ARCTIC OCEAN SYNTHESIS: ANALYSIS OF CLIMATE CHANGE IMPACTS IN THE CHUKCHI AND BEAUFORT SEAS WITH STRATEGIES FOR FUTURE RESEARCH

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INTRODUCTION

There is now strong scientific evidence that the Arctic Ocean is changing, with a profound effect on this ecosystem and the way it will be utilized by humans (ACIA 2004, www.amap.no/acia). The most notable present physical trends are manifested in the temperature increase, the reduction of the total ice volume, and the extent of the sea ice (Fig. 1; Walsh 2008). Other changes in the physical environment in the Arctic shelf regions include increased river discharge, rising sea-level, thawing of permafrost and coastal erosion. Changes in albedo (light reflectance) associated with snow and sea-ice trends can result in a positive feed-back on warming trends, with record summer minimums observed most of this decade (Comiso et al. 2008) and projection that the Arctic could be ice-free during summer by 2060 (Walsh 2008). The potential biological impacts include shifts in species distributions, changes in the timing and magnitude of production cycles, risk to marine species dependent on sea-ice, and increased exposure of organisms to UV radiation through loss of snow and ice cover. Impacts on society are wide ranging and include changing access to traditional foods, loss of hunting cultures, expanded marine shipping, increased access to marine natural resources, and enhanced Arctic fisheries (ACIA 2004). The challenges at both the regional and Pan-Arctic scales are to take the global-scale generalizations on climate change plus the functioning of each biological realm (e.g. Gradinger 1995, Smith and Schnack-Schiel 1990), and refine them with the details to assess past, present and future patterns.

The ecosystems of the Arctic Ocean and northern Bering Sea are less well known than most US oceanographic regions because of their remoteness and the extensive seasonal and permanent ice cover that interferes with physical and biological sampling efforts. Although investigations of Alaskan waters began in 1888 with the US Fisheries Bureau flagship *Albatross,* no hydrographic or biological sampling appears to have occurred north of Bering Strait at the time. For much of the last century, drifting ships (e.g., Nansen's Fram) and ice stations (e.g., T3, ARLIS 1&2, Russian drift stations "North Pole", NP-2, 3-5) were the only means of peering through the ice cover for much of the year. In contrast, there is a longer history of access to the shallower coastal seas that generally become ice-free for some period during the late summer months. Thus, for many oceanographic disciplines, seasonal observations are largely restricted to the basins, while the most spatially extensive observations are highly biased toward areas and periods where ice cover is minimal.

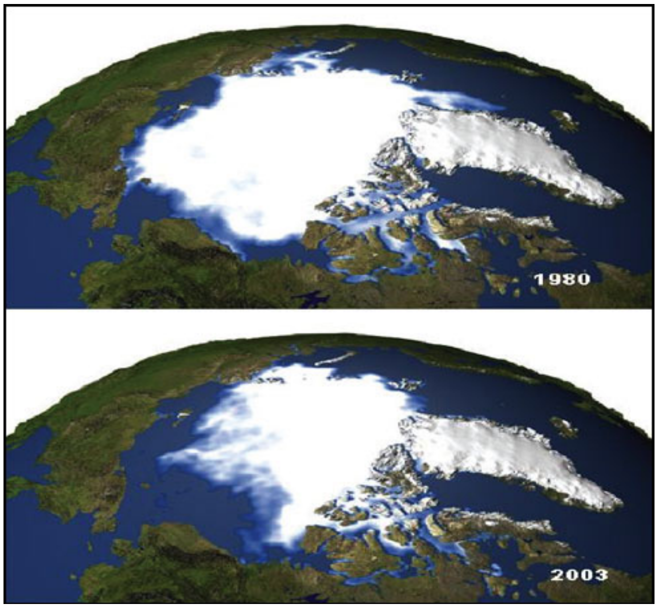

Fig. 1: Interannual changes in the minimum summer sea ice extent of Arctic sea ice: 1980 versus 2003 (http://science.hq.nasa.gov/directorate/04review.html)

The Beaufort and Chukchi seas together represent the 'Arctic', one of Alaska's 3 Large Marine Ecosystems (LME) as defined by NPRB. Large scientific programs in this LME and the adjacent sub-polar Bering Sea within the last three decades include the earlier Alaskan Outer Continental Shelf Environmental Assessment Program (OCSEAP) and the Inner Shelf Transfer and Recycling (ISHTAR) program, plus the more recent Surface Heat Budget of the Arctic Ocean (SHEBA) drift across the Chukchi Plateau, the 1994 Arctic Ocean Transect, the Shelf-Basin Interactions (SBI, http://sbi.utk.edu) program on the Beaufort and Chukchi Shelves, the Canadian Arctic Shelf Exchange Study (CASES; http://www.cases.quebec-ocean.ulaval.ca/welcome.asp), the Circumpolar Canadian Flaw Lead program (CFL-http://www.ipy-cfl.ca/) - cross-basin cruises by NOAA's Ocean Exploration (OE) Program (http://www.oceanexplorer.noaa.gov/explorations/05arctic/welcome.html, http://www.oceanexplorer.noaa.gov/explorations/02arctic/welcome.html), and the Canadian/Japanese Joint Western Arctic Climate Study (JWACS). The more recent international Arctic shelf studies frequently contributed into the larger framework of the Shelf-Basin-Exchange (SBE) initiative of the Arctic Ocean Science Board (AOSB, www.aosb.org). Though extensive, results from many of these more recent programs are just beginning to appear in the scientific literature.

What have remained problematic are the political boundary bisecting this region and access to the relevant Russian literature to complete our understanding of the dynamics of this region. Some relevant synthesis of the Russian literature has been conducted using data from Bering Strait southward (e.g. Coyle et al. 1996); but aside from compilations of species lists (e.g. Sirenko 2001), synthesis including Russian data is generally scarce from regions to the north of the Strait (e.g. Grebmeier 1993, Feder et al. 1994). Notable exceptions have been data from the five Joint US-USSR Bering Pacific (BERPAC) cruises executed between 1977 and 1993 (Tsyban 1999), and the Joint Russian-American Long-term Census of the Arctic (RUSALCA) cruises begun in 2004 (http://www.arctic.noaa.gov/aro/russian-american/). In addition to these co-ordinated efforts, a multitude of smaller research efforts funded by various government agencies (e.g. NSF, USGS, USFWS, NOAA, NPRB), as well as the oil and gas industry, have looked at individual components of the physical, chemical and biological aspects in less co-ordinated context amassing a considerable body work, most often directed toward fish, seabirds and marine mammals. The recent oil and gas exploration leases awarded in the Chukchi Sea are also expected to spur a new body of knowledge in the coming years.

The recent changes in the sea ice regime have prompted concern that polar systems and their biological communities may be particularly sensitive to climate change (e.g. Sturm et al. 2003, Grebmeier et al. 2006a,b), in part because they are so highly adapted to the extremes of this environment (Pörtner and Playle 1998). For the Chukchi and Beaufort seas, ecosystem changes could be profound if changes in bentho-pelagic coupling lead to increased pelagic production and a reduction of benthic production (e.g. Grebmeier et al. 2006b). Such reorganization in the way the ecosystem operates will ultimately alter the pathways and magnitude of energy that passes into upper trophic levels such as fish, sea-birds and marine mammals, and impact the people dependent on those resources. Similar concerns for the sub-arctic Bering Sea stimulated a new research effort funded jointly by NSF and NPRB, which reaches from physical forcing to ecosystem and human impacts (http://bsierp.nprb.org/).

There is, therefore, urgency to integrate and synthesize the present state of knowledge of the biology and oceanography of this region as required baseline information against which to observe and understand ongoing changes. A multidisciplinary team was assembled at the University of Alaska Fairbanks, to undertake such an activity, specifically for the Chukchi and Beaufort seas and nearby waters, which are of particular interest to NPRB. We attempted to qualitatively synthesize past and present knowledge gained during research programs in the Chukchi and Beaufort seas by holding an interdisciplinary workshop in the spring of 2006 to bring together experts from the United States, Russia, Canada, and Japan. The goal of this effort was directed at summarizing the current state of knowledge and then identifying: (1) the most crucial information gaps, (2) 'pulse points' in the biological/physical environment that require monitoring, and (3) how climate change might impact biota through its influence on: sea ice extent/characteristics, shelf currents and transport through Bering Strait, coastal currents along Alaska's north coast and their relationship to various biological processes and life histories. The workshop was held February 16-17, 2006, consisting of 8 of the 10 working groups (35 participants), with logistical conflicts forcing a sea-bird working group (7 participants) to meet March 22-23, and the sea-ice working group (7 contributors) to convene electronically. Numerous other scientists contributed during preparation of the report (see Appendix 1). This report summarizes the findings of each of the ten working groups involved, and subsequently provides recommendations on a multidisciplinary ecosystem approach for addressing perceived needs.

The 10 working groups included: physical oceanography, chemical oceanography, sea-ice, primary production/phytoplankton, microbes (other than phytoplankton), zooplankton, benthos, fish, seabirds, and marine mammals. Each group was charged with keeping their reports short, and providing their own perspectives on information gaps and research needs. Under such contraints, group summations of the literature will necessarily be incomplete and selective, and we consequently note there is a vast body of reports and grey literature for some disciplines that are not adequately reflected within this synthesis. Following the working group reports there is a more holistic view of what changes might be expected, and what future multidisciplinary efforts might be undertaken by NPRB to monitor such changes, with the expectation that only a fraction of their financial resources would be committed to this region. A guide to the acronyms employed throughout this document appears in Appendix 2.

PHYSICAL OCEANOGRAPHY

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Introduction

The Chukchi and Beaufort seas are the northernmost shelf seas bordering Alaska. Although properly a part of the western Arctic Ocean, both shelves are intimately linked, atmospherically and oceanographically, to the Pacific Ocean. The atmospheric connection is primarily via the Aleutian Low, whose varying position and strength and interactions with polar air masses affect regional meteorological conditions. The oceanographic connection is solely through Bering Strait, where the mean northward flow transports waters and organisms from the Bering Sea shelf and adjacent basin. The Pacific connection 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. Moreover, because of this connection to the Pacific it is convenient to consider the Chukchi and Beaufort shelves as part of an ecosystem/environmental continuum with the Bering Sea shelf.

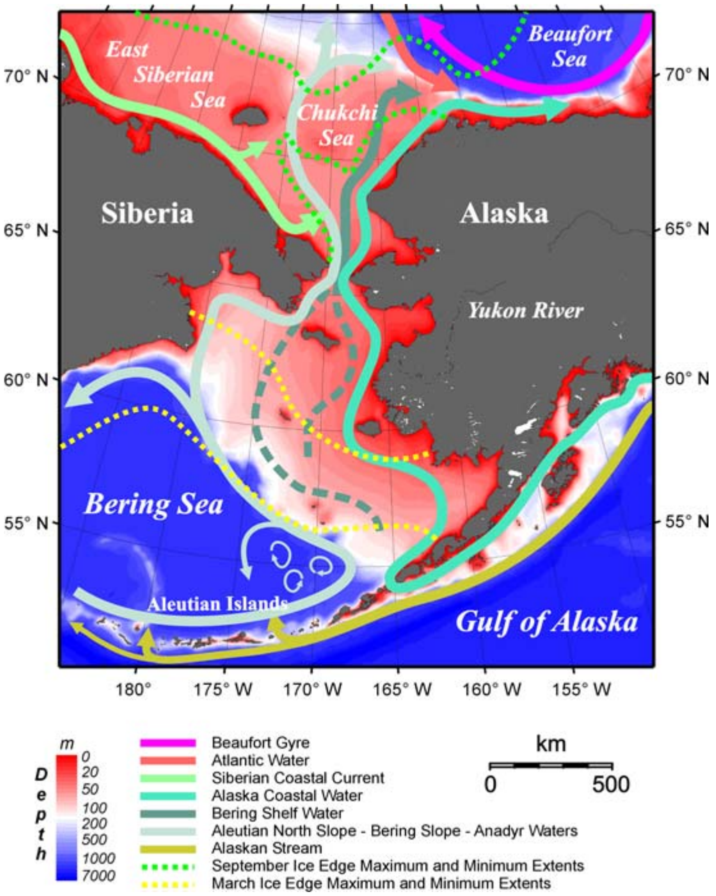

Fig. 2. Schematic circulation map of the Bering-Chukchi-Beaufort seas ecosystem

Often the region is operationally divided into three major regions of study. We will follow that tradition here to focus our discussions, but fully recognise that these are inter-related domains in terms of physical, chemical and biological processes.

Bering Strait

Bering Strait is the narrowest (~80 km wide and 50 m deep) constriction along the pathway by which Pacific waters enter the Arctic Ocean (Fig. 2). As such, the strait is an optimum point for the long-term monitoring of this flow and its variability (Roach et al. 1995, Woodgate et al. 2005a, Aagaard et al. 2006, Woodgate et al. 2006) and thus for detecting changes in the Bering Sea and assessing how these changes will influence the western Arctic Ocean. Indeed, the volume and properties of the water flowing northward through Bering Strait reflect the time-dependent, integrated output of both the physical and biogeochemical components of the Bering

Sea ecosystem. For example, the salt and nutrient loads of the strait throughflow represent the net effects of upwelling from the deep Bering Sea basin, biochemical cycling on the Bering shelf, and areally integrated freshwater fluxes. The latter includes the freezing and melting of sea ice (Schumacher et al. 1983, Danielson et al. 2006), river runoff, the net atmospheric moisture flux, and freshwater contributions from the Gulf of Alaska (Weingartner et al. 2005a) all of which play an important role in the salt and nutrient budgets of the Bering Sea shelf (Aagaard et al. 2006).

North of the strait, the throughflow exerts important influences at both regional and global scales. Its low salinity and nutrient-rich waters (compared to Arctic Ocean surface waters) sustain the enormously high productivity of the southern Chukchi Sea (Walsh et al. 1989, Grebmeier and McRoy 1989, Springer and McRoy 1993), provide essential nutrients to the Western Arctic ecosystem, and, by conditioning the density structure of the western Arctic Ocean, influences the ice cover (Walsh et al. 1997, Carmack 1986, Steele et al. 2004, Woodgate et al. 2005b, Weingartner et al. 2005b, Shimada et al. 2006). In summer Pacific waters are a heat source that may provide nearly 20% of the oceanic heat flux to the upper levels of the Arctic Ocean, and may be significant in the recent retreat of sea ice over the western Arctic (Francis et al. 2005, Stroeve et al. 2005, Woodgate et al. 2006). The Bering Strait inflow provides nearly 50% of the total freshwater input to the Arctic Ocean and is the largest freshwater source for the Arctic Ocean (Aagaard and Carmack 1989, Woodgate and Aagaard 2005, Serreze et al. *submitted*). Because of the density dependence upon salinity at these high latitudes the salinity (or freshwater content) of the strait throughflow governs the fate of Pacific waters entering the Arctic Ocean. Quantifying the heat and freshwater fluxes through Bering Strait is critical for predicting changes in the physical, biogeochemical, and ecosystem structure of the Chukchi and Beaufort seas.

The strait is also a migratory corridor for a rich and diverse annual movement of marine mammals and birds over vast distances (Moore and Reeves 1993, Ainley and DeMaster 1997, Tynan and DeMaster 1997) and it is an important source of zooplankton to the Chukchi and Beaufort seas (Springer and McRoy 1993) and for the carbon that fuels the enormous benthic communities of the Chukchi Sea (Grebmeier et al. 1988, 1989, Grebmeier and McRoy 1989, Walsh et al. 1997), which are important for sustaining the large numbers of marine mammals that seasonally inhabit the Chukchi shelf. Finally the strait is an important pathway by which ocean-borne contaminants from the Pacific enter the Arctic (Macdonald and Bewers 1996, Macdonald et al. 2003).

At the global scale, Bering Strait is an essential link in the global hydrologic cycle by balancing the water budgets of the North Pacific and the North Atlantic (Wijffels et al. 1992). Models suggest that the Bering Strait freshwater flux affects the Atlantic meridional overturning circulation and possibly influences North Atlantic climate (Goosse et al. 1997, Weijer et al. 2001, Hasumi 2002, Wadley and Bigg 2002) and influences the structure of the western boundary currents (including the Gulf Stream) in the Atlantic Ocean (Huang and Schmitt 1993).

In summary, the flow of Pacific waters through the Bering Strait has profound local, regional and global consequences. It is an optimal location for monitoring properties that: (1) reflect changes in the Bering Sea, (2) influence the marine ecosystems of the Arctic Ocean and (3) have consequences on the global circulation and world climate. The small size and constricted nature of the strait make it an ideal location for cost-effective, long-term monitoring of key ecosystem variables.

Bering Strait Measurement History

Flow measurements using year-round moored oceanographic instruments measuring currents, temperature, and salinity began in the late 1970s and were continued intermittently in the 1980s as part of the NSF's Inner Shelf Transport and Recycling (ISHSTAR) Program. Since 1990 year-round measurements have been maintained nearly continuously with support from NSF, NOAA, ONR, and AOOS. Although several important caveats discussed below affect these measurements, the long-term mean transport appears to be ~800,000 m^3 s^{-1} (Coachman and Aagaard 1981, Roach et al. 1995, Woodgate et al. 2005b) with a mean salinity of ~32 (Woodgate and Aagaard 2005). The mean northward flow is forced by the large-scale pressure gradient between the Pacific and Arctic oceans (Coachman et al. 1975, Aagaard et al. 2006) and opposes the mean southward winds. Nevertheless flow variations are primarily wind-forced and can be large over a wide range of time scales (Woodgate et al. 2005b). There is also significant seasonal and annual variability in the wind-driven transport and in the water properties (Coachman and Aagaard 1988, Roach et al. 1995, Woodgate et al. 2005b, Woodgate et al. 2005c).

Strait waters are derived from three sources: salty, nutrient-rich Anadyr Water that is upwelled from the northern Bering continental slope, flows across the Gulf of Anadyr and then primarily through the western channel of the strait; lower salinity and lower nutrient Bering Shelf Water formed over the central Bering shelf that feeds both channels of the strait; and low-salinity, nutrient-poor Alaska Coastal Water formed from river runoff along the coast of the Bering Sea. The coastal water flows through the east channel and is often a narrow (~10 km wide) swift plume along the Alaskan coast termed the Alaska Coastal Current (ACC).

The historical measurements were constrained in several important respects. First, measurements in the western channel (Russian EEZ) were limited to only three years prior to 1995 due to political access restrictions. Consequently measurements made in US waters were extrapolated to the Russian EEZ (details provided by Roach et al. 1995 and Woodgate et al. 2005b). Access improved in summer 2004 with Russian clearance obtained for scientific work conducted under the auspices of the NOAA-sponsored RUSALCA (Russian-American Long-term Census of the Arctic) program. Second, all of the instruments were deployed within 10 m of the seabed to minimize the risk of damage from drifting ice keels. Thus temperature and salinity stratification effects are missed in the historical measurements. Third, the early current measurements were obtained from a single near-bottom depth so that current shear was not captured. More recently, this problem is being overcome by deploying acoustic Doppler current profilers. Finally, most of the measurements were obtained from the central portion of the eastern channel of Bering Strait (within the US EEZ) and then extrapolated across the strait. This approach appears to significantly underestimate the mass, salt, and heat fluxes across the strait since the mid-channel measurements do not adequately capture the ACC. Within the past three years measurements have been maintained in the ACC leading to substantial improvements in monitoring heat, freshwater, and mass transports (Woodgate and Aagaard 2005).

Bering Strait Measurement Status and Recommendations

It appears that measurements in the western channel of Bering Strait will continue as part of NOAA's RUSALCA program and in the eastern channel of the strait with support from the NOAA and NSF through at least 2010. Support beyond this period is uncertain, although Woodgate, Weingartner, and Whitledge are submitting proposals to NOAA and NSF to continue measurements through 2012. The proposed measurements are to include estimates of stratification, nitrate flux and phytoplankton production using moored nitrate samplers and fluorometers.

The workshop participants agreed 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 collaborate with NSF, NOAA, and AOOS to support long-term monitoring in the strait. At the time of this writing there are two proposals pending at NSF and NOAA (submitted by R. Woodgate, T. Weingartner, and T. Whitledge) to continue the moored measurement program (including moored nitrate analyzers) over the next four years as part of the International Polar Year Program. In addition, J. Grebmeier and L. Cooper have a proposal pending at NSF to continue and expand a Long-term Ecosystem Observatory at Little Diomede Island. The observatory includes a collaboration with the residents of Little Diomede Island and will include collecting near-surface and year-round samples of nutrients, chemical tracers, and biological productivity.

Chukchi Sea

The shallow (~50 m) Chukchi Sea shelf extends ~800 km northward from Bering Strait to the shelfbreak at about the 200 m isobath. The mean flow over much of the shelf is northward due to the Pacific-Arctic pressure gradient and opposes the prevailing northeasterly winds. The Bering Strait influx of heat, nutrients, carbon, and organisms bestows the Chukchi shelf with physical and ecological characteristics that are unique among arctic shelves (Grebmeier and Harvey 2005).

Much of our understanding of the Chukchi shelf derives from the early syntheses of Coachman et al. (1975) and Walsh et al. (1989) and more recently (since 1985) in the papers by Aagaard et al. (1985), Aagaard and Roach (1989), Weingartner et al. (1998), Weingartner et al. (1999), Münchow and Carmack (1997), Münchow et al. (1999), Münchow et al. (2000), Weingartner et al. (2005b) and Woodgate et al. (2005b). The physical oceanographic summary of the Chukchi shelf is drawn primarily from these papers.

Mean Circulation

The Bering Strait throughflow crosses the Chukchi Sea along three principal pathways associated with distinct bathymetric features (Fig. 2, 3). A western branch flows northwestward from the strait and exits the shelf through Herald Valley. While most of this outflow probably descends through Herald Valley, some of it may spread flow eastward across the central shelf. A second branch flows northward across the central channel shelf and then probably splits; with some water continuing eastward toward the Alaskan coast while the remainder flows northeastward toward the continental slope. The third branch flows northeastwards along the Alaskan coast towards Barrow Canyon at the junction of the Chukchi and Beaufort shelves. In summer this flow includes the northward extension of the Alaska Coastal Current (ACC) that originates south of Bering Strait. Within Barrow Canyon the ACC is joined by waters flowing eastward from the central shelf and the merged flow then moves downcanyon toward the shelfbreak. Mean current speeds within Herald Valley and Barrow Canyon are swift (~25 cm s^{-1}), more moderate in the central channel (~10 cm s^{-1}), but generally $\leq$5 cm s^{-1} elsewhere on the shelf. Long-term transport estimates for these three pathways are only approximate but suggest that the flow across the central Chukchi shelf is ~200,000 m^3 s^{-1} while the branches in both

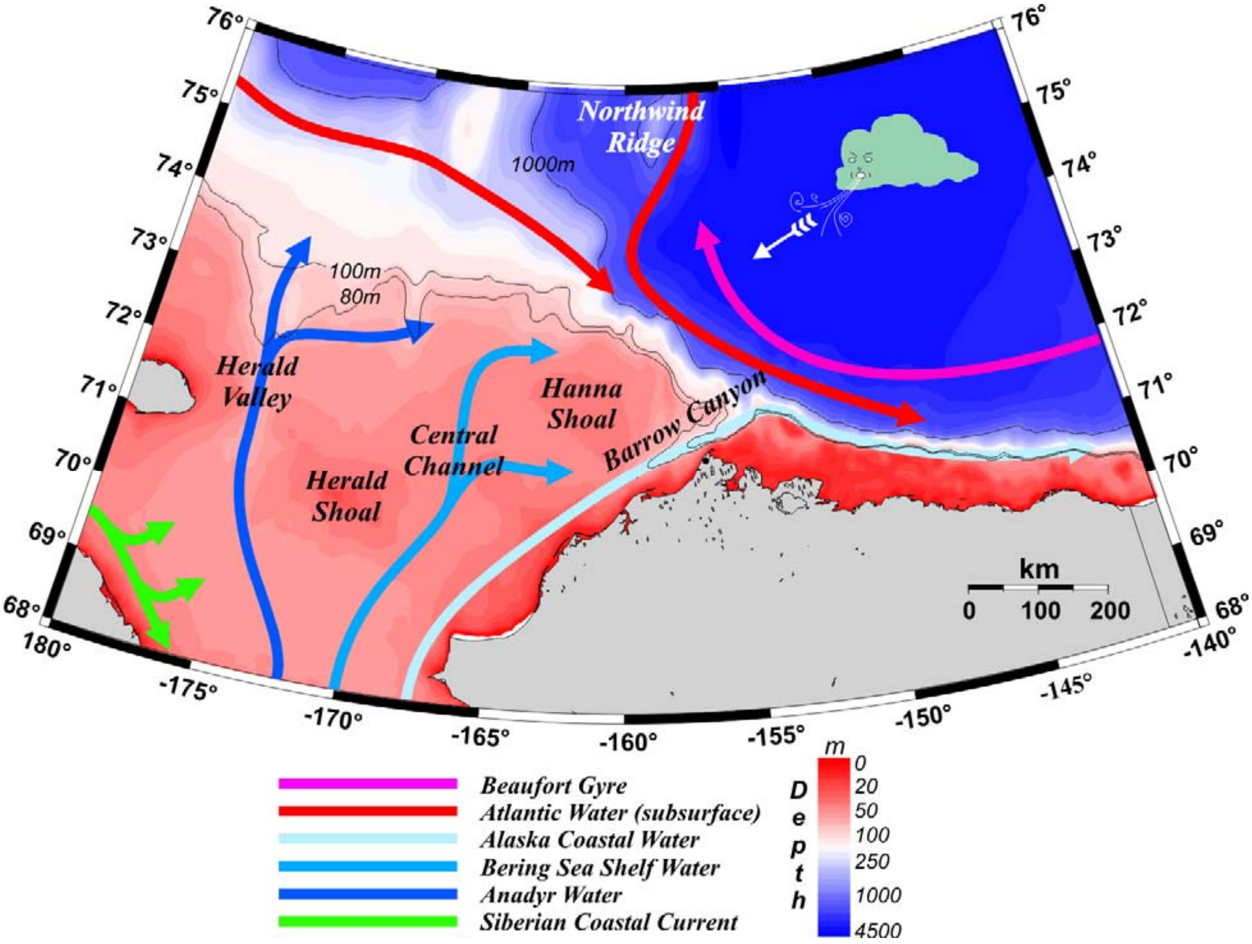

Fig. 3. Schematic circulation map of the Northern Chukchi Sea region

Herald Valley and Barrow Canyon carry ~300,000 $m^3 s^{-1}$. In summer and fall the influence of the warm Bering Sea inflow along these pathways is manifested in the form of "melt-back embayments" indenting the ice edge (Paquette and Bourke 1981). Finally, there is also a small fraction of the strait throughflow that flows westward through Long Strait into the East Siberian Sea, which appears to be an important nutrient source to this shelf (Codispoti and Richards 1968, Codispoti et al. 1991).

The nutrient and carbon loads carried along these branches differ (Walsh et al. 1989, Hansell et al. 1993, Cooper et al. 1997). The Herald Valley outflow is saltier, colder, and richer in nutrients and marine-derived carbon than the waters transported in the Alaskan Coastal Current, whereas waters crossing the central shelf have intermediate properties. In fact, Herald Valley waters include the branch from Bering Strait and a dense (cold, salty) water mass formed in winter on the Chukchi shelf probably in the vicinity of Wrangel Island. These water masses vertically mix with one another as they descend the valley and create a new water mass (Pickart et al. *accepted*). In winter, shelf waters decrease to the freezing point and salinities increase due to salt rejection from growing sea ice. The seasonal changes in shelf salinities have important implications on the fate of the nutrients and carbon in the Chukchi shelf waters that enter the basin. Low density summer waters are confined to the upper 75 m of the shelfbreak and slope, whereas denser winter waters descend to 100 – 150 m depth.

There are two other aspects of the Chukchi shelf circulation of importance. The first is the buoyancy-influenced Siberian Coastal Current (SCC) that originates in the East Siberian Sea and flows southeastward along the Siberian coast into the Chukchi Sea. The SCC carries cold, low-salinity, nutrient-poor ice-melt and river waters that enter the East Siberian and Laptev seas. The SCC is confined to within ~60 km of the Chukotkan coast and bounded on its offshore side by an unstable front, which appears to be an important bowhead whale foraging zone (Moore et al. 1995). Nearing Bering Strait the SCC narrows and turns offshore to mix with waters exiting the strait. Most of the resulting mix is most likely transported through Herald Valley and across the central shelf. It also appears likely that surface waters over the outer shelf and slope are flowing westward on average (Muench et al. 1991) bringing sea ice and cold, low-salinity waters of the polar mixed layer over the outer shelf and slope.

The mean circulation results from the large scale pressure field between the Pacific and Arctic oceans and opposes the mean winds, which are from the northeast. The winds are, however, the principal cause of flow variability. Wind forcing varies seasonally with both wind magnitude and variability being largest in fall-winter and smallest in summer. In particular, in fall and winter the winds can frequently reverse the shelf flow field or re-distribute the flow from one branch to another (Weingartner et al. 1998). As a consequence of this seasonality, transit times along the three flow pathways across the Chukchi shelf are from 3-6 months in spring and summer but longer in fall and winter.

In general, wind-forced current fluctuations are coherent over much of the shelf, although, for reasons not known, the correlation is substantially weaker over the western shelf than for the eastern shelf (Woodgate et al. 2005b). Westward winds induce upwelling at the continental slope, which could be an important nutrient source at the shelfbreak. While no measurements have been made of this phenomenon along the Chukchi slope, data from Barrow Canyon indicate that wind-forced upwelling carries waters from ~250 m depth or more toward the head of the canyon, which lies ~150 km from the canyon mouth (Aagaard and Roach 1990, Weingartner et al. 1998). Winds also appear to be important in the dynamics of the SCC. For example, in some years the winds along the Chukotkan coast are persistently upwelling and prevent the SCC from entering the Chukchi Sea (Münchow et al. 1999, Weingartner et al. 1999). The consequences of this variability are unknown, but if the SCC front is an important foraging zone for bowhead whales, its absence in some years could affect whale foraging behavior.

The other major sources of current variability are associated with mesoscale (10 – 50 km) instabilities associated with relatively large cross-frontal density gradients. Mesoscale flows can be vigorous (>20 cm/s) and uncorrelated with winds. The instabilities initially appear as meanders along the front, but can rapidly grow in strength and/or detach into eddies that move across the axis of the front. Eddies and meanders are very prominent within the SCC front and promote cross-shore mixing between SCC and Bering Strait waters flowing northward through Hope Sea Valley. Eddies and cross-shore mixing result from frontal instabilities along the edge of polynyas due to the large salinity differences between high salinity polynya waters and less saline offshore waters (Gawarkiewicz and Chapman 1995). Finally, fronts associated with melting along the ice-edge often include vigorous three-dimensional mesoscale motions (Liu et al. 1994, Muench et al. 1991) that often lead to enhanced biological production at the ice edge. Moreover, the mixing and circulation fields associated with the mesoscale motions associated with the SCC and ice edge may also be important in establishing biologically rich mesoscale patches.

Measurement History

Prior to the 1970s several hydrographic expeditions collected data throughout the Chukchi Sea as summarized in *Coachman et al.* (1975). In the 1970s and 1980s several year-round moored measurement programs were conducted in the US EEZ and supported by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) as summarized by *Aagaard* (1988). Beginning in 1990 NSF, ONR and MMS supported a number of physical oceanographic programs, the results of which were summarized above. Most recently, these included the NSF-ONR sponsored Shelf-Basin Interaction (SBI) which recently completed a three-year field program (2001-2004). The SBI program focused primarily upon biogeochemical processes over the outer shelf and shelfbreak and the data from this program are still undergoing analysis.

Recommendations:

- The connection between the western (Russian EEZ) and eastern (US EEZ) portions of the shelf is poorly understood. The western Chukchi Sea might be an important source of nutrients on the outer shelf. In similar fashion the connections between the East Siberian Sea and Chukchi Sea are poorly understood. These issues likely affect shelf production processes, are pathways for potential sources of contaminants from Russia, and are needed to evaluate numerical bio-physical ecosystem models.
- Circulation processes along the Chukchi shelfbreak are poorly understood but the circulation here is part of a broader circulation field that connects the Chukchi and Beaufort slopes (discussed next) and carries waters draining from the western Chukchi shelf through Herald Valley to the eastern Beaufort. (This also relates to #1)
- The region around Hanna Shoal in the northeast Chukchi Sea is poorly understood. Here outer shelf and slope waters are very likely brought back onto the shelf and there appears to be renewed interest in this area for oil and gas exploration and extraction.
- The seasonal cycle of stratification has not been measured for any Arctic shelf. This cycle is critical for understanding the dynamical response of the oceans to atmospheric forcing and for understanding primary and secondary biological production. Recent technological developments now permit stratification measurements to be made in seasonally ice-covered waters.
- The northern Chukchi and Beaufort seas are undergoing rapid ice retreat in conjunction with the rest of the Arctic, although the summer retreat in this sector is particularly rapid and over the past few years is ~7.0%/year. This implies a change in ocean dynamics since the ice edge is extending beyond the shelfbreak, which might drastically alter the upwelling response (Carmack and Chapman 2003). This might lead to a considerably different ecosystem since the amount of light and nutrients available to the euphotic zone will likely change.
- Mesoscale processes at the ice-edge are poorly understood since existing measurements lack the necessary resolution to resolve properly the temporal and spatial scales of the bio-physical processes occurring here. New technologies (towed-instruments and/or autonomous underwater vehicles) are now available that permit these processes to be better understood and quantified.

- The causes of the rapid change are not completely understood but likely involve the complex interplay between horizontal oceanic heat advection and the large albedo gradient across the ice edge.
- Many of these recommendations require sampling in both the Russian and US EEZs and will require obtaining clearance from the Russian government. In recent years, NOAA (as part of the RUSALCA program) has succeeded in securing clearances. We therefore recommend that NPRB partner with NOAA in this research. If oil/gas exploration interest increases in the Chukchi Sea, MMS will be interested in additional marine research and collaborations with this agency are most appropriate.
- A reduction in the sea ice cover and a lengthening of the ice free season, particularly in fall when wind speeds are strongest, suggest that wind waves, and possibly storm surges, will become larger resulting in more rapid coastal erosion. Research is needed to understand how the wind wave field and storm surges will change in response to changes in sea ice concentration and extent.

Beaufort Sea

The Alaskan Beaufort Sea (ABS) shelf is ~80 km wide (Fig. 4) and extends ~500 km eastward from Point Barrow to the Convention Line along the Mackenzie Beaufort Sea shelf in the Canadian EEZ. Bottom depths increase gradually from the coast to the 80 m isobath and then plunge rapidly along the shelfbreak and slope. There is little along-shelf variability in bathymetry, except for Barrow Canyon which forms the western shelf boundary and Mackenzie Valley along the eastern boundary. In contrast, the continental slope is highly corrugated (M.

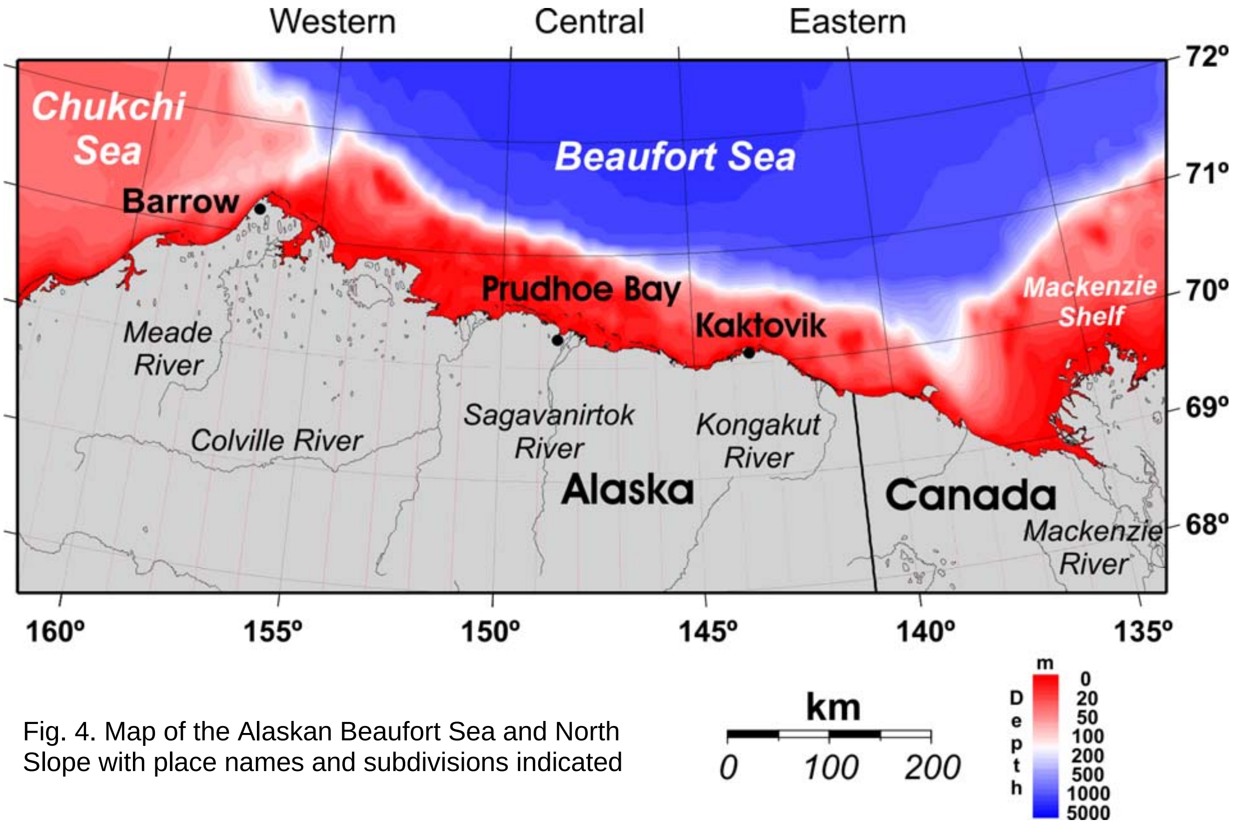

Fig. 4. Map of the Alaskan Beaufort Sea and North Slope with place names and subdivisions indicated

Edwards, pers. comm.) and nearly doubles in width between the western and eastern ABS.

The prevailing winds are from the northeast and force a westward wind-driven flow over the shelf and an onshore and westward drift of first- and multi-year sea ice from the basin onto the shelf. The wind-field will promote upwelling of nutrient laden sub-surface waters at the shelfbreak with this process probably being critical to the shelf nutrient supply. The ABS is also subject to seasonally varying mesoscale winds that may substantially alter the synoptic wind field. For example, summer sea breezes enhance westward winds within ~25 km of the coast (Kozo 1982a, b). Sea breezes could have a substantial influence on the nearshore circulation field. From October through April, mountain barrier winds (Kozo 1980, 1984) can result in along-shore divergence in the shelf wind field. Barrier winds develop when cold, southward-flowing surface air is blocked by the Brooks Range and induces eastward surface winds over a horizontal scale of 200 – 300 km. The barrier effect does not influence the western ABS since here the mountains lie more than 300 km from the coast. However, the eastern ABS is only 60 km north of the mountains and so well within the influence of the barrier winds. Consequently, during barrier events the winds can be westward over the western ABS but eastward over the eastern shelf. Kozo (1984) estimated that the mountain barrier jet effect occurs ~20% of the time between October and April.

Sea ice may cover the shelf throughout the year, although in recent years most of the shelf has been ice-free from late July through early October. The ABS ice cover consists of two distinct components; freely-drifting pack ice over the middle and outer shelf and the virtually immobile landfast ice on the inner shelf. 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 (Barnes et al. 1984a). Landfast ice is relatively smooth adjacent to the coast but can be highly deformed offshore and ridging increases throughout winter (Tucker et al. 1979). Deformation can, however, vary considerably along the shelf and it appears that the landfast ice zone on the Mackenzie shelf is less deformed than on the Alaskan Beaufort shelf (Tucker et al. 1979). Ice keels can gouge the seafloor (Barnes et al. 1984a) and form piles of grounded ice, stamukhi, along the seaward edge of the landfast ice. The stamukhi may be important in protecting the inner shelf from forcing by the drifting pack ice (Reimnitz and Kempena 1984).

The different ice types (pack vs. landfast) profoundly affect the underlying shelf circulation. Wind-forced currents over the mid- and outer shelf regions can be vigorous due to the stress transmitted to the ocean by the drifting ice. In contrast, the immobility of the landfast ice isolates underlying shelf waters from surface stresses. Hence nearshore currents are feeble during the landfast ice season, but vigorous once the landfast ice detaches from its coastal anchor (Weingartner et al. 2005c). The transition in stress at the landfast ice edge likely results in strong along-ice jets and secondary circulations (cross-shore motions and intense vertical flow that are either up- or downwelling depending upon the direction of the wind). However, the landfast ice and stamukhi zone appears to be an effective barrier to the exchange between the inner and outer portions of the shelf (Macdonald and Carmack 1991).

ABS waters reflect the influence of three distinct oceanic regimes and the coastal boundary. The first regime consists of Pacific Ocean waters (modified on the Bering and Chukchi shelves) that exit the Chukchi shelf through Barrow Canyon (Mountain et al. 1976, Aagaard and Roach 1990, Weingartner et al. 1998, Weingartner et al. 2005b). Some of this outflow continues eastward (in the surface layer in summer) and/or as a subsurface current along the Beaufort shelfbreak and slope and contributes to the upper halocline of the Canada Basin (Mountain et al. 1976, Aagaard 1984, Pickart 2004, Pickart et al. 2005) and some appears to spread westward and/or offshore in the polar mixed layer (Shimada et al. 2001). Very likely, however, some of the canyon outflow rounds Pt. Barrow and continues onto the inner portion of the Beaufort shelf, although the frequency and the extent to which this occurs are unknown.

The offshore boundary of the shelf comprises the second oceanic regime and includes the outer shelf and continental slope. Over the upper 50 m the westward flow constitutes the southern limb of the wind-driven Beaufort Gyre and transports the cold, dilute waters of the polar mixed layer. Below this layer the flow is eastward over most of the slope but concentrated in a narrow (~20 km wide) jet with a mean core speed of 8 cm s^{-1} centered at ~170 m. (The subsurface flow is called the Beaufort undercurrent or shelfbreak jet (Aagaard 1984, Pickart 2004). The jet probably extends along the Chukchi Sea slope and carries dense winter water from this shelf (including outflows from the central and western Chukchi) and also warmer, saltier Atlantic Water upwelled from deeper depths. Wind-driven upwelling is occasionally strong enough to advect the undercurrent onto the shelf perhaps as far inshore as the 50 m isobath. The undercurrent appears to continue along the entire ABS slope (Aagaard et al. 1989), but its fate beyond this point is unknown. Indeed limited current measurements along the Mackenzie shelfbreak suggest that the shelfbreak flow here is westward (Kulikov et al. 1998) suggesting that the shelfbreak flow is convergent near the Convention Line. The slope flow appears to be highly unstable and thus it is likely a source for the numerous eddies that infiltrate the Canada Basin.

