

Chapter 10

Marine Life in the Arctic

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10.1 Introduction

The Arctic Ocean Diversity project (ArcOD), one of the regional field projects of the international Census of Marine Life, is an international collaborative effort to inventory biodiversity in Arctic marine realms on a pan-Arctic scale. Over 100 scientists in a dozen nations have contributed to ArcOD-related efforts, including many conducted during the International Polar Year 2007–9.

The Arctic seas are among the most extreme regions on Earth. Total darkness in winter is paired with low temperatures, strong winds, and heavy snow cover, whereas in summer permanent light produces ice and snow melt with temperatures around the freezing point. Arctic marine biota must deal with extreme seasonality of light, temperature, salinity, and sea ice, and year-round seawater temperatures that are close to freezing. The prevalence of such conditions for millions of years has led to the evolution of truly unique Arctic endemic flora and fauna.

The in- and outflow of water, mainly through Fram Strait and Bering Strait (Fig. 10.1), and cross-Arctic currents plus animal migrations make the Arctic Seas a mixing bowl of different species assemblages that compete for resources like light, substrate, nutrients, and food. Nevertheless, distinct community patterns have arisen within

individual Arctic seas, realms, and/or water masses. These biological communities sustain very productive marine food webs regionally and provide subsistence foods around the Arctic.

Historical collections and identification of marine organisms are valuable resources for today's Arctic research. They not only led to the description of many new species, for example by Steller during Bering's expedition (1738–1740), but also to industrial exploitation of the Arctic seas by commercial whalers and quick extinction of the great auk (in 1844) and the Arctic Steller's sea cow (in 1768) shortly after their description. The central Arctic Ocean was the focus of scientific curiosity for decades, including theories of an ice-free central Arctic Ocean in the nineteenth century by German geographer Petermann (Tammiksaar *et al.* 1999). Although many of the ideas about the central Arctic were wrong, they promoted Arctic exploration. The *FRAM* drift led by F. Nansen (1893–1896) is particularly noteworthy because of the wealth of physical and biological data collected, including species descriptions of then unknown ice biota.

During the mid-twentieth century, drifting ice stations became long-term research platforms for the USA and the Soviet Union (Kosobokova 1980; Perovich *et al.* 1999). In 1991, modern non-nuclear research vessels sampled the North Pole area for the first time in a systematic way (see, for example, Gradinger & Nürnberg 1996). Even today, the central Arctic remains the domain of ice camps and ice breakers with access mainly in the summer months. In contrast, the shallow seasonally ice-covered Arctic shelves

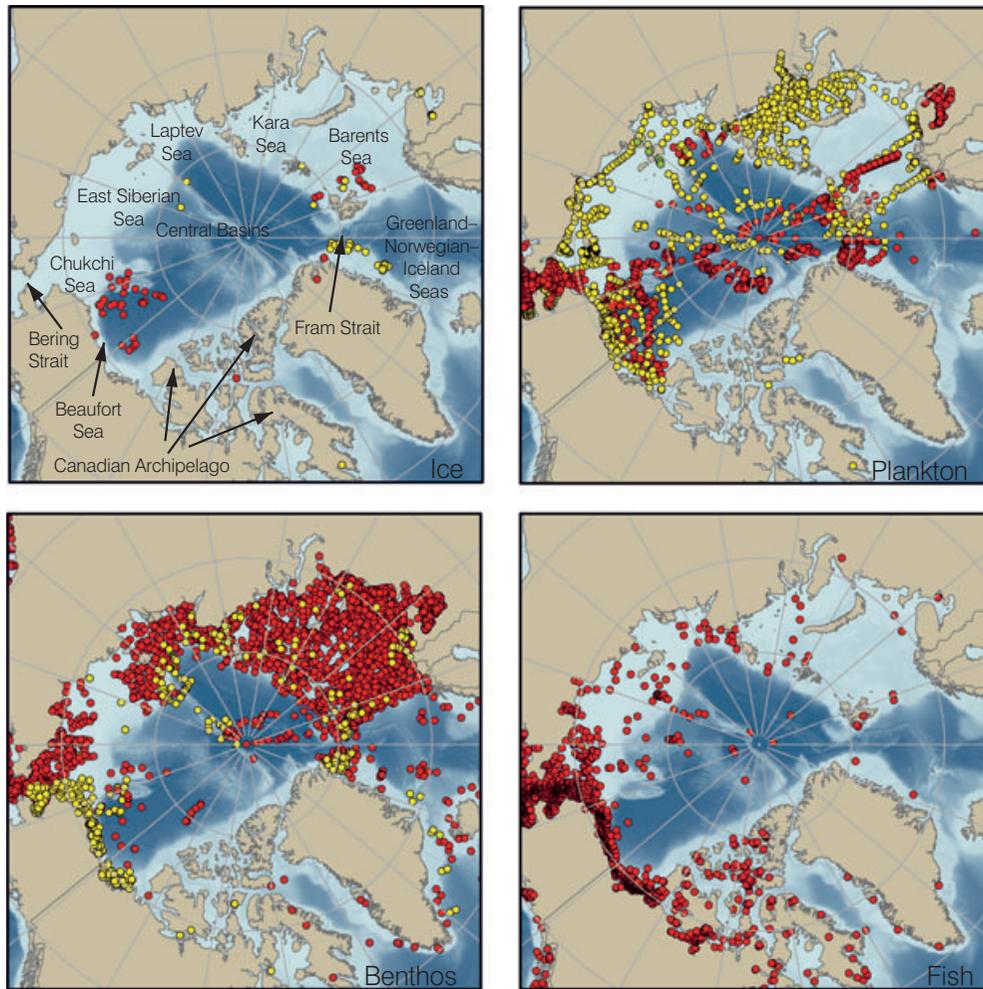


Fig. 10.1

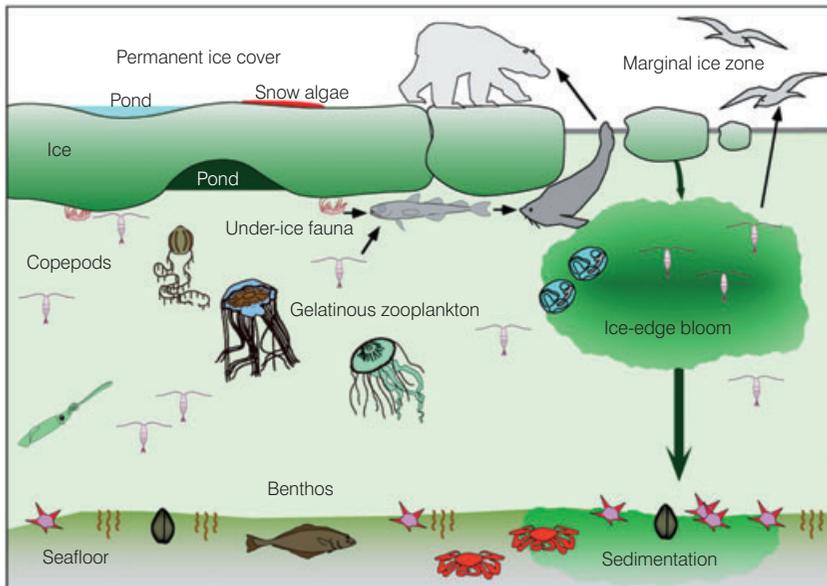
The Arctic data records compiled by ArcOD. Red dots are records already available on OBIS (www.iobis.org). Yellow dots are records prepared for posting online, but not online yet.

have always been more accessible. On the extensive Russian shelves faunistic exploration began over 200 years ago: in the late seventeenth century, the Zoological Museum in St. Petersburg acquired its first collections from the Barents, Kara, and White Seas, with these extensive Russian collections leading to a detailed species list of Arctic invertebrates (Sirenko 2001). On the North American shelf, the onset of oil drilling in the nearshore Beaufort Sea in the late 1970s initiated major research efforts, resulting in a wealth of biological data (see, for example, Horner 1981).

Over recent decades drastic changes have occurred in the Arctic, most notably in the physical settings. Sea ice has decreased in the summer months, reducing not only the substrate for ice-related flora and fauna, but also increasing light levels and temperatures in regions previously covered with ice continuously (Perovich *et al.* 2007). Although

some of the observed changes are related to natural causes, the main driver is thought to be the human footprint, and a completely ice-free Arctic (in summer) is predicted for 2030–2050, or at the latest by 2100 (Walsh 2008).

The predicted total loss of summer ice and the increased human presence will alter Arctic ecosystem functioning (Fig. 10.2) with regional changes in primary production, species distributions (including extinctions and invasions), toxic algal blooms, and indigenous subsistence use (Bluhm & Gradinger 2008). To address these issues scientifically, new research in poorly studied regions is needed with the rescue of historical data on species' distributions. Using recent ArcOD achievements, we discuss some of the urgent issues listed above, and suggest future research and Census activities in the Arctic beyond the end of the first Census.

