Chapter 5. Arctic Climate Change—A Tale of Two Cods

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Abstract

Climate effects on the ecology of the Arctic marine environments are of local, regional, national, and circumpolar interest and concern. Habitats are changing at the species level and there will be winners and losers with population limiting factors and the related temperature effects. In this chapter, the potential effects of warming temperatures on Arctic Cod and Saffron Cod in the eastern Bering Sea are evaluated. A Bering Sea study area was selected because, in contrast to the Chukchi and Beaufort Seas, a large volume of long-term fishery data was available for 1982–2006. A generalized additive modeling (GAM) approach was used to explore the effects of depth, bottom temperature, and surface temperature on the distribution and abundance of the cod species as well each species' response to warming conditions. The GAMs estimate significant contraction and expansion in the marine distributions and abundances of Arctic Cod and Saffron Cod, respectfully, as simulated bottom temperatures increase in 0.2 °C increments over shelf and slope habitats to a maximum of 2 °C. In the vernacular of "winners and losers," the GAMs suggest that Saffron Cod will be a winner and Arctic Cod a loser in warming habitat conditions. The model simulation results were examined with respect to their application to species interactions and other ecosystem functions in the Chukchi and Beaufort Seas where each cod is more abundant and of greater ecological importance.

Introduction

Global climate change is an increasingly important ecological driver for oceanic and nearshore ecosystems, potentially affecting economically important fisheries stocks and ecosystem structure and function. Arctic systems are estimated to be especially vulnerable because of projected air and sea temperature increases (Anisimov and others, 2007). Summer sea ice extent in the Arctic has been decreasing at a rapid rate with some estimations indicating it will completely disappear by 2050 (Wang and Overland, 2009; Overland and Wang, 2013). Additionally, Arctic systems are changing almost twice as fast as anywhere on Earth from warming temperatures and melting ice (National Aeronautics and Space Administration, 2012); United Nations Environment Programme, 2013). Climate conditions in the eastern Bering Sea (EBS) have been highly variable over recent decades (Mueter and Litzow, 2008). In the EBS, winter sea-ice cover is the dominant factor creating a cold pool where bottom temperatures persist through the summer at less than 2 °C (Litzow, 2007; Stabeno and others, 2012b). Since 1954, this sea-ice cover in the EBS has decreased significantly coincident with an increase in summer bottom temperatures (Mueter and Litzow, 2008). The southernmost edge of the cold pool in the EBS has shifted about 230 km northward since 1982 (Litzow, 2007). Benthic community shifts in the center of distributions northward also have been associated with these changing climate conditions in the EBS (Mueter and Litzow, 2008).

A major challenge becomes how to estimate the effects of these climate alterations on Arctic biota. Given the complexity of projecting future effects, numerous approaches are being used in terrestrial and aquatic environments. These approaches range from laboratory tolerance experiments (Wernberg and others, 2012) to trait-based analyses (for example, Moyle and others, 2013; Lee and others, U.S. Environmental Protection Agency, written commun., 2014) to more mechanistically based food webs (for example, Aydin and others, 2007) and individual-based models (Chang and others, 2010). Each approach has strengths and limitations, as well as drastically different data requirements.

This chapter resulted from cooperative research between the U.S. Geological Survey and U.S. Environmental Protection Agency focusing on potential climate effects on Arctic Cod and common interests in the species because of its human and ecological values. The research was implemented as a demonstration project to feature the application of a modeling approach to assess distributional shifts in important fish populations in response to potential climate change effects in the northern Bering Sea.

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Species Distribution Models

One approach that has gained considerable attention in projecting species responses to climate change is the use of statistically based species distribution models (SDMs, also known as niche or bioclimatic envelope models [Olden and others, 2008; Elith and Leathwick, 2009]). These models establish statistical relations between a species' extant distribution and (or) abundance and a corresponding suite of environmental factors. This relation then can be used to project species' responses to climate-induced environmental changes. A major advantage of SDMs is that they can use data from existing field surveys. Additionally, as pointed out by Heikkinen and others (2006), they are a "particularly valuable" tool for providing insights into effects of climate warming for species where the range-limiting physiological factors are poorly known. However, SDMs have a number of limitations (Heikkinen and others, 2006; Robinson and others, 2011). They require a moderately large dataset, and if effects of warming temperatures in northern latitudes are being investigated, it is important that the dataset include the southern range of the species. If abundance is being modeled, directly comparable sampling techniques are also essential. One concern of many ecologists is that most SDMs do not incorporate life history attributes or biological interactions and, accordingly, the simulated responses may not result from the direct effects of the environmental factors in the model, but rather result from indirect effects on productivity, predator-prey interactions, or other biotic interactions. Given this final limitation, it is perhaps best to view SDMs as statistical "idiot savants" and interpret the results through an ecological lens.

Species Selection and Climate Change

With these caveats in mind, SDMs were generated for two Arctic fish, Arctic Cod (*Boreogadus saida*) and Saffron Cod (*Eleginus gracilis*) in the EBS using sea bottom temperature, sea surface temperature, and bottom depths as key environmental drivers. The Arctic Cod and Saffron Cod were selected as target species, partly because of their importance to higher trophic levels and because they have different biogeographic distributions; therefore, they potentially display different responses to climate warming. After the models were generated, various climate change scenarios were applied to explore how increases in temperature are likely to alter their distributions and abundances in the EBS. Besides projecting potential changes in the EBS, changes that occur in the EBS are likely to be an early harbinger of changes in more northerly environments especially as they pertain to the potential for expanding commercial fisheries. To generate these models, the extensive bottom-trawl survey data from the National Oceanic and Atmospheric Administration (NOAA) Resource Assessment and Conservation Engineering (RACE) Division program (National Oceanic and Atmospheric Administration, 2013) were used. The RACE surveys in the EBS, Aleutian Islands (AI), and Gulf of Alaska (GOA) over the past three decades provide a large sample set for modeling and meet the criteria of having data from the southern part of the range for Arctic Cod and Saffron Cod. The circumpolar distribution of Arctic Cod and its intermediate position and importance in regional food webs makes this species a strong candidate as an indicator of environmental change and, in this regard, its interactions with congeners are of special interest.

Life History Considerations

The geographic range of Arctic Cod is circumpolar including the Chukchi Sea southward into the EBS. They are found from the surface to 1,390 m deep, although they were only captured from 30–150 m in the NOAA RACE surveys. Adaptations, such as anti-freeze proteins, allow this species to live in very cold waters and to use sea ice habitats to hide from predators, spawn, and forage for food. Spawning occurs in the late autumn–early winter. Eggs and larvae are pelagic, and larvae generally hatch in spring. Young Arctic Cod mostly feed on plankton in the upper water column, graduating to a diet of marine worms, adult copepods, and shrimps. Adult Arctic Cod grow to a maximum of 46 cm (Wienerroither and others, 2011) with an average length about 25 cm (Cohen and others, 1990) and are critical to marine food webs, providing food for other fishes such as Dolly Varden (*Salvelinus malma*), seabirds, and marine mammals. Although Arctic Cod are not fished commercially in North America, they are harvested in Russia and are considered an excellent table fish (Hebert and Wearing-Wilde, 2002).

Saffron Cod also are in Arctic and subarctic seas and, off Alaska coasts, have been sampled as far south as the GOA. They typically are in nearshore waters less than 50 m deep. Physiological adaptations such as the antifreeze proteins in Arctic Cod also allow this species to survive in cold waters. In winter, they live under the ice in nearshore habitats and probably move slightly offshore in summer. Saffron Cod grow to a maximum length of 55 cm, live much longer, and are more likely to spawn on multiple occasions than Arctic Cod. Spawning occurs in winter and eggs are demersal. In early spring, eggs hatch and pelagic larvae are transported beneath the ice into tidally influenced bays/inlets of 2–10 m depths. Saffron Cod are epibenthic feeders and juveniles may associate with jellyfish. Like Arctic Cod, Saffron Cod are important in nearshore food webs and are consumed by other marine fishes, birds, and mammals. They are seasonally important in some coastal subsistence fisheries.

Species Interactions

Interactions between adult Arctic Cod and Saffron Cod, such as competition and predation, are not well known even though each species niche is similar with respect to trophic level and position (chapters 2 and 4). Neither species is especially abundant in the EBS especially when compared to other cod and flatfish species. Under current environmental conditions, therefore, the existing information would at least tentatively indicate reduced competition between the species including limited predation by one species on the other. How differences in spawning season affect interspecific competition and predation are not known, nor are effects of cannibalism (an intraspecific interaction common in gadids) on population dynamics. The differences in vertical distribution and the apparent absence of biotic interactions are significant with respect to climate change modeling. If interactions exist, they could reduce the accuracy of model simulations.

Methods

Data Source

Data were obtained from the NOAA Alaska Fisheries Science Center's RACE Division (http://www.afsc.noaa.gov/RACE/groundfish/default.php). The RACE resource assessment program was implemented in 1971 to monitor the condition of demersal fish and crab stocks on shelf regions off the coast of Alaska. This historical dataset for the Pacific Ocean and EBS includes trawl sampling by NOAA within the benthic zone of the United States continental shelf and slope areas of the U.S. Exclusive Economic Zone.

The distribution of NOAA sampling varies by region and year, but fish monitoring protocols are consistent across the regions (Stauffer, 2004). In the EBS region, monitoring sites are located in the center of a regional grid of evenly distributed cells (37 × 37 km cells), with occasional samples collected at other sites in support of other research and management needs (fig. 5.1). In the EBS, monitoring stations were typically sampled every year (1982–2006), although Norton Sound in the northern Bering Sea was sampled only in 1985 and 1991.

For the AI and GOA regions, sampling stations were randomly selected from within grid cells (fig. 5.1) that were identified through management and ecological strata allocations. Sampling was biennial and took place between 1984 and 2006 in AI and 1983 and 2007 in GOA.

For the NOAA monitoring, physical attributes of each station were measured at the same time as all biological sampling and included bottom depth, bottom-water temperature, surface-water temperature, species composition, weight (all species), and number (fish only). Latitudes and longitudes at the start of the haul were used to describe sampling station locations. Only trawls with good performance (catch >0) were included in analyses (Stauffer, 2004).

