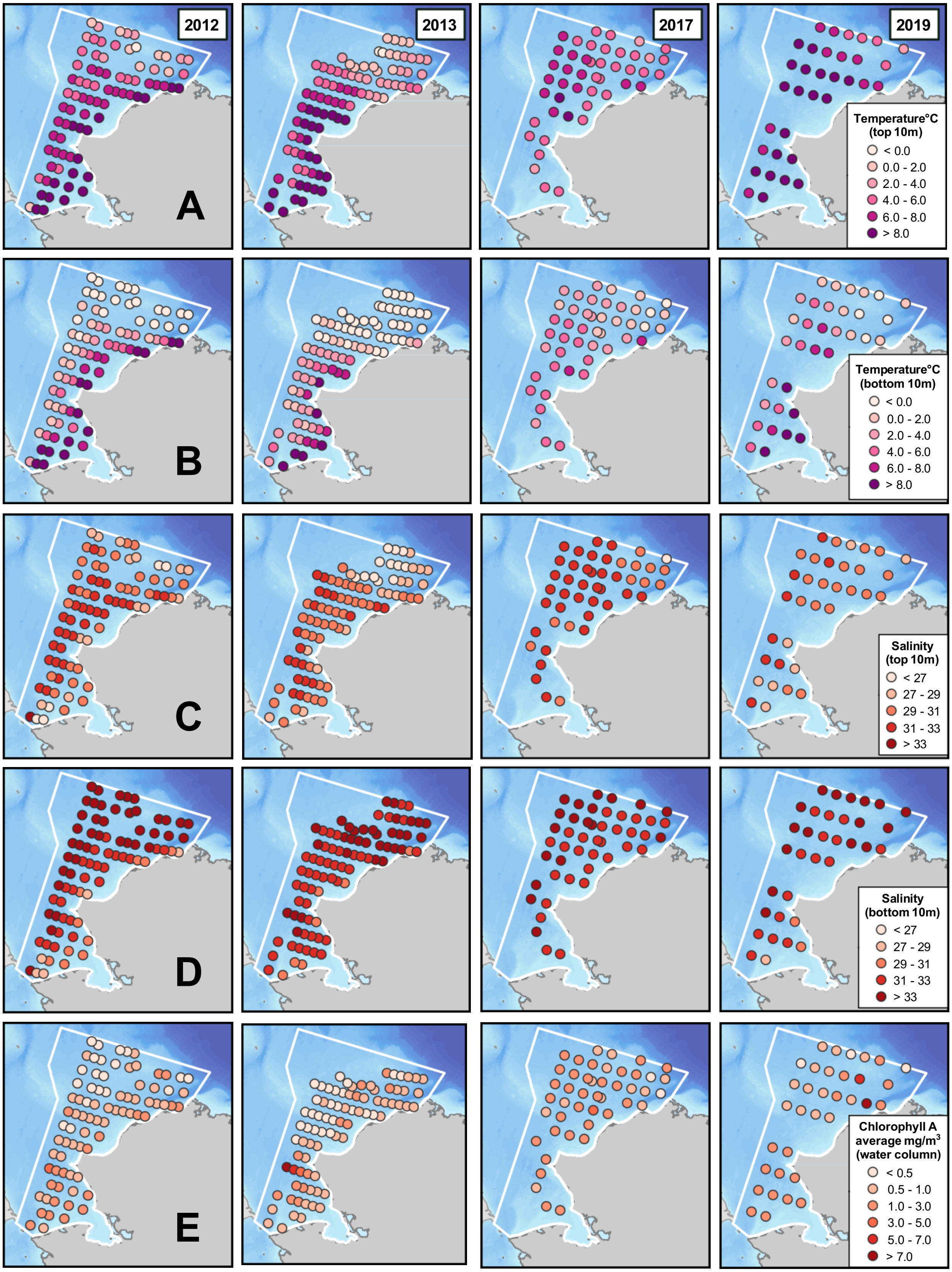
Supplemental Material_Kuletz et al. _ Seabirds in a warming Arctic

Text S1. Oceanographic Samples

Methods. - At each station, temperature and salinity of the water column were measured using a Conductivity-Temperature-Depth data logger (CTD; FastCat Sea-bird Electronics SBE43 or SBE 49). To measure chlorophyll-a (hereafter, chlorophyll), water was sampled every 10 m from 0 to 50 m or bottom, whichever was shallower. Samples were filtered onto glass fiber filters (GFFs, 0.7um nominal pore size), filters stored at -80 ºC and analyzed within 6 months with a benchtop fluorometer using the acidification technique (Parsons et al. 1984). Samples were then averaged over the water column and mean water column density calculated (mg m^{-3}). Chlorophyll was sampled at fewer stations than the other variables in 2012 and 2013, therefore we used natural neighbor interpolation to map the chlorophyll values throughout the study area. We then applied the values from the interpolated surface for stations that were missing *in situ* measurements of chlorophyll. Temperature and salinity in the upper and bottom 10 m and mean water column chlorophyll for each survey station are shown in Fig. S1.