**Fig. 10.2**

The Arctic's three realms: sea ice, water column, and benthos. The realms are tightly linked through life cycles, vertical migration, and carbon flux.

10.2 The Background

ArcOD's main effort focused on the least explored waters of the Arctic Ocean with its southern boundaries in Bering Strait of the Pacific Sector, and Fram Strait and the Barents Sea of the Atlantic sector, while including the sub-Arctic to some extent. True Arctic boundaries are difficult to define, as currents and ice drift distribute biota within and outside the above boundaries. Definitions vary among countries, agencies, and habitats in focus. Based on water temperature and ice cover, the Arctic extends well south of the Arctic Circle on the western side of the North Atlantic and North Pacific. In contrast, Arctic waters are displaced by communities of more southern fauna along the eastern side of the North Atlantic in the Barents Sea, and by Pacific water in the Bering and Chukchi Seas. Consequently the Arctic Ocean's flora and fauna are a varying mixture of Pacific, Atlantic, and true Arctic endemic species.

10.2.1 The environment

The Arctic Ocean contains 31% of the world ocean's shelves with 53% of the Arctic Ocean shallower than 200 m (Jakobsson *et al.* 2004, Fig. 10.1). Shelf extent varies from very narrow shelves in the Beaufort Sea to the wide Russian shelves. The central Arctic is a deep-sea system divided into abyssal basins by the Gakkel and Lomonosov ridges. The only current deep water connection to the world's ocean is through Fram Strait. The connection to the Pacific has opened and closed several times over the past few million years related to glacial and interglacial periods, with its last deep water connection about 80 million years ago (Bilyard & Carey 1980).

The well-adapted Arctic marine biota comprises viruses, bacteria, protists, and metazoans, including marine mammals. Abiotic forcing factors shape biological patterns and community composition, and cause strong seasonality of biological production and animal migrations. Arctic seas are exposed to winter months of complete darkness followed by intense summer solar irradiance that exceeds daily irradiances measured at the equator. Sea ice and associated snow cover with high albedo and attenuation effectively reduce the available light for phytoplankton growth to a few percent of surface irradiance (Perovich *et al.* 2007) making the timing and extent of sea ice and its melt a major controlling factor throughout the Arctic.

Sea ice covers the entire Arctic during winter with its maximum extent in February (around 14 million km²) (Thomas & Dieckmann 2009) and a minimum summer ice extent in September of historically around 7 million km² (so-called multi-year ice). Recent trends indicate a drastic loss in the extent of the summer multi-year ice by about 8.6% per decade (Serreze *et al.* 2007) and a decrease in sea ice thickness (Rothrock *et al.* 1999). Arctic pack ice drifts with ocean currents in two major drift systems, the anticyclonic Beaufort Gyre and the Transpolar Drift System. Some seasonal coastal sea ice is attached to land and stationary, therefore called fast-ice.

The central Arctic Ocean is permanently stratified owing to the input of fresh water from huge, mostly Russian river systems that reduce the salinity of Arctic surface waters to typically less than 32, whereas deep-water salinities typically exceed 34. River plumes can extend for hundreds of kilometers into the central Arctic. Melting of relatively fresh sea ice causes reduced-salinity lenses that are 5–40 m thick in the marginal ice zones (Perovich *et al.* 1999). Inorganic nutrient concentrations exhibit

strong regional gradients from high nutrient regimes, like the Chukchi Sea shelf, to oligotrophic conditions in the Beaufort Gyre (Gradinger 2009a) that are maintained by ocean currents combined with upwelling along shelf slopes and by riverine inputs.

Sea floor sediments are typically muddy on the outer shelves and in the central basins, and coarser with sand and gravel on the inner shelves or at locations with stronger ocean currents (Naidu 1988). Local accumulations of boulders and rocky islands like Svalbard provide hard substrates. Sedimentation is often dominated by terrigenous materials from riverine discharge and coastal erosion or by glacial deposits, while organic content is greatest in areas of high nutrient concentration and productivity.

10.2.2 Knowledge of Arctic marine species before the Census

Before the Census, the only web-based resource containing Arctic marine information was the non-searchable database by the US National Marine Fisheries Service on plankton. Additional information was scattered in reports, publications, and reviews mainly for pelagic and benthic biota. The most complete taxonomic list had been compiled by Sirenko (2001) (Table 10.1) listing 4,784 free-living invertebrate species.

10.2.2.1 Biota in sea ice

Sea ice is a habitat, feeding ground, refuge, breeding and/or nursery ground for several metazoan species (Fig. 10.3), as well as autotrophs, bacteria, and protozoans (Fig. 10.2) including ice-endemic species. The specialized, sympagic (=ice-associated) community lives within a brine filled network of pores and channels or at the ice-water interface. Several hundred diatom species are considered the most important sympagic primary producers (Horner 1985; Quillfeldt *et al.* 2003), while realizing the significance of flagellated protists (Ikävalko & Gradinger 1997). Ice algal activity exhibits strong regional gradients (Gradinger 2009a) with maximum contributions of approximately 50% of total primary productivity in the central Arctic (Gosselin *et al.* 1997). Typically ice algal blooms start mid-March and are released during ice melt.

Protozoan and metazoan ice meiofauna, in particular acoels, nematodes, copepods, and rotifers, can be abundant in all ice types, whereas nearshore larvae and juveniles of benthic taxa like polychaetes migrate seasonally into the ice matrix (Gradinger 2002). The variety of under-ice structures provides a wide range of different microhabitats for a partly endemic fauna, mainly gammaridean amphipods (Bluhm *et al.* 2010b). Amphipod abundances vary from fewer than 1 to several hundred individuals per square meter. They transfer particulate organic matter from the sea ice to the water column through the release of fecal

pellets and are a major food source for Arctic cod (*Boreogadus saida*) that occurs with sea ice and acts as the major link from the ice-related food web to seals and whales (Gradinger & Bluhm 2004).

Biodiversity in sea ice habitats was – and still is – poorly known for several groups, but sea ice faunal species richness is low compared with water column and interstitial sediment faunas, with only a few species per higher taxonomic group (Table 10.2), likely because of extreme temperatures (to below -10°C), high brine salinities (to greater than 100) in the ice interior during winter and early spring, and because of size constraints within the brine channel network (Gradinger 2002).

10.2.2.2 Biota in the water column

Pelagic communities are intricately coupled to the seasonal cycles of pelagic primary production and the seasonal downward flux of ice-algae during breakup (section 10.2.1). Typically phytoplankton production begins with ice melt in April and ends in early September with a growth curve characterized by a single peak in primary production in late June to early July (Sakshaug 2004). Enhanced plankton activity occurs on the Arctic shelf areas, where the seasonal retreat of the sea ice allows for the formation of ice-edge algal blooms with reduced surface salinity increasing vertical stability. The often large herbivorous zooplankton species accumulate substantial lipid reserves for winter survival and early reproduction in the following spring (Pasternak *et al.* 2001). Predatory zooplankton species rely on continuous availability of their prey, and generalists and scavengers show broad flexible diets (Laakmann *et al.* 2009). In all cases, the low metabolic rates at cold temperatures allow low rates of annual primary production to support relatively large stocks of zooplankton.

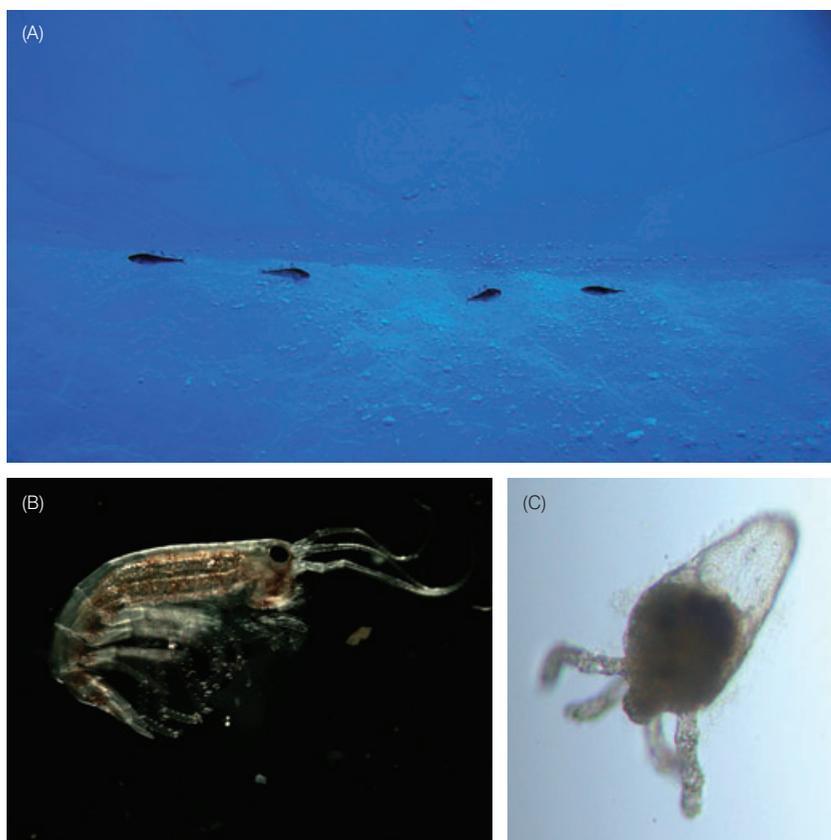
Phytoplankton blooms in spring are mainly dominated by diatoms and *Phaeocystis pouchetii* (Gradinger & Baumann 1991). Arctic estuarine systems harbor defined phytoplankton species assemblages, dominated by freshwater, brackish water, or full marine taxa (Nöthig *et al.* 2003); however, relatively few studies have closely examined the taxonomic composition of the phytoplankton communities (Booth & Horner 1997). The relevance of bacteria and heterotrophic protist communities and their role in the Arctic ecosystem (Sherr *et al.* 1997) was largely unknown, causing large uncertainties regarding their contribution to the Arctic carbon cycle (Pomeroy *et al.* 1990).