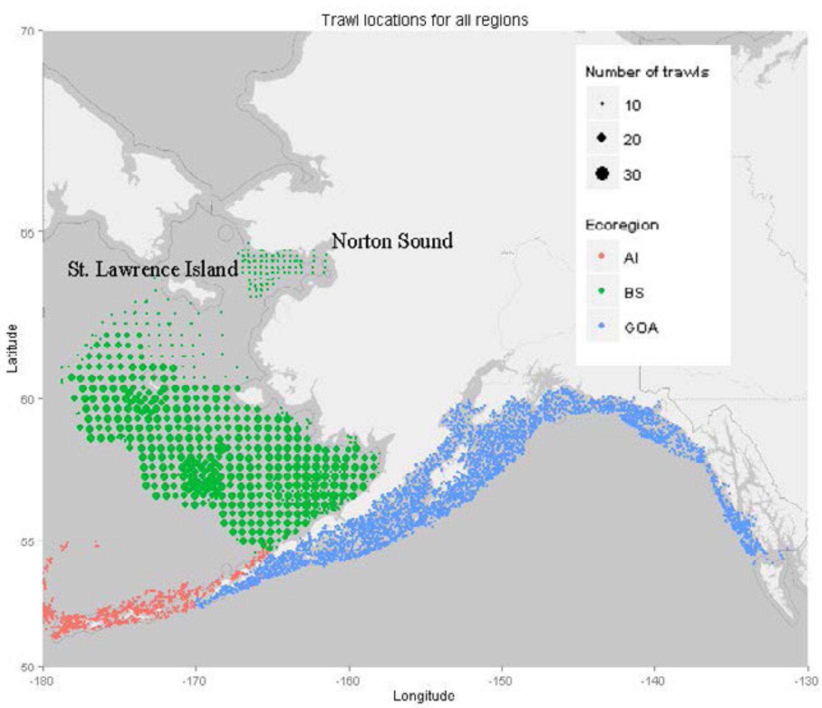

Figure 5.1. NOAA fishery-resource-assessment survey areas in the Eastern Bering Sea, Aleutian Islands, and Gulf of Alaska from NOAA RACE data collected between 1981 and 2006.

Trawls with haul depths inconsistent with reported station depths were excluded from analyses (n=6). Fish abundance is expressed in terms of catch (C in total numbers of individuals caught per station), relative abundance (numbers per kilometer), and density (numbers per kilometer and kilograms per hectare) in the RACE database. Initial examination of the trawl data revealed that the distributions of Arctic Cod and Saffron Cod were almost exclusively in the EBS (table 5.1). Therefore, species models were developed using only EBS station data (fig. 5.1).

Statistical and Modeling Approaches

Frequency histograms of bottom depths, bottom temperatures, and surface temperatures were created from data collected at all stations sampled in the EBS, AI, and GOA. The histograms were compared to similar summaries from all stations where Arctic Cod and Saffron Cod were collected, to describe the niche spaces sampled for each environmental variable. The initial histograms including data from all survey stations sampled compared with similar presentations for each species, allowed comparisons of the total marine environmental space sampled and the niche space of each species. Generalized additive models (GAMs) were used to more rigorously quantify the effects of depth and temperature on cod occurrences (presence/absence) and abundances. GAMs are smoothing models used to fit non-linear data using thin plate regression splines. All analyses were done in R 2.15.1 (R Core Team, 2012). The mixed GAM computation vehicle (*mgcv*) 1.7-18 package was used for the GAM analyses (Wood, 2003; 2006; 2011). A simultaneous confidence interval of 95 percent was used to delimit the credible regions (Wood, 2006) of each species simulated response to depth and temperature variables.

Only data collected from the EBS were used in the GAMs because Arctic Cod and Saffron Cod were rarely sampled in AI and GOA resource assessment areas. The observed effects of bottom temperatures (°C), surface temperatures (°C), bottom depths (m), and their interactions on abundance (C) as [ln (abundance + 1)] and distribution (presence/absence frequency of occurrence) were evaluated in the GAMs. Restricted maximum likelihood techniques were used to determine optimal smoothing functions in the regression analyses. The binomial family was used to estimate occurrence by depth and temperature relations. To select the best predictive model, we compared candidate GAM models with combinations of the three environmental variables including model runs with only one or two variables. Different smoothing functions also were evaluated. The best model for each fish species (occurrence and abundance) was selected from the candidate models using Akaike Information Criterion (AIC; Akaike, 1973). In addition to AIC, environmental-response curves were developed to select among models with similar AIC scores. Environmental response curves are a way of displaying model simulations. To generate these plots, the model was used to simulate a species probability of occurrence or abundance in relation to a single environmental variable while holding the other environmental variables constant.

Spatial Interpolation of Environmental Data

Data from the World Ocean Database (National Oceanic and Atmospheric Administration, 2009) were downloaded and analyzed to examine the content and structure of bottom and surface temperatures to potentially increase the spatial extent of model simulations. Various interpolation schemes were applied to these data and tested for compatibility with the environmental values in the NOAA RACE data. Paired t-tests indicated that these data were not sufficiently compatible with the NOAA RACE data to expand the spatial extent of model simulations with any reliability; therefore, for this research, model simulations were limited to coverage within a smaller spatial extent that could be reliably interpolated with the NOAA RACE environmental data.

The three environmental variables (bottom depth, bottom temperature, and surface temperature) from the NOAA RACE program were spatially interpolated to create continuous coverage raster grids describing these variables across the EBS. An Inverse Distance Weighted (IDW) interpolation was completed in ArcGIS 10. The physical data for spatial interpolation were collected from a network of circular sample areas (37 km radius) in accordance with a random sampling plan that included greater than or equal to 12 sample points per area. The size of the circular area for spatial data collection was selected to approximate the grid size used in the NOAA RACE fish monitoring design. The resolution of all layers was set to 4.7 km. The data were then clipped to a buffer around the edge of the regular set of sampling stations to reduce extraneous information. The clipped region does not include Norton Sound because this area was sampled only during 2 years and the temperature varied significantly between 1985 and 1991. Consequently, although all EBS trawls were used in model development and analysis, data in Norton Sound were determined to be too sparse to create an interpolated average for each of the environmental surfaces. The clipped region is the spatial extent of estimated distributions and abundances of the cod species.

Simulated Effects of Climate Warming

To compare the accuracy of the model simulations to the measured data, the best GAMs for each fish species were used to simulate cod distributions and abundances based on the spatial interpolations of the environmental data. To evaluate the potential effects of climate change on each species, +0.2 °C was incrementally added to every cell of the spatially interpolated bottom-water temperature layer until the total change measured a +2 °C increase. Bottom temperature was varied because this variable had the greatest influence on the distributions and abundances of each species in GAMs. At each increment, GAMs were applied to established frequency baselines to predict changes in distributions (probability of occurrence) and abundances [ln (abundance + 1)] of the Arctic Cod and Saffron Cod. The predicted changes described are for total habitat and estimated numbers of fish. Total probability is calculated as the cumulative sum of individual probabilities of occurrence estimated for each species in all the grid cells in the EBS. Because the GAMs underestimate abundance, the predicted effects of bottom temperatures are best considered as indicators of relative change. The predicted changes also are shown as habitat maps for each species.

Results and Discussion

Catch Characteristics of the RACE Surveys, 1982–2006

Physical and biological data from 18,470 trawl samples from NOAA surveys off Alaska were used to evaluate climate-warming effects on the distribution and abundance of Arctic Cod and Saffron Cod in the EBS. Trawl depths ranged from 0 to 1,000 m with most fish sampling occurring at stations located between 0 and 200 m. Bottom temperatures in the Bering Sea surveys ranged from 2 °C to about 14 °C with most measurements between 0 and 8 °C. Surface temperatures ranged from 0 to 16 °C with a few measurements indicating warmer temperatures.

Of the 9,423 trawls completed in the EBS between 1982 and 2006, about 10.5 percent or 901 trawls contained Arctic Cod (table 5.1). Arctic Cod were widely distributed across the shelf and were sampled in Norton Sound and southeast of St. Lawrence Island (fig. 5.2). Highest abundance was associated with the coldest bottom temperatures in northern parts of the study area.

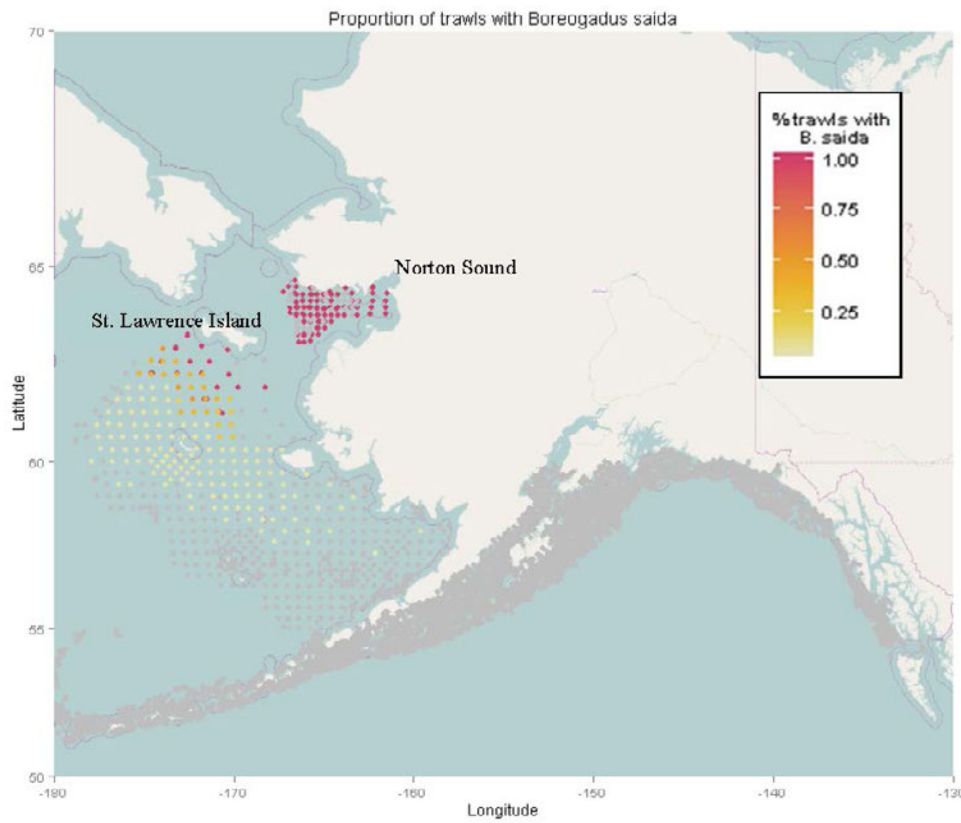

Figure 5.2. Locations where Arctic Cod (*Boreogadus saida*) samples were collected by NOAA in the eastern Bering Sea (source: NOAA RACE database, 1981–2006) (National Oceanic and Atmospheric Administration, 2013). The colors of the dots indicate the percentage of trawls in which Arctic Cod were captured. This analysis of presence-absence is possible because the same station locations are consistently sampled in the NOAA RACE resource assessment surveys. The NOAA RACE database includes samples collected in Norton Sound in 1985 (n = 74) and 1991 (n = 47).

