PHYSICAL OCEANOGRAPHY

PROJECT AREA

This project covers portions of the Chukchi, Beaufort, and Bering seas. Specifically, the atlas covers the southern Beaufort Sea from Point Barrow, Alaska, east to Banks Island and the entrance to Amundsen Gulf in Canada; the southern Chukchi Sea from Point Barrow west past Wrangel Island, Russia; and the northern Bering Sea, including St. Lawrence Island, Norton Sound, and the Bering Strait. The northern Bering Sea is included in the Arctic Marine Atlas to capture the important ecological connectivity across these waters. The U.S. waters on this map cover an area the size of Texas.

Description

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This map displays topographic and bathymetric information based on a 1-kilometer (km) digital elevation model. The U.S. Exclusive Economic Zone (EEZ) is shown. This line, which represents our nation's area of exclusive rights to marine resources, extends up to 200 nautical miles offshore, which is beyond the northern boundary of the map. The U.S.-Russia EEZ indicates the international boundary and also the International Date Line. The U.S.-Canada EEZ boundary is in dispute, based on whether the line should be drawn perpendicular and equidistant from the nations' seaward baselines or projected straight along the 141st meridian (the terrestrial international boundary). The line drawn here shows the U.S. interpretation. Included are the names of common landmarks, including water and land features such as seas, bays, rivers, communities, islands, peninsulas, and political boundaries.

See related maps and descriptions of Bathymetry, Ecoregions, Energy Development and Protected Areas, and Human Impact.

Data Compilation and Mapping Methods

The topographic/bathymetric hillshade was created from the 1-km digital elevation model of the Alaska Ocean Observing System (AOOS). Political boundaries, communities, major rivers and lakes, and the 1:63,360 Alaska coastline were based on data available at the Alaska State Geospatial Data Clearinghouse and the Arctic Research Mapping Application at armap.org. Russia and Canada coastlines and the EEZ boundaries were provided by Alaska Center for the Environment.

Data Quality

This map has a data quality rating of good because it provides a complete geographic picture of the project area and key features.

The U.S.-Canada EEZ shown is in dispute, and the U.S. interpretation is depicted on the map. Although the northern extent of the U.S. EEZ is outside the project area, this boundary is subject to change with further interpretation of the Law of the Sea Treaty, assuming the U.S. will eventually ratify it. Researchers based at the University of New Hampshire are currently working on mapping the extended continental shelf in the Arctic to determine the true extent of the U.S. EEZ. Current estimates indicate the EEZ may extend much farther than originally anticipated.

Summary and Synthesis

The future U.S. EEZ may extend into areas not currently under their jurisdiction. Areas like the Chukchi Plateau in the northern Chukchi Sea may be key northern wildlife refugia following great sea ice losses associated with climate change. Newly discovered sea mounts in the Canada Basin may be home to undiscovered species.

Map Data Sources

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Bathymetry

Description

Bathymetry describes the underwater depth of the sea floor. Alaska's Arctic waters are characterized by a shallow outer continental shelf (OCS) with depths from 30 to 100 meters. The broad, shallow Chukchi Sea shelf begins at the Bering Strait and continues about 800 km northward to the 200-meter (m) depth contour. The Beaufort Sea shelf is a narrower band approximately 80 km wide. At the edge of the shallow OCS is a very steep slope that quickly drops to almost 4,000 m deep—an area known as the Canada Basin. Important landforms include the shelf break, Barrow Canyon, the shallow Hanna and Herald shoals, and even shallower nearshore areas. The Beaufort and Chukchi coasts are characterized by numerous spits, barrier islands, and shallow lagoons, which are often important wildlife habitat.

Researchers are currently working on mapping the extended continental shelf in the Arctic to determine the true extent of the U.S. EEZ. Their multi-scanner sonar is mapping this area in much greater detail and, in more northerly areas, is redefining our image of the seafloor. The researchers have already located previously unknown seamounts and steep seafloor topography extending the continental shelf north of the Chukchi Plateau (~80˚ to 85˚ N latitude).

See related maps and descriptions of Ecoregions, Ocean Circulation, Sea Ice Dynamics, Sea Floor Substrate, Chlorophyll-a, Net Primary Productivity, Benthic Biomass, Opilio Crab, Spectacled Eider, Steller's Eider, King Eider, Common Eider, Important Bird Areas, Pacific Walrus, Bearded Seal, Bowhead Whale, Beluga Whale, and Gray Whale.

