Additional details on aerial surveys and methodologies

During 1988 – 2012, the years used in our study, the broader survey area spanned a large region which was partitioned into survey blocks of various sizes between 140 – 169° W, and between the Bering Strait (65° 40' N) and 73° N. Surveys in most years were conducted between early September and late October, with surveys beginning earlier and ending later in some years. Most surveys were flown in a de Havilland Twin Otter Series 300 or an Aero Commander 690A, both equipped with bubble windows affording full trackline viewing. Surveys conducted west of 154° W prior to 1992 were flown in a Grumman Turbo Goose model G21G aircraft with flat windows (Moore & Clarke, 1992). Surveys were conducted at altitudes between 305 m – 458 m, at speeds between 204 – 296 km/h, and in Beaufort wind forces ≤ 5.

Two general aerial survey designs were used before and after 2009. Prior to 2009 in the Beaufort and Chukchi seas (Clarke, Christman, Brower, & Ferguson, 2012; Moore & Clarke, 1992; Treacy, 2000), and in the Beaufort Sea through 2012 (Clarke, Christman, Brower, & Ferguson, 2013), survey blocks to be visited were selected in a non-random manner that sought to distribute effort evenly across the study area, while considering the location of suitable weather conditions. Within survey blocks, transect lines were oriented north-south and separated by a minimum of 30 minutes of longitude. The western- and eastern-most extent of transect lines within survey blocks were selected randomly. Transect lines were connected at the northern and southern ends of the survey block by crosslegs. Beginning in 2009 in the north-western Chukchi Sea (west of 157° W) (Clarke et al., 2012), fixed transects oriented perpendicular to the coast were positioned 19 km apart, and were revised annually. Selection of transects sought to maximize coverage of the broader survey area. An additional transect, paralleling the coast at a distance of 1 km offshore, was also surveyed (Fig S1.1, S1.2).

Additional details on the Biology Ice Ocean Modeling and Assimilation System

BIOMAS couples three sub-models for sea ice, ocean circulation, and the pelagic ecosystem, respectively. The ecosystem model is adapted to the Arctic Ocean based on an 11-component Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) biogeochemical model (Kishi et al., 2007). With nitrogen and silicon as model currencies (Zhang et al., 2010, table 1), this model includes two phytoplankton components (diatom and flagellate), three zooplankton components (microzooplankton, copepods, and predator zooplankton), dissolved organic nitrogen, detrital particulate organic nitrogen, particulate organic silica, nitrate, ammonium, and silicate.

The orthogonal curvilinear model mesh covers the northern hemisphere north of 39°N, with the "north pole" of the mesh displaced into the land of Alaska. The model has high spatial resolution in the Chukchi, Beaufort, and Bering seas, with grid sizes varying between 4 and 10 km. The model employs a Z-coordinate configuration in the vertical dimension and has 30 ocean layers of varying thicknesses. To better resolve the mixed layer and euphotic zone, the top six layers have a fine resolution of 5 m and the upper 100 m has a total of 13 layers (Zhang et al., 2015). The model is driven by the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis atmospheric forcing. BIOMAS is first integrated from 1971 to 1987 as a spin-up. After the spin-up, the model proceeds to integrate over the period 1988 – 2015.

Calculation of Area Under the Receiver Operator Characteristic Curve

We calculated one area under the receiver operator characteristic (ROC) curve (AUC) (Fielding & Bell, 1997; Hanley & McNeil, 1982) for each set of test years and model (Maxent and BRT) by concatenating predictions from all 8-day periods in the test years and evaluating them as if they were one prediction. Presence records and the predicted habitat suitability from the time and place of the presence record were linked. We generated points along the receiver operator characteristic curve at 50 equally spaced threshold values between 0 and 1. The true positive classification rate (TPR) was calculated from the percentage of presence records over versus under the threshold value. The fractional predicted area (FPA) (Phillips et al., 2006) was estimated using a random sample of 10,000 grid cells from each prediction surface and measuring the percentage of predicted habitat values over versus under the threshold value. We plotted the TPR versus FPA to generate the ROC curve, and we measured AUC using the trapezoidal rule. This general method is implemented in the Maxent software, but our application required custom code to handle multiple prediction surfaces.