In contrast, the highest abundance of Saffron Cod outside of Norton Sound was in Kuskokwim Bay and to the north and west of Nunivak Island (fig. 5.3). Saffron Cod were not collected in samples farther offshore (fig. 5.3). Of the 9,423 trawls completed by NOAA in the EBS, 5.7 percent or 531 trawls contained Saffron Cod (table 5.1). Both cod species were captured together in only about 1 percent or 109 trawls. About 81 percent or 89 of the 109 trawls that captured both cod species was in Norton Sound.

Table 5.1. Number of trawls completed by National Oceanic and Atmospheric Administration's marine fishery resource assessment completed where Arctic Cod and Saffron Cod were collected in the eastern Bering Sea, Aleutian Islands, and Gulf of Alaska.

Trawls	Eastern Bering Sea	Aleutian Islands	Gulf of Alaska
Total	9,423	3,202	5,845
Arctic Cod	901	0	0
Saffron Cod	531	0	7

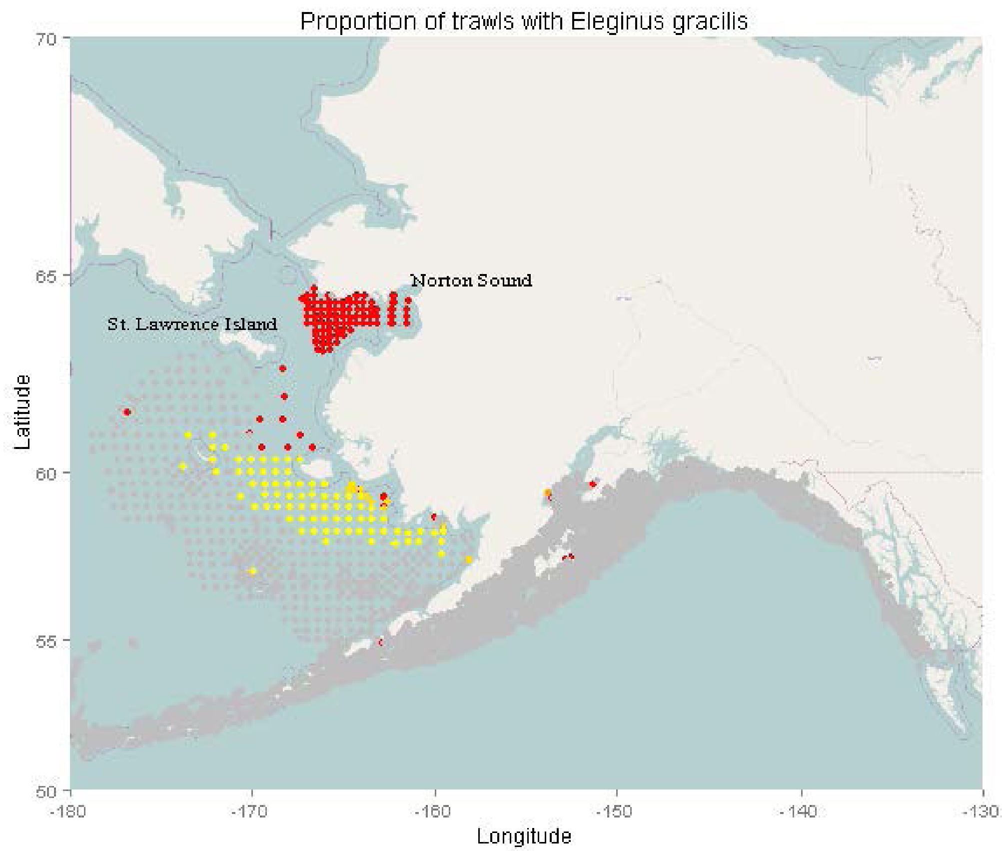

Figure 5.3. Locations where Saffron Cod (*Eleginus gracilis*) samples were collected by NOAA in the eastern Bering Sea (source: NOAA RACE database, 1981–2006) (National Oceanic and Atmospheric Administration, 2013). The colors of the dots indicate the percentage of trawls in which Saffron Cod were captured. This analysis of presence-absence is possible because the same station locations are consistently sampled in the NOAA RACE resource assessment surveys. The NOAA RACE database includes samples collected in Norton Sound in 1985 (n = 74) and 1991 (n = 47).

Environmental Variables and Models

The physical and biological variables reported in the NOAA surveys and used in this study are summarized in figure 5.4. The histograms present frequency data for selected measurements made throughout the three Alaska regions sampled (figs. 5.4a, d, g) and for capture sites of Arctic Cod (figs. 5.4b, e, h) and Saffron Cod (figs. 5.4c, f, i).

The catch data indicate some overlap in species distributions in shallow waters (figs. 5.4b and c), but distinct differences in their response to bottom temperatures (figs. 5.4e and f). Arctic Cod were most frequently found at trawl stations having bottom temperatures of less than about 3 °C (fig. 5.4e) and Saffron Cod were more frequently detected in warmer waters (fig. 5.4f). These distributional relations were further supported in the GAM analyses (appendix C). Overall,

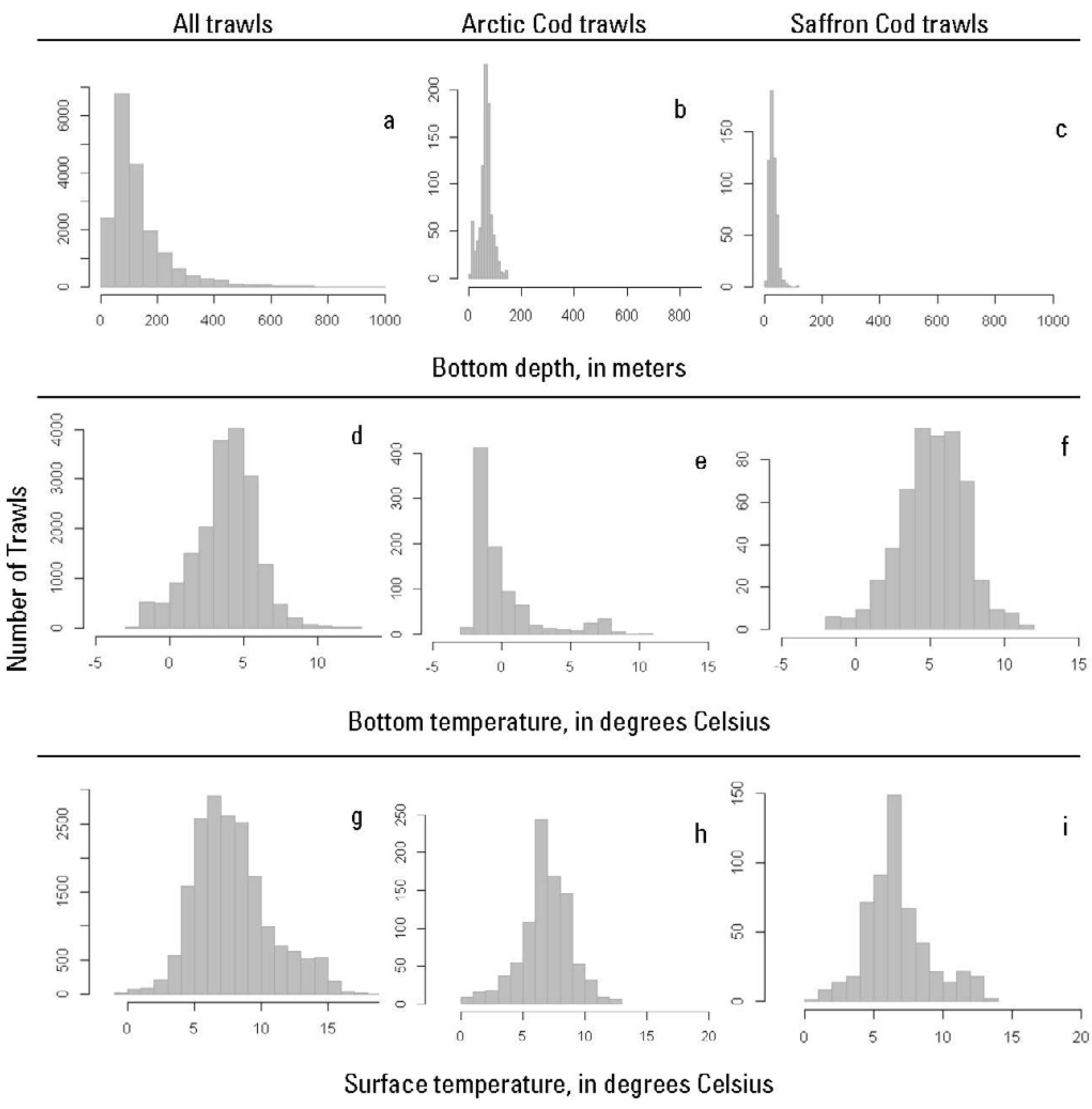

Figure 5.4. Histograms showing bottom depth, bottom temperature, and surface temperature for all trawl samples collected in eastern Bering Sea, Aleutian Islands, and Gulf of Alaska. Trawl samples include 901 Arctic Cod and 538 Saffron Cod. Total samples, 18,470.

the models that performed best (lowest AIC scores) for distribution and abundance of both species contained all three environmental variables. These models are highlighted in the tables included in appendix C. When individual physical variables were modeled as a predictor of abundance in the EBS, bottom temperature was the strongest single predictor with an $r^2 = 0.46$ for Arctic Cod, and $r^2 = 0.35$ for Saffron Cod. In comparison, surface temperature was the weakest single predictor with an $r^2 = 0.006$ and $r^2 = 0.11$ for Arctic Cod and Saffron Cod, respectively.

