Prepared in cooperation with Bureau of Ocean Energy Management, Environmental Studies Program (OCS Study, BOEM 2016-048)

Alaska Arctic Marine Fish Ecology Catalog

Scientific Investigations Report 2016–5038

U.S. Department of the Interior
U.S. Geological Survey

Bureau of Ocean Energy Management

Cover: Photographs of various fish studied for this report. Background photograph shows Arctic icebergs and ice floes. Photograph from iStock™, dated March 23, 2011.

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By Lyman K. Thorsteinson and Milton S. Love, editors

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

[Inch/Pound to International System of Units]

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

[International Systems of Units to Inch/Pound]

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic kilometer per year (km^3/yr)	0.000811	acre-foot per year (acre-ft/yr)
kilometer per day (km/d)	0.6214	mile per day (mi/d)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
	Density	
kilogram per hectare (kg/ha)	0.06242	pound per cubic foot (lb/ft^3)
gram carbon per square meter (g C/m^3)	62.4220	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

ACW	Alaska Coastal Water
ADFG	Alaska Department of Fish and Game
AFGP	antifreeze blycoprotein
AFP	antifreeze protein
AFS	American Fisheries Society
AFS-ASIH	American Fisheries Society-American Society of Ichthyologists and Herpetologists
AFSC	Alaska Fisheries Science Center
AI	Aleutian Islands
AIC	Akaike information criterion
AMAP	Arctic Monitoring and Assessment Programme
AO	Arctic Oscillation
AW	Anadyr Water
AOOS	Alaska Ocean Observing System
ArcOD	Arctic Ocean Diversity
BSW	Bering Sea Water
BOEM	Bureau of Ocean Energy Management
C	carbon
Cl^-	chloride
CO_2	carbon dioxide
CoML	Census of Marine Life
CPUE	catch-per-unit-effort
DBO	Distributed Biological Observatory DIDSON. Dual Frequency Identification Sonar
DOI	U.S. Department of the Interior
EBSA	Ecological and Biologically Sensitive Area
eDNA	environmental DNA
EIS	Environmental Impact Statement
EEZ	U.S. Exclusive Economic Zone
EBS	Eastern Bering Sea
EPA	U.S. Environmental Protection Agency
FL	fork length
GAM	Generalized Additive Model
GI	ganodosomal index
GOA	Gulf of Alaska
IARPC	Interagency Arctic Research Policy Commission
IDW	Inverse Distance Weighted interpolation
ITIS	Integrated Taxonomic Information System
LME	large marine ecosystem
M	natural mortality
Ma	million years
MCA	Metabolic Cold Adaptation

Abbreviations—Continued

MMS	Minerals Management Service
Na^+	sodium
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
NPFMC	North Pacific Fisheries Management Council
NPRB	North Pacific Research Board
NSF	National Science Foundation
OA	ocean acidification
OBIS	Ocean Biogeographic Information System
OCS	Outer Continental Shelf
OR1	Online Resource 1
psu	practical salinity unit
RACE	Research Assessment and Conservation Engineering
rm	intrinsic rate of increase
RUSALCA	Russian-American Long-term Census of the Arctic
SDM	species distribution model
SL	standard length
SST	sea surface temperature
T	Trophic Index
TL	total length
tm	age at first maturity
UAF	University of Alaska, Fairbanks
USCGC	U.S. Coast Guard Cutter
USGS	U.S. Geological Survey
VBGM	von Bertalanffy growth model
WFRC	USGS Western Fisheries Research Center
YOY	young-of-the-year

Chapter 1. Alaska Arctic Marine Fish Ecology Catalog—Chukchi and Beaufort Seas

By Lyman K. Thorsteinson[1]

Abstract

The marine fishes in waters of the United States north of the Bering Strait have received new and increased scientific attention over the past decade (2005–15) in conjunction with frontier qualities of the region and societal concerns about the effects of Arctic climate change. Commercial fisheries are negligible in the Chukchi and Beaufort Seas, but many marine species have important traditional and cultural values to Alaska Native residents. Although baseline conditions are rapidly changing, effective decisions about research and monitoring investments must be based on reliable information and plausible future scenarios. For the first time, this synthesis presents a comprehensive evaluation of the marine fish fauna from both seas in a single reference. Although many unknowns and uncertainties remain in the scientific understanding, information presented here is foundational with respect to understanding marine ecosystems and addressing dual missions of the U.S. Department of the Interior for energy development and resource conservation. This chapter describes the Department's information need with respect to planned offshore oil and gas development, provides an overview of the *Alaska Arctic Marine Fish Ecology Catalog*, and presents regional background information, synthesis methodologies, and definitions for commonly used terms and concepts throughout the report.

Introduction

Accurate natural resource inventories and knowledge of baseline conditions for Arctic resources and ecosystems are essential for estimating effects of the U.S. Department of the Interior (DOI) offshore oil and gas-leasing program. The exploration and development of these offshore resources is managed by the DOI Bureau of Ocean Energy Management (BOEM). This document, *Alaska Arctic Marine Fish Ecology Catalog*, addresses a specific need of BOEM to inform its decision making with respect to the fisheries ecosystems in Arctic Outer Continental Shelf (OCS) Planning Areas. This report is a compilation of species accounts of the marine fishes known from United States sectors of the Chukchi and Beaufort Seas. Certain diadromous (for example, Pacific salmon, char, and whitefishes) species are treated as marine fishes (McDowall, 1987) because much of their life cycle is in marine and brackish environments. This synthesis of information is meant to provide current information and understanding of this fauna and its relative vulnerability to changing Arctic conditions.

The National Environmental Policy Act (NEPA) requires the BOEM to prepare an Environmental Impact Statement (EIS) for each offshore oil and gas lease sale area offered through the DOI leasing program. The EISs provide an assessment of the potential environmental effects associated with major development proposals and communicate this information to decision-makers and the broader public (Wood, 2008). In complying with the NEPA, the BOEM relies on the best available science to evaluate potential effects on regional ecosystems and living resources. Our objectives were to review and synthesize current fish biology, ecology, and fisheries information to assist BOEM's NEPA analysts in assessing environmental effects from planned future offshore oil and gas development on the Arctic OCS.

BOEM's NEPA analysts require detailed information about the biodiversity, life history, and population ecology of regional biota to assess adversity of impact in the EIS process. For Arctic marine fishes, impact is evaluated in terms of potential declines in abundance or changes in geographic distribution and recovery of populations to pre-impact status (thresholds of significance analysis, see Miner and Rivasplata, 1994, and Musick, 1999). To illustrate, adverse effects would require three of more generations for a population to recover (Bureau of Ocean Energy Management Regulation and Enforcement, 2011). The population understanding required for a robust EIS analysis is similar to what is required to assess Essential Fish Habitat under provisions of the Magnuson-Stevens Fishery Conservation and Management Act.

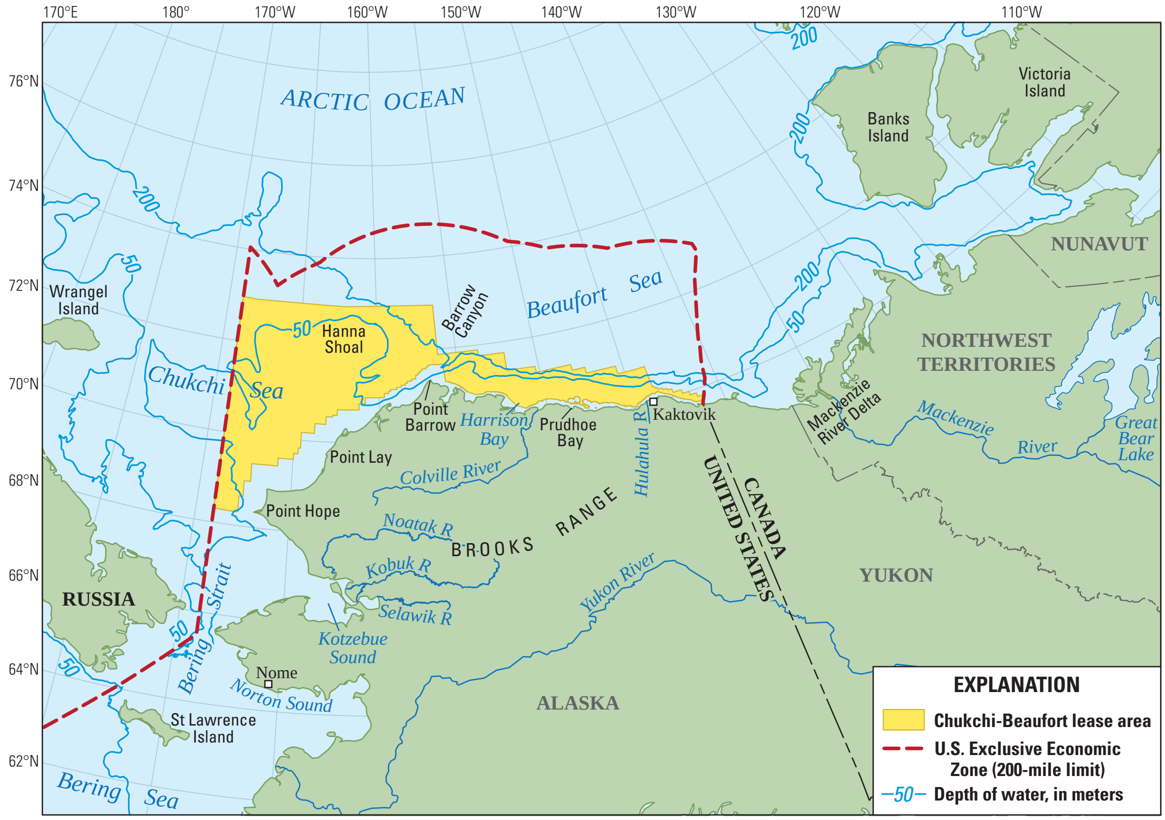
[1]U.S. Geological Survey.

The compilation of species information provides BOEM's NEPA analysts and others with a single, authoritative scientific reference about the biology and ecology of marine fishes in the United States Chukchi and Beaufort Seas. Biodiversity is broadly assessed with respect to current understanding of (1) classification and taxonomy, (2) abundance and geographic distribution, and (3) life history and population ecology. A focus of this study has been on new information and discoveries about this fauna since the publication of *Fishes of Alaska* (Mecklenburg and others, 2002). As such, the species checklist, geographic distribution maps, and depth profiles represent new biodiversity products to science. This synthesis is unique because it is based on confirmed species occurrences in United States sectors of the Chukchi and Beaufort Seas. Confirmation is an important process because it assures the reliability of resource information in management areas of direct concern to decision makers. For most species, the link between occurrence and abundance remains tenuous given the nature of sampling conducted to date. As such, quantitative aspects of the dynamics of fish populations and their interactions with the Arctic marine environment are hindered by inadequacies of existing data and relative lack of Alaskan records. The emphasis on population dynamics and ecologic relationships in the species accounts provides an important basis for assessment of outstanding needs.

Although knowledge about the marine fish fauna in the Alaska Arctic is among the poorest in the state, it has been slowly improving over time. However, much life history information presented in this report was acquired from scientific observations outside Alaska. As such, basic taxonomic science and population understanding is needed to support modern assessments and potential fisheries in the Arctic high seas. The goals of this report are to present the most current information about what is known about the marine fishes in the Arctic area of the United States with a special focus on geographic distributions, vertical structure, abundance, and life history parameters of key populations. The section, "Outline of Species Accounts" in chapter 3 serves as a users' guide to information presented in the individual species descriptions.

Study Area

The primary geographical boundaries encompass Arctic OCS Planning Areas (Bureau of Ocean Energy Management (2012) in the U.S. Chukchi and Beaufort Seas (hereafter Chukchi and Beaufort Seas, fig. 1.1) and the U.S. Exclusive Economic Zone (EEZ) including the Arctic Management Area. The eastern boundary of the Beaufort Sea EEZ extends to the north and offshore of the Alaska-Canada Border. The Chukchi Sea extends from Point Barrow in Alaska and the Beaufort Sea in the east to the United States–Russia Maritime Boundary in the west. The Bering Strait forms the southern boundary of the Chukchi Sea. Some chapters, especially those addressing species descriptions (chapter 3) and discussing species diversity and possible geographic origins (chapter 4), include comparative information from adjacent seas and broader basin and ocean considerations, respectively.



Base modified from USGS and other digital data. U.S.-Russia Maritime Boundary follows the EEZ/200-mile limit line, western edge. Coordinate reference system: projection, Lambert Azimuthal Equal Area; latitude of origin, 75.0°; horizontal datum, North American Datum of 1983.