References for supplementary text

Clarke, J. T., Christman, C. L., Brower, A. A., & Ferguson, M. C. (2012). *Distribution and Relative Abundance of Marine Mammals in the Alaskan Chukchi and Beaufort Seas, 2011*. (Annual Report, OCS Study BOEM 2012-009.). National Marine Mammal Laboratory, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, F/AKC3, Seattle, WA 98115-6349

Clarke, J. T., Christman, C. L., Brower, A. A., & Ferguson, M. C. (2013). *Distribution and Relative Abundance of Marine Mammals in the Northeastern Chukchi and Western Beaufort Seas, 2012*. (Annual Report, OCS Study BOEM 2013-00117.). National Marine Mammal Laboratory, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, F/AKC3, Seattle, WA 98115-6349

Fielding, A. H., & Bell, J. F. (1997). A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation*, *24*(01), 38–49

Hanley, J. A., & McNeil, B. J. (1982). The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology*, *143*(1), 29–36. https://doi.org/10.1148/radiology.143.1.7063747

Moore, S. E., & Clarke, J. T. (1992). *Distribution, Abundance and Behavior of Endangered Whales in the Alaskan Chukchi and Western Beaufort Seas, 1991: With a Review 1982–1991* (OCS Study MMS-92-0029. Final Report prepared for the U.S. Minerals Management Service, Alaska OCS Region, prepared by SAIC, Maritime Services Division, 237 p.)

Treacy, S.D. (2000). *Aerial Surveys of Endangered Whales in the Beaufort Sea, Fa11 1998-1999*. Final Report to the U.S. Minerals Management Service, Alaska OCS Region.

Kishi, M. J., Kashiwai, M., Ware, D. M., Megrey, B. A., Eslinger, D. L., Werner, F. E., … Zvalinsky, V. I. (2007). NEMURO—a lower trophic level model for the North Pacific marine ecosystem. *Ecological Modelling*, *202*(1–2), 12–25. https://doi.org/10.1016/j.ecolmodel.2006.08.021

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, *190*(3–4), 231–259

Zhang, J. L., Spitz, Y. H., Steele, M., Ashjian, C., Campbell, R., Berline, L., & Matrai, P. (2010). Modeling the impact of declining sea ice on the Arctic marine planktonic ecosystem. *Journal of Geophysical Research-Oceans*, *115*, C10015–C10015. https://doi.org/10.1029/2009JC005387

Zhang, J. L., Ashjian, C., Campbell, R., Spitz, Y. H., Steele, M., & Hill, V. (2015). The influence of sea ice and snow cover and nutrient availability on the formation of massive under-ice phytoplankton blooms in the Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *118*, 122–135. https://doi.org/10.1016/j.dsr2.2015.02.008

Table S1.1 Number of grid cells that had survey effort and that had records of bowhead whale presence, after removing duplicate records within each grid cell, 8-day period and year.

Year	Number of Effort Cells	Number of Presence Cells
1988	8640	37
1989	9890	151
1990	7420	246
1991	9122	48
1992	12562	108
1993	11666	191
1994	8588	94
1995	7566	238
1996	8145	59
1997	8588	373
1998	11244	332
1999	7447	180
2000	7018	79
2001	5753	28
2002	6556	63
2003	5284	119
2004	7756	197
2005	6076	71
2006	5723	115
2007	4897	124
2008	5870	102
2009	7251	84
2010	6372	112
2011	7631	51
2012	6751	176

Table S1.2 Boosted regression tree model settings and associated predictive deviance for each model.

