oppel et al. 2008, 2009, Lovvorn et al. 2015), including two species listed under the Endangered Species Act, the Steller's eider (*Polysticta stelleri*) and spectacled eider (*Somateria fischeri*). In addition, seabirds and sea ducks are valued species harvested by local indigenous communities (Naves et al. 2021).

Methods

We derived vessel traffic data from over 600 GB of satellite Automatic Information System (AIS) signal archive purchased from exactEarth Ltd. Through an iterative process of data validation, spatial interpolation, and attribute-based aggregation (Kapsar et al. 2022; Fig. 1), we distilled this large volume of data into a lattice of 25 km (625 km^2) hexagons (n = 6,553). Using these hexagons, we grouped total seabird observations, and observations for three taxonomic groups (sea ducks, auklets, shearwaters), by season. We weighted seabird densities by survey effort, using a minimum effort threshold of 1% to remove hexagons that did not have a sufficient portion surveyed. Both vessel traffic and effort-weighted seabird densities were reclassified into three categories: below-average, above-average, and greater than above-average, + 1 standard deviation (per Renner and Kuletz 2015). We then classified risk into four categories based on the classifications of vessel traffic and seabird density. Low risk areas had below average seabird density and vessel traffic. Medium risk areas had above average vessel traffic or seabird density. High risk areas experienced above average vessel traffic and seabird density, while very high risk areas experienced seabird densities and vessel traffic greater than one standard deviation above average.

For each season, we examined risk for total birds (all species combined) for marine waters of Alaska from the northern Gulf of Alaska to the western Beaufort Sea. Additionally, we focused our analyses on the Bering Strait region in order to better capture emerging risk factors given observed increases in open-water season and extent, as well as resulting increases in vessel traffic. After all bird and vessel densities were calculated, we extracted only hexagons partially or entirely north of 60°N (excluding Cook Inlet). For the summer season, this Bering Strait subset consisted of 750 of 1687 total hexagons with sufficient survey effort, and the fall season subset comprised of 590 of the 1296 total hexagons. From this subset, we reclassified vessel traffic and effort-weighted seabird densities using the same three categories (below-average, above-average, and greater than above-average + 1 standard deviation).

We performed all calculations for summer (June, July, and August) and fall (September, October, and November) seasons. Summer corresponds to high seabird abundance in Pacific Arctic waters, as birds attend breeding colonies and forage in offshore waters. While daylight is nearly constant in Alaska during summer, storms and dense fog, common in offshore areas of Alaska, can increase seabird-vessel collisions (Merkel and Johansen 2011, Gjerdrum et al. 2021). Fall is a period of migration, with large numbers of marine birds traveling through ‘choke points’ like the Bering Strait and Unimak Pass (Oppel et al. 2008, 2009, Kuletz et al. 2015), as they migrate south prior to winter. Fall is also a period of increasing darkness, which increases collision risks to seabirds attracted to vessel lights (Merkel and Johansen 2011).

Results

Broad-scale patterns of risk

During summer (June–August), areas of highest risk to seabird-vessel interactions were concentrated around Unimak Pass in the Aleutian Islands and the northern coast of the Alaska Peninsula. In addition, there were isolated highest-risk cells over the underwater Pribilof Canyon in the southern Bering Sea shelf edge, and near Cape Navarin on the Russian coastline (Fig. 2). The Cape Navarin area also had a large halo of moderate and high-risk cells. Other areas of moderate to high risk included cells near the ports of Homer, Kodiak, Utqiaġvik, and Prudhoe Bay, and throughout Bering Strait. During fall (Fig. 3), the number and spatial extent of highest risk cells were reduced in the Bering and Chukchi seas, but remained high in Unimak Pass, and to lesser extent, in the Bering Strait. In contrast, moderate to high-risk areas increased or remained active during fall in some areas of the northern Gulf of Alaska. There was insufficient seabird data for analysis of Russian waters during fall.

Risk to focal taxa in the Northern Bering – Chukchi Sea

Sea ducks. - During summer, sea ducks had few sites of elevated risk (Fig. 4), with isolated highest-risk cells near the ports of Utqiaġvik and Prudhoe Bay, and high risk areas between Wainwright and Utqiaġvik, and the west side of Bering Strait. The number of cells of high risk greatly increased for sea ducks during fall, extending from Pt. Barrow throughout Chukchi coastal regions and the eastern middle shelf of the northern Bering Sea (Fig. 4).

Aethia Auklets. – During summer, the only cells of highest-risk to auklets were located in Russian waters off Cape Navarin, with large areas of high-risk identified off the Chukotka Peninsula and throughout both sides of Bering Strait (Fig. 5). A smaller area of high-risk cells occurred near the Hanna Shoal region. During fall, highest-risk sites occurred north of Bering Strait in Russian waters, and over Hanna Shoal, with high-risk cells in the Chirikov Basin (northern Bering Sea), outer Hope Basin (southern Chukchi Sea) and from Icy Cape to Hanna Shoal in the northern Chukchi Sea (Fig. 5).

Shearwaters. – Risk to shearwaters was very low during summer, with a few high-risk cells between Wainwright and Pt. Barrow (Fig. 6). During fall, risk greatly increased, with high-risk cells occurring throughout the inner shelf waters from Pt. Barrow to Cape Thompson, and north and south of Bering Strait. Also in the southern Chukchi was a cluster of high-risk cells near Cape Krusenstern, northwest of Kotzebue Sound (Fig. 6).

Discussion

Unimak Pass is the major route for the ‘Great Circle’ shipping route and during summer, it also hosts some of the highest densities of seabirds in the world (Byrd et al. 2005, Renner et al. 2008). Similar to our results, a risk assessment for the Aleutian Islands (Renner and Kuletz 2015) also identified Unimak Pass as having the highest risk to seabirds among the Aleutian Islands and surrounding waters. The high-risk regions north of Unimak Pass along the continental shelf edge, and the isolated cell over the underwater Pribilof Canyon, likely reflect the intense commercial fishing occurring in these areas, in addition to seasonally high seabird densities. The moderate to high-risk areas off Cape Navarin reflect commercial fishing and shipping traffic from the Russian port located there.

The Bering Strait also has moderate to high exposure of seabirds to vessel traffic, despite having much less vessel traffic than areas farther south. The Bering Strait region includes islands with large seabird colonies, each comprised of millions of nesting birds (USFWS 2014), as well as the presence of migratory species that don’t breed in Alaska or that travel to the Chukchi Sea in late summer to forage (Kuletz et al. 2015, Gall et al. 2017). Bering Strait was also recognized as a region of high risk in an analysis of the entire circumpolar area, due to the overlap of seabirds and shipping activity (Humphries and Huettmann 2014). The Chukchi nearshore waters also host high seasonal abundances of seabirds (Kuletz et al. 2015), but currently have low vessel traffic, and the risk to seabirds along the ‘Chukchi Corridor’ is relatively low in the context of a statewide analysis (Fig. 2, 3).

The elevated risk on the Gulf of Alaska shelf occurs where most of Alaska’s human population lives and thus vessel activity occurs near many fishing and commercial ports in the region. The lack of sea ice (with exception of upper Cook Inlet) and human population means that vessel activity continues throughout the year. Seabird densities generally decline in most offshore waters from late fall through winter, but total bird densities remain high in many inshore waters, although species composition changes (Renner et al. 2017). Many species of marine birds increase in these nearshore waters, particularly sea ducks, which overwinter in bays and inlets of southcentral Alaska (Larned 2006, Renner et al. 2017), resulting in elevated seabird risk year-round. Our results suggest that seabird risk actually increases during fall in this region (Fig. 3), compared to summer months (Fig. 2).

Seasonal risks in the northern Bering and Chukchi seas

A more focused analysis of the northern Bering, Chukchi, and western Beaufort seas reveals clear differences in seabird risk between summer and fall, as well as among species groups. During summer, risk at sea is much lower for sea ducks, which may still be near nesting areas or inshore estuaries (Oppel et al., 2008, 2009). Risk is also low in summer for shearwaters, which spend early summer in the southern Bering Sea and do not reach full numbers in the Chukchi Sea until September (Gall et al. 2017, Kuletz et al. 2015).

Both the sea duck and shearwater groups show an increase in risk during their fall migration period. For sea ducks, areas of high risk extend from the western Beaufort Sea through the east side of the northern Bering Sea, whereas shearwater risk is primarily in the Chukchi Sea. An isolated area of high risk also becomes evident west of Kotzebue Sound (Fig. 6), suggesting that traffic from Kotzebue could warrant attention in the fall. The shearwater pattern likely reflects their later seasonal exodus from the Chukchi Sea, but could also partially be an artifact of a lack of data in the western Bering during fall. Based on short-tailed shearwaters fitted with geolocator tags, once they begin their southward migration they appear to head directly south and pass through the area quickly, and may travel via the western Bering Sea (D. Boyle and D. Sutherland, University of Melbourne, unpublished data), thus resulting in apparent low risk in the northern Bering Sea.