0 50 100 200 MILES
0 50 100 200 KILOMETERS

Figure 1.1. Bureau of Ocean Energy Management administrative boundaries for Outer Continental Shelf oil and gas leasing in the Chukchi and Beaufort Seas, Alaska.

Environmental Setting

Physical and biological components of the Arctic marine environment as they relate to marine regional descriptions of fish habitats and their use by fish and other biota were described by DeGange and Thorsteinson (2011)[2]. The descriptions of physical oceanography, substrates, and biological productivity supporting marine fish habitats and populations are primarily based on this review. Information about the distribution of Arctic marine birds and mammals, potential competitors and predators of marine fishes, is not reported here but is available in DeGange and Thorsteinson (2011).

Regional Oceanography

Large-scale features of the Chukchi and Beaufort Seas oceanography were reviewed by Weingartner and others (2008). Surface circulation in the Beaufort Sea is dominated by the southern edge of the perpetual clockwise Beaufort Gyre of the Canadian Basin (fig. 1.2). The subsurface Beaufort Undercurrent Atlantic water masses and flows in the opposite direction, to the east, over the shelf (fig. 1.2). Bering Sea waters generally follow topography, moving north across the Chukchi Sea shelf and to the east over the shelf edge and slope (fig. 1.2). Currents in the shallower waters of the inner Beaufort Sea Shelf (fig. 1.2) primarily are wind driven and, thus, can flow either east or west. Because the predominant wind direction during the summer ice-free season is from the east, near-shore flow generally is from east to west.

Oceanographers have observed regional, seasonal, and interannual variability in water mass properties in the Chukchi and Beaufort Seas. Generally, the temperature and salinity characteristics of the major water masses are:

- Alaska Coastal Water—warm (2–13 °C), low salinity (to 32.2 practical salinity units [psu]);
- Bering Sea Water—warm (>0.0 °C); well-mixed and moderate salinity (about 32.5 psu;
- Anadyr Water—cold (<0.0 °C), marine salinities (32.8–33.2 psu);
- Siberian coastal waters—cold (<0.0 °C), low salinity (24 psu);
- Atlantic Water (at depths > 220 m)—warm (>0 °C), highly salinity (>34 psu); and
- Beaufort Gyre—cold (<0.0 °C), moderate to high salinity (31–34 psu).

In the Chukchi Sea, the summer water masses are cold in the east and warm in the west. Similarly, warm brackish waters (5–10 °C, <15 psu) occur adjacent to Alaska's north coast during summer (to about 10 km off the coast) and cold marine waters (<1 °C, 28 psu) farther offshore.

Under persistent east winds, bottom marine water can move onshore, where it is forced to the surface. This upwelling of marine water can cause some otherwise brackish and warm areas along the coast to become colder and more saline. This replacement of brackish with marine waters results in the transport of warmer, less saline waters offshore.

The Chukchi Sea receives water that flows northward through the Bering Strait, driven by the 0.5 m drop in sea level between the Aleutian Basin of the Bering Sea and the Arctic Ocean (fig. 1.2). Coachman and others (1975) provide a good overview of the northward movement of Bering Sea waters into the Chukchi Sea. Three distinct water masses, each of different origin, move northward through the Bering Strait. Anadyr Water, cold, high salinity, nutrient-laden oceanic water that originates along the slope of the Bering Sea Shelf, flows northward through Anadyr Strait, west of St. Lawrence Island and into the central Chukchi Sea (fig. 1.2). As much as 72 percent of the water transported through the Bering Strait in the summer may come through Anadyr Strait. Alaska Coastal Water originates in the Gulf of Alaska. This low salinity, seasonally warm water hugs the Alaska coast as it transits the Bering Sea into the Chukchi Sea. Alaska Coastal Water is influenced by freshwater run-off from major rivers in western Alaska. Bering Shelf Water is the resident water mass of the central shelf region south of St. Lawrence Island. This water mass is intermediate with respect to its hydrographic properties when compared to Anadyr Water and Alaska Coastal Water, is advected northward on both sides of St. Lawrence Island, and then flows through the Bering Strait where it mixes with the other water masses. These waters are an important source of plankton and carbon in the Chukchi and Beaufort Seas, and influence the seasonal distribution and abundance of marine biota and migration behaviors of many species (Piatt and Springer, 2003; Hopcroft and others, 2008; Weingartner and others, 2008; Crawford and others, 2012). The deep waters offshore in the northern Chukchi Sea also are a potentially important source of nutrient-rich waters.

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[2]This review of large-scale physical oceanography was guided by DeGange and Thorsteinson (2011) who presented information previously reported in Minerals Management Service (2008) and Weingartner and others (2008). The summaries of primary and secondary levels of ecosystem production are from Bluhm and others (2008), Hopcroft and others (2008), Stockwell and others (2008), and Yager and others (2008). Other key references included Carmack and Wassmann (2006); Grebmeier and Maslowski, 2014; Moore and Stabeno, 2015; and Grebmeier and others (2015).

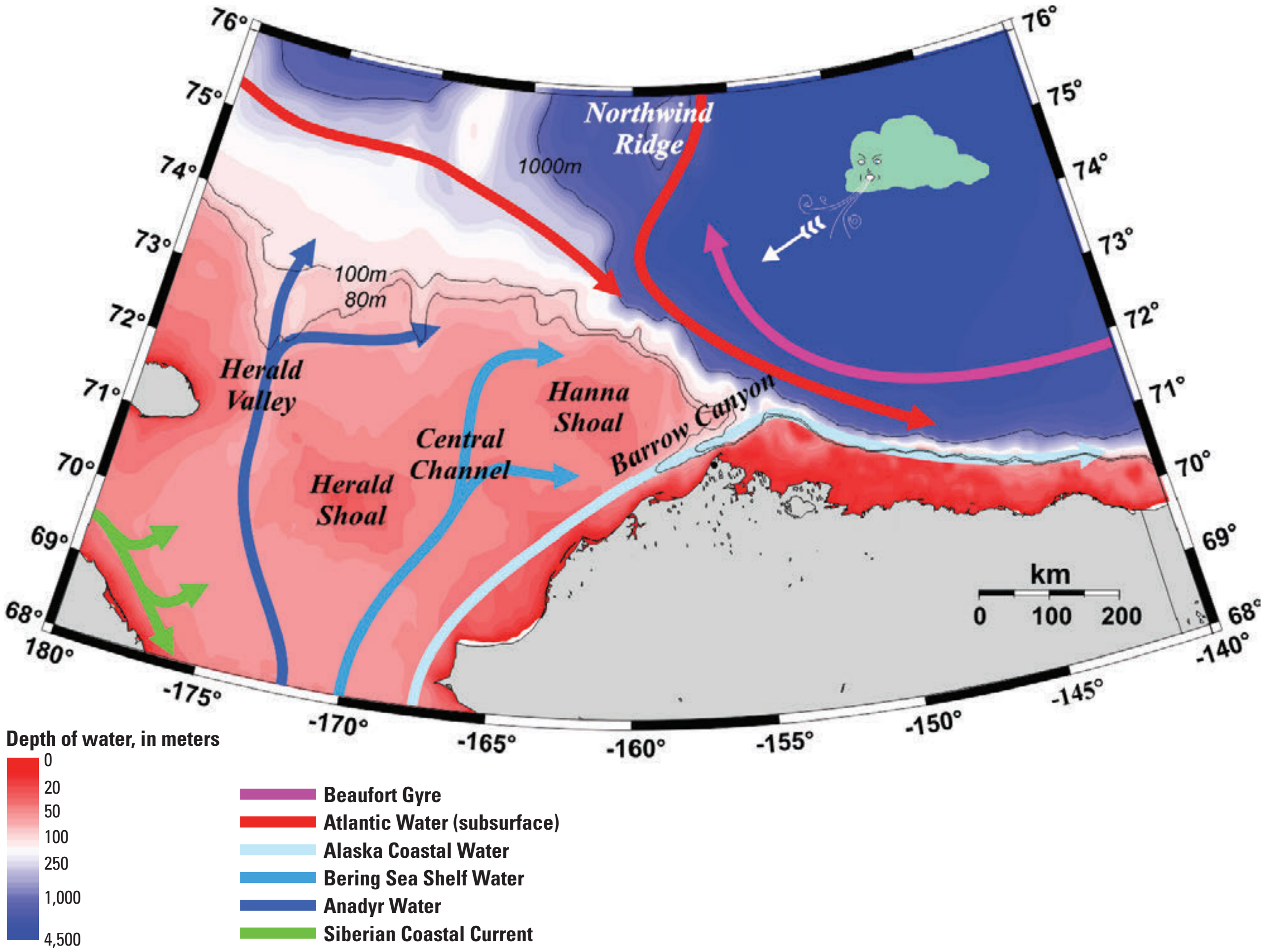

Figure 1.2. Schematic circulation map of the northern Chukchi Sea and western Beaufort Sea. From Weingartner and others (2008).

Bering Sea Cold Pool

Mecklenburg and others (2011) described the boundaries of an "*arctic region*" to include the Arctic Ocean and its seas and adjacent waters of the North Atlantic and North Pacific southward to an ichthyofaunal boundary (Arctic–Boreal species in chapter 2). Mecklenburg and others (2011, p. 110) reported that, "*...position of the boundary is reflected in major differences in species composition associated with seafloor topography, such as sills and canyons, and water characteristics, such as temperature and salinity, that form barriers against fish movements.*" In the northern Bering Sea, the location of the 2 °C isotherm during summer months, generally south of St. Lawrence Island, demarks this zoogeographic boundary and the northern edge, or ecotone, of marine waters associated with the Bering Sea cold pool (bottom temperatures ≤ 2 °C) that relates to the seasonal presence of sea ice (see chapters 4 and 5).

Sea Ice Dynamics

The presence of ice in the Arctic is one of the most important physical conditions to deal with for developing offshore OCS oil and gas resources. The seasonal sea ice cycle is a pervasive force in the Arctic, influences human activities and many aspects of the region's natural history, and demonstrates great seasonal and inter-annual variability off the coast of Alaska. Generally, there are two forms of sea ice: fast ice that is anchored along the shore and free-floating pack ice that moves with winds and currents. Shore fast and pack ice interact to cause an extensive, somewhat predictable, system of flaw leads (swathes of open water in between ice) and polynyas off the coasts of the Chukchi and Beaufort Seas eastward to the Canadian Archipelago. These flaw leads and polynyas become more prevalent in spring and are biologically significant features with respect to the timing and location of seasonal movements and northward migrations of wildlife species, such as bowhead whales and marine birds.

Maximum sea-ice cover occurs in March or early April, lagging minimum insolation in late December by 3 months because of the heat capacity of the ocean and the cold atmosphere. During these months, essentially all of the Beaufort and Chukchi Seas are ice-covered (fig. 1.3). Winter ice extent in the Arctic has decreased since the late 1970s (fig. 1.3) along the southern margins of sea-ice extent, but not severely (fig. 1.4). Maximum retreat of the sea ice occurs in September, again lagging maximum insolation by about 3 months. The extent of sea-ice loss in Septembers since the satellite record began has been remarkable (fig. 1.5). By September, in normal years, the ice pulls away from the Arctic coasts of Canada, Alaska, and Siberia, leaving a nearly continuous, relatively ice-free corridor that varies in width around the permanent ice pack. In recent years (2010–15), the ice-free corridor has expanded to hundreds of kilometers in the East Siberian Sea and offshore of the northern Alaska coast. The contrasts between 1980, a representative year with extensive ice cover, and 1987, when sea-ice extent in the Arctic was at a record minimum, and the long-term median ice edge are evident (fig. 1.5).

In addition to decreases in sea-ice extent during late summer and autumn, the amount of multi-year compared with summer sea ice in the Arctic also is changing; conditions are moving toward an abundance of younger and thinner sea ice (figs. 1.3–1.6). The longer sea ice remains in the Arctic Ocean the thicker it becomes because of additional freezing and deformation. The thinning of Arctic Ocean sea ice has occurred largely because of the export of older, thicker sea ice out of the Arctic through Fram Strait, east of Greenland. This is important because young, thin ice is more vulnerable to the melting that results from warm air and water temperatures, perpetuating a feedback cycle because the open ocean absorbs solar insolation.