Fig. S1. Distribution of oceanographic samples during four Chukchi Surveys. Years were categorized as cool years (2012, 2013) or heatwave years (2017, 2019). Shown are water temperature for the upper layer (10 m) of the water column (A), water temperature for the bottom layer (10 m) of the water column (B), salinity for the upper layer (10 m) of the water column (C), salinity for the bottom layer (10 m) of the water column (D), and averaged water column chlorophyll density (mg m^{-3}).


2012
2013
2017
2019
A
B
C
D
E
Temperature°C (top 10m)
< 0.0
0.0 - 2.0
2.0 - 4.0
4.0 - 6.0
6.0 - 8.0
> 8.0
Temperature°C (bottom 10m)
< 0.0
0.0 - 2.0
2.0 - 4.0
4.0 - 6.0
6.0 - 8.0
> 8.0
Salinity (top 10m)
< 27
27 - 29
29 - 31
31 - 33
> 33
Salinity (bottom 10m)
< 27
27 - 29
29 - 31
31 - 33
> 33
Chlorophyll A average mg/m3 (water column)
< 0.5
0.5 - 1.0
1.0 - 3.0
3.0 - 5.0
5.0 - 7.0
> 7.0

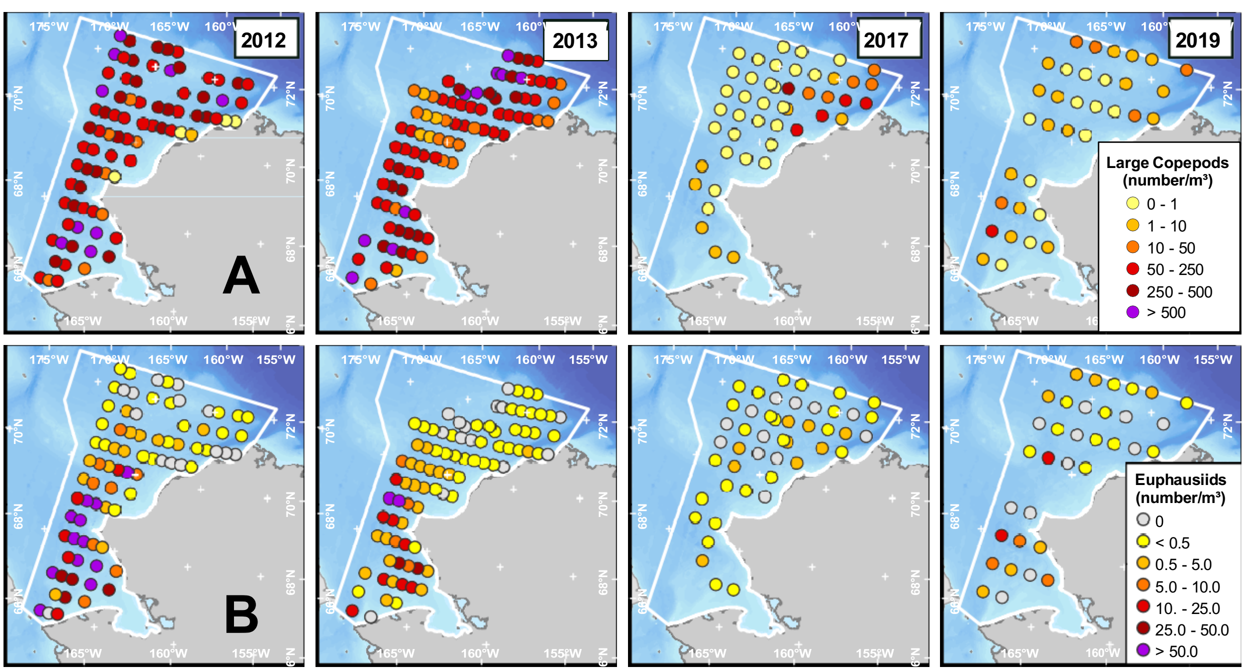
Text S2. Zooplankton samples

Methods. _Zooplankton samples were collected at each trawl station from surface to near bottom using a double oblique bongo (60 cm diameter frame with 505-µm mesh nets) and single or double 150-µm or 153-µm mesh nets. (For details see Kimmel & Duffy-Anderson 2020).

Volume filtered was estimated using a General Oceanics flowmeter mounted inside the mouth of each net for paired bongo nets. Samples were preserved in 5% buffered formalin/seawater. Zooplankton were identified to the lowest taxonomic level and stage possible at the Plankton Sorting and Identification Center (PSIC) in Szczecin, Poland. Samples identified at the PSIC were verified at the AFSC, Seattle, Washington, USA.