Model name	Learning rate	Tree complexity	Number trees	Predictive deviance
model.tc9.lr01	0.010	9	2200	0.56492
model.tc9.lr005	0.005	9	4050	0.56605
model.tc7.lr01	0.010	7	3250	0.56636
model.tc8.lr005	0.005	8	4050	0.56661
model.tc8.lr01	0.010	8	2600	0.56707
model.tc9.lr05	0.050	9	450	0.56727
model.tc7.lr005	0.005	7	4500	0.56915
model.tc6.lr01	0.010	6	3100	0.56948
model.tc8.lr05	0.050	8	600	0.56982
model.tc6.lr005	0.005	6	4900	0.56988
model.tc6.lr05	0.050	6	600	0.57078
model.tc5.lr01	0.010	5	3450	0.57081
model.tc7.lr1	0.100	7	200	0.57092
model.tc7.lr05	0.050	7	450	0.57138
model.tc9.lr1	0.100	9	250	0.57176
model.tc5.lr05	0.050	5	950	0.57193
model.tc4.lr01	0.010	4	3900	0.57318
model.tc5.lr005	0.005	5	4850	0.57348
model.tc4.lr005	0.005	4	5500	0.57352
model.tc8.lr1	0.100	8	250	0.57405
model.tc6.lr1	0.100	6	300	0.57453
model.tc4.lr05	0.050	4	950	0.57480
model.tc5.lr1	0.100	5	400	0.57604
model.tc3.lr01	0.010	3	4100	0.57624
model.tc3.lr05	0.050	3	1300	0.57662
model.tc4.lr1	0.100	4	350	0.57687
model.tc3.lr1	0.100	3	550	0.57849
model.tc3.lr005	0.005	3	5550	0.57857
model.tc2.lr05	0.050	2	1050	0.58172
model.tc2.lr1	0.100	2	950	0.58217
model.tc2.lr01	0.010	2	4400	0.58329
model.tc2.lr005	0.005	2	5950	0.58554

Table S1.3 Number of training years, test years, and folds and model performance scores from models that included all BIOMAS variables and bathymetry, and models that only use BIOMAS variables. Reference Fig 2.

					models using all BIOMAS variables and bathymetry				models using all BIOMAS covariates			
					AUC		TSS		AUC		TSS	
Number test years	Number training years	Number folds	mean(std) number of presences	mean(std) number of absences	Maxent	BRT	Maxent	BRT	Maxent	BRT	Maxent	BRT
1	24	25	3243 (87)	9865 (13)	0.811	0.825	0.559	0.559	0.756	0.768	0.469	0.463
2	23	12	3101 (143)	9870 (13)	0.819	0.825	0.542	0.541	0.775	0.774	0.466	0.454
3	22	8	2970 (173)	9870 (9)	0.823	0.835	0.53	0.54	0.773	0.783	0.473	0.46
4	21	6	2823 (106)	9865 (16)	0.826	0.831	0.531	0.528	0.786	0.786	0.473	0.477
5	20	5	2702 (144)	9870 (12)	0.82	0.828	0.509	0.519	0.772	0.773	0.46	0.436
6	19	4	2571 (191)	9871 (9)	0.82	0.824	0.51	0.51	0.769	0.773	0.443	0.441
7	18	3	2430 (177)	9864 (7)	0.814	0.823	0.511	0.518	0.771	0.764	0.462	0.435
8	17	3	2376 (61)	9862 (12)	0.831	0.829	0.531	0.515	0.786	0.775	0.461	0.45
9	16	2	2054 (209)	9865 (3)	0.799	0.804	0.485	0.483	0.756	0.75	0.425	0.396
10	15	2	2019 (33)	9879 (8)	0.829	0.828	0.51	0.518	0.779	0.775	0.462	0.44
11	14	2	1869 (286)	9854 (9)	0.839	0.836	0.522	0.523	0.791	0.783	0.48	0.457
12	13	2	1721 (506)	9860 (6)	0.819	0.823	0.504	0.495	0.775	0.774	0.452	0.437
13	12	2	1658 (506)	9852 (3)	0.819	0.823	0.503	0.498	0.766	0.768	0.445	0.422
14	11	2	1509 (286)	9879 (6)	0.827	0.819	0.506	0.497	0.788	0.763	0.462	0.421
15	10	2	1360 (33)	9863 (11)	0.816	0.819	0.507	0.502	0.765	0.759	0.461	0.424
16	9	2	1325 (209)	9860 (4)	0.823	0.828	0.516	0.513	0.769	0.767	0.452	0.427
17	8	3	1002 (61)	9878 (4)	0.809	0.81	0.499	0.506	0.762	0.753	0.439	0.399
18	7	3	948 (177)	9874 (6)	0.798	0.798	0.485	0.476	0.752	0.735	0.408	0.368
19	6	4	807 (191)	9866 (24)	0.794	0.804	0.483	0.477	0.739	0.743	0.392	0.385
20	5	5	676 (144)	9871 (13)	0.786	0.785	0.474	0.45	0.724	0.724	0.369	0.348
21	4	6	555 (106)	9865 (36)	0.787	0.792	0.472	0.463	0.737	0.731	0.404	0.375
22	3	8	408 (173)	9872 (35)	0.79	0.766	0.466	0.422	0.747	0.701	0.402	0.322
23	2	12	278 (143)	9862 (47)	0.753	0.734	0.435	0.381	0.697	0.668	0.337	0.27
24	1	25	135 (87)	9859 (64)	0.719	0.661	0.391	0.278	0.645	0.62	0.281	0.216