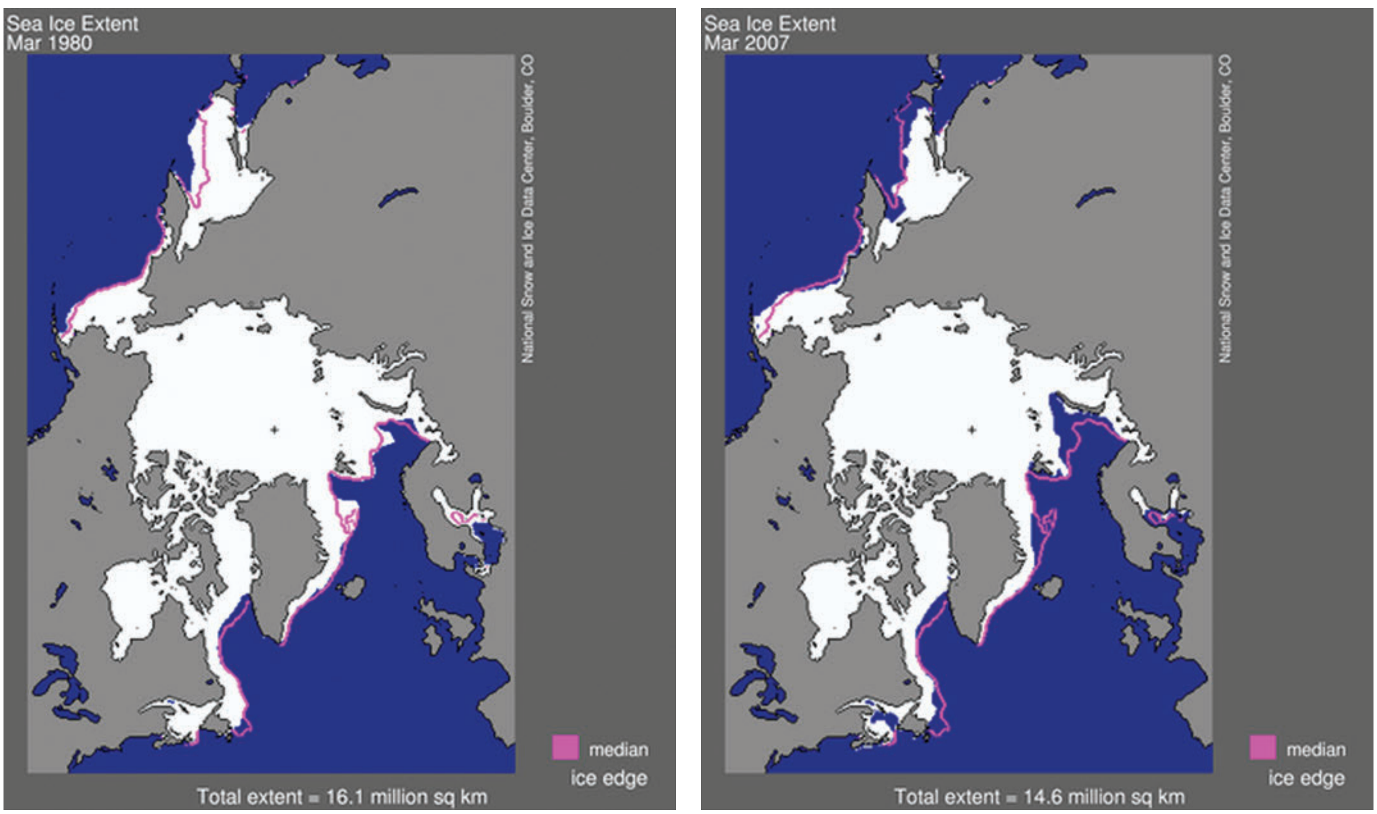

Figure 1.3. Extent of sea ice for single months and single years, using 1980 as an example of an extensive ice cover year, and 2007 as the record minimum year—maximum winter extent. The border plots the long-term median ice edge based on data from 1979 to 2000. From National Snow and Ice Data Center, 2011a, monthly sea ice extent for 1980 and 2007: National Snow and Ice Data Center database, accessed April 15, 2011, at http://nsidc.org/.

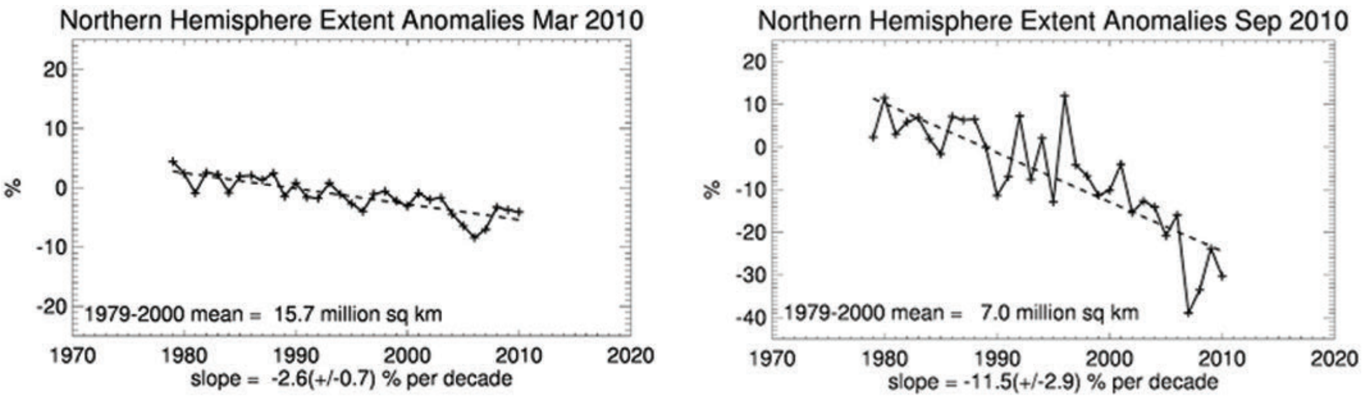

Figure 1.4. Sea-ice extent anomalies for March (maximum sea-ice extent) and September (minimal sea-ice extent) expressed as percentage-departure from average (that is, anomalies as compared to the 1979–2000 mean). From National Snow and Ice Data Center (2011b).

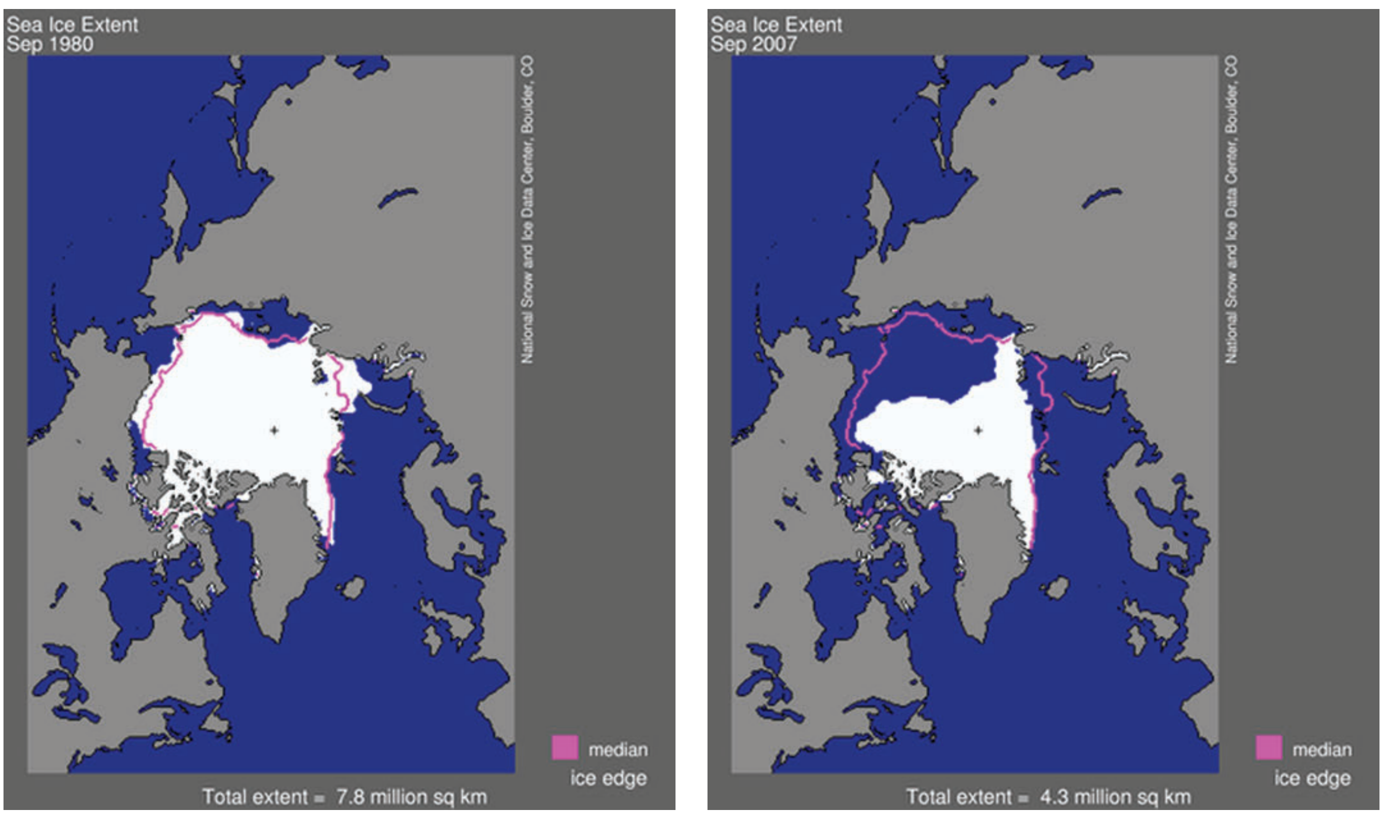

Figure 1.5. Extent of sea ice for single months and single years, using 1980 as an example of an extensive ice cover year, and 2007 as the record minimum year. The border plots the long-term median ice edge based on data from 1979 to 2000. Source: National Snow and Ice Data Center (2011a).

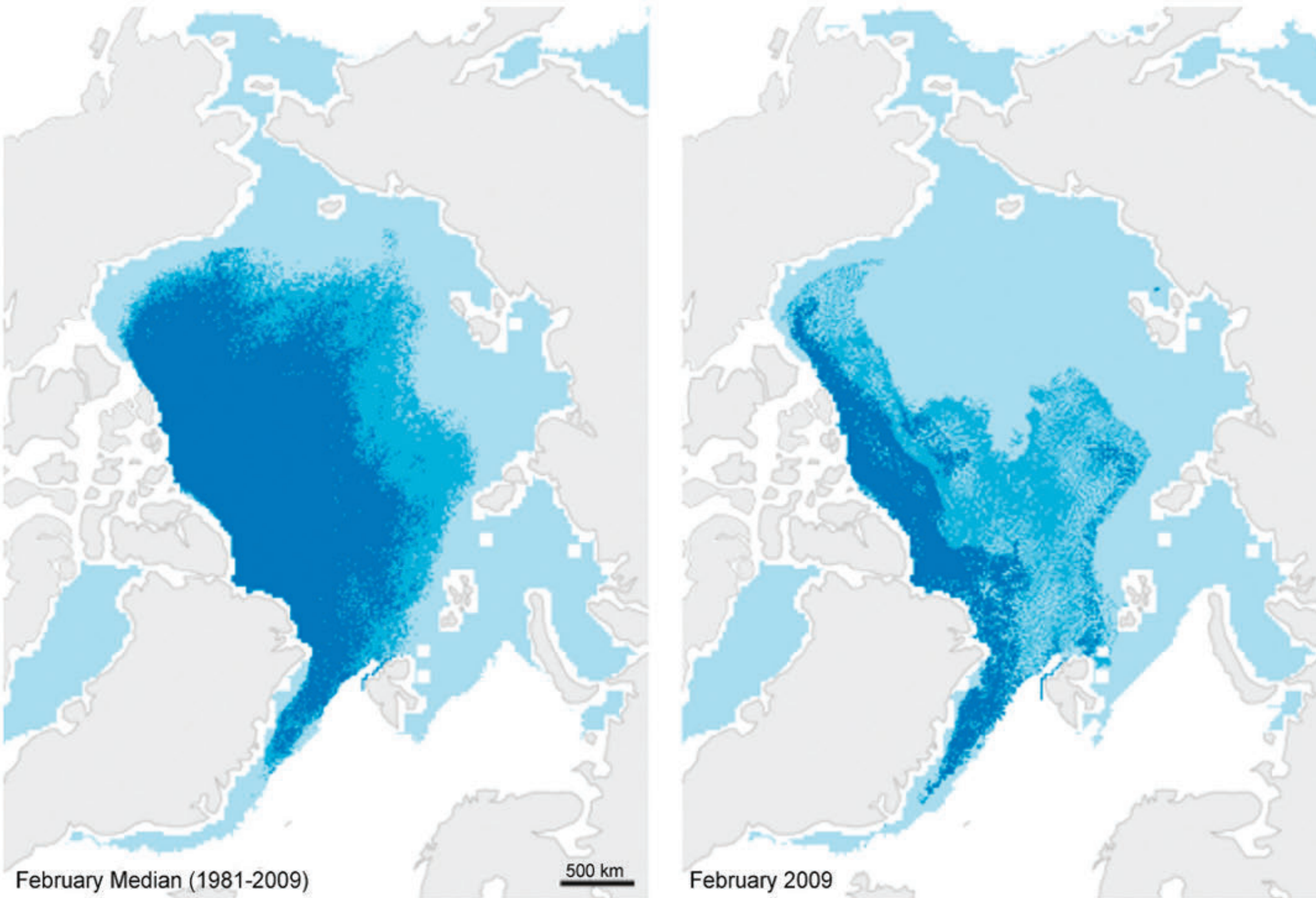

Figure 1.6. Old and new ice in the Arctic for February. These maps show the median age of February sea ice from (*A*) 1981 to 2009 and (*B*) February 2009. As of February 2009, ice older than 2 years accounted for less than 10 percent of the ice cover. Dark blue indicates ice greater than 2 years old; medium blue indicates 2-year-old ice; pale blue indicates annual ice. From National Snow and Ice Data Center (2011c), accessed April 15, 2011, at http://nsidc.org/sotc/sea_ice.html.