The southernmost edge of Arctic Cod distribution is coincident with the southern boundary of the cold pool and does not extend beyond the 2 °C isotherm in the EBS. The location of this isotherm and geography of the cold pool varies from year to year (fig. 5.5). The Arctic Cod distributional pattern relative to the cold pool is consistent with the results of our predictive distribution (occurrence by presence/absence) and abundance modeling (appendix tables C1, C4, and fig. 5.6), which indicates the species is not likely to occur at locations where bottom temperatures are much warmer than 2 °C (fig. 5.6c). Catch and model simulations indicate that Arctic Cod are most common on the inner shelf and that their abundance generally decreases from 0 to 200 m, with few fish predicted to occur at depths greater than 200 m (figs. 5.6a and b). A similar pattern of decreasing abundance with increasing bottom temperatures is evident in figure 5.6d. An interesting exception to this regional pattern occurred in the northern Bering Sea where the model predicted a slight increase in Arctic Cod abundance at bottom temperatures ranging between 2 and 4 °C, declining abundance as temperatures warmed to 7–8 °C, and a return to an increasing abundance pattern at temperatures higher than this. However, the uncertainty (dashed lines in fig. 5.6d) associated with estimated abundance at bottom temperatures greater than 4 °C is great and these results are questionable. The underlying statistical anomalies supporting abundance patterns in the northern Bering Sea may relate to interannual variations in hydrographic conditions across the northern Bering Sea shelf (Stabeno and others, 2012a; 2012b) and the associated interannual changes in the geographic extent of the cold pool. During warm years, the distribution of Arctic Cod would be geographically constricted in southern parts of its range providing at least a partial explanation for simulated abundance patterns in the northern Bering Sea. Arctic Cod responded to surface temperature with an optimal temperature of about 8 °C; however, this variable was less important than bottom temperature (figs. 5.6e and f).

The presence/absence model selected to develop environmental response curves for Saffron Cod was not determined to be the best fit as indicated by AIC score, but it seemed to perform better than others based on the environmental response curves (appendix table C5). The model performed well enough to predict the probability of occurrence ($r^2 = 0.42$), and overall, demonstrated that depth, surface temperature, and bottom temperature are major determinants of this species patterns of distribution and abundance (fig. 5.7). The model simulation results indicated that Saffron Cod prefer a warm, shallow habitat and that although bottom temperature is not a strong predictor of distribution (fig. 5.7), it is for abundance (fig. 5.7d).

The selected models were used to predict the probability of species' distribution and abundance in response to depth and temperature using the inverse distance weighted methods in ArcGIS 10 (fig. 5.8). The darkest area in figure 5.8b indicates the location of the cold pool.

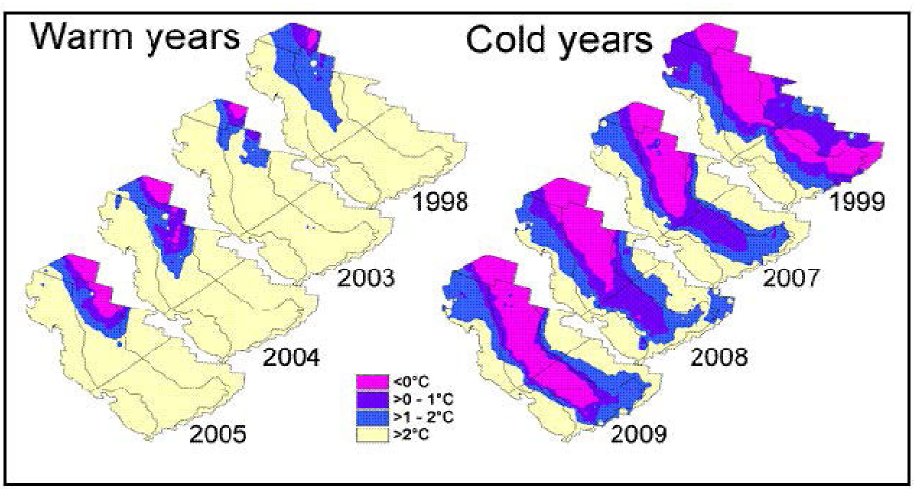

Figure 5.5. Average bottom temperatures from the bottom trawl survey comparing the extent of the cold pool (<2 °C) during years warmer and colder than the 1982–2008 grand mean, eastern Bering Sea shelf (National Oceanic and Atmospheric Administration, 2014).

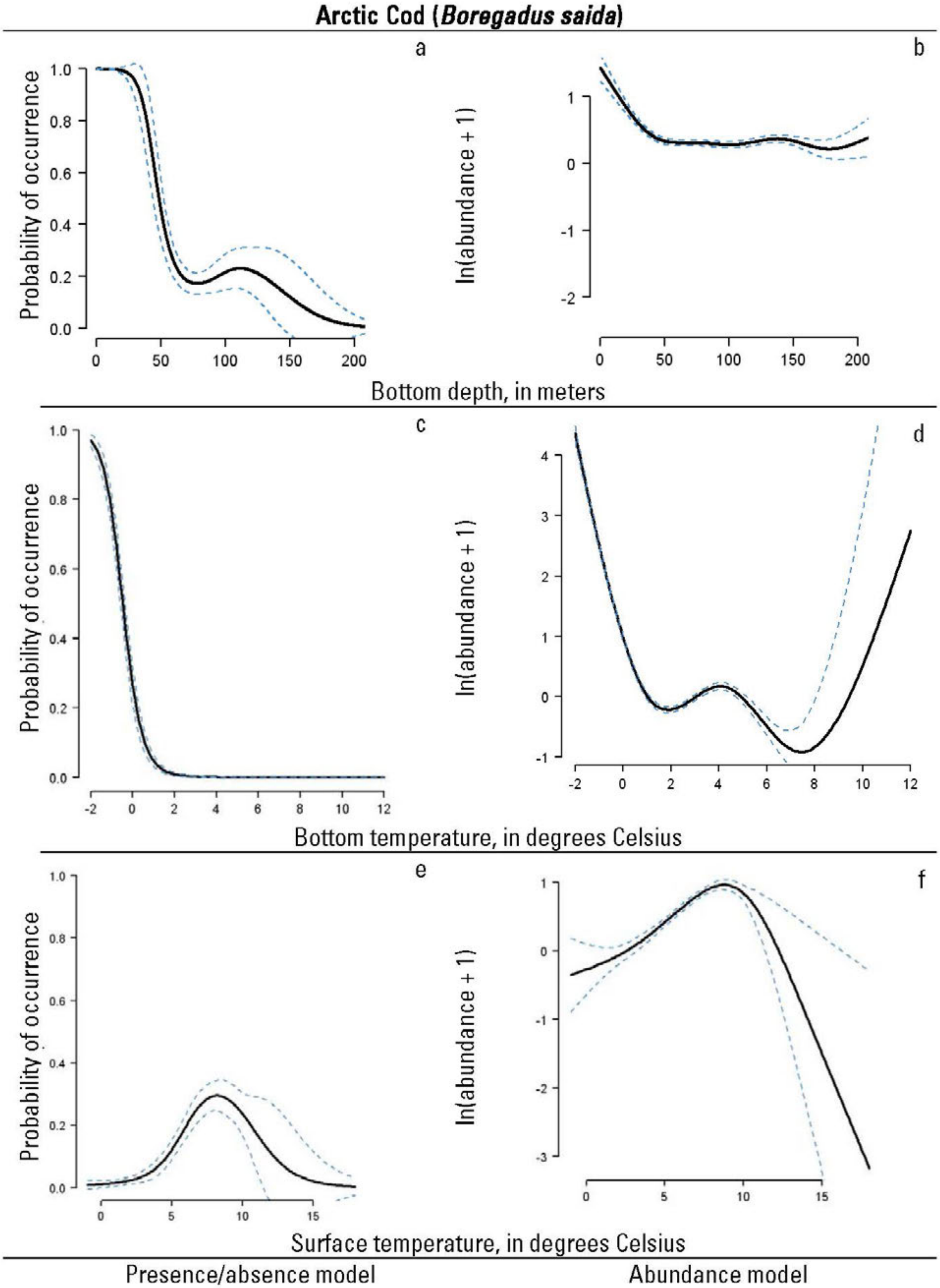

Figure 5.6. Environmental response curves for the selected presence/absence and abundance models for Arctic Cod in the eastern Bering Sea. Solid curves are the function estimates and dashed curves delimit the 95 percent confidence regions for each function.