The Mackenzie shelf forms the eastern boundary of the ABS and comprises the third oceanic regime. Although there are few measurements in this area, we suggest that the year-round discharge from the Mackenzie River profoundly influences the eastern ABS (Carmack et al. 1989, Macdonald et al. 1989, Macdonald and Carmack 1991). Mackenzie shelf waters have been detected throughout much of the Canada basin, including the continental slope of the Chukchi and western Beaufort Sea as far as 160^{o}W longitude (Guay and Falkner 1998, MacDonald et al. 1999). It thus seems likely that the prevailing northeasterly winds force Mackenzie shelf waters onto the ABS as well. Indeed, the migratory behavior of arctic cisco offers indirect evidence for intrusions of Mackenzie River waters onto the inner shelf of the ABS because these fish require a nearshore band of low-salinity water in order to complete their annual migration between the Mackenzie and Colville rivers each summer (Colonell and Galloway 1997). This migratory path is presumably maintained by the westward wind-forced drift of low-salinity water from the Mackenzie shelf.

The coastal boundary of the ABS includes numerous, small arctic rivers (Fig. 4), including the relatively large Colville River, that primarily enter the central and eastern portions of the ABS. Unlike the Mackenzie River, which flows year-round because it has a deep channel and is fed by temperate sources, arctic rivers are shallow and their watersheds are entirely underlain by permafrost, which profoundly influence the annual discharge cycle. The discharge cycle consists of the 2-week spring freshet, which occurs between late May and June, followed by a rapid decrease and then a more gradual decay to negligible runoff by early October. Consequently nearly 90% of the annual discharge occurs during the spring freshet and there is no measurable winter discharge from arctic rivers.

ABS water properties are controlled by the annual freeze-thaw cycle and inflows from the oceanic and coastal boundaries. In winter temperatures are at or near the freezing point (except perhaps after upwelling events that bring warm water from the Atlantic layer onto the outer shelf). Near-freezing waters remain on the shelf year-round, although in near-shore, highly stratified plumes temperatures can be 5–10°C above the freezing point. Salinities (hence density) vary widely in space and time. Shelf salinities are between 32 and 33 in winter, with higher values (33-40) in some of the coastal lagoons. During the spring freshet, river waters spread offshore beneath the landfast ice in highly stratified, thin (1-2 m) plumes, although it is not known how far offshore the plumes spread. Plume salinities are <5, whereas the salinity in the waters offshore or beneath the plume is 32-33. Once the landfast ice detaches from the coast, plume and ambient waters mix. The freshwater is carried offshore during upwelling events or in filaments generated by instabilities, or it is advected alongshore in a coastal current under downwelling favorable winds. The hydrographic and circulation structure of the ABS are poorly understood but probably complicated because of the diverse water sources feeding this shelf. For example, the different water sources applied at the lateral boundaries of the ABS (Pacific waters in the west and Mackenzie shelf waters in the east) suggest that there are along-shelf gradients in both density and nutrients that affect circulation and biological production patterns on the ABS. Similarly, cross-shelf differences are probably quite large. In summer and fall, these gradients are established by river runoff, ice melt, and shelfbreak processes, while in winter the shelfbreak processes and the landfast/pack ice boundary likely lead to spatial heterogeneity. How these gradients affect biological production patterns remains unknown.

The under-ice plumes carry a massive suspended sediment load that settles onto the inner shelf under the quiescent conditions beneath the landfast ice (Weingartner et al. 2005c). Once the landfast ice detaches from the coast, bottom sediments are re-suspended and advected along- and offshore by currents. Re-suspension is vigorous during fall storms and upon ice formation, with a considerable amount of sediment incorporated into the sea ice matrix where it remains until the following summer when the ice melts or is transported offshore. Thus the landfast ice plays an important role in the fate of terrigenous sediments supplied to the ABS. Since these sediments are an important carbon source to this ecosystem (Dunton et al. *in press*), changes in the hydrological and/or sea ice regime of the ABS are likely to substantially influence the ABS ecosystem.

Measurement History

During the 1970s considerable research was conducted under the auspices of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) in anticipation of oil and gas industrial development along the North Slope. That research is summarized in the book edited by Barnes et al. (1984b). These efforts were followed in the mid 1980s by additional work conducted by Aagaard et al. (1989) over the continental shelf and slope. Beginning in 1999 MMS commissioned studies to assess circulation and thermohaline variability in the nearshore (shoreward of the 15 m isobath) zone of the ABS. This research included the first year-round moored measurements ever made in the landfast ice zone and those results are summarized in Weingartner et al. (2005). Additional measurements of shelfbreak processes have been made in the western Beaufort Sea with support from the NSF-ONR sponsored Shelf-Basin Interaction (SBI), which recently completed a three-year field program (2001-2004). Similarly, the area around the McKenzie River inside the Canadian EEZ has recently received significant attention by the Canadian Arctic Shelf Exchange Study (CASES-2002-2004). These data are presently being analyzed.

Recommendations:

- The mesoscale wind field is poorly understood and these winds might be important in ABS shelf and slope dynamics. Mesoscale meteorological model and observational studies of the barrier winds and sea breeze effect should be undertaken in conjunction with a review of existing data to determine the scales of the along- and cross-shelf winds, the sensitivity of the mesoscale wind field to ambient conditions (including the large scale synoptic fields and the broad scale distribution of ice), and their frequency of occurrence.
- The dynamics of shelf sea ice, and in particular, the landfast ice zone are poorly understood in comparison to the ice dynamics of the basin. 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. Observations are needed of the sea ice distribution (thickness, concentration, and under-ice topography), ice velocity, and deformation fields over the shelf since these properties affect ice mechanics and the surface stress distribution over the shelf.
- Circulation processes at the seaward edge of the landfast ice edge are complex insofar as these involve ice dynamics and wind and buoyancy forcing. Ice edge processes are critical in understanding how the inner shelf communicates with the outer shelf.
- The behavior of river plumes propagating over and beneath the landfast ice during the spring freshet is unknown. Under ice propagation characteristics play an important role in the distribution of suspended and dissolved terrestrial materials and may influence the distribution of organisms. The overflow might also influence the timing of landfast ice decay (Dean et al. 1994, Searcy et al. 1996). Climate change will bring about substantial alterations in the ice environment and the arctic hydrologic cycle and thus influence the mobilization and dispersal of terrestrial and deposited materials on this shelf. Both ice melt and runoff affect the seasonally varying stratification, which needs to be measured.
- Sediment transport and erosion processes in the ABS are not understood and a better understanding of these processes is required in order to understand how climate change will influence the coast and shelf (and eventually the basin). Climate change will drastically affect these processes due to changes in the hydrologic cycle, the sea ice environment, shelf circulation, wind-waves and storm surges.
- The large-scale circulation and thermohaline structure of the ABS needs to be resolved with ample consideration given to the large interannual variability in winds and ice conditions. Measurements need to be conducted synoptically across the shelf in the western, central, and eastern Beaufort Sea so that the influence of source waters from the lateral ocean boundaries (ABS continental slope, Chukchi and Mackenzie shelves) on the ABS ecosystem can be ascertained. Measurements should include the use of geochemical tracers to resolve the sources of the various water masses.
- A preliminary review of the 60-year long Barrow wind record suggests that wind intensities and extremes have increased over the past 15 years. Summer/fall ice retreat over the last decade has also been consistently unprecedented. These changes will have a major influence on the wind wave and storm surge climate of the Beaufort Sea. Measurements and models of both the wave regime and storm surges should be conducted for the Beaufort shelf.

CHEMICAL OCEANOGRAPHY

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Introduction

Chemical measurements in the Arctic Ocean have the general utility of tracing water masses (e.g. Kadko and Meunch 2005) or delineating physical or biological processes such as studying the pathways and fate of organic carbon in the water column (e.g. Mathis et al. 2005, Bates et al. 2005a,b, Davis et al. 2005) and sediments (Moran et al. 2005). A great role of chemical oceanography is studying nutrients required by organisms that ultimately become limiting to their growth (i.e. the non-conservative elements) and the carbon parameters (e.g. DIC, DOC, POC) that are impacted by the physics and biogeochemistry of the region. Most research emphasizes nitrogen (as ammonium, nitrite and nitrate), phosphorus (as phosphate), silica (as silicate) and increasingly iron, although other elements can at times also become limiting. The distribution of nutrients is intricately coupled to physical oceanographic processes, modified by biological processes, and ultimately related to geological processes as organic material sediments. Thus chemical oceanography represents a major connection between these disciplines, with chemical measurements greatly enhancing the understanding of physical, biological and geological processes that significantly affect Arctic ecosystems.

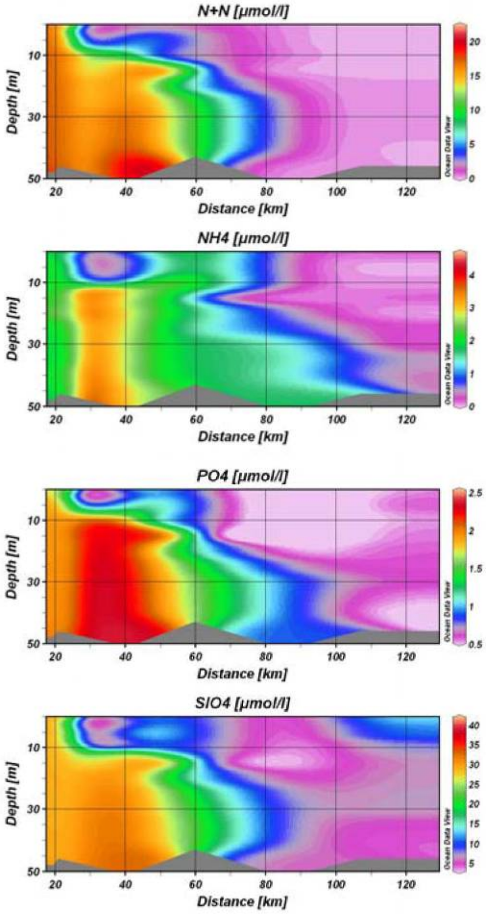

Fig. 5. Nutrient Concentration across Bering Straight in August 2004, showing the stong gradients from Russia (left side) to Alaska (right side)

In polar waters, nutrient concentrations undergo seasonal depletion in surface waters due to photosynthesis during spring/summer and renewal during winter when photosynthesis stops and surface waters are mixed with or replaced by nutrient rich deep waters. The carbon cycle also experiences a similar seasonal pattern with the lowest values of pCO_2 and the highest levels of organic carbon concurring with the lowest nutrient levels in the upper mixed layer at the termination of the spring bloom. Similarly the flux of elements from the pelagic to the benthic realm undergoes a predictable seasonal pattern, although in shallow waters such as the Chukchi Sea this can be complicated by resuspension of sediments by variable currents or deep-mixing during storm events.

Bering Strait

Bering Strait is the conduit for the main source of water flowing from the Pacific into the Arctic Ocean. The volume and properties of the water flowing northward through Bering Strait reflect the time-dependent, integrated output of both the physical and biogeochemical components of the Bering Sea ecosystem. The concentrations of nutrients that flow through the strait represent the combined mixture of upwelled water from the deep Bering Sea basin, Bering Sea shelf water that has been located on the shelf for several months, and Alaskan Coastal Water that is derived from freshwater sources from the south. The nutrient content of these three water types varies markedly (Fig. 5) such that there are approximately one hundred-fold higher concentrations of nitrate in the water column on the western side of Bering Strait compared to the eastern side (Walsh et al. 1989). North of Bering Strait, the nutrient-rich waters support the enormously high productivity of the southern Chukchi Sea (Walsh et al. 1989, Springer and McRoy 1993) and provide essential nutrients to the Western Arctic ecosystem.

Bering Strait Measurement History and Status:

There is a long history of discrete nutrient measurements conducted in the Bering Strait in conjunction with most major research programs beginning in the 1960s, that worked either to the north or south of the straits (e.g. OCSEAP, ISHTAR, BERPAC- see below). Beginning in 1999, the advent of long-term chemical sensors allowed the incorporation of nutrient measurement to moorings deployed on the east side of the straits. In 2004, measurements began in the western channel of Bering Strait as part of NOAA’s RUSALCA program and in the eastern channel of Bering Strait with support from the Alaskan Ocean Observing System (AOOS). The advent of In Situ Ultraviolet Spectrophotometers (ISUS) has allowed for more reliable nitrate measurements without the necessity of chemical reagents, with such samplers being the instruments of choice on these 2004 deployments.

Bering Strait Recommendations:

The physical/chemical workshop participants met in a combined session and agreed that:

- Long-term monitoring in Bering Strait is critical to understanding how both the Bering and Chukchi-Beaufort ecosystems respond to future change.
- We recommend that NPRB collaborate with NSF, NOAA, and AOOS in supporting long-term monitoring in the strait.

At the time of this writing there are two proposals pending at NSF and NOAA (submitted by R. Woodgate, T. Weingartner, and T. Whitledge) to continue the moored measurement program (including moored nitrate analyzers) over the next four years as part of the International Polar Year Program. In addition, J. Grebmeier and L. Cooper have a proposal pending at NSF to continue and to expand a Long-term Ecosystem Observatory at Little Diomede Island. The observatory includes a collaboration with the residents of Little Diomede Island and will include collecting near-surface and year-round samples of nutrients, chemical tracers, and biological productivity.

Chukchi Sea

The nutrients carried into the Chukchi Sea by the northward flow from Bering Strait exhibit the continued East to West concentration gradients, thus shelf waters flowing on the western side of the Chukchi have much higher nutrient content compared to the eastern side (Walsh et al. 1989, Hansell et al. 1993, Cooper et al. 1997, Lee et al. *submitted*). The Herald Valley outflow on the western side is saltier, colder, and richer in nutrients and marine-derived carbon than the waters transported on the eastern side in the Alaskan Coastal Current. The seasonal changes in shelf salinities have important implications on the fate of the nutrients and carbon in the Chukchi shelf waters that enter the Arctic Basin. Low density summer waters are confined to the upper 75 m of the shelf break and slope, whereas denser winter waters descend to 100 – 150 m depth.

Each spring and summer, the Chukchi Sea experiences a short, but intense phytoplankton bloom that is controlled by sea ice cover, nutrient availability, and river runoff. During the bloom, dissolved inorganic carbon (DIC) concentrations are drawn down in the mixed layer (shelf ~100 µmol kg^{-1}; shelf-break ~ 50 µmol kg^{-1}; basin <5 µmol kg^{-1}) and converted to organic carbon. Prior to the bloom, surface layer seawater partial pressure of CO_2 (pCO_2) ranges from ~200-320 µatm, indicative of under-saturation with respect to atmospheric pCO_2, although sea-ice cover keeps rates of air-to-sea CO_2 flux generally low (<1 mmoles CO2 m^{-2} d^{-1}). By summertime, after sea-ice retreat, seawater pCO2 contents had decreased to very low values (<80-220 µatm) in response to high rates of localized primary and net community production (NCP) and biological uptake of DIC. In the seasonally sea-ice free regions of the Chukchi Sea shelf, rates of air-to-sea CO2 fluxes are high, ranging from ~30-90 mmoles CO2 m^{-2} d^{-1} (Bates et al. 2006). In regions of the Chukchi Sea slope (and western Beaufort Sea shelf and Arctic Ocean basin) where sea-ice cover remains high (>80%), air-to-sea CO_2 fluxes remain generally low (<1 mmoles CO_2 m^{-2} d^{-1}). Seasonal (i.e., May to September) and annual net air-to-sea CO_2 fluxes from the Chukchi Sea shelf are estimated to be ~27 + 7 Tg C yr^{-1}, and 39 + 7 Tg C yr^{-1}, respectively. The Chukchi Sea represents the largest oceanic CO_2 sink in the marginal coastal seas adjacent to the Arctic Ocean. An active continental shelf pump of carbon, driven by the northward transport of nutrient-rich water of Pacific Ocean origin, high rates of primary and net community production during the sea-ice free period, and lateral export of organic carbon, maintains the Chukchi Sea shelf and slope as a perennial ocean CO_2 sink.

The highest rates of net community production (NCP) occur over the northeastern part of the Chukchi shelf near the head of Barrow Canyon which has historically been a hotspot for biological activity in the region. Between spring and summer normalized concentrations of DIC in the mixed layer can decrease by as much as 300 µmol kg^{-1}, while DOC and dissolved organic nitrogen (DON) can increase by ~15 and 10 µmol kg^{-1}, respectively. Estimates of NCP near the head of Barrow Canyon show rates of ~1500 mg C m^{-2} d^{-1} while estimates of NCP over the shelf-break and deep Canada Basin are low because there is very little primary production in the interior of the western Arctic Ocean due to near zero concentrations of inorganic nitrate in the mixed layer (Mathis et al. 2007b).

Conservative tracers, such as $\delta^{18}O$ and salinity can be used to estimate the production of organic carbon between spring and summer. It has been shown that ~ 10% of the DIC consumed during NCP is converted to DOC. The remaining carbon deficit (90% of DIC drawdown) is most likely exported from the mixed layer as POC. A carbon mass balance for the region shows that rates of vertical export are highest near Point Barrow (64 mmol C m^{-2} d^{-1}), but more commonly ranged from 10-35 mmol C m^{-2} d^{-1} over the remainder of the shelf. At the shelf-break and in the Canada Basin export production was <10 mmol C m^{-2} d^{-1} (Lepore et al. 2006).

During the summertime sea-ice retreat period, high rates of primary production and NCP act to increase the saturation states of surface waters to aragonite and calcite, while subsurface waters become undersaturated with respect of aragonite due primarily to remineralization of organic matter to CO2 and suppression of CaCO3 saturation states. At the northern shelf break of the Chukchi Sea, strongly undersaturated aragonite conditions can be found below the mixed layer at ~40-150 m deep (Bates et al. *in press*). The seasonal aragonite undersaturation of waters observed on the Chukchi Sea shelf is likely a recent phenomenon that results from the uptake of anthropogenic CO_2 and subsequent ocean acidification, with seasonality of saturation states superimposed. These undersaturated waters are potentially highly corrosive to calcifying benthic fauna (e.g., bivalves, echinoderms) found on the shelf, with implications for the food sources of large mammals (e.g., walrus, whales). The benthic ecosystem of the Chukchi Sea is thus potentially vulnerable to future ocean acidification and further suppression of $CaCO_3$ mineral saturation states.

Chukchi Sea Measurement History and Status

Prior to the 1970s several hydrographic expeditions collected chemical data throughout the Chukchi Sea as summarized in Coachman et al. (1975). Unfortunately, most of the OCSEAP data collected in the US coastal regions were not placed in electronic formats and are not available although efforts are in progress to make these data available (http://www.st.nmfs.gov/plankton/ and see below). In the mid-1980s the ISHTAR program conducted multiple cruises and in 1988 sampled both US and Soviet EEZ's as a part of BERPAC. During this period there were approximately 15 cruises that collected hydrography and nutrient data with approximately two thirds of the data residing in NODC data archives. Much of the remaining data is being collected from paper cruise reports and will be submitted to data archives in 2007. Recently, the SBI program completed its three-year field program (2001-2004) focused primarily upon biogeochemical processes over the outer shelf and shelf break, and the data from this program are mostly submitted to the National Snow and Ice Data Center. Much of the data is presently undergoing analysis, although nutrient data (Codispoti 2005) and tracers (Kadko and Meunch 2005) and carbon dynamics (Mathis et al. 2005, Bates et al. 2005a,b, Davis et al. 2005) and sediments fluxes (Moran et al. 2005) were published in a special issue of Deep-Sea Research II in 2005. Hydrography and nutrient data from RUSALCA 2004 cruise have recently been submitted to the National Snow and Ice Data Center. A limited number of CTD stations were collected during mooring recovery/deployment cruises in 2005 and 2006 and will also be submitted to NSIDC within the time frame of one year after data clearance by sponsoring US and Russian agencies.

Chukchi Sea Recommendations:

The combined chemical/physical oceanography workshop participants recommended that:

- Chemical water mass tracer techniques should be utilized to improve our understanding of circulation on the Chukchi Sea shelf.

Even with the recent SBI program there is a lack of measurements that bridge the shelf and the Canada Basin portion of the Arctic Basin which would require significant amounts of sampling time on heavy icebreakers that could penetrate the perennial pack ice. Chemical tracers of shelf material using short-lived radioisotopes such as thorium should be undertaken to provide estimates of recent export of particulate organic carbon. Water and sediment measurements of Th can provide estimates of the age of sediments and thus allow the calculation of deposition rate.

Beaufort Sea

The prevailing winds on the Beaufort Sea shelf are from the northeast and force a westward wind-driven flow over the shelf. The wind-field will promote upwelling of nutrient laden sub-surface waters at the shelf break with this process probably being critical to the shelf nutrient supply. The offshore boundary of the shelf comprises the second oceanic regime and includes the outer shelf and continental slope. Over the upper 50 m the westward flow constitutes the southern limb of the wind-driven Beaufort Gyre and transports the cold, dilute waters of the polar mixed layer. Below this layer the flow is eastward over most of the slope but concentrated in a narrow (~20 km wide) jet called the Beaufort undercurrent. The jet probably extends along the Chukchi Sea slope and carries dense winter water from this shelf (including outflows from the central and western Chukchi) and also warmer, saltier Atlantic Water upwelled from deeper depths. Wind-driven upwelling is occasionally strong enough to advect the undercurrent onto the shelf perhaps as far inshore as the 50 m isobath.

The Mackenzie shelf forms the eastern boundary of the ABS and comprises the third oceanic regime. The year-round discharge from the Mackenzie River is thought to profoundly influence the eastern Beaufort Sea (Carmack et al. 1989, Macdonald et al. 1989, Macdonald and Carmack 1991). Mackenzie shelf waters have been detected throughout much of the Canada Basin, including the continental slope of the Chukchi and western Beaufort Sea as far as 160^{o}W longitude using barium as a riverine tracer (Guay and Falkner 1998).

Beaufort Sea Measurement History and Status

During the 1970s considerable research was conducted initially as the WEBSEC cruises by the US Coast Guard (Ingham et al. 1972, Hufford et al. 1974) and later under the auspices of the Outer Continental Shelf Environmental Assessment Program (OCSEAP). The OCSEAP research is summarized in numerous technical reports, the most relevant of which is Horner (1981), with much of this information available online at NMFS. Additional measurements of shelf break processes have been made in the western Beaufort Sea with support from the NSF-ONR sponsored Shelf-Basin Interaction (SBI), which recently completed a three-year field program (2001-2004). Similarly, the area around the McKenzie River inside the Canadian EEZ has recently received significant attention by the Canadian Arctic Shelf Exchange Study (CASES – 2002-2004). Nearly year-round observations of both nutrient and carbon cycles are just beginning to appear (Forest et al. 2007, 2008, Trembley et al. 2008, Emmerton et al. *in press*).

Beaufort Sea Recommendations:

The combined chemical/physical oceanography workshop participants recommended that chemical water mass tracer techniques should be utilized to improve our understanding of circulation on the Beaufort Sea shelf. The realization that shelf break upwelling processes are possibly larger than previously estimated should be examined more closely with chemical tracer techniques, especially ^{129}Iodine which can provide an estimate of possible fraction of Atlantic water that is upwelled.

The impacts of the influx of relatively large amounts of freshwater discharge from the Mackenzie River and smaller amounts from the North Slope rivers are not well understood. The riverine waters can be easily identified from barium concentrations and possibly alkalinity determinations.

Panarctic Baselines

In addition to efforts begun by NODC and NMFS, an NSF-funded project is currently underway to consolidate all existing Arctic data on nutrients, chlorophyll and primary production (Matria, Codispoti, Gosselin, Hill, Light, Steele -PIs) to help establish historical patterns, using the ARCNUT database originally developed by G. Cota and L. Pomeroy. Once consolidated the data will be available both to examine long-term trends and improved parameterization of biophysical models within the Arctic. The maps already show a rich historical record of the major nutrients in the Beaufort and Chukchi seas (Fig. 6).

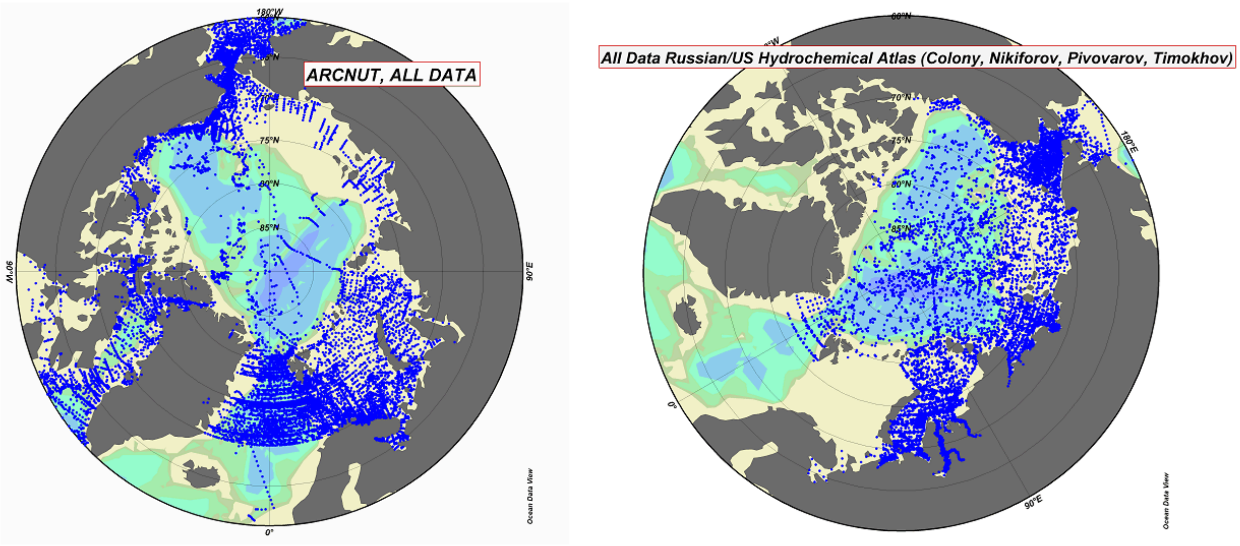

Fig. 6. Distribution of sample locations in the ArcNut Database

SEA ICE

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Introduction

Fig. 7. An open lead within the sea ice (credit Ian MacDonald/TAMU)

Sea ice covers about 7% of the surface of the earth. Within Arctic and sub-Arctic Seas, first-year sea ice (FYI) dominates on the extensive shallow shelves, while multi-year sea ice (MYI) cover predominates in the deeper basins. On a seasonal scale (Thomas and Dieckmann 2003), minimum ice cover is reached in the Arctic in September (long term mean of 9.3 10^6 km^2), maximum extent occurs in February/March (15.7 10^6 km^2). The bulk of the sea ice in the Arctic is thicker than 2 m, due to both thermo-dynamic and dynamic growth, with maximum thicknesses of more than 30 m in pressure ridges (Haas 2003). While drifting pack ice dominates in most of the Arctic Seas, nearshore land-fast ice is found around the Arctic (including Alaskan waters) for many months each fall through spring (Mahoney et al. 2007a). Sea ice is transported throughout the Arctic in two major drift patterns, the Beaufort Gyre and the Transpolar drift. Extent, location and strength of these patterns are closely linked to the atmospheric driving forces, as expressed for example in the Arctic Oscillation index (Rigor et al. 2002), and may contribute to the interannual variability in the Arctic ice characteristics on a pan-Arctic scale (Maslanik et al. 2007, Sereeze et al. 2007, Stroeve et al. 2007).

Satellites provide excellent tools to assess the variability of the sea ice extent on multiple temporal and spatial scales, while determination of ice thickness is currently restricted to local assessments either through coring, moorings or electromagnetic induction techniques (Haas 2003). From satellite observations, we now appreciate that the Chukchi and Beaufort seas exhibit substantial interannual variability in summer minimum ice extent, with record low concentrations in the last decade (e.g., Stroeve et al. 2005, 2007), leaving the Beaufort and Chukchi seas ice-free well above 75˚N latitude. In contrast, the early and mid-1980s were characterized by heavy ice years in the same area, with almost the entire US Beaufort Sea sector ice-covered throughout the summers of 1980, 1983 and 1985 (Gloersen et al. 1992). The fraction of different ice types (in particular first- versus multi-year ice) can also vary substantially with a current trend towards younger ice (Maslanik et al. 2007), and the current challenge is to understand the multitude of causes for the observed variability and how it impacts the biology of sea ice-related communities.

The seasonality of light is remarkable in Arctic areas and organisms experience day lengths from 0 to 24 h. In addition to the seasonal light regime, sea ice further modifies light conditions relevant for growth of primary producers. Under-ice photon flux is primarily controlled by the thickness and characteristics of the snow and ice, and the enclosed sediment and biota (Maykut 1985, Gradinger 2008). Other sea ice physical properties like temperature and salinity vary over a wide range with distinct differences between fast ice, FYI and MYI. The brine salinity and the volume of the brine channels are dependent on the temperature and the salt content of the ice (Eicken 2003). A decrease in the ice temperature from -4 °C to -10 °C, for example, leads to an increase in brine salinity from 70 to 144. All these physical properties exhibit a strong control over the amount and characteristics of the biota associated with sea ice thus causing very distinct distribution patterns of the micro-and macroscopic life forms associated with sea ice (Gradinger 2002).

Background

Sea ice is an essential driver of the ecosystems in the Arctic, including the Chukchi and Beaufort seas. The strong linkages between sea ice and pelagic and benthic processes (for recent review see Bluhm and Gradinger, 2008) are discussed in the relevant chapters, as well as for fish, birds and mammals. The focus here is on the organisms and communities inhabiting either the three-dimensional network of brine channels between the ice crystals in fast and pack ice, or the "hard-bottom" substrate of the ice-water interface (Horner 1985). Due to the scarcity of observations related to sea ice flora and fauna, this report will use a more pan-Arctic approach but highlight information available from the Chukchi and Beaufort seas. Both coastal and offshore locations of Arctic seas harbor high concentrations of viruses, bacteria, algae, protozoans and metazoans at changing densities in space and time (e.g. Gradinger et al. 1991, Gosselin et al. 1997, Melnikov 1997, Michel et al. 2002, Gradinger et al. 2005, Wells and Deming 2006). The spatial and temporal variability of biological sea ice parameters occurs on various scales which are directly linked to environmental variables, in particular light availability and nutrient supply, as modulated by the snow cover, ice morphology and microstructure and sediment incorporation (Sullivan et al. 1985, Gosselin et al. 1986, Legendre et al. 1991, Gradinger et al. 1991, Eicken et al. 1991, Junge et al. 2004, Gradinger 2008).

The discoveries of sea-ice related life date back to the exploration of Arctic Seas in the 19th century. For example, Nansen (1906) provided a detailed description of protozoans occurring in the melt puddles on top of MYI. Major new and more recent contributions in the nearshore and shelf waters of the Chukchi and Beaufort seas are linked to large interdisciplinary research efforts like the Environmental Assessment of the Alaskan Continental Shelf and more recently the US funded SHEBA (Surface Heat Budget of the Arctic Ocean) and SBI (Shelf-Basin Interaction Studies) expeditions and the Canadian CASES (Canadian Arctic Shelf Exchange Study) program. The Barents Sea is likely the best studied sub-Arctic region for its sea ice biological characteristics mainly based on Norwegian and Russian research efforts (e.g. Loenne and Gulliksen 1991, Melnikov 2002), while the Bering Sea conditions were largely unexplored and are currently targeted as part of the NSF/NPRB funded BEST/BSIERP (http://bsierp.nprb.org/) research efforts. For SBI and CASES, many new and relevant scientific papers will be published over the next 5 years, focusing on the ecological and physical aspects of sea ice on the Chukchi and Beaufort Sea shelves and slopes. The increase in knowledge related to sea ice ecology over the last two decades is reflected in a recently published textbook on the physics, chemistry, geology and biology of sea ice (Thomas and Dieckmann 2003) which will likely be updated in 2008/2009. Despite this progress, data on the activity and biomass of sea ice biota are still sparse and greatly limited in time and space due to difficulties in accessing sea ice habitats at different times of year, and substantial challenges posed to adapting standard methodologies to the ice environment. Currently no remote sensing tool or monitoring network exists to assess all relevant parameters simultaneously. Due to these constraints, the overall dataset on Arctic ice algal biomass and productivity is approximately one to two orders of magnitude smaller than that assembled for the pelagic realm. For illustration, a bibliographic search on peer-reviewed journal articles using "Aquatic Sciences and Fisheries Abstracts (ASFA) covering the period 1978 to 2008 (August 6) on "*Arctic*" and "*sea ice algae*" revealed 36 contributions, while "*Arctic*" and "*phytoplankton*" were studied in 800 publications. The first and still valid contributions in understanding the biology of sea ice in the Chukchi and Beaufort regions were initiated within the Outer Continental Shelf Environmental Assessment Program. They were conducted by different agencies, universities and companies (for complete list of reports see http://www.arlis.org/docs/vol1/OCSEAP2/index.html,) leading not only to OCSEAP reports but also to a wealth of peer-reviewed publications by Horner, Carey, Kern and other colleagues (see Horner 1985 for excellent summary).

Ice-based primary production varies regionally and accounts for between 4 and 26 % in FYI-covered waters (Legendre et al. 1992). It may increase to ≥50 % in MYI-covered areas (Gosselin et al. 1997). This growth mainly occurs in spring and summer, when algal blooms form in the bottom layer of the sea ice reaching biomass values above 70 mg Chl *a* m^{-2} in land-fast and FYI of North American waters (Cota et al. 1987, Hsiao 1992, Smith et al. 1993, Robineau et al. 1994, Gradinger 2008) and only about 1 mg Chl *a* m^{-2} in the MYI of the Transpolar Drift system and the Beaufort Gyre (Gradinger 1999, Gradinger et al. 2005). The regional differences in sea ice primary production are largely driven by small- and large scale changes in the nutrient availability (Smith et al. 1990, Gradinger 1999a, 2008). As for all biogeochemical processes in the Chukchi and western Beaufort seas, the productivity of sea ice is also strongly dependent on exchange processes with the adjacent deep Arctic Ocean and through Bering Sea inflow as explained below.

Within the Chukchi/Beaufort region, highest ice algal biomass was observed in the FYI in the nutrient rich parts of the Chukchi shelf during the SBI 2002 and 2004 expeditions, which were among the highest ever found in Arctic pack ice (Fig. 8, > 20 mg chlorophyll a m^{-2}), while values in the more oligotrophic Alaskan Beaufort shelf and slope region were significantly lower (Gradinger 2008). Although the accumulated biomass within the ice reached substantial values specifically in the Chukchi shelf region, the overall contribution to total annual primary production was <10% (Gradinger 2008). The organic matter produced within the ice serves as the base for the sympagic (=ice-associated) food web comprised of sea ice meiofauna, amphipods, Arctic cod (*Boreogadus saida*), seals and birds (Bradstreet and Cross 1982). In all Arctic seas including the Chukchi and Beaufort seas, metazoan meiofauna abundance increases with the onset of this production in all ice types and meiofauna thrives on ice-derived organic matter (e.g., Kern and Carey 1983, Carey 1985, Carey 1992, Gradinger 1999a, 2002). Ice meiofauna is typically dominated in FYI and MYI by turbellarians, crustaceans, nematodes and rotifers (Carey 1985, Grainger and Hsiao 1990, Gradinger et al. 1999, Nozais et al. 2001, Gradinger et al. 2005) and abundances vary regionally in correlation with the available biomass of sea ice primary producers. Meiofauna abundances decrease from the nearshore fast ice (up to 350,000 animals m^{-2}) to the deep sea basin by about three orders of magnitude (Gradinger et al. 2005). In coastal ice, especially in the fast-ice regions, larvae and juveniles of benthic invertebrates (e.g. polychaetes) augment the sea ice faunal inventory including several studies in the Beaufort Sea coastal regions (Carey and Montagna 1982, Cross 1982, Kern and Carey 1983, Grainger et al. 1985). The under-ice macrofauna (mainly amphipods) observed in the pack ice of the Chukchi and Beaufort Seas (Gradinger and Bluhm 2004) are typical for high Arctic pack ice systems: *Gammarus wilkitzkii*, *Onisimus* spp. and *Apherusa glacialis* (Barnard 1959, Pike and Welch 1990, Melnikov 1997, Werner 1997, Hop et al. 2000). Under-ice amphipods occur in abundances of 1 to 1000 m^{-2} in coastal areas (Carey 1985) and with, on average, 1-40 individuals m^{-2} in offshore pack ice (Poltermann 1998, Hop et al. 2000, Werner and Gradinger 2002, Gradinger and Bluhm 2004) – again it appears that the abundances are closely linked to food availability, although studies understanding the spatial complexity of sea ice flora and fauna distribution on smaller scales are still rare (Hop et al. 2000). Overall, the ice-associated macrofauna species composition seems to be very consistent across the whole Arctic in the off shore regions, with some additional contributors (e.g. *Onisimus litoralis*) occurring in nearshore waters (Carey 1985). The only fish species occurring regularly with Arctic sea ice is Arctic cod (*Boreogadus saida*). Arctic cod may be the keystone species in Arctic waters in that it provides the most important trophic link from lower trophic levels (copepods and under-ice amphipods) to other fish, birds, seals and whales (Frost and Lowry 1981, Bradstreet and Cross 1982, Bradstreet et al. 1986, Lønne and Gulliksen 1989, Lønne and Gabrielsen 1992, Gradinger and Bluhm 2004). Arctic cod can occur in small groups in protected seawater wedges within the offshore pack ice (Gradinger and Bluhm 2004) but also makes onshore-offshore migrations, partially forming dense swarms of several million fish (e.g., Craig et al. 1985, Gjøsaeter and Ushakov 1997).

The diversity of life in the Arctic sea ice is insufficiently described, although current species lists contain several hundred species of algae, proto- and metazoans as seasonal or permanent sea ice inhabitants (e.g. Horner 1985, von Quillfeldt et al. 2005). Several of these species are either unique to specific regions of the Arctic, or specific ice types, and have on occasion been used to reconstruct the drift or the geological history of sea ice extent in Arctic waters (e.g., Abelmann 1992). The pioneering work by Horner and others (as summarized in the textbook edited by Horner 1985) provided a first look into this diversity of life, also for the Chukchi/Beaufort seas. The currently most complete analysis of diatoms, which typically dominate the ice algal communities (Melnikov 2002), from Chukchi Sea ice by von Quillfeldt et al. (2005) revealed the occurrence of more than 250 species of diatoms in only two FYI Chukchi Sea ice cores. Currently

Fig. 8. Protistan life abounds in sea ice, as viewed after melting (credit Rolf Gradinger/UAF)

several manuscripts are in preparation describing new species of algae and metazoans (e.g. Bluhm et al. 2007) in the Arctic ice environment. Compared to eukaryotes, even less is known about the diversity of prokaryotic life within the ice (Brinkmeyer et al. 2004, Junge et al. 2004). The high levels of dissolved organic carbon and extracellular polymeric substances in specifically coastal Arctic sea ice (e.g. Krembs et al. 2002) including the Chukchi Sea (Meiners et al. 2008), sustain an active microbial loop even at temperatures as low as -20°C, whose components have not been well identified, as also true for the rest of the Arctic marine ecosystem (see microbe section of this report).

The relevance of sea ice produced organic matter extends well beyond the period of ice cover into the melting season. Ice melt leads not only to freshening of the surface layer of the ocean but also to a biomass release which is discussed as an important early food pulse to support pelagic and benthic herbivores, and detritivores on the Amerasian shelves (Carey 1987, Grebmeier and McRoy 1989, McMahon et al. 2006, Bluhm and Gradinger 2008). The specific species and isotopic composition of ice algal communities (Gradinger 2008) can be used to assess their contribution to the marine food web (Hobson and Welch 1992, Hobson et al. 1995) with recent studies pointing towards selective consumption of sinking ice algae by benthic biota (McMahon et al. 2006). The pelagic algal bloom induced in the regions of ice melt (either in marginal ice zones and/or polynyas) can substantially increase the vertical particle flux and be higher than measurements in adjacent open water regions (see chapter on phytoplankton). The timing of the phytoplankton blooms as a result of variable ice conditions (e.g. Tremblay et al. 2006) can affect food web dynamics through shifts in energy flow between bottom-up and top-down control, with potential impact on the recruitment of commercially important fish species (Michaud et al. 1996, Arrigo and van Dijken 2004, Bluhm and Gradinger 2008). Despite their influential role, the development of biogeochemcial models of sea ice cycles is still at an early stage, focusing mainly on processes in the ice-water interface (e.g. Lavoie et al. 2005, Jin et al. 2006), and the models are not yet linked to any complete ecosystem models for an Arctic region including the Chukchi or Beaufort seas.

Impacts of the Current and Predicted Loss of Sea Ice

Arctic ecosystems in general are challenged by the large-scale warming trend of approximately 2°C over the last 100 years (Overpeck et al. 1997, Serreze et al. 2000). Model runs presented in the ACIA (2004) report indicate the potential of a complete loss of Arctic summer sea ice cover by 2100 and an increase in the overall contribution of FYI through reductions in MYI. The western Arctic has already experienced some of the most dramatic ice retreat over the past few decades as compared to the entire Arctic (Comiso 2002). In the past five years, the Arctic and in particular the western Arctic have experienced the lowest summer minimum ice concentrations recorded since the start of systematic observations (Stroeve et al. 2005) with a decrease exceeding the loss predicted by modeling efforts (Stroeve et al. 2007). Recent evidence suggests that these changes are now also apparent in the winter ice cover (Meier et al. 2005). In parallel with this decrease in summer minimum ice extent, ice thicknesses and the amount of MYI have decreased substantially in the Beaufort and Chukchi Seas, most likely as a result of changes in ice circulation, coupled with reduced ice accretion (Maslanik et al. 2007, Rigor and Wallace 2004, Tucker et al. 2001). The enhanced inflow of warm Pacific summer water appears to contribute significantly to the local and regional ice thinning in the Chukchi and Beaufort sea ice (Shimada et al. 2006).

The socioeconomic relevance of the observed and predicted changes in the sea ice regime ranges from impacts on subsistence hunt (George et al. 2004) to opening of shipping routes across the Arctic and increased access to marine resources (ACIA 2004), all requiring proactive environmental planning to mitigate potential impacts (e.g. Roberts 2007).