Seafloor Substrates

Soft sediments dominate the sea floors of the continental shelves of the Beaufort and Chukchi Seas. These are largely combinations of muds, sands, and gravels (fig. 1.7). These soft-sediment bottoms support high densities and biomass of benthic invertebrates, particularly in the extensive shallow shelf areas of the Chukchi Sea where productivity is high (for example, Hanna Shoal and Barrow Canyon [fig. 1.1]). Only two areas with hard substrates have been identified in the entire region (Smith, 2010) (fig. 1.7)—one in Peard Bay, southwest of Barrow, and the other in Steffanson Sound near Prudhoe Bay that is known as the "boulder patch" (Dunton and others, 1982). The boulder patch is characterized as sediment with greater than 10 percent boulder cover. It provides attachment habitat for the endemic kelp *Laminaria solidungula* and other macroalgae, which are the primary carbon source for consumers living there.

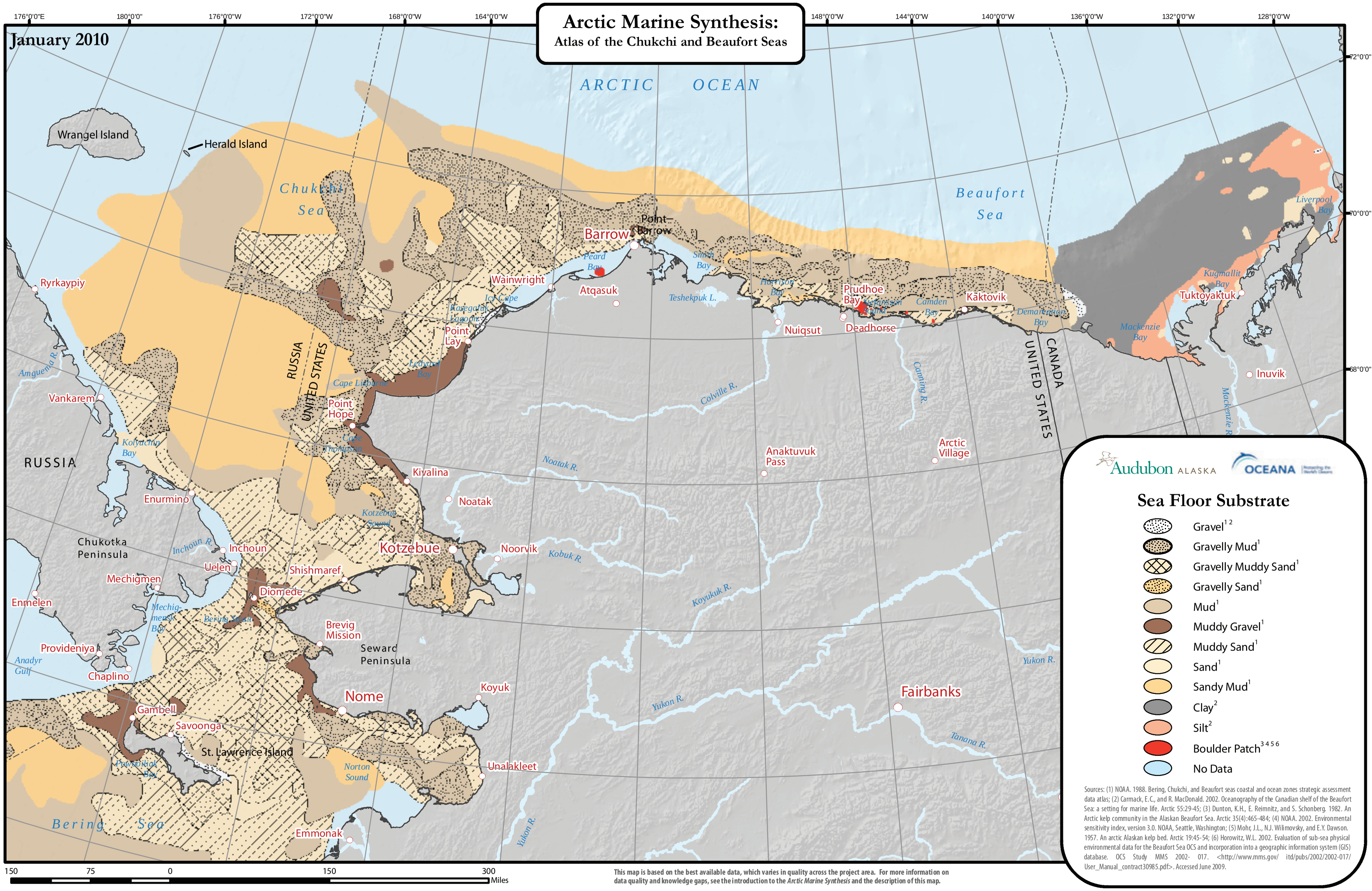

Figure 1.7. Seafloor substrates of the Alaska Beaufort and Chukchi Seas. From Smith (2010).

Benthos

Benthic food supply originates in surface waters and is highly seasonal in the Arctic. Densities of sediment particles and their nutritional values range vastly from the nutrient rich waters of the northern Bering and Chukchi Seas to the oligotrophic deep waters of the Arctic Basins. Less is known about the benthos from the Beaufort Sea although preliminary data from ongoing BOEM surveys suggest there is much less biomass and diversity, and that different ecological processes occur (appendix A). Generally, however, comparisons of energy fluxes show that the benthic systems receive more energy in the Arctic than from temperate and tropical systems.

Much of the broad, shallow shelf of the Chukchi Sea is strongly influenced by northward flowing nutrient-rich Pacific Ocean water through the Bering Strait, resulting in high benthic biomass, which is among the highest worldwide in soft-sediment macrofaunal communities (for example, Grebmeier and Maslowski, 2014; fig. 1.8). Specifically, the south-central Chukchi Sea has the highest algal and faunal biomass on the combined Bering Sea and Chukchi Sea shelf because of the high settlement rates of organic production that is not grazed by microbes and zooplankton. These rich benthic communities, tied to high pelagic production and advection, serve as prey for various diving sea birds and marine mammals, a key feature of the productive Chukchi Sea. About 1,200 species are known from the Chukchi Sea fauna to date with amphipods, clams, and polychaetes dominating infaunal community. Important macrofauna prey species for higher trophics include bivalves taken by walrus, in particular *Macoma* spp. and *Mya truncata*, and benthic amphipods used by gray whales and bearded seals. Within the epifauna, ophiuroids dominate abundance and biomass in much of the surveyed Chukchi Sea, and other patchily distributed echinoderms (especially asteroids), gastropods, ascidians, sponges, cnidarians, and bryozoans are locally abundant.

The comparatively narrow Beaufort Sea Shelf is influenced by large freshwater inflow from numerous small rivers and streams, the larger Colville and Mackenzie Rivers (fig. 1.1), and permafrost resulting in estuarine conditions in the nearshore. Because of this freshwater flow, non-marine sources of carbon may play an increasingly important role for the benthic food web in parts of the nearshore Beaufort Sea. The Beaufort Sea floor is dominated by soft sediments (fig. 1.7), but high ice cover and associated scouring, along with glacial erratics, have left coarser sediments (gravel and boulders) in various areas of the Beaufort Sea. The Alaskan part of the Beaufort Sea coast is fringed by sandy barrier islands forming numerous shallow lagoons with average depths less than 5 m and ecological traits different from those in the open water. Compared to the Chukchi Sea, productivity and benthic biomass in the Alaskan Beaufort Sea are dramatically lower. Consequently, benthic-pelagic coupling is not as pronounced as in the Chukchi Sea and food chains are shorter. Much less is known about the slopes of the Chukchi Sea and especially the Beaufort Sea, and the adjacent basins (Bluhm and others, 2008). The existing investigations of the slopes and abyssal infaunal benthos in the western Arctic revealed low abundances and biomass values relative to the shelves, especially with increasing water depth and distance from the shelves. At taxonomic levels of phylum and orders, the soft-bottom deep Arctic macrofauna appear to be similar to the shelf communities: polychaetes, bivalves, and crustaceans are dominant, but on a family, genus, and species level, inventories differ from the shelves.

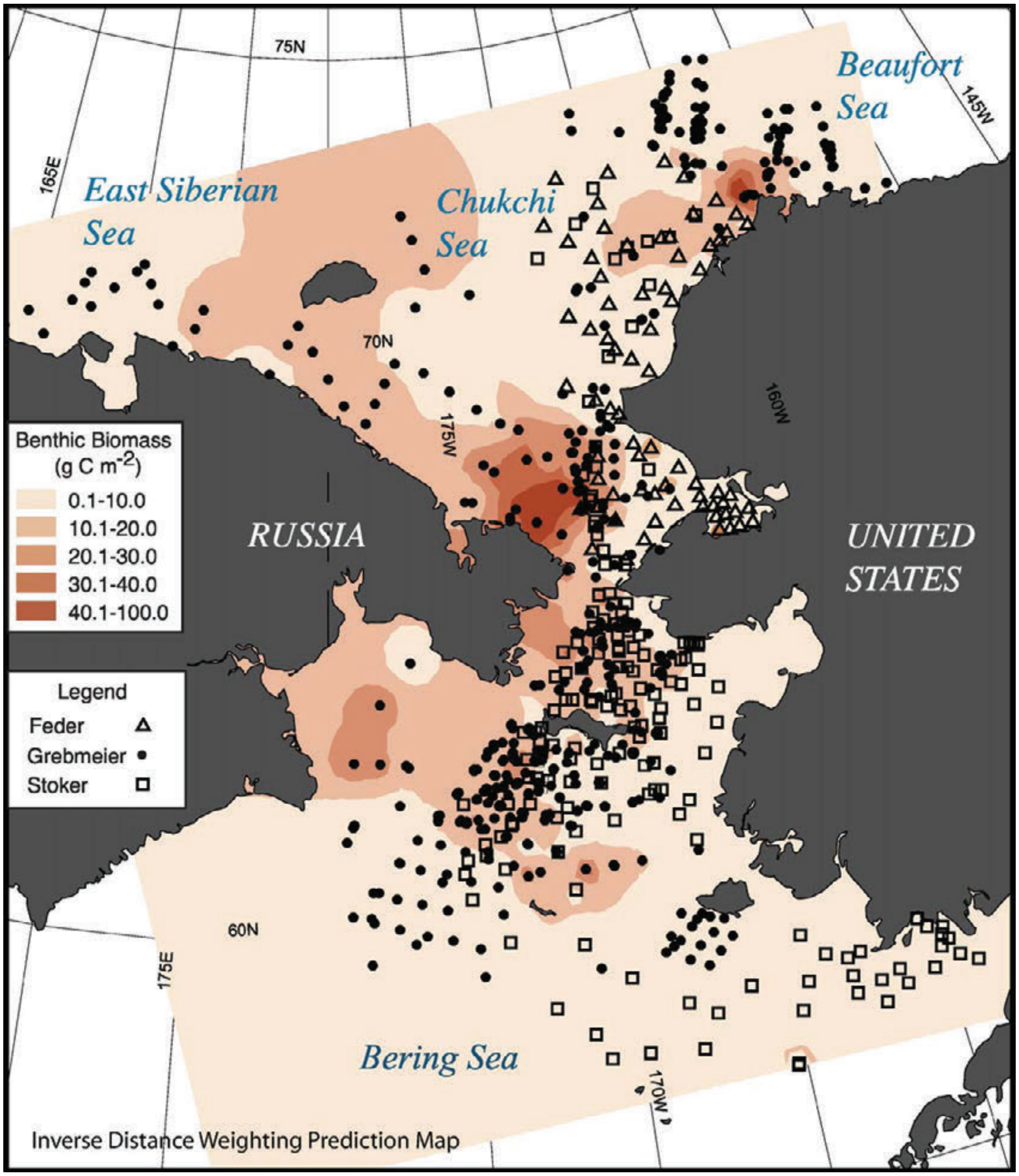

Figure 1.8. Benthic biomass distribution in the Chukchi and northern Bering Seas. From Grebmeier and others, 2006a. Feder and Stoker station locations reference historical sampling stations by University of Alaska-Fairbanks researchers in the Bering and Chukchi Seas as part of NOAA's Outer Continental Shelf Environmental Assessment Program. (g C m^{-2}, grams of carbon per square meter.)

