2. Setting the scene

Tom Christensen[1], Courtney Price[2], Marianne Olsen[3], Tom Barry[2], Kári Lárusson[2]

[1] Aarhus University, [2] CAFF International Secretariat, [3] Norwegian Environment Agency

2.1 Arctic marine ecosystems

The processes that control Arctic marine ecosystems differ from other ocean environments. The absence of light during winter months limits primary production, which then bursts into action upon the return of the spring sun. Large areas of sea ice also characterize Arctic Marine Areas (AMAs), and appear seasonally over extensive shelves and more permanently as a large central area of multi-year pack ice.

Marine areas in the Arctic are often highly stratified because freshwater flows from rivers and melting ice make the upper layer of the ocean less salty compared with other oceans. Currents from Atlantic and Pacific water masses mix elements such as nutrients, organic matter, plankton, and larvae of fish and invertebrates at different depths and in different patterns. Relatively warm and salty Atlantic water enters the Arctic through the eastern part of Fram Strait and less salty Pacific water enters through the Bering Strait, while the western Fram Strait acts as the major outflow from the Arctic Ocean (Eamer et al. 2013, Meltofte 2013; Figure 2.1). Arctic marine biodiversity is linked to these dynamic patterns of ocean conditions. Fish species associated with warm Atlantic waters thrive in the Barents and Greenland Seas, while bottom-dwelling invertebrates of Pacific origin are found in the Chukchi, Beaufort and northern East Siberian Seas (Eamer et al. 2013). Other related physical features, including polynyas, leads, marginal ice zones and upwelling zones have major impacts on Arctic marine ecosystems.

Some key elements that determine the diversity of species and ecosystems in the Arctic marine environment are the high degree of seasonality in environmental conditions, critical influence of the large continental shelves and sea ice,

Box 2.1 Some features of the sea ice environment

Marine areas seasonally or permanently covered by sea ice are a globally unique habitat. Ice edges and open water areas favour wind-driven mixing of the seawater that enhances local production and can create biological hotspots. Some key features of the sea ice environment in the Arctic include:

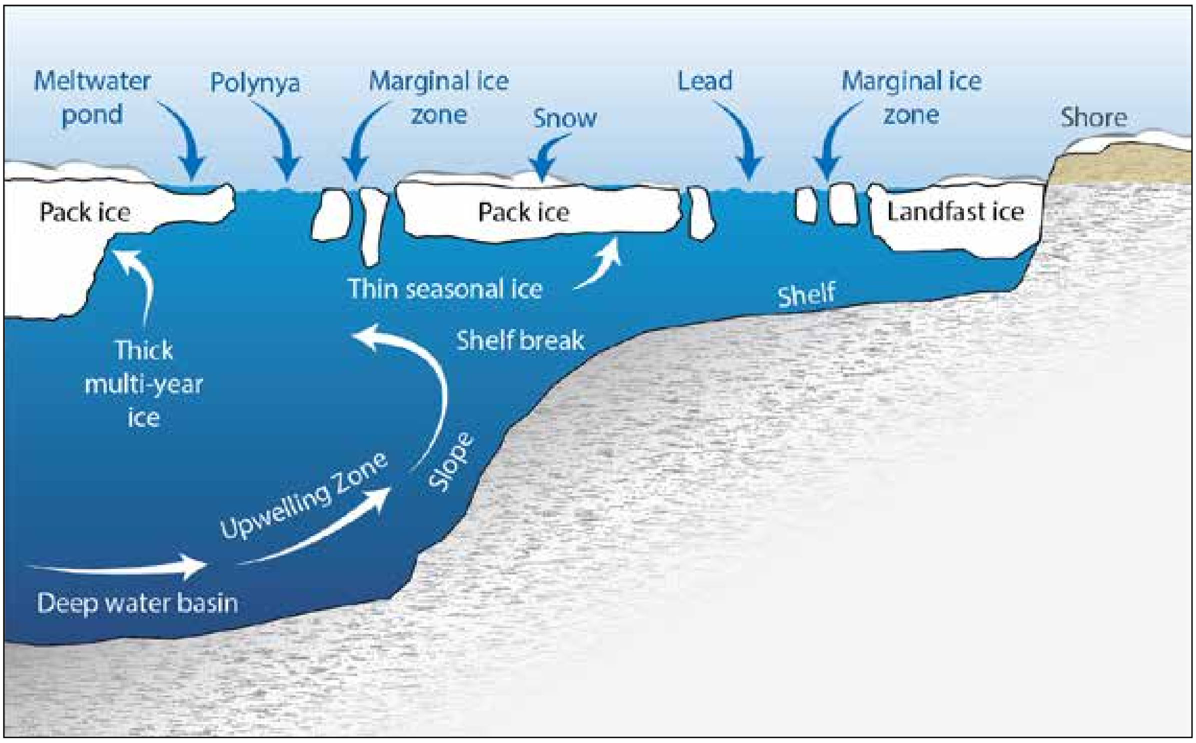
Polynyas: areas of permanently or frequently open water in winter surrounded by sea ice