Alterations in the ice regime will impact the biology of the ice itself through alterations of the light regime and the timing of ice formation and ice and snow melt. Thinner ice and snow can lead to increased biological productivity, assuming sufficient supply by inorganic nutrients (Bluhm and Gradinger 2008). Not only temperature increases but also the freshening of the surface waters through increased ice melt (McPhee et al. 1998) combined with river runoff (Macdonald et al. 1999) can lead to alteration in ecosystem structure, certainly at the lower end of the food chain (Bluhm and Gradinger 2008). In the case of the sea ice system, Melnikov et al. (2002) observed a complete lack of metazoans in FYI and MYI collected during the SHEBA drift in the Beaufort Sea, which could not be substantiated by observations by Gradinger et al. (2005). Even more important, the loss of MYI can lead to a loss of biodiversity from microbes to marine mammals on a basin-wide scale across the Arctic. 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. Several authors (e.g., Anderson et al. 1990, Gradinger 1995, Gosselin et al. 1997) anticipate an increase in the overall primary productivity in presently ice-covered Arctic waters due to increased irradiative fluxes into the water column which could lead to either increased pelagic and/or benthic activity and biomass. In contrast, a recent study of sediment entrainment and transport by sea ice has found a significant amount of particulate material in

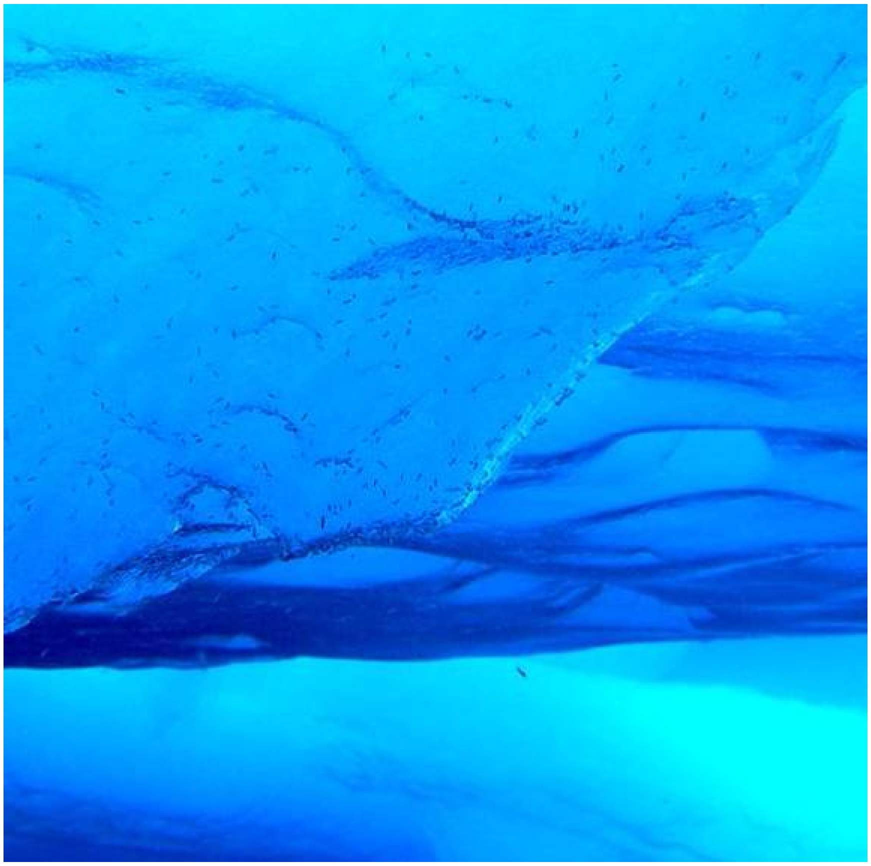

Fig. 9. Sea ice as seen from below can support high densities of amphipods (dark blotches above, with close-up shown to the right). Some species are only found associatesd with sea ice and may be at risk as summer ice declines (credit Katrin Iken/UAF)

Beaufort and Chukchi sea ice (Eicken et al. 2005) fostered by changes in the near-shore ice regime. The amount of sediment-laden ice was such that significant impacts on primary (algal) and bacterial production in sea ice can be expected in the sea ice that remains (Gradinger et al. *in prep*.). Thus, it remains difficult to predict how overall productivity will be altered under reduced-ice scenarios in a regional context.

Changes in the nearshore ice environment are much more subtle and complex than can be suggested by a simplistic interpretation of large-scale sea ice change. Landfast ice extent in the eastern Chukchi and Alaskan Beaufort seas has not changed with respect to maximum area covered by sea ice, while onset of formation and break-up occur later and earlier, respectively, compared to observations in the 1970s (Eicken et al. 2006, Mahoney et al. 2007b). Most importantly, the land-fast ice appears to be much less stable during the winter season, with significant impacts on activities by coastal residents and ice-associated fauna (Eicken et al. 2005, George et al. 2004, Huntington 2000, Mahoney et al. 2007b) with some communities switching from marine to terrestrial-based food gathering activities (Huntington 2000). At the same time, seal breeding success (and hence polar bear stocks) is dependent strongly on stability and snow cover of land-fast ice (see marine mammal chapter). It is not at all clear how these different factors will play out together, but a potential impact on marine ecosystems, and subsistence hunts (George et al. 2004) is likely.

Open Questions and Research Needs

Based on the limited knowledge of the structure and functioning of the ice-based ecosystem, we developed a series of research topics to be addressed over the next decade to understand the impact of this drastic change in the ice environment from thick multiyear to thin first-year ice, in conjunction with reduced summer sea ice extent on the ecology and oceanography of the shelf seas:

Methodological challenges:

- To develop and improve strategies, tools and instruments to measure sea ice parameters remotely (through satellites, moorings, ROVs and AUVs) and *in situ*.
- To develop organic biomarkers for ice and pelagic systems to distinguish these in sediment traps and sediments, and then selectively use well-dated sediment cores to recover ice histories from the century to millennium scale.
- To develop coupled biogeochemical models to assess and predict the impact of changes in sea ice parameters on sea ice biodiversity and productivity
- To develop models that link sea ice productivity to pelagic and benthic realms. Such a model will help understand how alterations in the primary production regime in ice and water will cascade through the entire food web, affecting net production, structure and species composition.

The scientific focus of sea ice research in the coming years should be:

- To understand whether the retreating summer minimum ice extent in the Chukchi and Beaufort Seas observed over the past several years is part of a continuing trend and explained by ice-albedo feedback mechanisms.

- To understand the role of the variability in multiyear ice concentration and ice drift into Chukchi and Beaufort seas in determining the extent of summer ice retreat, stabilization of nearshore ice environment and impact on biological production in the ice.
- To understand the potential combined impact of changing snow accumulation rates and ocean heat fluxes on ice mass budget and ice-algal communities. Changes in these forcing parameters could lead to a potential loss of highly productive bottom communities earlier in the season due to bottom melt and potential development of surface infiltration layers.
- To understand the functioning of the sea ice related food web, identify and focus on keystone species (with Arctic cod as potential candidate).
- To understand the linkages between the ice system and pelagic systems in terms of production, seed populations, vertical flux of organic carbon.
- To understand the fate of ice derived material (both sediment and organic matter) and identify its partitioning between pelagic consumption and sedimentation to the sea floor.
- To understand the linkages between sea ice physical properties and the export of organic matter from the sea ice.
- To understand the impact of changing ice regime on the biological hot spots in the Chukchi and southwestern Beaufort Sea ice which are among the most biologically productive ecosystems anywhere.
- To understand the annual and interannual variability of physical, chemical and biological sea ice parameters in relation to climate forcing functions.

Final Comments and Recommendations

The limited baseline information on ice-associated biological processes hampers efforts to provide good estimates of how this system responds to change, or even to follow the current changes occurring in the Chukchi and Beaufort seas. Physical, chemical and biological parameters need to be monitored and tied together in ecosystem models to successfully provide a quantitative assessment of the predicted impacts of Arctic warming on the ice based food webs and be useful and accessible to a wide range of users. Areas of fast ice, FYI and MYI cover need to be sampled, as implications of changes in sea ice cover will be different for each of these ice regimes, including those impacts on coastal subsistence activities that depend on marine mammals.

- The development of a strategy and its incorporation of time series measurements of sea ice parameters (beyond thickness, drift and extent) are essential. Such a network of observations would cover fast ice, FYI and MYI characteristics in the Chukchi and Beaufort seas.
- Measurements should be tied into existing, and new time series studies with a defined minimum set of criteria and methods to be followed. Parameters to be included are
    - snow depth, ice thickness, ice type, ice drift
    - spectral light, biomass and diversity of sea ice biota
    - dynamics of the ice based food web
    - fate of ice biomass after ice melt (through sediment trap and benthic studies).

- Minimum requirements for such a measurement network should include a combination of remote sensing tools (both satellites and ROV/AUV approaches), moorings and repeated field sampling relevant to model development, and be made available to stakeholders.
- Studies need to be done in a regional context due to the unique nature of both ice physical and biological parameters on gradients in latitudes, and from the shore across the shelves to the deep sea.
- Sea ice studies need to be part of larger interdisciplinary investigations providing the context and synergetic strength to understand the current state and potential impacts of loss of ice in the ecosystems of the Chukchi and Beaufort seas.

Providing access to the ice covered parts of the region of interest on a long-term basis will be key to the success of such projects. Improvements are on the horizon with improved research facilities in Barrow, Alaska (suitable for fast ice research) and a new ice-strengthened research vessel for UAF expected to be funded in the next decade. Interagency cooperation in funding and supporting interdisciplinary studies should be strengthened similar to efforts in the Bering Sea.

Measuring sea ice parameters at consistent locations as part of an ocean observing network, plus ship board expeditions, will allow us to address the above mentioned questions. Addressing these questions is urgent, not only in the framework of Arctic warming, but in consideration of the increasing levels of oil and gas exploration and production expected in this region. At the same time, sovereignty and boundary demarcation are being reexamined with the potential for increased shipping and other industrial activities. With the potential for industrial hazards increasing, and with much of the activities driven by increasing access due to less severe ice conditions, the questions raised in this document need to take geopolitical and socio-economic change in the region into account. This is particularly important in order to avoid the difficulties encountered in the Bering Sea region where attribution of changes in the ecosystem and implications for policy-makers are intensely debated. Similar (if not more substantial) problems are likely to arise in the Chukchi and Beaufort seas, in particular if there is a lack of key baseline data that allow a more penetrating analysis, and separation of natural and anthropogenic effects on ecosystem health and viability.

PHYTOPLANKTON (PRIMARY PRODUCTION)

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Introduction

Both severity of weather and ice coverage have been prominent logistical deterrents preventing intensive studies of Arctic primary productivity patterns and phytoplankton distributions. Although studies of phytoplankton composition and abundance have been carried out for more than one hundred years, relatively few studies on marine primary production exist that address regional and seasonal differences for the Arctic. Furthermore, while earlier studies emphasized taxonomic composition and species abundance (as cell counts) this has been largely replaced by measurement of chlorophyll concentration as a serogate of phytoplankton biomass. The reported values of primary productivity in the Arctic Ocean indicate that spatial and seasonal change is largely due to latitudinal variations of seasonal changes of solar irradiance, distributions and thickness of sea ice and the stability of water column, in addition to the spatial structure of sea ice itself.

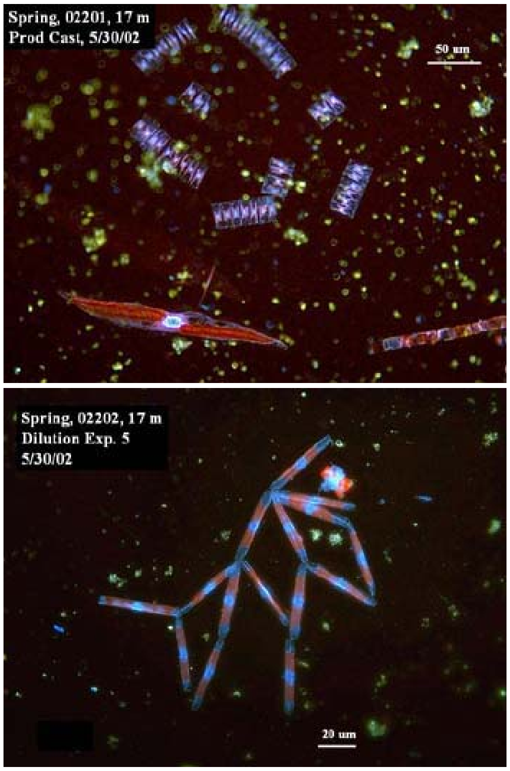

Fig. 10. Arctic spring phytoplankton as seen by epifluorescence microscopy, after DAPI staining (credit Evelyn and Barry Sherr / OSU)

Because of extreme conditions in light, ice coverage and cold temperature, the Arctic Ocean has been generally categorized as a low productivity region (Apollonio 1959, English 1961, Andersen 1989). The duration of the production period is sensitive to the extent, thickness and seasonal melt dynamics of sea ice, all of which are a resultant of regional climate patterns (Fortier et al. 2002, Laxon et al. 2003, Tremblay et al. 2006). Recent primary productivity and DOC measurements have suggested a more active carbon cycling in the surface waters of the Arctic Ocean (Gosselin et al. 1997, Guay et al. 1999, Tremblay et al. 2006) than previously estimated. These new estimates suggest a nearly 10-fold increase in the annual primary productivity of Arctic waters over older estimates. Decreases in ice extent and sea-ice thickness, especially in coastal regions, indicate that Arctic environments are changing in response to increased temperatures (Maslanik et al. 1996, Martin et al. 1997, Rothrock et al. 1999, Rothrock et al. 2003). Ultimately, the estimation of primary productivity, not only in the water column but in both sea ice and phytomicrobenthos, is tightly coupled with these dynamic changes of sea ice extent.

Background

Within the Arctic, the combination of cold temperature, occurrence of sea ice and extreme seasonal variations in light regimes controls phytoplankton growth and governs the spatial and temporal growth patterns of phytoplankton (Smith and Sakshaug 1990). The stabilizing effect of an ice covered sea allows production to occur near to the surface under low light intensities (Andersen 1989). A large number of planktonic algae thrive in Arctic waters but there seem to be relatively few truly Arctic species (Heimdal 1989). Still, little is known about the species distributions and taxonomy of phytoplankton in the central Arctic Ocean. Recently, the importance of autotrophic dinoflagellates and autotrophic flagellates was documented for the central Arctic Ocean (Booth and Horner 1997, Sheer et al. 2003). Picoplankton was found to be a dominant component under thick ice within this study. For the Beaufort/Chukchi seas, Hill et al. (2005) also report higher fractions of larger phytoplankton (>5um) over the shelves (up to 70%) than on the slope and in the basins.

Phytoplankton biomass undergoes stronger seasonal cycles than observed in other oceans, as illustrated in recent seasonal data from the CASES program (Fig. 11; Trembley at al. 2008) with in situ fluorescence data to estimate chlorophyll concentration. Estimates of phytoplankton biomass vary widely depending on the region, with the highest values generally found in the Chukchi Sea, as shown by two related synthesis efforts (Fig. 12 from Grebmeier et al. 2006, Dunton et al. 2005). Notably the high concentrations in the East Siberan Sea are probably artifactual, and there are relatively fewer data in the Beaufort Sea than the Chukchi.

Like other oceans, algal production and biomass in the Arctic are primarily controlled by light, stratification and nutrient fields (Smith and Sakshaug 1990). Data on spatial and/or temporal differences on a basin-wide scale are, however, lacking or have not been compiled. Gosselin et al. (1997) summarized mean annual phytoplankton production estimates for arctic waters and suggest a new value of 15 g C m^{-2}. Incorporating ice algae production and assessing DOC release from phytoplankton and ice algae, this new estimate is at least one order of

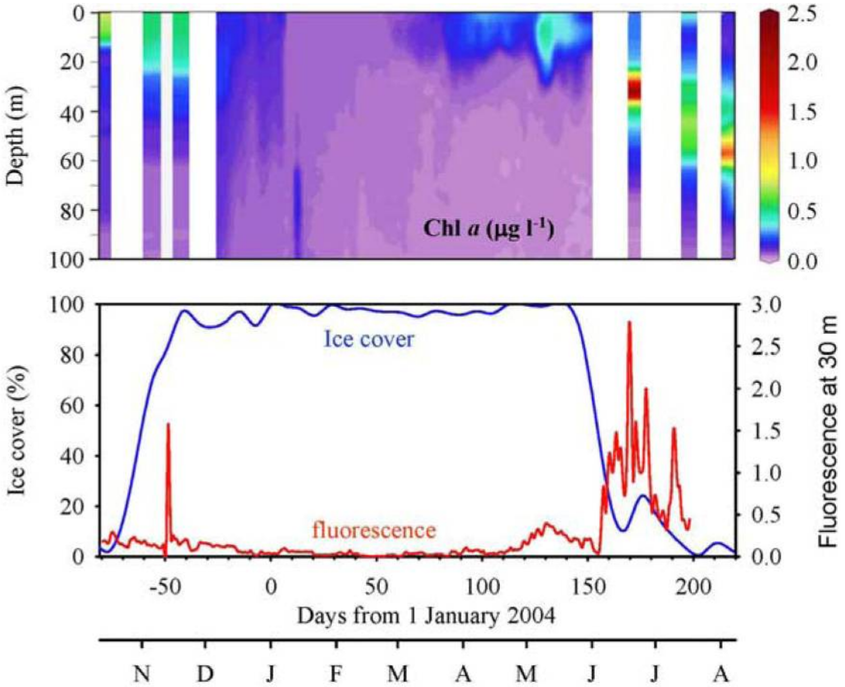

Fig. 11. Time series of (top) chl a estimated with a Rosette-mounted fluorometer (sampling frequency was twice daily during the freeze-in period) and nearby sampling sites and (bottom) the mean extent of fast ice in Franklin bay (blue line) and the fluorescence (red line, arbitrary units) at 30 m at the nearby mooring site (from Trembley et al. 2008).

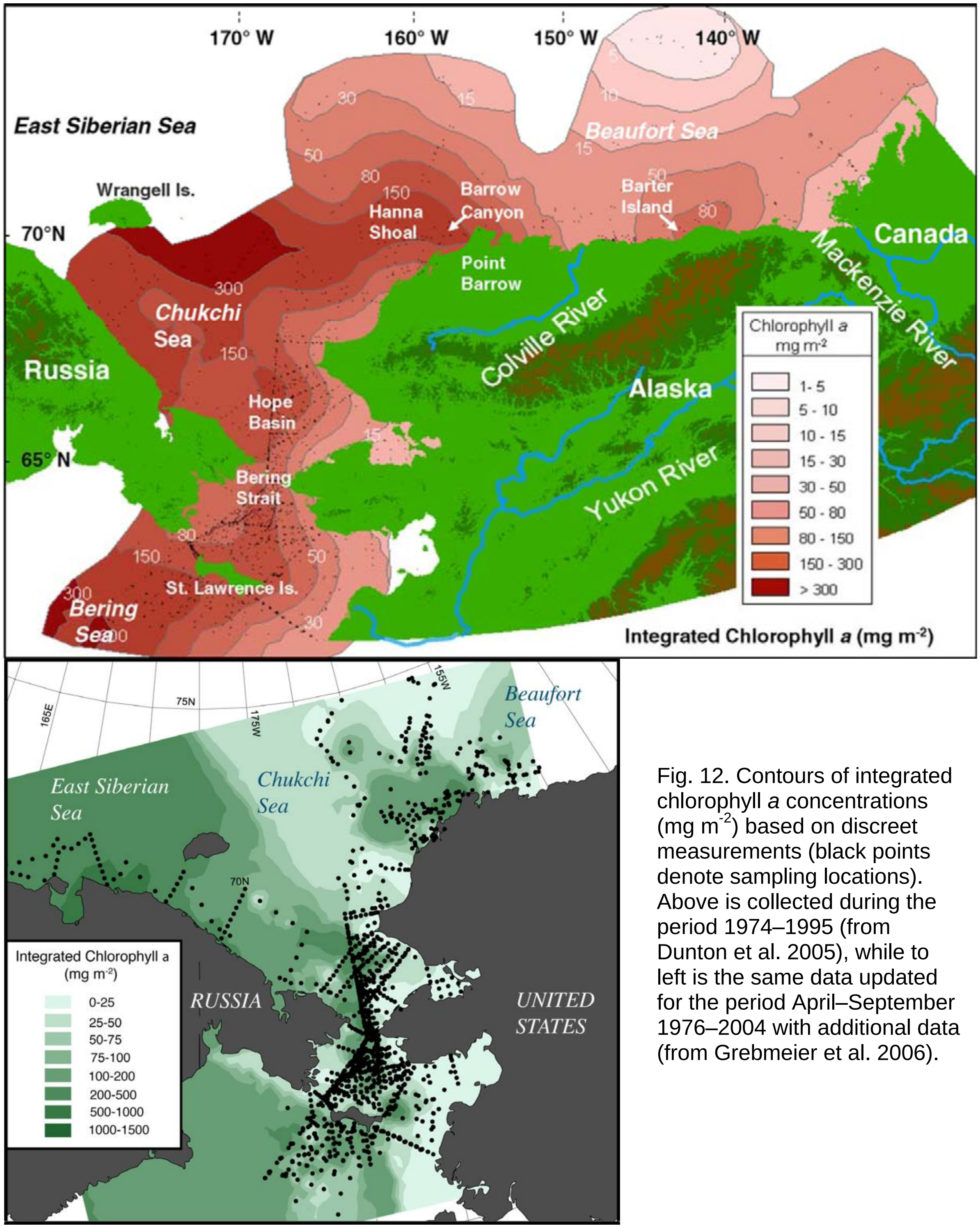

Fig. 12. Contours of integrated chlorophyll *a* concentrations (mg m^{-2}) based on discreet measurements (black points denote sampling locations). Above is collected during the period 1974–1995 (from Dunton et al. 2005), while to left is the same data updated for the period April–September 1976–2004 with additional data (from Grebmeier et al. 2006).

magnitude greater than the estimates of Apollonio (1959) and English (1961). On the shelves, advection of nutrients through Bering Strait and local nutrient re-mineralization sustain extremely high primary production values on the Chukchi Sea shelf (Table 1). More recently Bates et al. (2005) calculated daily net production values >1 g C m^{-2} d^{-1} for the Northeast Chukchi Sea shelf and much lower values in the oligotrophic Arctic Ocean basin in 2002.

Similarly, Lee et al. (2007) calculated daily net production values averaging 0.6 and frequently >1 g C m^{-2} d^{-1} in the Chukchi Sea and suggested annual production 55 g C m^{-2} for the whole Chukchi Sea and 145 g C m^{-2} for the plume of Anadyr–Bering Shelf. These data compare well to the gradients proposed in the modeling study by Walsh et al. (2005).

In addition to the phytoplankton, ice algae contribute to the total primary production of the Arctic Ocean (Alexander et al. 1974, Horner and Schrader 1982, Demers et al. 1986, Gosselin et al. 1997, Booth and Horner 1997, Mock and Gradinger 1999, 2000) with higher production values in first-year ice compared to the multi-year ice zone. The contributions of ice algae to total primary production range from less than 1% in coastal regions (Alexander and Chapman 1981) up to 60 % in the central Arctic Ocean (Gosselin et al. 1997).

Table 1. Comparison of daily primary productivity in Bering Strait and the Chukchi Sea

Source	Productivity (g C m^{-2} d^{-1})	Method	Place or water mass	Season
McRoy et al. (1972)	4.1	^{14}C uptake	Western Being Strait	
Hameedi (1978)	0.1–1.0	^{14}C uptake	Chukchi Sea	July
	>3.0		Central Chukchi Sea	
Sambrotto et al. (1984)	2.7	NO_3^- disappearance	Western Bering Strait	
Springer (1988)	1.5–16	^{14}C uptake	Central Chukchi Sea	11 July–2 August
Korsak (1992)	1.7	^{14}C uptake	Chukchi Sea	28 July–31 Aug
Zeeman (1992)	1.6	^{14}C uptake	Chukchi Sea	28 July–31 Aug
	0.8		Bering Strait	
Hansell et al. (1993)	4.8–6.0	NO_3^- disappearance	Anadyr Water in the north of Bering Strait	
Springer & McRoy (1993)	4.7	^{14}C uptake and Chl-*a* conc.	Central Chukchi Sea	28 July–31 Aug
Hill et al. (2005)	0.8	^{14}C uptake	Northeastern Chukchi Sea	Summer
Lee et al. (2007)	0.6	^{13}C uptake	Chukchi Sea	10–22 August, 2004
	1.4		Central Chukchi Sea	

Needs/Recommendations

Since phytoplankton groups are involved in food-web dynamics, global changes impacting sea ice processes will in turn affect upper trophic levels in both the water column and the benthos. Regional climatic shifts resulting from global warming may directly influence ice extent, ice thickness, regional wind patterns and water column dynamics. Examples for such changes were recently observed in the Bering Sea. In 1997, atmospheric forcing strongly perturbed the southeastern Bering Sea ecosystem. The unusual climate, as reported by Overland et al. (2001) and the resultant physical conditions (Stabeno et al. 2001) influenced primary production and phytoplankton species composition in the Bering Sea (Stockwell et al. 2001). The first documented *Emiliania huxleyi* bloom for the Bering Sea began in the anomalously warm, nutrient-depleted, shallow upper mixed layer (Stockwell et al. 2001). As a result, zooplankton populations, planktivorous seabirds and salmon populations were all impacted. Similar events could occur within the Arctic if current warming trends continue.

Based on the described system parameters and likely changes in the physical/chemical environment, we determined some of the more direct and pressing research needs:

- The determination of baseline estimates of primary production for water column assemblages, ice algae communities and both the micro- and macroalgae of benthic communities is necessary for various Arctic environments. Understanding how ice coverage affects water column stability, light distribution, nutrient regeneration, and ultimately production, is essential in understanding these environments under reduced ice thickness or extent. To date, most studies are limited to one to three field years. It is difficult to assess temporal variability with such a limited dataset. Essential components within these studies are nutrient uptake studies, photosynthesis versus irradiance studies, and a more detailed look at Redfield stoichiometry. An NSF Funded project is currently underway to consolidate all existing Arctic data on nutrients, chlorophyll and primary production (Matria, Codispoti, Gosselin, Hill, Light, Steele -PIs) to help establish historical patterns.
- Determination of the relative contributions of phytoplankton, ice algae and benthic algal production is an essential component in understanding food web interactions. Timing of the various carbon pulses to the water column and to the benthos, in turn, fuel zooplankton and benthic production. An excellent example of this has been provided for the Beaufort Sea (Horner and Schrader 1982) but more is needed.
- Although species assemblages and occasionally size distributions have been examined for selected Arctic regions, comprehensive data remain sketchy. Understanding of seasonal succession is lacking. Regional differences in species assemblages are not understood. The relative importance of flagellates versus diatoms is restricted primarily to a single cruise covering great distances. More detailed information within a given region is needed in order for both spatial and temporal comparisons.
- Impacts of potentially harmful species must be assessed under scenarios of increased water temperature within coastal Arctic waters. Species associated with paralytic shellfish poisoning and amnesic shellfish poison are prime candidates in potential range extensions. The potential for nuisance blooms species, such as *Phaeocystis* spp., may increase in Arctic waters as temperatures increase.
- Large geographical areas require the ability to remotely evaluate biological, chemical and physical processes. This includes the use of satellites with properly tested algorithms (ground truth information is essential), moored sensors in the vicinity of pulse points (sensors should included biological, chemical and physical detectors), and unmanned submersible vehicles.
- Under reduced ice extent scenarios, potential changes in water chemistry, nutrient regeneration patterns, water column turbidity, erosion events, acidification, nutrient availability, wind field stresses and the timing of blooms as well as nutrient drawdown may all impact potential primary production patterns within a given region.
- An important component to any assessment of phytoplankton primary production and species distributions would be the compilation of an Arctic bibliography. Having this document, regional or temporal deficiencies could be assessed. Perhaps a synthesis paper could also be generated from this data base.

MICROBES

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Introduction

The importance of microbes in marine ecosystems has been well established by extensive research in low latitude systems. Microbial communities, including phytoplankton, protists, the two main groups of prokaryotes: Bacteria and Archaea, fungi and viruses are, by far, the most abundant and the most taxonomically and genetically diverse organisms in the biosphere. Microbes dominate the biological activity, biomass, production and remineralization in marine systems, while large organisms and higher trophic levels (crustaceans, fish, birds and mammals) play a quantitatively minor role in many biogeochemical processes. Microbes are the main drivers of biogeochemical cycles and the major producers and consumers of carbon dioxide and other greenhouse gases. They are significant players in regulating the biosphere. In addition, microbes can be important sentinels of environmental change, because alterations in the structure and biomass of microbial communities can herald changes not only in pathways of nutrient and energy transfer in foodwebs, but also in biogeochemical cycles.

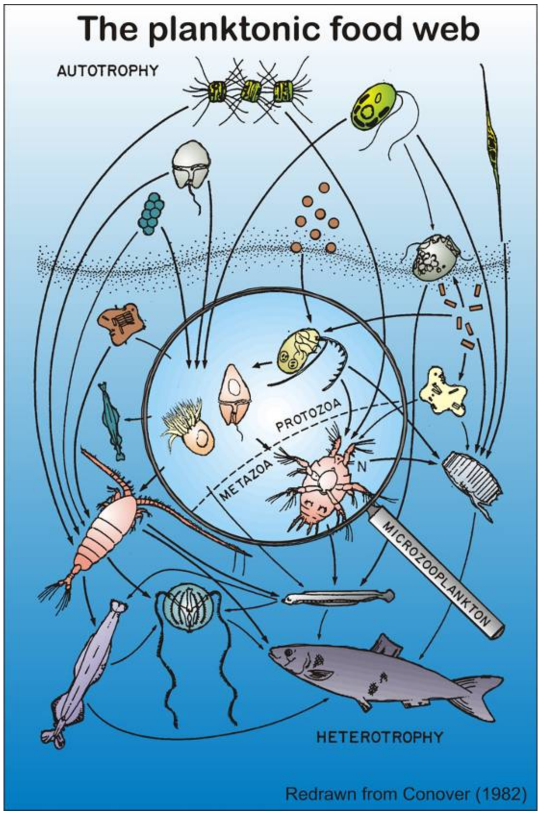

Fig. 13. Heterotrophic microbes hold a pivitol role in the oceans as the major remineralizers of detritus and consumers of phytoplankton (credit Dave Montagnes/ U.Liverpool)

In contrast to the extensive research in temperate marine systems, much less is known about microbes in the Arctic Ocean and surrounding seas. The role of microbes in the Arctic and other perennially cold oceans has been debated since Sorokin first proposed inhibition of microbial activity by low temperature (see review by Karl 1993). Recently, however, scientists have become increasingly aware that extreme environments harbor unique, highly adapted microorganisms. Cold-loving (psychrophilic) bacteria have been actively studied for more than seventy years and their potential biotechnological applications will no doubt continue to inspire research for years to come.

Yet, in spite of this previous research, many questions about marine microbes in the Arctic remain unanswered. These unknowns prevent us from predicting with any confidence the impact of climate change on food webs and basic biogeochemical processes in the Arctic. Here we briefly review what is known about marine microbial communities in the Arctic and highlight some of the major unanswered questions in Arctic microbial ecology and biogeochemistry.

Background

Extensive research in low latitude ecosystems has demonstrated that microorganisms play several essential roles in the marine food web (Pomeroy 1974, Azam et al. 1983), including: (1) decomposers of non-living organic matter (regenerating nutrients for the traditional herbivorous food web); (2) transport vectors linking "unavailable" detritus and dissolved organic carbon (DOC) to higher trophic levels; and (3) the bulk of respiration and metabolism in seawater (Williams et al. 1981). In low latitude marine and freshwater ecosystems, heterotrophic prokaryotes consume roughly 50% of primary production and are largely responsible for the high retention of carbon and other elements in the upper surface layer. Because of this retention and recycling, only a small fraction of primary production escapes mineralization and is available for higher trophic levels or sinks to the benthos. Whether this is the case for the present Arctic is unclear. Even less clear is how microbial communities will respond to climate change in the Arctic.

Biomass of heterotrophic microbes in Arctic surface waters, including bacterioplankton and heterotrophic protists, shows a strong response to seasonal changes in phytoplankton stocks. For example, in both the Chukchi Sea and the Canada Basin, surface mixed layer concentrations of bacteria start out low in the spring (0.3-0.4 x 10^9 L^{-1}), increase over the course of the bloom (up to 0.9 x 10^9 L^{-1};Yager et al. 2001), and are highest in late summer (Steward et al. 1996, Sherr et al. 2003, Hodges et al. 2005). Heterotrophic protist biomass was also found to follow development of the spring-summer phytoplankton blooms in the Canada Basin (Sherr et al. 2003). Depth profiles of bacterial biomass during the summer generally show high values near the surface correlating with high particulate organic carbon (POC) and nitrogen (PON) or chlorophyll *a* concentrations (Hodges et al. 2005), but subsurface peaks are common offshore (Lovejoy et al. 2002a) down to 100 m (Steward et al. 1996).

Although these features are also seen in low-latitude oceans, other field data comparing autotrophic to heterotrophic microbial biomass and activity indicate that cold marine ecosystems may be unique. Bacterial abundance is generally lower for a given concentration of chlorophyll *a* (Karl et al. 1991, Smith et al. 1995, Yager 1996) when compared to non-arctic marine ecosystems (Cole et al. 1988). The most common explanation, based on sub-arctic research (Pomeroy and Deibel 1986, Pomeroy and Wiebe 1988, Pomeroy and Wiebe, 2001), is that the low temperatures cause disproportionately low growth rates in bacteria compared to phyto–plankton. Bacterial growth limitation is thought to occur at low temperatures because substrate uptake is impaired by reduced reaction rates, decreased membrane fluidity (see Gounot 1991, for review), and slower diffusion rates (Jumars et al. 1993). An enhanced threshold concentration of organic substrate has been proposed for all bacteria living at low temperatures (Wiebe et al. 1992). The greatest degree of uncoupling occurs during high chlorophyll concentration (Karl 1993), suggesting that blooms are the critical conditions for studying this issue.

The concepts that phagotrophic protists are significant consumers of bacterioplankton and phytoplankton, and that the larger size classes of phagotrophic protists can be an important source of food for mesozooplankton, have inspired a reformulation of our paradigms of the functioning of food webs in the ocean. To date, compared to phytoplankton and mesozooplankton, much less is known about the composition, distribution and rates of activity of phagotrophic protists in the Arctic Ocean; this is an obvious deficit in our understanding of pelagic ecosystems in this region. Heterotrophic protists include nanoflagellates, ciliates, and dinoflagellates. Choanoflagellates are abundant in the Arctic Ocean and may be major consumers of both bacterial and small phytoplankton cells (Sherr et al. 1997). Microzooplankton, protists 20 – 200 µm in size, have previously been reported to graze from 37-114% of primary production in Canadian Arctic systems (Paranjape 1987) and 55-68% of the production of < 200 µm sized phytoplankton in Norwegian fjords (Archer et al. 2000). Recent work in the Gulf of Alaska (Strom et al. 2007), the Bering Sea (Olson and Strom 2002, BEST program), and shelf and slope regions of the western Arctic Ocean (SBI program) (Sherr et al. *in press*, Campbell et al. *in press*) has confirmed the role of microzooplankton as consumers of phytoplankton in sub-Arctic and Arctic food webs. The high standing stock biomass (up to 60 µg C l^{-1}) of heterotrophic protists is dominated by large ciliates and heterotrophic dinoflagellates in the Chukchi Sea (Sheer and Sheer, 2007, Sherr et al. *in press*). Although it is likely that phytoplankton and sea ice algae still represent a crucial, and at times critical, food source for the mesozooplankton, utilization of microzooplankton as food now is recognized as being of similar import, particularly during periods when phytoplankton standing stock is low, dominated by small cells, or of poor quality. Campbell et al. (*in press*) found that microzooplankton were generally preferred prey for copepods in the Chukchi and Beaufort Seas in both spring and summer seasons.

Since strong local pulses of primary production or blooms are a frequent characteristic of high-latitude oceans including the Chukchi and Beaufort Seas, the response of microbes (including both heterotrophic bacteria and phagotrophic protists) to these pulses determines the rate of remineralization and the fraction of total production exported to the benthos (Pomeroy and Wiebe 1988, Wiebe and Pomeroy 1991). Weak microbial activity in the Arctic would contribute to the uniquely high degree of bentho-pelagic coupling in many shelf regions of the Arctic (Dunton et al. 2005) and the consequent strength of the demersal fishery (Petersen and Curtis, 1980). In their recent review, however, Pomeroy and Wiebe (2001) conclude that "inhibitory effects are not sufficient to alter overall ecosystem function" and thus more research is needed to find an alternate explanation for the larger export fractions in cold oceans. A key question is: do the factors controlling bacterial activity in cold oceans differ substantially from those in temperate waters? Despite predictions based on the results above, recent studies from a variety of polar areas have found that bacterial growth rates in cold regions can be similar to those in temperate zones (Cota et al. 1996, Rivkin et al. 1996, Yager 1996, Rich et al. 1997, Carlson et al. 1998, Ducklow et al. 1998, Rivkin and Anderson 2000, Kirchman et al. 2005, Kirchman et al. *in press*).

More data are needed specifically for the Western Arctic, and we lack estimates of growth rates for Archaea, which may have different biogeochemical roles than Bacteria (see below). If growth rates for these microbes in the Arctic are potentially similar to those in low latitude oceans, it raises questions about why prokaryotic biomass appears lower and why activity of heterotrophic prokaryotes may be less able to respond to large blooms of phytoplankton in the Arctic than elsewhere. Community structure may be the key. The types of bacteria present in a community can significantly impact local microbial activity and biogeochemical cycling. Archaea may be more abundant in the western Arctic than in low-latitude oceans (Kirchman et al. 2007), especially in regions impacted by rivers. Archaea can be up to 15% of the total bacterial community in particle-rich waters near river outflows (Wells et al. 2006). Riemann et al. (2000) used mesocosms to demonstrate that marine bacterial community composition and ectoenzyme activity could change dramatically in response to short term (1-2 d) changes in a phytoplankton bloom. Before the development of modern molecular biology, numerical taxonomy (phenotypic characterizations of cultivable bacteria) was used to describe bacterial community structure and metabolic capabilities. For example, Kaneko et al. (1977, 1979) used this technique extensively to characterize bacterial types isolated from nearshore waters of the Beaufort Sea. They demonstrated changes in cultivable bacterial phenotypes according to season, geography, and in response to algal blooms. Isolated strains were either psychrophilic or psychrotolerant and tended to differ significantly from those found in other marine environments. While the conclusions that can be drawn about in situ communities from cultivable sub-populations are limited (Ferguson et al. 1984), the results predict high potential for genetic diversity in the Arctic and the importance of strong seasonality. This same type of community succession may be at work in the Chukchi Sea (Yager et al. 2001) where a clear shift in community structure and functioning occurred along an algal bloom gradient.

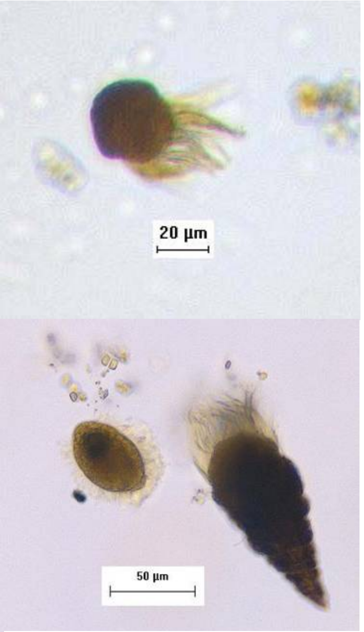

Fig. 14. Ciliated protists are one of the more prominent grazers within the Arctic's micriobial community (credit Evelyn & Barry Sherr / OSU)

The need to understand and predict the interplay of community structure and function in cold marine regions becomes increasingly critical in the face of planetary change (Aagaard et al. 1999). Large, long-term changes in Arctic Ocean circulation and structure have occurred (Steele and Boyd 1998). Temperature and contaminant levels (Carmack et al. 1997) and ultra-violet radiation are increasing (AMAP 1997), sea ice extent and thickness are decreasing (Cavalieri et al. 1997), and upper layer hydrography is changing (Swift et al. 1997, Morrison et al. 1998). Increased riverine and terrestrial organic matter contributions to the coastal Arctic are expected. These changes have generated a great deal of discussion about potential effects on primary productivity (e.g., Walsh et al. 1989, 2005), zooplankton and fish ecology (e.g., Conover et al. 1995), and marine mammals (e.g., Tynan and DeMaster 1997), but much less is known about effects on microbes other than large phytoplankton. Microorganisms are poised to react to these changes (Lovejoy et al. 2002b) but understanding how the current ecosystem functions will be vital for predicting the response to future perturbation.

Research Needs in Arctic Microbial Ecology: the Impact of Global Climate Change

Since microbes are involved in every biogeochemical process potentially impacted by global change and since we know so little, the list of necessary research topics is long. Below are some of the more direct and pressing research needs:

- **Microbial Community Structure** There is an urgent need to study microbial community structure over time and across regions in the Arctic. This means not only biomass measurements such as prokaryote, heterotrophic protist and phytoplankton abundance along with Chl *a*, but also the use of emerging molecular technologies to identify what microorganisms are the dominant players under specific nutrient, dissolved organic and inorganic carbon (DOC, DIC), and particulate organic matter (POM) conditions. In short, microbial diversity studies need to be coupled with processes studies measuring respiration, heterotrophic and primary production, and trophic links within microbial food webs. We recommend that studies of microbial diversity and rate processes be embedded in all biological-oriented arctic missions and as many physical oceanographic missions as practical. Unlike studies of larger organisms, microbial studies require only routine water samples and do not involve major ship maneuvers so this is a feasible goal. Funding to support microbial studies would result in major advances for small additional cost.