Table S1.4 Correlation between modelled environmental predictor variables between 21 August and 31 October, 1988 – 2012. Temp = average water temperature 0 – 100 m, Ice = sea ice thickness, Dia = diatoms 0 – 100 m, Flag = flagellates 0 – 100 m, Cop = Copepods 0 – 100 m, Pred Zoop = predatory zooplankton 0 – 100 m, Zoop = mean of copepods and predatory zooplankton 0 – 100 m. Depth = bathymetry.

	Temp	Ice	Dia	Flag	Cop	Pred Zoop	Zoop	Depth
Temp	1	-0.43	0.58	0.58	0.61	0.62	0.65	0.46
Ice		1	-0.27	-0.39	-0.35	-0.29	-0.35	-0.22
Dia			1	0.53	0.8	0.64	0.79	0.38
Flag				1	0.76	0.4	0.69	0.34
Cop					1	0.74	NA	0.55
Pred Zoop						1	NA	0.68
Zoop							1	0.62
Depth								1

Table S1.5 Input data for, and performance scores from, Maxent and BRT models evaluated with 5 years of data and trained with 20 years of data for models that included all BIOMAS variables and bathymetry. Reference Fig 6a and Fig 7a.

	fold 1	fold 2	fold 3	fold 4	fold 5	mean	standard deviation
No. presences	2515	2629	2870	2872	2626	2702	143.7
No. absences	9852	9886	9865	9878	9867	9870	11.6
Maxent AUC	0.799	0.792	0.835	0.819	0.854	0.82	0.02
BRT AUC	0.815	0.814	0.836	0.809	0.864	0.83	0.02
Maxent TSS	0.492	0.466	0.503	0.505	0.581	0.51	0.038
BRT TSS	0.496	0.528	0.504	0.482	0.585	0.52	0.036
N=5 test years	1998	1990	1992	1989	1988		
	2003	1991	1995	1996	1994		
	2007	1993	2001	2000	1997		
	2010	1999	2002	2006	2004		
	2012	2009	2005	2008	2011		

Table S1.6 Model performance scores from Maxent and BRT models with 17 different combinations of variables. Variables used in each model indicated by initials in the 'model' column. I=sea ice, Z=zooplankton, T=sea temperature, F=flagellates, B=bathymetry. Reference Fig 3.