Owing to high abundance and ease of capture, the taxonomic composition and life history of the larger more common copepods in the Arctic Ocean was relatively well understood (Smith & Schnack-Schiel 1990). Historically, effort has concentrated on abundant copepods of the genus *Calanus*; however, although smaller copepod taxa are numerically dominant, relatively few studies have used sufficiently fine meshes to assess their contribution fully (Kosobokova 1980). A broad assemblage of other

Table 10.1

Species numbers of free-living invertebrates in the Arctic Seas.

Reference	Total invertebrate species	White Sea	Barents Sea	Kara Sea	Laptev Sea	East Siberian Sea	Chukchi Sea	Canadian Arctic	Central Basins
Zenkevitch 1963	N/A	1,015	1,851	1,432	522	N/A	820		
Sirenko & Piepenburg 1994	3,746	1,100	2,500	1,580	1,337	962	946		
Sirenko 2001	4,784	1,817	3,245	1,671	1,472	1,011	1,168		837
Sirenko 2004 ^a ; Sirenko & Vassilenko 2009 ^b ; P. Archambault personal communication ^c ; ArcOD ^d	>5,000 ^d				1,793 ^a		1,469 ^b	>1,405 ^c	>1125 ^d

**Fig. 10.3**

Examples of Arctic sea ice fauna. **(A)** Arctic cod, *Boreogadus saida* (about 10 cm long). **(B)** Under-ice amphipod, *Apherusa glacialis* (approximately 1 cm long). **(C)** Sea ice hydroid, *Sympagohydra tuuli* (approximately 400 μ m long), a species new to science. Photographs: A, K. Iken; B, B. Bluhm; C, R. Gradinger; all University of Alaska Fairbanks.

holoplanktonic groups was only occasionally reported in full detail (Mumm 1991). These understudied non-copepod groups held the greatest promise for discovery of new species and trophic importance. Like other oceans, knowledge of deep-water zooplankton was poor because of the time and logistics associated with their collection (Kosobokova & Hirche 2000).

Among the non-copepod groups, larvaceans (=appendicularians) are abundant in Arctic polynyas (Deibel & Daly 2007) and the central Arctic (Kosobokova & Hirche 2000). The basic biodiversity and importance of gelatinous animals were particularly under-appreciated (Stepanjants 1989; Siferd & Conover 1992). Arctic chaetognaths represent considerable biomass (Mumm 1991), and can control

Calanus populations (Falkenhaus & Sakshaug 1991) as can hyperiid amphipods (Auel & Werner 2003).

Sirenko (2001) (Table 10.1) listed about 300 species of multicellular holozooplankton with about half of these copepods, and the arthropods contributing about three-quarters total. Of the remainder, the cnidarians contributed about 50 species, whereas others contributed a dozen species or less each. Sirenko's list also contained about 125 species of planktonic heterotrophic protists, with several important heterotrophic groups still unconsidered. The number of described phytoplankton taxa has increased over time from 115 to more than 300 (Sakshaug 2004).

10.2.2.3 Biota at the sea floor

Benthic communities generally depend on food supplied from the water column, with sediment and water mass characteristics as environmental forcing factors (section 10.2.1). In high latitudes, the quantity of settling food particles rather than temperature per se is restraining the growth and survival of benthic organisms. Faunal densities generally decrease with water depth and sediment thickness in response to the decreasing food supply (Schewe & Soltwedel 2003). On the Arctic shelves, organic particle input is relatively large over the ice-free period, and benthos, therefore, plays a greater role in the marine carbon cycle than at lower latitudes (Grebmeier & Barry 1991). High benthic biomass in some areas provides major feeding grounds for resident and migrating mammals and sea birds (see, for example, Gould *et al.* 1982) in particular at frontal systems, polynyas, and along ice edges (Schewe & Soltwedel 2003). The Arctic shelf macro- and megafauna had received the most attention whereas meiofauna and microbial communities were considerably less studied.

Nematodes and copepods are the most abundant metazoan meiofauna (Schewe & Soltwedel 1999). Less common taxa include kinorhynchs, tardigrades, rotifers, gastrotrichs, and tantulocarids. Foraminifera dominate unicellular meiofauna and can constitute more than 50% of total meiofauna abundance (Schewe & Soltwedel 2003). Macrofaunal abundance and biomass are typically dominated by crustaceans, in particular amphipods, polychaetes, and bivalve mollusks (Grebmeier *et al.* 2006) with massive biomass levels on some Arctic shelves like the northern Bering and southern Chukchi Seas (Sirenko & Gagaev 2007). The most species-rich macrofaunal groups include amphipods and polychaetes (Sirenko 2001). Studies on slope and deep-sea benthos found low infaunal abundances and biomass (Kröncke 1998) dominated by deposit feeding groups (Iken *et al.* 2005), with abundances overlapping with the lower values from the North Atlantic deep sea. Epibenthic megafauna (visible fauna on underwater imagery and caught in trawls) was mostly studied on shelves, where echinoderms, particularly ophiuroids, dominated with up to several hundred individuals per square meter (Piepenburg *et al.* 1996). Other abundant epibenthic

faunal taxa include crabs, anemones, sea urchins, and sea cucumbers (Feder *et al.* 2005). For shelf epifauna, bryozoans and gastropods are particularly species rich, followed by sponges and echinoderms (Sirenko 2001; Feder *et al.* 2005).

Over 90% of the Arctic invertebrate species inventory are benthic, and most are macrofaunal (Sirenko 2001) (Table 10.2). By far the highest numbers of species were recorded for the Barents Sea, largely because of its long research history and the occurrence of many boreal-Atlantic species. In other Arctic Seas, numbers ranged from just over 1,000 to almost 3,000, again mostly benthic. Before ArcOD-related research, approximately 350–400 benthic macro- and megafauna species were listed for the deep central Eurasian Arctic.

10.3 ArcOD Activities

ArcOD was from the beginning an international pan-Arctic effort initiated mainly by US and Russian scientists, but including many European and Canadian researchers. In addition to its international character, ArcOD also placed emphasis on rescuing and consolidating historic and new data and making those available through the Census database, the Ocean Biogeographic Information System (OBIS). So far (April 2010), ArcOD has posted 42 datasets to OBIS representing 200,000 records (Fig. 10.1), likely exceeding 250,000 by the end of 2010.

ArcOD scientists collected new samples and generated new observations. Challenges of sampling in ice-covered waters are numerous and they impair the ability to tow collecting gear that collect the most mobile species or reach the area of interest because of ice. In a few cases, failure to generate the interest of professional taxonomists in a less common group has created gaps. ArcOD identified the need for a complete set of taxonomic guides for all Arctic groups that is coming to fruition under the leadership of Zoological Institute of the Russian Academy of Sciences (Vassilenko & Petryashov 2009; Sirenko & Buzhinskaya, personal communication). Online species pages (www.arcodiv.org) provide additional information and imagery useful to the interested public as well as ecologists and taxonomists, and will ultimately become accessible through the Encyclopedia of Life initiative.

Much knowledge has been gained in the field of Arctic biodiversity in the past decade under ArcOD, other programmatic umbrellas, and many individual studies with a significant fraction of this information, including most results gathered during the International Polar Year 2007–9, to be published after this book is printed. Below, we summarize knowledge gained in specific areas with strongest ArcOD participation, including examples of progress based on taxonomic, regional, methodological, and hypothesis-driven efforts.

10.3.1 Improvements in traditional and molecular taxonomic inventories

ArcOD's discovery of over 60 invertebrate species new to science is based on substantial efforts dedicated to new collections and to more complete re-analyses of previously collected materials in different habitats and Arctic regions.