The *Aethia* auklets differ in their apparent risk from the other two seabird groups, with many high-risk areas identified during summer as well as fall. During summer, high-risk areas for auklets occurred near nesting colonies at Cape Navarin and in the Bering Strait region. Up to 6 million auklets nest on King Island and Little and Big Diomede islands (USFWS 2014), located in the strait. The small cluster of high-risk cells near Hanna Shoal in the northern Chukchi Sea is an area with high densities of crested auklets, which occupy the area to forage and molt from late summer through early fall (Gall et al. 2017, Kuletz et al. 2015, 2019). During fall, most high-risk areas for auklets shift north, reflecting the continued post-breeding migration of auklets into the Chukchi, which appears to overlap with vessel traffic in outer Hope Basin (mainly least auklets) and near Hanna Shoal (mainly crested auklets). These post-breeding staging areas may be indicative of heightened temporal and spatial sensitivity for auklets from disturbance to foraging and potential oil spills or contaminants, due to periods of flightlessness while molting.

Conclusion

Our analysis examined only the overlap of high seabird and vessel activity, which can be valuable when evaluating risk due to exposure to vessel accidents, oiling, and contamination. However, it does not yet include additional factors associated with an increase in seabird-vessel collisions, such as hours of darkness and frequency of storms and fog, all of which increase the probability of seabird-vessel or platform collisions (Merkel and Johansen 2011, Gjerdrum et al. 2021). These environmental factors could multiply the risk estimates for an area such as Bering Strait, which is an important corridor between the Chukchi and Bering seas for seabirds and marine mammals, as it is for shipping activity. As sea ice decreases and shipping occurs into the darker months of fall and winter, such risks could increase for birds using those areas, including endangered eiders that winter in the northern Bering Sea (Petersen et al. 1999). Our results also illustrate the value of conducting focused risk assessments for specific regions, which can highlight seasonal and spatial components of risk not evident at broad spatial scales.

Acknowledgements

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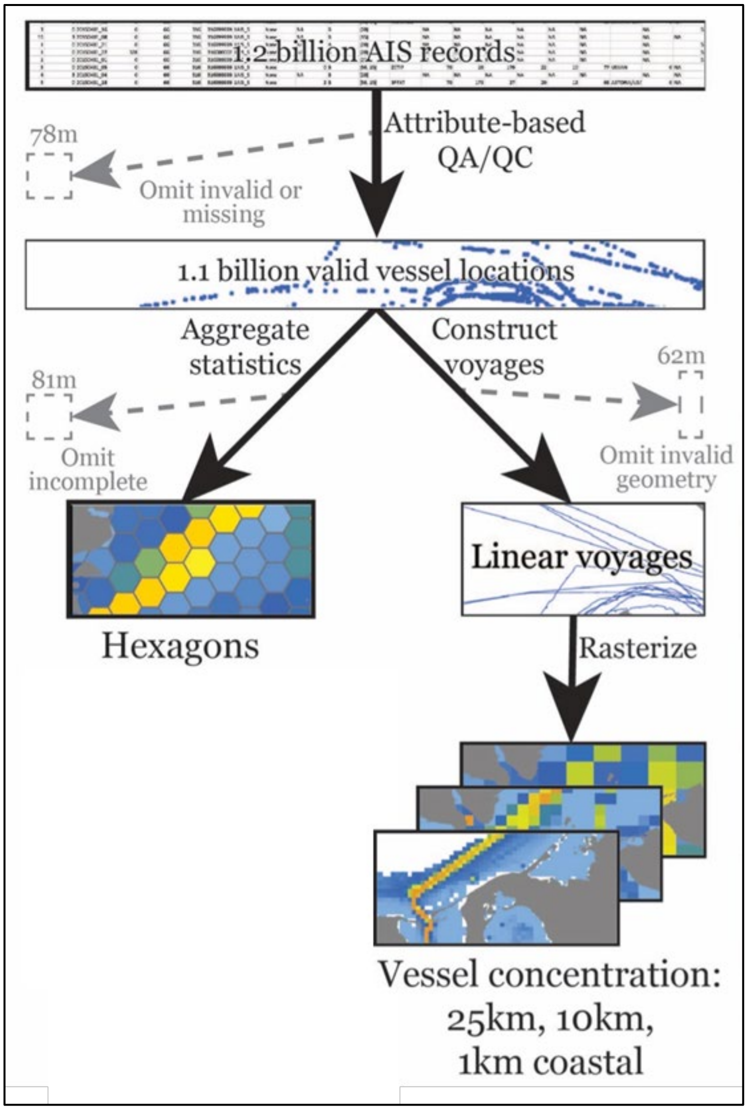

Figure 1. Schematic of the processing of raw AIS vessel data into GIS coverage for risk analysis.

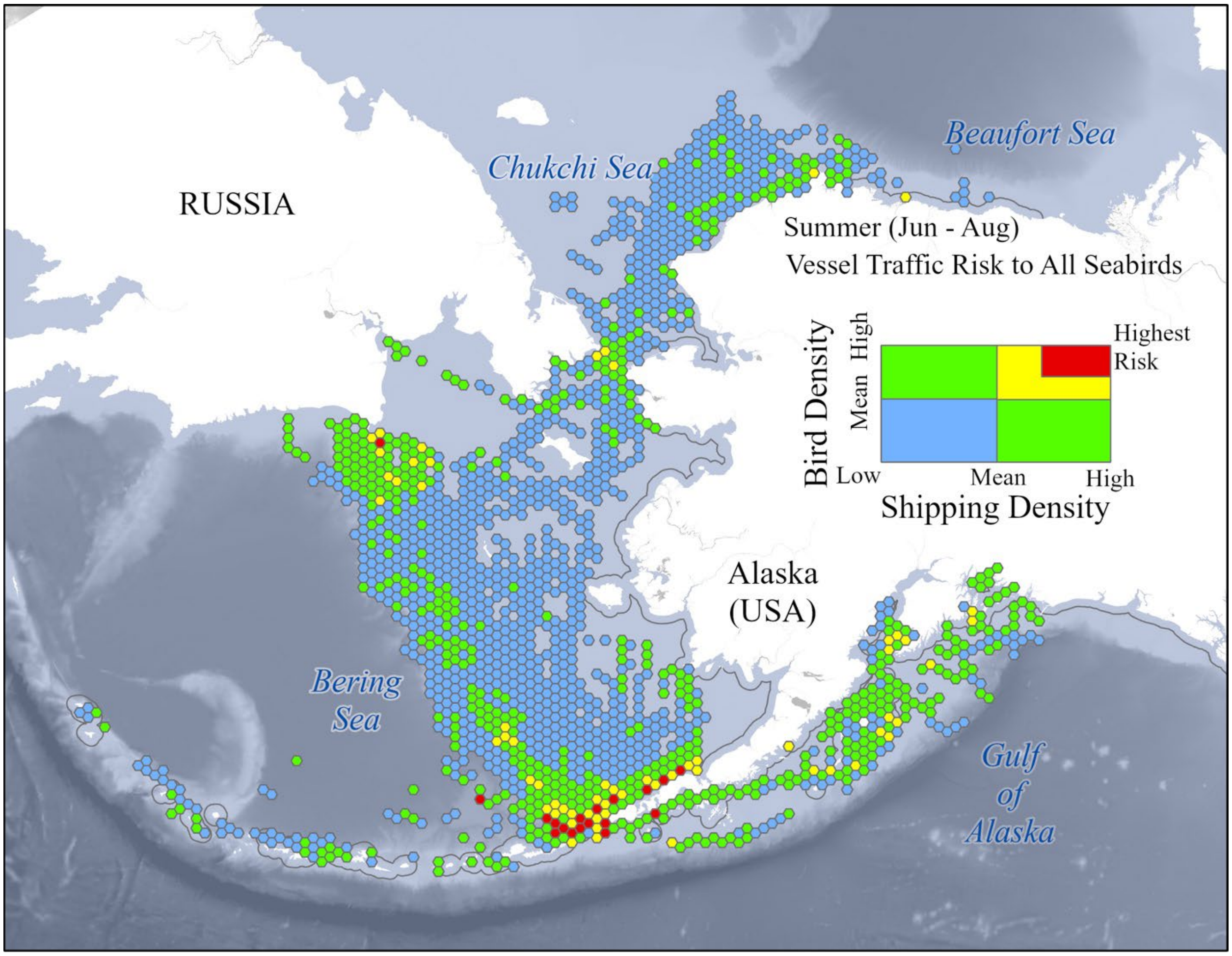

Figure 2. Summer (Jun – Aug) vessel traffic risk to total seabirds (all species combined).