	mean				standard deviation			
	AUC		TSS		AUC		TSS	
model	Maxent	BRT	Maxent	BRT	Maxent	BRT	Maxent	BRT
IZTBF	0.82	0.828	0.509	0.519	0.023	0.02	0.038	0.036
B	0.802	0.792	0.51	0.508	0.006	0.011	0.024	0.012
IZTF	0.772	0.773	0.46	0.436	0.025	0.023	0.049	0.037
IZ	0.768	0.767	0.452	0.431	0.036	0.029	0.071	0.069
ZT	0.775	0.759	0.448	0.416	0.041	0.036	0.069	0.06
ZTF	0.768	0.763	0.442	0.423	0.032	0.033	0.051	0.054
IZT	0.766	0.765	0.452	0.422	0.039	0.026	0.07	0.04
Z	0.768	0.755	0.446	0.431	0.023	0.025	0.056	0.051
IZF	0.757	0.76	0.455	0.425	0.032	0.028	0.062	0.06
ZF	0.76	0.753	0.431	0.418	0.02	0.019	0.038	0.032
TF	0.728	0.717	0.383	0.345	0.039	0.047	0.074	0.072
T	0.727	0.711	0.418	0.343	0.045	0.051	0.057	0.08
ITF	0.715	0.713	0.368	0.346	0.04	0.032	0.071	0.058
IT	0.707	0.71	0.377	0.343	0.053	0.033	0.082	0.065
F	0.681	0.661	0.274	0.232	0.027	0.017	0.042	0.031
IF	0.677	0.662	0.29	0.26	0.043	0.036	0.077	0.073
I	0.641	0.623	0.27	0.242	0.046	0.039	0.083	0.075

Figure S1.1 Survey effort for each year from 21 August – 31 October. Effort is shown from transect, connect, search and circle flight types (see Methods section).