In the sea ice realm, ArcOD-related efforts added to the ice-associated species inventory in all size classes and in a variety of taxa. Sea-ice cores from Bering Sea shelf pack ice are currently being analyzed for bacterial and archaeal diversity using molecular tools (R. Gradinger & G. Herndl, unpublished observations). A comprehensive review of the pan-Arctic literature ice-associated protists (excluding ciliates) resulted in a list of more than 1,000 sympagic species (M. Poulin *et al.*, personal communication). For meiofauna, the first true predator in the brine channel system, the hydroid *Sympagohydra tuuli*, was described (Piraino *et al.* 2008) (Fig. 10.3 and Table 10.2). Juveniles of the polychaete *Scolelepis squamata* were identified as a seasonally common taxon in coastal fast ice in the Chukchi and Beaufort Seas (Bluhm *et al.* 2010a) with other less common polychaete species yet to be identified. Specimens of the groups Acoela, Nematoda, Harpacticoida, and Rotifera from various types of sea ice are currently with European taxonomists for species identifications. Within the macrofauna, we discovered large aggregations of an Arctic euphausiid (*Thysanoessa raschii*) under Bering Sea ice in spring 2008, the first record of winter ice-association for the Arctic (R. Gradinger, B.A. Bluhm, & K. Iken, unpublished observations). We also discovered that sea-ice pressure ridges might be crucial for survival of sympagic fauna during periods of enhanced summer ice melt (Gradinger *et al.* 2010) because sea-ice ridges protrude into the deeper higher-salinity water, and hence may be a less stressful environment than encountered under level ice.

Within the plankton, at least six new species of small primarily epibenthic copepods have recently been discovered and are under description (V. Andronov, personal communication) (Table 10.2). Deepwater expeditions increased the known range of several amphipod species (T.N. Semenova, personal communication), as well as discovered a new pelagic ostracod species (M. Angel, personal communication). As expected, the largest gain in knowledge for the zooplankton has occurred within gelatinous groups. By using a remotely operated vehicles (ROV), more than 50 different "gelatinous" taxa were identified in the Canada Basin (Raskoff *et al.* 2010). Of five new species of ctenophores, only two could be placed within known genera (*Bathychytena*, *Aulacoctena*) (Table 10.2). Within the cnidarians, a new species of hydromedusae was described within a new genus (Raskoff 2010) (Fig. 10.4) that was surprisingly common at a depth of approximately 1 km. At

least four described species of hydromedusae were observed in the Arctic for the first time (Raskoff *et al.* 2010). Within the pelagic tunicates one new species was collected at great depth, several other likely new species were observed by ROVs, and the first records of *Fritillaria polaris* and *Oikopleura gorksyi* were made outside of their type locality (R.R. Hopcroft, unpublished observation). Russian taxonomists continue to go through more recent ArcOD deep-water collections to characterize these communities better.

Most of the new species discovered during ArcOD research were in the benthic realm (Table 10.2), where species richness is generally highest. Most of those were found in the Arctic deep sea, specifically in the polychaetes and crustaceans (Gagaev 2008, 2009), two particularly species-rich groups in soft sediments. More unexpected was the finding of five new bryozoan species around Svalbard (Kuklinski & Taylor 2006, 2008) (Fig. 10.5), because Svalbard's fjords, in particular Kongsfjorden and Hornsund Fjord, are well-studied by the many international field stations located there. Similarly noteworthy are the finds of three new gastropod species in the Bering and Chukchi Seas (Chaban 2008; Sirenko 2009), two of which were actually collected over 70 years ago. All of these and other species, including several amphipods (B. Stransky, unpublished observations), cnidarians (Rodriguez *et al.* 2009), and a sea cucumber (Rogacheva 2007), are in the larger and better studied size fractions. Considerably less taxonomic effort was spent on meiofaunal groups during ArcOD, but new species were recorded among benthic and hyperbenthic copepods (see, for example, Kotwicki & Fiers 2005), Komokiacea (O. Kamenskaya, unpublished observations), and the nematodes (J. Sharma, personal communication). A benthic boundary layer study in the Beaufort Sea (Connelly 2008) discovered six new copepod species.

The compilation of close to 10,000 data records of western Arctic fishes and verification of most of the identifications in museums around the world has resulted in major improvements regarding the taxonomy and distribution of Arctic fishes (Mecklenburg *et al.* 2007, 2008). Some species like Pacific cod, *Gadus macrocephalus*, now present in the western Arctic were historically absent from the area (C.W. Mecklenburg, personal communication). The black snailfish *Paraliparis bathybius* collected from the Canada Basin in 2005 is the first record of this species from the western Arctic. For other species, the known range in the region was extended further north: walleye pollock, *Theragra chalcogramma*, was found 200 km north of its previous northernmost record (Mecklenburg *et al.* 2007). Instances of misidentifications were uncovered, for example virtually all Arctic specimens identified as sturgeon poacher, *Podothecus accipenserinus*, turned out to be the veteran poacher *P. veternus*.

Most of the discoveries of new species were related to (1) the exploration of previously poorly studied areas such as the Canada Basin (Gradinger & Bluhm 2005; Bluhm

Table 10.2

Arctic marine species inventory by taxa and realm. Estimates are primarily based on Sirenko (2001) with estimates for additional taxa per references provided. Updates to Sirenko's estimates are based on contributions by ArcOD researchers (mostly cited in the text) and are to be considered conservative.

Taxon	Species numbers, marine Arctic (Sirenko 2001 and updated)	Arctic sea ice	Arctic plankton	Arctic benthos	Species new to science (range extensions) in ArcOD
Bacteria	4,500–450,000 ^a	>115 ^b	1,500 ^c	?	Many
Archaea	Up to 5,000 ^a	?	1,400 ^d	?	Many
Cyanobacteria	1		1		
Macrophytes	130–160 ^e			130–160	
Bacillariophyta	1,227 ^f	731 ^f	1059 ^f		
Other Protista	1,568 ^f	296 ^f	815 ^f	570	
Porifera	163			163	
Cnidaria	227	1	83	161	5 (7)
Ctenophora	7		7		5
Tentaculata	341			341	6
Sipunculida	12			12	
Plathelminthes	137	>3		134	
Gnathostomulida	1			1	
Nemertini	80		2	78	
Aschelminthes	422	>11	16	403	
Mollusca	487		5	482	3 (7)
Annelida	571	4	6	565	11 (27)
Tardigrada	7			7	
Arthropoda	1,547	>20	214	1,317	31 (12)
Chaetognatha	5		5		
Hemichordata	1			1	
Echinodermata	151			151	1 (1)
Urochordata	60		3	57	1 (2)
Pisces	415	2			(3)
Aves	82				
Mammalia	16	7		3	

^aEstimates, C. Lovejoy *et al.*, unpublished observations.

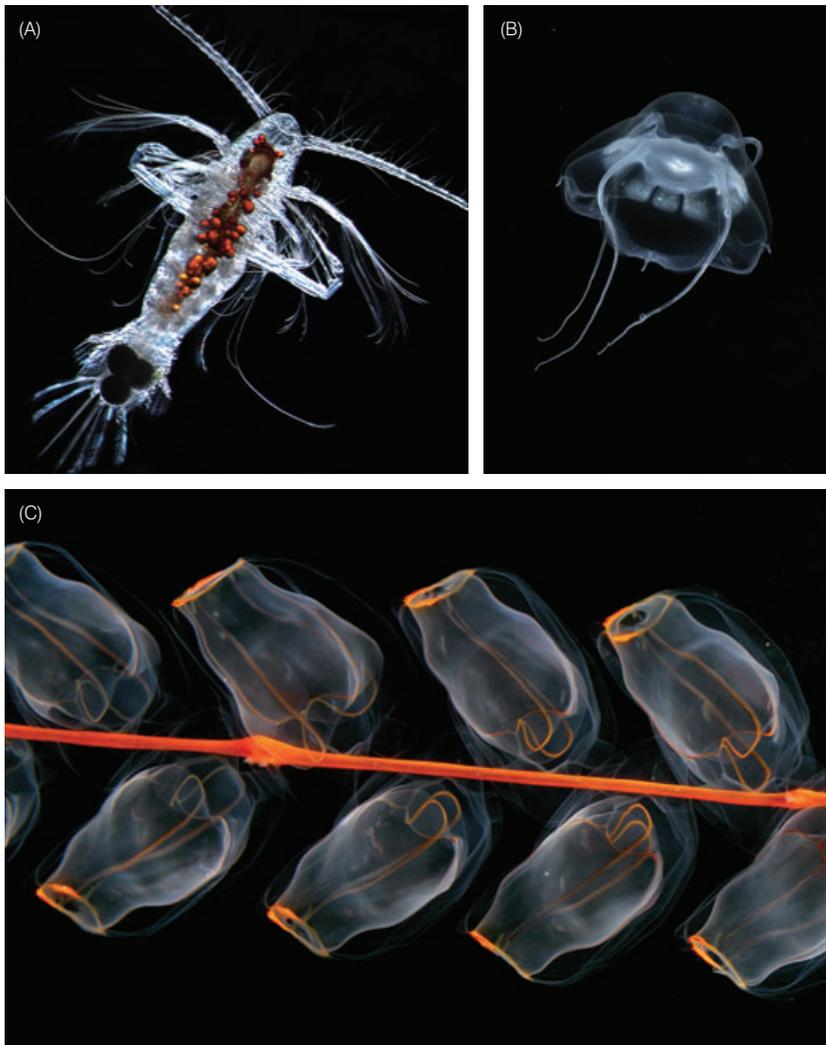
^bBrinkmeyer *et al.* (2003).