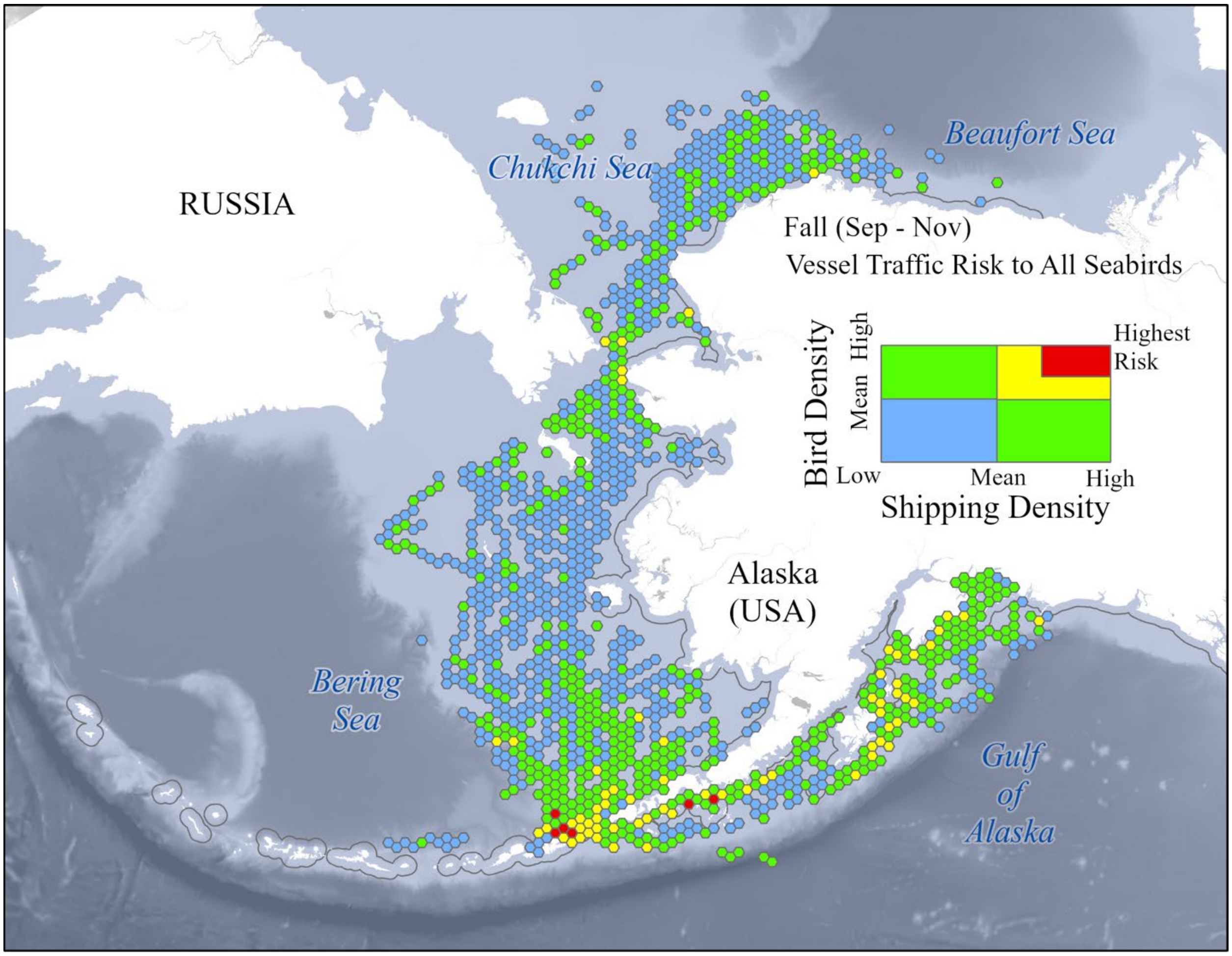

Figure 3. Fall (Sep – Nov) vessel traffic risk to total seabirds (all species combined).

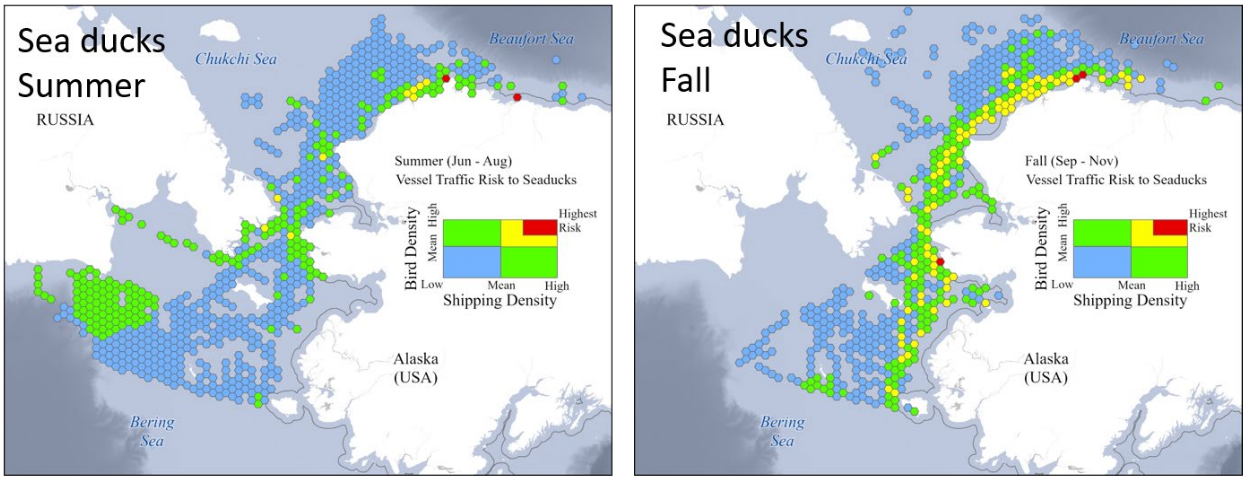

Figure 4. Vessel traffic risk to sea ducks during summer (left) and fall (right) in the northern Bering and Chukchi seas.

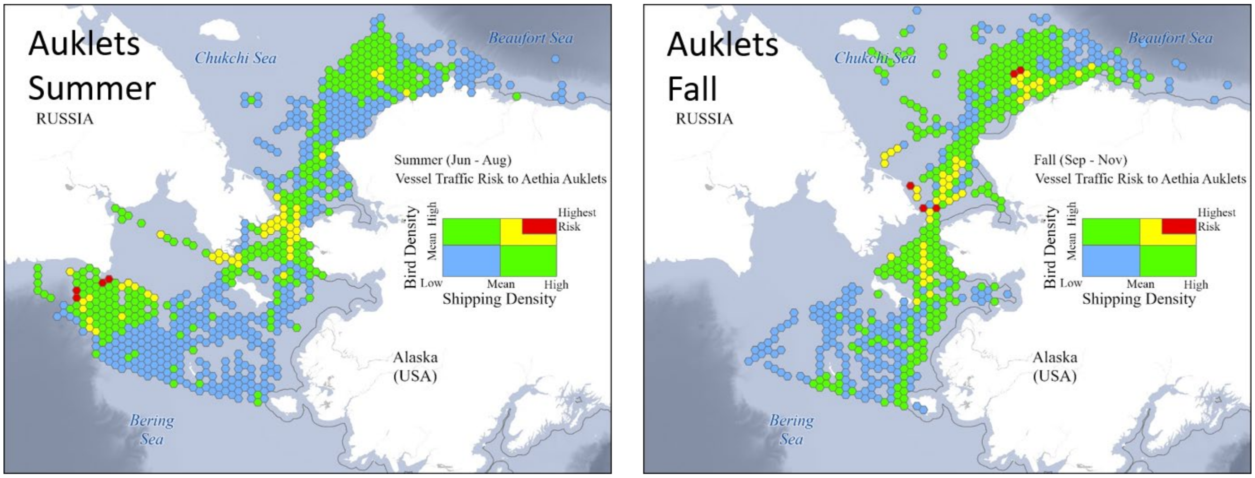

Figure 5. Vessel traffic risk to *Aethia* auklets during summer (left) and fall (right) in the northern Bering and Chukchi seas.

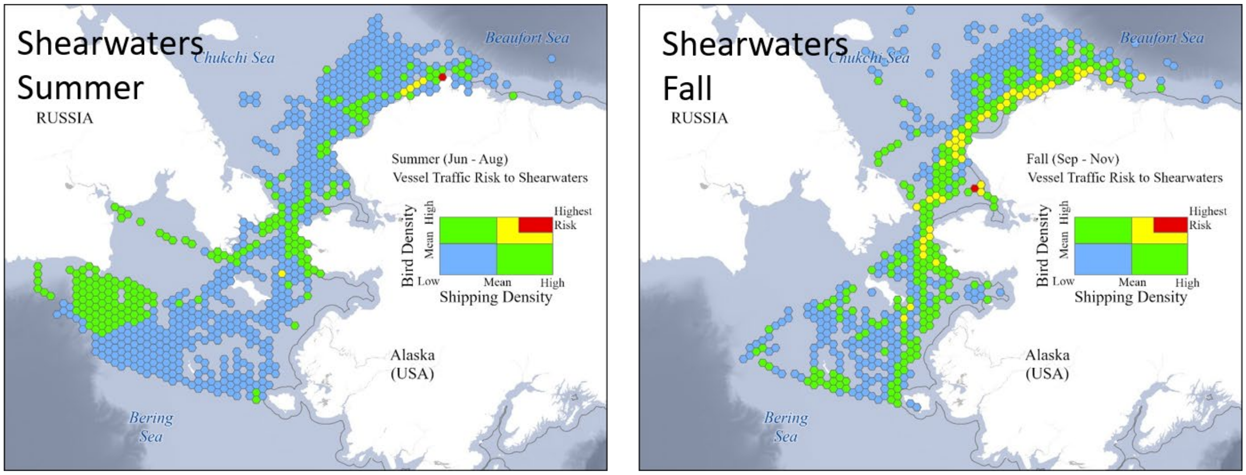

Figure 6. Vessel traffic risk to shearwaters during summer (left) and fall (right) in the northern Bering and Chukchi seas.