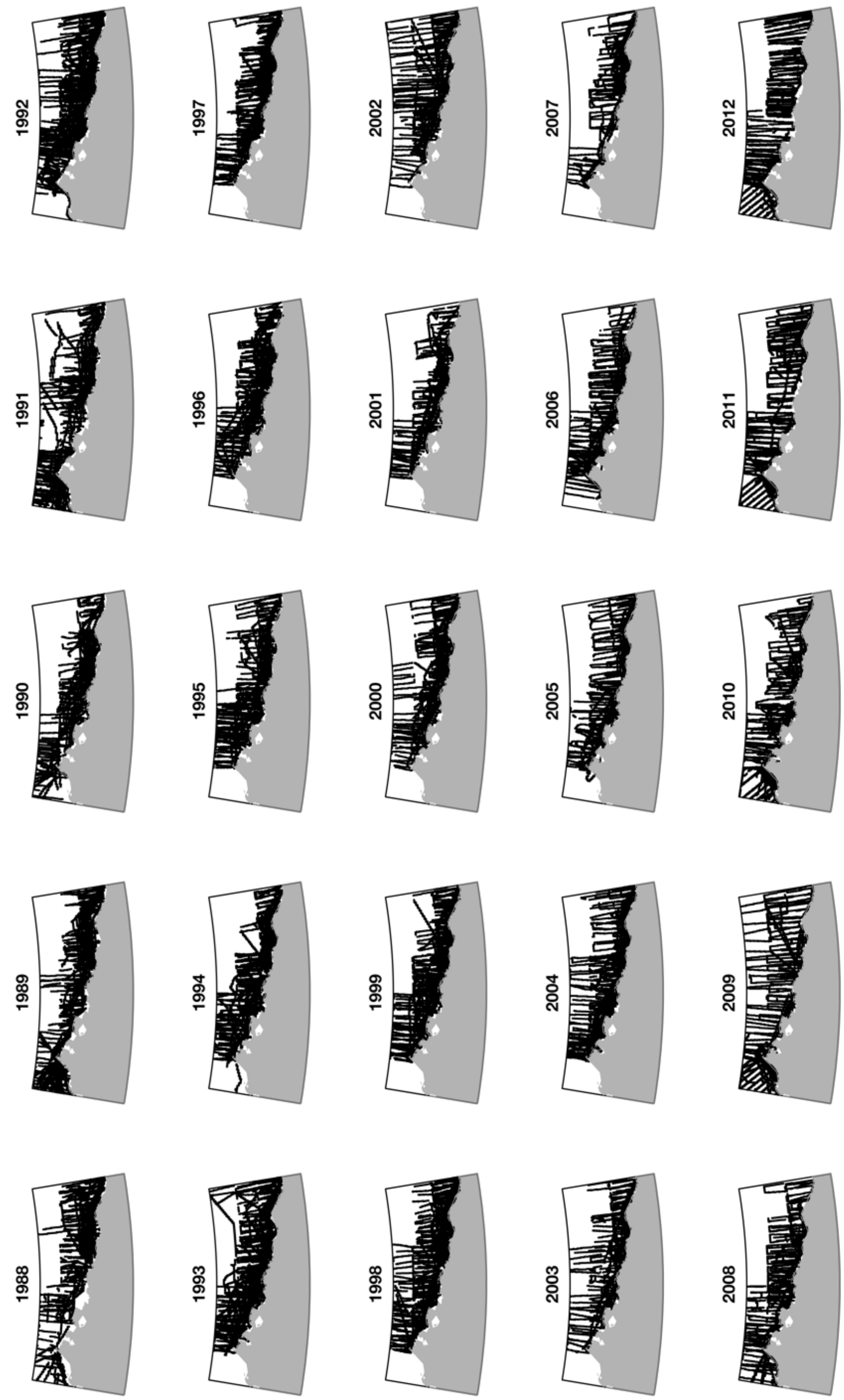

Figure S1.2 Sighting rates for each year calculated from presence-absence data within 8-day periods from 21 August – 31 October. Sighting rate = number of times each grid cell was surveyed divided by the number of sightings. See Figure S1.1 for locations where sighting rate = zero.