Data Compilation and Mapping Methods

The topographic/bathymetric hillshade and bathymetric contour lines were distilled from the AOOS 1-km digital elevation model. Contours are displayed in 10-m increments from 0 to -100 m; in 50 m increments from -100 to -500 m; and in 100 m increments from -500 to -3,800 m.

Data Quality

This map has a data quality rating of good because it provides a complete geographic picture with a consistent 1-km grid cell size. Bathymetry data is not perfect, however. They are based on depth locations from a variety of studies during the last century. The seafloor is difficult to map in the Arctic because of inclement weather and sea ice. Although historical sounding data may have significant location errors, the area displayed here is believed to be decently accurate. Inaccuracies are more likely to occur moving northward out of the project area because those areas are more difficult to access and depths are more sparsely recorded.

Summary and Synthesis

Shallow areas adjacent to the coast, barrier islands, shallow lagoons, and Herald and Hanna Shoals are home to concentrated wildlife populations.

Map Data Sources

AOOS. 2009. 1 km topographic/bathymetric map of Alaska. Raster dataset. <http://ak.aoos.org/aoos/tools.html>. Accessed February 2009.

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Audubon Alaska. 2009. Bathymetric contour lines. GIS feature class (based on AOOS 2009).

Audubon Alaska. 2009. Chukchi Sea shoals. GIS feature class (based on AOOS 2009).

ECOREGIONS

Description

Ecoregions denote areas of general similarity in the type, quality, and quantity of environmental resources. According to the U.S. Environmental Protection Agency (EPA 2010), ecoregions are "designed to serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components… These general purpose regions are critical for structuring and implementing ecosystem management strategies across federal agencies, state agencies, and nongovernment organizations that are responsible for different types of resources within the same geographical areas."

Marine ecoregions are based on characteristics such as bathymetry, currents, temperature, and primary production, although the current dataset is based primarily on bottom topography and current flow. Further divisions reflect persistent fronts as well as heterogeneity in plankton, fish, and bird communities present. Alaska's marine ecoregions cover coastal, inner shelf, outer shelf, slope, and oceanic regions (Piatt and Springer 2007). The ecoregion boundaries may provide useful guidance as planning areas. Each area with specific environmental considerations and has habitat for a suite of species.

Terrestrial ecoregions are based on field research and experience of ecologists and regional experts. Types of data incorporated include vegetation, geology, topography, soils, permafrost, hydrography, and glaciation (Nowacki et al. 2001).

See related maps and descriptions of Bathymetry, Ocean Circulation, Sea Ice Dynamics, Sea Surface Temperature, Sea Floor Substrate, Chlorophyll-a, Net Primary Productivity, Zooplankton, Benthic Biomass, all fish and wildlife, and Energy Development and Protected Areas.

Data Compilation and Mapping Methods

Data were downloaded from the Internet and displayed on the map. No changes or updates were made.

Data Quality

Data limitations are addressed by Piatt and Springer (2007) in their chapter on marine ecoregions of Alaska. They state that the mapping presents an initial effort that will no doubt be refined. Boundaries, shapes, and number of ecoregions are currently based primarily on bottom topography and current flow. More analysis is needed using both physical and biological data.

This map has a data quality rating of good because it provides a complete geographic picture of marine and terrestrial ecoregions with the noted exception of the marine waters around Wrangel Island. The map is deserving of this rating because the data were created using a structured and consistent methodology, the ecoregions cover the majority of the project area, and the data are appropriate for the scale of mapping (1:5,000,000). Ecoregion boundaries should be refined as information becomes available.

Summary and Synthesis

Representation of the different ecoregions should be considered when protection measures are discussed.