^cActually found, D. Kirchman *et al.*, unpublished observations.

^dActually found, surface and deep waters, Galand *et al.* (2009).

^eR. Wilce and D. Garbary, personal communication.

^fM. Poulin *et al.*, unpublished observations, for "Other Protista" combined with Sirenko (2001).

**Fig. 10.4**

Examples of Arctic zooplankton. (A) Copepod, *Euaugaptilus hyperboreus* (about 1 cm long). (B) Species of narcomedusa new to science (up to 3 cm). (C) Close-up of anterior nectophore region of siphonophore, *Marrus orthocanna* (whole specimen up to 2 m). Photographs: A, R. Hopcroft, University of Alaska Fairbanks; B and C, K. Raskoff, Monterey Peninsula College.

et al. 2010a), (2) study of poorly studied taxonomic groups such as gelatinous zooplankton (Raskoff *et al.* 2005, 2010), (3) little-studied habitats such as the benthic boundary layer (Connelly 2008), or (4) the All-Taxa-Biodiversity-Inventory program in Svalbard. This long-term survey, the first of its kind, part of the European Union's marine biodiversity program BIOMARE, so far assembled over 1,400 marine taxa from an area of approximately 50 km² and depths ranging from 0 to 280 m (<http://www.iopan.gda.pl/projects/biodaff/>). The estimated number of species, assessed from species accumulation curves, shows near completeness for single taxa like Mollusca (Włodarska-Kowalczyk 2007), but substantial gaps for other taxa like minute Crustacea. Altogether, more than 2,000 metazoan species are expected to be identified in this small coastal Arctic area. The number of families of Polychaeta, for example, is a good indicator of marine species diversity for soft bottom Arctic benthos (Włodarska-Kowalczyk & Kedra 2007). This implies that, at least for Hornsund, species richness of a single, well-known taxon might be an indicator for general species richness of the area.

New records of known species are at least as important as new species discoveries. Recent intense taxonomic study in the Chukchi Sea added over 300 species to the Sirenko (2001) inventory, doubling the number of known species since Ushakov (1952) (Sirenko & Vassilenko 2009). The recent additions were primarily in groups such as Foraminifera, Polychaeta, and Mollusca, whereas other groups such as Plathelminthes, Nematelminthes, and Harpacticoida are still poorly studied. New records for the Canada Basin relative to the Sirenko (2001) list include at least 40 benthic species, mainly polychaetes from one expedition, 21 of which were not listed to occur anywhere in the Arctic (MacDonald *et al.* 2010). Reasons for new records may be previous poor sampling or actual range extensions possibly related to climate warming (Mecklenburg *et al.* 2007; Sirenko & Gagaev 2007).

In addition to traditional species identifications and descriptions, ArcOD has contributed to the international Barcoding effort. Molecular “barcoding” uses a short DNA sequence from the cytochrome *c* oxidase mitochondrial



Fig. 10.5

Examples of Arctic benthos. (A) Sea star, *Ctenodiscus crispatus* (5 cm across). (B) Sea cucumber *Kolga hyalina* (about 2 cm long). (C) A new bryozoan species, *Callopora weslawski*. Photographs: A and B, B. Bluhm, University of Alaska Fairbanks; C, P. Kuklinski, Institute of Oceanology Polish Academy of Sciences.

region (MtCOI) as a molecular diagnostic for species-level identification (Hebert *et al.* 2003). Within the microbes, metagenomics and pyrosequencing are additionally applied (Sogin *et al.* 2006). Conservative estimates of the number

of distinct Arctic bacteria are now approximately 1,500 (D. Kirchman *et al.*, unpublished observations) and approximately 700 for the Archaea (Galand *et al.* 2009) in both surface and deep waters. At present, extrapolating these estimates to the various water masses presenting the entire Arctic has large uncertainty, but 4,500–45,000 types of Eubacteria, 500–5,000 types of Archaea, and 450–4,500 eukaryotic protists might exist in the Arctic (C. Lovejoy, personal communication). Viral diversity still remains largely unknown, but first inventories are underway for Svalbard (B. Wrobel, personal communication).

Within the metazoan zooplankton, Bucklin *et al.* (2010) sequenced 41 species, including cnidarians, arthropod crustaceans, chaetognaths, and a nemertean (Table 10.3). Overall, MtCOI barcodes accurately discriminated known species of 10 different taxonomic groups of Arctic Ocean holozooplankton. Work continues on building a comprehensive DNA barcode database for the Arctic holozooplankton in conjunction with the Census of Marine Zooplankton (see Chapter 13).

Within the Arctic benthos, over 300 species from 96 families were barcoded (C. Carr, personal communication; S. Mincks, personal communication), mostly polychaete (116) and amphipod species (63) (Table 10.3). For several morphological species, several unique haplotypes were found that could represent different species based on the molecular evidence (C. Carr, personal communication).

Within the fish, 93 species were barcoded from the North Pacific, the Aleutians, and the northern Bering and Chukchi Seas (Mecklenburg & Mecklenburg 2008) (Table 10.3; more in progress). Results supported the distinction between some species whose validity had been questioned, whereas other accepted species appear to be synonymous (Mecklenburg & Mecklenburg 2008). The method has also linked juvenile stages with the adults of the species, which previously had not been recognized as such.

Ongoing collaboration with the Census of Antarctic Marine Life (see Chapter 11) seeks to determine if bipolar species are truly bipolar based on MtCOI. Sequences for other target regions have also been published to help aid and resolve the separation of sibling species (see, for example, Lane *et al.* 2008), and to resolve haplotype structure within populations (Nelson *et al.* 2009).

10.3.2 Regional inventories: the Chukchi Sea and adjacent Canada Basin

Two expeditions in 2002 and 2005 aimed at improving the biological baseline of the Canada deep-sea Basin, one of the least explored regions in the Arctic Ocean (Gradinger & Bluhm 2005; Bluhm *et al.* 2010a). Although biomass and abundance of the sea ice meiofauna (mainly

Table 10.3

Arctic marine taxa barcoded under the ArcOD umbrella.

Taxon	Number of species barcoded	Number of families barcoded	Investigators/reference
Cnidaria: Hydrozoa	6 (pelagic)	6	Bucklin <i>et al.</i> 2010
Cnidaria: Scyphozoa	1	1	Bucklin <i>et al.</i> 2010
Cnidaria: Anthozoa	2	2	S. Hardy Mincks, personal communication
Nemertea	1 (pelagic)	1	Bucklin <i>et al.</i> 2010
Polychaeta	152 (benthic)	26	C. Carr & A. Smith, personal communication
Mollusca: Bivalvia	7	6	S. Hardy Mincks, personal communication
Mollusca: Gastropoda	12	6	S. Hardy Mincks, personal communication
Mollusca: Polyplacophora	1	1	S. Hardy Mincks, personal communication
Copepoda	28 (pelagic)	12	Bucklin <i>et al.</i> 2010
Amphipoda	5 (pelagic) 63 (benthic)	16	Bucklin <i>et al.</i> 2010; C. Carr & A. Smith, personal communication; S. Hardy Mincks, personal communication
Decapoda	1 (pelagic) 5 (benthic)	1 3	Bucklin <i>et al.</i> 2010 S. Hardy Mincks, personal communication
Euphausiacea	1	1	Bucklin <i>et al.</i> 2010
Chaetognatha	2	2	Bucklin <i>et al.</i> 2010
Urochordata, Ascidiacea	1	1	S. Hardy Mincks, personal communication
Echinodermata: Asteroidea	13	5	S. Hardy Mincks, personal communication
Echinodermata: Ophiuroidea	2	2	S. Hardy Mincks, personal communication
Echinodermata: Holothuroidea	2	2	S. Hardy Mincks, personal communication
Pisces	92	27	C.W. Mecklenburg and D. Steinke, personal communication
Total	397	121	

Acoela, Nematoda, and Harpacticoida) (Fig. 10.6) and amphipods was similar to records from other Arctic offshore regions (Gradinger *et al.* 2005, 2010), abundances were significantly higher along deep-reaching keels of sea ice ridges (Gradinger *et al.* 2010). Community structure of net-caught zooplankton, mainly copepods (Fig. 10.6), was distinctly depth-stratified, with composition comparable to other Arctic basins, except for the several Pacific expatriates present (Hopcroft *et al.* 2005; Kosobokova & Hopcroft 2010). Assemblages of gelatinous zooplankton were also depth-stratified with shallower stations dominated by siphonophores and ctenophores and deeper stations by medusae (Raskoff *et al.* 2005, 2010). Large

predatory scyphomedusae in the upper 100 m were dominant in the chlorophyll maximum layer, where copepod biomass was also highest. Smaller cnidarian and ctenophore species occurred immediately underneath the sea ice (Purcell *et al.* 2009).