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Appendix 7: Application of joint dynamic species distribution models to at-sea survey data for seabirds in the Bering Strait and Chukchi Sea

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Report: VAST Analysis for N. Bering-Chukchi, 2022

Abstract

Mitigating risk to migratory birds from energy development requires information on the distribution and abundance of seabirds in offshore waters. Seabirds are highly mobile, with species-specific seasonal migrations that result in variable patterns of distribution in space and time. In remote offshore marine areas, obtaining useful and current information on resources is difficult to achieve and maintain, both fiscally and logistically, necessitating collaborative effort (Danielson et al. 2022). We used seabird at-sea survey data (2007-2021) and new modeling techniques to develop spatio-temporal models of seasonal abundance and distribution of species in waters of the Pacific Arctic. For six species groups selected as model test cases, we identified fine-scale distributions for each year, using data collected during summer to early fall (June through September). Our approach uses the best available data and can be updated as new data are generated, providing up-to-date information for regions with existing or potential future oil and gas development.

Introduction

Seabirds spend most of their lives at sea, and because they are relatively easy to see and count from ships, it is possible to get spatially referenced and continuous sightings data. The resulting transect data are highly amenable to Vector Autoregressive Spatiotemporal modeling (VAST, Thorson 2019) for estimating distribution and abundance of seabirds. In Alaska, at-sea survey data has been used to identify and manage marine bird populations that may be vulnerable to offshore activities such as shipping or oil and gas development (Kuletz et al. 2015, Renner and Kuletz 2015, Smith et al. 2019). However, the strongly seasonal presence of seabirds in the Chukchi Sea and Beaufort Planning Area (and oceanographically and biologically connected waters of the northern Bering Sea), coupled with the spatial autocorrelation inherent in continuous vessel-based transect data, creates challenges to providing reliable information on seabird offshore distribution and abundance. Here we demonstrate how a modeling approach first developed for fisheries (Thorsen et al. 2015, 2016) and more recently developed for ecosystem forecasting and population assessments using seabird survey data (Thorson et al 2021, Arimitsu et al. 2021) can be applied in the Pacific Arctic.

Methods

Study area: We examined seabird survey data from the northern Bering Sea, eastern Chukchi Sea, and Beaufort Sea, bounded by the International Date Line to the west, latitude ~62ºN to the south, latitude ~72ºN to the north, and longitude ~ 146ºW to the east. The study area is influenced by three water masses - Anadyr Water, Bering Shelf Water, and Alaska Coastal Water, which advect nutrients, heat, and plankton biomass northward from the Bering Sea and through the narrow Bering Strait (Coachman et al. 1975; Weingartner 1997, Weingartner et al. 2005). The currents enrich at least four areas with high marine productivity: Chirikov Basin (between Lawrence Island and Bering Strait), Hope Basin (between the strait and Cape Lisburne), Hanna Shoal (a 40m deep plateau in the northern Chukchi), and Barrow

Canyon (roughly parallel to the Chukchi coast from Wainwright to Point Barrow, where it empties into the Arctic Basin) (Eisner et al. 2013, Dunton et al. 2017, Weingartner et al. 2005).

Data selection and treatment: We modeled spatiotemporal variation in seabirds using survey data contained in the North Pacific Pelagic Seabird Database (NPPSD), a publicly available repository for at-sea survey data of seabirds in Alaska (Drew and Piatt, 2015). NPPSD includes contributions from Department of the Interior agencies such as the U.S. Fish and Wildlife Service (USFWS) and U.S Geological Survey, industry funded studies (conducted by ABR, Inc., Fairbanks, AK), and other non-governmental entities. The data, derived from strip transect surveys, were used to calculate species-specific density (birds/km^2) using standard USFWS protocol (see Kuletz et al. 2008 and Kuletz et al. 2022 for details). For the NPPSD and for this analysis, transects were summarized into 3.0−3.3 km long transect segments as the sample unit (Fig. 1).

We used survey data from 2007 to 2021 and the months of June through September; these months are mostly ice-free in the study region, although the earlier years had areas of pack ice or broken ice (the marginal ice zone) during June and sometimes July. These months also encompass most of the breeding season for locally nesting seabirds and is the period when seabirds have peak numbers, including migrants that nest outside of the study area (Kuletz et al. 2015, 2019). Though sampling effort was uneven across space and time (Fig. 1), we accounted for this variation in our modeling approach (see analysis section below).

We modeled species distributions of six representative taxa: shearwaters (primarily short-tailed shearwaters *Ardenna tenuirostris* and to a lesser extent sooty shearwater *A. grisea*), black-legged kittiwake (*Rissa tridactyla*), crested auklet (*Aethia cristatella*), least auklet (*A. pusilla*), murres (common murre *Uria aalge* and Thick-billed murre *U. lomvia*), and tufted puffin (*Fratercula cirrhata*).

Analysis: To model interannual variation in seabird distribution and abundance we used Joint Dynamic Species Distribution Models (JDSDM) as implemented in VAST v.3.9.0 with R version 4.1.2 (R Core Team, 2021). JDSDMs incorporate community dynamics (species' associations) to inform density predictions across space and time (Thorson et al. 2016). JDSDMs have been found to have greater predictive power than univariate models of seabird transect data in other study regions (Arimitsu et al. in review). Seabird count data were modeled with a Poisson-link delta model using a Gamma error distribution with an offset of effort (area surveyed, km^2) (Thorson, 2018, 2019). This approach jointly models encounter rates using presence/absence data and positive density using non-zero count data. We applied a factor-model decomposition to model covariation among species (Thorson et al., 2016), with two spatial and spatio-temporal factors, in order to reduce model complexity, increase interpretability, and reduce model run times compared to full rank models. To account for within-season variability in density we estimated effects of month (June, July, and September) relative to August, which was the month that had the most survey effort and the highest numbers of birds. The model implemented with month as a catchability covariate effectively produces annual grid-based density predictions conditioned upon August density levels. Bias-corrected density predictions were extrapolated to a 25 x 25 km grid overlaid on the study region, from which area-weighted abundance for each grid cell was calculated. Standard error was calculated using a generalization of the delta method. Using predicted densities of all species combined, we used hierarchical clustering to identify general patterns in seabird densities. For details and equations, see Thorson (2016, 2018, 2019) and Arimitsu et al. (2021).

Results and Discussion

Survey effort. – Survey effort varied temporally and spatially among years (Fig. 1), although consistency was obtained for sampling lines along the Distributed Biological Observatory (https://www.pmel.noaa.gov/dbo/) and other large scale ecosystem studies that employed systematic sampling grids (see Kuletz et al. 2022 and Labunski et al. 2022). The northwestern portion of our study area had particularly good coverage from 2008-2013, due to intensive surveys by ABR, Inc. and USFWS, with both programs supported by Bureau of Ocean Energy Management. Coverage was lacking in the northern Bering Sea during 2008-2011, and was sparse throughout the study area in 2014. Low survey coverage in 2020 and 2021 was due to reduced field operations during the Covid-19 pandemic. Unequal coverage across space and time makes the VAST modeling approach especially suitable for maximizing available data to derive useable information on distribution and abundance of seabirds.

Distribution of common species. – Modeled densities for the six species or species groups we examined show species-specific patterns that were generally consistent among years, with some exceptions. Shearwaters migrate from Australian breeding grounds to forage offshore of Alaska during the Arctic summer, when they often comprise over half of all seabirds in the study region (Gall et al. 2017, Kuletz et al. 2019). Unlike most of the other seabirds examined here, shearwaters show highly fragmented distributions and considerable variability among years (Fig. 2). Not being tied to colonies or chick-rearing responsibilities, shearwaters have greater flexibility to search for prey and aggregate where availability is greatest. Shearwater 'irruptions' (observations of sudden sharp increase in numbers of migrating birds) are evident in 2017 and 2019, along with a northward shift in distribution during these warm years (Kuletz et al. 2020). Northward shifts of shearwaters in 2019 apparently co-occurred with die-offs due to starvation in the southeastern Bering Sea (Kaler and Kuletz 2022). There are a few areas of consistent high use, such as offshore of Cape Lisburne, the mouth of Barrow Canyon, and between Point Barrow and Harrison Bay in the Beaufort Sea. The latter two have recorded sporadic, but high densities of euphausiids (Okkonen et al. 2011), which is the primary prey sought by shearwaters in Alaska (Nishizawa et al. 2017). However, shearwaters can forage underwater as well as at the surface and are omnivorous in diet, thus increasing their ability to respond to fluctuations in the prey field.