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OCEAN CIRCULATION

Description

Three large water masses (Anadyr Water, Bering Shelf Water, and Alaska Coastal Current) flow north from the Bering Sea and squeeze through the Bering Strait into the southern Chukchi Sea. This flow pattern "profoundly influences the wind and wave regimes, the seasonal distribution of sea ice, the regional hydrologic cycle, and the water masses and circulation characteristics of the Chukchi and Beaufort shelves… Consider the Chukchi and Beaufort shelves as part of an ecosystem/environmental continuum with the Bering Sea shelf" (Weingartner 2008). Low salinity, nutrient-rich waters of the Bering Sea contribute to some of the world's highest marine productivity, particularly in the Hope Basin of the southern Chukchi Sea (Springer and McRoy 1993; Weingartner 2008). Because of these circulation patterns, the Bering Strait is a migratory corridor for birds and marine mammals traveling vast distances, and is an important source of zooplankton and particulate organic carbon (Weingartner 2008).

The Siberian Coastal Current along Chukotka's northern coast carries cold, nutrient-poor ice-melt and river water from Siberia to just north of the Bering Strait where it mixes with Anadyr Water (Weingartner 2008) flowing north from Anadyr Gulf. The offshore side of this front is an important bowhead whale foraging or staging zone (Moore et al. 1995). Salty, nutrient-rich Anadyr Water and lower-salinity, lower-nutrient Bering Shelf waters flow across Hope Basin and split south of the Herald Shoal. Water flows through Herald Valley in the west and Central Channel in the east against a northeasterly prevailing wind (Weingartner et al. 2005; Weingartner 2008).

The low-salinity, nutrient-poor Alaska Coastal Current is formed from river runoff along the Alaskan Bering Sea coast. It follows the Alaska coast, eventually through Barrow Canyon and around Point Barrow, and finally disperses into the Beaufort Gyre and through Amundsen Gulf and M'Clure Strait (not shown) in the Beaufort Sea (Ahlnas and Garrison 1984; Weingartner 2006; Weingartner 2008). Solar-heated waters in Kotzebue Sound, Norton Sound, and shallow coastal areas to the south are major sources of the heat in the coastal current (Ahlnas and Garrison 1984). When it reaches the eastern Beaufort, the Alaska Coastal Water has mixed with Bering Shelf Water and Atlantic Water flowing in from the East Siberian Sea (Weingartner 2006). These waters mix with the low-salinity MacKenzie Shelf Water as well and circulate in the Beaufort Gyre. Some westward moving wind-driven MacKenzie Shelf Water moves along the coast back toward Alaska, providing low-salinity water that is important for migrating Arctic cisco (Weingartner 2008).

The wind-driven Beaufort Gyre travels clockwise in the Canada Basin (Weingartner 2008) and meets up with the Transpolar Drift (not shown) near the North Pole. The Transpolar Drift is a main transportation current for the entire Arctic Ocean, bringing water from Russia's Laptev Sea toward the Canada Basin before heading to Fram Strait between Greenland and Norway (Mysak 2001).

See related maps and descriptions of Bathymetry, Ecoregions, Sea Ice Dynamics, Sea Surface Temperature, Chlorophyll-a, Net Primary Productivity, Zooplankton, Important Bird Areas, Pacific Walrus, Bowhead Whale, and Energy Development and Protected Areas.

Data Compilation and Mapping Methods

Ocean circulation data were collected from several sources in the form of digital graphics. Those graphics were georeferenced and lines depicting currents were digitized. The map is a blend of the information collected; repetitive lines and conflicting information were removed.

Data Quality

Localized flow variations in the Arctic are often wind-driven. The difficulties associated with depiction of local currents and wind patterns are (1) measuring that information over large areas and (2) mapping patterns that change seasonally, if not monthly or daily. By contrast, the large circulation patterns shown on the map tend to depict the year-round movement of large water masses. The 60-year Barrow wind record suggests wind intensity has increased in the last 15 years, having an influence on wind-waves and storm surges (Weingartner 2008).

The map has a data quality rating of fair. It provides a good geographic picture of ocean circulation, but data across the project area are variable—some portions of the map are represented by reliable, high-quality data, and data for other portions are opinion-based or are missing altogether. Connections between the East Siberian Sea and the Chukchi Sea are not well understood in terms of transport of nutrients. Likewise, the dynamics between the western and eastern Chukchi Sea and circulation patterns along the shelf break need further study. Circulation around Hanna Shoal is poorly understood (Weingartner 2008). Localized currents, which are largely affected by prevailing winds, are not depicted here.

Summary and Synthesis

Circulation is a critical factor for larval connectivity of many species and productivity in many places. Understanding circulation patterns is important for understanding the biology of the region. Surface currents, which are often directed by wind, are key to predicting the impacts of Arctic contaminants, such as an oil spill. Further study of circulation and wind patterns will provide for better prediction of the impacts of pollutants and biological processes.