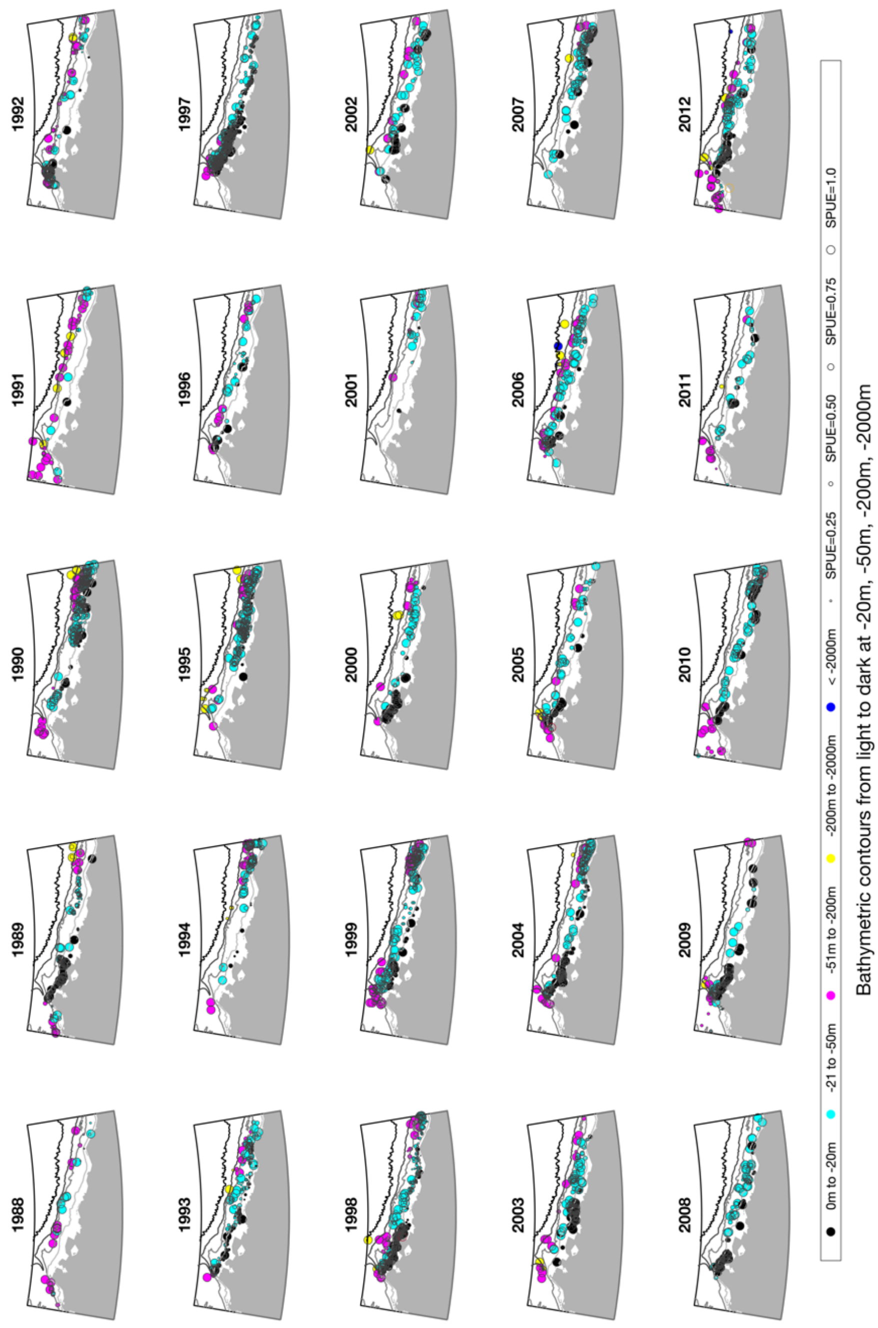

Figure S1.3 Annual mean value of BIOMAS derived predictor variables between 21 August and 31 October across the study area (blue), and associated bowhead whale presence records (red). (a) Zooplankton 0 – 100 m, (b) sea temperature 0 – 100 m, (c) sea ice thickness, and (d) flagellates 0 – 100 m. Width of shaded areas shows one standard deviation above and below the mean.