Black-legged kittiwakes, which are primarily piscivorous but will feed on euphausiids as well, were more southerly in distribution than shearwaters, and had strong clustering around their breeding colonies along the Cape Thompson and Cape Lisburne coastline (Fig. 3). They were also abundant in Bering Strait (a travel corridor) and had pockets of activity in Beaufort Sea coastal areas similar to those used by shearwaters. The use of this area by both kittiwakes and shearwaters is indicative of multi-trophic level prey availability.

Crested auklet distribution showed consistently bifurcated aggregations over time, with a southern cluster of activity near nesting colonies in the Chirikov Basin and Bering Strait and a northern cluster in the Hanna Shoal region used post-breeding (Fig. 4). In the latter region, this diving planktivore is a dominant species, and is likely foraging on the abundant large-bodied copepods (*Calanus* and *Neocalanus* spp.) that occur there (Grebmeier et al. 2006, Ashjian et al. 2017). Least auklet had a similar distribution to that of the larger crested auklet during 2009-2012 and again in 2015-2017, but otherwise tended to be consistently farther south (Fig. 5). Least auklet densities were particularly low in the northern Chukchi Sea during 2019-2021, which is also when nesting attempts were reportedly low in the Chirikov Basin (Will et al. 2020).

Murre density was fairly even across the study area to just north of Icy Cape, and they showed the strongest and most consistent northern boundary of distribution, with an abrupt break that varied among years between Icy Cape (~70ºN) and Peard Bay (~71ºN) offshore and south of Hanna Shoal (Fig. 6). The one exception occurred during the cooler year of 2012, when murres were found farther north and east into the Beaufort Sea. Although evenly distributed, murres did have their highest densities near colonies in the Chirikov Basin, Bering Strait (the Diomede islands) and the coast between capes Thompson and Lisburne (Fig. 6). During the warm years of 2017-2019, murres appeared to shift farther offshore and west, although lack of coverage beyond the international dateline makes it difficult to interpret patterns near that artificial boundary.

Tufted puffins (Fig. 7) also showed a clear and consistent pattern of distribution, with a more southern distribution than murres. As with murres, puffin densities were highest near breeding colonies. Diving piscivores in general tend to forage closer to nest sites than surface foragers (Sigler et al. 2012), presumably because of their higher wing loading and energetically expensive flight, and the need to bring whole fish to their chicks multiple times daily.

Abundance. – Interannual variation in population estimates from 2007-2021, while preliminary, show species-specific patterns (Fig. 8). Based on these estimates, shearwater abundance was stable until 2015, after which they increased until 2020, with increasing variance as abundance increased. Black-legged kittiwakes show a general increase (with exception of 2020-2021), least and crested auklets generally increased until after 2017 (although crested auklets had high abundance in 2021), and murres show a general decline since 2012. Tufted puffin abundance was highly variable among years, which may be an artifact of its much lower encounter rate overall; modeling species of low abundance requires additional model development.

The monthly effects estimates identify differences in density levels across months (Fig. 9). With the exception of black-legged kittiwakes, the patterns fit what is known about their breeding or migratory phenology. For example, shearwaters have very low densities in early summer (below the August baseline) because they are still migrating through the Bering Sea, and numbers peak in September (Gall et al. 2017, Kuletz et al. 2019) before they head back south. Least and crested auklets have low densities offshore during July when they are often at colonies, and have peak densities during the August-September post-breeding period, when many migrate to the Chukchi Sea. The lower density levels of kittiwakes in August compared to other months is contrary to expected patterns and may be indicative of a high proportion of non-breeding birds early in summer, followed by another influx in September by post-breeding birds.

Spatial coherence. – Hierarchical clustering of modeled bird densities (all species) across the study area identified persistent spatial patterns over time (Fig. 10). Seabird density clusters appear to correspond to known oceanographic domains (from south to north): (1) the western Chirikov Basin and Bering Strait (light green), influenced by the rich Anadyr Current; (2) the eastern Chirikov Basin and Bering Strait (dark blue), influenced by the low productivity Alaska Coastal Current; (3) Hope Basin to Icy Cape (black); (4) the Hanna Shoal region (yellow), a high productivity area that includes Herald Shoal, the Central Current and portions of Barrow Canyon; (5) The Beaufort shelf (teal), a shallow region with mostly low productivity except near Pt. Barrow. The spatial consistency in bird densities among years suggests there are strong and persistent physical drivers structuring distributions of seabird communities, at this large scale, during summer.

There is evidence of structural breakdown of the northwestern cluster (Hanna Shoal region – offshore, from Wainwright to Point Barrow) during 2019-2021 (Fig. 10). While this might partly be due to low survey coverage in 2020-2021, a breakdown in cohesion was evident in 2019 as well, when coverage was high (Fig. 1). The Hanna Shoal region is occupied in summer and fall by a seabird community dominated by crested auklets, which do not breed on the Chukchi coast but migrate there from the Bering Sea post-breeding to feed and possibly undergo molt (Kuletz et al. 2019). Earlier surveys of the region indicate that this is a recent phenomenon, likely precipitated by reduction in sea ice, as surveys in the 1970s-1980s did not find large numbers of auklets there (Gall et al. 2017). The breakdown in cohesion in seabird densities in the Hanna Shoal region started in 2019 (and possibly 2018; Fig. 10), which was concurrent with an unprecedented marine heat wave wherein seabird distributions changed and auklet numbers were low in the Hanna Shoal region (Kuletz et al. 2020), and auklets failed to breed or were not successful (Will et al. 2020). There are also clusters of unrelated cells in this region in 2012; in this case, large areas of sea ice trapped on the shoals may have limited access to open water for diving planktivores like auklets.

Conclusion

Gridded density estimates of seabird species that span seasonal time-scales provide a means of understanding abundance and distribution patterns and associated drivers for areas being considered for energy exploration and development. These analyses also provide information on where more data are required to reduce uncertainty in abundance estimates. JDSDMs as implemented in VAST are uniquely suited for at-sea seabird survey data in the Pacific Arctic. VAST can be applied to non-randomized sampling designs with unequal sampling in space and time (Thorson et al. 2016, Thorson 2019). Moreover, the implementation of the computationally complex but efficient spatial smoother used in VAST is facilitated by the extensive and continuous ship-based observations. VAST is flexible and designed to handle survey-specific detection issues commonly encountered in biological data (Thorson 2019). Using species covariance to predict densities improves spatial mapping particularly for seabirds with similar foraging behaviors, habitat associations, or prey choices. Habitat variables in the marine environment are dynamic and can change in days, if not hours, thus incorporating community associations into models, rather than physical habitat variables directly, may be particularly useful for seabirds. Drawbacks to this approach are (1) it requires considerable computer power and program run times, and (2) methods to improve predictive capability for rare species are still in development. However, computing capability within the VAST modeling framework is under active development, and initial results using models that incorporate Tweedie distributions (which can implicitly model zeros) are encouraging. Future work will involve exploration of models that incorporate detection factors, model outputs that include gridded density predictions along with their uncertainty, and to explore potential drivers of species distributions.