Abundance, biomass, and diversity of benthic macrofauna (approximately 100 taxa) declined with increasing water depth and clustered into groups characterized by depth and location with overall low abundances and biomass similar to findings from the Eurasian Arctic deep sea (Bluhm *et al.* 2005; MacDonald *et al.* 2010). High abundance of the sea cucumber *Kolga hyalina* (Fig. 10.6) characterized a suspected pockmark on the Chukchi Cap

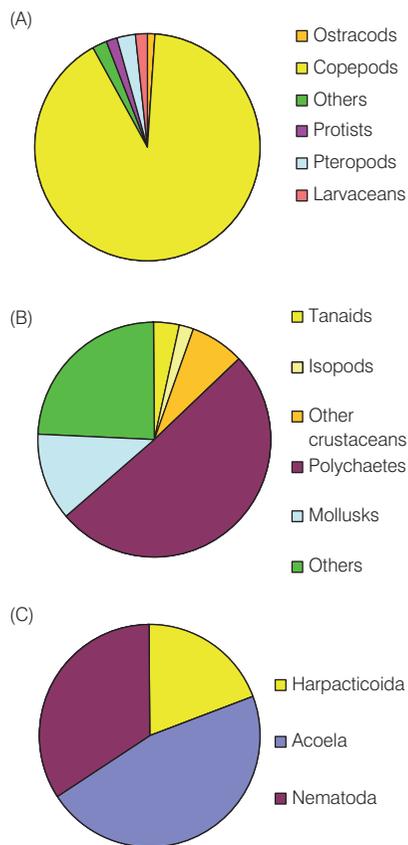


Fig. 10.6

Composition of Arctic net-caught zooplankton (A), benthic macrofauna communities (B), and sea ice meiofauna (C). Example is from the Canada Basin (2005). Data from Gradinger *et al.* (2010), Kosobokova & Hopcroft (2010), and MacDonald *et al.* (2010).

(MacDonald *et al.* 2010). Only six putative demersal fish species were observed from ROV imagery (Stein *et al.* 2005). During opportunistic visual surveys, six and seven marine mammal species were encountered in 2002 and 2005, respectively, and 16 bird species were encountered in 2005 with highest sighting numbers related to specific oceanographic features (Harwood *et al.* 2005; Moore *et al.* 2010). A long (stable-isotope-based) food web of four trophic levels points towards low food availability and a high degree of organic matter reworking (Iken *et al.* 2005).

The Russian–American Long-term Census of the Arctic (RUSALCA) conducts long-term research relevant to climate change in Bering Strait and the Chukchi Sea (Bluhm *et al.* 2009). Zooplankton communities were represented by six assemblages coinciding with prevalent thermohaline water mass characteristics (Hopcroft *et al.* 2008). One of the numerically dominant copepod genera, *Pseudocalanus*, was represented by three species with distinct spatial distribution patterns, although their weight-specific egg production rates were similar (Hopcroft & Kosobokova 2010).

Small demersal fishes (see Mecklenburg *et al.* (2007) for taxonomy) and ichthyoplankton on the Chukchi Shelf also formed distinct regional assemblages related to hydrographical features and sediment type (Norcross *et al.* 2010).

High abundances and biomass of macrobenthos north-west of Bering Strait were dominated by the bivalve *Macoma calcaria* (Sirenko & Gagaev 2007) and were linked to local hydrography retaining the larval pool. Benthic epifaunal biomass was dominated by echinoderms and crustaceans and represented in six distinct assemblages, separated largely based on substrate type and latitude with less influence by indices of food availability (Bluhm *et al.* 2009). Comparisons with previous studies in the region suggest an increase in overall epibenthic biomass since 1976. Regional differences in mean stable isotopic signatures in the benthic food web were mainly driven by the isotopically depleted particulate organic matter source in the Alaska Coastal Water (Iken *et al.* 2010).

10.3.3 Natural variability versus climate warming

Concern over global biodiversity loss is widespread, and Arctic biodiversity is believed to be changed by climate warming (Bluhm & Gradinger 2008). Although Arctic endemic taxa may be endangered, overall species numbers might increase with species-rich warm-water communities thriving in the region. Only a few long-term studies, some with ArcOD involvement, have been performed: several in Svalbard including a 30-year-long study of the rocky sublittoral (Beuchel *et al.* 2006), a 10-year-long zooplankton survey (Hop *et al.* 2006), and a 10-year-long study of the soft bottom (Kedra *et al.* 2009). Repeated sampling efforts included a shelf megafauna survey at Svalbard resurveyed after 50 and 100 years (Dyer *et al.* 1984), occurrence of Decapoda in Isfjorden investigated after 50 and 100 years (Berge *et al.* 2009), a soft bottom survey in VanMijen Fjord after 20 years (Renaud *et al.* 2007), and a Svalbard intertidal survey repeated after 20 years (Wiktor & Węśławski 2008). The results of those surveys demonstrate the high stability of the presence of the species pool in coastal–fjordic waters and very drastic interannual changes in the occurrence of single species. With ongoing warming, warmer-water species replaced cold-water species, but played the same role in the ecosystem. Examples of such species pairs include species in the genera *Sclerocrangon*, *Calanus*, *Themisto*, *Gammarus*, and *Limacina* (Węśławski *et al.* 2008).

Low Arctic biodiversity is usually associated with high population density of a few species. The charismatic icons of the Arctic are huge numbers of seabirds, seals, and walrus, unmatched anywhere on Earth during the feeding season. The underlying reason is the large size of polar marine herbivores (copepods, krill, pteropods) and their high lipid content (Pasternak *et al.* 2001). Exceptionally

efficient and often short polar food chains (diatom–krill–whale) are now under change because of increasing inflow of warm, Atlantic waters that bring smaller species of herbivores. This leads directly to a change in food web structure as primary production is going to be dissipated among several small, fast-growing subarctic species (Węśławski *et al.* 2007, 2008) and a higher contribution of pelagic versus benthic secondary production (Carroll & Carroll 2003).

To separate this temporal from spatial variability one needs to know the scale of patch sizes of equal biodiversity. Several recent studies, testing this problem in nested sampling approaches (see, for example, Włodarska-Kowalczyk & Węśławski 2008), demonstrated that on even, flat soft-sediment seabed, the patch size of uniform biodiversity was several hundreds of meters in diameter. The uniformity was lower (diversity is more patchy) in undisturbed shelf areas, and higher (diversity is low and even) at coastal sites under the influence of siltation and strong glacial sedimentation. Similar analyses were performed for Arctic sea ice, which supports mosaic and patchy distribution of organisms, based on local differences in snow cover, ice thickness, undersurface of ice, sediment load, etc. (Wiktor & Szymelfenig 2002; Gradinger *et al.* 2009, 2010). Low diversity of marine habitats appears to contribute to the overall low species richness in the Arctic.

10.3.4 Biogeography

Global changes of climate, water mass circulation, and geomorphology in the Pliocene and Pleistocene modified the composition and distribution of Arctic benthic fauna over time. In ArcOD we evaluated the different origins of modern Arctic fauna as a whole, as well as of faunas of certain large regions and bathymetric zones in the Arctic Ocean. Faunistic elements recognized in the modern Arctic benthos include (1) faunas originating from the North Pacific and (2) North Atlantic, (3) deep-sea cosmopolitans, and (4) endemic species of autochthonous (local) origin. The opening of Bering Strait approximately 5.3 million years ago resulted in intensive colonization of the Arctic Basin from the North Pacific. Formation of the warm Gulf Stream moved distribution limits of many boreal species northward. Geomorphological and hydrological changes of the Faeroe–Iceland Rise opened dispersal pathways into the Arctic Basin to the North Atlantic deep-sea fauna that in turn has strong links to the Antarctic. At the same time, changes in the Arctic Basin stimulated local species radiation.

Although a comprehensive review will be published by A.N. Mironov and A.V. Gebruk (editors), some example results are given here. For Arctic shallow-water asteroid fauna (A.B. Dilman, unpublished observations) the number of species of Atlantic origin exceeds that of Pacific origin. The only exception is the Chukchi Sea, where more species are in common with the Pacific. At the same time, however,

asteroid species dominating on the Arctic shelves belong to genera that dispersed from the Pacific Ocean. The ratio of species of Pacific origin decreases from the Barents Sea towards the Laptev Sea, but then increases in the East-Siberian Sea and the Chukchi Sea. The East-Siberian Sea acts as a barrier for the dispersal of species, which can be seen in various biogeographical indicators, such as species richness, biogeographical structure of fauna, patterns of vertical distribution, and the ratio of cold-temperature to warm-temperature species (A.N. Mironov & A.B. Dilman, unpublished observations).