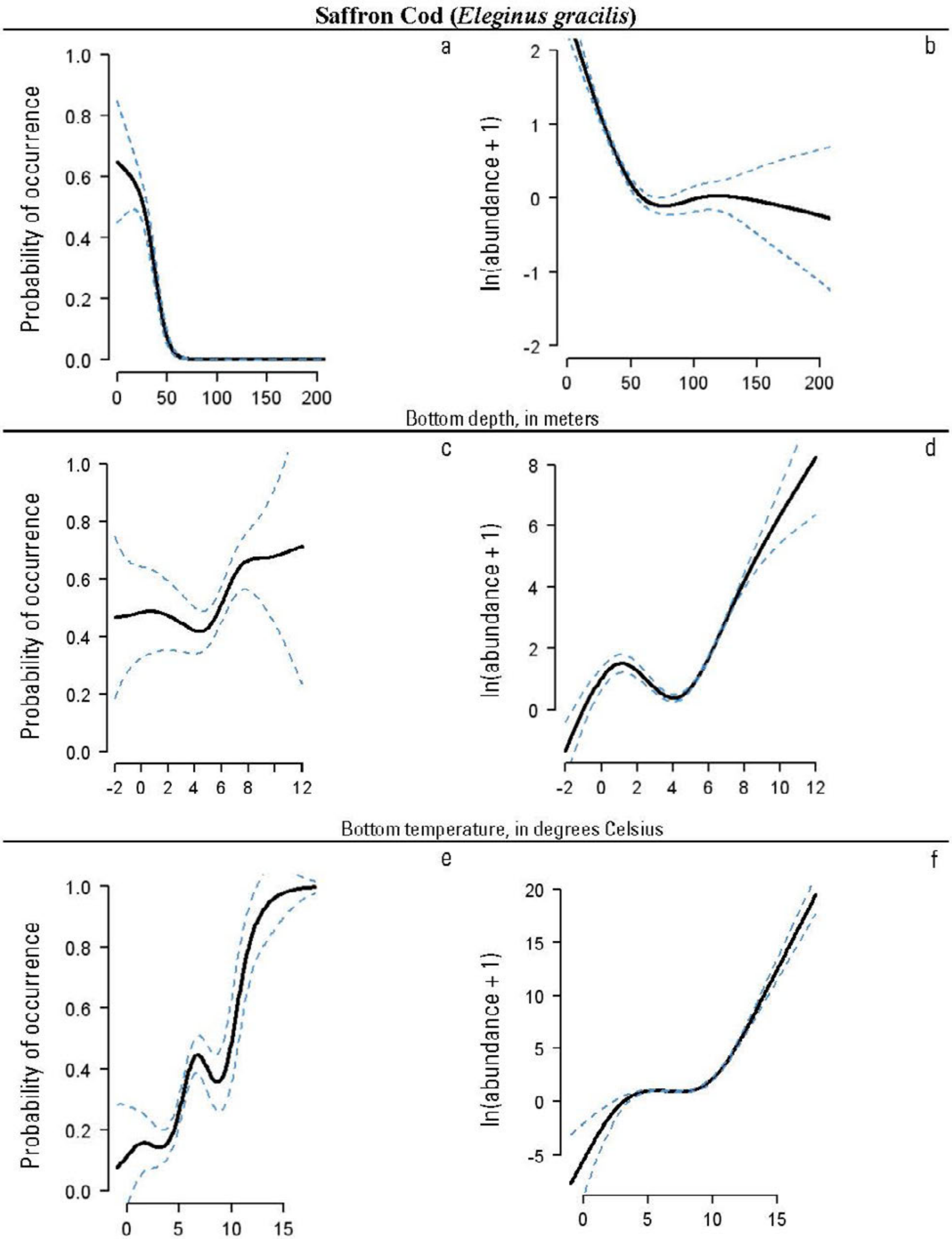

Figure 5.7. Environmental response curves for the selected presence/absence and abundance models for Saffron Cod in the eastern Bering Sea. Solid curves are the function estimates and dashed curves delimit the 95 percent confidence regions for each function.

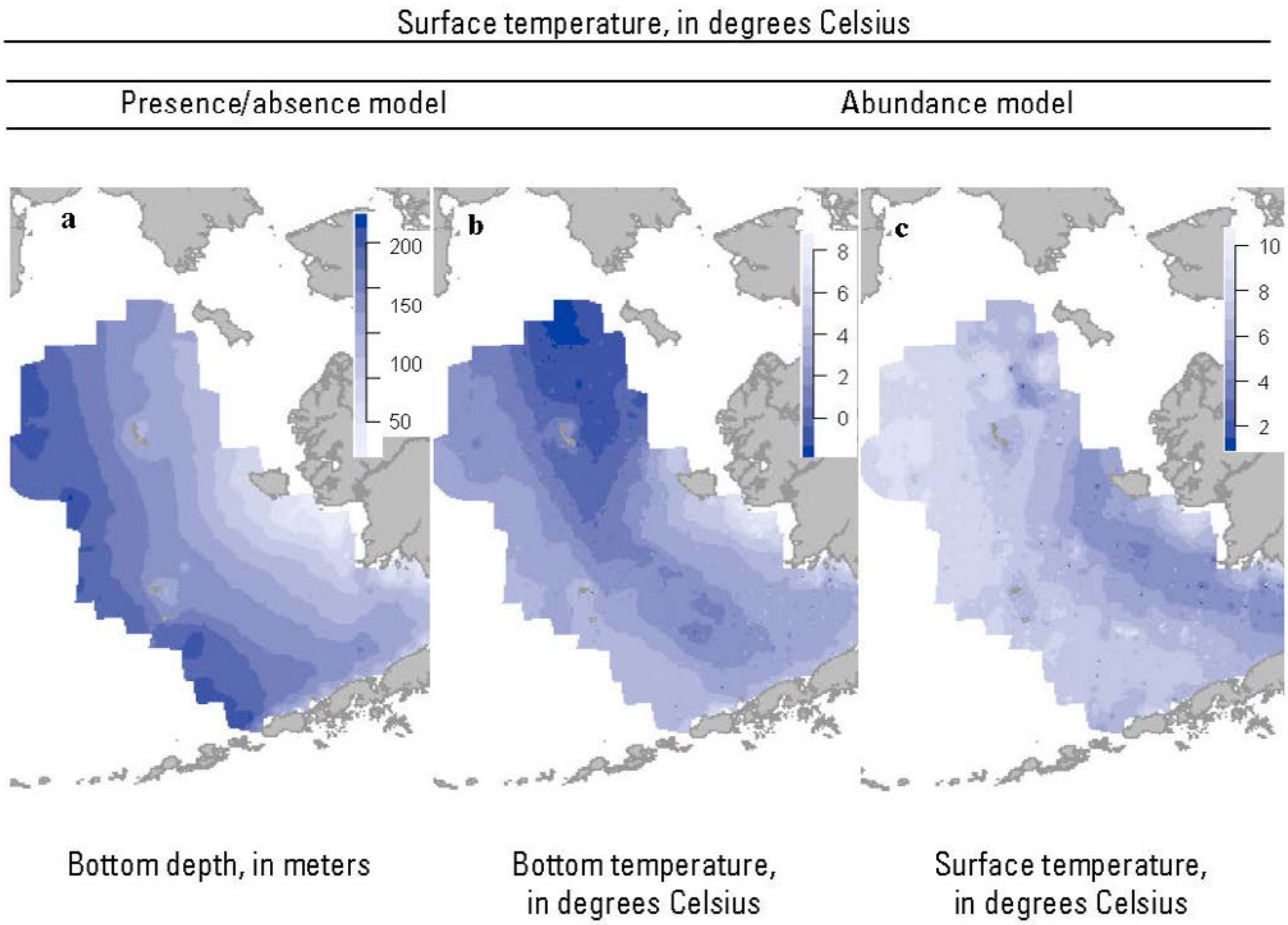

Figure 5.8. Physical description of the marine environment by (a) depth, and mean distributions of (b) bottom temperature, and (c) surface temperatures of the eastern Bering Sea (source: National Oceanic and Atmospheric Administration, 2012). Data from 1982–2006 interpolated using inverse distance weighted methods in ArcGIS 10.

Model performance was evaluated by making comparisons of the observed and simulated patterns of Arctic Cod distribution and abundance over shelf and slope habitats as determined by depth and temperature attributes (fig. 5.9). Generally, the models performed reasonably well with respect to regional spatial patterns although they tended to underestimate the observed distribution and abundance associated with NOAA's survey data. For example, the distribution of Arctic Cod presented in figure 5.9a closely approximates the model-predicted occurrence in figure 5.8b. The same relation holds true for abundance (figs. 5.9c and d).

The analysis of temperature effects on the distribution (fig. 5.10) and abundance (fig. 5.11, table 5.2) of Arctic Cod shows a gradual reduction in the species range in the EBS with warming bottom temperatures. As bottom temperatures increase, the model also showed how the cold pool contracts northward and predicted that Arctic Cod distributions will similarly shift northward in association with the disappearance of cold water habitats. The main concentration of Arctic Cod to the southwest of St. Lawrence Island almost completely disappears with an overall increase of 2 °C. There is great uncertainty associated with predictions of increasing abundance in the more southern areas of the species range, which reflects the difficulties of quantitative analysis with sparse datasets due to low detection rates of Arctic Cod in warmer environments.

The GAM models underestimated reported distribution and abundance patterns of Saffron Cod developed from NOAA catch data (fig. 5.12, table 5.3). For instance, the difference between observed and modeled patterns is especially evident in this species distribution in figures 5.12a and b. The reason for the difference may relate to the Saffron Cod's apparent restricted distribution near the Yukon Kuskokwim Delta and the limited sampling in the RACE surveys in nearshore environments of the inner shelf compared to offshore areas where commercial fisheries occur. The low frequency of Saffron Cod occurrence in trawl catches in deeper and colder parts of the EBS is probably responsible for the model's performance. It is important to remember that the value of the models is as a tool for simulating relative changes in response to changing environmental conditions (figs. 5.13 and 5.14).