- **Role of Archaea in the C and N cycle.** Archaea seem to be of special significance in Arctic waters (Galand et al. 2006 *in press*, Garneau et al. 2006, Wells and Deming 2003) with population densities in surface waters that are more typical of deep oceanic waters elsewhere (Kirchman et al. 2007, Alonso-Sáez et al. *in press*). Despite over 20 years since initial reports of Archaea in marine waters there is little understanding of their functional significance. When compared to deep oceans, the Arctic with its surface populations supplies tantalizing clues about the ecological roles of marine pelagic Archaea. Conditions that are similar between the two environments are prolonged darkness and little freshly produced organic material over much of the year. However, the striking differences include high pressure and a rain of aged particulate material in deep water. Whereas surface winter arctic populations are not subject to extreme pressure and there is little POM available for much of the year. More work is needed on documenting Archaeal diversity and function over seasonal and spatial scales.
- Archaea have the capacity to be involved in all steps in the nitrogen cycle (Cabello et al. 2004), but what little is known of archaeal nitrogen metabolism has been gained from the study of thermophilic and halophilic strains. Work in low latitude oceans suggests that some archaea may be chemoautotrophs fueled by ammonium oxidation (Francis et al. 2005), and there is some evidence of this for the Chukchi Sea (Kirchman et al. 2007) The importance of bacterial versus Archaeal nitrogen cycling is unknown in oceanic waters but would appear to be sensitive to different forcing variables. For example the short production season may favor organisms with both assimilatory and dissimilatory nitrogen pathways such as found in several archeaons (Cabello et al. 2004). Many Archaea are important methanogens and are responsible for the bulk of naturally produced methane, a potent greenhouse gas. A recent environmental survey has found Archaeal methanogens in Arctic waters (Galand et al. 2006). More work is required to document factors selecting for methanogens in Arctic marine and coastal environments also in the framework of methane hydrates at the sea floor.
- **Mortality: viral lysis and grazing**. For a given biomass chl *a* level, prokaryotes are less abundant in arctic waters than elsewhere. It is possible that these low abundances are due to the two major loss processes for microbes: viral lysis and grazing. Additional studies on microbial loss mechanisms are urgently required as the dominant loss process influences the structure of an ecosystem and its ability to support higher trophic levels. Viral morality will result in a release of readily utilizable DOM for bacteria and increased respiration whereas grazing losses result in a repackaging of POM from phytoplankton or bacteria to protists that are suitable sources of food for zooplankton. The Arctic harbors characteristic bacterial grazers (e.g. Sherr et al. 1997, Sherr et al. 2003), which suggests that trophic interactions rather than or in conjunction with DOM supply may be responsible for observed bacterial abundances (Lovejoy et al. 2006, Massana et al. 2006). Phagotrophic protists are known to consume phytoplankton of all size classes in Arctic and sub-Arctic systems (Olson and Strom 2002, Sherr et al. 1997, Sherr and Sherr 2007, Strom et al. 2007, Sherr et al. *in press* (SBI data)), thus protists may at times exert top-down control on

phytoplankton as well as on bacterioplankton.'

- **The fate of terrestrial carbon and nutrients from terrestrial runoff**. The biological importance of terrestrial DOM is unclear, and will depend on the timing and magnitude of freshwater runoff. The response of microbes to variation in runoff due to climate change is unclear. In contrast to marine DOM, terrestrial DOM contains high concentrations of chromophores and is more susceptible to photochemical reactions. Rapid runoff and little mixing may lead to increased photooxidation of terrestrial DOM and release of CO_2 directly into the atmosphere. Recent work points to high production of carbon monoxide (CO) in sea ice potentially due to photo bleaching of colored dissolved organic matter (CDOM), but with high CO consumption during open water by specific bacterial groups (Tolli et al. 2006, Xie et al. 2005). High CDOM in the freshwater discharge and seasonal ice formation could result in increased CO to the atmosphere or conversely may provide additional substrate for biological heterotrophic production with more going into food webs than suspected.
- Runoff may carry in more particulate organic carbon which could affect the partitioning among free- living, attached and benthic bacteria and Archaea. The accelerating loss of permafrost in the Arctic will contribute substantially to the input of POC and DOC (including CDOM) in riverine runoff, and alter the importance of terrestrial sources to the nearshore environment. These changes in the relative importance of these compartments will influence rates and the number of trophic transfers required for mineralization of organic material to CO_2 and ammonium.
- **Role of sediment microbes in Arctic biogeochemical cycles**. There have been few studies on sediment microbes in the Arctic. These microbes are involved in all of the biogeochemical processes mentioned above. In particular there is nothing known of how changing surface ice conditions and currents will affect the following key processes: N cycling and denitrification; release of volatiles and other compounds from sediments; the relative importance of bacterial vs. meiofaunal respiration; sediment methane oxidation vs. escape into the upper water column and ultimately the atmosphere. A specific concern is whether higher temperatures might lead to increased rates of denitrification (and possibly of anaerobic ammonia oxidation) in Arctic sediments.
- **The potential role of psychrophilic microbes for bioremediation of organic pollutants concentrated in the Arcti**c (Carmack et al. 1997, AMAP 1997). Volatile contaminant levels are extremely high in arctic surface waters due to cold trapping. These contaminants make their way up the food chain and impact the health and reproductive capacities of higher trophic levels, including humans. Although microbes have been used successfully in temperate regions to clean up polluted waters, little research has been done along these lines in the Arctic.

Pulse-points and areas of interest

The Arctic Ocean is a very complex system with several regions that differ substantially in ice cover, nutrient concentrations, megafauna populations, and terrestrial inputs, to name just a few variables. All of these are likely to impact microbial communities and food webs and the biogeochemical processes mediated by microbes. We need to examine several Arctic regions in order to more confidently predict the response of the Arctic ecosystem to climate change.

However, as a start we suggest that initial effort be put into the following regions: (1) The upgraded station at **Barrow** should be a site for a time series of basic measurements of microbial communities and select biogeochemical parameters (e.g. nutrient concentrations). (2) Clearly the changing source waters entering through **Bering Strait** near Little Diomede have already had major effects on pelagic variability. While some research is planned to examine changing source waters, more work is needed on the microbial communities being brought into the Arctic via Bering Strait. (3) **Hannah shoal**s is historically a deposition center with high sediment remineralization. The ongoing productivity of this region depends on the timing and position of ice edge. It is not clear how biological productivity in Hannah Shoals will change in response to changes in the ice edge position. (4) The influence of Arctic rivers such as the **Mackenzie or Yukon** into the Beaufort Sea flaw lead, where ice first opens, needs to be further investigated. Climate change is predicted to have a large impact on Arctic rivers and the material they export to Arctic coastal waters. It is not clear how changes in terrestrial inputs mediated by rivers like the Mackenzie and the Yukon will affect microbial communities and the biogeochemical processes.

ZOOPLANKTON

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Introduction

Zooplankton, both heterotrophic protists and metazoans, are the major grazers and modifiers of the primary production in the pelagic realm of the Arctic (Campbell et al. *in press*, Sherr et al. *in press*). Recent and projected changes in the extent and timing of the ice cover will have profound impacts on protistan and metazoan zooplankton communities, because seasonal cycles are intricately coupled to the timing of ice-breakup and phytoplankton blooms (Smith and Schnack-Schiel 1990). The seasonal success of the zooplankton communities in turn determines the resources available to many higher trophic levels such as fish, seabirds, and marine mammals (Hunt et al. 2002). Thus, changes in zooplankton communities lead to changes at higher trophic levels that in the Arctic will ultimately impact local subsistence harvesting. The roles of heterotrophic protists (a.k.a. microzooplankton) in planktonic food webs were evaluated in the "Microbe" chapter. This chapter will focus on the larger metazoan zooplankton.

Fig. 15. Typical zooplankton of the Chukchi Sea, the copepod *Calanus marshallae*, and a potential predator the hydromedusae *Euphysa flammea* (credit Russ Hopcroft/UAF)

In order to detect and quantify future and ongoing changes in Arctic zooplankton, it is essential that we collect and collate detailed and extensive baseline information on these communities as our current knowledge is fragmented and incomplete. The Chukchi Sea in particular represents a complex gateway into the Arctic where variation in climate may have profound impacts. Large quantities of Pacific zooplankton enter the region through the Bering Strait, in a complicated mixture of water masses (i.e. Alaska Coastal, Bering Shelf, and Anadyr Water), each with unique assemblages and quantities of zooplankton (Springer et al. 1989, Coyle et al. 1996, Hopcroft and Kosobokova, *accepted*). This inflow is diluted by Coastal Arctic waters carried by the East Siberian Current and from the deeper waters of the Canada Basin or Chukchi Plateau (Weingartner et al. 1998, 2005, Pickart et al. 2008), at times flowing eastward along the shelf-break toward the Beaufort Sea (Ashjian et al. 2005). The influx of the "rich" Pacific water determines the reproductive success of both the imported and resident zooplankton communities (Deibel et al. 2005, Plourde et al. 2005). 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 within the Chukchi Sea. Zooplankton abundance and community structure also determine the fate of local production, and the fate of production advected through Bering Strait, and thus affect the amount and quality of carbon exported to the benthic communities in this region.

In contrast, the Beaufort Sea is primarily Arctic in faunal character (McConnell 1977, Horner et al. 1981), with cross-shelf exchange mechanisms more important in determining the relative contribution of "oceanic", "shelf" and estuarine species (Lane et al. 2008). In the Eastern Beaufort, the outflow of the McKenzie River has significant impact on both the composition of the zooplankton, and its productivity cycles (Parsons et al. 1989, Hopky et al. 1994a-c, Darnis et al. *in press*). 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.

Sampling History

Historically, the zooplankton communities of the western Arctic and northern Bering Sea have not been well studied compared to most US oceanographic regions. The relative paucity of information north of the Bering Strait is a consequence not only of its remoteness and seasonal ice-cover, but equally because of the limited commercial harvesting there in comparison to the southeastern Bering Sea. Nonetheless, there is a long but scattered history of biological investigations involving zooplankton sampling in the western Arctic.

Although physical oceanographic measurements typically have earlier histories, the first scientific records of zooplankton work in the Bering Strait and Chukchi Sea appear to be those of Johnson (1934), Stepanova (1937a,b), Bogorov (1939), and Jaschnov (1940), all of whom noted the significant influence of Pacific fauna in the Chukchi Sea. Further work resumed after World War II, with Russian studies in the Far Eastern Seas laying the foundation for our understanding of this broad region (Brodsky 1950, 1957), and even today the English translation of his work remains a primary taxonomic reference for the region. Work more specific to the Chukchi region appeared in Virketis (1952). North American work in the region initially maintained a quantitative and taxonomic dimension (Johnson 1953, 1956, 1958), but then interest waned. The results of the 1959 and 1960 *Brown Bear* cruises were never published as more than zooplankton community displacement volumes (English 1966), and although the USCG Cutter *Northwind* appears to have sampled zooplankton in the Bering Strait and Chukchi Sea during the 1960's, the data is either unpublished or buried in the gray literature. The Western Beaufort Sea Ecological Cruises (WEBSEC; Ingham et al. 1972, Hufford et al. 1974) quantitatively sampled the Chukchi Sea from the USCG *Glacier* in 1970 (Wing 1974), and the Beaufort Sea in 1971 (McConnell 1977) but Beaufort Sea samples collected in 1972 were never processed. The nearshore community was assessed only infrequently (Redburn 1974). During the same period other larger-scale and longer-term US studies focussed on deep Canada Basin regions including the T-3 and AIDJEX ice stations (Hughes 1968, Scott 1969, Pautzke 1979, English and Horner unpublished).

A new wave of activity began with exploration for oil in offshore waters. Samples collected in the northern Bering and Chukchi seas (Cooney 1977) by the Alaskan OCSEAP Program were never published as more than presence-absence data, except for Norton Sound where abundance and biomass were presented (Neimark 1979). Limited additional quantitative zooplankton sampling occurred in the Chukchi Sea under the OCSEAP program (English and Horner 1977) as most OCSEAP effort became focused on the nearby waters of the Beaufort Sea (*ibid*, Horner 1981, Horner and Schrader 1984, Horner and Murphy 1985) and southeast Bering Sea (Cooney 1977, followed by PROBES, FOCI). Industry sponsored studies in the Beaufort Sea never embraced the study of zooplankton, and the drop nets (e.g. Griffiths and Dillinger 1981, Moulton et al. 1984, Cannon et al. 1987, Envirosphere 1983, Knutze et al. 1990, Knutze and Jewett 1991) or pumps (Tarbox et la. 1979) used by them in shallow nearshore waters to assess (epibenthic) fish prey were either too coarse, too inefficient or the collections were too superficially analyzed to assess holozooplankton. It was the mid-1980's before quantitative zooplankton sampling resumed in the Bering Strait and Chukchi Sea with the ISHTAR program (Springer et al. 1989). A notable exception to the political boundaries imposed on most post-WWII sampling in the Bering and Chukchi seas has been the Joint US-USSR BERPAC program, with five such cruises executed between 1977 and 1993 (Tsyban 1999). The Trans-arctic Section (Thibault et al. 1999) plus the SHEBA drift across the Chukchi Plateau in 1997-1998 (Ashjian et al. 2003) round out the research of the 20th century.

This decade, our knowledge of zooplankton in the western Arctic has begun to improve considerably due to ongoing efforts such as the NSF SBI program on the Beaufort and Chukchi shelves (e.g. Plourde et al. 2005, Lane et al. 2008, Campbell et al. *in press*), plus cross-basin cruises by NOAA's OE Program (e.g. Hopcroft et al. 2005, Raskoff et al. 2005 *accepted*, Kosobokova and Hopcroft *submitted*), the Basin-oriented JWACS, and the CASES Program (Seuthe et al. 2007, Forest et al. 2007, Darnis et al. *in press*) on the Canadian continental shelf in the McKenzie Delta region. In 2007 the Bering-Aleutian Salmon International Survey (BASIS) expanded its sampling northward into the southern Chukchi Sea. Additional sampling activities have been spurred in part by the International Polar Year with oceanographic cruises conducted by Hokkaido University (2007-2008) in the Chukchi, the Chinese Polar Institute's Icebreaker *Xue Long* (2008) and Canadian Circumpolar Flaw Lead program (http://www.ipy-cfl.ca/) in the Beaufort Sea off Bank's Island. The 2008 sale of new prospect leases in the Chukchi Sea is also stimulating ecosystem surveys including zooplankton.

Nonetheless, there remains a significant gap in knowledge from Russian waters in the western Chukchi Sea, and in particular, of simultaneous assessment of the zooplankton entering from both sides of the Bering Strait that ultimately drive much of the productivity in this region. This gap is now being addressed by NOAA's RUSALCA program. Solely Russian research in this region has undoubtedly continued since the 1950's, but the results are often buried in their own "gray" literature, and are generally unavailable to the international community (see Herman, 1989). Collaborations now being fostered by the RUSALCA program and the Arctic Ocean Biodiversity (ArcOD) project of the Census of Marine Life are working to make this missing Russian data accessible.

One common shortcoming of studies prior to ~1990 is that sampling techniques were not standardized, and in particular, the use of 303 to ~600 µm mesh nets as employed in these studies missed the majority of the zooplankton community numerically, and a substantial proportion of the community biomass and diversity. This makes quantitative comparison between studies problematic. For the most part, Arctic studies have now standardized on 150 µm mesh nets (e.g. Smith and Vidal 1984, Smith et al. 1985, Kosobokova and Hirche 2000, Ashjian et al. 2003, Hopcroft et al. 2005, Lane et al. 2008, Hopcroft and Kosobokova *accepted*) that more completely sample the numerically dominant copepods in the genera *Oithona*, *Oncaea*, *Microcalanus* and *Pseudocalanus* (*ibid,* Auel and Hagen 2002, Hopcroft et al. 2005). BERPAC 1988 is thus particularly relevant as it encompassed stations from the southern Bering Sea through to the mid Chukchi Sea, and reported quantitative zooplankton data using a 186 µm mesh net (Kulikov 1992) that would provide collections comparable to recent US collections with 150 µm mesh nets. Sampling during the CASES program used 50 µm, 200 µm, and 500 µm meshes to collect zooplankton along the inshore-offshore gradient of communities in the eastern Beaufort Sea. In fact, to ensure that all developmental stages of these species, including nauplii, are sampled, a mesh as fine as 53 µm is required (Ashjian et al. 2003, Hopcroft et al. 2005). Many of these more recent studies have been conducted primarily in deeper waters, while in the shallow waters of the Chukchi and Beaufort Seas we can expect an even larger contribution of smaller neritic species in several of the water masses that will be encountered (e.g. Grice 1962, Horner 1981, Conover and Huntley 1991, Darnis et al. *in press*). [A complete assessment of all metazoan zooplankton is required if one hopes to accurately estimate both grazing and respiration by zooplankton communities.]

Fig. 16. Species in the egg-carrying copepod genus *Pseudocalanus* are among the most important species on the Chukchi and Beaufort Shelves

Current State of Knowledge

Zooplankton of the Arctic continental shelves have now been studied in variable taxonomic detail in the Barents, Kara, Laptev and Chukchi/Beaufort Seas (reviews by Smith and Schnack-Schiel 1990), the Canadian Archipelago, and the North Water Polynya in northern Baffin Bay (e.g. Conover and Huntley 1991, Fortier et al. 2000, Ringuette et al. 2002, Deibel and Daly 2008), while the East Siberian Sea has been particularly understudied (Pavshtiks, 1984, 1994). Seasonal cycles are generally best described in the deeper basins because such studies have been executed from drifting ice stations that can be occupied year-round (e.g. Dawson 1978, Kosobokova 1980, Pautzke 1979, Ashjian et al. 2003). Although we now have a relatively complete idea of the species that have been described regionally in the Arctic (303 species, of which 156 are copepods - Sirenko 2001), we still lack unbiased and comprehensive estimates of the abundance, biomass and composition of the zooplankton in the Chukchi and Beaufort seas, due to sampling inadequacies of the past. Extensive and detailed sampling by the recent CASES, OE, RUSALCA and SBI programs address some of these shortcomings.

Due to their high abundance, and ease of capture with traditional plankton nets, the taxonomic composition (Brodsky 1983, Sirenko 2001) and life history of the larger more common copepods in the Arctic Ocean are relatively well understood (Smith and Schnack-Schiel 1990). Historically, effort has concentrated on the large, long-lived polar copepods of the genus *Calanus* because they appear to dominate zooplankton biomass (e.g. Smith and Schnack-Schiel 1990, Mumm et al. 1998, Thibault et al. 1999, Ashjian et al. 2003, Hopcroft et al. 2005). During the productive season, *Calanus* feed on algae and heterotrophic protists (Campbell et al. *in press*) continuously in the surface layers (especially the marginal ice zones), spawning (Plourde et al. 2005) and/or accumulating surplus energy in the form of lipids (e.g. Hygum et al. 2000, Stevens et al. 2004a,b). This chemical energy is utilized for over-wintering (diapause) at depth and to fuel reproduction in the following spring (Pasternack et al. 2001). The life-cycles of these *Calanus* species have been estimated to take 2-4 years (e.g. Hirche 1997, Kosobokova 1999), and notable differences occur in the habitat preferences and reproductive strategies of the different *Calanus* species occurring in the Arctic (Hirche and Kwasniewski 1997, Hirche and Kosobokova 2003). For example, the extended open-water period provided by arctic polynyas can shorten the life span of *Calanus* spp. by as much as one year (Ringuette et al. 2002). A wide variety of other large predatory and detritus-feeding species is also present, with a unique feature of polar environments being the relatively shallow occurrence of many of these genera compared to other oceans (Kosobokova and Hirche 2000, Kosobokova et al. 2007).

As in most oceans, smaller copepod taxa are actually numerically dominant (e.g. Pautzke 1979, Kosobokova 1980, Conover and Huntley 1991, Kosobokova and Hirche 2000, Auel and Hagen 2002, Ashjian et al. 2003, Hopcroft et al. 2005), but unlike other oceans, small copepods may contribute relatively little to the total copepod biomass in Arctic oceanic waters (Hopcroft et al. 2005). These smaller species are less capable of storing lipids, and are thought to complete their life cycles annually (McLaren 1969, Kosobokova 1980, Ashjian et al. 2003), although multiple generations per year might be possible and could greatly impact their ecological importance in Arctic waters (e.g. Hopcroft et al. 2005). Small and medium-bodied copepods become more important in shallower "on shelf" waters (e.g. Horner 1984, Conover and Huntley 1991, Lane et al. 2008, Hopcroft and Kosobokova *accepted*) where they can complete their entire life cycle, while larger "diapausing" species such as *Calanus* rely on advective processes to move them into and off of shelf waters (Deibel and Daly, 2008). In the Chukchi and Barents seas, faunal influences from the Pacific and Atlantic, respectively, are obvious (e.g. Coyle et al. 1996, Olli et al. 2007, Hopcroft and Kosobokova *accepted*), with the combined affects of the Lomonosov Ridge and the Transpolar Drift helping to demarcate the extent of these subpolar contributions (Kosobokova and Hirche 2000).

Although copepods typically predominate throughout the Arctic, there is a broad assemblage of other holoplanktonic groups (e.g. Sirenko 2001) that are only occasionally reported in full detail (e.g. Mumm 1991, Richter 1994, Kosobokova and Hirche 2000). These non-copepod groups in particular hold the greatest promise for discovery of new species and trophic importance because they have been largely ignored or biased against by collection techniques. Thus, euphausiids are less abundant and less speciose in arctic waters then elsewhere (Smith and Schnack-Schiel 1990), but can be important prey for higher trophic levels such as bowhead whales, birds, and fishes (Moore et al. 1995), even though they are difficult to accurately assess in ice-covered waters. Recently, it has been suggested that the euphausiid populations concentrated around Barrow may be largely dependent on advection into the region (Berline et al. 2008). Larvaceans (=Appendicularians) have been shown to be abundant in Arctic polynyas (Ashjian et al. 1995, Acuña et al. 1999, Deibel et al. 2005), common in the central Arctic (Kosobokova and Hirche 2000, Auel and Hagen 2002, Hopcroft et al. 2005, Kosobokova and Hopcroft *submitted*), and are also transported in high numbers through Bering Strait and into the Chukchi Sea (Springer et al. 1989, Shiga et al. 1998, Hopcroft and Kosobokova *accepted*). 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 (Kosobokova and Hirche 2000, Auel and Hagen 2002, Hopcroft and Kosobokova *accepted,* Kosobokova and Hopcroft *submitted*). Arctic chaetognaths may represent considerable biomass (ibid), and are thought to be important in controlling *Calanus* populations (Falkenhaug and Sakshaug 1991). Hyperiid amphipods can also be common in Arctic waters (Mumm 1993, Auel and Werner 2003), and have a similar potential to graze a notable proportion of the *Calanus* population (Auel and Werner 2003).

Relatively little is known of the abundance, composition or ecology of the delicate gelatinous zooplankton (Fig. 17), such as jellyfish (e.g. Naumov 1960, 1961, Stepanjants 1989, Raskoff et al. 2005 *accepted*) and ctenophores (Ospovat 1985, Siferd and Conover 1992, Purcell et al. *accepted*), which utilize the more "herbivorous" zooplankton as food. There are indications that climate change has resulted in increased numbers of jellyfish in the Bering Sea in recent years (Brodeur et al. 1999), which subsequently collapsed, leaving a profound impact on the availability of food to higher trophic levels such as seabirds and marine mammals. Scientists have recorded jellyfish piled up several feet deep along large expanses of Barrow, Alaska, shorelines, however the scientific literature fails to encompass such events, although OE cruises have shown them to be abundant even in the Canada Basin (Raskoff et al. 2005 *accepted*). The ecological impact of such predators can be substantial (Swanberg and Båmstedt 1991, Purcell 2003, Purcell et al. 2000 *accepted*). The basic biodiversity of all these gelatinous animals is grossly underestimated in polar waters (Pagès 1997, Pesant et al. 1998, 2000).

Within the Chukchi Sea and adjoining basin there is considerable diversity of both small and large jelly-fish, hydromedusae and ctenophores that are often overlooked (Raskoff et al. 2005 *accepted*): more than a dozen species were encountered in RUSALCA 2004 (Hopcroft and Kosobokova *accepted*). There were also considerable populations of larvaceans, particularly the large Arctic *Oikopleura vanhoeffeni* throughout the Chukchi area (Lane et al. 2008, Hopcroft and Kosobokova *accepted*). Larvaceans are increasingly implicated as key players in polar systems (e.g. Acuna et al. 1999, Hopcroft et al. 2005, Deibel et al. 2005) due to their high grazing and growth rates. At times, biomass of larvaceans rivals that of the copepods, particularly at ice-edge stations where some of the highest recorded densities for *Oikopleura vanhoeffeni* have been observed (Hopcroft and Kosobokova *accepted*). Shifts from copepod-dominated communities to larvacean-dominated ones can have large consequences for the export of phytoplankton to the benthos (Gorsky and Fenaux 1998, Alldredge 2005). The meroplanktonic larvae of benthic

Fig. 17. The ctenophore *Bolinopsis infundibulum* is a common zooplankton predator in the Arctic, but so fragile it does not survive collection with plankton nets (credit Russ Hopcroft/UAF and Kevin Raskoff /MPC)

organisms were also exceptionally common throughout the sampling region in 2004 (Hopcroft and Kosobokova *accepted*).

The spatial distribution of the zooplankton communities in the Chukchi Sea is known to be strongly tied to the different water masses present. Such patterns were first recognized qualitatively by Russian researchers as early as the 1930s (Stepanova, 1937a,b), and are to a large extent a continuation of patterns observed in the northern Bering Sea (see review by Coyle et al. 1996). These patterns were reiterated by later Russian studies (e.g. Pavshtiks 1984) that identified at least 3 water types in the region. Although the first years of the ISHTAR program were restricted to sampling in US waters, oceanic Anadyr waters, continental shelf and low-saline nearshore waters were all recognized (Springer et al. 1989). Cross-basin studies by the BERPAC program also identified 3 zooplankton clusters within the Chukchi Sea, but failed to articulate their species assemblages or associate them with specific water masses (Kulikov, 1992). In recent years, the wider availability of multivariate approaches to assess zooplankton communities has greatly facilitated the quantitative interpretation of community patterns and this approach is becoming increasingly standard (Fig. 18). Thus, the 2004 RUSALCA cruise also identified up to 7 assemblages of zooplankton, mostly of Bering Sea origin, that were strongly tied to water mass types (Hopcroft and Kosobokova,

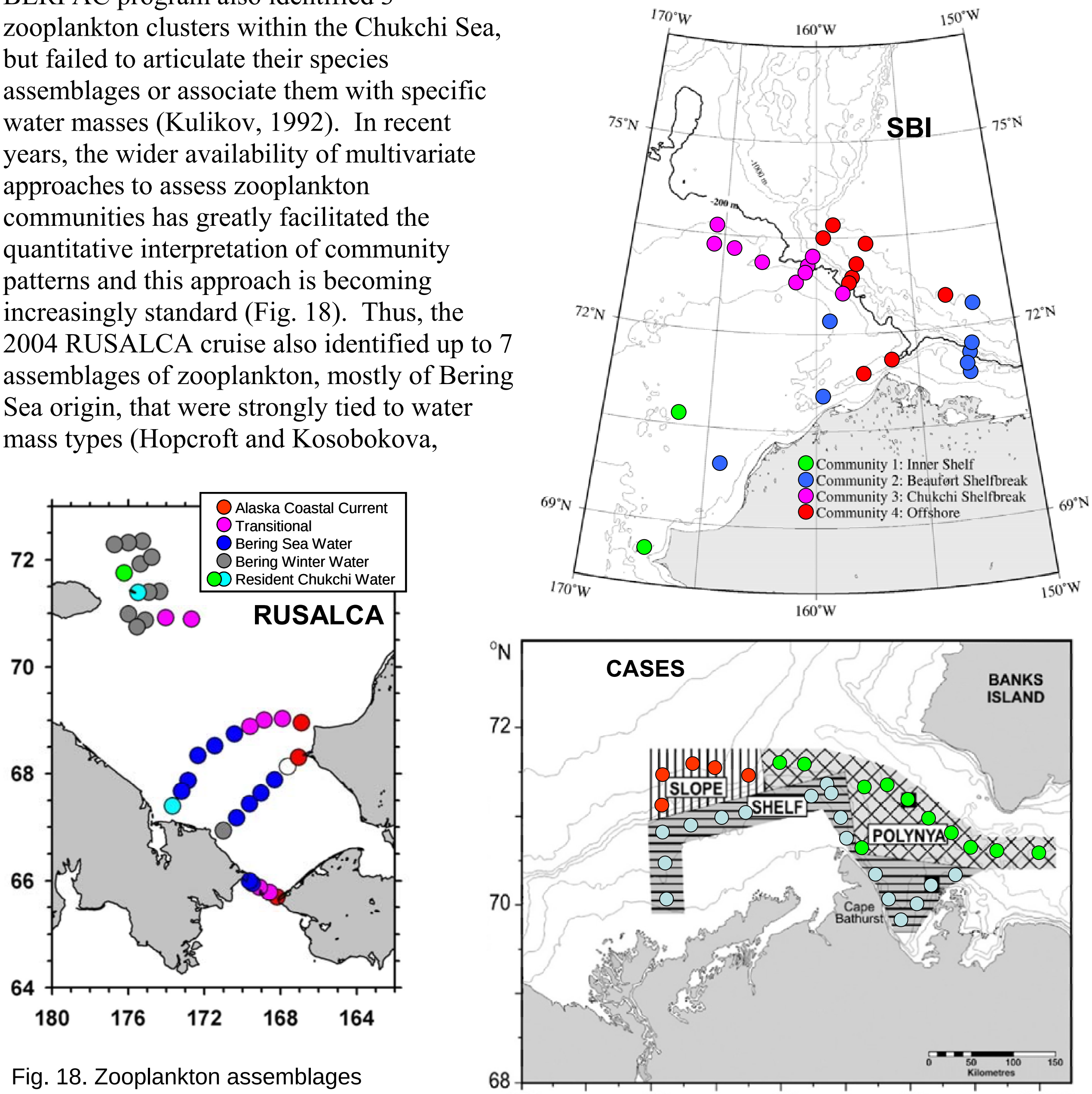

Fig. 18. Zooplankton assemblages identified by recent sampling programs

accepted), with concurrent sampling for ichthyoplankton showing remarkably similar patterns (Norcross et al. *submitted*). The SBI program identified 4 or 5 zooplankton community assemblages in the northeastern Chukchi (Lane et al. 2008), with some of Chukchi Sea and some of Beaufort Sea affinity. The CASES program, in the eastern Beaufort Sea found that in addition to the estuarine assemblage associated with the Mackenzie River plume (Grainger 1995), three distinct assemblages were delineated: a shelf assemblage dominated by *Pseudocalanus*; a polynya assemblage dominated by *Calanus hyperboreus*; and a slope assemblage characterized by carnivores (Darnis et al. *in press*). In contrast to the Chukchi Sea where water mass type was the strongest determinant of community structure, depth was the strongest determinant of the zooplankton assemblages in the CASES program, followed by the duration of the ice-free season.

Climate Change: Potential Effects on Zooplankton

The ongoing reduction of the sea ice cover will have major impacts 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 mesozooplankton. 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. Using polynyas as models of the future ice regime on Arctic shelves (Ringuette et al. 2002), the timing of recruitment and population development of *Calanus* and *Pseudocalanus* was advanced in the North Water Polynya relative to non-polynya waters, but not that of the smaller copepods (*Microcalanus pygmaeus, Oithona similis, Oncaea borealis*). They predicted that a climate-induced reduction of ice cover duration on Arctic shelves will favor the population growth of the predominant large calanoid copepods and *Pseudocalanus*. Similarly, under climate warming, the reduction of ice cover on the Mackenzie Shelf will affect zooplankton distribution patterns, to the potential advantage of *Pseudocalanus* spp. (Darnis et al. *in press*). Both Arctic cod (*Boreogadus saida*) and its congender the much larger Atlantic cod (*Gadus morhua*) prey primarily on the naupliar stages of *Pseudocalanus* during the larval stage (e.g. Michaud et al. 1996, Last 1980). Therefore, initially at least, a proliferation of *Pseudocalanus* should improve the early survival and population levels of the Arctic cod (Darnis et al. *in press*), thus improving food availability to vertebrate predators (seals, birds, whales), the majority of which feed primarily on this small fish (Welch et al. 1992). In the long-term, however, the reduction of the sea-ice cover is likely to bring about an “Atlantification” of the Canadian Arctic shelves and the replacement of the present Arctic cod-dominated ecosystem by an Atlantic cod-dominated ecosystem (Barber et al. 2006). There is limited indication as yet on how gelatinous zooplankton may respond to changes in ice cover, although larvaceans will likely increase in importance (Deibel et al. 2005) and other predatory groups may also increase (Mills 1995, 2001).

In terms of mechanisms, planktonic communities of the Chukchi Sea and, to a lesser extent, the Beaufort Sea could undergo climate related changes either through shifts in the absolute transport rate, and thus penetration, of Pacific species into the Arctic, or by environmental changes that ultimately affect their survival. It has been estimated that 1.8 million metric tons of Bering Sea zooplankton are carried into the Chukchi Sea, and partly on into the Beaufort Sea, annually (Springer et al. 1989) and that this, along with the entrained nutrients and phytoplankton communities, are responsible for the high water column and benthic productivity of the Chukchi Sea in comparison to adjoining regions of the Arctic Ocean (e.g. Plourde et al.

2005, Lane et al. 2008). During RUSALCA 2004 one would characterize the southern Chukchi zooplankton fauna as primarily Pacific in character, and there were clear signs that Pacific species were carried northward along the eastern side of Herald Valley. During the SHEBA drift, noticeable numbers of the Pacific copepod *Metridia pacifica* were observed over the Chukchi Plateau from February to June 1998 (Ashjian et al. 2003). Future increases in transport (Woodgate et al. 2006) could carry even more Pacific zooplankton through Bering Strait with even further penetration into the Arctic. In contrast, a reduction in transport of Bering Sea water would not only decrease the overall productivity of the Chukchi and western Beaufort seas, but give them a more Arctic Ocean faunal character. Thus, changes in the transport rates ultimately affect the species composition of this region as well as the absolute zooplankton biomass, and such shifts may result in changes in the size structure of zooplankton communities. Since most higher trophic levels select their prey based on size, the consequences of size-structure shifts could be more important than changes in zooplankton biomass (Lane et al. 2008).

Alternatively, we could envision that climate change could affect the survival of the Pacific species currently advected into the Arctic. It is generally believed that current Arctic temperatures are too cold for the long-term survival of many Pacific species, and that once transported into the Arctic Ocean, they are unable to establish viable populations (Smith and Schnack-Schiel 1990), and simply become sources of carbon for the resident communities (Grebmeier et al. 1995). While this generalization may apply to the large-bodied Pacific species, highly adapted to the seasonal cycles of the Pacific, the smaller-bodied forms (many of which are common to both the Bering Sea and Chukchi Sea) may remain viable in Arctic waters because they respond more directly to current environmental conditions (e.g. Hopcroft and Kosobokova *accepted*-b). Additionally, as smaller species typically grow faster and have shorter generation times than larger species (Hirst and Bunker 2003), we might expect them to represent a continual seeding of new production to the region. Long-term rise in mean temperature could eventually improve the survival of larger-bodied Pacific forms, to the point that they might form viable populations year-round in the Arctic, thereby shifting the advantage away from the smaller bodied forms, and creating competition with the resident species. Interestingly, egg production experiments conducted on the abundant *Pseudocalanus* copepods during RUSALCA suggested that the Pacific species in this genus are as productive in the Chukchi Sea during summer as are its Arctic equivalents (Hopcroft and Kosobokova, *accepted-b*). This has several implications: (1) weight per weight, Pacific species are equally fit as the resident species during summer, (2) changes in species composition *per se* need not necessarily alter the productivity of this system (provided biomass stays constant), and (3) because the Pacific species are smaller, their increased prevalence would influence the efficiency of coupling to higher trophic levels. Reproductive effort by species is also related to overall productivity regimes (Plourde et al. 2005, Hopcroft and Kosobokova, Hopcroft and Kosobokova *accepted-b*), and thus examining the reproductive potential of the dominant imported and resident species provides important insight into ecosystem function under climate change scenarios.

Finally, climate change could simply be non-selective in terms of species, and lead to increased or decreased rates of primary production in the Arctic. Increased rates of primary production, and/or a longer season over which production occurs should, in theory, support more zooplankton. Throughout the Arctic, we are hampered by lack of long-term data with which to access long-term trends, but several recent studies in this region and adjoining basins (Ashjian et al. 2003, Hopcroft et al. 2005, Lane et al. 2008) suggest abundance and biomass of copepods (and some other taxa) are higher than observed several decades ago, currently averaging from 3-

70 mg DW m^{-3} in the upper 100m compared to historical values of <1-3 mg DW m^{-3}.

In recent decades, zooplankton sampling efforts have concentrated mainly on the southeast Chukchi Sea, and neglected the less extensive Beaufort Sea, in part because its ice-free periods are shorter than in the Chukchi Sea. In general almost as much is known of the adjoining Canada Basin than of the Beaufort shelves, although the suggestion is that significant Beaufort data may exist for some groups as gray literature generated by agencies and consulting firms. The Beaufort is generally more dominated by true Arctic fauna, and is distinguished from the basin by a larger contribution of neritic than oceanic species. At present, our knowledge of this region is relatively dated (Redburn 1974, English and Horner 1977, Horner 1981, Horner and Schrader, 1984, Hopky 1994a-d), but data emerging from the SBI (Llinás 2007, Lane et al. 2008) and CASES (Darnis et al. *in press*) programs are improving our knowledge. In all regions, there is an increasing shortage of data outside the summer melt-back period (e.g. Forest et al. 2007, Seuthe et al. 2007), and many important processes, especially reproduction, occur well in advance of the summer in many species.

Regardless of the mechanisms leading to community shifts, it is important to note that these shifts may occur by displacement or replacement of Arctic species by closely related subarctic species. Often, the morphological differences between these species is minor, making definitive identification problematic (e.g. Plourde et al. 2005), and increasingly molecular techniques may be required to resolve these patterns (Hill et al. 2001, Lindegue et al. 2006). Proper validation and vouchering of taxonomic specimens become increasingly relevant under climate change situations (e.g. OCSEAP vouchers are housed at the California Academy of Sciences). Errors made in identification compromise our ability to see historical biogeographic patterns and how these may be changing over time. The Ocean Biogeographic System (OBIS: www.iobis.org) provides an example of this problem when one finds numerous older records of what is now considered "Atlantic" *Calanus* species in the Bering Sea. There is a clear need for continued rescue and digitization of older data to help resolve these long-term patterns, quality control of databases, and appropriate GIS software to visualize such distributions and trends. Co-operative efforts to this end are already underway (e.g. AOOS and ArcOD) and we encourage future efforts by NPRB to support such collaborative efforts.

Recommendations

- Now that some recent baselines have been established, it is critical that we establish long-term repeated measurements from the Bering Strait northward throughout the Chukchi Sea, and extending into the Beaufort Sea. Multiple net sizes and types will be required to fully access all zooplankton groups.
- Continued annual sampling at a series of fixed stations/transects during a consistent seasonal time-window is required to establish long-term and interannual trends.
- Observations must extend into the Russian EEZ. Several east-west transect lines such as Barrow to Wrangel Island (e.g. RUSALCA) in the Chukchi Sea, and several cross shelf transects in the Beaufort (e.g. from Prudhoe Bay) would be consistent with these needs.
- Detailed taxonomic/molecular analysis is necessary to resolve problematic species and voucher collections of specimens should be available for all studies.

- Consolidation of existing data into a central database is required, with funds available for data rescue. Retrospective analysis of existing collections should be performed where needed. [The Arctic Ocean Biodiversity (ArcOD http://www.arcodiv.org) and NMFS http://www.st.nmfs.gov/plankton/ are currently partnering in such efforts. Some data rescue is currently underway through NPRB funding.]
- There is useful agency- and industry-sponsored research that appears only in the grey literature: the general inaccessibility of this data is reflected in its absence from this synthesis. Such reports need to have their data rescued and be made electronically available.
- Process-oriented work is essential to establish the rates of growth, reproduction and grazing by keystone species, and how these relate to environmental variables (in particular temperature). The lack of basic information on growth rates and generation time of even the dominant species prevents us from even first order calculations of the productivity of Arctic communities.
- Year round sampling is needed to establish seasonal cycles of species and communities
- Overall, significant gaps still remain for understanding the abundance/ biomass/production of smaller species, meroplankton and more fragile soft-bodied species, and for the latter, even their taxonomic diversity. Better knowledge of meroplankton abundance and distribution is highly relevant to understanding recruitment to the rich benthic communities in this region. The benthic boundary layer may have a particularly rich assemblage of traditionally "planktonic" species, yet is virtually unstudied.
- Partnering with other agencies, programs and industry is suggested to address these goals.

BENTHOS

AUTHORS: Bodil Bluhm, Ken Dunton, Jackie Grebmeier, Boris Sirenko

Introduction

Benthic ecosystems in general integrate water column processes over longer periods than planktonic and sea ice communities (Piepenburg et al. 1997, Mincks et al. 2005) due to the relatively slow growth and high longevity of many polar benthic marine organisms (Brey and Clarke 1993, Arntz et al. 1994). Benthic organisms are, therefore, less affected by inter-annual variability or smaller-scale fluctuations in water column productivity than the pelagic, usually shorter-lived fauna (Carey 1991). Hence, benthic fauna indicate interannually persistent sites of carbon deposition versus food-limited regions (Grebmeier et al. 2006b) and are, therefore, a useful indicator of potential change in a system. Long-term changes due to climatic impacts are likely to be reflected in the benthic community on temporal scales of years to decades (Piepenburg et al. 2001, Dunton et al. 2005).

Fig. 19: Typical Chukchi Sea benthos. Top: Epi(mega)fauna from hard bottom. Middle: Epi/megafauna from soft bottom. Bottom: Macro(in)fauna. Photos: Bodil Bluhm, UAF.

Major environmental determinants of Arctic benthic community structure on a pan-Arctic scale include food supply (Hobson et al. 2002, Iken et al. 2005), substrate type and grain size (Klages et al. 2004), salinity (Jørgensen et al. 1999, Deubel et al. 2003), temperature (Dayton 1990, Pörtner and Playle 1998) and, in shallow water, ice scouring (Conlan and Kvitek 2005). Benthic food supply originates in surface waters and is highly seasonal in the Arctic (Michel et al. 2002, Wassmann et al. 2004). Densities of sedimenting particles and their nutritional values range vastly from the nutrient rich waters of the northern Bering and Chukchi seas (Fukuchi et al. 1993, Springer et al. 1996) to the oligotrophic deep waters of the Arctic basins (Hargrave 2004). In general, however, comparisons of energy fluxes showed that the benthic systems receive more energy in Arctic than temperate and tropical systems (Petersen and Curtis 1980), although there are significant regional differences within the Arctic itself. Settling food particles add to the soft sediments predominating in the Arctic (Naidu et al. 1993, Jorgensen and Brown 2005). Grain size of these sediments, along with the above listed factors, determines faunal community composition (Grebmeier and Barry 1991, Feder et al. 1994b). Exceptions to the soft bottom sediment regions in the focus area are local accumulations of boulders in the Beaufort Sea (Dunton et al. 1982), nearshore coastal regions, Barrow Canyon (and other canyons) and portions of Bering Strait. In near-shore areas, benthic biomass and diversity intermittently decline due to ice-scour resulting in a patchwork of different successional stages (Conlan and Kvitek 2005). In addition, nearshore areas are under the influence of freshwater run-off, particularly in the Beaufort Sea (Wacasey 1974). Low numbers of euryhaline and brackish water benthic species, some particularly well adapted to high sedimentation rates, dominate the shelf regions in estuaries (Deubel et al. 2003) where benthic biomass can be lower than under fully marine conditions (Jørgensen et al. 1999).