Acknowledgements

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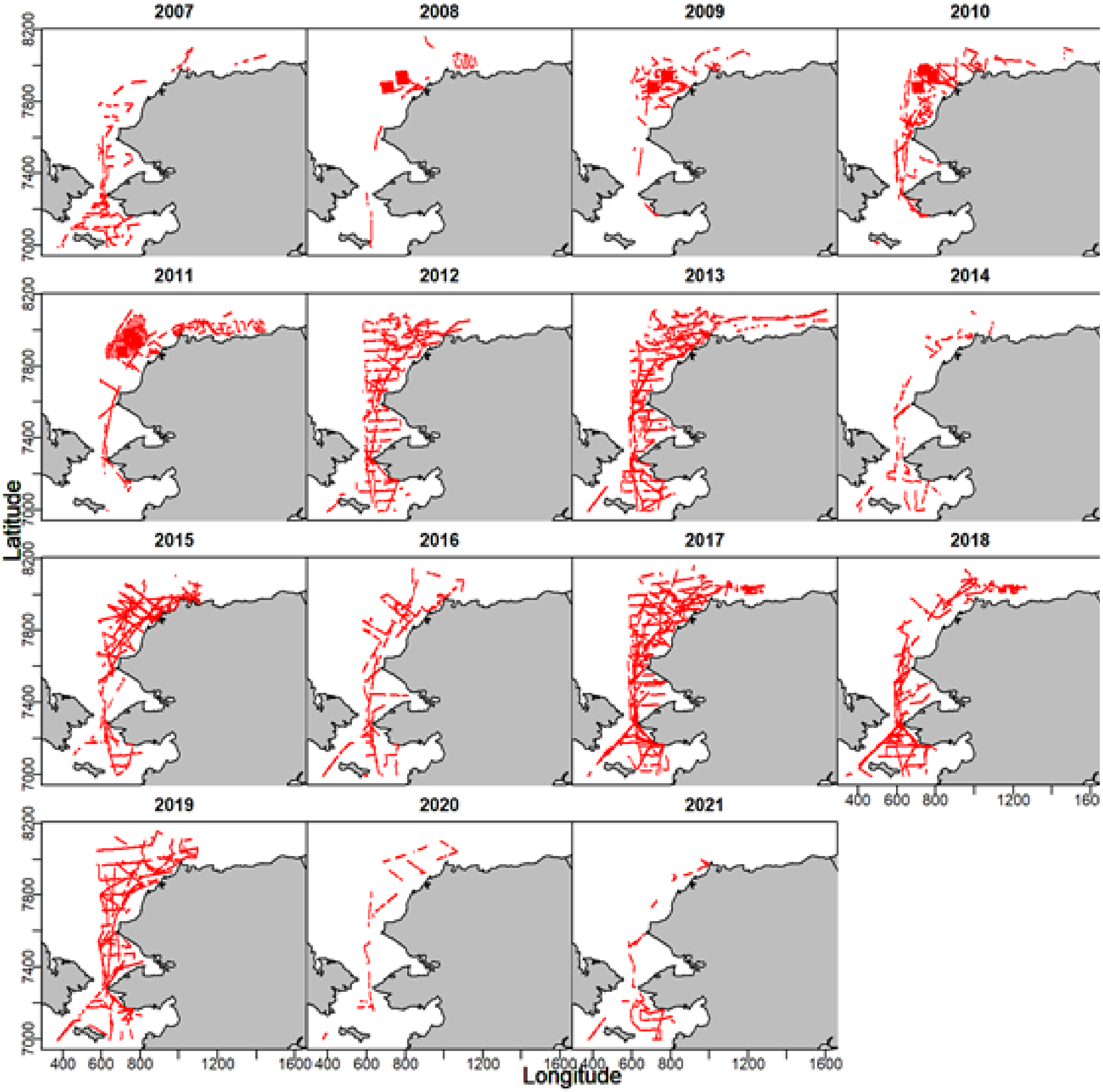

Figure. 1. At-sea seabird survey coverage (transect lines in red) for the Northern Bering, Chukchi, and Beaufort Seas study area during June-September 2007-2021.

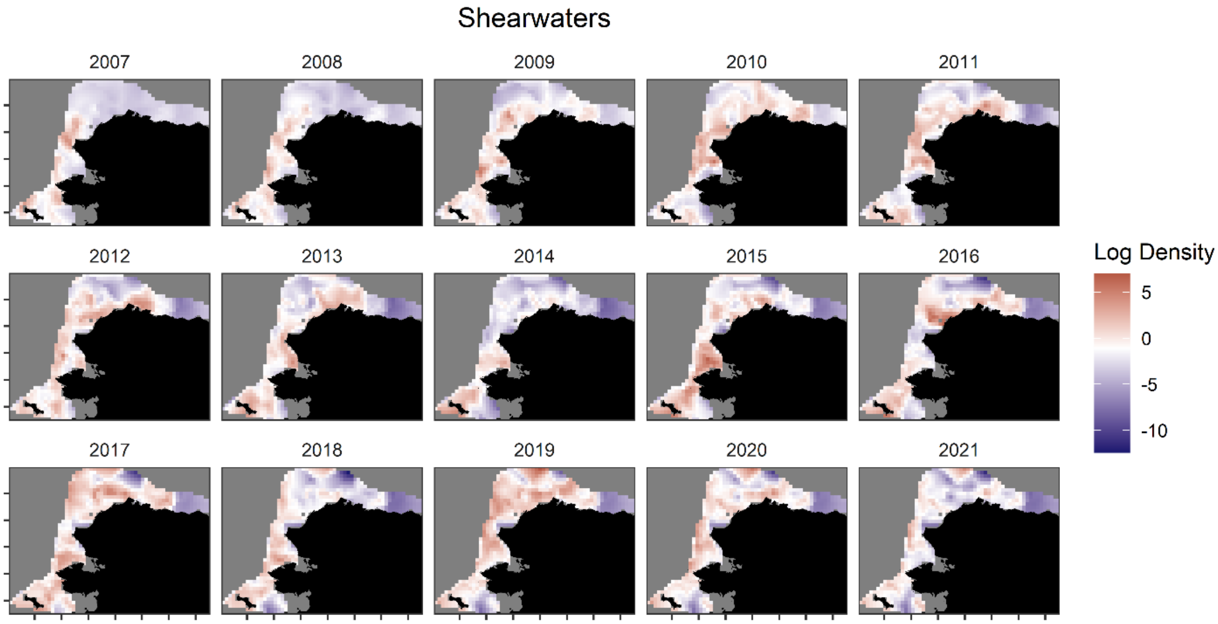

Figure 2. Interannual variability of predicted distributions (log density, color) for shearwaters (*Ardenna* spp).

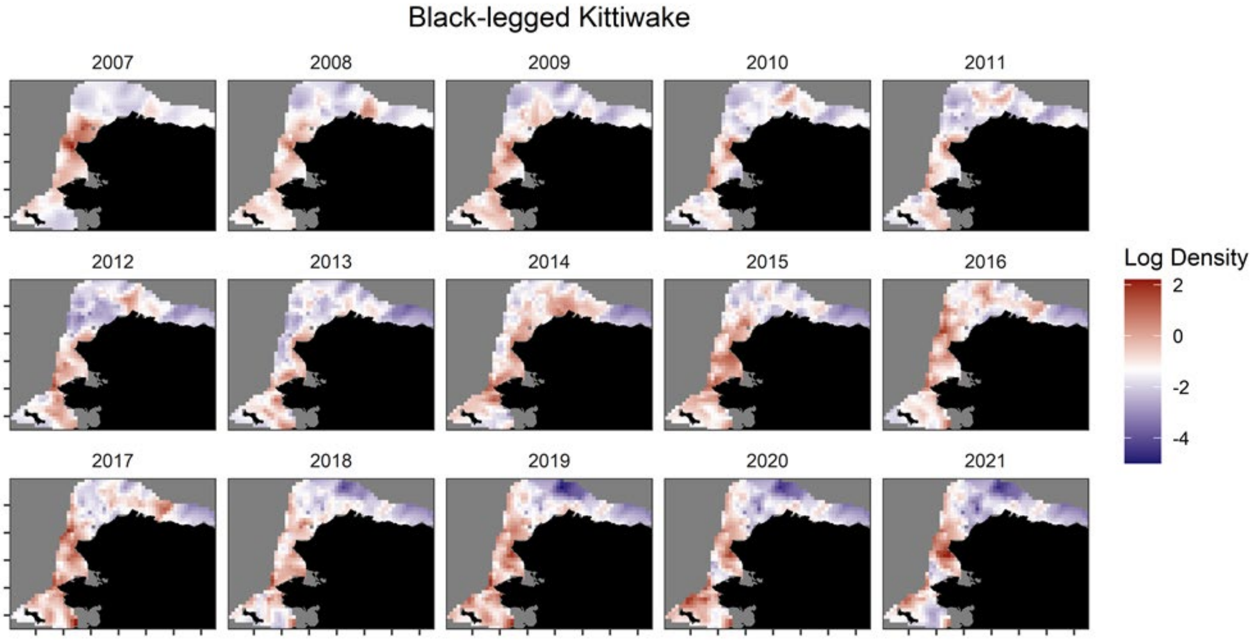

Figure 3. Interannual variability of predicted distributions (log density, color) for black-legged kittiwakes (*Rissa tridactyla*).