Primary and Secondary Production

In the Arctic, the combination of cold temperature, the occurrence of sea ice, and the extreme seasonal variations in light regimes controls phytoplankton growth and governs its spatial and temporal growth patterns. The stabilizing effect of sea ice allows production to occur near the surface under low light intensities. A large number of planktonic algae thrive in Arctic waters, but there seem to be relatively few truly Arctic species. Estimates of phytoplankton biomass vary widely depending on the region, with the highest amounts in the Chukchi Sea. Algal production and biomass in the Arctic primarily are controlled by light, stratification, and nutrient fields. On the shelves, advection and turbulent mixing of nutrients through the Bering Strait and local nutrient remineralization sustain extremely high primary production values on the Chukchi Sea Shelf (fig. 1.9). Much of the production is not grazed, falls to the sea floor, and fuels benthic communities. In addition to phytoplankton, ice algae contribute to the total primary production of the Arctic Ocean with higher production values in first-year ice compared to multi-year ice. The contributions of ice algae to total primary production range from less than 1 percent in coastal regions to as much as 60 percent in the central Arctic Ocean.

Secondary producers include the microbes, protists, and zooplankton that consume phytoplankton and algae. Compared to phytoplankton and mesozooplankton, much less is known about the composition, distribution, and rates of activity of microbes and protists in the Arctic Ocean, and this confounds the ability to estimate the effect of climate change or other disturbances on food webs and basic biogeochemical processes. Biomass of heterotrophic microbes in Arctic surface waters shows a strong response to seasonal changes in phytoplankton stocks. In the Chukchi Sea, concentrations of bacteria are low in spring, increase over the course of the bloom, and are highest in late summer. Heterotrophic protists include nanoflagellates, ciliates, and dinoflagella.

Recent work in the Gulf of Alaska, the Bering Sea, and shelf and slope regions of the western Arctic Ocean has confirmed the role of these organisms, known as microzooplankton, as consumers of phytoplankton in sub-Arctic and Arctic food webs. Although it is likely that phytoplankton and sea ice algae still represent a crucial food source for the larger zooplankton, use of microzooplankton as food is recognized as being of similar import, particularly during periods when phytoplankton standing stock is low or of poor quality. Because strong local pulses of primary production are a frequent characteristic of high-latitude oceans, including the Chukchi and Beaufort Seas, the response of microbes (including both bacteria and protists) to these pulses determines the rate of remineralization and the fraction of total production exported to the benthos. Weak microbial activity in the Arctic contributes to the high degree of bentho-pelagic coupling in many shelf regions of the Arctic and the consequent strength of demersal ecosystems.

Zooplanktons are the major grazers of the primary production in the Arctic and determine the resources available to many higher trophic levels, such as fishes, seabirds, and marine mammals. In the Chukchi Sea, large quantities of Pacific zooplankton enter the region through the Bering Strait, in a complicated mixture of water masses. The influx of the rich Pacific water determines the reproductive success of both the imported and resident zooplankton communities. Both inter-annual and long-term variation in climate will affect the relative transport of these various water masses and hence the composition, distribution, standing stock, and production of zooplankton and their predators in the Chukchi Sea. Zooplankton abundance and community structure also affect the amount and quality of carbon exported to the benthic communities in this region. In contrast, the Beaufort Sea primarily is Arctic in character, with cross-shelf exchange mechanisms more important in determining the relative contribution of “oceanic,” “shelf,” and “estuarine” species. In the Eastern Beaufort Sea, the outflow of the McKenzie River has significant effect on both the composition of the zooplankton and its productivity. Thus, the Beaufort Sea is responding to a fundamentally different set of factors than the Chukchi Sea, even if they are both driven by similar climate-related variations and trends.

Although copepods typically predominate throughout the Arctic, there is a broad assemblage of other planktonic groups. Euphausiids are less abundant and diverse in Arctic waters than elsewhere, but can be important prey for higher trophic levels such as bowhead whales, birds, and fishes. Larvaceans (Appendicularians) have been shown to be abundant in Arctic polynyas, and are transported in high numbers through the Bering Strait into the Chukchi Sea. Similarly, important and common predatory groups, such as the chaetognaths, amphipods, ctenophores, and cnidarians have been reported on in detail by only a few surveys. Hyperiid amphipods also can be common in Arctic waters and, like chaetognaths, have a potential to graze a large proportion of the *Calanus* population. Relatively little is known of the abundance, composition, or ecology of the delicate gelatinous zooplankton, such as jellyfish. There are indications that climate change has resulted in increased numbers of jellyfish in the Bering Sea in recent years. Scientists have recorded jellyfish piled up several feet deep along shorelines near Barrow, Alaska. The ecological effect of these predators is substantial and underestimated in polar waters.

The ongoing reduction of the sea-ice cover will have major effects on the ecosystems and biogeochemical fluxes on the extensive continental shelves of the Arctic Ocean. Many processes involved in the regulation of the vertical and trophic fluxes of particulate organic carbon, and the production of dissolved organic carbon, are controlled by the zooplankton. Knowledge of zooplankton community ecology, especially the temporal and spatial distribution patterns of the different classes of zooplankton, is needed to understand the role of sea-ice variability in dictating fluxes of biogenic carbon on and off the shelves.

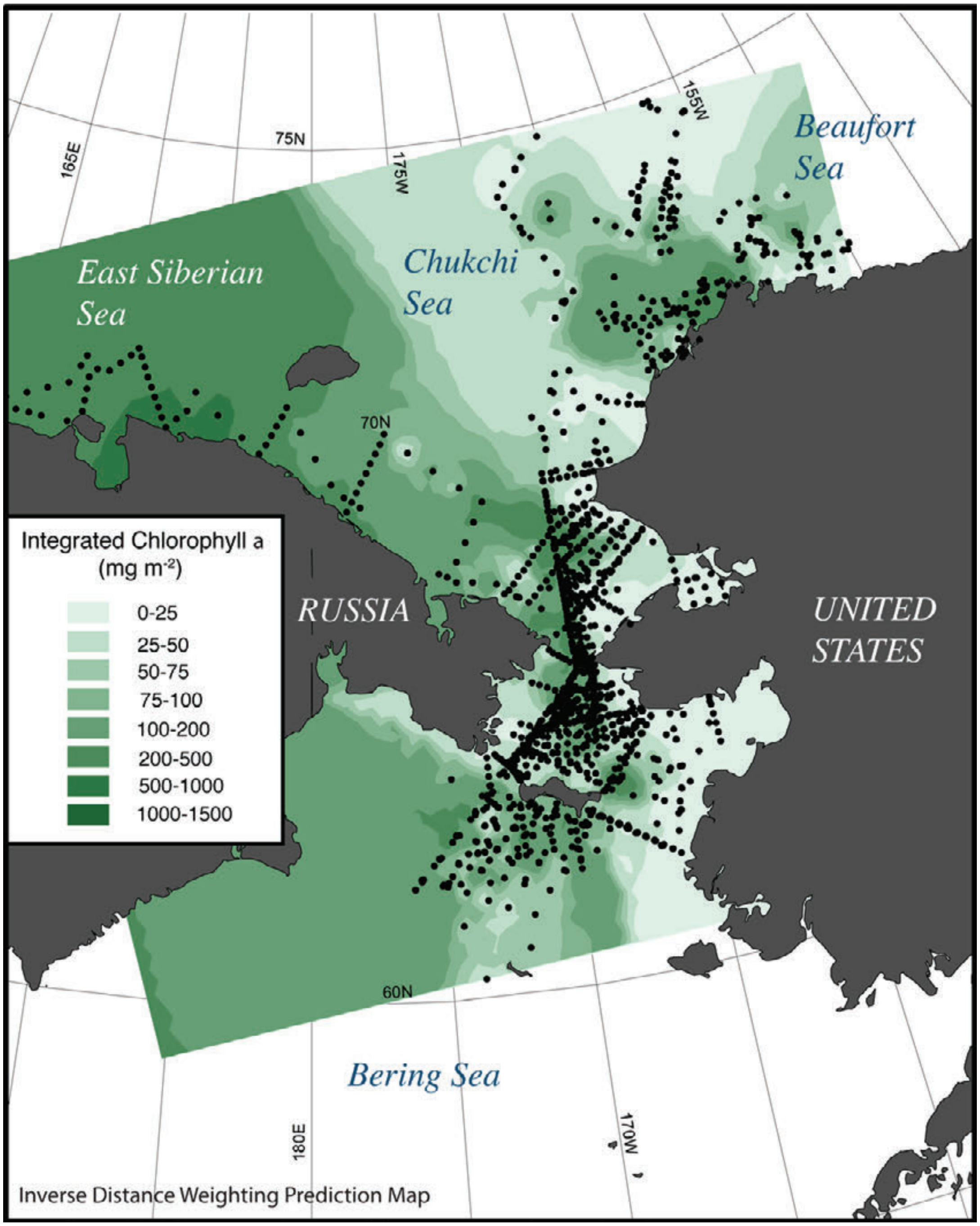

Figure 1.9. Contours of integrated chlorophyll *a* concentrations, in milligrams per square meter [mg m^{-2}]) based on discrete measurements at sampling locations in the northern Bering Sea, east Siberian Sea, and Chukchi and Beaufort Seas, April–September 1976–2004 (Grebmeier and others, 2006a).

Environmental Context Within the Pacific Arctic Region

The information summarized in the section, "Environmental Setting" focused on the United States Chukchi and Beaufort Seas, and included relevant physical and biological information from the Pacific Arctic Region. The description of the Pacific Arctic Region includes the northern Bering Sea, Chukchi and Beaufort Seas, East Siberian Sea, and western sectors of the Canadian Arctic Archipelago (for example, Grebmeier and others, 2015). Regional information, from data collections outside the United States, was included because large scale understanding of physical and biological processes (for example, the delineation of boundaries for the Arctic Large Marine Ecosystem [Protection of the Arctic Marine Environment, 2013] evaluates interactions and connections at scales of the northeast Pacific and Arctic Ocean) is needed to address historical and ecological biogeography objectives of this study (chapter 4). Additional focus and synthesis on the environmental features of the Pacific Arctic Region address scale issues by drawing special attention to the importance of shelf geography and advection on regional ecology (this chapter) as it pertains to marine fish distributional patterns described in chapters 3 and 4.

Geographic relations between advection, sea ice, and stratification properties were reviewed by Carmack and Wassmann (2006) to classify shelf typologies and compare regional connections between physical habitats and biota in Arctic seas. Inflow, interior, and outflow shelves were described for the Pacific Arctic Region and collectively these shelf types were estimated to cover 2,145 × 10^3 km^2 or approximately 35 percent of the entire shelf area of the Arctic Ocean (6,048 × 10^3 km^2). Continental shelf area is greatest in the East Siberian Sea (16 percent of total Arctic Ocean shelf area) followed by the Chukchi Sea (10 percent), Beaufort Sea (3 percent), and Canadian Arctic Archipelago (about 2 percent). The total volume of seawater over Arctic shelves is 829 × 10^3 km^3 of which 7 percent is associated with the East Siberian Sea, 6 percent the Chukchi Sea, about 4–5 percent in the Canadian Arctic Archipelago, and 3 percent the Beaufort Sea.