Current Knowledge: Benthos in the Beaufort and Chukchi Seas

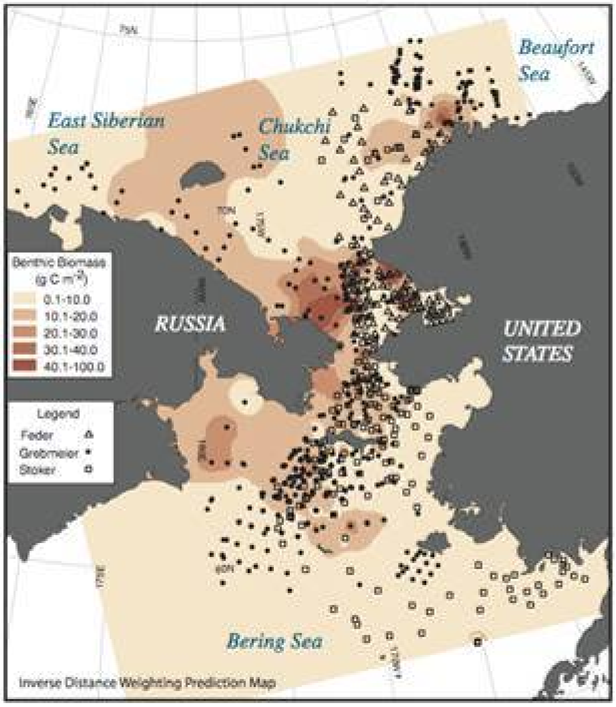

Fig. 20: Benthic biomass distribution in the Chukchi and northern Bering Seas. (From Grebmeier et al. 2006b.

Much of the broad, shallow shelf of the Chukchi Sea is strongly influenced by northward flowing nutrient-rich Pacific water through Bering Strait (Coachman et al. 1975, Springer and McRoy 1993), resulting in regionally very high benthic biomass, which is among the highest worldwide in soft-sediment macrofaunal communities (Grebmeier et al. 2006b; Fig. 20). Specifically, the south-central Chukchi Sea has the highest algal and faunal biomass on the combined Bering Sea shelf and southern Chukchi Sea (Walsh et al. 1989, Springer et al. 1996, Grebmeier 1993, Feder et al. 2007). Depth-integrated chlorophyll *a* was as high at 500-1000 mg chlorophyll *a* m^{-2} and oxygen uptake rates of the sediment were also high, with peak values up to 40 mmol O_2 m^{-2} day^{-1} (Grebmeier and McRoy 1989, Grebmeier 1993, Grebmeier and Dunton 2000). This efficient uptake is the result of tight benthic-pelagic coupling driven by large sedimentation of the often advected organic matter from the water column supporting a high biomass of benthic fauna, with macro-infaunal biomass reaching 25-60 g C m^{-2} (Grebmeier et al. 1988, Grebmeier et al. 2006b). High epibenthic abundance and biomass have also been reported from this area (up to 53,000 individuals km^{-2}; >2,000 kg wet weight km^{-2}; Feder et al. 2005, Bluhm et al. *in prep*.), although even higher values were measured near Point Hope and towards Kotzebue Sound, respectively (Feder et al. 2005). A hydrographic front in this region appears to be influential for the high production on the Bering Shelf Anadyr Water side (Feder et al. 2005, Grebmeier et al. 2006b, Bluhm et al. 2007). These rich benthic communities, tied to high pelagic production and advection, serve as prey for a range of diving sea birds and marine mammals (Feder and Jewett 1981, Oliver et al. 1983, Lovvorn et al. 2003), a key feature of the productive Chukchi Sea. Under the Alaska Coastal Current in the eastern Chukchi and under Bering Shelf Water in the NW Chukchi, benthic biomass is variable, but overall lower (range <10 g C m^{-2}, Sirenko and Gagaev 2005, Feder et al. 2006) and coupling to the water column is less tight (Dunton et al. 2006, Iken et al. in revision).

Close to 1200 species are known from the Chukchi Sea fauna to date (Sirenko 2001; note, however, that few microbial and meiofaunal species are included in this species inventory) with amphipods, clams and polychaetes dominating infaunal community biomass (Grebmeier et al. 1989, Feder et al. 1994a, b, 2007, Sirenko 1998, Sirenko and Gagaev 2007). Important macrofauna prey species for higher trophics include bivalves taken by walrus, in particular *Macoma* spp. and *Mya truncata (*Oliver et al. 1983*),* and benthic amphipods utilized by gray whales and bearded seals (Bogoslovskaya et al. 1981). 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 also locally common (Sparks and Pereyra 1960, Jewett and Feder 1981, Sirenko and Koltun 1992, Feder et al. 1994a, Ambrose et al. 2001, Feder et al. 2005, Grebmeier et al. 2006: Table 4, Bluhm et al. *in prep*.). Compared to other Arctic seas, the Chukchi Sea houses the highest proportion of Pacific-boreal species (27% according to Dunton 1992); this number can be expected to increase with climate warming (see below).

The comparatively narrow Beaufort Sea shelf, in contrast, is highly influenced by large freshwater inflow and, with it, suspended matter from small rivers, and the Colville and Mackenzie Rivers and the permafrost, resulting in estuarine conditions at least in nearshore areas (Wacasey 1974, Norton and Weller 1984, Dunton et al. 2006). The Beaufort Sea seafloor is dominated by soft sediments (Barnes and Reimnitz 1974), 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 (Dunton et al. 1982). 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 (Craig et al. 1984). Compared to the Chukchi Sea, the *in situ* productivity and benthic biomass in the Alaskan Beaufort Sea are dramatically lower (Fig. 21) (Dunton et al. 2005). Consequently, benthic-

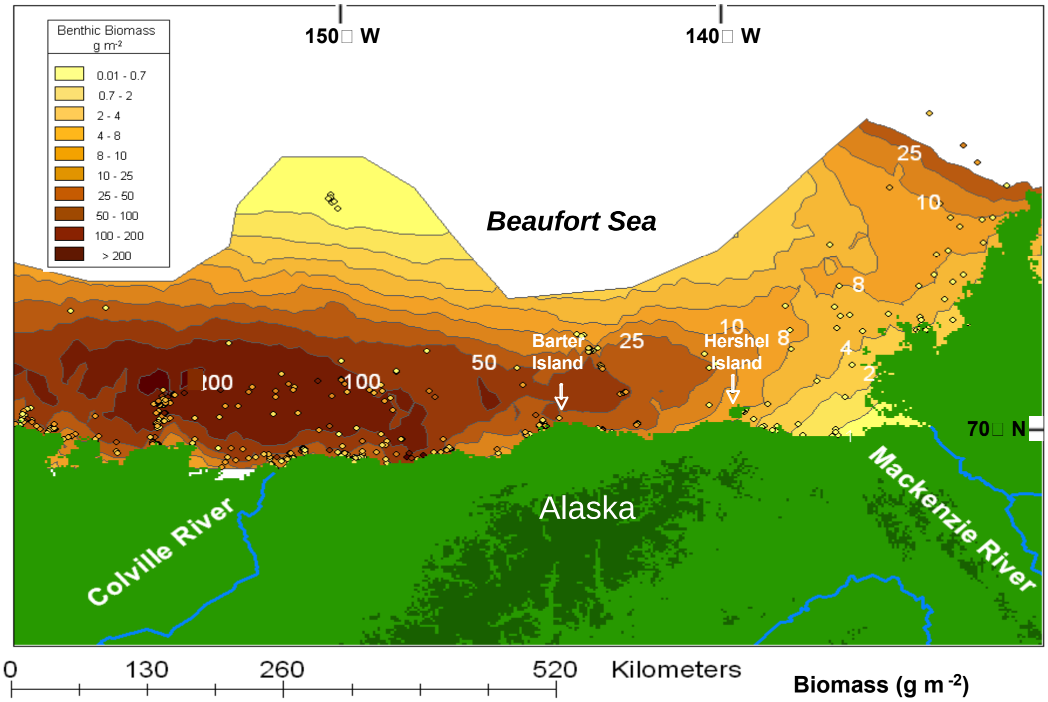

Fig. 21. Benthic biomass distribution in the Beaufort Sea. (From Dunton et al. 2005)

pelagic coupling is not as pronounced as in the Chukchi Sea and food chains are longer (Dunton et al. 2006). Areas very close to shore are depleted in benthic faunal biomass and species richness, especially infauna, due to ice-scouring (Feder and Schamel 1976, Conlan and Kvitek 2005) and low salinity conditions (Wacasey 1974, 1975). The decreasing influence of advective influx of nutrient-rich Pacific waters towards the east is reflected in declining benthic infaunal biomass towards the eastern Alaskan Beaufort Sea (from over 100 g m^{-2} to less than 10 g m^{-2}; Fig. 21; Carey et al. 1974, Carey and Ruff 1977, Dunton et al. 2005). Although the importance of terrigenous carbon from river runoff in nearshore systems is still debated, non-marine sources of carbon may play an increasingly important role for the benthic foodweb in parts of the nearshore Beaufort Sea outside the Pacific-influenced area (Parsons et al. 1989, Dunton et al. 2006). Lower quality terrestrial carbon limits benthic production, although areas with higher bacterial content may provide an additional organic carbon source that promotes patches of higher prey production. This working hypothesis is based on: (1) sediment stable isotopic data showing the presence of terrestrial organic matter along the Alaskan Beaufort Sea coast and onto the inner shelf (Naidu et al. 2000); (2) faunistic stable isotope signatures from lagoons and the nearshore Mackenzie Shelf indicating terrigenous carbon utilization (Parsons et al. 1989, Dunton et al. 2006); and (3) current research by Warwick and Lovejoy (Laval University) highlighting the contributions of microbes attached to terrestrial sediments as potential sources of organic carbon for marine ecosystems. The scientists contributing to this report had different opinions about the potential role of terrestrial carbon which reflect the need for further research.

The decreasing influence of Pacific water is also reflected in the lower proportion of Pacific-boreal species present, relative to the Chukchi Sea (15% according to Dunton 1992, but note that this number needs updating). The benthic communities in the sandy, silty or muddy sediments contain a low diversity infauna, dominated by bivalve mollusks, polychaete worms and amphipods (McGinitie 1955, Wacasey 1974, Feder and Schamel 1976, Carey and Ruff 1977, Carey et al. 1984, Sackmann 1987). Lowest species richness was found nearshore in estuaries (Wacasey 1975). Abundant fauna in the coastal lagoons investigated include polychaetes and bivalves, amphipods, isopods and hyperbenthic mysids, although infaunal taxa are limited to the deepest portions of the lagoons, since shallow areas freeze solid during the winter (Craig et al. 1984). Epimegafauna data are very sparse in the Alaskan Beaufort Sea. Isopods, mysids and amphipods were dominant at a few locations near the Colville River mouth with highest abundances seaward of the lagoons (Crane 1974) and echinoderms, especially brittle stars, dominated the shelf further offshore (Carey 1976). Epifaunal communities in the Canadian Beaufort Sea were dominated by locally very abundant ophiuroid beds and, at other locations, by epifaunal amphipods (Renaud, Aitken, Conlan, unpubl.), isopods, anemones and seastars (Wacasey et al. 1977). Amidst these soft-bottom communities, local patches of boulders provide for abundant and diverse marine life through hard substrate availability for macroalgae and sessile epibenthic macrofauna (Dunton et al. 1982, 1984). The only well-studied boulder area in the Chukchi/Beaufort seas complex is the Boulder Patch in Stefansson Sound located adjacent to the oil production areas of Prudhoe Bay where sessile fauna such as sponges, encrusting bryozoans, hydroids, soft corals, tube worms, and others thrive on the rocky and macroalgal substrates (Dunton et al. 1982, Dunton 1992, Iken and Konar 2002, Konar 2003). Recolonization of these boulders after disturbance is apparently very slow (Konar 2007).

Much less is known about the slopes of the Chukchi and especially the Beaufort Sea, and about the adjacent basins. The existing investigations of the slopes and abyssal infaunal benthos in the western Arctic revealed low abundances (<100-8,000 individuals m^{-2}) and biomass values

(<8 g wet weight m^{-2}) relative to the shelves, especially with increasing water depth and distance from the shelves (Paul and Menzies 1974, Carey and Ruff 1977, Clough et al. 1997 and 2005, Bluhm et al. 2005, Grebmeier et al. 2006b, MacDonald et al. *submitted*). More data for the Chukchi Sea slope and the Mackenzie slope will become available in the next years as SBI and CASES results are published (e.g. Grebmeier et al., Conlan et al. *in press*). 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 (Sirenko 2001, Bluhm et al. 2005).

Highlighting Key Findings of Arctic Benthic Research with a Regional Focus on the Chukchi and Beaufort Seas (not prioritized)

- The degree of *pelagic-benthic coupling* in Arctic regions is a key determinant for benthic biomass, and it directly influences benthic community abundance and biomass. In the Chukchi Sea under the nutrient-rich Pacific waters, pelagic-benthic coupling is very tight, resulting in short food webs and high benthic biomass (Grebmeier and Barry 1991, Grebmeier et al. 2006b); the situation appears to be similar in parts of the Canadian Beaufort Sea (Renaud et al. pers. com.). Pelagic-benthic-coupling is less pronounced under the Alaska Coastal Current and in the nearshore waters of the Alaskan Beaufort Sea. These nutrient-poor waters are less productive and food chains linking the water column to the benthos are more complex and lengthy (Grebmeier et al. 1989, Grebmeier and Dunton 2000, Dunton et al. 2006).
- Linked to the above point, *tight cryo-benthic coupling* with fast sedimentation of early production related to sea ice (ice algal production, phytoplankton production in leads, polynyas and marginal ice zones) contributes to benthic nutrition, fast C-incorporation and carbon cycling/O_2 demand (Ambrose et al. 2005, McMahon et al. 2006, Renaud et al. 2007). In addition, larvae and juveniles of benthic invertebrates utilize the sea ice as a feeding habitat (Carey and Montagna 1982, Gradinger and Bluhm 2005).
- *Advective transport* of food resources plays a significant role in supporting benthic biomass in several Arctic Seas (Feder et al. 1994a, 2007, Dunton et al. 2005, Grebmeier et al. 2006b). In the Beaufort / Chukchi system, the nutrient-rich Anadyr water northward transport supplies especially the southern Chukchi Sea, but extends into the western Beaufort Sea. Advective off-shelf transport carries organic matter down the Chukchi slope into the deep basin, e.g. through Barrow Canyon (DSR II, special issue 2005, e.g. Cooper et al. 2005, Moran et al. 2005; more SBI and CASES results on this are forthcoming).
- *Resource partitioning* studies of energy flow through the benthic communities suggest that the often-overlooked benthic epifauna (also referred to as benthic megafauna) need to be considered in overall benthic energy budgets and models of carbon cycling. This appears to be true for both Arctic shelf systems that are commonly inhabited by abundant echinoderm populations, especially ophiuroids (Piepenburg 2000, Ambrose et al. 2001, Feder et al. 2005), and the adjacent deep-sea (Iken et al. 2005, MacDonald et al. *submitted*).
- In contrast to previous assessments summarizing the Arctic as having poor *biodiversity* in association with the concept of latitudinal biodiversity clines, Arctic and Antarctic waters seem to be characterized by intermediate species richness on a global scale (Gutt et al.

2004). Recent Census of Marine Life-related and other studies in the Chukchi Sea and adjacent Canada Basin demonstrate that a biodiversity inventory is not yet complete (Sirenko 2001, 2006, Bluhm et al. 2005, Renaud et al. 2006, Gagaev 2008). As driving forces for benthic biodiversity, habitat heterogeneity, food supply, evolutionary factors, disturbance and other factors have been documented (Gray 2002, Gage 2004, Renaud et al. 2006).

- Benthic biomass and community structure appear to have different *major environmental determinants*. Arctic benthic biomass is largely driven by carbon supply but community structure can be dependent on bottom structure, current conditions, and other physical forces (Grebmeier et al. 1989, Grebmeier and McRoy 1989, Feder et al. 2005, 2007).
- *Regional differences*. Environmental settings such as ice cover, impact of fluvial run-off, pelagic production regime, strength of pelagic-benthic coupling and, hence, food supply to the benthos vary greatly among the various Arctic seas, impeding the up-scaling of local and regional findings (Klages et al. 2003, Piepenburg 2005). Hot spots in the Beaufort / Chukchi seas include the southern Chukchi Sea; Barrow, Mackenzie and Kugmallit Canyons (Clough et al. 2005, Grebmeier et al. 2006a, b, Conlan et al. 2006), and near Barter Island (Dunton et al. 2005).
- Evidence of *long-term change* finds expression in Arctic benthic communities. Potential evidence includes infaunal biomass declines, epifauna biomass increases, community shifts, and suspected northward species range extension in the Chukchi Sea (for details and references see next section). These changes have at least partially been attributed to regime shifts and long-term climate change, although other factors may also play a role.

Important reviews about the benthos in the Chukchi and Beaufort seas were recently prepared by Grebmeier et al. 2006b and Dunton et al. 2006, respectively. Relevant reviews on Arctic and polar benthos are in Dayton et al. (1990) and Piepenburg (2005).

Potential and Documented Impacts of the Ongoing Arctic Change

From a benthic perspective, most likely and partially already documented changes in the Arctic include changes that influence benthic communities, and changes in the benthic realm itself. *Habitat changes* include climate warming (Grebmeier et al. 2006a), reduced ice cover (Parkinson et al. 1999, Serreze et al. 2003), longer open water season (Stroeve et al. 2005), changing volume flux through Bering Strait (Woodgate et al. 2006), increased frequency and intensity of storms (Clark and Serreze 2000), increased river and freshwater run off (Peterson et al. 2002, Dyurgerov and Carter 2004), and increased ice scouring and coastal erosion (ACIA 2004). The recent ACIA (2004) report is a valuable and detailed source of information about observed and predicted changes in the Arctic in general.

Recently, several studies documented *changes in benthic biomass* occurring over the past decades. Under the nutrient-rich Anadyr / Bering Shelf Waters, infaunal ampeliscid amphipod biomass declined in the Chirikov Basin (Moore et al. 2003, Coyle et al. 2007) and infaunal biomass declined south of St. Lawrence Island (Dunton et al. 2005, Grebmeier et al. 2006a). Smaller scale studies, however, documented higher infaunal biomass in the 2000s versus the 1970s/1980s in the same areas (Wenzel 2007, Merrill et al. unpubl.). Epifauna biomass, in contrast, increased under the influence of the Alaska Coastal Current in Norton Sound

(Hamazaki et al. 2005) and Kotzebue Sound (Feder et al. 2005) as well as in the (heavily fished) southeastern Bering Sea (Conners et al. 2002). Biomass decline was also reported from the ongoing CASES study in the Beaufort Sea in the zone of ice scour at depths <55 m (Aitken and Conlan, pers. com.). These changes have at least partially been attributed to regime shifts and long-term climate change, although other factors may also play a role.

Several authors have proposed that the currently benthos-dominated Arctic shelves with tight *cryo-pelagic-benthic coupling* may be replaced, as a result of climate warming, by systems that are dominated by water column communities (microbial and zooplankton) and processes (Fig. 22; Carroll and Carroll 2003, Piepenburg 2005, Grebmeier et al. 2006b, Bluhm and Gradinger 2008). Higher trophic level consumers currently exploiting benthic resources, such as diving ducks (Lovvorn et al. 2003), walrus (Oliver et al. 1983), gray whales (Bogoslovskaya et al. 1981) and bearded seal (Lowry et al. 1980) would likely be strongly affected by such a shift (Laidre et al. 2008, Bluhm and Gradinger 2008).

Benthic community changes, such as switches from long-lived slow-growing Arctic to faster-growing temperate species, can be expected in the southern areas of the Arctic. Suspected northern range extensions, possibly due to climate change, have recently been documented in the Chukchi Sea for some epifaunal megafauna (Sirenko and Gagaev 2007). Other species shifts were noted for bivalves (Richman and Lovvorn 2003). Future or ongoing changes related to increased freshwater discharge, increased turbidity and sedimentation, and increased influx of low salinity waters are conceivable (Bluhm and Gradinger 2008).

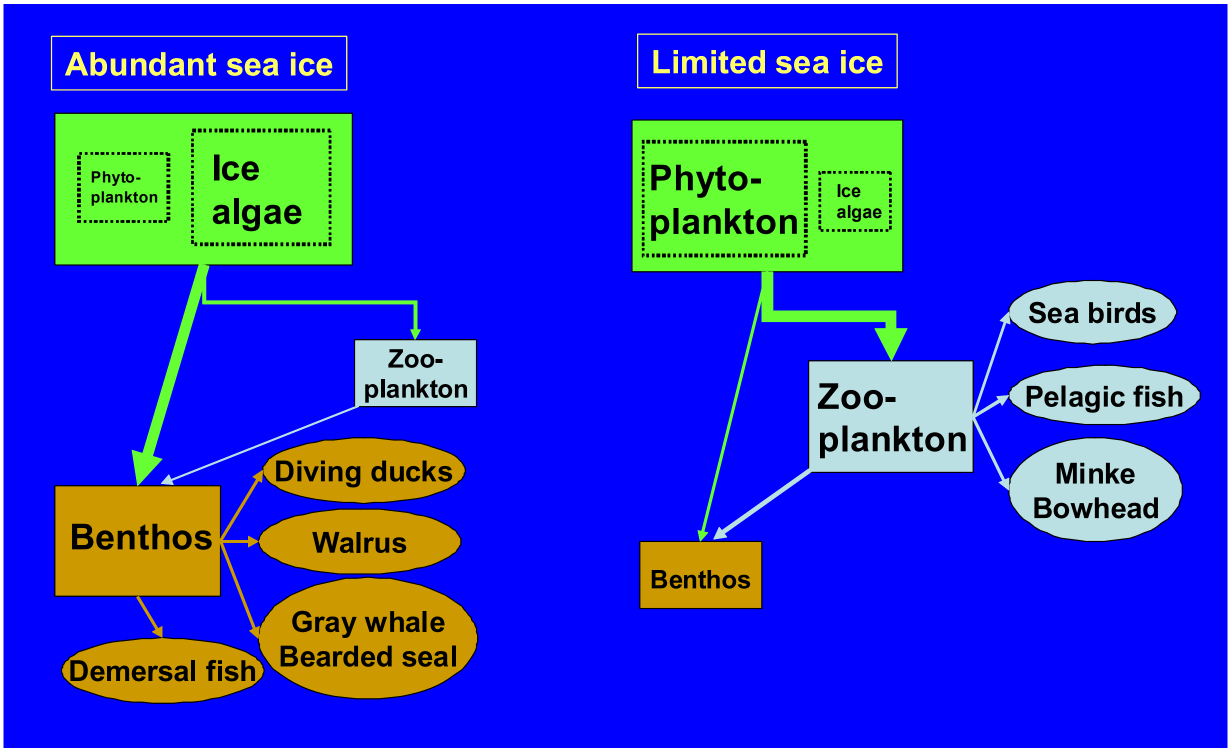

Fig. 22. A change in ecosystem structure that may result from changes in sea ice and seasonal cycles of temperature in the Chukchi and other Arctic marginal seas (Adapted from Caroll and Caroll 2003)

Most Important Information Gaps

Although a considerable number of benthic studies have been conducted in the Chukchi (summary in Grebmeier et al. 2006b) and Beaufort Seas (Dunton et al. 2005) in the last decades (with more SBI, CASES, RUSALCA, as well as individual publications forthcoming in the coming years), the most obvious important need is collecting *long-term time series* in consistent areas with consistent parameters measured. In contrast to physical and chemical oceanographic variables, it has so far been very difficult and from a practical standpoint, virtually impossible to collect benthic data from moored instruments or other observing systems; many benthic measurements still require costly field expeditions. (However, observations from moored instruments from other disciplines are very valuable in terms of interpreting benthic findings). Benthic monitoring should ideally be undertaken annually, or at least biannually or every 3 years to be able to separate short-term variability from long-term change. In addition, *seasonal gaps*, in particular winter measurements, need to be filled. Areas that should be monitored are discussed in the recommendations section.

Besides these temporal gaps, *geographic gaps* in which few or no benthic measurements have been collected need to be filled. These include: the Alaskan eastern Beaufort Sea, the Alaskan Beaufort Sea slope, the NW/W Chukchi Sea including Herald Valley and Long Strait, and much of the nearshore areas of the Chukchi and Beaufort Seas.

Taxonomic gaps occur not only in the geographic gaps, but also in otherwise well-studied areas. To assess community changes, range extensions and the role of different functional and taxonomic groups, a more complete inventory of the benthic fauna in all size classes is necessary including estimates of their genetic diversity. Dominant species in the infauna and the epifauna are known, but we lack knowledge of specific geographic distributions (see *geographic gaps*). Microbial and meiofaunal communities are poorly known (Steward et al. 1996, Shirley and Storch 1999). Modest efforts to fill some of these gaps are underway by the ArcOD CoML and related projects.

Basic biology such as life cycles, larval stages, development and growth rates, is unknown for even the common taxa such as polychaetes, bivalves, amphipods, ophiuroids and sea stars. The few studies on Arctic invertebrate population dynamics suggest low growth rates and high longevity (e.g., Bluhm et al. 1998).

The *role of terrestrial carbon* in Arctic benthic food webs remains unclear (see above). While terrestrial carbon has long been thought to be largely unavailable to the food chain beyond bacteria, recent studies in the lagoon systems of the nearshore Alaskan Beaufort Sea (Dunton et al. 2006) suggest that this may not be the case, at least not in nearshore areas and/or lagoons. With increasing erosion and river run-off, the degree of availability of terrestrial carbon to benthic communities may be of major importance with respect to the future productivity of Arctic coastal areas. The degree of importance would be expected to vary with terrestrial carbon source location and the importance of other sources, all of which should be quantified. Microbial processes should also be studied in this context.

Along the lines of the previous point, our knowledge of *coupling mechanisms and linkages* needs to be complemented, e.g. in terms of the contribution of ice algae to benthic food supply, benthic macrofauna (infauna) to megafauna (epifauna) biomass relationships, nearshore-offshore coupling etc.

All the above information including their natural variability needs then to be combined to assess *climate change effects and their mechanisms* on an ecosystem level.

Operationally, a two system approach would be appropriate: shelf studies versus nearshore studies. The nearshore areas are particularly influenced by the increasing amount of river run-off, while large areas of the offshore shelf waters are critically influenced by the Pacific waters flowing northward.

From a benthic perspective, major questions to be addressed in the coming years could include:

- What are the key environmental determinants for the Chukchi vs Beaufort seas that are of highest sensitivity to climate forcing and thus ecosystem change?
- What are the effects of changes in the Pacific inflow on the benthos in the Chukchi and Beaufort Seas?
- What are the quality and fate of carbon from rivers and permafrost for the benthos and how will it change?
- What impact will warming have on the carbon cycle and benthic communities nearshore versus offshore?

Recommendations

- **Partnering with other agencies and programs:** Several ongoing US and international programs are already working on filling some of the gaps. Since no one program or funding agency will be able to address all the above gaps within their funding capabilities, we recommend that NPRB partner with other agencies in the framework of their ongoing and future programs in the Chukchi and Beaufort Seas. Partnering could, for example, be achieved through co-funding expeditions, through contributing ship time and / or individual projects of programs, or by focusing on particular target parameters that complement other efforts. An example of such a collaborative program is the ongoing BEST-BSIERP research in the Bering Sea.
- The Shelf-Basin Interactions Program (SBI) and Canadian Shelf Exchange Study (CASES) focus on the linkages between the Chukchi shelf and the Arctic Basin (SBI) and the McKenzie shelf and the Arctic Basin (CASES) in a climate change context. Many of the below listed parameters to be measured were indeed measured in certain areas during the field seasons of 2002-2004. The Russian American Long-Term Census of the Arctic (RUSALCA) is set up to monitor climate change effects with an ecosystem approach in the Chukchi Sea. MMS conducted a fish and habitat survey in the Beaufort Sea in 2008. The Arctic Ocean Diversity project of the Census of Marine Life, with support from various agencies, seeks to improve the biotic inventory of the Arctic by 2010. Upcoming expeditions into the Chukchi and Beaufort Seas that will survey benthic communities include RUSALCA (NOAA; 2009 and 2012 cruises planned) and other NOAA activities, SNACS and its successor (NSF, Beaufort Sea field work, 2006-?), AK-EMAP coastal survey in the Chukchi Sea (EPA, 2009) and oil and gas exploration-related surveys in 2008 and 2009 (NE Chukchi Sea lease area).. Other nations currently active in the Beaufort and Chukchi Seas include Japan (*Oshoro Maru* and *Mirai* cruises to the Chukchi Sea 2007 and 2008), China (*Xue Long* cruise 2008), Canada (icebreakers in the Beaufort Sea usually

every year) and probably others.

- **Time series at 'pulse points'**: Regional pulse points for regular monitoring should include the biomass hotspots in the southern Chukchi Sea (Hope Basin), Barrow Canyon and the Barter Island area (and/or areas on the Mackenzie shelf in collaboration with Canadian researchers). Secondly, source areas of organic carbon and inorganic input should receive special attention such as the inflow of nutrient-rich Anadyr water through Bering Strait and river and permafrost run-off along the coastlines. The importance lies in regular sampling of the same areas to establish long-term time series.
- **Consistent parameters for monitoring:** From a benthic perspective, parameters to be monitored on a continuous basis include those required from other disciplines and those benthic researchers would measure themselves. Parameters from other disciplines required to interpret benthic data in an ecosystem context include temperature and salinity throughout the water column, current speed and direction, ice extent and thickness, chlorophyll/phaeopigment concentrations in ice and water column, primary productivity in ice and water column, water column C/N ratios, nutrient concentrations, turbidity, POC and DOC pools, transient tracers to follow materials and /or water masses (such as stable isotopes) and zooplankton biomass.
- Parameters measured by benthic researchers should include those focusing on inventories and distributions and those focusing on processes. The former should include species richness and composition, species and community distribution, abundance, and biomass (infauna, epifauna). In addition, sea bottom characteristics such as sediment grain size, total organic carbon, sediment chlorophyll phaeopigments and sediment C/N ratios should be measured routinely. Benthic processes to be monitored should include sedimentation from the water column to the benthos, carbon turnover (through O_2 uptake of total sediment community, infauna and selected megafauna), stable isotope signatures of end members and fauna, utilization of marine versus terrestrial carbon, and sediment-nutrient regeneration. In the nearshore, UV intensity measurements would be useful also.
- **Integration with other disciplines:** The benthic system is one of several ecosystem components. For a comprehensive integrated ecosystem-based assessment, benthic field projects and results need to be integrated with results from other disciplines, in particular physical, chemical and biological oceanographic measurements (see parameters required from other disciplines). Benthic results themselves are required in the context of food web studies (in particular with regards to diving sea birds, demersal fishes and benthic-feeding marine mammals) as well as for use as system-level indicators of long-term oceanographic conditions. In expeditions that are not interdisciplinary, benthic studies should attempt to measure as many of the above parameters as possible. We strongly recommend NRPB undertake multi-disciplinary integrated efforts with an ecosystem-level approach.
- **Central data archiving and integration:** In order to make more efficient, quantitative and analytical use of data produced over time, data archiving is essential in publicly accessible data archives. A dedicated and appropriately funded effort needs to be made to assemble historic benthic data and, along with newer data, integrate the results using modern analytical tools such as GIS models. The ArcOD-CoML database could serve as a basis for the faunistic side of such an effort.

FISHES

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Introduction

As in the rest of the world's oceans, fishes in the western Arctic Ocean and its marginal seas, including the Chukchi and Beaufort Seas, are the primary consumers of the lower invertebrate trophic levels, and are predators within their own guild. In turn, they constitute an important prey source for seabirds and marine mammals. Despite their considerable ecological importance, the fishes inhabiting the Arctic Ocean and its seas are understudied and available information is scant compared to neighboring areas. Short ice-free periods, remoteness and logistical difficulties, plus the lack of substantial commercial fisheries, other commercial use of the Arctic, low human population, and political boundaries between Russia, the United States, and Canada have limited the accumulation of basic knowledge on biodiversity and on the biology, habitat, distribution, and abundance of individual species of fish. Virtually all standard fish sampling techniques are either non-operational or relatively ineffective during times of ice-cover. Not surprisingly, we know the most about species that move in and out of rivers (salmons, trouts, whitefishes) because of the logistical practicality of sampling during such migrations. This practicality is also heavily correlated with the species that are harvested for commercial or subsistence purposes, further motivating the study of such "useful" species by both government agencies and industry.

Fig. 23. The catch from a typical trawl in the Chukchi Sea showing several fish species mixed within a collection dominated by invertebrates (Credit Sarah Mincks/UAF)

Sampling and Study History

Several late 19th century expeditions of discovery, both land-based and ship-based, collected scientific information on the fishes of the western Arctic, and their samples were archived in museums for documentation and research. Bean (1883) listed 21 species known to occur in the Arctic Ocean north of Bering Strait based on the holdings of the US National

Museum. Included were collections made in Alaska in Bering Strait and near Kotzebue Sound, Cape Lisburne, Cape Sabine, Icy Cape, Point Belcher, and Point Barrow in 1880 by the US Coast Guard Survey schooner *Yukon*, and in 1881 by the US Revenue cutter *Corwin*. The US Army Signal Corps' international polar expedition collected fishes in the neighborhood of Point Barrow, reporting 18 species in the open-water season, almost all obtained from the natives fishing through the ice (Murdoch 1885). In 1896, the ichthyological team of Scofield and Seale took passage on vessels of the Pacific Steam Whaling Company to collect fishes at Port Clarence and Point Barrow, Alaska, and Herschel Island in the western Canadian Beaufort Sea (Scofield 1899). All of the early Arctic marine fish studies were restricted to nearshore waters.

Fishes were not sampled in the offshore and deep waters of the western Arctic until much later than in nearshore waters. Andriashev (1937) reported on fishes collected in 1932 and 1933 on two Soviet expeditions covering the northern Bering Sea, the coast of the Chukchi Peninsula, and entire Chukchi Sea. Other notable Arctic fish collections include those of Barsukov (1958) from the nearshore and intertidal waters of Provideniya Bay, Chukchi Peninsula. Walters (1955) reported on collections of fishes made in the vicinity of Point Barrow, Alaska, in the late 1940s. Alverson and Wilimovsky (1966) and Quast (1972) conducted trawl surveys in the eastern Chukchi Sea south of Icy Cape in 1959 and 1970, respectively, and Frost and Lowry (1983) sampled by bottom trawl offshore of Icy Cape, Chukchi Sea, to the US-Canada border in the Beaufort Sea in 1976-1977. Fechhelm et al. (1985) surveyed nearshore waters of the northeastern Chukchi Sea. Barber et al. (1994, 1997) conducted fisheries oceanography investigations of the offshore and nearshore waters of the northeastern Chukchi Sea in 1989-1991. Hokkaido University (1991, 1992, 1993) conducted fisheries investigations of the northern Bering Sea and both the southeastern and northeastern Chukchi Sea in 1990-1992, but the collections have not been reviewed and reported in the literature. Results of benthic and pelagic fish sampling in Bering Strait and both the eastern and western Chukchi Sea conducted by the RUSALCA program in 2004 have recently been made available or published (Mecklenburg and Sheiko 2006, Mecklenburg et al. 2007, Norcross et al. 2006), or submitted for publication (Norcross et al. *submitted*).

The offshore Beaufort Sea has been almost unsampled by ichthyological and fisheries oceanographic expeditions. Jarvela and Thorsteinson (1999) sampled offshore waters of the central Beaufort Sea coast, and reviewed previous fish collections. The only Alaskan Beaufort offshore fish survey documented by voucher specimens is that of Frost and Lowry (1983) mentioned above. Vouchered collections from the Canadian Beaufort nearshore include those from the Canadian Arctic Expedition to the western Beaufort ending in 1918 which were reported by Walters (1953a), and the 1960 *Salvelinus* expedition to the vicinity of Herschel Island, Yukon Territory reported by McAllister (1962). Fishes collected in the western Canadian High Arctic at Mould Bay, Prince Patrick Island in 1951 were described by Walters (1953b).

Most research over the past few decades on abundance and ecology of fishes in Alaska's Arctic waters is a direct result of oil and gas development, and therefore has been focused in nearshore waters of the northeast Chukchi Sea (e.g., Barber et al. 1997) and Prudhoe Bay of the Beaufort Sea (Thorsteinson et al. 1990, Benner and Middleton 1991, NRC 1994, Johnson 1997, Wilson and Gallaway 1997, Griffiths et al. 1998, Fechhelm et al. 2008). Most knowledge of Arctic fishes is about freshwater and anadromous fishes, with information about offshore marine species being extremely limited.

The most intensive fisheries research in the western Arctic has been in the central Beaufort Sea, on the North Slope of Alaska near Prudhoe Bay. Reports on fishes of the North Slope by LGL, one of the most prolific industry-sponsored environmental consulting groups, are listed in Gilders et al. (2000) and available online by topic at http://www.lgl.com/pub.htm. A long-term time series on fish abundance and life history has been gathered during annual surveys nearshore of Prudhoe Bay begun in 1981; annual reports analyze the present year's results and place them in the context of the historical data (e.g., Fechhelm et al. 2008). The Prudhoe surveys are usually within a few kilometers of shore in extremely shallow water (<2 m), and therefore focus on anadromous fishes, although a few marine fishes are also considered: Arctic cod *Boreogadus saida,* saffron cod *Eleginus gracilis,* Arctic flounder *Pleuronectes glacialis,* fourhorn sculpin *Myoxocephalus quadricornis,* and rainbow smelt *Osmerus mordax.* One of these Prudhoe surveys, the Endicott Environmental Monitoring Program, included research on trophic ecology (e.g., Knutzen et al. 1990, Knutzen and Jewett 1991), and fisheries (e.g., Nelson et al. 1987), in addition to fish distribution and abundance (e.g., Reub et al. 1991).

The most extensively studied fishes in the Alaskan Beaufort Sea are those species which are targets of commercial or subsistence fisheries: Arctic cod, ciscoes and other whitefishes, salmons, and trouts. Studies of the common whitefishes in this area include Arctic cisco *Coregonus autumnalis* (Bond and Erickson 1997, Bryan and Fechhelm 1997, Colonell and Gallaway 1997, Jarvela and Thorsteinson 1997), least cisco *C. sardinella* and humpback whitefish *C. pidschian* (Moulton et al. 1997), and broad whitefish *C. nasus* (Gallaway et al. 1997, Tallman 1997). The most commonly occurring trout is Dolly Varden *Salvelinus malma* (DeCicco 1997, Jarvela and Thorsteinson 1997), but there are taxonomic problems confusing identity of Dolly Varden with Arctic char *S. alpinus* (Reist et al. 1997). Four of the anadromous fishes are considered to be sentinel species, and are studied most intensively: Arctic cisco, least cisco, broad whitefish, and Dolly Varden (US Army Corps of Engineers 1980, 1984).

Current State of Knowledge

Basic knowledge on marine and anadromous fishes of the Eurasian Arctic, including the Chukchi Sea and adjacent area, was most recently summarized in the Russian monograph *Fishes of the Northern Seas of the USSR* (Andriashev 1954), with an English translation in 1964. Published at about the same time, the taxonomy and zoogeography of western Arctic fishes were the focus of *Fishes of Western Arctic America and Eastern Arctic Siberia* (Walters 1955). Taxonomic relationships, geographic distribution, and basic morphology of the fishes of Alaska and adjacent marine waters of Russia and Canada were more recently reviewed in *Fishes of Alaska* (Mecklenburg et al. 2002). Information on Canadian Arctic fishes, including ecology, may be found in the *Encyclopedia of Canadian Fishes* (Coad 1995). An annotated list of Canadian Arctic fishes is available in a recent data report, and a detailed atlas is in progress (Coad and Reist 2004). High Arctic and Arctic Basin fish records have not been reviewed recently and exist mainly in diverse literature sources and museum collections.

A major source of information on fish communities and ecological systems of Alaskan Arctic seas is the large body of data produced by the federal Outer Continental Shelf Environmental Assessment Program (OCSEAP), a joint effort of the US Department of Commerce, NOAA, and US Department of the Interior, Bureau of Land Management (now Minerals Management Service). From 1975 through 1991 the OCSEAP managed the environmental studies necessary to assess the impacts of oil and gas development on the Alaskan outer continental shelf. The numerous reports by principal investigators, regional syntheses by OCSEAP managers and consultants, and related publications are listed in a comprehensive bibliography (OCSEAP 1990). OCSEAP synthesis reports were prepared on the Arctic marine environment (Carey 1978, Norton et al. 1981, Craig and Skvorc 1982, Becker 1987), the Chukchi and Beaufort Seas (Truett 1984), and the northeastern Bering Sea (Jarvela 1984, Truett 1985, Thorsteinson et al. 1989). Data collected by OCSEAP investigators were digitized and stored in the NOAA National Oceanographic Data Center (NODC) database (http://www.nodc.noaa.gov/). The OCSEAP data on fish distribution and ecology were incorporated in an Arctic Fisheries Database (Bacon and Carns 1993).

Another database with potential utility for locating and retrieving valuable data sets is the Databank for Arctic Anadromous Fish (Slaybaugh et al. 1989). Compiled for Standard Alaska Production Company, the databank includes geographically and taxonomically relevant fisheries data culled from the review of 1200 scientific publications, state and federal government reports, and consultant reports of limited distribution. The database was compiled as source material for subsequent environmental assessment studies.

Considerable information about fishes in the shallow nearshore area by the Endicott causeway on the North Slope was collected for the Endicott Environmental Monitoring Program during the 1980s. These reports thoroughly analyze the distribution and abundance (e.g., Reub et al. 1991), trophic ecology (e.g., Knutzen et al. 1990, Knutzen and Jewett 1991), and fisheries (e.g., Nelson et al. 1987) of the nearshore anadromous whitefishes and trouts. Distribution and abundance of Arctic cod and fourhorn sculpin, the most abundant marine fishes in this area, were also examined. Raw and synthesized data are available in printed form in a series of annual final reports.

The OCSEAP Arctic Fisheries Database (Bacon and Carns 1993) and Standard Alaska's anadromous fish database (Slaybaugh et al. 1989) are not in formats usable by current Windows-based applications, and the anadromous fish database may be available only within Standard Alaska. These and other relevant databases, if they can be made available, must be made compatible with current computer applications to make them accessible. Results of resource surveys by other US federal and state resource management agencies should also be reviewed for fish distribution, abundance, and ecology information. For instance, National Marine Fisheries Service (NMFS) survey results are made available in the NOAA Technical Memorandum series. The NMFS has sampled very little north of Bering Strait, but has abundant data from the adjacent northern Bering Sea (e.g., Sample and Nichol 1994) which should be considered when assessing potential species range extensions into Arctic waters.