The Bering Strait is an optimal point for long-term monitoring to detect changes in the Bering Sea, and assess the influence on the western Arctic Ocean, including effects of contaminants. In the Arctic Ocean Synthesis published in 2008, Weingartner suggests that "long-term monitoring in Bering Strait is critical to understanding how both the Bering and Chukchi-Beaufort ecosystems may respond to future change. We recommend that NPRB [North Pacific Research Board] collaborate with NSF [National Science Foundation], NOAA [National Oceanic and Atmospheric Administration], and AOOS [Alaska Ocean Observing System] to support long-term monitoring in the strait."

Hanna Shoal tends to hold cold water and sea ice long into the summer and is an important foraging area for ice-dependent species. Interest in oil and gas development makes study of currents in this area a top priority to understand how oil and gas activities may impact this important area.

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Weingartner, T., K. Aagaard, R. Woodgate, S. Danielson, Y. Sasaki, and D. Cavalieri. 2005. Circulation on the north central Chukchi Sea shelf. Deep Sea Research Part II: Topical Studies in Oceanography 52:3150-3174.

SEA ICE DYNAMICS

Description

Sea ice is a defining ecosystem characteristic in the Arctic Ocean. This important Arctic habitat component consists of multiple types of features that influence the distribution of marine productivity and wildlife, such as pack ice, ice floes, leads, polynyas, landfast ice, river overflood, and under-ice freshwater pooling. The ice reaches it maximum extent in March, reaching in some years nearly to the Aleutian Islands in the eastern Bering Sea. In September each year, sea ice reaches its minimum extent, receding past the U.S. EEZ, more than 200 miles offshore north of 75º latitude. This constantly changing, essential feature is the key to why the Arctic marine environment is so incredibly dynamic. The pack ice edge waxes and wanes annually, moving across an area approximately 2,000-2,500 km long. Given that this change from maximum to minimum extent happens over a six-month period, the edge advances on average about 10-15 km per day. Although the minimum sea ice extent varies significantly from year to year, the trend is an annually receding ice edge in all months of the year (Comiso 2002; Comiso et al. 2008) with a lobe remaining in the northeast portion of the project area in recent years.

It is not known just how these dynamic sea ice features will change in a warming climate. Predictions of future sea ice conditions include earlier melting, later freeze-up, an increase in open water, retraction of sea ice from the productive continental shelf, declining multi-year ice, and less stability in landfast ice (USFWS 2010). Wang and Overland (2009) predict a nearly sea ice-free Arctic summer in approximately 25 years. In their petition to regulate greenhouse gases under the Clean Air Act, Oceana et al. (2008) discuss the recent rapid changes in sea ice extent:

> Arctic climate change is causing sea ice to melt at rates faster than even the most dramatic predictions from several years ago… Predictions from earlier this decade did not even include forecasts that the Arctic would be seasonally ice-free during this century…Such a dramatic change in sea ice extent likely has not occurred for roughly 125,000 years, at a time when sea level was 4 to 6 meters (13 to 20 feet) higher than it is today. The rate at which sea ice is melting exceeds even the most dire predictions from just a few years ago and indicates the severity of the changes occurring as a result of greenhouse gas emissions.

During a time of such rapid change, Hanna and Herald shoals appear to be important sea ice areas over the long term. These shallow areas divert warm water masses flowing northward from the Bering Sea, holding colder water long into the summer season (Weingartner et al. 2005). As a result, sea ice persists there longer into the season as well (Martin and Drucker 1997; Spall 2007). A pack ice feature near Hanna Shoal called Post Office Point was historically a meeting point known for its reliable ice all summer long. The area was given its name because ships would meet at this dependable location to exchange mail and information at sea (Aldrich 1915; Bockstoce 1986). Recent warming has changed the structure of this persistent lobe of ice, and the minimum September sea ice extent has come that far south only once in the last decade (National Snow and Ice Data Center 2010). In comparison, Hanna Shoal and Post Office Point were ice-covered seven out of ten years in the 1980s and four out of ten years in the 1990s. Nonetheless, Post Office Point and Hanna and Herald shoals continue to be areas of persistent ice floes, which are very important for ice-associated wildlife. Although the pack ice is expected to further recede with climate change, the seafloor topography is likely to continue to divert warm waters. Hanna and Herald shoals have the potential to provide substantial lingering ice floes well into the future compared to other areas in the region (Spall 2007), and may become a last stronghold for some ice-associated species.