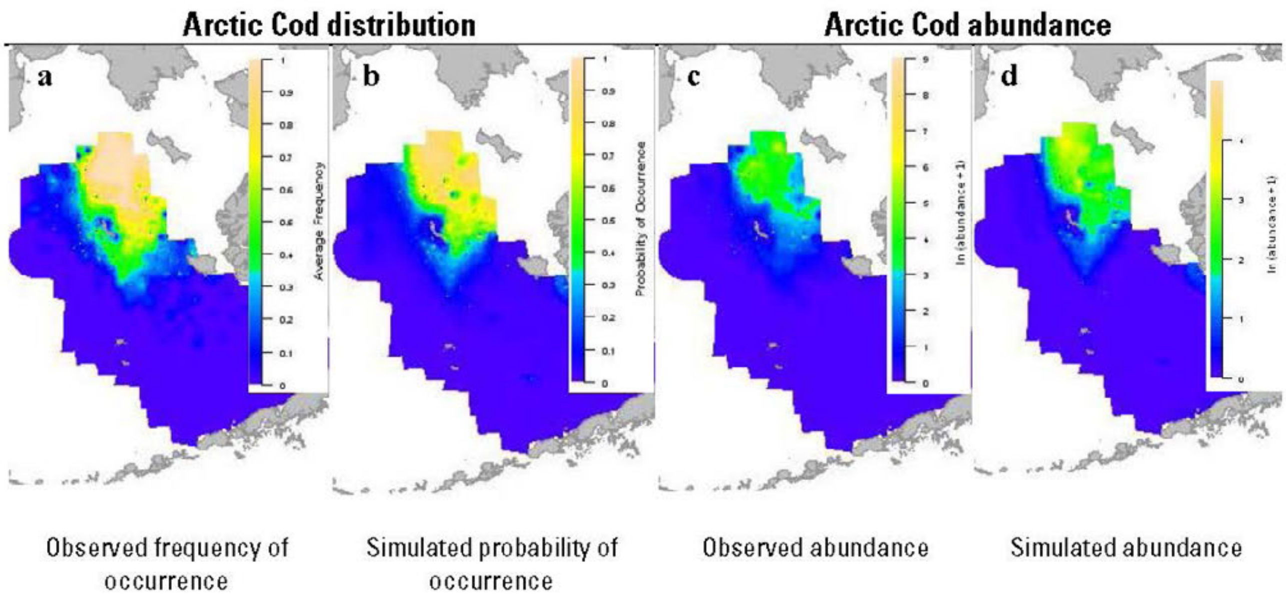

Figure 5.9. Observed and simulated distribution and abundance of Arctic Cod in the eastern Bering Sea (source: National Oceanic and Atmospheric Administration, 2012) . Simulations were generated using best performing Generalized Additive Models and fishery resource data from 1982 to 2006 (see appendix C).

Table 5.2. Changes in Arctic Cod habitat and relative abundance simulated with incremental warming of bottom temperature (+ 0.2 °C increments) and where surface temperature and depth are constant in the eastern Bering Sea.

[°C, degrees Celsius]

Simulated change in total Arctic Cod habitat			Simulated change in Arctic Cod abundance	
Temperature increase (°C)	Total probability	Total area (percent)	Total abundance (number of fish)	Relative abundance compared to time zero (percent)
Time Zero	3,274	12.12	39,416	100
0.2	2,825	10.45	27,884	71
0.4	2,397	8.87	19,950	51
0.6	2,002	7.41	14,525	37
0.8	1,654	6.12	10,857	28
1.0	1,363	5.05	8,434	21
1.2	1,137	4.21	6,922	18
1.4	974	3.61	6,083	15
1.6	869	3.22	5,757	15
1.8	811	3.00	5,833	15
2.0	790	2.92	6,212	16

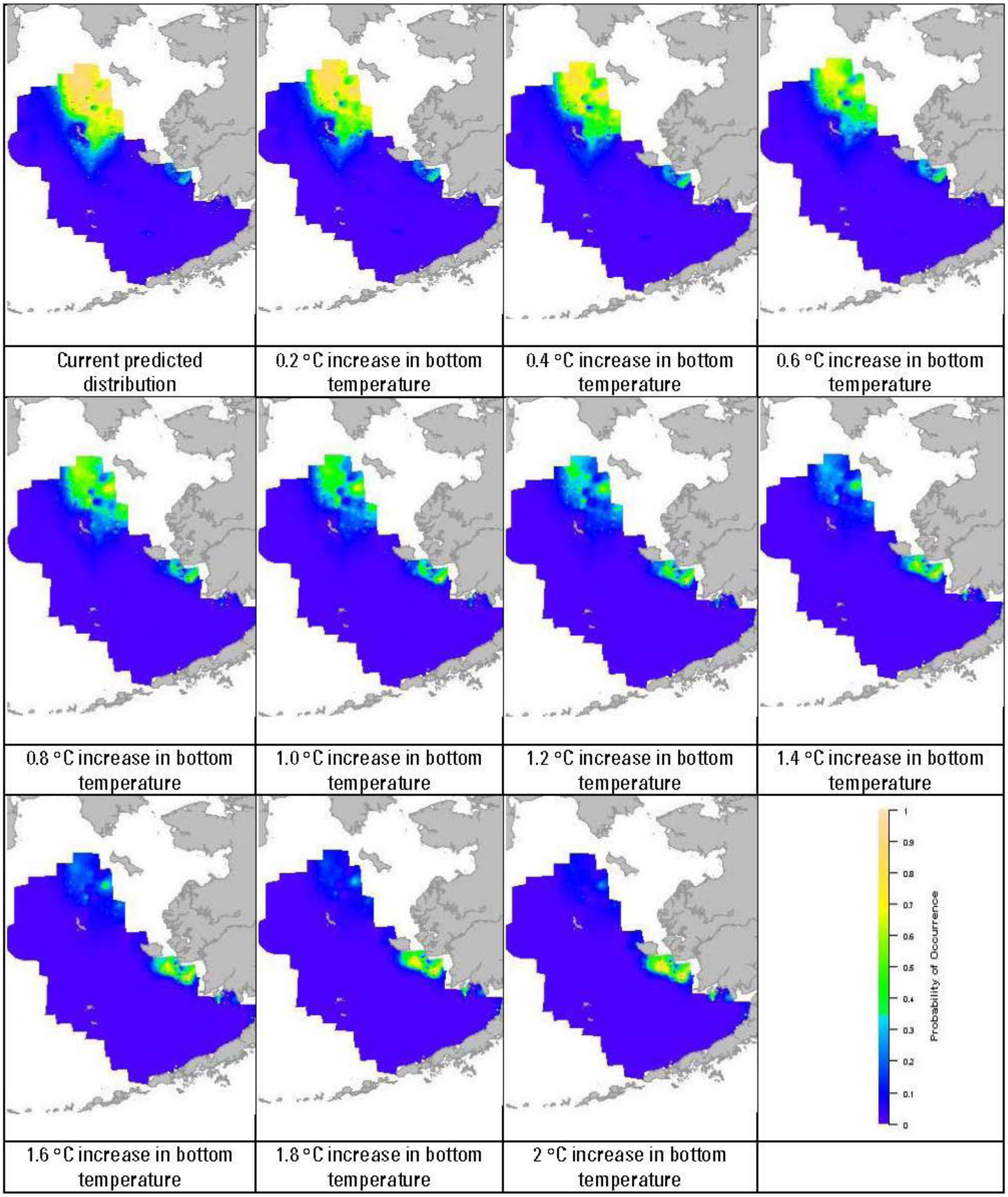

Figure 5.10. Changes in the distribution of Arctic Cod (probability of occurrence) in the eastern Bering Sea as simulated bottom temperatures increase in 0.2 °C increments.

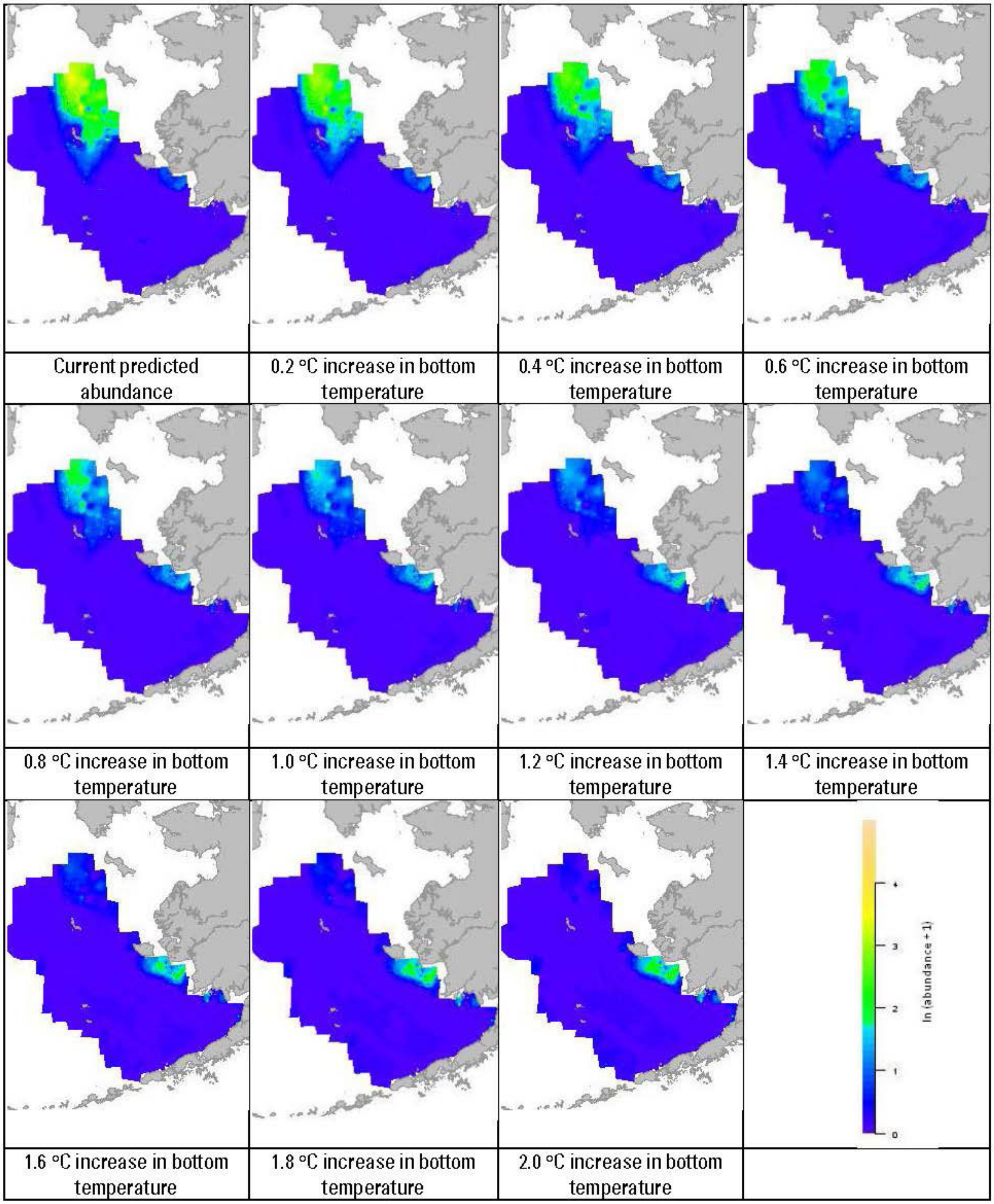

Figure 5.11. Changes in the abundance of Arctic Cod in the eastern Bering Sea as simulated bottom temperatures increase in 0.2 °C increments.