The prey category 'Large copepods' included copepods ≥ 2 mm length, and were comprised primarily of *Calanus glacialis,* with smaller numbers of *C. hyperboreus, C. marshallae*, and *Neocalanus* spp. The prey category of Euphausiids included various stages (furcila, juvenile, and adult) of *Thysanoessa* spp.

Fig. S2. Distribution of large copepods (A) and euphausiids (B) based on samples from four Chukchi surveys during cool years (2012, 2013) and heatwave years (2017, 2019).



Text S3. Fish samples

Methods. - The abundance and distribution of pelagic fish along the survey transects was quantified by means of acoustic-trawl surveys (see De Robertis et al. 2017, Levine et al. 2023). Acoustic data was collected using a Simrad EK60 scientific echosounder operating at 38 and 120 kHz from 6.5 m from the sea surface to 0.5 m above bottom while the vessel was underway. Midwater trawl hauls with a Marinovich pelagic trawl were used to characterize the size and species composition of fish aggregations along the survey trackline. Trawl catches were corrected for escapement from the trawl meshes (De Robertis et al. 2023) and combined with the acoustic observations to estimate abundance (De Robertis et al. 2017).

Six species of fish were abundant enough to allow for abundance estimates via acoustic-trawl methods (De Robertis et al. 2017, Levine et al. 2023): juvenile Pacific herring *Clupea pallasii*, Pacific capelin *Mallotus villosus*, saffron cod *Eleginus gracilis*, Arctic cod *Boreogadus saida*, juvenile Pacific cod *Gadus macrocephalus*, and walleye pollock *Gadus chalcogrammus*. To consider fish that may be consumed by seabirds, we only included fish ≤ 15.5 cm in length, which accounted for almost all of the fish (>99.6 % in all years) observed in these surveys (De Robertis et al. 2017, Levine et al. 2023, and Table S1). Most pelagic fish prey were larger than 10 cm (see Table S1). Because of their numerical dominance, Arctic cod and walleye pollock were considered as independent prey items, while the remaining less abundant fish species (herring, capelin, saffron cod, Pacific cod), were combined into a single category of 'other fish'. Abundances of Arctic cod, age-0 walleye pollock and other fish for each survey station are shown in Fig. S3.

Fig. S3. Distribution of fish during four Chukchi surveys during cool years (2012, 2013) and heatwave years (2017, 2019). Shown are distribution of Arctic cod (A), age-0 walleye pollock (B), and other fish (C) for each year. Only fish ≤ 15.5 cm length were included.