Leads: linear stretches of open water in sea ice, often between landfast ice and pack ice

Marginal ice zones: transition areas from pack ice to open water

Upwelling zones: where deep, often nutrient–rich water rises to the surface due to wind or currents interacting with bathymetry

These and other features of the sea ice environment are illustrated below:



Box figure 2.1. Some features of the sea ice environment. Marine areas seasonally or permanently covered by sea ice are a globally unique habitat. Ice edges and open water areas favour wind-driven mixing of the seawater that enhances local production and can create biological hotspots. Adapted from Eamer et al. (2013).

and the connection to other oceans via 'corridors' (Meltofte 2013, Hunt et al. 2016). Despite extreme environmental conditions, Arctic marine ecosystems support a great diversity of life, including species found nowhere else on Earth. The Arctic marine environment supports over 5,000 animal species, including commercially valuable fish species, large populations of migratory birds and some of the world's largest seabird colonies, and unique and iconic Arctic species such as polar bear (*Ursus maritimus*), walrus (*Odobenus rosmarus*) and narwhal (*Monodon monoceros*) (Meltofte 2013). There are also tens of thousands of less understood, but vitally important species of bacteria, microbes, algae, single-celled organisms and parasites, with many more species to be discovered (Meltofte 2013). Zooplankton represent key links between primary producers and middle trophic levels (e.g., fish and seabirds), with *Calanus* copepods and pelagic or ice-associated amphipods as the most important groups in the Arctic for lipid production and transfer to higher trophic levels as well as to the benthos though vertical flux (Falk-Petersen et al. 2009, Søreide et al. 2013).

When sufficient light penetrates the ice pack in spring, it kick-starts the development of ice algae in early spring. A phytoplankton bloom will usually take place later in the summer in the water column. These events deliver energy and materials to zooplankton and other trophic levels, resonating throughout the food web (Eamer et al. 2013). Most Arctic marine species are highly seasonal and specialized when it comes to feeding, reproduction and migration patterns, so the timing and duration of sea ice retreat and ice-free ocean determine when, where and for how long species can accomplish activities that are vital to survival.

The food web extends well beyond just the transfer of energy to encompass diverse cultural and social benefits that humans derive from their environment. Importantly, Arctic marine ecosystems support human life. Indigenous peoples of the Arctic have lived with the polar environment for thousands of years, and many marine species are important not just for food and clothing, but hold special significance for spiritual and cultural meaning and purpose (Raymond-Yakoubian et al. 2014, ICC-Alaska 2015, Slavik 2015). Non-indigenous Arctic residents also hold a special relationship to the sea, recognizing it as a force that shapes their individual livelihoods, as well as economies and cultures (Einarsson et al. 2011, Schweitzer 2014).

2.2 Physical drivers

The Circumpolar Biodiversity Monitoring Program's (CBMP) *Arctic Biodiversity Marine Monitoring Plan* (*CBMP Marine Plan*) identifies several priority drivers that influence the chosen Focal Ecosystem Components (FECs) (Gill et al. 2011). What follows are descriptions of key physical parameters that influence Arctic marine ecosystems. This section addresses physical drivers (i.e. natural variability parameters) that result in change over time, whereas Chapter 2.3 summarizes some anthropogenic drivers. The most relevant climate system parameters are included in the physical driver's section, although climate change is also an anthropogenic driver. Physical or anthropogenic drivers that have particular effects on FECs will be revisited in Chapter 3.