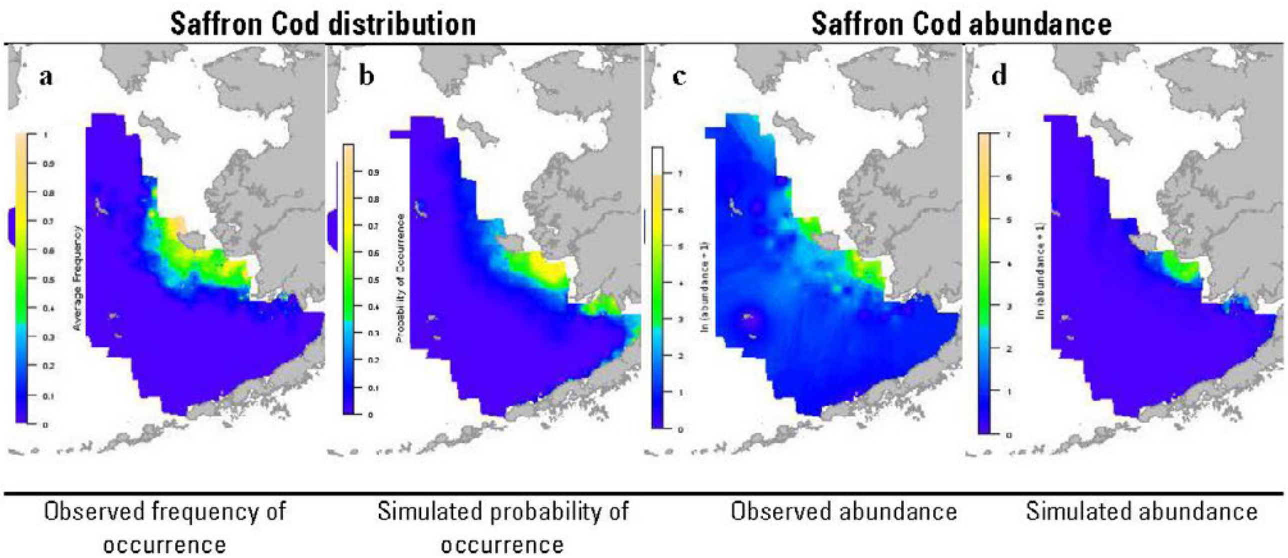

Figure 5.12. Observed and simulated distribution and abundance of Saffron Cod in the eastern Bering Sea (source: National Oceanic and Atmospheric Administration, 2012; fishery resource data from 1982–2006). Simulations were generated using best performing GAM models (see appendix C).

Table 5.3. Changes in Saffron Cod habitat and relative abundance simulated with incremental warming of bottom temperature (+0.2 °C increments) and where surface temperature and depth are constant in the eastern Bering Sea.

[°C, degrees Celsius]

Simulated change in total Saffron Cod habitat			Simulated change in Saffron Cod abundance	
Temperature increase (°C)	Total probability	Total area (percent)	Total abundance (number of fish)	Relative abundance compared to time zero (percent)
Time Zero	1,487	2.83	14,139	100
0.2	1,499	3.08	18,493	131
0.4	1,516	3.29	24,362	172
0.6	1,537	3.49	32,216	228
0.8	1,562	3.69	42,649	302
1.0	1,593	3.89	56,400	399
1.2	1,628	4.08	74,371	526
1.4	1,667	4.26	97,638	691
1.6	1,710	4.48	127,454	901
1.8	1,757	4.74	165,274	1,169
2.0	1,806	3.92	212,793	1,505

The models for Saffron Cod and Arctic Cod predict increases in the range and abundance in and around Kuskokwim Bay as bottom temperatures increase. This is probably a modeling artifact for Arctic Cod but not for Saffron Cod. The model simulation results shown in figures 5.12 and 5.13 suggest that habitats more suitable for Saffron Cod than for Arctic Cod would be created with warming bottom temperatures. The models predicted an increase in Saffron Cod distribution to the north, south, and offshore (fig. 5.12) to and potentially at depths greater than 50 m beyond the outer boundary of the coastal domain described for EBS (Kinder and Schumacher, 1981). Similarly, as bottom temperatures increase, Saffron Cod abundance shows a gradual increase in Kuskokwim Bay northward beyond Nunivak Island, south to Bristol Bay and farther offshore (fig. 5.13).

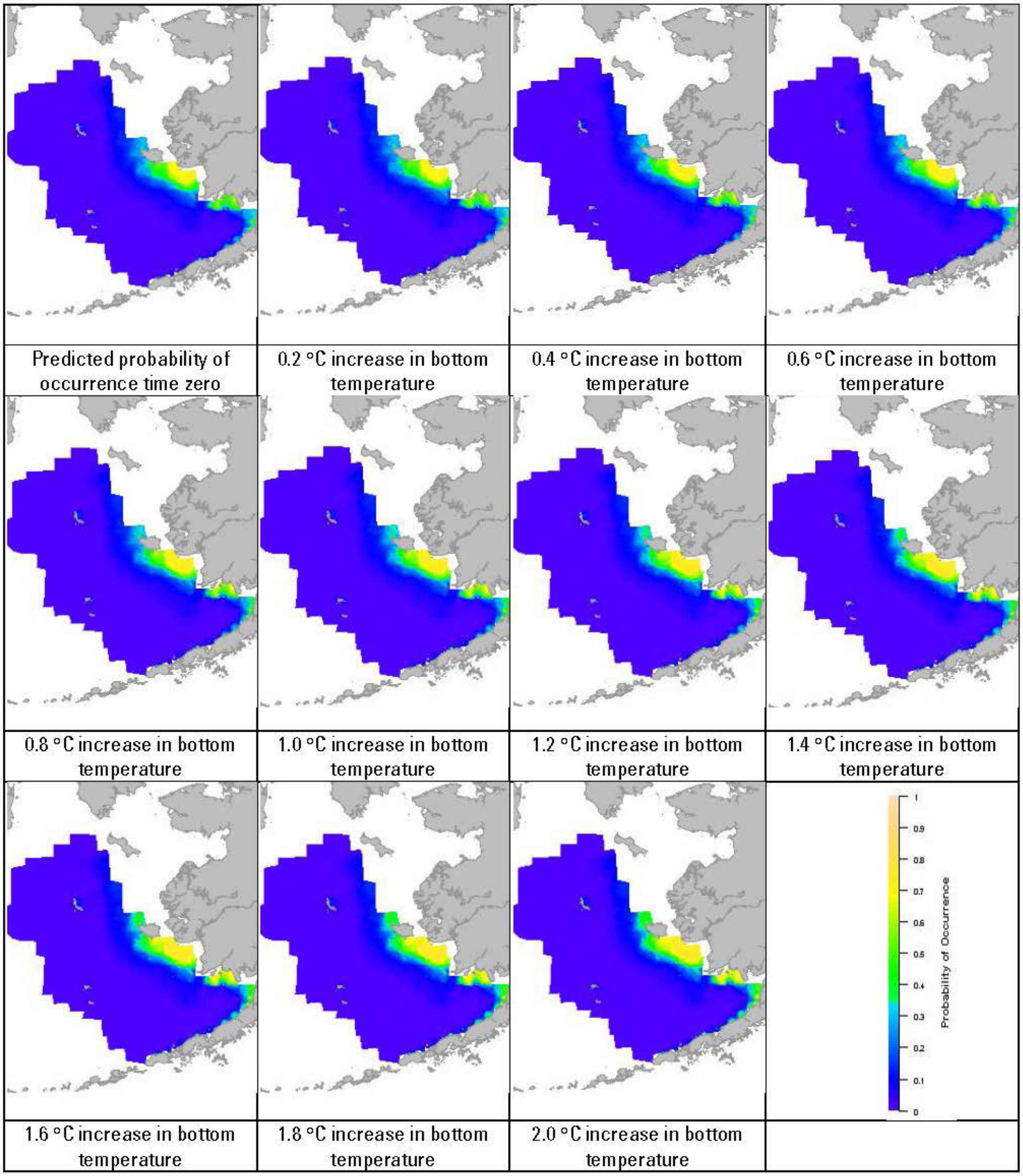

Figure 5.13. Changes in the distribution of Arctic Cod (probability of occurrence) in the eastern Bering Sea simulated as bottom temperatures increase in 0.2 °C increments.