The northern Bering/Chukchi Sea is a shallow inflow shelf (mean depth = 58 m) as the transport of Pacific water through the Bering Strait connects Pacific and Arctic Oceans (S ~ 32 psu, V_T ~ 1 Sv) (fig. 1.2; salinity and annual mean volume as reported by Woodgate and others, 2015). As these waters flow across the Chukchi shelf they are responsive to atmospheric forcing and are strongly modified by geophysical and physical processes before their subduction along the break and upper slope. Freshwater transport from rivers, ice (primarily first year ice), and stratified waters of the Bering Sea is significant and supports strong seasonal stratification and high primary productivity in the Chukchi Sea. The Bering Sea inflows, especially from upwelled deep waters, are rich in nutrients and biogenic materials such as phytoplankton, zooplankton, and meroplankton. Large herbivores are not abundant in the zooplankton community overlying shelf waters and the grazing efficiency is low. The advection of freshwater and suspended organic matter combined with high primary production and inefficient cropping over shallow depths results in tight pelagic-benthic coupling and high standing stocks of benthic communities (Renaud and others, 2008). As a consequence of the large vertical flux of locally and advected carbon, the Chukchi shelf (and southwestern Beaufort Sea) are also the site of substantial denitrification and high benthic biomass in offshore areas compared to the more river-influenced central and eastern Beaufort Sea. Benthic ecosystems and short food chains are adaptations to the fluxes and cycling of carbon as evidenced in the composition and life history traits of the benthos and seasonal migrations of large numbers of benthic feeding animals in the Bering Strait and Chukchi Sea each year.

The East Siberian Sea (mean depth = 48 m) and Beaufort Sea are interior shelves (mean depth = 80 m). According to Carmark and Wassman (2006), interior shelves are shallow and characterized by strong effect of major Arctic rivers (for example, Kolyma and Mackenzie Rivers). Interior shelves exhibit a positive estuarine flow (plume spreading) in summer and a negative estuarine circulation (brine release) in winter. During summer, sediments and organic matter are transported to the nearshore in a highly variable mix of riverine, estuarine, and marine waters. The horizontal exchange of water masses is thus considerable and variation in salinity is significant. Carmack and others (2015) defined the brackish water mass that forms near the coast (≤30 m) as the River Coastal Domain. In deeper waters beyond the shelf break, boundary currents flow to the east and contain Arctic water derived from Atlantic and Pacific origins. Interior shelf waters are turbid (large terrigenous loads) and seafloors featureless except in large river areas where small valleys continue across the bed. The interior shelves are characterized by a predominance of landfast ice that melts during summer and flaw polynyas in winter. Primary production and the general biological activity are low over offshore areas of the interior shelves due to high turbidity, export of surface waters below the ice cover, and nutrient limitation due to stratification. Suspended biomass of planktonic organisms is thus low, but that of benthic organisms is relatively high. This relates to benthic foods from marine advection and local production and significant imports from littoral and riverine sources. Shoreline erosion delivers large amounts of peat to coastal waters and represents a major source of carbon in lagoonal food webs (Dunton and others, 2005; 2006; 2012). During winter, the lagoons freeze to depths about 2–5 m, often to the bottom, a disruption so great that the epibenthic community at the base of their food webs must re-colonize them annually.

The Beaufort Sea is a narrow interior shelf. The primary production in some of the coastal lagoon ecosystems of the United States Beaufort Shelf is less than 10 grams of carbon per meter (g C m^2/yr) as light penetration in spreading and meandering river plumes is extremely limited. Land fast ice cover is persistently strong and severely limits primary production. Primary production on the adjacent Canadian Beaufort Shelf with its mixture of land fast and multi-year ice, flow polynyas, stamukhi, and higher light penetration outside the river plumes, is high, in the range of 30 to 70 g C m^2/yr. High freshwater inputs from numerous rivers and streams produce an environment that is decidedly estuarine in character, especially during the late spring and the summer months. Coastal erosion and river discharge are largely responsible for introducing high concentrations of suspended sediment from upland regions into the nearshore zone and often trapped in nearshore lagoons. Shelf energetics are characterized by a relatively low autochthonous production and a rich terrestrial, allochthonous carbon supply, especially in more productive regions. Benthic biomass is relatively rich in terrestrial carbon. Zooplankton populations, however, are poorly developed in the inner coastal region and the brackish waters that form along the coast each summer allows access to more marine foraging areas outside of the lagoons by several species of amphidromous fishes of importance in traditional economies.

In contrast the East Siberian Sea is a wide interior shelf. The wide interior shelves may extend far offshore (about 800 km) before reaching the shelf break. Most of the trophic dynamics in this sea remain to be resolved. This sea is heavily covered by land fast ice, is shallow (<50 m), and is exposed to most of the discharge of freshwater to the Arctic Ocean when the Lena River is considered. As a consequence, total primary production is low and the contribution from ice algae is probably significant. Stratification is strong during the productive season and the biota is dominated by benthos. High chlorophyll *a* concentrations in the sediments indicate a tight coupling between sympagic and pelagic primary production and nutrient supply to the benthos throughout the entire Laptev Sea. However, pronounced regional differences exist in the magnitude of primary production. The shallow nature of the ecosystem implies that the effect of zooplankton on carbon flux is limited and may increase toward the shelf break. Preliminary carbon budgets indicate that a high proportion of primary production is channeled through the benthic food web. As in the case of the narrow interior shelves input of allochthonous organic carbon seems to be required to balance the overall carbon demand. Despite its refractory nature, the supply of riverine dissolved organic carbon and particulate matter of terrestrial origin, mediated by microbial food webs, may be significant for this shelf.

The Canadian Arctic Archipelago is a network outflow shelf (mean depth = 124 m). Outflow shelves allow Arctic Water to drain back into the North Atlantic. The Canadian Arctic Archipelago is a complicated network of channels, straits, and sounds, and water mass transit times are long enough for thermohaline and biogeochemical changes to occur en route. There are no large rivers in this system, but moderately sized rivers enter from the Canadian mainland; there is other, local freshwater run-off. Stratification derives primarily from ice melt. Land fast ice in the region is regular, but strongly variable with regard to depth, time of melt, and snow-cover. The archipelago is ice-covered during most of the year with extensive, but variable ice melt and stratification observed during summer and early autumn. Primary production on outflow shelves is spatially variable. Over the southern parts of outflow shelves the primary production can be significant and is highly seasonal, quickly nutrient limited, and highly variable between years. The comparatively great depth implies that much of the carbon flux is channeled through plankton, with additional supplies from sympagic biota. Existing measurements of total primary production in the entire Archipelago suggest that it may support as much as 32 percent of the total primary production of pan-Arctic shelves. The zooplankton dynamics are even more variable, probably because of irregular advection episodes through the Archipelago. Ice fauna and flora are rich in the Archipelago and close pelagic–benthic coupling results in rich benthic communities in the shallow sections. However, primary production is generally low and the transport of organic matter (mostly of terrestrial origin) and ice biota by multi-year ice and the Transpolar Drift is significant along longitudinal outflow shelves. Interannual comparisons of ice algae production in Barrow Strait (to the east of M'Clure Strait, Canada) reveal strong year-to-year variability, ranging from 2 to 23 g C m^2 y^1 (Smith and others,1988). Thus, this outflow shelf probably experiences similar significant variability in its planktonic/sympagic primary production.

A conceptual model for the Pacific Arctic Region relates observed patterns in ecosystem structure and function to advection and related functional attributes (fig. 1.10; Grebmeier and others, 2015). The patterns are consistent with shelf processes described by Carmack and Wassman, (2006) denoting significance to areas of convergence in the Chukchi and Beaufort Seas and along the shelf break, large freshwater influences from the Mackenzie River and through the Bering Strait, and within different water masses of the Chukchi Sea. The conceptual model also is consistent with information about the physical environment and the marine resources in this chapter and portrays the role of advection more clearly with respect to seasonality and patterns in species distribution and abundance and further description of biological connections between Chukchi and Beaufort Sea shelves and other Pacific Arctic environments (for example, northern Bering Shelf and nearshore waters).

Two other conceptual models also inform current understanding of the present state: (1) a food web model linking physical factors to biological distribution and abundance and food web relationships (Wiese and others, 2013); and (2) a marine-pulsed model focusing on the seasonality of production cycles and biological activity as they relate to connections between riverine exports, benthic-pelagic coupling and remineralization, advection, winds and episodic upwelling events, and sea ice coverage (Moore and Stabeno, 2015). The advection, food web, and marine-pulsed models are complementary, building on the unifying constructs of the contiguous domain, and depict current understanding and suggest how energy pathways and efficiencies in benthic and pelagic communities could be affected by the changes in meteorology (temperature, winds and cloudiness), sea ice (timing and extent of open water) hydrology (freshwater discharge), hydrography (stratification and halocline), and plankton dynamics (timing, intensity, magnitude, and production) and related ecological efficiencies (energy transfers between trophic levels).

Advection is a key forcing function for the Arctic marine environment in general and the Pacific Arctic Region in particular (Grebmeier and others, 2015). In this conceptual model, advection of water, ice, and biological constituents through the Bering Strait creates the energetic pathways and connections that affect much of the region and influence regional productivity and abundance of biota. Sea ice is a primary forcing factor in the region and is inherently connected to advection. Because of a steep decadal decline in seasonal sea ice coverage in the Chukchi Sea, it is thought to be among the most vulnerable Arctic continental seas for ecosystem change (Wiese and others, 2013; Grebmeier and others, 2015).

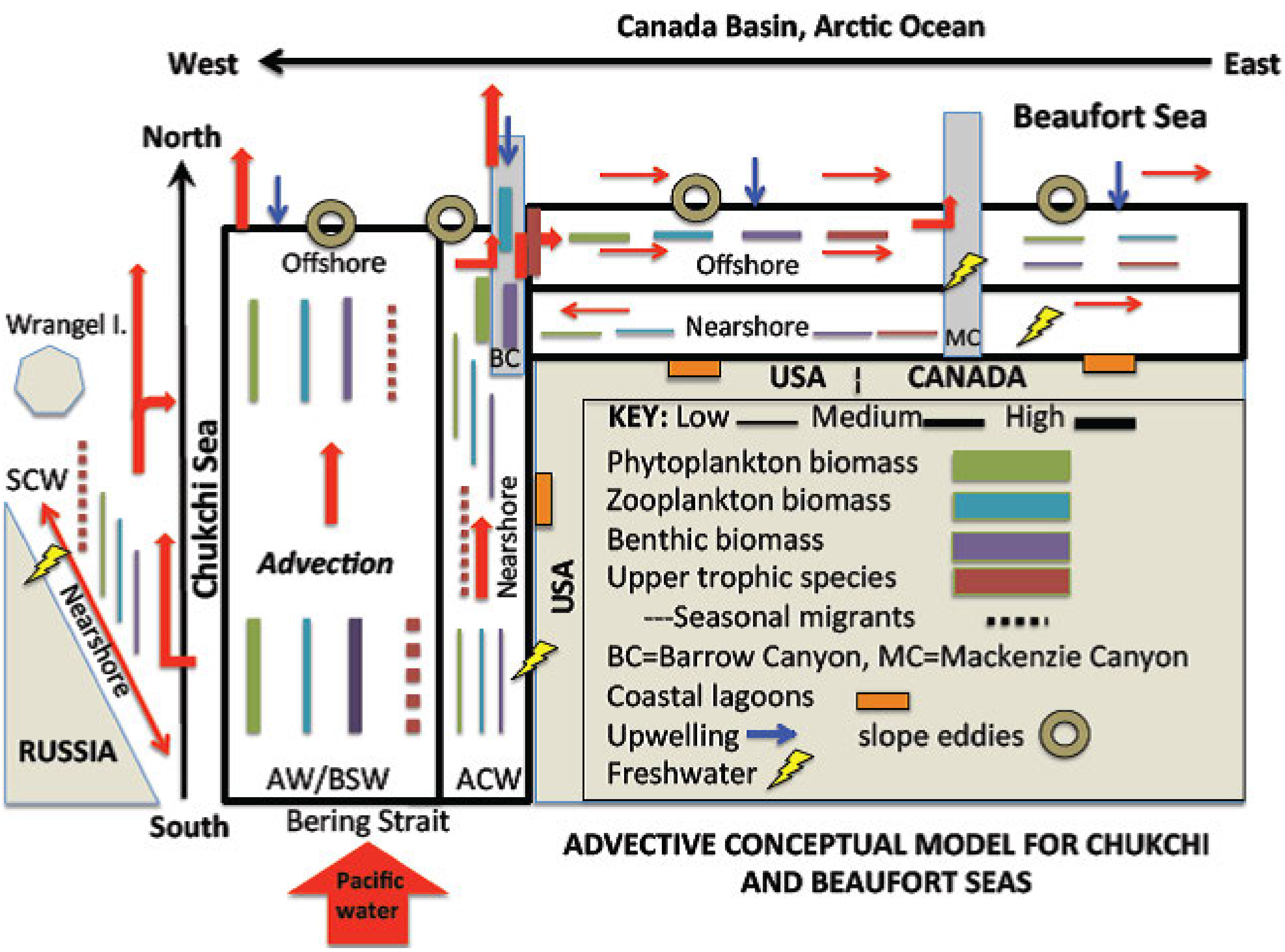

Figure 1.10. Advective conceptual model for Pacific Arctic Region (emphasis on Chukchi and Beaufort Seas, Alaska. (From Grebmeier and others, 2015). A 30-meter contour separates nearshore and offshore regions. The inflow of Pacific water masses (Anadyr Water [AW], Bering Shelf Water [BSW], and Alaska Coastal Water [ACW]) is critical to ecosystem dynamics, for example benthic ecosystem functioning, and transport processes in this conceptual framework. The East Siberian Coastal Current, not shown, while important, may be of less significant to the United States Chukchi and Beaufort Sea marine ecosystem dynamics.