Polynyas (recurrent, predictable open water areas in the sea ice) and open leads are important congregation and feeding areas for mammals and birds in the winter months (Stringer and Groves 1991; Stirling 1997). Polynyas are continually changing in size and shifting position, which can make them difficult to map. However, these openings are found consistently in some areas that are adjacent to land or grounded pack ice where the ice is blown offshore by the prevailing wind or pulled away by currents. In the Chukchi and Bering seas, there are two distinct classes of polynyas: persistent open areas off south-facing coasts and less frequently occurring wind-driven openings that occur off north-facing coasts (Stringer and Groves 1991).

Another important sea ice feature is landfast ice, which is stable ice that is fastened to the shore and remains much of the year. This feature provides an important platform for wildlife and subsistence hunters. In the Alaskan Beaufort Sea, landfast ice "first forms in October and is anchored to the coast. It then rapidly extends some 20-40 km offshore to eventually cover ~25% of the shelf area and remains in place through June" (Weingartner 2008). Landfast ice in this area has not changed in extent, although formation and breakup are occurring later and earlier compared to data from the 1970s; the ice is also less stable, with impacts on local hunting (Gradinger 2008).

Thawing Arctic rivers flowing into the sea meet up with remaining landfast ice at the coast. These meeting locations create river overflood on top of the sea ice and force pockets of freshwater under the ice. Overflood areas eventually funnel into open leads, in a feature known as strudel drainage (Hearon et al. 2009). These areas, which can cause large scour holes in the seafloor. Because they are a concern for infrastructure development, overflood areas have been mapped for the Alaskan Beaufort coast. Temporary freshwater lakes beneath the sea ice are captured by an inverted ice dam where the edge of the stable landfast ice and the drifting pack ice meet, otherwise known as a stamukhi zone (Carmack and MacDonald 2002). Such prominent features are known to occur in MacKenzie and Kugmallit bays at the outflow of the MacKenzie River.

Variation in ice cover is the dominant factor in the spatial pattern of primary productivity from phytoplankton (Wang et al. 2005). Much of the phytoplankton blooms and wildlife activity occurring in the Arctic environment is concentrated at the ice edge. The sea ice is very important to primary productivity as a platform for large algal blooms happening in the bottom of the sea ice in spring and summer (Horner and Schrader 1982; Gradinger 2008; Laidre et al. 2008). Production associated with the sea ice is the base of an ice-associated food web that includes amphipods, Arctic cod, seabirds, and seals. "It remains unresolved how changes in the diversity and productivity of the ice related biota combined with changes of the timing and regions of ice melt and formation will impact the ice itself and the tight sea ice-pelagic-benthic couplings in the arctic shelf seas" (Gradinger 2008). Complicated by climate warming, baseline biophysical processes are difficult to measure. Nonetheless, an effort should be made to better understand sea ice dynamics in relation to climate change, which has the potential to significantly change the Arctic marine ecosystem as we currently know it.

See related maps and descriptions of Bathymetry, Ecoregions, Ocean Circulation, Sea Surface Temperature, Observed Climate Change, Chlorophyll-a, Net Primary Productivity, Benthic Biomass, Capelin, Spectacled Eider, Steller's Eider, King Eider, Ivory Gull, Kittlitz's Murrelet, Important Bird Areas, Polar Bear, Arctic Fox, Pacific Walrus, Ribbon Seal, Spotted Seal, Ringed Seal, Bearded Seal, Bowhead Whale, Beluga Whale, Gray Whale, Energy Development and Protected Areas, and Predicted Climate Change.

Data Compilation and Mapping Methods

Data representing sea ice concentration for the circumpolar north were collected for 60 months from January 2003 to December 2007 (National Ice Center 2008). Because we are interested in ice habitat availability for marine mammals, a 50% or greater ice concentration was used to define ice extent. This approach followed the USGS protocol for estimating habitat selection by polar bears (Durner et al. 2007). Areas with ≥50% ice were reclassified to 1, and areas with <50% ice were reclassified to 0. The 60 data layers were added together and divided by 5, yielding a raster grid of average number of months per year with ≥50% sea ice concentration.