10.3.5 Beyond the Arctic and ArcOD: Arctic–Antarctic comparisons

The common textbook notion is that biodiversity in Arctic seas is low compared with the Antarctic and particularly compared with temperate and warm waters. Although this is supported by higher total species numbers in warmer seas, it is less supported when comparing species numbers in specific comparable habitats, or within comparable taxonomic groups. Kendall and Aschan (1993), who analyzed soft-bottom benthos from tropical, temperate, and Arctic sites, found almost identical values for indices of diversity at all sites when including the same type of sediment and water depths. More recently, polychaete diversity was found to be equal at an evolutionary old Antarctic site and evolutionary young Arctic site (Włodarska-Kowalczyk *et al.* 2007). This implies that differences in total species richness between areas are driven by habitat diversity. In the Arctic, biogenic reefs, caves, and deep rocky structures are rare, absent or, in some cases, un(der)-sampled such as the deep-sea Arctic benthos. Complete lists on overall species richness for the Arctic and Antarctic are still being compiled and numbers for metazoan species currently range around 8,200 for the Antarctic (www.scarmarbin.be/rams.php?p=stats) and about 6,000 for the Arctic (Table 10.2) (see Chapter 11). Extensive Arctic–Antarctic comparisons are ongoing in collaboration with the Census of Antarctic Marine Life.

10.4 Unknown Aspects

Arctic regions contain a variety of complex habitats that are difficult to access and historically have not been in the focal point of political and scientific interests. Despite a recent increase in overall interest, numerous Arctic research cruises, well-equipped field-stations, drifting stations, and easier access to many areas (because of substantial shrinkage of the ice cover), certain geographic areas, taxa, and habitats still remain poorly sampled. The previous lack of interest is now leading to uncertainties about the extent of

ongoing changes. The ecological consequences and implications of ongoing change to biodiversity can never be understood if we do not fully understand the status quo with its regional and temporal variability.

10.4.1 Taxonomic gaps: microbes

Contrary to earlier opinions (Pomeroy *et al.* 1990), recent findings indicate an active microbial contribution in the Arctic (Kirchman *et al.* 2009) (see Chapter 12). We now know that viruses (Le Romancer *et al.* 2007; B. Wrobel, personal communication), Archaea, Eubacteria, and protists (Lovejoy *et al.* 2006; C. Lovejoy *et al.*, unpublished observations) thrive in all Arctic habitats, from nearshore to deep water, with gaps in their regional patterns, biodiversity inventory, and physiological adaptations. Arctic and Antarctic eubacterial communities are distinctly different (Bano *et al.* 2004), and Arctic bacterial diversity in Arctic samples is lower than Antarctica (Junge *et al.* 2002; Fuhrman *et al.* 2008). Microhabitats (Meiners *et al.* 2008) add to bacterial diversity together with unique habitats like naturally occurring methane and oil seeps along slopes and ridges (LaMontagne *et al.* 2004). However, most bacteria have never been cultured to study their physiology (Ducklow *et al.* 2007) and we do not know how microbial diversity connects to the Arctic food web structures.

Although species diversity for protists with hard structures like diatoms has been studied in Arctic waters for decades (Horner 1985; M. Poulin *et al.*, unpublished observations), only limited information on species inventories and abundance is available for other flagellated taxa. Cyanobacteria appear to be less relevant in offshore regions, but more abundant close to shore (Waleron *et al.* 2007) whereas flagellated eukaryotes (for example prasinophytes) occur in high abundances with apparently low diversity (Lovejoy *et al.* 2006).

10.4.2 Regional gaps

Despite considerable sampling efforts in the past decade, the Arctic deep-sea remains undersampled for all realms (Fig. 10.1). Biodiversity inventories of other deep-sea areas have revealed increased species numbers with increasing sampling effort (Brandt *et al.* 2007). Based on species discoveries during two recent deep-sea cruises and a lack of an asymptote in species accumulation curves (B.A. Bluhm *et al.*, unpublished observations), we estimate that possibly hundreds of species (excluding microbes) await discovery in the Arctic deep sea.

Of the shelf seas, the East Siberian Sea is the most understudied in terms of biodiversity (Fig. 10.1) whereas other Russian seas were intensively sampled. Information is also scarce in the Canadian Archipelago and northern Greenland, partly related to the typically heavy ice cover. Biodiversity work there has primarily concentrated around field

stations and research institutes, like in Disco Bay, northeast Greenland or Resolute Bay (Conover & Huntley 1991; Michel *et al.* 2006).

10.4.3 Poorly explored habitats

Examples of underexplored habitats include the deep-sea ridge systems that extend thousands of kilometers across the Arctic sea floor. Although biodiversity on both ridge sides may not be that different (Schewe & Soltwedel 1999; K.N. Kosobokova *et al.*, unpublished observations), faunal diversity and densities may vary greatly between ridge tops and sides (Kosobokova & Hirche 2000), possibly related to variability in the overlying nutrient concentrations and primary production. The scarceness of studies, however, precludes general conclusions on the biodiversity at any of the prominent Arctic ridge systems.

Within the realm of the sea ice, sea-ice pressure ridges house major unknowns with respect to their biology. Ridges form when ice piles up under pressure, reaching drafts greater than 20 m even in summer (Eicken *et al.* 2005). Based on ArcOD findings (Gradinger *et al.* 2010), we propose that pressure ridges will be especially relevant for the survival of sea-ice-related invertebrates over the coming decades in areas of dramatic sea ice loss.

Biodiversity is probably better studied in nearshore areas around field stations or logistics centers than anywhere else in the Arctic, but is not studied at all in other nearshore locations, because larger research vessels cannot venture into shallow water. The highly localized geographic coverage relative to transect-oriented station grids typically used elsewhere is problematic because even relatively nearby locations of similar habitats can have rather different biotic inventories (Iken & Konar 2009). Projects like an inventory of many coastal Chukchi Sea sites in 2010 (S. Jewett & D. Dasher, personal communication) will improve the situation.

Arctic seamounts and pockmarks are poorly mapped and inventoried. An ArcOD survey of a suspected pockmark feature on the Chukchi Plateau showed elevated densities of megafauna but no signs of seepage (MacDonald *et al.* 2010), but it is unclear if this observation can be generalized.

10.4.4 Underexplored temporal variability

Environmental conditions in the Arctic are extremely variable and natural variability is overlaid by – and often difficult to separate from – long-term climate change. As the most climatically sensitive region of the Northern hemisphere, the Arctic has experienced changes exceeding the natural variability, including shrinkage of the sea ice cover and thickness, increased precipitations and river run off, seasonal warming and other atmospheric changes, increased ocean mixing, wave generation, and coastal flooding (Walsh

2008). Yet, few time series of biological variables have been collected because of the difficulty associated with re-sampling communities throughout the year and/or over multiple years or even decades. Seasonal changes in algal and faunal abundance and diversity are most dramatic in sea ice and the water column (Story-Manes & Gradinger 2009; Makabe *et al.* 2010), with dampened variability in benthic communities because of their typically slower growth rates and longer lifespans. Interannual and inter-decadal alterations have been detected both in pelagic (Brodeur *et al.* 2002) and benthic habitats (Grebmeier *et al.* 2006).

Opposing trends, the difficulty to identify underlying causes clearly, the overall scarceness of even short time series, and the lack of complete inventories stress the need for the creation of integrated ecosystem biological observing systems as part of the global ocean observing system effort (section 10.5). Different ecosystem components respond to variability in different ways and should not be evaluated independently of each other. Some efforts underway in this direction are outlined in section 10.5.1.

10.5 Into the Future

10.5.1 Time series, networks, monitoring strategies

Long-term time series using a combination of both traditional and recent sampling technologies are essential to understand the changing Arctic. Future observational networks will need to consist of regional nodes, connected in a pan-Arctic scheme, as regional trends may differ. For example, the Chukchi and Beaufort Seas have experienced substantial thinning and reduction of the ice cover (Serreze *et al.* 2007), whereas less change (if any) occurred north of Greenland (Melling 2002).

No comprehensive pan-Arctic observational network is currently in place to assess changes in biodiversity. Several networks, however, are under discussion such as through the International Arctic Council, where ArcOD participates in the marine expert group within the Conservation of Arctic Flora and Fauna (CAFF) program (Vongraven *et al.* 2009). These could be operational as the first Census draws to a close in late 2010 with the caveat that little financial support will be in place at that time. On a national level, the Study on Environmental Arctic Change (SEARCH), an interagency US-based effort to understand system-scale change in the Arctic, has as one of their science-guiding questions “what changes in populations, biodiversity, key species, and living resources are associated with Arctic Change” (yet none of their 70 projects include “biodiversity” in the title). Some successful examples for national programs do exist. Any future network

must be interdisciplinary in nature, linking changes in ocean physics and chemistry to biological patterns, in order to create meaningful predictions.