Methods, Sources, and Terminology

Standard methods of literature review for published and unpublished data sources were followed. The search process for data and information included reviews of: current and historical studies; peer-reviewed journal and monographs; regional guides; museum specimens; technical reports and survey databases; searchable Web-based databases; oral communications; limited new data collection; and use of defensible unpublished scientific data.

Unless otherwise noted we conformed with conventions of scientific and common nomenclature used by Nelson and others (2004), Nelson and Bouchard (2013), Love and others (2005), Mecklenburg and others (2011), Maslenikov and others (2013), and Mecklenburg and Steinke (2015). This publication includes a key list of Arctic species referred to as the Online Resource 1 (OR1). The American Fisheries Society-American Society of Ichthyologists and Herpetologists (AFS-ASIH) recently completed an update to its list of common and scientific names (Page and others, 2013). In this report, *Boreogadus saidi* refers to Arctic Cod instead of Polar Cod (Page and others, 2013). *Arctogadus glacialis* is called Ice Cod. Other changes in nomenclature as they pertain to differences in taxonomy since the *Fishes of Alaska* (Mecklenburg and others, 2002) was published are noted. The *Fishes of Alaska* is a critical companion document to this report for the physical description of species including the key diagnostic features of anatomy for proper identifications.

Synthesis Methods

The preparation of species accounts involved several interrelated tasks including (1) documenting marine fish biodiversity; (2) defining terminology relative to the fauna and environment; (3) developing a standard template for information delivery (outline of species accounts); (4) acquiring and reviewing biological, ecological, and economic data and information; (5) producing species accounts; (6) synthesizing environmental (physical, biological, and ecological) information; and (7) managing the scientific review. The second and third tasks were most challenging because of limitations in existing data and the related need for consistent, reliable information in each species account. Pilot efforts involved the development of prototype species accounts and their review and improvement in an iterative process that introduced an evolutionary quality to product formation and information portrayal. The pilots highlighted the need for clarity in usage of standard terminologies being applied to Arctic baselines.

The fifth synthesis task involved an in-depth analysis of the collective body of the biological and ecological information presented in the species accounts to give it proper context to the biogeography of the fauna. Synthesis efforts were framed using historical and ecological components of biogeography (Nelson, 2006) to describe patterns of species occurrence, habitat and population relationships, and the ecosystem processes that affect the distribution and abundance of marine fishes in the Chukchi and Beaufort Seas. These environmental influences reflect physical, biological, and ecological attributes and interactions in the region and include human uses, such as fisheries, that can affect the population dynamics, community dynamics, and species presence in an area. In addition to providing information about environmental constraints (limiting factors) to marine fish populations, the BOEM requested more generalized information about the region's physical setting, adaptation and acclimation, life history strategies, marine fish assemblages, foraging and feeding behaviors, seasonality, growth and reproduction, predation and disease, population abundance and production, and human uses. We were asked to consider potential effects of climate change and, in light of all of the above, provide our impressions of information needs and research directions. Our opinions on potential effects of climate change should be viewed as hypotheses and, our thoughts on information needs are directed at the Arctic scientific community, in general, and no single organization, in particular. In many instances, these opinions were directed at deficiencies in understanding of species biology and ecology and basic information needs for any assessment or management action.

Biodiversity Assessment

The assessment of regional biodiversity included: (1) developing and updating an Arctic marine fish checklist; (2) reviewing recent (since *Fishes of Alaska* was published) ichthyologic sampling and management documents; (3) searching online databases; (4) systematic investigations that include documenting current taxonomic understanding with genetic information, historical museum collections, and voucher specimens; (5) acquiring digital images (photographic and line drawings); (6) creating visualization products that include distribution maps and vertical species profiles; and (7) conducting peer reviews.

Arctic Marine Fish Checklist

A provisional working list of marine fishes inhabiting the Chukchi and Beaufort Seas was initially prepared. This important first list incorporated new discoveries and taxonomic resolutions from ichthyologic sampling, genetic analysis, and museum studies conducted since the regional monograph *Fishes of Alaska* (Mecklenburg and others, 2002) and checklist of fishes (Love and others, 2005) were published. The list included only marine fish species confirmed from the region and greatly benefited from recently completed and ongoing field, laboratory, and museum research establishing new baselines for marine fish in the Pacific Arctic Region (Mecklenburg and Steinke, 2015). It was evident to BOEM and the U.S. Geological Survey (USGS) that much new information on species distribution and occurrence had been collected in the decade following publication of the *Fishes of Alaska* and, as noted by Mecklenburg and Steinke (2015), this reference is no longer complete for the region. An important objective of this study was to illustrate the relationship of the final checklist to Mecklenburg and others (2002), which remains an important companion document and primary source for taxonomic information and identification guides for Alaskan fishes.

In addition to Mecklenburg and others (2002), other key references included reviews and syntheses on the taxonomy and zoogeography of Arctic marine fishes by Mecklenburg and others (2007), Mecklenburg and others (2011, 2013, 2014), Mecklenburg and Steinke (2015), and Maslenikov and others (2013). A new atlas and identification guide for the marine fishes of the Pacific Arctic Region is an important source of information about the diversity, taxonomy, and geographic distribution of marine fishes in the Chukchi and Beaufort Seas (Mecklenburg and others, 2016).

Scientific Reviews

Recent publications, technical reports, and unpublished data were reviewed for new species occurrences and expansions in range. Survey results from fish sampling in the Chukchi Sea (Mecklenburg and others, 2007, 2011; Norcross and others, 2009, 2013a) and Chukchi Borderlands (for example, Mecklenburg and others, 2013; Longshan and others, 2014) and industry research (Gallaway and Norcross, 2011; Norcross and others, 2013b) were reviewed. Surveys from the southwestern Beaufort Sea (Johnson and others, 2010; Parker-Stetter and others, 2011; Rand and Logerwell, 2011; and Johnson and others, 2012) were reviewed for new information from nearshore and shelf waters. Additionally, National Oceanic and Atmospheric Administration (NOAA), University of Alaska-Fairbanks (UAF), and RUSALCA scientists are involved in ongoing fishery investigations for BOEM's Alaska OCS Region in the Chukchi and Beaufort Seas. Taxonomic support provided to these studies and other research (for example, Mecklenburg and Steinke, 2015) and analysis of previously unprocessed samples from WEBSEC-71 (1971) (Hufford, 1974) was a source of new records from the Beaufort Sea.

Relevant environmental analyses and Arctic resource management plans done by the BOEM (Minerals Management Service [MMS], 2008) and North Pacific Fishery Management Council (NPFMC, 2009), respectively, were reviewed in this assessment of biodiversity, human uses, and environmental relationships. The DOI synthesis of priority science needs for continued oil and gas development in the Arctic was consulted for information about the region's environmental setting, living resource information, and USGS-identified research needs (Holland-Bartels and Pierce, 2011). A supplemental draft EIS addressing possible offshore oil and gas development in the U.S. Chukchi and Beaufort Seas was reviewed for species and community assemblage information (National Oceanic and Atmospheric Administration, 2013). A significant study of subsistence use and traditional ecological knowledge of whitefish in the southeastern Chukchi Sea (Georgette and Shiedt, 2005) provided an important source of information about Iñupiat taxonomy and seasonal use of whitefishes in the Noatak, Kobuk, and Selawik Rivers of Kotzebue Sound (fig. 1.7).

Searchable Databases

The exploration of the Arctic is at the forefront of ecological research to document and understand marine ecosystems and population ecologies with respect to climate change, possible commercial fisheries, and other stressor effects. In recent years, active research in conjunction with RUSALCA, Census of Marine Life (CoML) programs [that is, Pan-Arctic Inventory/Arctic Ocean Diversity (ArcOD) and Marine Barcode of Life] has emphasized fishery objectives for resource inventory. In this capacity, data for this report were from the Global Marine Life Database, Census of Marine Life Community Database, and CoML bibliographic database (for example, Mecklenburg and others, 2007 and Mecklenburg and Mecklenburg, 2009). Other searchable Web-based databases used included: FishBase; BOEM Arctic Fisheries Database; United Nations Ocean Biogeographic Information System (OBIS Database); Encyclopedia of Life; World Register of Marine Species; Catalogue of Life Species; and Integrated Taxonomic Information System (ITIS). NOAA's on-line database services provide access to life history and distributional information for nearshore atlases; offshore fishery resources were accessed at the National Oceanic and Atmospheric Administration Web site (http://alaskafisheries.noaa.gov). The automated database at the University of Washington School of Fisheries and Ocean Sciences provided key access to type specimens and mapping tools.

The BOEM database, "Alaska Scientific and Technical Publications" (http://www.boem.gov/Alaska-Scientific-Publications/), was a significant resource for marine fishery, subsistence, and socioeconomic data. A summary of ongoing and recently completed BOEM fishery studies is provided in appendix A. A major synthesis by Braund and Kruse (2009) provided an authoritative review of subsistence harvest patterns for fish and wildlife patterns over the past 30 years (from the mid-1980s). During this period, the OCS subsistence studies and this synthesis focused on coastal harvest patterns in the Alaska North Slope villages of Wainwright, Barrow, Nuiqsut, and Kaktovik. An early study by Craig (1987) provided important baseline documentation of subsistence patterns and Iñupiat taxonomy from the Chukchi and Beaufort Seas.

Systematic Investigations

Recent information about the taxonomy and biogeography of Alaskan Arctic fishes has come from numerous analyses using field and museum studies, DNA sequencing, and exhaustive literature review, as well as efforts to synthesize the accumulated results for the Pacific Arctic region; particularly the works of Mecklenburg and others (2006, 2007, 2011, 2013, 2014, 2016), Mecklenburg and Mecklenburg (2009), and Mecklenburg and Steinke (2015). Voucher specimens provide a crucial link to historical data sets, allowing determination of existing baselines and accurate identification of new field collections. Museum collections housing the specimens are globally located and managed by many institutions. The following collections are some of those studied for the works just cited: California Academy of Sciences, San Francisco; Canadian Museum of Nature, Gatineau, Quebec; Hokkaido University Museum of Zoology, Hakodate, Japan; U.S. National Museum of Natural History, Washington, D.C.; NOAA, Alaska Fisheries Science Center, Auke Bay Laboratory, Juneau, Alaska; University of Alaska Museum, Fairbanks, Alaska; University of British Columbia, Vancouver, Canada; University of Washington, Seattle; and Zoological Institute, St. Petersburg, Russia. Detailed data on voucher specimens examined, including the authors' verified or redetermined identifications, have been published (for example, Mecklenburg and others, 2006; Mecklenburg and Mecklenburg, 2009; and Mecklenburg and others, 2011, Online Resources 1 and 2) and the most recent results are available from the museums' online search databases. In many instances, the museum studies have revealed previously misidentified or unreported specimens and have led to extensions or contractions in known patterns of distribution; these results are reported here in abbreviated form from the authors' more detailed works. The origins, classification, diversity, human uses, and vulnerabilities of circumpolar freshwater and marine Arctic fishes were reviewed as part of the most recent Arctic Biodiversity Assessment (Christiansen and others, 2013).