Box 2.2: Key physical drivers of change

Physical drivers are identified in the CBMP *Arctic Marine Biodiversity Monitoring Plan* (*CBMP Marine Plan*; Gill et al. 2011). The physical drivers were further developed during the implementation of the *CBMP Marine Plan*, and do not strictly follow the categories used in the *CBMP Marine Plan*.

These are:

- Sea surface temperature
- Ocean currents and frontal boundaries
- Sea surface salinity
- Ocean acidification
- Nutrients
- Sea ice, including
    - ice cover
    - ice concentration
    - ice dynamics
    - marginal ice zones
    - landfast ice
    - polynyas and leads

Monitoring temperature, light, sea ice cover, storm events and other abiotic drivers, including those described in Box 2.2, are outside the scope of the CBMP, although information on key abiotic parameters is important to correctly interpret and analyse biodiversity and ecosystem information in a comprehensive way.

Most of the drivers mentioned in Box 2.2 can be linked with climate system parameters. When considering physical drivers, the CBMP distinguishes between variability and change. Variability can be regarded as the short-term, non-directional shift in parameter values, usually within some reasonably predictable range of limits, whereas change is a long-term, directional trend or shift in some aspect of the climate system (or other recipient systems) due to external forcings or internal feedback. Climate change embodies both alterations in parameter variability as well as changes in those parameters.

Arctic Ocean ***sea surface temperature*** have been recorded during many research and monitoring projects. According to the IPCC (2013) and NOAA (2015), the available data are insufficient to reliably calculate long-term trends for the vast majority of the Arctic marine environment (Fig. 2.3). However, existing monitoring in some areas suggests that the Arctic marine environment is undergoing a rapid warming trend, which follows a general documented warming trend in global ocean temperatures over the past 30 years (AMAP 2013). For example, temperatures recorded for the Barents Sea has increased since the 1970s (Johannesen et al. 2012, Smedsrud et al. 2013). As the world's oceans absorb more heat, sea surface temperatures will increase and ocean circulation patterns that transport warm and cold water around the globe will change. A rise in seawater temperature of up to 4°C is expected in the Atlantic sector of the Arctic Ocean, which is expected to have direct and indirect impacts on marine biodiversity (Müller et al. 2009, Meltofte 2013, Hunt et al. 2016). Such changes in temperature can affect any and/or all aspects of species life cycles, including breeding, rearing, feeding, predator-prey relations, population cycles, and timing and duration of migration (Meltofte 2013).

Large ***ocean currents*** encircle the world like a conveyor belt and are highly connected to the atmosphere, playing a major role in global weather patterns and affecting ocean life. The Arctic plays a key role in the global climate system through the production of North Atlantic Deep Water, which helps drive the circulation of the world's oceans. Simplified Arctic Ocean currents (Fig. 2.1) show that the main circulation patterns follow the continental shelf breaks and margins of the basins in the Arctic Ocean. Different global models predict different types of changes, which can cause changes to Arctic ecosystems (AMAP 2013, Meltofte 2013).

Ocean frontal boundaries separate two distinct water masses. With sharp gradients in parameters such as temperature and nutrient richness, ocean frontal boundaries often create hot spots for biological production (Meltofte 2013). These frontal boundaries can shift location from year to year depending on physical parameters such as river inputs and salinity, and temperature in water masses advected from other areas. The area of the Barents Sea where cold, less saline Arctic water meets warm, saline Atlantic water (i.e., the Polar Front) is known to be an area of high biological production. Arctic and more southern species tend to meet in this area because of increased food availability and because thermal barriers prevent further distribution northwards for southern species. There are similar patterns in other places in the Arctic, including in the Bering Sea (Meltofte 2013).