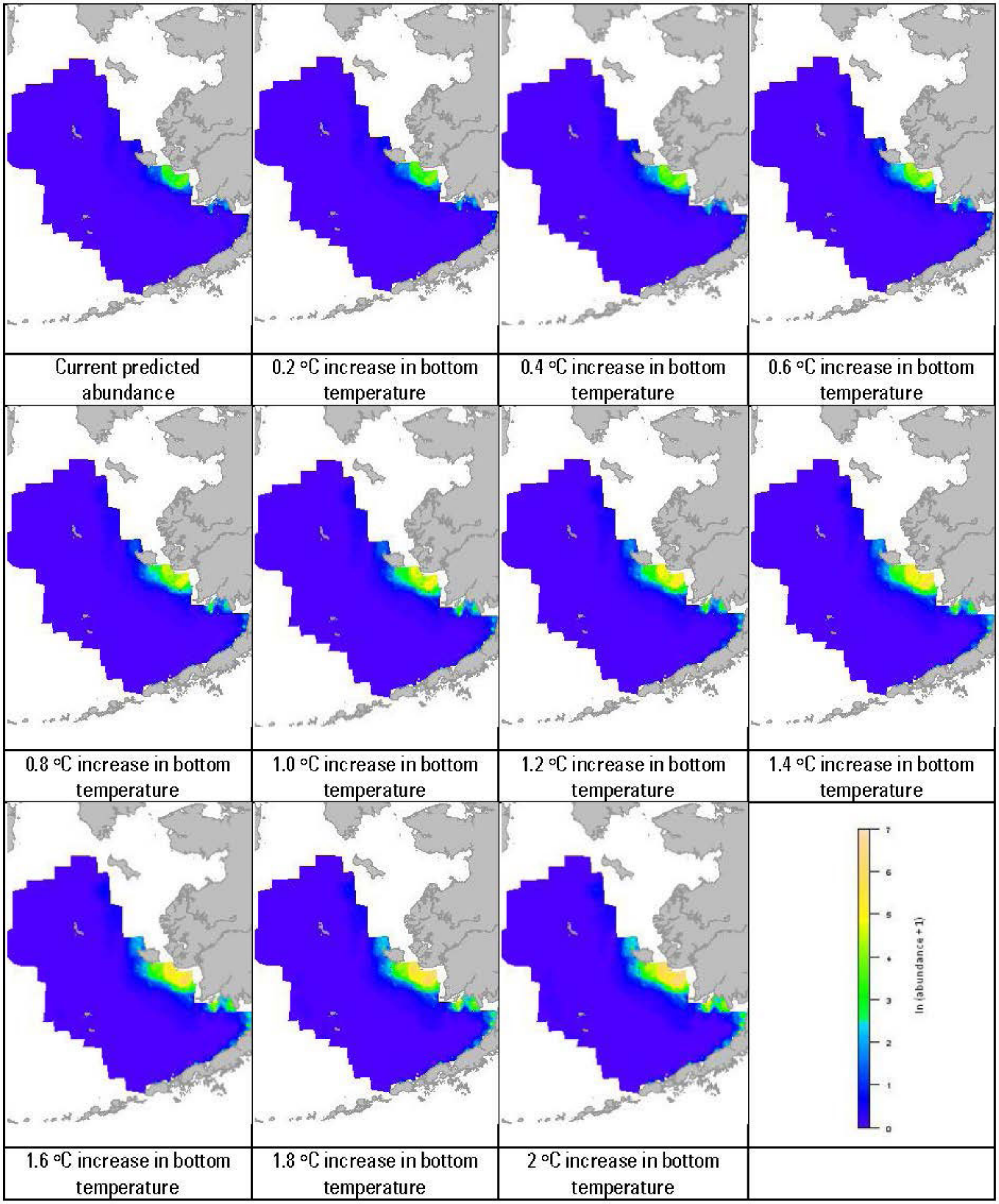

Figure 5.14. Changes in the abundance of Saffron Cod in the eastern Bering Sea simulated as bottom temperatures increase in 0.2 °C increments.

Norton Sound

The NOAA RACE database accessed herein included 2 years (1985 and 1991) of data collected from Norton Sound. Although Arctic Cod were frequently caught in the trawl catches, the thermal environmental conditions seem to be different to the preferred ranges suggested in figure 5.4. Mean bottom temperatures in the Norton Sound trawls were relatively warm in both years (7 °C in 1985 and 6.1 °C in 1991) and, on first inspection, seem to approach or exceed the upper limits of thermal preferentia for this species. Perhaps this result reflects greater thermal tolerance for this species than described by the RACE data set. The occurrence of Arctic Cod also could be indicative of bathymetric migrations, habitat differences by life cycle stages, or other kinds of ecological benefits conferred by warmer waters. An example of the latter could be physiological (for example, growth) or related to increased prey abundance that overrides optimal temperature preferences.

The model outputs would also suggest that, because the mean bottom temperature decreased from 7 °C in 1985 to 6.1 °C in 1991, the distribution and abundance of Arctic Cod should have increased. However, although mean bottom temperatures showed a 0.85 °C decrease between 1985 and 1991, the presence and abundance of Arctic Cod also decreased from 65 of 74 trawls in 1985 to 24 of 47 trawls in 1991. Likewise, the average number of Arctic Cod per trawl in Norton Sound in 1985 was 82.7 compared to 6.9 in 1991. Corresponding changes in surface temperatures, however, showed an opposite trend with a mean temperature of 6.6 °C in 1985 and 11.7 °C in 1991.

Although Arctic Cod in Norton Sound generally respond negatively to increases in bottom temperatures, other factor(s), such as food abundance, may be involved. The large volumes of freshwater discharged by the Yukon and Kuskokwim Rivers creates hydrographic conditions in Norton Sound that may be similar to conditions in the nearshore Alaska Beaufort Sea in summer. The regional comparison is significant in that Arctic Cod are a common, if not dominant species, in nearshore waters farther north. Their occurrence in marine and brackish habitats of the Beaufort Sea has been related to invertebrate-driven food webs that are also important in Norton Sound (Thorsteinson and others, 1989). In comparison, the mean abundance and distribution of Saffron Cod remained about the same in 1985 and 1991 despite the observed environmental changes. A potential future project could include improving the models as more data become available in this area and farther north.

Arctic Applications

The overlap in habitats of Arctic Cod and Saffron Cod is much greater in the Chukchi and Beaufort Seas (chapter 3) than has been described for the EBS. However, because of the incomplete nature of fishery data from the high Arctic, it is difficult to describe how changing distribution patterns might affect interactions between these species. It is known that Arctic Cod play a keystone role in the bioenergetics of Arctic food webs as a consumer of primary and higher levels of biological production and are a significant prey resource for many marine fishes, birds, and mammals. The potential for large-scale changes in the forage base of the Chukchi and Beaufort Seas suggests the possibility for cascading ecosystem effects and corresponding needs for long-term and multivariate approaches to data collection and greater attention to scientific goals for population and functional understanding. A broadening of the ecological lens in climate change modeling is needed to understand the adaptive capacity and resilience of these species and their interaction with others. Although Arctic and Saffron cods are not currently of commercial importance in North America, their ecological and subsistence values are considerable and worthy of marine indicator status. Environmental changes that affect their distribution and abundance could alter the structure and function of the marine ecosystem and change the traditional and economic uses of these and other organisms in Arctic food webs.

The SDM results suggest that based on warming temperatures, without viewing climate effects more broadly, similar distributional changes as predicted for the EBS might be projected for the Chukchi and Beaufort Seas. These changes include a constriction in range to the north in Arctic Cod and a similar expansion in range to the north by Saffron Cod. Warming of bottom temperatures in the northern Bering Sea can be expected to result in other large-scale shifts in distributions of other marine fishes including Walleye Pollock, a species that, although presently known from the Chukchi and western Beaufort Seas, seems to be limited in numbers and biological condition in cold-water environments. Pollock are extremely abundant in the EBS and the comparatively low relative abundances of Arctic Cod and Saffron Cod relates to the zoogeographic boundary in the northern Bering Sea discussed in chapters 2 and 4. The observed distribution and abundance data from the EBS suggests that deeper shelf and upper slope habitats are not occupied by Arctic Cod, in contrast to distribution and abundance in the Chukchi and Beaufort Seas, which suggests predation and other competitive processes with Pollock and other species, in addition to temperature, may be occurring.

Favorable environmental temperatures associated with possible large-scale changes toward more pelagic regimes over the Chukchi Sea shelf could result in difficult to estimate changes in predator-prey dynamics and species composition of regional fish assemblages (Grebmeier and others, 2006a). Questions about the stock composition in Arctic Cod and Saffron Cod populations and areas of life history importance (for example, spawning locations) are currently outstanding and thus expansions to the north would not necessarily translate to the Arctic Cod's extirpation from the Chukchi Sea. Movements to deeper, colder and more stable marine environments might remove these species from easily accessible coastal fishing areas, or at least make harvest more difficult, for subsistence users.

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Summary

The GAMs generated using NOAA's RACE survey data appear to be sufficiently dynamic to simulate the general response of Arctic Cod and Saffron Cod to climate-related changes in deeper shelf waters of the EBS. The modeling results suggest that both species likely will be affected by global warming trends, but in different ways. Analysis of fish catch and bottom water temperature data from the NOAA surveys further suggest that the southern boundaries of the cold pool in EBS vary annually in spatial extent and generally correspond to the southern range limit of Arctic Cod, an endemic Arctic species. It is hypothesized that Arctic Cod distribution in the northern Bering Sea will shift (contract) to the north with warming bottom temperatures. The presence of sea ice in the Bering Sea during winter and persistent cold bottom temperatures to the south of St. Lawrence Island will likely dampen this warming effect for the foreseeable future.

The model simulations presented in this chapter support this premise and indicate that Arctic Cod are sensitive to changes in bottom temperature and depth. For example, the model simulations indicate that small increases in bottom temperature will dramatically reduce their distribution and abundance. Significantly, a 2 °C increase in bottom temperatures is expected to reduce Arctic Cod distribution in the EBS by approximately 80 percent and its relative abundance by 90 percent. By comparison, the model simulations indicate a nearly opposite effect on Saffron Cod. Their distribution, with a 2 °C increase in bottom temperatures, would be expected to expand by approximately 28 percent with a corresponding increase in abundance of 92 percent. As data become available, the application of GAMs in the Chukchi and Beaufort Seas would enhance assessments of effects of climate change on marine ecosystems and subsistence in regions where Arctic Cod, and to a lesser extent Saffron Cod, are more important in food web dynamics.

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