Genetic Analyses

Mecklenburg and others (2011, 2014, 2016) and Mecklenburg and Steinke (2015) described the DNA analyses (barcoding) performed on Arctic fish specimens as part of the CoML, RUSALCA, and other fisheries investigations. This analytical tool has provided critical information to ichthyologists to help resolve taxonomic problems, assist difficult identifications, and, in many instances, generate hypotheses about potential population structuring. Many of the Arctic fishes that have been barcoded were collected in the Chukchi and Beaufort Seas and in other parts of Alaska. Online Resources 3 and 4 of Mecklenburg and others (2011) provide museum catalog numbers and collection data for barcoded specimens. That collection has been increased, and data on additional specimens may be found on the Barcode of Life Data System (BOLD) Web site from links supplied by Mecklenburg and Steinke (2015).

Other sources of genetic identification information were found in the literature review. Research on Pacific salmon has been extensive in Alaska including north through Kotzebue Sound. BOEM and other organizations including the North Pacific Research Board (NPRB) are funding new research on the genetic diversity and population structure of Arctic Gadidae (for example, Arctic, Saffron, and Ice cod) and the new results and ongoing studies are, or will, assist in addressing existing taxonomic complexities (for example, see appendix A and Nelson and Bouchard, 2013).

Digital Images

Many recent high-quality images of marine fishes were obtained from active Arctic researchers who photographed freshly sampled specimens in the field. For example, most of the images in this report are products of research of Mecklenburg and others (2016). Each photograph is properly attributed with names of providers and date and location of sample collection.

Distribution Maps and Vertical Species Profiles

ArcGIS geographic range maps were developed for each confirmed species from the Chukchi and Beaufort Seas. Vertical distribution profiles were created in Adobe software to portray specific information in a generalized life cycle schemata depicting water column distributions of life stages over continental shelf and slope habitats. The maps and profiles depicting geographic distributions and vertical distribution information are composite products from multiple sources of data collection and observation. A BOEM study with objectives of compiling existing fishery data sets for the Chukchi and Beaufort Seas into an electronic format was not completed in time for use herein. Although the data were acquired through traditional sources, easier access to, and manipulation of these data, in concert with the results of ongoing fishery research, would improve the efficiency and number of Alaskan records in future updates.

Peer Review

USGS standards for science quality (USGS Fundamental Science Practices) were followed (http://www.usgs.gov/fsp/) for this study and report. The USGS process includes technical and policy reviews for technical reports and journal publications. For this report, we relied on external subject matter experts due to the diversity of species and ecological topics addressed. The USGS reviews were supported by BOEM technical reviews that included additional internal and external scientists having appropriate ichthyologic expertise.

Operational Definitions

In some cases, especially in the species accounts and synthesis discussions, highly technical information relative to various aspects of marine biogeography is presented. In several disciplinary areas, especially those dealing with quantitative population ecology, special attention to defining the scientific terminology used was needed. To facilitate consistency and understanding, a glossary of key terms was developed as an aide for users. The glossary (chapter 7) defines many of the more complex terms and quantitative relationships used in the species accounts. Each definition is appropriately cited so that, if they are not clear, additional sources can be quickly accessed and referenced. Other terms commonly used to describe spatial relationships in biogeography, involve ecological scaling considerations of importance to conservation and are described in the section, "Geospatial Terminology." The terms described in this chapter are used widely throughout the report and, for that reason, are introduced here. Abundance terminology represented a special case where the derivation of a unique classification scheme for the Arctic region was necessary and developed in chapter 2 with application to other chapters as well.

Geospatial Terminology

This study focuses on the biological geography of marine fishes in Alaska's Arctic Ocean and describes their distribution and abundance using various spatial terms. Some have zoogeographic meaning (for example, realm and province) and others refer to common descriptions of a species occurrence by scale (for example, region, area, and local). The mapping classifications for biogeographic realms and faunal provinces used herein are as described by Lourie and Vincent (2004) and Spalding and others (2007), respectively. The Arctic region, as described by Briggs and Bowan (2012), adds additional clarity to the boundaries of marine provinces by considering the zoogeography of fishes of fishes. For Alaska, Sigler and others (2011) described three provinces that relate to conventional management areas in the United States segments of the northern Bering Sea and the Chukchi and Beaufort Seas.

In each case, the biogeographic concepts relate to ecological patterns and processes, and thus to conservation. Lourie and Vincent (2004, p. 1,005) noted that, "…*biodiversity exists on multiple scales biologically, spatially and temporally, and these scales are, to some extent, independent of one another*." They related spatial scales of conservation planning to physical, temporal, and biological patterns and processes, to mapping scale as follows (Lourie and Vincent (2004, p. 1,007):

> *(1) global approximate map scale 1:100 million – ocean basin divisions, major currents, global climate, historical biogeography, highly migratory species, large marine ecosystems (LMEs); (2) regional, 1:10 million – regional currents, historical biogeography, genetic connectivity, widespread species, individual LMEs or ecoregion; (3) provincial, 1.1 million – small scale currents, upwelling, genetic connectivity, major habitats with LME or ecoregion restricted-range species, bioregion; (4) local, 1:500,000 – local gyres and eddies, watershed runoff, coastal geomorphology, ecological connectivity, planning unit; (5) site, 1:10,000 – tides, watershed runoff, ecological connections, habitat specialists, habitats within planning unit, zoning for marine protected areas.*

The scales are germane because they give additional texture to how (unless otherwise specified) the concepts of realm and province should be understood and, generally, the geographic distinctions between "region" and "area" as used in this report. Typically, "region" is used to refer to large-scale patterns and process (for example, scale 3 in Lourie and Vincent [2004]) and "area" refers to local or site specific ecological conditions (for example, scales 4 and 5).

The use of other geographical or habitat terms, including inshore, coastal, nearshore, and offshore in this report are somewhat more ambiguous with respect to meaning or area involved. For example, in some instances "coastal" may have a legal meaning with respect to a state's territorial waters, or meteorological and oceanographic meaning with respect to wave influence. Similarly, "nearshore" also may have multiple oceanographic meanings including reference to littoral zone components, photic zones, or waters extending to the shelf break. There can be considerable overlap in area with respect to how these terms are applied with respect to the notion of "close to shore." In an attempt to reduce such ambiguity, some practical distinctions are made for these terms based on scientific knowledge of Arctic fish habitat characteristics (depth, temperature and salinity influences, and distance from shore) and realities of their sampling by proven fisheries techniques:

- Inshore reflects the area from shoreline to depths of 2 m. This reflects the shallow water areas where much of the historical fish baseline data were collected in the Chukchi and Beaufort Seas surveys with fyke net and gill net sampling techniques. Freshwater influences typically are important seasonally, especially in the Beaufort Sea.

- Coastal habitats can include lower reaches of rivers and streams, deltas, inshore, and deep waters adjacent to the coast. Lagoons and shallow waters adjacent to outer coasts of barrier islands are included in the category. Freshwater influences are seasonally important in coastal habitats.

- Nearshore, *or* nearshore marine, as used herein, generally refers to those waters located inside the 10-m isobath. This depth is often where large (class 1) oceanographic vessels cease to operate for safety reasons. Additionally, the presence of brackish water can be a factor in describing the distance that nearshore waters occur from the coast. For example, during summer, brackish waters can extend more than 10 km offshore and often overlay cold more saline water masses deep in the water column. The nearshore includes inshore and coastal habitats, but tend to extend farther offshore.

- Offshore as used here describes shelf, slope, and deep-water habitats located beyond the nearshore.
- Nearshore-Marine refers to a descriptive adaptive model in this report as evidenced by those species having distribution patterns that are widespread over nearshore, shelf, and slope environments. An example would be the distribution of Arctic Cod in the United States Chukchi and Beaufort Seas.

A fish species can be distributed in one or more habitats in time and space. This report provides a comprehensive examination of how fish in Arctic environments have adapted, which depending on life strategy adaptations, represents a continuum of habitats on a gradient from freshwater to marine. For each species, patterns of habitat use are multi-dimensional with respect to areas and volumes occupied, space and time, and life cycle requirements for reproduction, growth and survival, dispersal, and other life functions. The distribution and abundance of life stages for each species throughout the water column are presented in chapter 3 to capture these relationships in the context of life zones (Allen and Smith, 1988) that portray key aspects of reproductive ecology by depth and location. Depictions in this report are unique for this region because the shelf break is depicted at 75 m on the basis of the bathymetry of the Chukchi and western Beaufort Seas.

Organization of the Catalog

The BOEM requested that the USGS conduct a synthesis of available environmental information addressing Arctic marine fish biology and ecology in the following areas: environmental and biological constraints; oceanographic overview; adaptation and acclimation; life history strategies; fish assemblages; foraging and feeding behavior; bioenergetics; use of time and space; growth and reproduction; migration; predation, parasitism, competition, and mutualism; dynamics of population abundance and production; conservation; subsistence; climate change; and information needs. The resultant *Arctic Marine Fish Ecology Catalog* is organized in eight chapters, a glossary, and three appendixes.

Chapters 1–3 provide detailed characterizations of the United States Arctic region's environmental setting and marine fish biodiversity and establish much of the physical and biological background information supporting ecological synthesis and management objectives of this project. Chapter 1 provides a broad overview of the Arctic marine environment and scientific goals and methods of this synthesis as it pertains to BOEM information needs as well as other users. Additional purposes are to describe the meaning of commonly used oceanographic and zoogeographic terminologies to avoid possible ambiguity associated with their use herein. Chapter 2 presents an inventory of the marine fish known from the United States Chukchi and Beaufort Seas including an analysis of changes resulting from new data and information acquired from the region since the early 2000s. Chapter 3 includes more than 100 species accounts and describes current knowledge about the biology and ecology for each marine fish known from the United States Arctic region using information from studies in Alaska and elsewhere within the species ranges. The species accounts are quick references to some topics (for example, climate change) and are described in more detail in chapters 5–6.

Chapter 4 provides a synthesis of information that, in its entirety, addresses the ecological objectives requested by BOEM. The USGS approach to this synthesis was to evaluate data and information about the descriptive and interpretive components of biogeography as described by Nelson (2006). By necessity, much information is incorporated by reference in this description of historical and environmental influences on marine fish presence and patterns of distribution and abundance in the United States Arctic marine environment.

Chapter 5 focuses on the modeling of climate change effects on the distribution of Arctic and Saffron cod in the Bering Sea. The Bering Sea was selected because of the extensive fishery data that are available from this region. Arctic and Saffron cod were selected because they are notably important in Arctic food webs and subsistence fisheries north of the Bering Strait. Our emphasis on modeling approach and distributional effects represent an important potential application to the Chukchi and Beaufort Seas as Arctic fishery data become more widely accessible in electronic formats. The results of modeling in the Bering Sea are considered in light of potential warming effects in the Chukchi and Beaufort Seas.

Chapter 6 focuses on how scientific information about the Arctic marine fish can inform policy and the conservation and management of Arctic species. Information needs relate to environmental assessment for OCS oil and gas development, fisheries management, and understanding potential effects of climate change. A traits-based approach can be used to assist resource management until population-level information and dynamics are better known. The information needs for high-priority species identified in chapter 3 also are evaluated with respect to future research and ecosystem-based management.

This report includes many descriptive and quantitative terms and complex concepts common in scientific literature. A "Glossary of Ecological Terms" is provided in chapter 7 to reduce confusion about these terms and concepts as used in this report. Chapter 8 provides a list of scientific references cited in narrative sections of the report. Each species account presented in chapter 3 includes a listing of the scientific reports and articles used.

Appendix A describes age, weight, and size relationships for marine fish species where data are available. The information supports life history and population dynamic sections of the report in chapters 4 and 6. Appendix B provides additional information about the availability of recent fishery investigations supported by BOEM as well ongoing studies, and topics where new information is anticipated. Appendix C provides summaries of the models developed to examine temperature effects on Arctic and Saffron cods in chapter 5.

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Summary

The need for reliable fishery information for National Environmental Policy Act analysis related to offshore oil and gas development in Chukchi and Beaufort Sea Planning Areas is described. The conduct of systematic surveys in these areas has been hampered by environmental and budgetary constraints and thus, in many respects, the existing data remain scattered and fragmented and are difficult to access. Lack of access to quantitative catch and observational data from ongoing research precluded our full use of modern geospatial technologies. Despite, this limitation, new information and visualization products were developed for each species of confirmed presence in the study area. The biological and ecological information presented in this report is regional in scale and, unless otherwise noted, local variations in seasonal fish habitat and abundance can be found in the literature cited. Given the spatial resolution of existing data, background descriptions of the physical and biological environments of the Chukchi and Beaufort Seas are presented at the landscape scale. All methods, terminologies, and operational definitions for this study are described. The organization of the report and linkages between chapters are described as they relate to the Bureau of Ocean Energy Management's information need for this synthesis.