Changes in ***sea surface salinity*** can alter the physical and chemical environment, affecting ocean currents and potentially altering marine food webs (Carmack and Wassmann 2006). Pacific water enters the Arctic Ocean

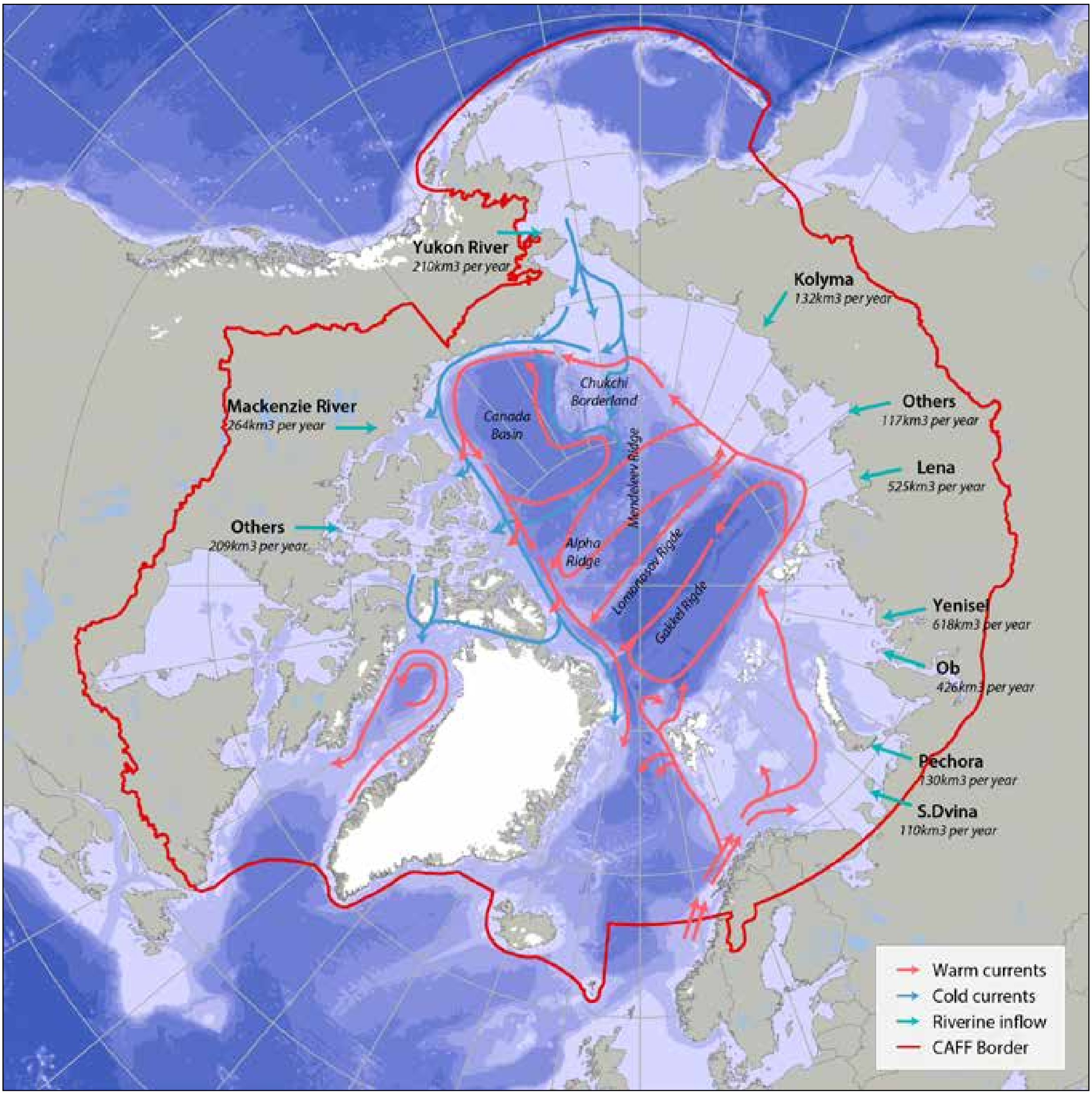


Figure 2.1. Bathymetric features, warm currents (red arrows), cold currents (blue arrows) and riverine inflow in the Arctic. Adapted from Jakobsen et al. (2012).