The National Ice Center original datasets also classified landfast ice; similarly, the number of months per year with landfast ice were added then averaged for the five year period. We then considered MMS data on recurrent leads in the Beaufort Sea and a portion of the northwest Chukchi Sea (Eiken et al. 2005). The Eiken et al. recurrent leads data were distilled from remotely sensed imagery, providing monthly median extent grids averaged over eight years from October to July. The ten monthly median grids were added, resulting in a grid depicting the number of months with landfast ice present. Finally, with both landfast ice datasets on screen, along with landfast ice from NOAA (1988) and leads and polynyas from Stringer and Groves (1991) and USFWS (1995), we drew landfast ice boundaries. We also updated polynya boundaries, combining information from Stringer and Groves (1991), USFWS (1995), Eiken et al. (2005), and Carmack and MacDonald (2002).

Shoal boundaries follow the -40 m isobath, and were distilled from the AOOS 1-km digital elevation model. The seasonal freshwater lake created by the MacKenzie Delta was from Carmack and MacDonald (2002). River overflood data was from Hearon et al. (2009).

Data Quality

This map has a data quality rating of fair. It provides a fairly complete geographic picture of sea ice dynamics, but data across the project area are variable—some portions of the map are represented by reliable, high-quality data and data for other portions are opinion-based or are missing altogether.

National Ice Center ice concentration datasets are based on 25-km grid cells. Even at a scale as broad as the project area, the data resolution is somewhat low. Minimum sea ice extent lines are drawn at a global scale, and lack sufficient resolution for planning.

Landfast ice from MacKenzie Bay to Kasegaluk Lagoon is based primarily on data from remotely sensed imagery. These excellent data exceed the quality of landfast ice in other portions of the map, which was primarily from NOAA's 1988 atlas. Polynyas are continually changing in size and shifting position, which makes them difficult to map; lines presented here are based primarily on data from Stringer and Groves (1991), which mapped the median extent. A study mapping recurring leads and polynyas like the one conducted by Eiken et al. (2005) is currently under way for a greater portion of the Chukchi Sea. This mapping information is important and very useful, and we suggest that such studies should be extended to include all of the U.S. EEZ, and preferably the entire project area.

The impacts of climate change on landfast and pack ice is poorly understood. Weingartner (2008) asserts "climate change will result in large alterations to both pack and landfast ice (and their interactions). These changes will alter the shelf circulation and have a critical influence on erosion processes."

Areas of seasonal freshwater trapped beneath sea ice were not mapped outside the MacKenzie Bay area. Areas of river overflood were not mapped outside the Beaufort coast.

Summary and Synthesis

Hanna and Herald shoals are key conservation areas. These shallow, cold water pockets sustain lingering ice floes that provide important wildlife habitat, which may become vital to survival of some species, such as walrus, as the climate warms. The interactions between sea ice, sea ice biota (e.g., ice algae), primary production in the water column, zooplankton, and the benthos are in need of further study (Hopcroft et al. 2008). Polynyas and leads should be mapped across the project area in greater detail, with seasonal and interannual variability addressed. Finally, an oil spill during the winter months could devastate wildlife feeding and breathing in leads and polynyas. Identification of potential oil spill effects should adequately consider the effects of sea ice dynamics.

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SEA FLOOR SUBSTRATE

Description

Sea floor sediments influence the assemblage of benthic organisms and, in turn, foraging areas of bottom-feeding birds and mammals. The Arctic continental shelf is made up of mostly soft sediments (mud or sand) and gravel. Sediment heterogeneity, sediment type, and sorting, along with temperature, are major regulating factors on benthic community structure and diversity (Grebmeier et al. 1989).

Rare boulder patch communities are the only known places capable of supporting kelp forests, which support unique benthic communities. Where these rarities are found, they are important habitats for a diversity of benthic, demersal, and pelagic species. The boulder patch in Stefansson Sound (near Prudhoe Bay) is home to a diversity of invertebrates and algae that are the most biologically diverse community yet discovered in Alaska's Beaufort Sea (Dunton et al. 1982; Dunton and Schonberg 2000).