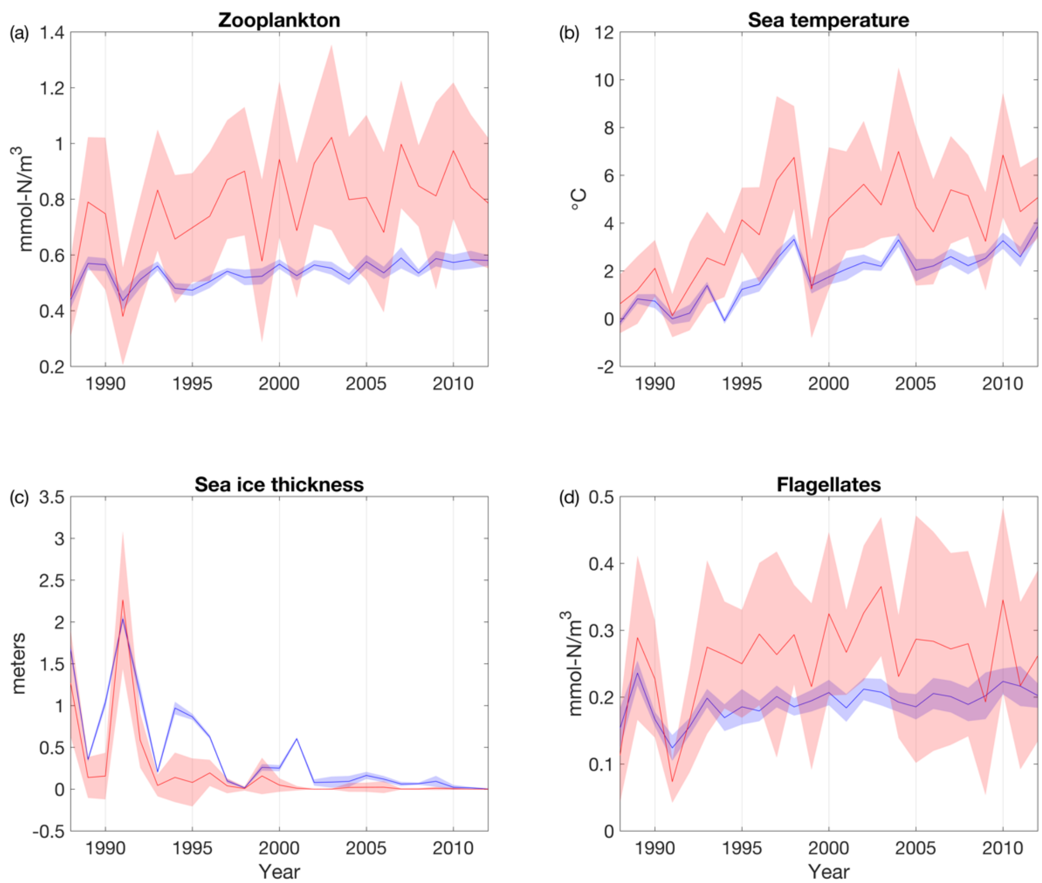

Figure S1.4 Pearson correlation coefficient between predicted values from Maxent and BRT models using bathymetry and BIOMAS variables sea ice, zooplankton, temperature and flagellates (a) and from the models using only BIOMAS variables sea ice, zooplankton, temperature and flagellates (b). Calculations were performed on results of models that used 5 test years and 20 training years (Table S1.5). Grey is the land of Alaska, USA.

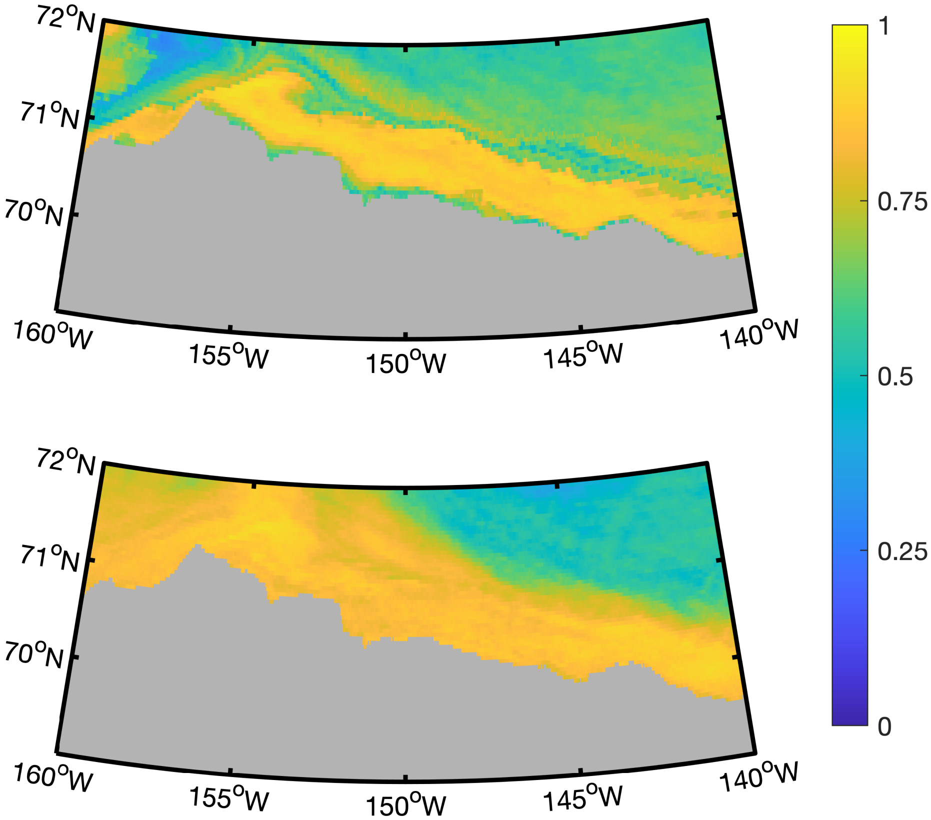

Figure S1.5 Mean of 8-day predictions of habitat suitability across years (1988 – 2012) from Maxent and BRT models using only bathymetry. Dates above plots are the first day of the 8-day prediction. Habitat suitability varies from low (0) to high (1) per the colorbar. Grey is the land of Alaska. Boundaries for each subplot are 140 – 160 °W and 69 – 72 °N (Fig 1). Model results shown for models using 5 test years and 20 training years (Table S1.5). Prediction maps are identical for each 8-day period because bathymetry is static.