The Canadian oil exploration and production effort in the western Beaufort also produced a large body of literature and reports, with much valuable information on abundance, ecology, and life histories of fishes. Several Canadian data reports (not all stimulated by environmental impact assessment) have been reproduced and are available on the internet (http://inter01.dfo-mpo.gc.ca/waves2/index.html): e.g., Lawrence et al. (1984) on coastal fishes of the southeastern Beaufort Sea; Bond and Erickson (1989) on nearshore fishes of Phillips Bay, Yukon Territory; Percy (1975) on fishes of the Mackenzie Delta; Lacho (1991) on stomach contents of fishes from Tuktoyaktuk Harbor, N.W.T.; and Chiperzak et al. (2003a-c) on larval and postlarval fishes from the Canadian Beaufort Sea shelf. These studies have produced a large body of data that should be mined, and such an effort appears to be under way (see Coad and Reist 2004).

Fig. 24. Arctic cod hide deep within a sea ice crevice to avoid predators (credit Katrin Iken/UAF)

The ecology and life history of few Arctic marine fishes have not been studied in any detail. The most thoroughly studied species has the highest commercial importance: the Arctic cod (Hop et al. 1997). Very little is known about marine species that have no commercial or cultural significance (Power 1997). Most of what is known about ecology and life history of Alaskan Arctic marine fishes in the Beaufort Sea comes from work associated with marine mammals (Frost and Lowry 1981a, 1984) and oil and gas exploration (Craig and McCart 1976; Craig et al. 1982, 1984; Fechhelm et al. 2008). Recent distributional, biological, and ecological knowledge about fishes in the northeastern Chukchi Sea comes from a set of cruises in 1989-1991 (Barber et al. 1997, Coyle et al. 1997, Gillispie et al. 1997, Smith et al. 1997a-c, Wyllie-Echeverria et al. 1997), and a 2004 cruise which sampled in the western Chukchi as well (Mecklenburg et al. 2006, 2007; Norcross et al. 2006, *accepted*).

Little is known of the fishes inhabiting the greater depths of the continental slope, plains, and basins north of Siberia and Alaska. Most of our distributional records from this region of the Arctic Basin come from drifting ice stations of adjacent nations, such as Lamont Geological Observatory's station Charlie (Walters 1961) and the Soviet Union's North Pole (Severny Polyus) series of stations continuing today in operation by the Russian Federation (Andriashev 1957; Tsinovskiy 1980, 1981). A few deepwater fishes were photographed in the Canada Basin north of Alaska by a remotely operated vehicle (ROV) in 2002 (Stein et al. 2005) and 2005; the 2005 expedition collected four fish representing three species (Bluhm et al. unpubl.).

The fish fauna in the Arctic have low diversity because they are evolutionarily in the early stages of development (Eastman 1997, Power 1997). Arctic conditions require multiple physiological adaptations because of low temperatures, ice cover, and darkness-affected primary and secondary production. Freshwater discharge affects the salinity, sediment, and nutrients in nearshore waters. A list of fishes from Arctic seas and adjacent waters gives 416 marine, diadromous (mostly anadromous), and freshwater fish species which enter brackish water (Andriashev and Chernova 1995). In the early 1990s, reviews indicated 72 fish species present in the Chukchi Sea (MMS 1991) and 62 species in the Beaufort Sea (MMS 1990). Our work on recent and historical collections of Arctic fishes confirms the presence of 104 species in the Chukchi and Beaufort Seas; 85 species have been documented from the Chukchi Sea, and 68 from the Beaufort Sea (Mecklenburgs, unpubl. data). Most of the marine species are benthic or demersal, living on or closely associated with the bottom like most eelpouts (Zoarcidae), sculpins (Cottidae), and snailfishes (Liparidae). Few are pelagic, freely moving about in the water column like the glacial lanternfish *Benthosema glaciale,* which is mesopelagic at depths down to 1,250 m during the day and rises to epipelagic depths near the surface at night; or both demersal and pelagic, like the ice-loving (cryopelagic) Arctic cod, one of several species in the cod family (Gadidae). The Cottidae, Zoarcidae, Stichaeidae (pricklebacks), and Agonidae (poachers) are the most speciose marine fish families in the western Arctic. The family Salmonidae (salmonids) includes the Arctic anadromous fishes: ciscoes and whitefishes, trouts and chars, and salmons, most of which inhabit inshore and nearshore waters but a few (such as species of Pacific salmon) may range far offshore during their ocean years. Many of the fish species recorded from the Beaufort and Chukchi Seas are the same, with the greatest differences in diversity between these seas due to the Atlantic species that have crossed the Arctic only to the Beaufort Sea, and the Pacific species that moved north of Bering Strait only as far as the Chukchi Sea.

A symposium on “Fish Ecology in Arctic North America” held in May 1992 in Fairbanks, Alaska, was meant to “summarize current knowledge of the biology and ecology of freshwater, anadromous, and marine fishes in Arctic Alaska and Canada.” Most of the papers published from this symposium were, however, reports of research at the time rather than the review papers hoped for (Reynolds 1997). Only one eloquent “Review of Fish Ecology in Arctic North America” (Power 1997) covered the environment of Arctic fishes (marine, lacustrine, and fluvial) and how fishes survive in the Arctic environment by utilizing morphology, behavior, and physiology. This fundamental lack of all but the most basic ecological knowledge of Arctic marine fishes is thus reflected in the content of this synthesis. The general consensus seems to be that little is known and much work needs to be done on Arctic marine fishes (Johnson 1997, Power 1997, Mecklenburg et al. 2002, MMS 2006).

One of the key Arctic marine species is the Arctic cod, in that it represents one of the most important links from lower trophic levels (copepods and under-ice amphipods) to other fishes, birds, seals, and whales (Frost and Lowry 1981b, Bradstreet and Cross 1982, Bradstreet et al. 1986, Lønne and Gulliksen 1989, Lønne and Gabrielsen 1992, Gradinger and Bluhm 2004). In the Beaufort Sea and northeastern Chukchi Sea, calanoid copepods are the predominant prey of Arctic cod; this is in contrast to the subarctic Bering Sea where the main prey were gammarid amphipods, and to a lesser extent mysids, shrimps, and hyperiid amphipods (Lowry and Frost 1981). Larval stages of the Arctic cod prey primarily on the naupliar stages of *Pseudocalanus* copepods, at least in the Greenland Sea (Michaud et al. 1996). The Arctic cod is the most northerly distributed cod, occurring roughly between 60°N and the North Pole, nearshore as well as offshore (Andriashev 1954). It frequently dominates the fish fauna in Beaufort Sea coastal waters (Jarvela and Thorsteinson 1999) and lagoons (Craig et al. 1982). The Arctic cod is adapted to polar conditions both physiologically (Enevoldsen et al. 2003) and in its habitat use, e.g., through its common association with sea ice (Andriashev et al. 1980, Bradstreet et al. 1986, Lønne and Gulliksen 1989). Juvenile Arctic cod have been observed in small groups (<10 individuals) near or within fissures of sea ice, where presumably they seek ice-associated prey and protection from predators (K. Iken, unpubl. data). Arctic cod also can occur in dense and large schools (Craig et al. 1982), and several million fish may immigrate to coastal lagoons in the Beaufort Sea in some years. In nearshore Alaskan waters, fishing for Arctic cod has always been a major recreational and subsistence event in native communities in the summer months (mainly August), when pack ice drifts close to shore (Murdoch 1885, Braund et al. 1989).

While extensive fish stock assessments have been conducted in the southeastern Bering Sea and in the Barents and Greenland Seas, other than Arctic cod, pelagic and demersal fishes have received little attention in the Chukchi and Beaufort Seas. Communities of ichthyoplankton and of demersal fishes are roughly separated along the boundaries of the various water masses of the Chukchi Sea (Norcross et al. *submitted*), and in the more intensively sampled northeastern Chukchi Sea, demersal fish communities are correlated with sediment and salinity (Barber et al. 1997). In the northeastern Chukchi Sea, two cods (Arctic cod and saffron cod) made up 69-83% of the fishes in offshore demersal trawls in 1990 and 1991; sculpins, flatfishes, and eelpouts contributed much of the remaining catches (Barber et al. 1997). In the offshore southern and northwestern Chukchi Sea, two sculpins (Arctic staghorn sculpin *Gymnocanthus tricuspis* and shorthorn sculpin *Myoxocephalus scorpius*) were dominant in 2004, followed by Bering flounder *Hippoglossoides robustus* and Arctic cod; few saffron cod were caught, representing only 2.3% of the total bottom trawl catch (Mecklenburg et al. 2007). Saffron cod composed 5% of the catch by total numbers of fish in ship- and land-based synoptic surveys in 1983 north of Point Hope to Icy Cape, making them 5th in overall abundance within the sample after Arctic staghorn sculpin, Arctic cod, shorthorn sculpin, and hamecon *Artediellus scaber* (7%) (Fechhelm et al. 1985). In bottom trawl surveys of offshore waters from Icy Cape in the Chukchi Sea and along the Beaufort shelf edge in 1976 and 1977, Arctic cod, polar eelpout *Lycodes polaris,* and twohorn sculpin *Icelus bicornis* accounted for 65% of all fishes caught; hamecon were 4th in abundance (Frost and Lowry 1983). In a 3-year study in the Beaufort Sea, Arctic cod, capelin, and snailfishes dominated epipelagic catches in coastal waters with the 0+ age class being most abundant (Jarvela and Thorsteinson 1999). The patchy nature of these studies, potential habitat differences, and differences in gear types make it difficult to see any consistent patterns in these observations.

Interannual variation in biomass and abundance of individual species indicates the importance of long-term research. In the northeastern Chukchi Sea, the population biology of two demersal fishes additional to Arctic cod was examined by Smith and others (1997a, c). The distribution, abundance, age, growth, and reproduction of Bering flounder (Smith et al. 1997c) and Arctic staghorn sculpin were examined from 1990 and 1991 collections (Smith et al. 1997a). Both species showed large interannual variation in biomass and abundance, with considerably smaller catches in 1991 than in 1990; authors note that these species are subject to an unstable physical environment that may cause mass mortalities, recruitment failures, or both. Arctic cod, however, appear to be a very adaptable species, and this may explain their overwhelming success in Arctic marine waters (Lowry and Frost 1981).

In nearshore Beaufort habitats, the anadromous Arctic cisco, least cisco, and Arctic char, and the marine fourhorn sculpin were abundant during the OCSEAP program in the late 1970s (Craig et al. 1984). Due to their anadromous life styles, these fish spend a portion of their time in estuaries and marine habitats close to shore. The most abundant marine species in the nearshore Beaufort Sea in the vicinity of Prudhoe Bay in a 2002 fish monitoring study were Arctic cod, Arctic flounder, rainbow smelt, and fourhorn sculpin (Fechhelm et al. 2003). Monitoring studies, such as the long-term industry-sponsored fish monitoring study in the Prudhoe Bay region begun in 1981 (Fechhelm et al. 2008), have documented local changes in abundance and condition. For instance, Arctic flounder and rainbow smelt experienced sharp increases in abundance starting in 1990 that continued as high abundances through 2007 and are attributed to climate shifts. The stock of small (<350 mm) Dolly Varden has continued to remain robust, and although abundance of large Dolly Varden in 2007 was the fourth lowest observed over the monitoring period, this may simply reflect density-dependent processes and the stock's age structure. An elevated catch rate for humpback whitefish east of West Dock is attributed to a breach constructed in 1995-96, allowing this species to extend its coastal distribution farther to the east (Fechhelm et al. 2008).

Although knowledge of trophic ecology of marine fishes is extremely limited, a few sources describe the diet of fishes in the western Arctic (e.g., Coyle et al. 1997, Atkinson and Pearcy 1992). Coyle et al. (1997) examined diet of four abundant fishes in the northeast Chukchi Sea, and observed that Arctic cod preyed primarily on planktonic and epibenthic organisms; saffron cod consumed epibenthic and benthic fauna; Arctic staghorn sculpin consumed polychaetes and mollusks; and Bering flounder ate fishes and crustaceans. Diets of saffron cod and Arctic cod were most similar. Diets of five demersal species of the Canadian Beaufort Sea were examined by Atkinson and Pearcy (1992), including a poacher, two sculpins, one flatfish, and one prickleback. There were no significant correlations between diets of these fishes, implying a division of resources and low interspecific competition. Arctic alligatorfish *Ulcina olrikii*, Arctic staghorn sculpin, Arctic flounder, and slender eelblenny *Lumpenus fabricii* consumed benthic and epibenthic animals, while the ribbed sculpin *Triglops pingelii* fed almost exclusively on zooplankton. The marine fish diet studies are important baseline data, but should be expanded with additional information on food web linkages to provide basic information on trophic flows and the potential for interspecific interactions. Lowry and Frost (1981) found that Arctic cod occupy different trophic levels in the Chukchi and Beaufort Seas than in the Bering Sea. Iken et al. (*submitted*) indicate lower trophic levels on the western vs. eastern side of the Chukchi Sea for species of planktonic and epibenthic invertebrates (i.e., prey of fishes), together with three fish species: Arctic staghorn sculpin, shorthorn sculpin, and slender eelblenny. These two studies suggest a need to examine trophic ecology within each water mass, rather than to assume that species occupy the same niche throughout their distributional range.

Although the trophic ecology of marine fishes is poorly understood, a baseline of fish abundance, distribution, and trophic ecology of anadromous fishes is well established near Prudhoe Bay in the Beaufort Sea. The diets of whitefishes including Arctic cisco, least cisco, and broad whitefish, and Arctic char were examined relative to fish size, seasonality (early vs. later in the summer), and prey availability (Knutzen et al. 1990, Knutzen and Jewett 1991). Small whitefishes mostly ate copepods, and larger whitefishes ate more mysids and amphipods; small Arctic char fed on amphipods, isopods, and insects, and larger Arctic char consumed mainly fishes. Earlier in the summer (July), fishes fed mainly on freshwater-tolerant invertebrates such as copepods, insect larvae, and the amphipod *Pontoporeia affinis*, whereas by August, salinity-tolerant invertebrates such as mysids and other amphipods were more heavily consumed.

Information Gaps in a Climate Change Context

Basic ecology of Arctic marine fishes is a significant gap in knowledge, but knowledge of species ranges, population abundance, and demographics is also woefully inadequate. Quantitative estimates of abundance are only available for exploited (anadromous) species (Reist 1997). Simple distribution maps of Arctic marine species are needed that are readily accessible and up-to-date; and presence/absence information, such as from museum collections, should be evaluated and mapped to improve knowledge of range and habitat use. The historical distributional background represents a critical gap, with databases needed against which to compare future distributions of adult fish in the western Arctic.

Taxonomic, distributional, morphological, and ecological information on marine fishes from the northern seas of Russia was reviewed most recently more than half a century ago (Andriashev 1954). Since that time, Russian authors have published prolifically on taxonomy and morphology of Arctic fishes, records of species occurrence, and ecology and life history. Some of this information is available in the English edition of the Russian *Journal of Ichthyology,* but most of the recent work, and all of the older material, is dispersed among publications and reports in the Russian language. As well, there is a body of unpublished information on fisheries, including bycatch and abundance, which was not publicly available under the regime of the Soviet Union. Such data need to be located, evaluated, and digitized, and selected materials need to be translated into English, to make this body of information readily accessible to the international community.

Spatial-temporal data on which to base ecological knowledge are extremely limited and restricted to the ice-free summer periods because of the extreme difficulty of trawling under ice. Recent and planned multidisciplinary and fisheries oceanographic demersal and pelagic sampling, such as that by the RUSALCA program in 2004 (Mecklenburg and Sheiko 2006; Mecklenburg et al. 2007; Norcross et al. 2006 *submitted*) and currently planned for 2009, and the recently completed investigations in the eastern Chukchi Sea by Hokkaido University (R/V *Oshoro Maru* in 2007 and 2008) and NMFS (R/V *Oscar Dyson* in 2007) (Holladay, unpubl. data; Mecklenburg, unpubl. data), will provide such ecological context that is missing in most other studies. Other important ecological information lacking about most Arctic fishes includes trophic ecology, life histories, migration patterns, growth rates, feeding habits, reproduction, and offshore distribution (NRC 1994). Basic ecological knowledge is needed for fishes by life stage, including adults, juveniles, and larvae (e.g., Fortier et al. 2006), and by depth and lifestyle preferences from benthic and demersal to epipelagic. At present, Arctic larval fish collections are extremely rare and confined to 1979 (Tarbox and Moulton 1980), 1984-1987 (Hopky et al. 1994, Chiperzak et al. 2003a-c), 1989-91 (Wyllie-Echeverria et al. 1997), 2004 (Norcross et al. 2006 *submitted*), and 2007 (R/V *Oscar Dyson* cruise OD0710). Because research in the Arctic has been driven by commercial development, the cost/benefit ratio may prohibit obtaining such basic ecological knowledge about fishes (NRC 1994); however, new opportunities may arise with renewed oil exploration efforts.

Some valuable databases with information on fish ecology and life history are available on the internet, but they suffer from the lack of information on fishes of the Arctic. FishBase (www.fishbase.org) (Froese and Pauly 2006) is easily accessible and easy to use, but entry of data into the system lags far behind publication of new works. FishBase contains little information on Arctic fishes except those species also found in subarctic or temperate waters; its

Fig. 25. Polar eelpout *Lycodes polaris* collected during RUSALCA 2004 expedition (credit Catherine Mecklenburg / Point Stephens Research)

information about ecology and life history strategies collected in more temperate regions should not be casually extrapolated into the Arctic region. A recently developed larval fish database, otherwise excellent, is limited by the few Arctic collections and, hence, lack of life history information on Arctic species: http://access.afsc.noaa.gov/ichthyo/index.cfm. A database specific to the Arctic is currently under development by ArcOD. The Ocean Biogeographic Information System (OBIS) is an on-line, open-access data portal with information on worldwide distribution, ecological, and environmental information relative to marine animals, including fishes. Interpretation of information within these databases and portals should consider the existence of voucher specimens, historical name changes, ongoing taxonomic reorganization, and potentially incorrect identifications within the individual data sets composing the data portal.

We speculate that a changing climate will have notable impacts on fish distribution, habitat, diet, the location and timing of spawning, among other topics, though considerably more data are needed to establish a baseline to substantiate anticipated changes. With Arctic warming, the northern Bering Sea is shifting from a shallow, ice-dominated system in which bottom-dwelling fishes prevail to one more dominated by pelagic fishes (Grebmeier et al. 2006). Observed changes in distribution and abundance of walleye pollock *Theragra chalcogramma* and Arctic cod in response to changes in sea ice cover and subsurface temperatures provide insight as to how Arctic climate change affects marine ecosystems (Wyllie-Echeverria and Wooster 1998). We can only speculate what may be occurring in the Chukchi Sea, offshore Beaufort Sea, and adjacent deeper waters of the Arctic Ocean given the paucity of information about fishes there. Currently the niche of benthic higher trophic level consumers in the Arctic is filled by seabirds and marine mammals (Grebmeier et al. 2006). However, with decrease of sea ice in the Chukchi Sea, demersal fishes moving northward from the Bering Sea might usurp the place of birds and mammals as benthic consumers. Others have suggested that in the long-term, the reduction of the sea-ice cover is likely to bring about an Atlantification of at least the Canadian Arctic shelves and the replacement of the present Arctic cod-dominated ecosystem by an Atlantic cod-dominated ecosystem (Barber et al. 2006).

Currently, available information is insufficient to accurately predict how ecosystem changes in the western Arctic will affect fish communities because of the incomplete understanding of species ranges, and how individual species fit into community structure. A continuing multidisciplinary program of ecosystem-oriented exploration is critical to creating the baseline data and to understanding the complexity of factors that will allow ecosystem changes to be detected, and predicted, in a changing Arctic climate.

A plethora of unresolved taxonomic questions and controversial classifications plagues efforts to evaluate and synthesize information on fishes of the Arctic. Because of the previous limited sampling for fishes in Arctic waters, all but the most common species are known from small numbers of specimens. The available specimens and distributional records are currently inadequate to determine taxonomic and distributional boundaries, especially for similar-looking species or subspecies which can inhabit the same seas but are difficult to distinguish and frequently misidentified. The lack of voucher specimens from many fish surveys makes it difficult to assess the accuracy and reliability of those surveys for contributing to databases and distributional synthesis.

Some of the taxonomic changes and mistakes in identification are significant enough to affect interpretation of long-term patterns. For example, the third most abundant species in northeastern Chukchi Sea bottom trawls in 1990 and 1991 was reported by Barber et al. (1997)

to be *Myoxocephalus* sp., but recent examination of the voucher specimens revealed that practically all were shorthorn sculpin *M. scorpius* (Mecklenburg et al. 2007), which occupied sixth place on Barber et al.'s list using the junior synonym name *M. verrucosus.* Combining *M. verrucosus* with *Myoxocephalus* sp. as *M. scorpius,* makes *M. scorpius* the second most abundant species in Barber's 1990-1991 survey, as in the more recent (2004) RUSALCA sample from the Chukchi Sea (Mecklenburg and Sheiko 2006, Mecklenburg et al. 2007).

Taxonomy and identification of Arctic fishes are also problematic for less-abundant species. Misidentifications of less common species may lead to inaccurate species geographic ranges and poor estimates of community diversity. For instance, archer eelpout *Lycodes sagittarius* and Arctic eelpout *L. reticulatus* were reported in 1983 shallow (< 50 m) sampling off Point Lay, Wainwright Inlet, and Ledyard Bay, Chukchi Sea (Fechhelm et al. 1985), but ichthyologists report that the archer eelpout is a deepwater species, occurring at depths greater than 335 m, while there are no documented records of Arctic eelpout in Alaska (Mecklenburg et al. 2002). White Sea eelpout *L. marisalbi* are relatively common in the Beaufort Sea and have often been confused with archer eelpout (Møller 2000; Mecklenburg, unpubl. data). Marbled eelpout *L. raridens,* which are common in the northern Bering and Chukchi Seas, are often mistaken for Arctic eelpout (Mecklenburg et al. 2002). An industry report lists 17 species from the Beaufort Sea adjacent to the North Slope oilfields (BP Exploration 2001), 5 of which are unlikely to occur in the area, but without archived voucher specimens, we cannot verify their identity.

Analyses of new samples, or reviews of old material, often propose taxonomic reshuffling or changes in nomenclature. Especially when these changes are based on a small number of specimens, interpretations differ on the significance of differences (e.g., whether they signify different species, subspecies, or ecophenotypic variations). For instance, new eelpouts (Zoarcidae) in the genus *Gymnelus* were described recently in the Arctic (Chernova 1999a-b, 2000); these new eelpouts may occur in the Chukchi Sea or may simply be synonyms of fish doctor *Gymnelus viridis* and halfbarred pout *G. hemifasciatus* (Anderson and Fedorov 2004), species which are familiar to fishery scientists working in the Bering, Chukchi, and Beaufort Seas. Additional research, seeking new diagnostic morphological characters and using new methods, including molecular genetic analyses such as DNA "barcoding" (see http://www.fishbol.org/), should be conducted to further examine these and other taxonomic questions (e.g., see Mecklenburg et al. 2002, 2007).

Much information can be gleaned from unpublished data sets and fish specimens archived in museums and other repositories worldwide (Fig. 26). Museums contain collections of Arctic fishes that have still not been reported in the literature or are incompletely reported. Persons conducting retrospective searches need to be aware that numerous changes in nomenclature and classification of Arctic fishes have occurred over the last 100 years and more, and that gray and peer-reviewed literature, museum records, and unpublished data sets contain numerous misidentifications.

Only more expeditions of discovery to provide new tissues and whole specimens for research, and continued study of existing material in museums, will resolve taxonomic questions. Meanwhile, a detailed summary of the problems affecting what we call, and how we classify, Arctic fishes would be extremely helpful to ichthyologists, other biologists, and resource managers. Taxonomy of northern fishes is dynamic, with recent addition of numerous new species, and reviews of taxonomic groups which result in consolidation of some species and

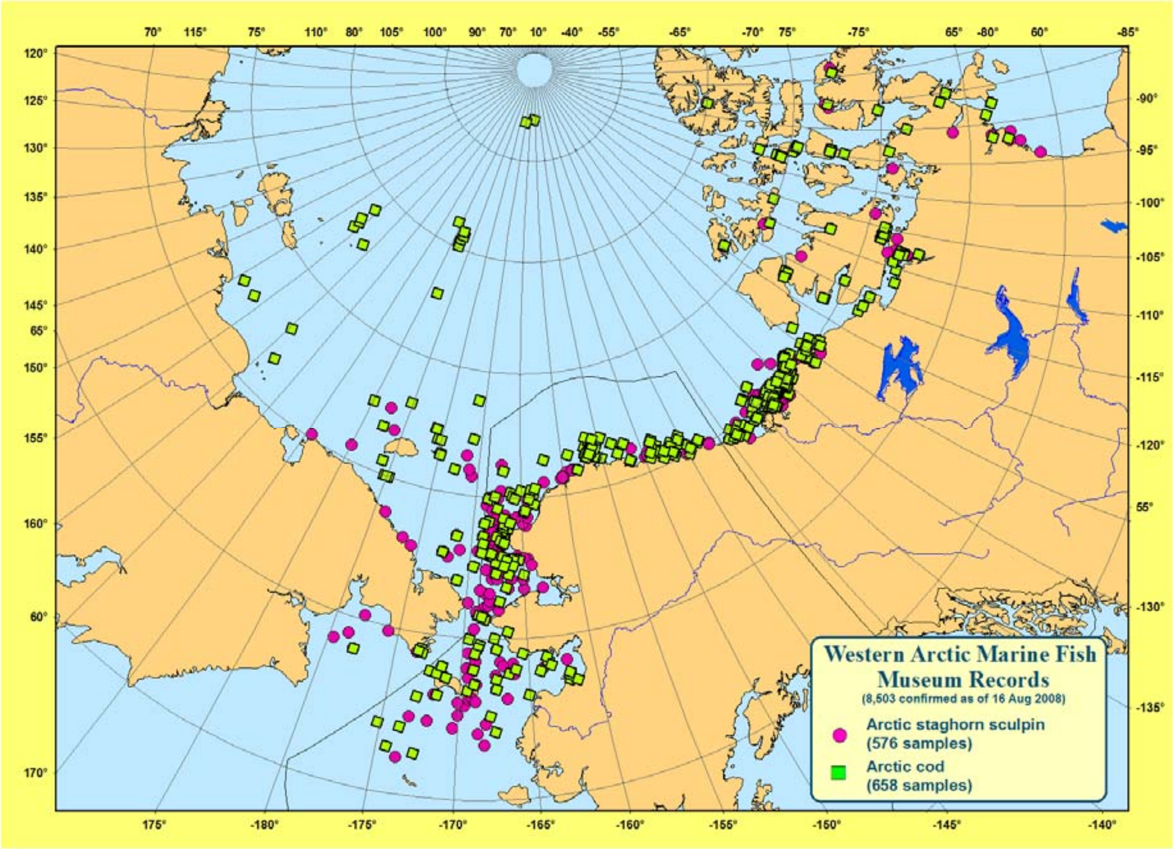

Fig. 26. Distribution of museum specimens of Arctic cod and Arctic staghorn sculpin in the western Arctic for which identity has been confirmed (credit TA Mecklenburg, Point Stephens Research)

splitting apart of others. Nomenclatural and taxonomic changes affecting nine fish families represented in Arctic marine waters were recently summarized in a series of annotated taxonomic checklists: Anderson and Fedorov (2004) on Zoarcidae (eelpouts); Chernova et al. (2004) on Liparidae (snailfishes); Evseenko (2003) on Pleuronectidae (flounders); Mecklenburg (2003a,b) on Anarhichadidae (wolffishes) and Pholidae (gunnels); Mecklenburg and Sheiko (2003, 2004) on Cyclopteridae and Stichaeidae (lumpsuckers and pricklebacks, respectively); Mecklenburg and Eschmeyer (2003) on Hexagrammidae (greenlings); and Sheiko and Mecklenburg (2004) on Agonidae (poachers) (http://www.calacademy.org/research/ichthyology/annotated/index.html). Other Arctic families, including some of the most speciose families such as the Cottidae (sculpins), have yet to be reviewed in the series but are planned. The American Fisheries Society and American Society of Ichthyologists and Herpetologists about every 10 years publishes a list of common and scientific names (e.g., Nelson et al. 2004) accepted by their standards as valid, but the list covers only fishes inhabiting the continental shelf of North America. Changes affecting names and numbers of marine and anadromous fish species in the western Arctic, including Siberian and North American Arctic seas and the adjacent high Arctic, and slope and basin depths, should be brought together and summarized in the form of an annotated list of species.

Identification skills are improving as advances in ichthyological knowledge translate into more accurate and helpful guides and keys to the species of this region. *Fishes of Alaska* (Mecklenburg et al. 2002) improved awareness and identification of fishes in the seas within the

200-mile limit off Alaska and adjacent waters of eastern Siberia and western Canada. Updated information for 33 species of Pacific-Arctic fishes, with color photographs of some species, was recently provided from the RUSALCA catch in 2004 and a retrospective examination of specimens (some dating back to the early 1800s) in US and Russian museums holding the largest permanent Arctic collections (Mecklenburg et al. 2007). That work has continued, with examination of historical fish collections in Canada and Japan as well as the United States, and of materials collected on Arctic cruises in 2007 and 2008, and is planned to continue at least through the duration of the CoML (2010) and RUSALCA (currently planned through 2012). Research cruises to the Chukchi and Beaufort Seas in 2007 and 2008, conducted partly in response to focus on the International Polar Year and exploration for oil and gas, as well as other ongoing programs (e.g., ArcOD section of CoML) focusing on the Arctic, will generate a wealth of new taxonomic and ecological information. Guides or monographs on western Arctic fishes, especially if available in web editions as well as print, would help consolidate and disperse this valuable new information, along with the verified and updated historical records, to enable consistency of identifications in future research and expeditions, and synthesize available information on selected aspects of morphology, life history, distribution, habitat, and diet.

Recommendations

- **Build databases and geographic information system (GIS) applications addressing descriptive synthesis, planning, analysis, and testing of hypotheses regarding Arctic fishes.** Numerous published and unpublished historical datasets need to be gleaned for useful data and incorporated into central databases. In a GIS application, existing fish distributional and ecological data could be related to, or overlaid on, physical and oceanographic data as a basic analysis of fish ecology, and to determine locations for future sampling efforts. Individual distributional records of Arctic fishes need to be evaluated for accuracy of species identities and locality information, and placed in a database for use in determining distributions, current and historical baselines, and regional and chronological changes in biodiversity.
- **Translate selected Russian literature and reports**. Valuable distributional, ecological, commercial fisheries, and taxonomic (e.g., species descriptions and reviews) information exists in numerous Russian-language publications and data reports. Much of the information is largely unknown to western scientists. Russian literature and reports on fishes and fisheries of the Siberian Arctic (eastern Russia) need to be evaluated and the most useful documents translated into English.
- **Conduct research toward resolving problematic taxonomy and develop annotated, up to date species lists and other syntheses of information on western Arctic fishes.** Special attention should be paid to resolving problems in Arctic fish taxonomy and developing annotated lists and other syntheses to update knowledge and increase accuracy of identifications and communication in the literature. Some products are needed now as baseline references from which to proceed, while others could be planned for completion toward the end of the Census of Marine Life (2010) or later. Continuing research on specimens of Arctic fishes in museums and from current expeditions is required to accumulate the materials and data to produce such syntheses. Analysis, writing, peer review, production, and distribution of these syntheses also need support.

- **Design and implement sampling schemes to address issues of fish ecology**. There is a documented northward ecosystem shift from the southern Bering Sea into the northern Bering Sea and Chukchi Sea (Grebmeier et al. 2006), thus sampling should focus on the Chukchi Sea and northward. We recommend repeating sampling in areas that have been previously sampled so that comparisons can be made. We particularly recommend a multidisciplinary sample plan that covers the diverse water masses of the Chukchi Sea and samples fishes in conjunction with oceanography, zooplankton, and invertebrates from the benthos and epibenthos. One of the biggest spatial gaps in information is the east coast of the Chukchi Peninsula in Russia, planned for sampling by the RUSALCA program in 2009 and 2012. It is important to survey both the western (Russia) and eastern (US) Chukchi Sea, because fishes freely move across international boundaries, and collections should be during late season ice-free times (August-September).
- **Establish long-term time-series**. In some areas fish sampling has occurred with some degree of historical frequency; e.g., Gulf of Anadyr, around St. Lawrence Island, Bering Strait, Norton Sound, Point Hope, Cape Lisburne, and Point Barrow. The most intense sampling has taken place in the nearshore Beaufort Sea (Craig and McCart 1976; Frost and Lowry 1981b, 1983, 1984; Craig et al. 1982, 1984). We suggest setting up small scale repeated collections in these areas and retaining historical sample locations for a basis of comparison. We recognize that historical sampling or ease of access is not an adequate reason for establishing a time series. Prior to implementing long-term repeated sampling, past collections should be re-analyzed for problematic species and retrospective analysis completed. Such re-analysis should be considered when evaluating locations at which to establish a fish ecology program.
- **Select and monitor indicator species.** Selection needs to take into account the abundance and ease of catching the species, ease of identifying the species when caught, and how well the species represent natural assemblages in the ichthyofauna. Fish assemblages have been recommended as a tool to monitor ecosystem responses to climate change (e.g., Fossheim et al. 2006). From what we know so far, appropriate indicator species in the Chukchi and Beaufort Seas are Arctic staghorn sculpin for the benthic assemblage and Arctic cod for the demersal or cryopelagic. At least those two should be monitored for any changes in abundance, distribution, and trophic ecology. Consideration needs also to be given to assemblages within each water mass, rather than to assume that species occupy the same niche throughout their distributional range. In the nearshore central Beaufort Sea, four anadromous fishes have been selected previously as indicator species: Arctic cisco, least cisco, broad whitefish, and Dolly Varden (US Army Corps of Engineers 1980, 1984); continued monitoring of those species is recommended.
- **Consider alternate sampling methods**. Standard fisheries collection methods are not effective in all Arctic locations or in all seasons. Some areas are too deep or the substrate is too soft or hard for trawling for demersal fishes and pots, traps, dredges, longlines, gillnets, and underwater cameras must be considered. During the heretofore practically unsampled ice season, those same passive methods of fishing need to be explored. Another unique method to consider is the use of seals as samplers, especially for pelagic fishes that are extremely difficult to sample (e.g., Frost and Lowry 1981b, 1984). We also recommend consulting local people who fish, to inquire about historical and current fishing methods and variability of fish and environment.

SEABIRDS

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Fig. 27. Murres, like manys seabirds, form large nesting colonies on coastal cliffs and promontories. (credit Sarah Iverson/UAF)

Introduction

A marine bird workshop, one of several disciplinary workshops of the Arctic Synthesis funded by the North Pacific Research Board, was held in Homer, Alaska, on 22-23 March 2006. The theme of the synthesis and workshops was climate change and the effect it has had and will have on marine ecosystems of the Western Arctic. The goals were to synthesize available information on this theme and to develop recommendations for research needs. We adopted the following definitions for operational terms:

- Western Arctic (WA): The Chukchi and Beaufort seas and the northern Bering Sea south to St. Lawrence I. We included the Bering Strait region because physical and biological processes occurring there are critical to ecosystem structure and food-web productivity of the Chukchi–Beaufort continental shelf and the Arctic Ocean. [For pragmatic reasons, this section focuses primarily on the US EEZ, but we recognize the importance of adjoining areas in Canada in Russia shared by many species.]
- Marine: Open-ocean and continental-shelf waters from the deep-ocean basin to the coast and the extensive estuarine-influenced barrier island–lagoon systems of the Chukchi and Beaufort seas.
- Marine birds: Species dependent on marine resources for all or most of their energy requirements while they are in the WA, or that depend on particular marine areas in the WA for staging during migration, whether they forage extensively or not. These include typical seabirds (such as alcids and gulls), seaducks (such as eiders and long-tailed ducks), and others (such as brant, phalaropes, and loons) that nest locally or migrate to or through the WA but do not nest there.

- Important: We evaluated the importance of breeding colonies, species, and regions. Breeding colonies were considered to be important if they contained large numbers of individuals or species in the WA, or if they contained a large proportion of the total number of a given species in the WA. (Cooper Island was considered important primarily due to historic data) Species were considered to be important for discussion purposes if declines in their abundance were a cause for concern or if elements of their biology were valuable indicators of ecosystem structure and dynamics. Regions within the WA were considered important if they are locations where large numbers of individuals, species, and/or species-complexes occur (for example to forage).

Two overarching questions formed the basis for our discussions:

- What do marine birds tell us about the structure and dynamics of marine ecosystems, and how can we use them as indicators of the effects of climate change on ecosystems? (i.e., seabirds as indicators of change)
- Will the ongoing and anticipated climate change (atmospheric and oceanographic) in the region cause serious declines in abundances of some species of marine birds? (i.e., seabirds as subjects for conservation concern) Alternatively, will climate change lead to significant increases in the abundance of other species?

These questions are closely related, in that a change in the abundance of a given species may in itself be an indicator of an effect of environmental change (in the absence of other factors, such as hunting, disturbance at nesting sites, loss of habitat, or introduction of contaminants because of human activities). However, the magnitudes of decline in abundances of several species in the Arctic are causes for concern and warrant dedicated research efforts to understand the reasons.

Background and Study History

Thirty-four species of marine birds nest in the US EEZ of the WA, and six species migrate to it for some portion of spring-fall to feed on locally-abundant prey resources (Table 2). A species-specific compilation of information for most of these has been completed recently (Denlinger 2006, http://alaska.fws.gov/mbsp/mbm/seabirds/species.htm), including their conservation status, life history, distribution, population size and trends, conservation concerns, and recommended management actions, and thus shall not be repeated at length here. Important seabird colonies are located on St. Lawrence I., King I., and the Diomede Is. in the Bering Strait region; at Bluff in Norton Sound; at Cape Espenberg on the northern shore of the Seward Peninsula; on Puffin I. and Chamisso I. in Kotzebue Sound (Sowls and Roseneau 1989); at Cape Thompson and Cape Lisburne in the eastern Chukchi Sea; and on Cooper I. in the western Beaufort Sea near Pt. Barrow (Fig. 28). Two other important colonies are located adjacent to the US EEZ – at Herschel I. in the Canadian Beaufort Sea and Herald I. in the Russian Chukchi Sea. Almost all of these sites have been recognized as Important Bird Areas by BirdLife International or have been nominated as such, based on the numbers of marine birds present.

Systematic research on seabirds in Alaska began at colonies in the WA a decade or more earlier than elsewhere—in 1959 at Cape Thompson (Swartz 1964) and 1964 at St. Lawrence I. (e.g., Bédard 1966a, 1966b). Studies began in 1975 at Cooper I. and 1975-76 at Bluff, Chamisso I., Cape Thompson, and Cape Lisburne (e.g., Divoky 1988, Springer et al. 1984, Murphy et al. 1986). The data on seabirds obtained by these and subsequent studies provide the most detailed,

Table 2. Marine birds of the Western Arctic. Population trends: + increasing, - decreasing, ? unknown.

Species	Nests in US EEZ	Population Trend	Conservation Concern
Yellow-billed loon	x	?	USFWS[1], AWL[2], BLM[3]
Red-throated loon	x	-	USFWS, AWL, BLM, COCEWIC[4]
Pacific loon	x	0	
Arctic loon	x	0	
Northern fulmar		0	
Short-tailed shearwater		-	
Pelagic cormorant	x	?	NAWCP[5]
King eider	x	-	AWL
Common eider	x	-	AWL
Spectacled eider	x	-	USFWS, AWL, SOA[6], ABC[7]
Steller's eider	x	-	USFWS, AWL, SOA, ABC
Long-tailed duck	x	-	AWL
Brant	x	-	AWL
Red-breasted merganser	x	?	
Pomarine jaeger	x	?	
Parasitic jaeger	x	?	
Long-tailed jaeger	x	?	
Herring gull	x	+	
Thayer's gull		?	
Slaty-backed gull		?	
Glaucous gull	x	+	
Glaucous-winged gull	X	?	
Sabine's gull	x	?	
Black-legged kittiwake	x	+	
Ivory gull		-	COSEWIC
Ross's gull		?	NAWCP
Arctic tern	x	-	USFWS, NAWCP
Aleutian tern	x	-	USFWS, AWL, NAWCP, ABC
Common murre	x	+	
Thick-billed murre	x	+	
Black guillemot	x	-	BLM
Pigeon guillemot	x	?	ABC
Kittlitz's murrelet	x	?	USFWS, AWL, BLM, NAWCP, ABC
Parakeet auklet	x	?	
Crested auklet	x	?	
Least auklet	x	?	
Dovekie	x	?	BLM
Horned puffin	x	+	
Tufted puffin	x	?	
Red phalarope	x	?	