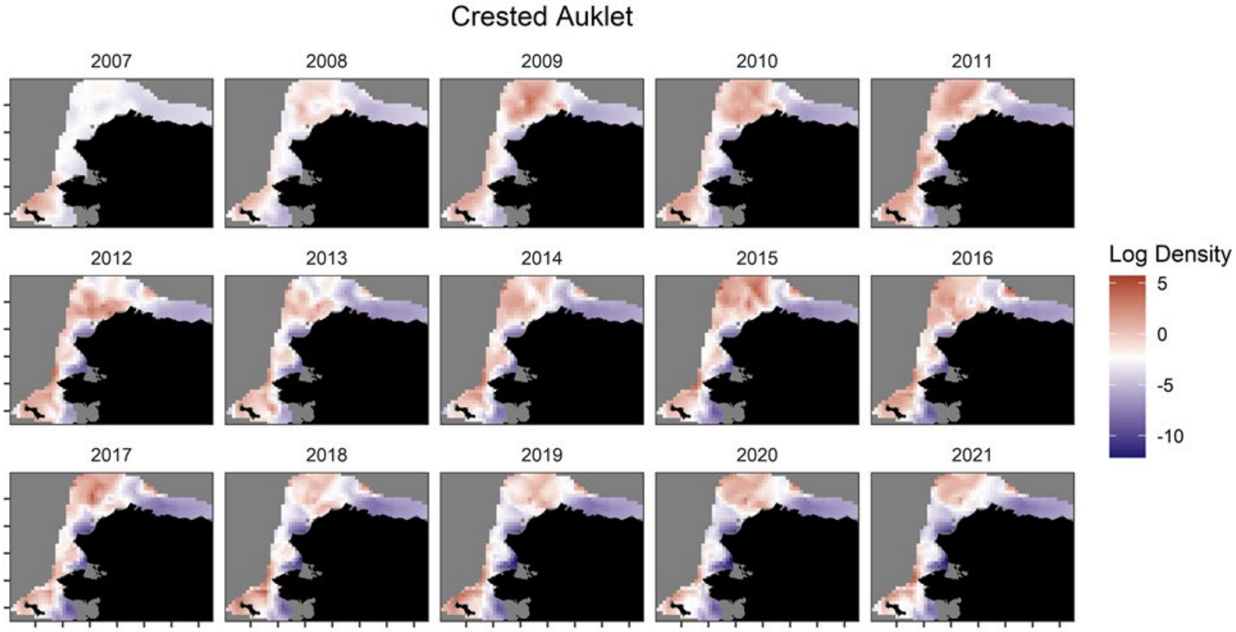

Figure 4. Interannual variability of predicted distributions (log density, color) for crested auklet (*Aethia cristatella*).

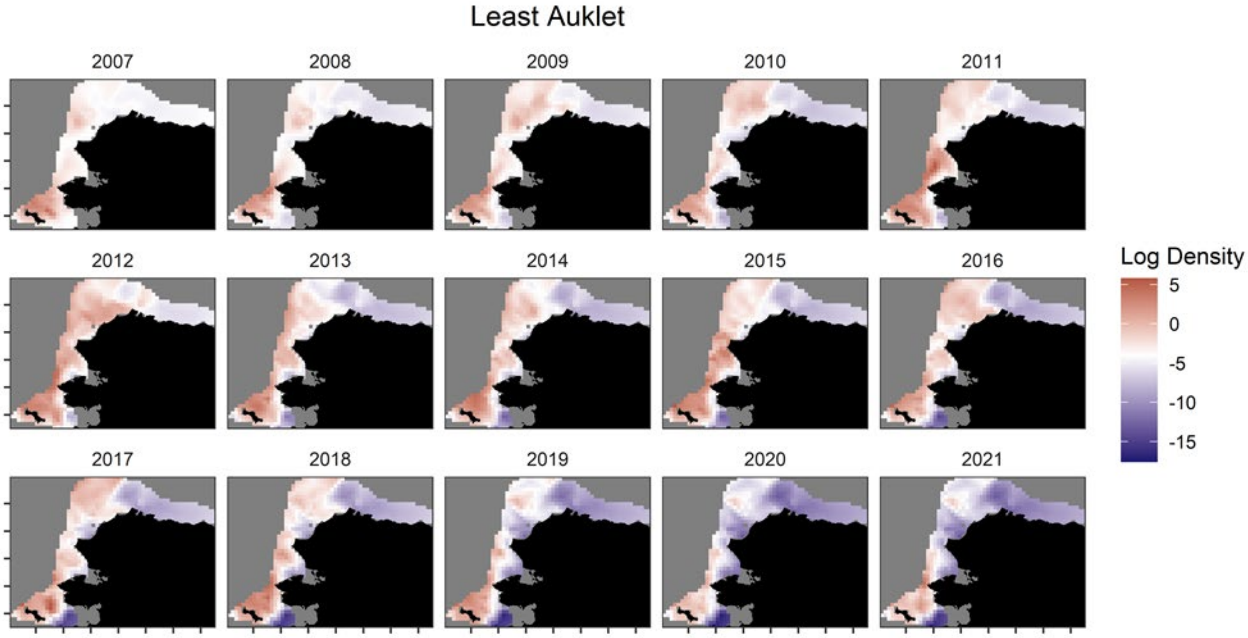

Figure 5. Interannual variability of predicted distributions (log density, color) for least auklet (*A. pusilla*).

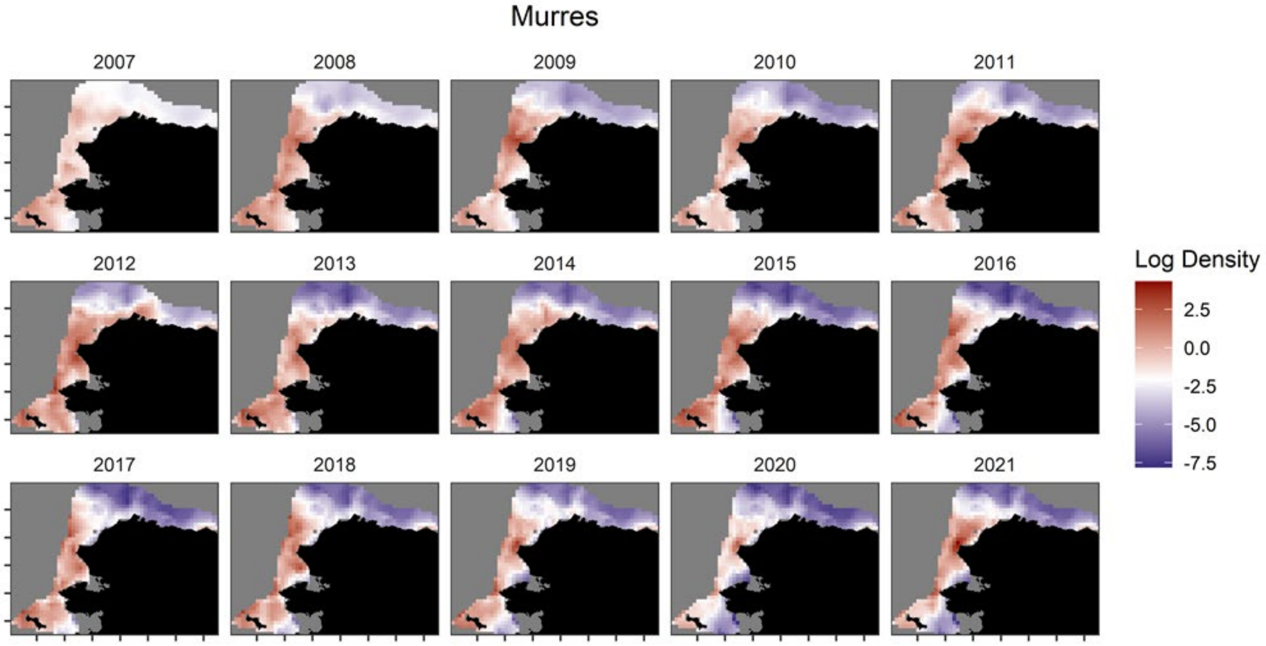

Figure 6. Interannual variability of predicted distributions (log density, color) for murres (common murre *Uria aalge* and Thick-billed murre *U. lomvia*).

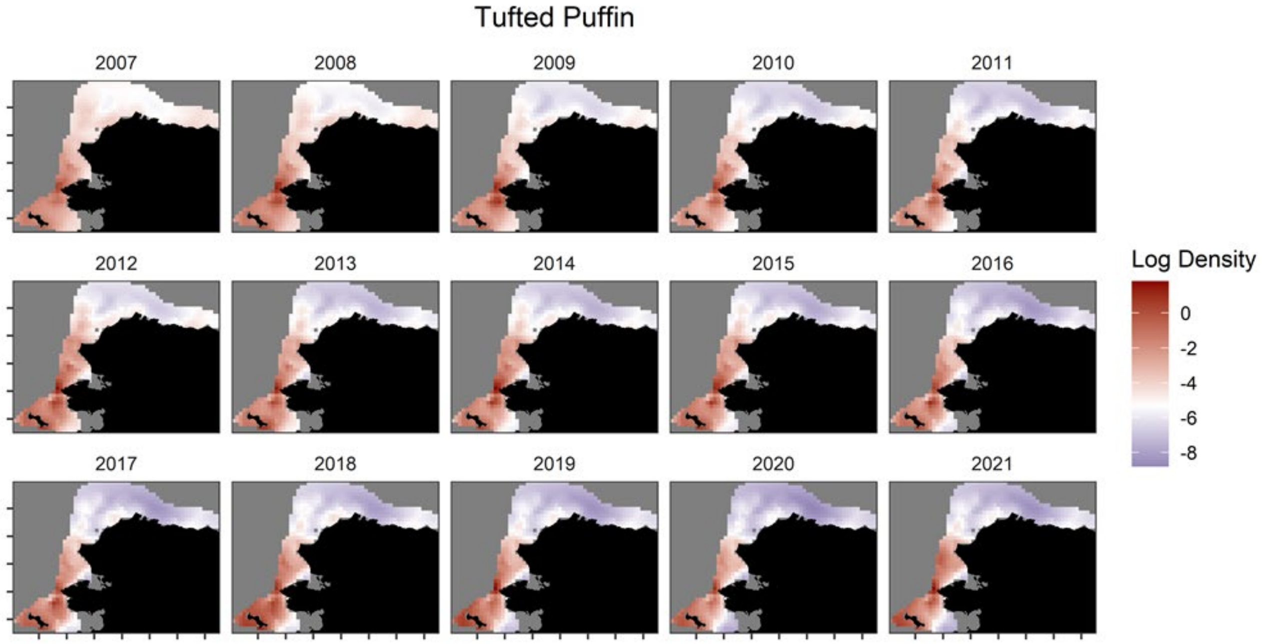

Figure 7. Interannual variability of predicted distributions (log density, color) for tufted puffin (*Fratercula cirrhata*).