See related maps and descriptions of Bathymetry, Ecoregions, Benthic Biomass, Opilio Crab, Spectacled Eider, Steller's Eider, King Eider, Common Eider, Long-Tailed Duck, Important Bird Areas, Pacific Walrus, Bearded Seal, and Gray Whale.

Data Compilation and Mapping Methods

Sea floor substrate was digitized from a georeferenced TIFF image in NOAA's *Bering, Chukchi, and Beaufort Seas Coastal and Ocean Zones Strategic Assessment Data Atlas* (1988). Boulder patch locations are a combination of data from Dunton et al. (1982), Horowitz (2002), Mohr et al. (1987), and NOAA's ESI (2002).

A scheme that lends itself to relating sediments to benthic habitat (grain size and sorting) was used by NOAA (1988) in creating the data shown in the map. The degree of sorting present in the source data was not shown here to simplify map display, but is available in the geospatial database.

Data Quality

This map has a data quality rating of poor because it provides an incomplete geographic picture of seafloor substrate. No data are available for large portions of the project area, and those areas for which data are available are mapped at a low resolution. It is unclear why bottom information is lacking for some nearshore areas, particularly near Barrow and Emmonak, while other areas further offshore have data.

Summary and Synthesis

The Arctic Ocean seafloor is not well understood. Filling data gaps will provide important habitat information that may yield information on the distribution of benthic organisms and foraging areas for birds and mammals. Boulder patch communities are rare centers of biological diversity that must be protected from development and disturbance, especially the patch present in Stefansson Sound. Anthropogenic disturbance could have significant impacts through sedimentation and pollution (Dunton and Schonberg 2000). Other unknown boulder patch communities are likely to exist, and further study is needed to identify these features.

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SEA SURFACE TEMPERATURE

Description

Sea surface temperature is useful for identifying consistent oceanographic features, such as upwelling and fronts between water masses. Upwelling is an important source of nutrients to upper water column. Frontal boundaries can indicate biological hotspots where production is concentrated. Sea surface temperature is derived from remotely sensed satellite data, which measure the temperature only at the surface of the water column. Surface waters in the project area have mean temperatures ranging from -0.5º to +8.5º C. The Chukchi, Beaufort, and Bering seas each have different average water temperatures, with the Bering Sea having the warmest water. The coldest waters are below freezing in the deep Canada Basin, and the warmest waters are found in the highly productive Norton Sound. Warm Bering Sea water flows through the Bering Strait into the Chukchi Sea—an important linkage that carries nutrients to the Arctic waters. Under this influence, the Chukchi Sea shelf waters are relatively warm, ranging from 1º to 6º C. In contrast, Beaufort Sea waters hover around freezing all year long. The MacKenzie River flows year-round, injecting a plume of slightly warmer water (~2º) into the Beaufort ecosystem. Areas are ice-free for various lengths of time between May and October. Generally between November and April each year, the project area is covered in continuous ice.

See related maps and descriptions of Ecoregions, Ocean Circulation, Sea Ice Dynamics, Observed Climate Change, Chlorophyll-a, Net Primary Productivity, Capelin, Pacific Herring, Saffron Cod, Pink Salmon, Chum Salmon, Kittlitz's Murrelet, and Predicted Climate Change.

Data Compilation and Mapping Methods

Data for all open water months (May to October) were collected for five years, from 2004 to 2008. Sea surface temperatures were collected by the Aqua MODIS satellite and served through the National Aeronautics and Space Administration (NASA) Ocean Color website as monthly 4-km raster grids (Feldman and McClain 2009). Some southern areas were ice-free for all six months each year, and northern areas were ice-free for only one month per year. Areas that were ice-free were classified as no data in the original datasets. The first step was to reclassify each of 30 grids to reflect ice-free (1) versus ice- or cloud-covered (0) areas. These reclassified grids were summed for each year, resulting in one grid per year showing the number of ice-free months for each cell in the project area. Next, sea surface temperature grids were summed for each year, then divided by the number of ice-free months grid for that year using the raster calculator. In other words, the total temperature for each cell was divided by the total number of samples for each cell, resulting in the average. This approach yielded the yearly mean sea surface temperature for each of five years. Last, the five years were averaged, for a final result reflecting the average yearly mean sea surface temperature during ice-free months.