[1] U.S. Fish & Wildlife Service. 2002. Birds of conservation concern 2002. Division of Migratory Bird Management, Arlington, Virginia. 99pp. [2] Stenhouse IJ & Senner SE (2005). Alaska WatchList - 2005. Audubon Alaska, Anchorage, AK. [3] Bureau of Land Management, Department of the Interior – Sensitive species (BLM Manual 6840). [4] Committee on the Status of Endangered Wildlife in Canada. [5] Waterbird Conservation for the Americas: The North American Waterbird Conservation Plan, Version 1 (2002). [6] State of Alaska – State Species of Concern. [7] American Bird Conservancy – Green List

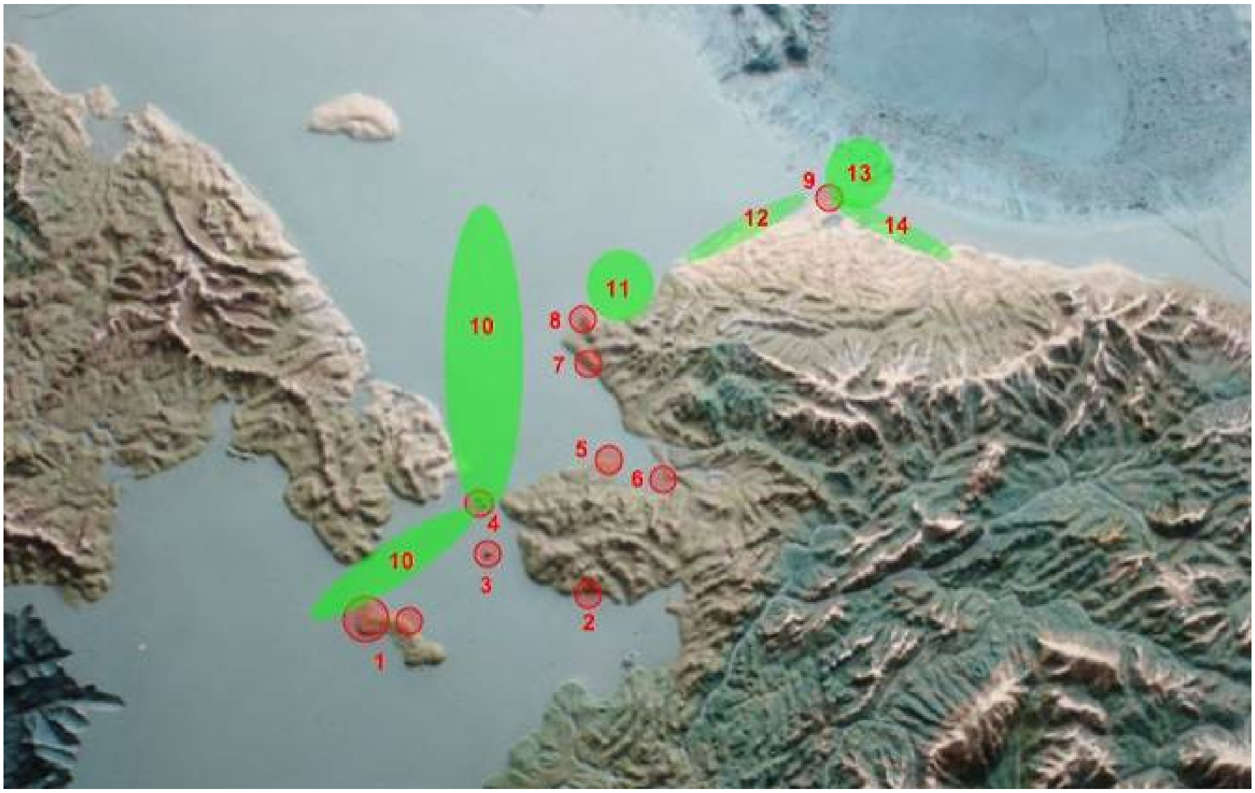

Fig. 28. Locations of important marine bird nesting and foraging areas in the US EEZ of the Western Arctic. 1- St. Lawrence Island. 2- Bluff, 3- King Island, 4 - Diomede Island, 5- Cape Espenberg, 6 - Chamisso and Puffin Island, 7 - Cape Thompson, 8 - Cape Lisburne, 9 - Cooper Island, 10 - Anadyr Stream, 11 - Ledyard Bay, 12 - Kasegaluk Lagoon, 13 - NE of Pt. Barrow, 14 - Smith Bay, Harrison Bay/Colville River Delta.

quantitative information available to assess biotic change in marine ecosystems of the WA during the past 30-50 years.

Spring and fall surveys and research on sea ducks began in 1882 in the vicinity of Pt. Barrow; continuing intermittent studies began there in 1953 (Woodby and Divoky 1982, Suydam et al. 2000a, 2000b). Systematic surveys and research on long-tailed ducks, common eiders, and other seaducks (tribe Mergini) began in the 1970s in some Beaufort Sea lagoons (see Johnson and Richardson 1981, Johnson and Herter 1989, Johnson and Gazey 1992); in 1972 at eider colonies on Egg I. in the Beaufort Sea (Schamel 1974, 1977); and in 1976 at eider colonies and loon nesting areas Cape Espenberg, Chukchi Sea (Seguin, 1979, 1981). Identification and delineation of key staging and molting areas for seaducks along the Beaufort and Chukchi Sea coasts, including Ledyard Bay, began in 1995 for spectacled eiders (Petersen et al. 1999, Troy *unpub. report*, USFWS *unpub. reports*), and was expanded to include common (Petersen and Flint 2002, Petersen *unpub data*, Dickson *unpub. data*), king (Dickson *unpub. data*), and Steller's eiders (USFWS 2002) and long-tailed ducks (Petersen *unpub. data*, USFWS *unpub. reports*). These and subsequent studies of seaducks (Flint et al. 2003, Johnson and Richarson 1981, Lovvorn et al. 2003, Wright 1989) plus those of benthic invertebrates continuing prey items (e.g., Grebmeier et al. 2006 and references therein) provide the quantitative information needed to assess effects of change in marine ecosystems, particularly related to changes in ice and food resources.

Overview of Current Knowledge

Numerous observations of variability and trends in demographic parameters, diet dependencies, and foraging locations of individual species and guilds have provided important insights into spatial characteristics of WA ecosystems and their status and behavior through time. Examples of these are summarized below. We emphasize, however, that the number of studies is small, and the spatial coverage of the WA by avian studies is poor compared to most other North American regions, thus their efficacy in describing the ecology of the region has its limits.

Marine birds as indicators

Pt. Barrow

The Pt. Barrow region includes Cooper I., Elson Lagoon, and an ill-defined region northeast of Pt. Barrow to some distance offshore where water from the Bering Sea enters the Beaufort Sea that is a major foraging area for marine birds and mammals. Of these components, the most prominent from the standpoint of information value is Cooper I.

Detailed information on Cooper I. seabirds has been obtained nearly annually for the past three decades (Divoky 1998, *unpubl. data*). As such, Cooper I. is the most studied site in the WA. Changes in populations of black guillemots in particular, as well as horned puffins, arctic terns, and brant, have provided important insights into environmental variability in the WA. The arrival and successful nesting of black guillemots and then horned puffins occurred when the environment had warmed sufficiently to provide the number of snow-free days required by the two species to lay eggs and raise chicks, approximately 80 days and 90 days, respectively. Over this same time, the colony of arctic terns declined from 75 pairs to 5 pairs as sea ice retreated earlier and farther offshore—the ice edge and unconsolidated pack ice are a critical foraging habitat for terns (Boekelheide 1979), as well as guillemots. Brant nested for the first time in 1990, following a shift in the Arctic Oscillation (AO) that led to environmental warming and early moat formation around the island, isolating it from Arctic foxes, and now number 50 pairs (G. Divoky *unpubl. data*). In contrast, the black guillemot population began a steep decline following the shift and the effect it had of reducing the extent of sea ice and the availability of Arctic cod to guillemots, but has been increasing again since the subsequent shift in 1998. The 1998 shift did not affect nesting conditions for brant. Other conspicuous changes in black guillemot breeding biology that occurred at the time of the 1989 AO shift were large step changes in laying dates, which became earlier, and productivity, which became much more variable as relatively poor years occurred more frequently (Moline et al. *in press*). All of these changes in black guillemot and Arctic tern populations can reasonably be explained by changes in prey availability due to changes in sea ice and ocean state.

The region northeast of Pt. Barrow is distinguished as an important foraging “hot-spot” in the Beaufort Sea by the presence of Ross’s gulls (perhaps the bulk of the world population) and ivory gulls that come here from distant nesting areas elsewhere in the Arctic to feed each fall (Divoky and Springer 1988, Divoky et al. 1988). Neither species winters in the Beaufort Sea; instead, they winter in the Bering Sea, the Okhotsk Sea and the northwestern Pacific Ocean, and their seasonal movements into the Pt. Barrow area appear to occur in response to exceptional foraging opportunities that are important to them in their annual cycles. This also is the only place in the Beaufort Sea where surface-feeding migrants (phalaropes, terns, and gulls) are known to feed in large numbers in offshore waters (Divoky 1984).

Cape Lisburne-Ledyard Bay

Data on murres and black-legged kittiwakes have been collected at the Cape Lisburne seabird colony in 24 out of the last 30 years, a time series that ranks among the top 5-6 longest and most complete in Alaska (Dragoo et al. 2004). The murre population at Cape Lisburne is one of the largest in Alaska, numbering on the order of 500,000 birds. Abundance grew steadily from the mid-1970s through the end of the century, approximately doubling over that time (D. Roseneau, *unpubl. data*). This pattern contrasts with trends for murres elsewhere in the Bering and Chukchi seas, which have been variable annually and have not increased substantially throughout this period at any other colony. Some 20,000 to 30,000 black-legged kittiwakes also nest at Cape Lisburne, and their average productivity is higher than at any other colonies in Alaska except perhaps Bluff (E. Murphy *unpubl. data*). Interannual variability in Kittiwake productivity is driven by prey abundance that is a function of ice cover (and its corollary, water temperatures), the rate of warming in the coastal zone, and the seasonal development of the nearshore food web (Springer et al. 1984).

Seabirds from Cape Lisburne forage in Ledyard Bay for most of the summer, removing some 200 T/day of prey, primarily forage fishes (including Arctic cod, saffron cod, sandlance, capelin, pricklebacks, and sculpins) and euphausiids (Springer et al. 1984). In addition, hundreds of thousands of king, common, and spectacled eiders and long-tailed ducks stage and molt in Ledyard Bay in spring and late summer-fall (Springer et al. 1985, Oppel *in prep.*, USFWS unpub. reports) while feeding on benthic invertebrates. In addition to marine birds, gray whales commonly feed there on benthic prey, as do apparently growing numbers of piscivorous minke whales (D. Roseneau unpubl. data). The total removal of biomass from Ledyard Bay in summer is considerable; however, the processes responsible for such high benthic productivity are not known.

Green Belt North

The immense number (millions) of planktivorous least and crested auklets nesting in colonies on St. Lawrence I., King I., and the Diomede Is. is a highly conspicuous indication of an exceptionally rich prey base. Only one other auklet colony in Alaska, at Kiska I. in the Aleutians, rivals these colonies in size (Sowls et al. 1978). Studies of auklet diets at St. Lawrence I. in the 1960s and 1981 provided the first, and unequivocal, demonstration of the paramount importance of the Anadyr Current to the production regime of the northern Bering-Chukchi continental shelf Bédard 1969a, Springer and Roseneau 1985). ISHTAR subsequently identified the Bering Strait region as one of the most highly productive marine regions in the world, owing to copious nutrients and zooplankton advected in the Anadyr Current northward from reservoirs in the Bering Sea basin (Springer et al. 1989, 1993). Recent research indicates that inter-annual variation in auklet prey-composition reflects the influence of both the Anadyr Current and Bering Shelf waters on prey availability (Gall et al. 2006).

Not only is this production engine critical to nesting seabirds in the Bering Strait region, but it also supports large numbers of non-breeding and post-breeding birds from those colonies, post-breeding red and red-necked phalaropes from arctic Alaska and Canada, and migrant short-tailed shearwaters from the southern hemisphere. Biomass yield in this domain is undoubtedly important to the annual energy budgets of these birds.

Species of concern

All four species of eiders (king, common, spectacled, and Steller's), long-tailed ducks, and yellow-billed and red-throated loons nest on the arctic coastal plain and barrier islands of the Beaufort and Chukchi seas (Johnson and Herter 1989) and depend on marine prey for 75% to 100% of the year. Eiders and loons in the WA have undergone significant declines in abundance in the past several decades (Suydam et al. 2000a,b), spectacled and Steller's eider numbers have declined significantly in recent decades, and these species now are protected under the Endangered Species Act. The causes of these declines are not known, but the fact that they have occurred is evidence of major changes in the environment.

Ivory gulls do not nest in the WA, but many migrate through the area to winter in the northern Bering Sea (Haney and MacDonald 1995). Ivory gulls recently have undergone a population decline of around 80% in their Canadian high-arctic nesting areas (Gilchrist and Mallory 2005). Like the other declining species, the cause is not known, but declining sea ice is the most likely candidate (Gilchrist and Mallory 2005).

Information Gaps

We unanimously agreed that the most important information gap for marine birds in the WA is an understanding of foraging ecology, including knowledge of diets, foraging areas, and variability in both parameters over time. Information on foraging ecology provides clear insights into ecosystem structure and dynamics and must be considered when searching for causes of population change.

A related major gap that also was unanimously acknowledged is that an understanding of the oceanographic processes responsible for making foraging "hot-spots" in the WA is needed. There is no available information about those processes supporting the apparently high productivity of Ledyard Bay polynya, the Pt. Barrow eddy, and the barrier-island lagoons (e.g., Johnson and Richarson 1981), or how that productivity might be altered by climate change. There is detailed information on production processes in the Bering Strait region and some waters northward, but no mechanisms have been proposed for how climate change may influence advection strength and flow of the Anadyr Current.

Second-tier information gaps include (in no particular order of importance):

- Metapopulation dynamics—are some colonies or areas consistently, or on average, more or less productive than others and, hence, serving as sources or sinks of birds, either regionally or beyond?
- Time scales of variability—what are the magnitude and importance to population change of interannual, decadal, and secular environmental variability?
- Direct effects of climate change—how will changes in sea ice, storm strength and frequency, wind intensity and direction, precipitation, wave height, coastal erosion, and other physical factors directly affect the abundance and productivity of marine birds?

Research Recommendations

We discussed numerous ideas and specific targets (e.g., species, locations, measurements) for research and agreed that the most important ones fell into the following themes. We chose to present research priorities as themes to encourage innovation among those who may propose studies on marine birds in the WA.

- **Foraging ecology:** The principal forage species of seabirds in the WA (and elsewhere in Alaska), are the same as those supporting other planktivorous and piscivorous taxa such as pinnipeds and cetaceans. Because marine birds are numerous and can be logistically simple and inexpensive to study from land, using them to sample the environment for forage species will be the most efficient means of monitoring variability in those forage populations. Moreover, change in the availability of forage species is one of the key drivers of population dynamics in many marine birds. A broader understanding of foraging ecology of marine birds would be achieved by connecting pelagic distributions with *in-situ* diet studies.
- **Consequences of variability in prey:** Knowledge of the consequences of variability in prey resources to marine birds is crucial to understanding and predicting effects of climate change on bird populations. Information on how individuals respond to the quantity and variability in prey is needed to address physiological, behavioral, and demographic issues related to population dynamics.
- **Process studies:** Foraging hot-spots in the WA are critical to numerous species of marine birds and mammals during significant portions of their annual cycles. In most cases, the oceanographic processes (physical, chemical, and biological) that make them so productive are not known. There is mounting evidence, and reason to believe, that climate change will alter basic features of local production regimes and will raise or lower the availability of important prey to seabird species, which generally forage at higher trophic levels. Hot-spots that must be targeted are Ledyard Bay and the Pt. Barrow eddy. Other high-priority hot spots are the barrier island-lagoon systems and the northern Green Belt.
- **Continuity:** To maximize the information that marine birds can provide on ecosystem components and variability and to obtain information needed to discover the cause(s) of population changes in some species, there must be continuity in research over time and space. Data streams should be maintained at important marine bird colonies and at foraging and migratory hot-spots. Continuance of long-term observations is a priority at locations where observations have been maintained annually and at locations with long histories of information, even if there have been stretches of many years between successive visits—continuity is important at both annual and decadal time scales. Spatial continuity also is important—comparisons between colonies located in the same habitat (e.g., upstream and downstream in the Alaska Coastal Current) and in different habitats (e.g., the Alaska Coastal Current and the Anadyr Current) will help one to understand better the nature and pervasiveness of environmental change.
- **Retrospective analyses and syntheses of information:** The success of future studies of marine birds in the WA will benefit from a thorough review and synthesis of what we already know about them. Such an exercise will lead to questions and hypotheses that can be tested by focused research.
- **Data archival:** There must be an efficient, user-friendly system to store and disseminate data, both historical and current, obtained from studies of marine birds and other components of the WA ecosystem.

MARINE MAMMALS

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Ian MacDonald / TAMU

Introduction

Marine mammals are top predators that structure arctic marine ecosystems and are an important source of food and cultural identity for arctic peoples (Metcalf and Robards 2008, Moore and Huntington 2008). Sea ice is central to arctic marine mammal habitats (Laidre et al. 2008), as it provides a platform for hunting, rearing young and resting for 'ice-obligate' species (e.g. Derocher et al. 1983, Stirling et al. 1993), is key to bio-oceanographic processes that lead to prey availability for 'ice-associated species' (Bluhm and Gradinger 2008) and is an important, if incomplete, refuge from predation (Stirling 1975, Bonner 1984, Kelly 2001). Changes in marine mammal populations have occurred over millennia in response to climate changes at various scales (e.g., Harrington 2008). In the case of bowhead whales (*Balaena mysticetus)*, for instance, shifts in distribution are inferred through the presence of skeletal remains in ice-bound areas of the high arctic (Dyke and Morris 1990). Pelagic commercial (Yankee) whaling greatly reduced bowhead and Pacific walrus (*Odobenus rosmarus*) numbers in the western arctic (Bockstoce 1986), and bowheads have still not reached pre-whaling abundance (George et al. 2004).

Some marine mammals, such as the ice-associated seals and polar bears (*Ursus maritimus*), have an obligate relationship with ice meaning that successful foraging and breeding depend on the presence of ice (Burns 1970, Fay 1974, Stirling et al. 1993, Moore and Huntington 2008, Laidre et al. 2008). Ice provides a substrate for hauling out, pupping and nurturing young. Ice also provides a substrate for invertebrate prey of ringed seals (*Phoca hispida*) (e.g. epontic communities). Some species, like belugas (*Delphinapterus leucas*) and perhaps bowhead whales, benefit from productivity associated with the ice and from the refuge it provides from predation, but they may be able to exist without it. The consequences of changing exposure to predators and competitors in an ice-free environment are uncertain, as are effects of changing ice and oceanographic conditions on fish and invertebrate prey. Humpback (*Megaptera novaeangliae*), minke (*Balaenoptera acutorostrata*) and gray whales (*Eschrichtius robustus*) are inhibited by ice and may benefit with sea ice retreat (George et al. 2005, Moore and Huntington 2008). Recent analyses suggest that even bowheads, a highly ice-adapted species, may benefit from limited ice retreat (George et al. 2005), or from the extreme variability in sea ice cover noted in areas used by bowheads for feeding and migrating (Moore and Laidre 2006) – at least in the short run. Finally, sea ice caused changes in marine mammal distribution (e.g. gray whales and walrus) may alter the structure of benthic communities by affecting nutrient turnover or physical characteristics of the seafloor (e.g. Oliver and Slattery 1985).

Extensive field studies, including tracking by satellite transmitters, have provided considerable detail on the use of sea ice by polar bears (Stirling et al. 1980, Amstrup et al. 1986, 2001a, 2001b, Derocher and Stirling 1995, Clark et al. 1997, Stirling and Lunn 1997, Ferguson et al. 1998, Stirling et al. 1999, Mauritzen et al. 2001, Taylor et al. 2001). Less advanced is our understanding of the specific ways that sea ice is important to pinnipeds (Vibe 1950, Burns 1970, Fay 1974, Lukin 1981, Smith and Hammill 1981, Smith and Lydersen 1991, Smith et al. 1991, Furgal et al. 1995, Kelly 2001, Barber and Iacozza 2004) and cetaceans (Burns et al. 1981, Crawford and Jorgenson 1990, Moore 2000) although satellite-linked telemetry is beginning to advance our knowledge of sea ice associations for pinnipeds (Lowry et al. 2000, C. Jay unpub. data), beluga (Heide-Jorgensen et al. 1998, Suydam et al. 2001, Richard et al. 2001, Laidre et al. in review) and to some extent gray and bowhead whales (Mate et al. 2000, 2006, L. Quakenbush unpub. data).

Arctic sea ice is decreasing in thickness, aerial extent, and seasonal duration (Chapman and Walsh 1993, Johannessen et al. 1995, Cavalieri et al. 1997, Rothrock et al. 1999, Vinnikov et al. 1999, Walsh and Chapman 2001, Parkinson and Cavalieri 2002, Serreze et al. 2007, Walsh 2008) more quickly than we are learning the specific ecology of the animals that depend on that habitat. This trend substantially escalated after 1989 when Arctic atmospheric circulation patterns underwent a regime shift (Johannessen et al. 1995, Deser et al. 2000, Overland et al. 2008). The extent and characteristics of ice have been very different during the last decade verses the 1970s (Walsh 2008) when the relationship of marine mammals to sea ice was last examined and described (Fay 1974, Burns et al. 1981). The effects of these changes can be positive or negative (or unknown) depending on the relationship of a particular species to sea ice (Moore and Huntington 2008, Laidre et al. 2008).

Most ice-associated marine mammal species are important sources of subsistence food in northern Alaska. They are regularly hunted by many Bering, Chukchi and Beaufort Sea communities. Such foods are important culturally as well as nutritionally (Stoker and Krupnik 1993, Braund 1988). This dual importance means that hunting and use of marine mammals will continue into the future. For species such as bearded seals (*Erignathus barbatus*), bowheads, gray whales, and perhaps beluga, current use is as great or greater than it was 50 years ago and may increase. Thus, in addition to their ecological importance and conservation concerns, it is important to study these species from a resource perspective (e.g., Metcalf and Robards 2008).

Finally, it is important to note that unlike most other groups, conservation concerns exist for many of the marine mammals. Bowheads are listed as endangered and have been for some time. In May 2008, the polar bears became listed as threatened. Petitions have also been recently submitted to list all the ice seals and walruses as threatened. In contrast, the Eastern North Pacific population of the grey whale has rebounded in recent decades and was delisted as a species of concern in 1994.

Below we discuss some of the current associations between marine mammals, habitat and human influences (see also, Hovelsrud et al. 2008, Ragen et al. 2008). We speculate on how climate change, ice-retreat and human influences (oil and gas development, hunting, etc.) could affect these species. We also list research recommendations for these species.

Study History

Marine mammal species that regularly occur in the Chukchi and Beaufort seas include polar bears, walruses, four species of ice-associated seals (ringed, bearded, spotted (*Phoca largha*) and ribbon (*Phoca fasciata*) seals), three odontocete cetaceans (belugas, killer whales (*Orcinus orca*) and harbor porpoises (*Phocoena phocoena*)) and three regularly occurring mysticete cetaceans (bowhead, gray and minke whales). Other marine mammal species, such as fin and humpback whales, occasionally occur north of Bering Strait but with little regularity.

Early studies of marine mammals in Alaska were conducted by federal (USFWS or NMFS) or state (ADF&G) agencies and the University of Alaska (e.g. Burns 1970, Fay 1974, 1982, Lentfer 1975, 1983). These studies were often initiated because a species was subject to hunting. There have been no systematic studies of killer whales, harbor porpoises, or minke whales in the Chukchi and Beaufort seas. Available information for these species – if it exists – is generally based on observations by researchers studying other species or reports of hunters and local residents. Even for marine mammals with dedicated research programs, much of the available information is still based on opportunistic reports of biologists, hunters and local residents.

One of the first extensive studies of ice seals in Alaska occurred as part of the Cape Thompson studies near Point Hope in the 1960s (Johnson et al. 1966). Most of the available information on vital rates of Alaska ice seals and belugas was collected under the OCSEAP program in the late 1970s and 1980s, was not published in the open literature and has not been revisited since then. ADF&G, however, has recently instigated an extensive biosampling program for ice seals and plans to analyze these recent samples in light of historical data. Recent beluga sampling is being conducted by the Alaska Beluga Whale Committee and the North Slope Borough (R. Suydam, unpubl. data). Studies of diet and trophic relationships of ice seals and belugas were also conducted under the OCSEAP program, and publications of those results are generally the most recent information available information.

Extensive research on the western arctic population of bowhead whales started in the mid-1970s due to pressure from the International Whaling Commission on the US to provide a reliable population estimate and assessment of the effects of removals. Population studies were initiated by NOAA/NMML in the late 1970s, then in the 1980s most of the responsibility shifted to the NSB. The OCSEAP program, and later Minerals Management Service, also funded studies of bowhead and gray whales.

Research on polar bears in Alaska began in 1967, with initial studies employing capture-recapture methods, that were aimed at estimates of population size and composition (Amstrup et al. 1986, Amstrup 1995, McDonald and Amstrup 2001, Amstrup et al. 2001). Radiotelemetry studies began in 1981 and made information available on movements and distribution (Amstrup et al. 1986, Amstrup and DeMaster 1988, Garner et al. 1994). Radiotelemetry data also provided the first reliable estimates of survival and recruitment rates for polar bears in Alaska (Amstrup and Durner 1995). Satellite telemetry was used starting in 1985 and has allowed movement rates to be quantified for female (Amstrup et al. 2000) and to a lesser extent male polar bears (Amstrup et al. 2001). Also, satellite telemetry has allowed us to define populations and determine probabilistic boundaries (Amstrup et al. 2004, Amstrup et al. 2005). In addition, radiotelemetry data helped to elucidate the timing and distribution of maternal denning in Alaska (Amstrup 1993, Amstrup and Gardner 1994) and the terrestrial habitats that female polar bears choose for denning (Durner et al. 2001, Durner et al. 2003, Durner et al. 2006). Although sample sizes have been small, tissues from captured animals have provided windows into genetic structure of polar bear populations (Cronin et al. 1991, Amstrup et al. 1993, Paetkau et al. 1999, Cronin et al. 2006).

Current State of Knowledge

Polar Bears


Ian MacDonald / TAMU

Polar bears are the apical predator of arctic marine systems (Amstrup 2003). They are entirely dependent upon sea ice for foraging. The sea ice provides a platform for hunting ringed and bearded seals (Stirling et al. 1993). The abundance and distribution of these seals are assumed to depend on seasonal and annual variability of ice characteristics (Burns 1970, Fay 1974, Burns et al. 1981) and ecosystem productivity (Stirling and Oritsland 1995). During their coevolution with ringed seals, polar bears have adapted to a multitude of seasonal ice characteristics (Stirling et al. 1993, Ferguson et al. 2000, Durner et al. 2004). Movements of polar bears in different geographic regions may be determined by differences in the sea ice (Amstrup et al. 2000, Ferguson et al. 2000). Therefore changes in polar bear population status and distribution are indicative of the health and status of the sea ice ecosystem (Stirling and Derocher 1993, Stirling 1997).

Observed and predicted changes in sea ice patterns may be used to estimate the future status of polar bears (Stirling and Parkinson 2006). Polar bears and their primary prey, ringed seals, are closely linked and understanding the population status of either polar bears or ringed seals has been used to help explain the population status of the other (Stirling and Øritsland 1995). The welfare of polar bears is dependent on the welfare of ringed seals and on the availability of seals at the water-sea ice-air interface. Polar bears also select habitat in order to avoid conspecifics or to locate mates (Stirling et al. 1993). How predicted sea ice changes may affect ringed seal availability to polar bears is yet to be determined.

Polar bears attempt to remain on sea ice over or near the shallow waters of the continental shelf (Durner et al. 2004). Ocean depth was the primary determinant of polar bear distribution during autumn, winter and spring. In winter polar bears select ice floes > 2000 m in diameter that are composed of a high proportion of young ice. They also select habitats near an ice edge and first year sea ice. Selection for floes > 2000 m in diameter, regardless of ice stage, continues in spring. Polar bears also select habitats with high concentrations of sea ice during spring. Habitat use in summer is primarily driven by selection for an ice interface and high concentrations of multiyear ice. Polar bears, however, also select first-year ice and young ice in close proximity to an ice interface (Durner et al 2004). The selection for multiyear ice during summer (Ferguson et al. 2000, Durner et al. 2004) is likely due to preference of bears for the stable platform that multiyear ice provides during the season of minimal ice. Proximity to an ice edge and a high ice concentration continue to be important habitat requirements for polar bears during autumn. In recent years, the relatively shallow waters over the Alaskan continental shelf, which are important foraging habitat for polar bears, have become unavailable during the late summer and early autumn due to retraction of sea ice from shore. Consequently, polar bears have been forced either onto shore where they cannot hunt for their preferred prey or beyond the continental shelf, where foraging opportunity is thought to be low. Nutritional stress of females is expected to result in decreased reproductive output and survival of young, and may lead to cannibalism among males (Amstrup et al. 2006).

The effects of climate change on body condition, productivity and survival of various sex/age classes, and corresponding information on status and trend are needed for polar bears in both the Chukchi and Beaufort seas. Baseline life history information (time series abundance and morphometric data) regarding polar bear population status and trend is available for the southern Beaufort Sea population, but not for the Chukchi Sea population. Research on the Chukchi Sea population has been hampered in the past due to the vastness and logistical complexities of conducting studies in the Chukchi and due to international jurisdictional issues. However, in the spring of 2008 the USFWS, in collaboration with the USGS, initiated a long-term mark-recapture study in the Chukchi Sea to investigate polar bear population life history parameters. The Chukchi and Beaufort Sea populations of polar bears are examples of pelagic polar basin populations (Garner et al. 1994, Scribner et al. 1997), and both are likely to respond in a similar fashion (although not necessarily at the same rate) to changing polar basin sea ice conditions. Future studies in both regions, therefore, must be designed to take advantage of the foundation of baseline studies available from the Beaufort.

Ice-associated seals (Ringed, bearded, spotted and ribbon seals)


NOAA

Ice-associated seals typically live 25 years or more with high rates of first-year mortality offset by high survivorship of adults. Females reach sexual maturity at 3–8 years and males typically one or two years later (Kelly 1988a-c, Quakenbush 1988). A single pup is born annually, and pregnancy rates typically exceed 90%. The timing of pupping coincides with maximal ice extent for spotted, ribbon, and bearded seals which breed near the edge of the pack ice or in other areas of broken pack. Ringed seals give birth in shorefast as well as in pack ice, and pupping is somewhat later and appears to coincide with optimal snow conditions for the occupation of subnivean lairs (Kelly 2001). Bearded seal pups are nursed for 2–3 weeks, ribbon seal pups for 3-4 weeks, spotted seal pups for 4-6 weeks, and ringed seal pups for 5-7 weeks (Burns 1970). Mating typically takes place at the end of lactation in late April or May extending, in the case of ringed seals into June. Subsequent to lactation and mating, adult seals undergo a molt in which the epidermal tissues are shed and replaced with new growth. Regeneration of the epidermis is energetically expensive and takes place over periods of 3 months or longer (Ashwell-Erickson et al. 1986). Growth of the new tissue requires elevated skin temperatures (Feltz and Fay 1966), and seals spend prolonged periods out of the water warming the skin in the sun during late spring or early summer.

Ice-associated seals are major predators on Arctic fishes and invertebrates (Lowry et al. 1978, 1980a,b, Frost and Lowry 1980, 1986, Bukhtiyarov et al. 1984). While we have some understanding of their trophic role in the Arctic habitat (Lowry and Frost 1981, Frost and Lowry 1984) most of this information is 20-30 years old. Furthermore, the difficulties and expenses associated with surveying populations still prevent us from obtaining accurate population estimates, and hence determining the true impact of ice-associated seals on the ecosystem.

Important data on stock structure are just beginning to emerge. These data are critical to: interpreting survey data; predicting impacts of harvests and environmental change; and assessing the vulnerability of populations to local extinction.

Twenty years ago, research recommendations often emphasized determining population size and monitoring harvests (Kelly 1988a-c, Quakenbush 1988). Population size and trends have remained largely unknown for ice-associated seals in Alaska due to the large areas over which they are distributed, the high costs of surveys, and inadequate knowledge of habitat selection and factors influencing the availability of seals for counting. In recent years, progress has been made in understanding habitat selection and behaviors influencing availability (Lowry et al 2000, Moulton et al. 2002, Kelly et al. 2003, Simpkins et al. 2003, Frost et al. 2004, Kelly 2005), but the difficulties of vast areas and high costs remain.

Today, the determination of stock structure and habitat requirements has taken on greater importance as sea ice and snow cover diminish. Recent evidence of limited gene flow among harbor seals (*Phoca vitulina*) (O'Corry-Crowe et al. 2003) and ringed seals (Kelly 2005, Swanson et al. *in press*) underscores the need to investigate population structure in all of the ice-associated seals. Understanding gene flow will be critical to assessing the vulnerability of populations to local extinction as the sea ice and snow cover of the Arctic Ocean diminish. Advances in satellite-linked telemetry have allowed substantial progress in tracking the movements and habitat use of spotted seals (Lowry et al. 1998, 2000) and, currently, ribbon seals, ringed seals, and bearded seals (Frost, Kelly and NMML unpubl. data.). Most satellite tags deployed to date stayed attached for less than a year and data were of limited use in making inferences about site fidelity and gene flow. However, in 2005 and 2006 ringed, spotted and ribbon seals were instrumented with tags designed to remain attached and transmit for more than a year (the University of Alaska Southeast and NMML, in cooperation with the Ice Seal Committee and the North Slope Borough) Already the tags on ringed seals have helped demonstrate interannual fidelity to breeding sites among ringed seals (Kelly, unpubl. data).

Tracking movements even for a year or two is inadequate to quantify gene flow in these long-lived species. Therefore, ADF&G and NMML have been collecting tissue samples from the Alaska Native subsistence harvest for the investigation of population structure. They reported high levels of genetic diversity in samples collected in the Bering Strait region, but recognized that they “may be sampling from an area where distinct sub-populations are sharing a common geographic area” making it “difficult to detect subdivisions” (ADF&G, Arctic Marine Mammal Program, December 2004 *submitted* to the Ice Seal Committee). In fact, outside of the breeding season, all species of ice-associated seals have been recorded moving hundreds and thousands of miles (Kapel et al. 1998, Lowry et al. 1998, Harwood et al. 2000, BP Kelly unpublished, KJ Frost unpublished, NMML unpublished). With support from the NPRB, the University of Alaska Southeast, Central Michigan University, and the Ice Seal Committee are analyzing micro satellite and mtDNA markers from samples collected only at breeding sites. The DNA is extracted from shed skin collected on the ice and from teeth archived in museums (Swanson et al. *in press*). Large sample sizes are available from those sources and the approach has potential application to the other species of ice-associated seals.

The importance of sea ice in the evolution of pinnipeds is reflected in increasing species richness with increasing latitude (Kelly 2001). Burns (1970) and Fay (1974) described some of the relationships of ice-associated seals to particular types of sea ice. Predicting the impacts of changing ice and snow cover on seals, however, will require considerably more detailed understanding of the ways in which ice and snow are used by those animals (Tynan and DeMaster 1997, Kelly 2001). Recent reports have shown, for example, the importance of the timing of snow and ice melt on survival of ringed seals (Kelly 2001, Smith and Harwood 2001, Stirling and Smith 2004). Other species are likely to be impacted differently depending on their ecological relationships to sea ice (Bluhm and Gradinger *in revision*).

In addition to their needs for specific ice and snow habitats, availability of prey also influences the distribution of seals. The diet of ice-associated seals throughout the year was described from samples taken at Point Hope in the Chukchi Sea (Johnson et al. 1966). Samples of stomach contents were collected at additional locations in Alaska primarily during spring through fall, although some were year-round (Lowry et al. 1978, 1980, Frost and Lowry 1980, 1986, Bukhtiyarov et al. 1984). These studies were generally adequate to characterize prey types, but larger samples and more geographic coverage are needed to better understand variability in diet, and how this may be related to the spatial variability in populations. Samples are currently being collected by ADF&G to facilitate comparisons with earlier studies. Ultimately diet needs to be linked to prey distributional data and "hot spots" to better understand the foraging ecology of these seals (Bluhm and Gradinger *in revision*).

Ice-associated seals remain important subsistence resources in Alaska. Periodically, ADF&G, NMFS, the U. S. Fish and Wildlife Service, and Alaska Native organizations including Kawerak, Inc. and the North Slope Borough have produced partial estimates of the subsistence harvest of ice-associated seals. There are no comprehensive attempts underway to estimate the harvest, but based on a variety of sources, NMFS estimates annual harvests in Alaska at approximately 5,000 spotted seals, 7,000 bearded seals, 10,000 ringed seals, and 200 ribbon seals (Angliss and Outlaw 2005). In the absence of reliable population estimates and a good understanding of stock structure, it is not possible to evaluate the population impact of these harvests. Given their importance in native diet, the potential impacts of offshore petroleum exploration and development remain of concern, especially in light of the damage to marine mammal populations resulting from the *Exxon Valdez* oil spill (Loughlin 1994). Impacts of oil development on ringed seals in the Beaufort Sea of Alaska have been documented on local but not larger scales (Kelly et al. 1988, Moulton et al. 2005).


NOAA

In recent decades, there have been several attempts to determine research needs and develop recommendations for efforts on ice-associated seas. In 1987, the U.S. Marine Mammal Commission (MMC) convened a workshop of marine mammal scientists to develop research and management recommendation for several species of marine mammals, including ice-associated pinnipeds, in Alaska (Lentfer 1988). The MMC considered as "critically important" determining diet and reproductive rates from analysis of stomach contents and reproductive organs of ribbon seals and spotted seals as well as enumerating spotted seals. They considered as "essential" conservation tasks the monitoring of harvests of ringed seals, bearded seals, ribbon seals, and spotted seals; improving estimates of population size for ringed seals and bearded seals; determining habitat requirements for ringed seals; and improving our understanding of population discreteness for all species.

In March 1994, the NMML hosted a workshop "on the use of ice-associated seals in the Bering and Chukchi seas as indicators of environmental change" (Davis 1996). The report called for an "analysis of the historical response in parameters such as life history, distribution and diet of ice-associated seal populations to fluctuations in environmental features (such as sea ice extent or the magnitude of the northward flow through the Bering Strait)." Prior to developing specific proposals, the report called for (1) an update to the overview in Lentfer (1988), (2) coalescing U.S. and Russian data on ice-associated seals into a single database, (3) resumption of biological sampling of the subsistence harvest of ice-associated seals, (4) synthesizing data from the Canadian Arctic and elsewhere to refine specific hypotheses, and (5) relating environmental variables to the distribution and life history patterns of spotted and ringed seals. In 2000 the MMC again held a workshop on the "impact of changes in sea ice and other environment parameters in the Arctic" in which many of the same recommendations emerged (http://www.mmc.gov/reports/workshop/seaice.html).

In 2005, representatives of the North Slope Borough, the Maniilaq Association, Kawerak, Inc., the Bristol Bay Native Association, and the Association of Village Council Presidents formed the Ice Seal Committee "to preserve and enhance the marine resources of ice-associated seals including the habitat; to protect and enhance Alaska Native culture, traditions, and especially activities associated with subsistence uses of ice-associated seals; to undertake education and research related to ice-associated seals." Toward those ends, the Ice Seal Committee, in cooperation with researchers from the National Marine Fisheries Service, the Alaska Department of Fish and Game, the University of Alaska Southeast, and the University of Alaska Fairbanks, is developing a "Coordinated Plan for Research on Ice-associated Seals in Alaska." That plan, still in draft, identifies specific research needs that appear within our recommendations.

Killer whales


NOAA

Killer whales are known predators on bowhead, beluga and gray whales (Lowry et al. 1987 a,b, George et al. 1994) and likely predators of smaller cetaceans and seals. Observations by Chukotka natives suggest that predation is increasing on gray whales in Russian waters. Killer whales are uncommon but regular as far north as Barrow and evidence of predation on gray whales and other marine mammals in Alaskan Chukchi waters is also fairly regular (Lowry et al. 1987b, George and Suydam 1998). Reduced ice may allow killer whales to access more northern waters and expose some species (such as bearded seal and belugas) to increased predation. Little is know about the origin or stock status of the transient (marine mammal eating) killer whale populations that frequent the northern Bering Sea and Alaskan arctic coast (Craig Matkin, pers. comm.), but investigations of the role of killer whales in the Aleutian Island-Bering Sea ecosystem are well underway (DeMaster et al. 2006, Wade et al. 2007).

Bowhead whales

Bowhead whales are long-lived marine species, with life expectancies of 100 years or more, during which they reach up to about 18 m in length. Bowheads undertake an annual migration from wintering areas in the northern Bering Sea to summering areas in the Alaskan and Canadian Beaufort Sea (Moore and Laidre 2006). They are generally associated with shelf and slope waters of the Arctic, where they feed primarily on copepods and euphausiids (Moore et al. 2000, Lowry et al 2005). Feeding in deep pelagic waters may occur but is not well documented. In part due to their large size and accessibility in nearshore waters, bowhead whales are an important nutritional and cultural species in the subsistence hunting activities of 10 coastal villages in Alaska, and hunts include participation by numerous inland communities as well. They are managed via a very conservative management scheme under the purview of the IWC and a joint NOAA/AEWC comanagement agreement. Whaling is considered the social-cultural 'glue' that defines and holds together these communities (Stoker and Krupnik 1993, Braund, 1988, SR Braund and Associates 1993). The Alaska Eskimo Whaling Commission (AEWC) argues that maintaining a healthy bowhead population is paramount to maintaining healthy communities.

The most recent (2001) abundance estimate for bowheads is 10,470 (SE =1,351) with a 95% confidence interval of 8,100 to 13,500. A time-series of population estimates from 1978-2001 strongly indicates the population is increasing at an estimated rate of 3.4% (95% CI 1.7% to 5%). Stock structure studies for the western Arctic or Bering-Chukchi-Beaufort Seas (BCBS) bowhead whale have been the focus of recent investigations. Analysis using new microsatellite markers suggests one panmictic stock (Givens et al. 2006), consistent with previous conclusions of the International Whaling Commission's (IWC) Scientific Committee.

Studies regarding responses of bowheads to ecosystem changes are few. Moore and Laidre (2006) examined trends in sea ice in bowhead whale habitats and found strong interannual variability, especially in areas used by bowheads for feeding. The time series of population abundance estimates corresponds with the period of maximum ice retreat and shows a clear increase in number for this species. Absolute and percent-calf production have also increased since 2001 and there is some evidence that calving intervals may have, in fact, shortened to 3 years for most females (George et al. 2004). Analysis of body condition and sea ice density suggests that body condition is better during periods of low ice density in the central-eastern Beaufort Sea feeding grounds (Nicholson et al. 2005). All these observations are consistent with recent evidence that bowheads appeared to be more widespread during warm inter-glacial periods (Savelle et al. 2000). There is some concern that gray whales have become more common in the western Beaufort Sea and may compete for prey with bowhead whales in these waters (Moore et al. 1986, 2006, Stafford et al. 2007). Nonetheless, although the long-term effects of ecosystem change on bowheads are hard to determine, from a purely ice-related perspective, they will likely fend relatively well compared with highly ice-dependent marine mammals like walrus and ice-seals.

Human impacts on bowheads have been the subject of considerable long-term studies over the last 3 decades (see Burns et al. 1993). The question of greatest concern, and most obvious initially, was with the effects of removals from subsistence hunting particularly when reliable population estimates were unavailable. Currently most studies are focused on the effects of oil and gas development on population stock structure. Documented impacts to bowhead whales due to oil and gas activities in North Slope adjacent marine waters have been from manmade noise. Major sources of noise include ship traffic, drilling, dredging, and seismic exploration, with seismic being the loudest. Most seismic exploration is carried out during the open water season, and thus, there is a time each year (late August until freeze up, usually late October) when seismic boats, fall migrating bowhead whales and subsistence hunters seeking the bowhead are all using the same waters (NRC, 2003). Several studies suggest that bowhead whales are perhaps the shyest of all large whales with reaction distances of over 30 km (and < 120 dB) to seismic and shipping noise. These reaction distances are among the largest and most consistent that we know of in the cetacean literature (Richardson 1999, 2000, 2006). Commercial fishing fleets may move north following expanding fish stocks and retreating ice, further contributing to increased noise. Other concerns include the effects of oil spills, fishing gear (Bering Sea) and commercial shipping – all of which could increase with ice-retreat and a warming climate.