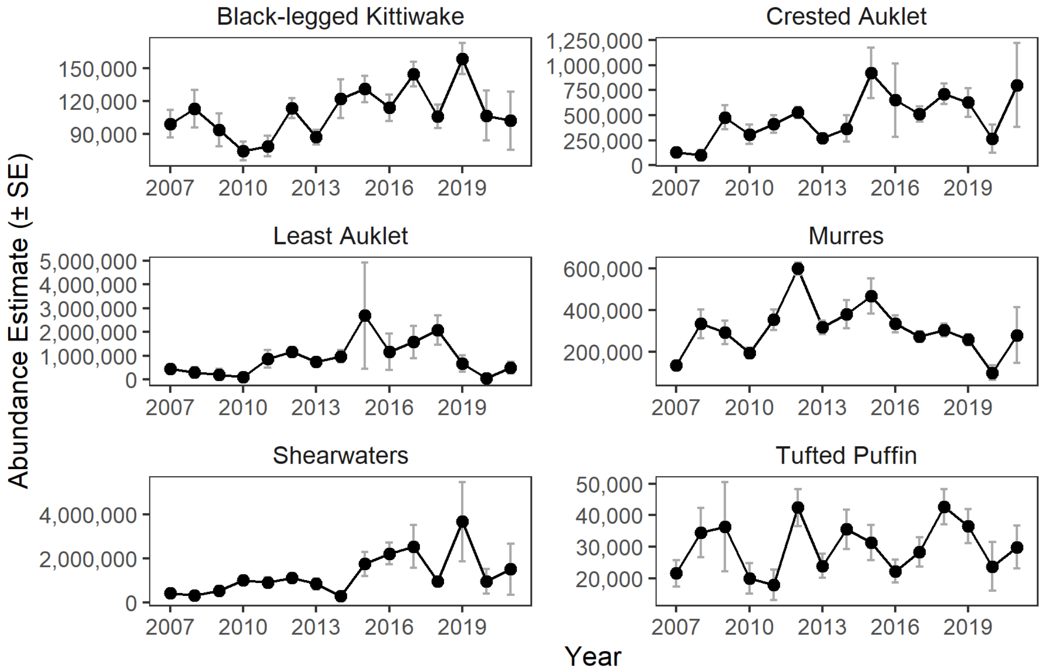

Figure 8. Annual abundance estimates (± SE) for six species groups common in the northern Bering-Chukchi Sea study area. Modeled abundances were derived from offshore at-sea survey data. Estimates are preliminary and a future analysis will evaluate whether habitat covariates, detection rates, and/or random effects of differences in methodology may improve model fit, however population estimates are within the expected range as described in literature for these species.

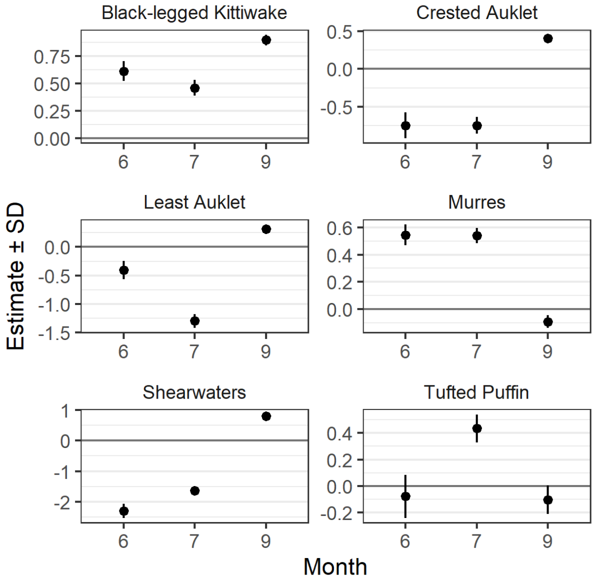

Figure 9. Estimated effects of month on Arctic seabird density levels for June, July, and September in relation to August density levels (grey solid line). August was used as the reference month because it had the highest survey effort and highest numbers of birds overall.

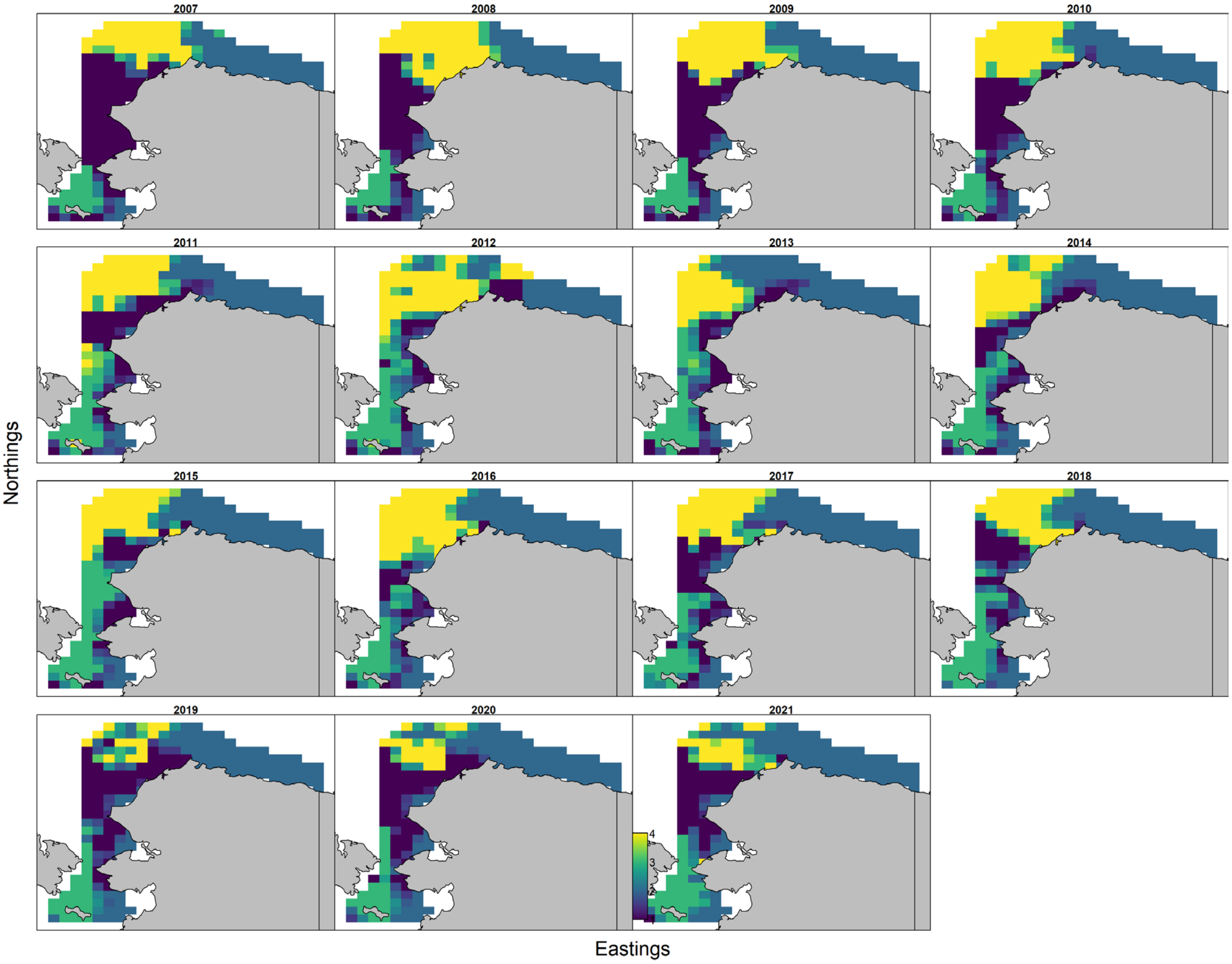

Figure 10. Annual spatial cohesion among cells (clustering of cells with similar densities of total birds) for the study area, 2007–2021. Cluster analysis used at-sea seabird surveys during the months of June through September. Cells of similar densities have the same colors.

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