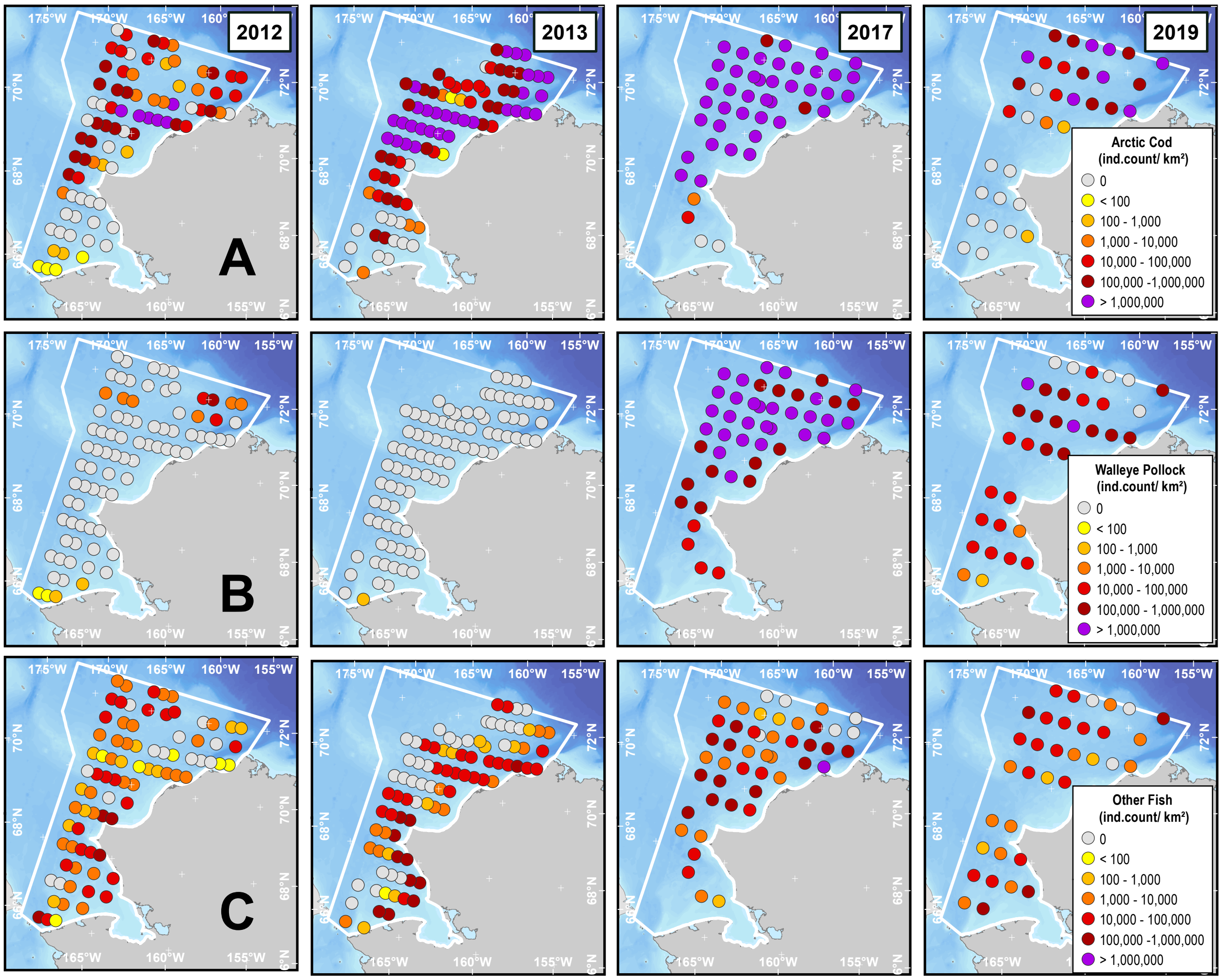


Table S1. The proportions of fishes (for all prey species considered) by size class, sampled during pelagic trawl sampling in the Chukchi Sea during four years (2012, 2013, 2017, 2019) of Chukchi surveys (see Methods, Kuletz et al. in press, and Text S3). Prey species included juvenile Arctic cod *Boreogadus saida*, walleye pollock *Gadus chalcogrammus*, and other fishes (Pacific herring *Clupea pallasii*, saffron cod *Eleginus gracilis*, Pacific cod *Gadus macrocephalus,* Pacific capelin *Mallotus villosus*).

	Percent of fishes for each year			
Size Class (cm)	**2012**	**2013**	**2017**	**2019**
0-5.5	94.56	96.21	84.3	75.5
5.5-10.5	2.39	3.63	15.6	22.1
10.5-15.5	2.65	0.04	0.01	2.27
>15.5	0.39	0.12	2.0E-5	0.07

Text S4. Sea ice in the Chukchi Sea study area

To define annual ice conditions specific to our study area, we summarized summer sea ice extent and timing of retreat from the study area (See Fig. 1) using the daily sea ice extent from the National Snow and Ice Data Center (ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/ north/daily/geotiff). The daily Sea Ice Index was gridded in 25-km^2 cells with a binary assignment of whether or not ice was present within the grid cell on a given day. We used a spatial overlay of the study area and determined the first dates for which the percentage of grid cells were without ice as: 51–26% ice cover, 25– 1% ice cover, and 0% ice cover. We report the date when all grid cells were < 1% ice covered.

During the cool years (2012, 2013), sea ice left the southern Chukchi Sea (Bering Strait to ~70°N) in early July and the northern Chukchi Sea (70–72 °N) by mid-August. During the heatwave years (2017, 2019), the southern Chukchi was ice-free by late June (a mean of ~12 days earlier than during the cool years), and the northern Chukchi was ice free by mid-July (nearly a month earlier than cool years).

Table S2. Dates that each region of the Chukchi study area became ice-free.

Year	Southern Chukchi	Northern Chukchi
2012	9 July	15 August
2013	1 July	11 August
2017	27 June	18 July
2019	20 June	10 July

LITERATURE CITED

De Robertis A, Levine R, Williams K, Wilson C (2023) Modifying a trawl to better retain small Arctic fishes. Deep Sea Res II 207: 105225

De Robertis A, Taylor K, Williams K, Wilson CD (2017) Species and size selectivity of two midwater trawls used in an acoustic survey of the Alaska Arctic. Deep Sea Res II 135: 40-50

Kimmel DG, Duffy-Anderson JT (2020) Zooplankton abundance trends and patterns in Shelikof Strait, western Gulf of Alaska, USA, 1990–2017. J Plank Res 42:334-354

Levine R, De Robertis A, Grunbaum D, Wildes S, Farley E, Stabeno PJ, Wilson CD (2023) Climate-driven shifts in the pelagic fish community of the Chukchi Sea. Deep Sea Res II 208:105244

Parsons TR, Maita Y, Lalli CM (1984) A manual of biological and chemical methods for seawater analysis. Publ Pergamon Press