Perhaps the largest unknown is how bowheads and subsistence communities will fare with increased human activities, especially rapid increases in oil and gas exploration and development (Ragen et al. 2008, Hovelsrud et al. 2008). They are among the shyest cetaceans and could abandon feeding areas if they become ensonified with industrial noise. Also, like their cousins the North Atlantic right whales, it is reasonable to assume that bowheads will suffer more entanglements (some leading to death) if exposed to increased crab fisheries and fishing activities (Burns 1993).

Pacific walruses


Joel-Garlich-Miller/USFWS

Pacific walruses are an important subsistence and economic resource, with total harvests in the U.S. and Russia estimated at about 6,000 animals per year (U.S. Fish and Wildlife Service 2001). Walruses rely on floating pack-ice as a substrate for resting, giving birth and nursing. Walruses generally require ice thicknesses of 60 cm or more to support their weight (Fay 1982, Richard 1990). Although walruses can break through ice up to 20 cm thick, they usually occupy areas with natural openings and are not found in areas of extensive, unbroken ice (Fay 1982). Thus, their concentrations in winter tend to be in areas of divergent ice flows or along the margins of persistent polynas. Concentrations in summer tend to be in areas of unconsolidated pack ice, usually within 100 km of the leading edge of the ice pack (Gilbert 1999). The availability of sea ice over appropriate depths for feeding is especially important for female walruses with dependent young that may not be capable of deep diving or long-term exposure in the water (Fay 1982). Walruses resting on the ice are passively transported to other feeding areas, which may help to prevent local depletions of their prey resource (Ray et al. 2006).

When suitable pack ice is not available, walruses must haul out to rest on land. Isolated islands, points and spits are most frequently occupied. Social factors, learned behavior, and proximity to their prey base are thought to influence the location of terrestrial haulout sites (Richard 1990). Many of the coastal haulouts in the Bering Sea see regular use through the ice-free season. Coastal haulouts in the Chukchi Sea usually do not form until late September or October after the sea ice has retreated to its minimum extent.

Although capable of diving to deeper depths, walruses are for the most part found in shallow waters of 100 m or less, possibly because of higher productivity of their benthic prey in shallower water. Walruses are known to forage on a wide assortment of benthic invertebrates (Fay 1982, Sheffield et al. 2001), relying principally on clams (e.g., *Mya*, *Serripes*, *Hiatella*, *Macoma*, *Nucula* and *Yoldia*; Fay 1982, Born et al. 2006). Prey densities are thought to vary across the continental shelf according to sediment type and structure; rates of recruitment and growth; and foraging pressure (Ray et al. 2006).

Between 1975 and 1990, aerial visual surveys were carried out by the United States and the former Soviet Union at five-year intervals, producing minimum population estimates for Pacific walruses ranging from 201,000 to 234,000 animals. The estimates generated from these surveys are considered conservative population estimates and are not useful for detecting trends (Hills and Gilbert 1994, Gilbert et al. 1992). Efforts to survey the Pacific walrus population were suspended after 1990 due to unresolved problems with survey methods that produced population estimates with unknown bias and unacceptably large confidence intervals for tracking population trends (Gilbert et al. 1992, Gilbert 1999).

In March and April of 2006, the U.S. Fish and Wildlife Service, in collaboration with the U.S. Geological Survey and scientists from Russia, conducted a range-wide survey of the Pacific walrus with the goal of estimating the size of the population. The study used a combination of aerial thermography and photography to count walruses over a large geographic area, and remotely-deployed satellite tags to measure the haul-out behavior of walruses (U.S. Fish and Wildlife Service and U.S. Geological Survey 2006). Development of the population estimate will be completed by early 2009. Repeating this survey in the future will allow the tracking of population trends.

Projected changes in the duration, thickness, and extent of seasonal pack ice in the Bering and Chukchi seas will likely affect walrus distributions and behavior (Tynan and DeMaster 1997, Metcalf and Robards 2008). Evidence is accumulating that the retreat of seasonal sea-ice in late summer off the continental shelf in the Chukchi Sea is impacting walruses. Female walruses with calves typically are distributed in summer in continental shelf waters where they use seasonal sea-ice as a platform for nursing and resting and can dive to the bottom to feed (Fay 1982). In 2004, nine sightings of walrus calves unaccompanied by adult females were documented (Cooper et al. 2006) consistent with predictions that retreat of sea-ice off Arctic continental shelves may impact negatively the feeding success and maternal care of walrus calves (Kelly 2001).

In summer 2007, sea ice extent reached a record minimum (Maslanik et al. 2007), retreating far offshore over the deep ocean basin where walruses cannot reach the sea floor to feed. In fall 2007, about 5,000 walruses hauled out at terrestrial sites in northern Alaska between Cape Lisburne and Barrow (J. Garlich-Miller unpubl. data). Many of these sites had not been used historically by walruses. Numbers of walruses hauled out at terrestrial sites in northern Chukotka are also increasing (Anatoly Kochnev, pers. comm.). One haulout, Vankarem, has increased from no use before 1997 to 30,000-40,000 walruses in 2007. Increased use of terrestrial haulouts by walruses is presumably in response to shortages of sea ice haulouts in areas shallow enough for walruses to forage. At terrestrial haulouts, walruses lose the advantages of continually moving sea ice as a feeding platform and become central place foragers, tied to land for resting and nursing. Impacts of thousands to tens of thousands of foraging walruses on benthic prey within the foraging radius of a haulout are not known.

Projected ecosystem changes in the Bering and Chukchi seas include changes in benthic community composition (Derocher et al. 2004, Hunt and Stabeno 2000, Overpeck et al. 2005, Grebmeier et al. 2006). In the northern Bering Sea, the ice-dominated shallow ecosystem that has supported some of the highest benthic faunal biomass densities in the world (Grebmeier et al. 1995) is being replaced by a system dominated more by pelagic fish (Grebmeier et al. 2006). These changes are predicted to be detrimental to benthic foragers such as walruses and gray whales.

Oil and gas exploration and development activities in the Chukchi Sea and North Aleutian Basin have the potential to impact walruses in a number of ways. Air and vessel traffic near haulouts may cause herds to stampede, resulting in disruption of energy budgets as well as possible physical injury or death. Noise from air traffic, seismic surveys, icebreakers, and supply ships may displace individuals and herds. Development of off-shore production facilities increases the potential for large off-shore oil spills; currently no successful methods exist for clean-up of oil in broken ice conditions. Walruses may be affected by oil spills directly, either through contact with oil or by ingesting contaminated prey, or indirectly through the loss of habitat or prey species.

There is uncertainty about the size and trend of the Pacific walrus population, and poor understanding of factors affecting population dynamics. A sustainable harvest level for the Pacific walrus cannot currently be determined. Walruses are dangerous to handle when awake and mortality is unacceptably high when they are anesthetized using current techniques. There is therefore a lack of information on demographic parameters that could be used to interpret changes in abundance and assess overall population health.

Important foraging areas for walruses throughout their range are poorly known. Species composition of available benthic prey is well known only for the St. Lawrence Island Polynya (Grebmeier et al. 1988, 1989). Deep-burrowing clams such as *Mya,* prey species preferred by walruses (Fay 1982), cannot be sampled effectively with traditional benthic sampling equipment and are therefore poorly understood. Walrus foraging strategies (e.g., foraging trip duration, distance traveled, prey selection) and calf-rearing strategies (e.g., milk composition, calf growth rates, calf weaning) are largely unknown. Little is known about how changes in climate, including changes in sea ice thickness, extent, and duration, may affect walruses or their benthic prey. Impacts of development such as offshore oil and gas recovery efforts are also largely unknown.


NOAA

Gray whales

The Eastern North Pacific (ENP) population of gray whales was removed from the endangered species list in 1994 (Rugh et al. 1999). The population is considered fully recovered from commercial whaling and is estimated to number between 17,000 and 18,000 whales (Rugh et al. 2005). An unusual mortality event was documented in 1999 and 2000, when roughly 250 and 300 whales, respectively, stranded dead (or, nearly so) on beaches stretching from Baja California to south-central Alaska (Gulland et al. 2005). While a reduction in prey in the northern Bering Sea was proposed as causal to the mortalities (Le Boeuf et al. 2000), disease and other factors could not be ruled out (Moore et al. 2001).

The ENP population of gray whales undertakes one of the longest migrations of any mammal, from feeding areas in the North Pacific and Arctic waters to calving grounds in lagoons of Baja California and the Sea of Cortes (Swartz et al. 2006). Gray whales are capable of feeding on a broad array of prey, from benthic crustaceans (infaunal and epifaunal) to zooplankton such as euphausiids and crab larvae, to small fishes and herring roe (Nerini 1984, Darling et al. 1998, Dunham and Duffus 1999, 2001, Bluhm et al. in revision). While whales seem to prefer shallow continental shelf and shoal habitats throughout their range (Swartz et al. 2006, Moore et al. 2000), there are sightings reported from deep waters of Monterey Bay and the Gulf of Alaska. Habitat requirements likely include continental shelf and shoal habitats for feeding, and protected waters such as small bays and lagoons for calf protection during the first weeks of life.

There are indications that ENP gray whales are responding to ecosystem change by feeding predominantly in the Chukchi rather than the northern Bering Sea, as they did in the 1980s (Moore et al. 2003), delaying their southbound migration and routinely feeding at sites along the migration route (Moore 2008). This shift northward is coincident with a suite of physical changes in the northern Bering Sea (Grebmeier et al. 2006), including the precipitous decline in infaunal amphipods in the Chirikov Basin, first noted by Highsmith and Coyle (1992). In addition to routine summer and autumn sightings of gray whales near Barrow, the calls of gray whales were recorded during winter 2003-04 on autonomous recorders co-located with a mooring line in the western Beaufort Sea (Stafford et al. 2007). In addition, gray whales are now routinely seen year-round offshore of the southeast coast of Kodiak Island (Moore et al. 2007) suggesting at least some whales are not undertaking the southbound migration each year. Some of these changes are likely mediated by the decline in sea ice documented over the past decade. This decline in sea ice also may influence calving rates, whereby years of extremely light ice in spring are correlated with high calf counts the following year (Perryman et al. 2002).

Human impacts to gray whales come in the form of direct harvest by Russian hunters, lethal bycatch in fishing gear, exposure to persistent organic pollutants including organochlorines and petroleum by-products, as well as exposure to a broad range of anthropogenic noise including that from oil and gas development (e.g. seismic airguns) and large tanker traffic at busy ports along the migration routes. Although removed from the endangered species list, there is still cause for concern for ENP gray whales, in that causal elements from the 1999-2000 mortality event remain unidentified, and bycatch and pollution threats are chronic and likely to increase in the future. One particular ‘mystery’ in this regard is the report of ‘stinky’ gray whales (i.e. whale blows & meat having a strong petro-chemical odor) along the Russian Chukotka coast (IWC.BRG Annex 2005).

Gray whales hold the potential to be remarkable sentinels for ecosystem variability and change (Moore 2008). While there exists a comparatively long record of population estimates (since 1967), information on basic ecology and responses to environmental variability dates from only about the mid-1980s. Data gaps include: (1) a ‘healthy gray whale’ profile; (2) energetic requirements in the face of prey switching and environmental variability; (3) the influence of sea ice on whale body condition and calving rates; (4) fine and broad-scale movements of whales among feeding sites and along the migration corridor; (5) isotopic and POP profiles to determine feeding cycles and pollutant loads; (6) a genetic profile of the ENP population in comparison to the Western Pacific population.

Beluga whales

Beluga whales in northern and eastern Alaska belong to four separate stocks, based on distribution in summer concentration areas (Seaman et al. 1986, Lowry et al. 1989, Frost and Lowry 1990) and more recently mtDNA studies (O'Corry-Crowe et al. 1997). The four are: Bristol Bay (BB), eastern Bering Sea (EBS), eastern Chukchi Sea (ECS), and Beaufort Sea (BS) stocks. The status of Kotzebue Sound belugas – whether or not they constitute a separate stock – is uncertain, but recent molecular genetic studies suggest they may be (O'Corry-Crowe et al. 2002). Adequate abundance estimates exist for BB (1,888), EBS (18,142) and BS (39,258) stocks but not for the ECS stock (3,710), for which adequate methodology has not been developed (Harwood et al. 1996, Lowry et al. 1999, Frost et al. 2002, Angliss and Outlaw 2005). Recent surveys indicate the BB population is likely increasing (L. Lowry and K. Frost, pers. Comm..).

Belugas migrate between wintering grounds in pack ice and shallow coastal or estuarine waters during at least part of the summer where they may concentrate in large numbers (Burns and Seaman 1988, Frost and Lowry 1990). Occupation of coastal areas is thought to be for some combination of feeding, calving, molting and perhaps thermal advantage to neonates. Satellite tagging studies conducted on ECS, BB and BS belugas have provided some information on movements and habitat use (Richard et al. 2001a,b, Suydam et al. 2001, ADF&G, unpubl. data). In summer, adult males from the Beaufort and eastern Chukchi Sea stocks travel far north into deep-water areas with heavy ice cover. Females and younger males often remain closer to shore, along the continental slope or in shallower continental shelf water. Southward migrations begin in September-November. Belugas tagged in Bristol Bay remained within the Bay throughout the summer and early fall. Almost nothing is known about distribution and movements in winter for any stock. Few of the satellite tags deployed to date have transmitted later than December, although one beluga tagged in the Beaufort Sea traveled as far south as St. Matthew Island by January (P Richard, unpublished).

Beluga diet has been studied for a few specific areas during summer. They eat a variety of demersal and pelagic fishes and invertebrates, and may capitalize on seasonally abundant species such as salmon and herring (Seaman et al. 1982, Frost et al. 1993). In some areas such as Bristol Bay or Norton Sound they co-occur with commercial salmon fisheries and may impact or be impacted by those fisheries.

The role of sea ice for belugas is poorly understood. Belugas sometimes occur in mostly ice free areas (Bristol Bay, Norton Sound in summer) and at others in very heavy pack ice (Chukchi and Beaufort Sea belugas in summer, most belugas in winter). Satellite tagging has shown that at least large males can occupy areas of very heavy, extensive pack ice of >90% coverage in summer. At other times of year, however, belugas may become entrapped in sea ice and perish (Burns and

Seaman 1986, Lowry et al. 1987). Whether their association with pack ice is associated with foraging, predator avoidance or both is unknown.

Gaps in Knowledge (Overview)

Marine mammals are a large and diverse group of organisms with dramatically different lifestyles and habitats. Some species, such as polar bears, have been well studied, while others, such as harbor porpoises, have not been studied at all in the Alaskan Arctic. Even for those species which have been the focus of some study, information is far from adequate for management purposes or evaluating effects of anthropogenic or climate mediated change. A few common themes regarding data gaps are evident across all marine mammals: (1) abundance estimates are few and stock structure is poorly known for most species; (2) information about wintering areas is virtually non-existent; (3) temporal and geographic variability in diet and foraging areas are poorly known; (4) information about vital rates, if it exists, is outdated and does not reflect current environmental conditions; (5) studies are limited in temporal and/or geographic scale; and (6) the effects of changing climate and decreasing ice cover are unknown. More specifically:

- Population **enumeration** is non-existent for most species but relatively good for a few. Without information on stock structure, however, data are difficult to interpret even for species where abundance estimates exist.
- The **population structure** of most arctic marine mammals remains unclear but is fundamental to management protocols and risk assessment from natural and anthropogenic forces. Polar bears and belugas, and to some extent bowheads, are some of the few species for which population structure is understood to any degree. Almost nothing is known about population structure of ice seals, which are hunted extensively for subsistence.
- There is little or no information about **wintering distribution** and habitats for any species except polar bears and gray whales. Existing data for most species are for non-winter months when researchers can access marine mammal habitat.
- **Trophic interactions** of marine mammals were first studied 30 years ago. Although trophic structure is generally understood for most species (e.g., general prey types, where they feed in the food web), the specifics of seasonal, annual and geographic variability in diet are poorly quantified and foraging areas are poorly described.
- Climate change, including changes in sea ice, will likely affect **arctic marine ecosystems** including primary productivity and therefore food webs, as well as predation on and by marine mammals. Climate change effects are likely to vary by when, where and how species forage. Thus, good empirical measurements of marine mammal distribution and abundance year round coupled with robust climate / oceanographic data and models are needed to help make reasonable predictions about population level effects of arctic marine mammals.
- Robust data, models, predictions and threshold levels quantifying the **anthropogenic effects** (noise, hydrocarbons, contaminants, shipping, displacement, attractants, air pollution, commercial fishing, etc.) from industrial development (mining, shipping, oil and gas) on marine mammals are needed for all species. To be useful, it is imperative that such

studies be peer reviewed at both the design and reporting stages. Sensible mitigation measures should be the end-product of these research efforts.

- **Long-term ecological monitoring** and life history analyses are needed for all marine mammals. Due to the great variability in the arctic system, measurements from infrequent studies can be very misleading. Measures from studies conducted 30 years ago may or may not reflect current population dynamics. Predictive ecological models are not useful without good data. These studies should include identification and long-term monitoring of ecological "hotspots."

Research Recommendations and Areas of Biological Significance

Marine mammals are a diverse group. They are managed by several agencies and research has commonly been conducted along taxonomic lines. Their importance to subsistence economies and to what degree they are hunted vary by region and affect local priorities for research and the availability of biological samples. For this reason, data gaps and resulting research recommendations are not the same for all species. Consequently, we present overall recommendations that apply to several or all marine mammal species inhabiting the Chuckchi and Beaufort seas, as well as more specific species-based recommendations. We think the following are important:

- **Conduct long-term studies at a few key areas** where several marine mammal species are readily available for study. This will facilitate evaluation of the effects of long-term changes in climate and ice on marine mammals. Because marine mammals are long-lived species (30-100 years), we achieve only snapshots in time from short-term or one-time-only studies. Long term studies should be conducted at geographic centers that are accessible to researchers in a cost effective manner, have local logistics support available, and are suitable for study of more than one species. To maximize their comparative value, they should be located in areas where studies have occurred in the past.
- **Conduct longitudinal studies of habitat use/foraging areas and trophic complexes** – that is, include marine mammals in long term and site specific oceanographic studies such that data on habitat are obtained concurrent with information on marine mammal habitat selection.
- **Compile** long term data on snow and ice conditions specific to marine mammal questions (snow melt dates in ringed seal denning habitat, snow quality in denning habitats for bears, ice remnants, spatial characteristics of ice coverage, role of multi-year ice) and make it accessible to marine mammal researchers. Collaboration among marine mammal and sea ice researchers would be beneficial.
- **Integrate snow, ice and** biological productivity data (benthos, zooplanktons, fish, etc.) with information on marine mammal distribution, abundance and concentration/foraging areas.
- **Conduct focused studies of key forage species**. Thirty years ago as part of OCSEAP synthesis efforts, the need for basic biological information about key forage species was highlighted by seabird and marine mammal researchers. Little progress has been made since those recommendations were made. Among the most important forage species are: arctic cod (*Boreogadis saida*), saffron cod (*Eleginus gracilis*), sandlance (*Ammodytes hexapterus*), capelin (*Mallotus villosus*), copepods (*Calanus spp.)* and euphausiids (*Thysanoessa spp.*)

- **Collaborate with Russian scientists** to conduct marine mammal abundance studies and determine high benthic and water column productivity in the western Chukchi/Chukotka coast region, which we do not adequately understand. Additionally, this region is important for belugas, bowheads, gray whales, walrus, and spotted seals during summer and fall.
- We recommend the following general areas as foci for long-term and/or coordinated and multi-disciplinary studies: Kaktovik, Barrow, Point Lay/Kasegaluk Lagoon/Ledyard Bay and Kotzebue Sound/Cape Krusenstern to Point Hope. These areas coincide with areas of high marine productivity as well as areas important to seabirds and humans.
    - **Kaktovik** is an area of transition between a river (Mackenzie)-influenced system and ocean- influenced system in the eastern Beaufort Sea. Beluga and bowhead whales migrate past Kaktovik in spring and fall, and ringed seals, bearded seals and polar bears are common in the area. Recent summer sightings of killer whales and occasional reports of gray whales in the area make it ideal for monitoring for ‘atypical’ arctic species in the face of climate change. Further, bowhead whale stomach contents provide evidence of copepod feeding in waters near Kaktovik, contrasting with euphausiids feeding in waters near Barrow reflecting a dynamic difference in ecosystem dynamics in the eastern and western Alaskan Beaufort Sea.
    - **Barrow** is an area of high productivity (benthic and water column) and dynamic oceanography associated with the Barrow Canyon, and hosts a wide variety of marine mammals. Bowheads and belugas migrate by Barrow in spring and fall; ringed and bearded seals and polar bears are common in the area; and gray whales and walruses are increasingly common. Barrow is at the juncture of the Chukchi and Beaufort Seas, is subject to varying current regimes, and is suitable for the study of many species and disciplines (not only mammals). Barrow has served as a research center for decades.
    - **Point Lay/Kasegaluk Lagoon coast/Ledyard Bay** is an important region for spotted seals and beluga whales as well as seabirds. There are baseline studies of belugas and spotted seals in the region. Many other marine mammals use this region either as a migratory corridor or for feeding. Northwest of this lagoon system lies Hanna Shoal, an important feeding area for gray whales and possibly an overlap area between marine mammal distribution and anticipated oil and gas development in the Alaskan Chukchi Sea.
    - **Kotzebue Sound/Cape Krusenstern to Pt. Hope** has very high benthic productivity, is used by thousands of spotted, bearded and ringed seals and is a migration corridor for belugas, bowheads and walruses. Most of these species are important for subsistence. Kotzebue Sound would make an ideal regional base for coordinated and multidisciplinary studies, not only of marine mammals but of forage fishes and benthos eaten by marine mammals.
    - **Gambel/Savoonga-St. Lawrence Island** occupies a transition zone between sub-arctic and high-arctic biomes. Long term studies of benthic productivity north and south of the island, especially in polynyas, are key to understanding effects of climate change to diving sea ducks (spectacled eiders), walrus, gray whales. The Chirikov Basin, north of the island, is a vital area for bowhead whale overwintering and pre-spring migration aggregation and remains, in part, a gray whale feeding location. Further, with climate change we anticipate incursions of temperate species (e.g., humpback, minke whales), given summertime reports of these species already.

Research Recommendations – Species Specific

Polar Bears

Status and Trend

- Conduct periodic inventory/assessment and obtain polar bear population size estimates for Beaufort and Bering/Chukchi seas polar bear stocks.
- Describe seasonal, annual, and multi-annual movements of polar bears in and adjacent to Alaska, Canada, and Russia.
- Monitor population life history parameters for polar bears in and adjacent to Alaska. Conduct capture-recapture, harvest monitoring, and biomonitoring sampling programs to assess disease, contaminant, and unusual mortality events.
- Conduct annual den surveys in Russia (Chukchi Sea population/reproductive trend).

Habitat

- Describe polar bear activity areas and characterize their relative importance using resources selection function procedures, forward-looking infrared (FLIR) imagery, TEK, RFID and other techniques.
- Den habitat delineation.
- Ice habitat associations (spatial/temporal component).
- Describe key or essential habitats (seasonally) "*pulse points*".
- FLIR den study: Test efficacy of FLIR in locating dens in known denning habitat and validate technique

Effects of Environmental Change

- Describe polar bear habitat use patterns and effects of a changing ice and snow environment (in combination with research conducted in Objective 1 & 2).
- Climate change study: Conduct resource selection function modeling of polar bear ice habitat preferences, model forecast effects of changing sea ice environment on polar bear populations; assess past and present polar bear population size relative to environmental co-variates; assess past and present changes in polar bear sex and age composition, body condition, and morphometry relative to measurable changes in the environment (sea ice).
- Prey utilization study: determine prey species in polar bear diet, shifts in composition, and effects of changing ice environment.
- Ice seal study: Determine ice seal movement, productivity, and population structure of ringed and bearded seals in a changing ice environment.
- Snow habitat: Evaluate snow quantity, quality, and timing relative to polar bear denning and ringed seal pupping.
- Terrestrial habitat use: Evaluate and compare polar bear life history strategies for bears using land habitats seasonally vs. bears solely utilizing sea ice habitats.

Assess Effects of Human Activities and Development on Polar Bears

- Identify, detect, mitigate, or prohibit possible adverse effects of various developments or activities on polar bears and their habitats.
- Offshore exploratory/production sites: Evaluate if offshore drill sites attract or preclude polar bear use and corresponding risks.
- Den buffers: Quantitatively determine distances for dist.urbance free buffers around known polar bear dens.
- Oil spill risk assessment: determine the risk to polar bears of oil spills in the marine environment… spatial/temporal component.

- Bear-human interaction study: Conduct a bear-human interaction studies to determine behavioral responses of bears to humans and potential consequences.

Ice Seals

Population Status and Trends

- Determine the stock structure of ice-associated seals (in relation to snow and ice).
- Develop reliable and cost effective means of enumerating populations.

Habitat and Trophic Relationships

- Investigate the diet, foraging behavior and under-ice foraging ecology at a few key locations that can be compared to historical and future data.
- Relate foraging ecology of seals to prey distributions and concentrations.
- Investigate habitat selection with emphasis on snow and ice conditions.
- Determine seasonal movements and over-wintering areas.

Responses to ecosystem change

- Determine effects of changing sea ice on population and community structure.
- Determine effect of changing snow and ice-melt dates on temporal or spatial shifts in denning habitat, reproductive rates and pup survival.
- Determine effect of changing snow and ice-melt dates on timing of molting.
- Determine changes in habitat use, and specifically investigate habitat use relative to climate change using traditional knowledge and scientific studies.
- Develop methods for residents of coastal communities to record and communicate observations of animal and environmental conditions.

Human Impacts

- Improve estimates of harvest, and develop sustainable methods of monitoring subsistence harvest levels.
- Measure the nutrients and contaminants in bearded seals to assess the risks and benefits to human consumers.
- Develop education programs for teaching traditional hunting methods, biology, and conservation within the school system.

Pacific Walrus

Population Status and Trends

- Continue to improve techniques for estimating population size and tracking trends so that surveys are more precise, accurate, and cost-effective.
- Describe seasonal, annual, and multi-annual movements of walruses on both ice and at terrestrial haulouts in Alaska and Russia.
- Continue development of methods for safely handling or anesthetizing live free-ranging walruses.
- Develop techniques for measuring demographic parameters (e.g., rates of survival, reproduction, and movement) that can be used to interpret changes in abundance by providing information about population dynamics and population health.
- Continue to investigate the genetic (stock) structure of the population

Habitat Needs

- Identify important benthic foraging areas and characterize importance by walrus sex and age, patterns of seasonal use, ice type and coverage, and prey species composition and density.

- Identify walrus migration routes.
- Identify terrestrial haulouts and characterize importance by walrus sex and age and patterns of seasonal use.
- Designate critical habitats and work to protect these areas in both Alaska and Russia.

Responses to Ecosystem Change

- Examine walrus-sea ice relationships and characterize walrus ice haulout choices by ice characteristics (ice age, type, thickness, floe size, percent open water, etc.) as well as by benthic characteristics (water depth, prey species composition, prey density).
- Use existing predictive sea-ice models to predict impacts on walruses of reduced sea ice thickness, extent, and duration.
- Monitor patterns of terrestrial and sea-ice haulout use by walruses, with consideration given to walrus sex, age, and reproductive status.
- Measure a selected suite of demographic parameters over appropriate spatial and temporal scales to track changes in walrus foraging strategies, recruitment, and other aspects of life history.

Human Impacts

- Conduct disturbance studies to determine behavioral responses of walruses to seismic sampling, vessel traffic, aircraft flights, and other types of potential disturbance.
- Evaluate whether offshore exploratory and production sites preclude or reduce use by walruses of surrounding benthic foraging areas.
- Quantify walrus responses to disturbance so that disturbance-free buffer areas can be created around important walrus terrestrial and sea-ice haulouts and foraging areas.
- Assess the risk associated with an oil spill in the marine environment to walruses, their terrestrial and ice haulouts, and their benthic foraging areas.
- Conduct harvest monitoring and biomonitoring sampling programs in both Alaska and Russia to assess harvest levels, disease, exposure to contaminants, and unusual mortality events.

Bowheads

Population Status, Heath Assessment and Trends

- Continue time series of abundance estimates (at 5-10 year intervals) and studies on stock status for the BCBS bowhead whale population.
- Continue detailed post-mortem examinations of bowhead whales but include all villages, not just Barrow and Kaktovik (current situation).

Habitat and Trophic Relationships

- Initiate integrative research to identify and characterize oceanographic parameters key to bowhead whale foraging success and behavioral ecology.
- Characterize wintering areas and determine the importance of winter feeding.
- Develop methods for documenting TEK in all bowhead hunting communities.

Responses to Ecosystem Change

- Include detailed Yankee commercial whaling data along with current data to determine long-term changes in ecology, distribution, ice-distribution, etc.

Human Impacts

- Continue time series of isotopic, toxicology, contaminant analyses.
- Develop modeling/database effort synthesizing all facets of bowhead whale historical catches, abundance data, energetics, feeding, reproductive, and TEK, etc. data with

respect to how cumulative impacts and climate variability, and anthropogenic activities might affect bowhead whales.

- Mitigate the influence of increasing anthropogenic inputs (offshore oil and gas development, seismic testing, shipping, possible commercial fishing, contaminants) on bowhead whales. We urge ecosystem-scale planning long before these activities become well-established (in the Arctic) such that they are properly managed both spatially and temporally.

REPORT SUMMARY

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In the western (Amerasian) Arctic, changes in the environment due to climate change may be broadly summarized to occur through two different, but somewhat coupled mechanisms. The first involves external forcing through shifts in the transport rates of Pacific waters and biological communities through Bering Strait and a stronger presence of Atlantic water and species assemblages advected across the Arctic Ocean to the region of interest. The second involves internal forcing where resident biological populations respond positively or negatively to altered timing of events in the annual cycle coincident with increased temperature, light, river run-off and/or altered sea ice regime. Both mechanisms propagate through the system, ultimately affecting abundance, distribution and productivity of all trophic levels, thus leading to changes in the way this ecosystem operates, and in the pathways and magnitude of energy flow into upper trophic levels such as fish, seabirds and marine mammals. Beginning at Bering Strait, the Chukchi Sea is the gateway (or pulse-point) into the Arctic where variation in climate will have impacts on the complex interplay of water masses of Pacific origin with those of the central Arctic Ocean, its marginal seas, and the Atlantic Ocean (Grebmeier and Harvey 2005). Large quantities of Pacific heat, nutrients, phytoplankton and zooplankton enter the region through the Bering Strait in a complicated mixture of water masses (i.e. Alaska Coastal, Bering Shelf, and Anadyr Water, Fig. 2.), each with unique assemblages and quantities of plankton (Springer et al. 1989, Coyle et al. 1996, Hopcroft and Kosobokova *accepted*). This inflow is diluted by Coastal Arctic waters carried along by the East Siberian Current (Weingartner et al. 1999) and water carried in from the deeper waters of the Canada Basin or Chukchi Plateau. Early in the season, the exact timing of the sea-ice breakup, the fate of the sympagic (=sea ice) community, and its match/mismatch to various components of the ecosystem can have profound impacts on this system and change the partitioning between benthic and pelagic productivity (Hunt et al. 2002, Bluhm and Gradinger 2008). For the most part, the high concentration of nutrients in Anadyr waters (Grebmeier and Barry 1991) stimulates massive sea ice algal and phytoplankton blooms (Hill et al. 2005, Gradinger, *in press*), that cannot be fully exploited by the zooplankton communities (Springer et al. 1996, Deibel et al. 2005, Campbell et al. *in press*). Hence, much of this high production is exported unmodified to the benthos (Fukuchi et al. 1993), resulting in impressively high biomass of benthic in- and epifauna (Grebmeier et al. 1989, 2006b, Feder et al. 2005, 2007). These rich benthic communities then serve as feeding grounds (biological hot spots) for the bottom-feeding Pacific walrus (Oliver et al. 1983), California gray whales (Highsmith and Coyle 1992), and diving birds (Lovvorn et al. 2003). The huge biomass of zooplankton imported to the Bering-Chukchi shelf in the flow of Anadyr Water accounts for the spectacular populations of seabirds, particularly planktivorous auklets, in the Bering Strait region (Springer et al. 1984, 1987, 1989), and undoubtedly supported resident bowhead whales prior to their decimation in the mid-1800s.

Both inter-annual and long-term variations in climate affect the relative transport of the different water masses through Bering Strait (Woodgate et al. 2006) and hence the composition, distribution, standing stock, and production of sea ice communities, phyto- and zooplankton, and the tightness of benthic-pelagic coupling in the Chukchi Sea (Grebmeier et al. 1995). There is significant concern that the Chukchi Sea may be undergoing an enhancement of energy utlilization within its pelagic realm, with a consequent decline in the production made available to the benthic communities (Feder et al. 2005, Grebmeier et al. 2006b). Resulting changes in prey base have also been documented for the northern Bering Sea (Grebmeier et al. 2006a, Coyle et al. 2007) and are likely to have significant effects on population dynamics and survival of the upper trophic levels (Bluhm and Gradinger 2008, Laidre et al. 2008). For example, recent observations indicate a shift in feeding grounds of gray whales from the northern Bering Sea to other areas, as they seek new and richer feeding grounds (Moore et al. 2003).

Although much of the primary production moving through the Chukchi Sea is exported to the benthos, significant production remains as the water flow bifurcates and moves northward off the shelf through the Herald Valley, the Central Channel and Barrow Canyon (Weingartner et al. 1998, 2005, Pickart et al. *submitted*). These flows are significant sources of carbon and nutrients to the continental slopes and the deep basin and play a critical role in structuring the stratification of the Arctic Ocean basin (Grebmeier and Harvey 2005). Although some sub-surface shelf break flow continues eastward along the Alaskan coast, part of the Beaufort Gyre surface flow is westward and therefore sea ice, planktonic and benthic productivity and biomass decline significantly over the narrow shelf of the Alaskan Beaufort Sea (Plourde et al. 2005, Dunton et al. 2005, Grebmeier et al. 2006a, Lane et al. 2008, Gradinger *in press*). Simultaneously, planktonic communities with considerable contribution from Pacific species in the Chukchi Sea shift to more Arctic fauna to the east of Barrow (e.g. Smith and Schnack-Schiel, 1990, Lane et al. 2008), while benthic communities show a more continuous compositional transition (e.g. Carey 1991, Dunton 1992). Within the Beaufort Sea, coastal erosion and river discharge result in high concentrations of suspended sediments, terrestrial dissolved and particulate organic carbon input, and a nearshore environment of estuarine character reflected in benthic community and food web structure (Dunton et al. 2006). One of the most prominent higher trophic species, the bowhead whale, ulitilzes the Beaufort Sea for their summer foraging on copepods, euphausiids and pelagic amphipods (Lowry et al. 2004). In the deep Canada Basin north of the Beaufort Shelf, circulation is dominated by the clockwise flow of the Beaufort Gyre (Pickart 2004). Thus, linkages between the opposing surface and sub-surface flows of the Canada Basin and the Beaufort Shelf, and the exchange of nutrients onto and off the shelf are key to understanding the productivity of this region, along with understanding the impacts of warmer surface waters with earlier and more extensive open water periods.

Workshop Outcomes & Recommendations

One important outcome of the workshop was the value placed on the plenary sessions where different disciplines presented overviews of "what's known" and could see the inter-relationships between their observation and that of other disciplines. These plenary and follow-up discussions were helpful in extracting a unified and interrelated set of the following needs (in no order of priority) for future research in this region, beyond the interests within each science discipline.

Data rescue/consolidation/archiving: A major challenge is the scattered and patchy nature of data from the Chukchi and Beaufort Seas. Considerable amounts of valuable data exist in gray literature, unpublished data, and traditional knowledge: efforts need to be continued (and require funding) to locate and digitize such information. The physical oceanographic community seems to be further along in this respect than other disciplines, and considerable effort is being made within the Alaska Ocean Observing System (AOOS – http://www.aoos.org). The Arctic Ocean Diversity (ArcOD – http://www.arcodiv.org) project is working in conjunction with AOOS on consolidating biological data, including datasets identified at the workshop. Some similar efforts are being made by other agencies (e.g. http://www.st.nmfs.gov/plankton/index.html), albeit generally restricted to single disciplines. Industry should make historical datasets and report more publicly available to maximize the value of their work. Developing one central data clearing house for all these activities like AOOS appears to be important to make best use of existing and newly produced datasets for all stakeholders (including federal and national agencies, commercial companies, and local stakeholders). OCSEAP funded a wide variety of studies in many disciplines. Data from many of these studies were not published in the peer-reviewed literature and are hard to find: these data should be made available.

Integrated analysis tools: Particularly for the biological observations, once databases are populated there are no readily accessible tools that allow for visualization and analysis of the data given their patchy temporal and spatial distribution, and this impedes progress. Development of such tools, and potentially training workshops in their use, was seen as a major need.

Interdisciplinary approach: It is becoming clear that data within each discipline are most valuable when coordinated with data from other disciplines as there is often a cause and effect relationship between observations. Multi-PI, integrated cruises and observational networks with joint goals are seen as the way to move forward,

Long-term time-series: All groups agreed the biggest impediment to observing and understanding the impact of climate change is the lack of continued sampling and data acquisition, by consistent methods, at a consistent set of locations. Agreement on where and when to prioritize sampling varied somewhat between groups, with the major split occurring between those disciplines used in an oceanographic approach (i.e. physics, chemistry, lower trophics and fish) versus those surveying upper trophic levels. The oceanographic group agreed that continued observations across all of Bering Strait are critical to maintain, also several east-west transect lines from the US to the Russian coast, such as Barrow to Wrangel Island in the Chukchi Sea, and several cross shelf transects in the Beaufort (e.g. from Barrow and Prudhoe Bay to the slope region) would be consistent with these needs. Lower trophic level groups emphasized the need to monitor the biomass hotspot in the southern Chukchi Sea. Upper trophics advocated for more extensive surveys, with efforts focused around breeding colonies, historical foraging grounds, or migration paths. Areas of emphasis for upper trophics include the Barrow region, Kakotovik, Kasegaluk Lagoon and Ledyard Bay, Kotzebue-Point Hope and Hope Basin.

Integration/collaboration with other agencies and programs: Great advantage was seen in building on the time-series and program planning already begun by other programs (e.g. use of historical stations), and partnering with existing and future programs. For example, NPRB could expand their BSIERP design into the Arctic (as BASIS did in 2007) and/or increase the frequency with which periodic Arctic surveys are conducted (e.g. RUSALCA biological surveys are only every 4 years) or the station coverage during a survey. Partnerships between agencies (e.g. NSF, MMS, NOAA, NMFS, USGS), industry and NPRB were suggested as a way to move forward through coordinated future multidisciplinary sampling programs.

Year-round observations: The oceanographic groups agreed that there is a major deficiency of year-round measurements/observations, with much of what is quantitatively measured confined to summer/fall. This was echoed by the marine mammal group, where ongoing use of acoustic arrays is providing new insights on habitat usage, but year-round observations appeared less relevant for seabirds because these species migrate out of the region in winter. Observations early in the year are particularly needed in the study of sea-ice biota.

Fill geographic and taxonomic gaps: Sampling in the region has never been systematic and notable geographic gaps still exist such as Long Strait, Herald Valley, the Beaufort Sea slope and nearshore regions in both the Chukchi and Beaufort. Sampling in these regions would improve our understanding of transport rates, map habitat utilization and species ranges, and understand processes. Taxonomic gaps exist in all lower trophic levels, plus fish, and appropriate methods should be incorporated into sampling programs to address these gaps prior to further impact by climate change.

Support infrastructure: For logistical reasons, Barrow was seen as a key location, especially with the new BARC research facilities (http://www.arcticscience.org/newfac.php) . A second, more southern research base would be useful in an area like Kotzebue. Travel from Barrow and Kotzebue would reduce the substantial transit time currently required for travel from Dutch Harbor and Nome. The need for a research capable vessel of 50-60 ft length to be based out of Barrow for the mostly ice-free season was voiced by several disciplines – the potential seasonal stationing of a Coast Guard vessel at Barrow may address this void. Additionally, UAF expects to have an ice capable ship suited for work in this region available within 3-4 years. Support/advocacy by NPRB for these facilities was seen as critical for their long-term viability.

***Biogeochemical and ecological modeling*: **The development of integrated biogeochemical models combined with the physical oceanographic settings was proposed to evaluate the impact of a changing environment on the ecosystems of the Chukchi and Beaufort Seas. Such models should cover (not necessarily within one single model) all trophic levels present in the region of interest and output should be made available to the public via the already mentioned data clearing house(s). Parameters of interest include changes in distribution ranges of taxa and also productivity parameters in relation to, for example, Arctic warming, ocean acidification and coastal erosion.

Taxonomic training and expertise: The expected changes in many groups will involve subtle taxonomic changes of congeneric species, or less frequently the invasion of alien species. The detection of such shifts requires expertly trained personnel involved in sample processing. Given the increasing lack of taxonomic expertise in many groups, investment in taxonomic training, and the vouchering and validation of species, are essential to detecting long-term change. Emerging molecular techniques may help ensure consistency of species identification between investigators over time.

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Appendix 2. List of acronyms

ABS	Alaskan Beaufort Sea
ACC	Alaska Coastal Current
ACIA	Arctic Climate Impact Assessment
AMAP	Arctic Monitoring and Assessment Program
AOOS	Alaska Ocean Observing System
ArcOD	Arctic Ocean Diversity
AUV	Autonomous underwater vehicle
BERPAC	US-USSR Bering Pacific program
CASES	Canadian Arctic Shelf Exchange Study
CoML	Census of Marine Life
CS	Chukchi Sea
DOC	Dissolved organic carbon
EEZ	Exclusive economic zone
FYI / MYI	First-year ice / multi-year ice
ISHTAR	Inner Shelf Transfer and Recycling
JWACS	Joint Western Arctic Climate Study
LME	Large Marine Ecosystem
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NSB	North Slope Borough
MMS	Minerals Management Service
OCSEAP	Outer Continental Shelf Environmental Assessment Program
OE	Ocean Exploration (NOAA)
ONR	Office of Naval Research
POC/PON/POM	Particulate organic carbon / nitrogen / matter
ROV	Remotely operated vehicle
RUSALCA	Russian American Long-Term Census of the Arctic
SBI	Shelf-Basin Interactions Program
SCC	Siberian Coastal Current
SHEBA	Surface Heat Budget of the Arctic Ocean
SLI	St. Lawrence Island
TEK	Traditional Ecological Knowledge
USFWS	United States Fish and Wildlife Service
WA	Western Arctic