Data Quality

This map has a data quality rating of good because it provides a complete geographic picture of sea surface temperature over the entire project area at a consistent 4-km resolution. Temperatures throughout the water column and at the seafloor are known data gaps.

These data are mapped at a good resolution for this scale of mapping. The data are available daily, or as weekly, monthly, seasonal, or annual averages beginning in July

2002. No data areas existed in the original data because of either cloud cover or sea ice cover. As explained above, those areas were eliminated from the average sea surface temperature analysis. Although data may not be available for a number of days because of ice or cloud cover, when the available data are averaged over a month, and those months are averaged over a year, and those years are averaged as well, the data gap of incomplete daily information tends to be minimized. There were no concerning data gaps in the information presented here.

Summary and Synthesis

Sea surface temperature is useful for identifying consistent oceanographic features, such as upwelling and fronts between water masses. Monitoring of sea surface temperature through satellite imagery should be continued. This information provides a baseline from which climate changes can be measured. Such long-term, consistent data at a good resolution with complete geographic coverage are very rare for the Arctic.

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OBSERVED CLIMATE CHANGE

Description

According to the Arctic Climate Impact Assessment (2005), the Arctic is warming twice as fast as the rest of the planet, which, along with other climate fluctuations, is causing marine waters to warm and sea ice to decline. Climate change has been observed throughout Alaska during the last two or more decades and is projected to increase in future decades. Wang and Overland (2009) predict a nearly sea ice-free Arctic summer in approximately 25 years.

This map, based on data published in the journal *Science*, shows that Arctic sea surface temperature in the project area rose as much as 1° C between 1985 and 2005 (Halpern et al. 2008). Steele et al. (2008) found some areas of the Arctic Ocean to have temperature anomalies as high as 5° C in 2007 when compared to longer term historical averages. Also mapped are the minimum sea ice extent boundaries for 1985 and 2005. These were chosen because they match the dates of the sea surface temperature analysis conducted by Halpern et al. (2008). Additionally, the 2007 ice extent is displayed because it was the year that Arctic sea ice had the smallest extent on record. Within the project area, the amount of minimum sea ice pack lost between 1985 and 2007 is equal to the states of California and Washington combined. Sea ice now retreats past the shelf break into very deep waters, where it is difficult or impossible for marine mammals (especially benthic feeders) to forage. This retreat of sea ice is a major area of concern for walrus and other ice-dependent wildlife.

See related maps and descriptions of Sea Ice Dynamics, Sea Surface Temperature, Chlorophyll-a, Net Primary Productivity, Zooplankton, Benthic Biomass, Capelin, Pacific Herring, Saffron Cod, Pink Salmon, Chum Salmon, Ivory Gull, Kittlitz's Murrelet, Northern Fulmar, Polar Bear, Pacific Walrus, Ribbon Seal, Spotted Seal, Ringed Seal, Bearded Seal, Bowhead Whale, Beluga Whale, Human Impact, and Predicted Climate Change.

Data Compilation and Mapping Methods

Observed sea surface temperature change was created by the National Center for Ecological Analysis and Synthesis (Halpern et al. 2008). Scientists there analyzed sea surface temperature anomalies, where temperature exceeds a threshold value; that value was the long-term weekly mean temperature from 1985 to 2005. They calculated difference in anomaly frequency between the period of 2000 to 2005 and 1985 to 1990 based on the number of times the anomaly exceeded the standard deviation for that location and week of the year. Sea surface temperature data were from the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Version 5.0 (Halpern et al. 2008).

Data Quality

This map has a data quality rating of good because it provides a complete geographic picture of sea surface temperature change and minimum sea ice extent over the entire project area. There were no data gaps in the project area. Halpern et al. (2008) described the following data limitation, "Our approach did not account for potential presence of thermo-tolerant species or local-scale oceanography that could modify how resistant a local ecosystem is to changes in SST [sea surface temperature]."

Summary and Synthesis

Higher sea surface temperatures indicate the Arctic environment is being altered, which will likely result in ecological change, especially in areas where annual variance in sea surface temperature is relatively low (Halpern et al. 2008). Areas of higher temperature increases may be more stressed and therefore more vulnerable to compounding effects of climate change and development. Development, commercial fishing, shipping traffic and other anthropogenic disturbance should proceed with extra caution in these areas.

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