Key components within monitoring networks are the following:

- a series of long-term monitoring sites (biological observatories) situated around the Arctic shelves and in the deep basins (section 10.5.3);
- pan-Arctic surveys using largely autonomous methodologies (section 10.5.2);
- exploratory expeditions completing the Arctic species inventory and conducting new research that augments the observatories.

For biodiversity research, the strategy must be to first identify a set of indices to assess changes in biodiversity, and make the connections between those changes and potential stressors (Vongraven *et al.* 2009). Such indices could, for example, include biomass of key ecosystem components, abundance of dominant or commercially important taxa, traditional biodiversity indices, distribution ranges, or ratios of Arctic to sub-Arctic species. Process measurements should also be included, as organic carbon partitioning between pelagic and benthic food webs is predicted to shift towards pelagic-dominated food webs (Carroll & Carroll 2003; Bluhm & Gradinger 2008). Such food web shifts will cascade through all trophic levels, and could change the key species within the affected regions. Indices should provide the information required to make sound political decisions to mitigate negative impacts to the ecosystems and Arctic human populations.

In addition to continuing the few existing time series, new observatories should be placed in regions where the rates of change appear to be greatest (Chukchi Sea: Hopcroft *et al.* 2010; Barents Sea: Stempniewicz *et al.* 2007). From a logistical perspective, the relative proximity of these regions to major research ports, and their longer ice-free season, greatly simplifies access to them relative to the central Arctic. Areas that have historically been perpetually covered by ice remain worthy of basic exploratory survey because they are so poorly characterized.

10.5.2 Technological developments

A major impediment in understanding the biological impacts of Arctic change is owing to logistical constraints. Few icebreakers are capable of hosting multidisciplinary research teams and expeditions are major investments for funding agencies. International cooperation is needed to connect national efforts, to standardize techniques, and create an operational network with fast data transfer and delivery.

Technology should extend the short-term observations made by traditional expeditions to year-round observations, although the broadest taxonomic coverage will remain achievable only using ships and land-based stations. Moored video systems, or even ice-mounted webcams in nearshore waters, can collect information during seasons when access to the region of interest is difficult. Autonomous underwater vehicles with image capturing capabilities will extend our options to look at the distribution of larger taxa on scales of hundreds of kilometers, even in ice-covered waters (Dowdeswell *et al.* 2008). ROVs (Fig. 10.7) place an observer virtually into the deep-sea environment to survey the larger, rarer, and more mobile animals (Raskoff *et al.* 2005, 2010). Moored instrumentation, including *in situ* imaging flow cytometers, video plankton recorders, or fish-tracking networks, is now commercially available. Autonomous underwater vehicles and gliders equipped with listening devices might extend the range of acoustic curtains, and record the presence of marine mammals in ice-covered waters. The major hurdle appears not to be readiness of scientists or instrumentation, but sufficient logistic and financial commitment by Arctic nations to put such a network in place.

10.5.3 Forward look

ArcOD has contributed to the considerable recent progress regarding biodiversity of the Arctic. The most urgent current need now is to determine how the human footprint is affecting the Arctic Ocean's flora and fauna, and the overall properties of the ecosystem these organisms collectively shape. Current model projections suggest climatic changes may become even more exaggerated over the coming decades (Overland & Wang 2007). Despite the need for continued observation, there is as yet no strong indication that species-level surveys will be expanded in the Arctic. This leads to the situation where our understanding of long-term patterns will be built upon temporally and regionally fragmented observations often focused on specific ecosystem components or by reducing the Arctic's complexity down to biogeochemical units.

As an indirect consequence of ice reduction, the human footprint within the Arctic is already increasing in numerous ways (Gradinger 2009b). Ice-free Arctic seas are considered the future shipping corridor between the industrial centers in the North Pacific and Europe. Reduced summer sea ice will allow intensified resource exploration, as evidenced by the recent oil and gas lease sales on the US Chukchi Sea shelf, and expanding exploration on the Russian and Norwegian shelves. The opening of Arctic seas in summer could allow commercial extraction of living marine resources in areas currently untouched by commercial exploitation. Increased human presence will inevitably leave its trace in the marine environment in

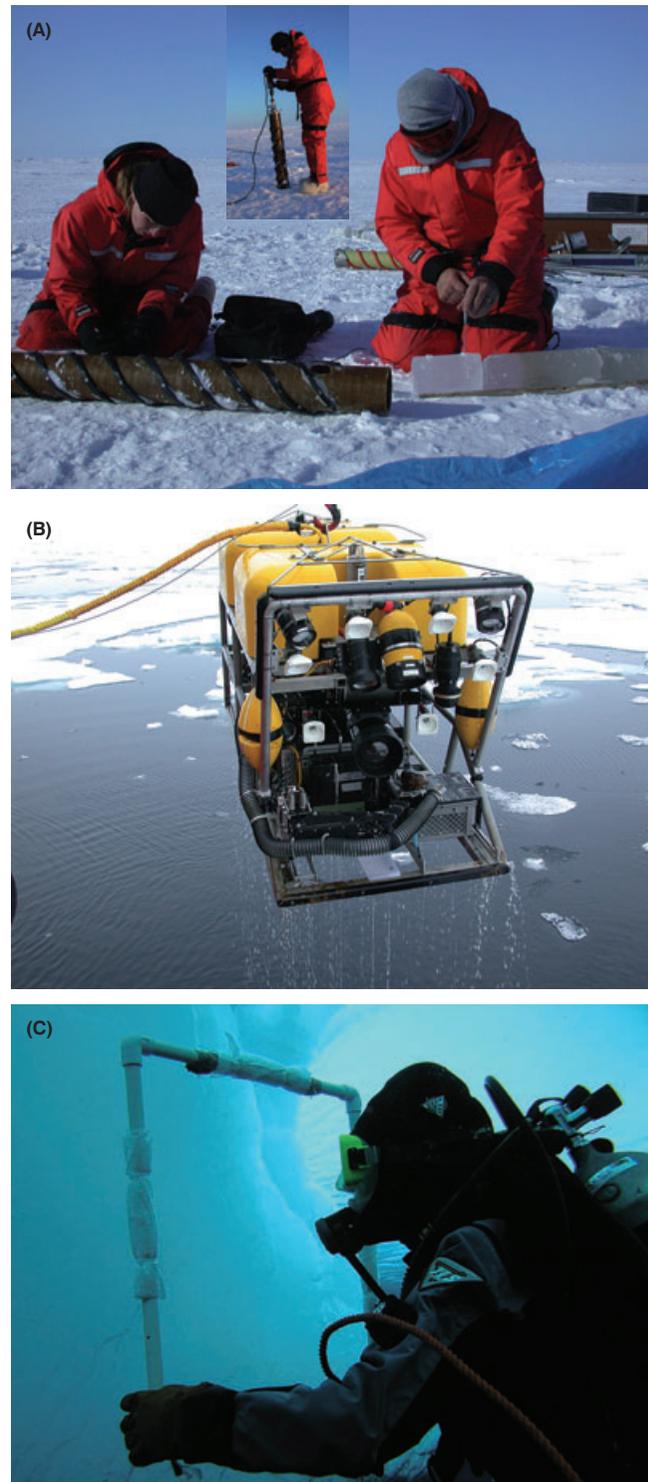


Fig. 10.7

Traditional and modern sampling techniques used in ArcOD. (A) Sea ice sampling using an ice corer. (B) Water column and benthic sampling using an ROV that can be operated in pack ice. (C) Under-ice sampling by SCUBA divers in Arctic pack ice. Photographs: A and B, B. Bluhm; C, S. Harper, both University of Alaska Fairbanks.

the form of industrial contaminants, harmful species, and changes in food web structure through commercial harvests.

Using historical information and estimates of what might happen over the next century (see, for example, Bluhm & Gradinger 2008; Gradinger 2009b) we believe the following patterns are likely. The currently observed changes in species patterns and ecosystem functioning will continue over the next decade(s), likely at an accelerated rate with changes at all trophic levels. These changes will impact the use of Arctic living resources by humans, both commercial and subsistence, and may even lead to long-term biodiversity changes in the Pacific and North Atlantic Oceans as increased species exchange occurs across the Arctic. The Pacific diatom *Neodenticula seminae* has already been observed in the North Atlantic (Reid *et al.* 2007). Arctic endemic biota will likely be most negatively affected, whereas less ice and higher temperatures will allow sub-Arctic species to move northward. The design of observational networks documenting biological change should develop benchmarks against which to follow such change. A discussion and agreement on the biological components of an ocean observing network is long overdue.

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