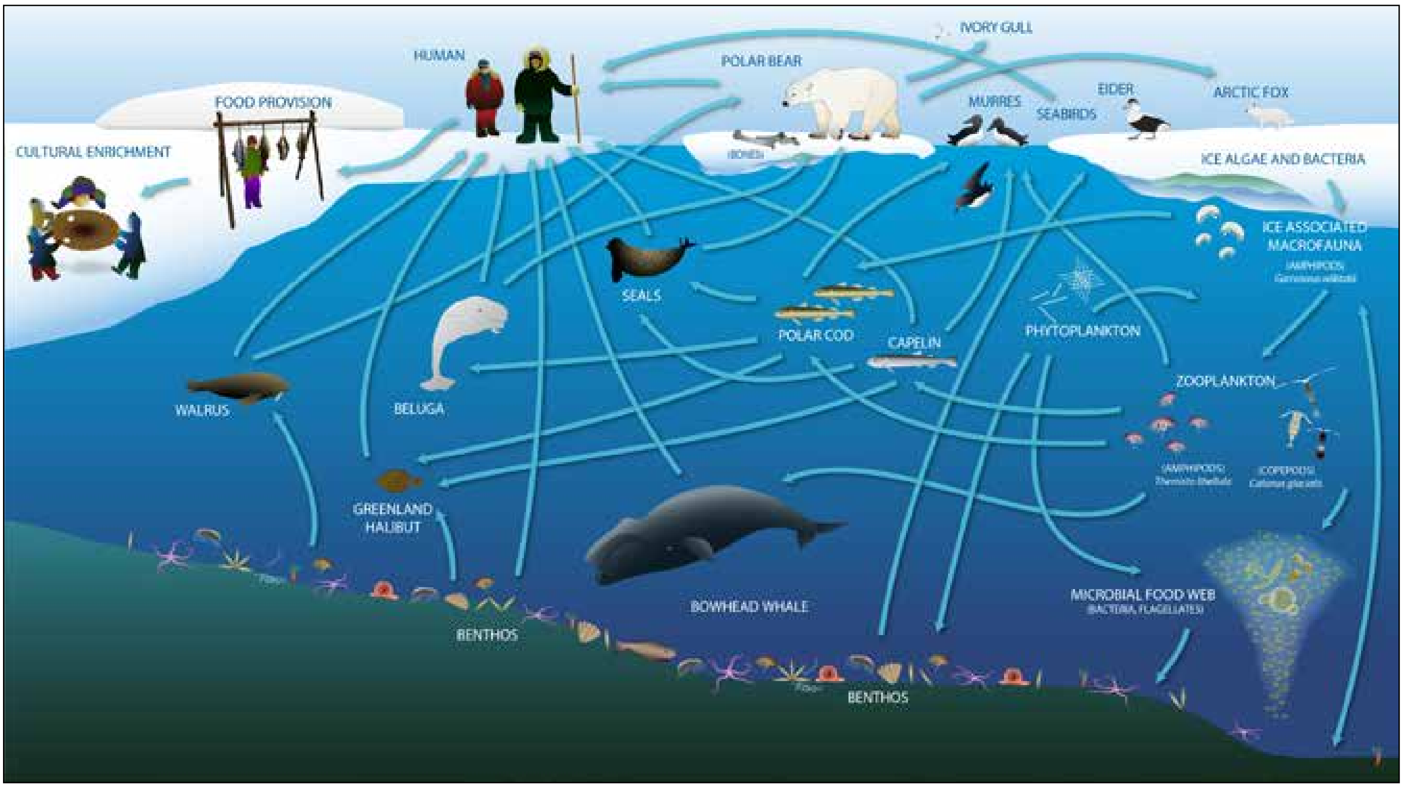


Figure 2.2a. Conventional conceptualization of energy flow in the High Arctic marine environment. The Arctic marine food web includes the exchange of energy and nutrition, and also provides cultural, social and spiritual meaning for human communities. Adapted from Darnis et al. (2012) and the Inuit Circumpolar Council-Alaska (2015).

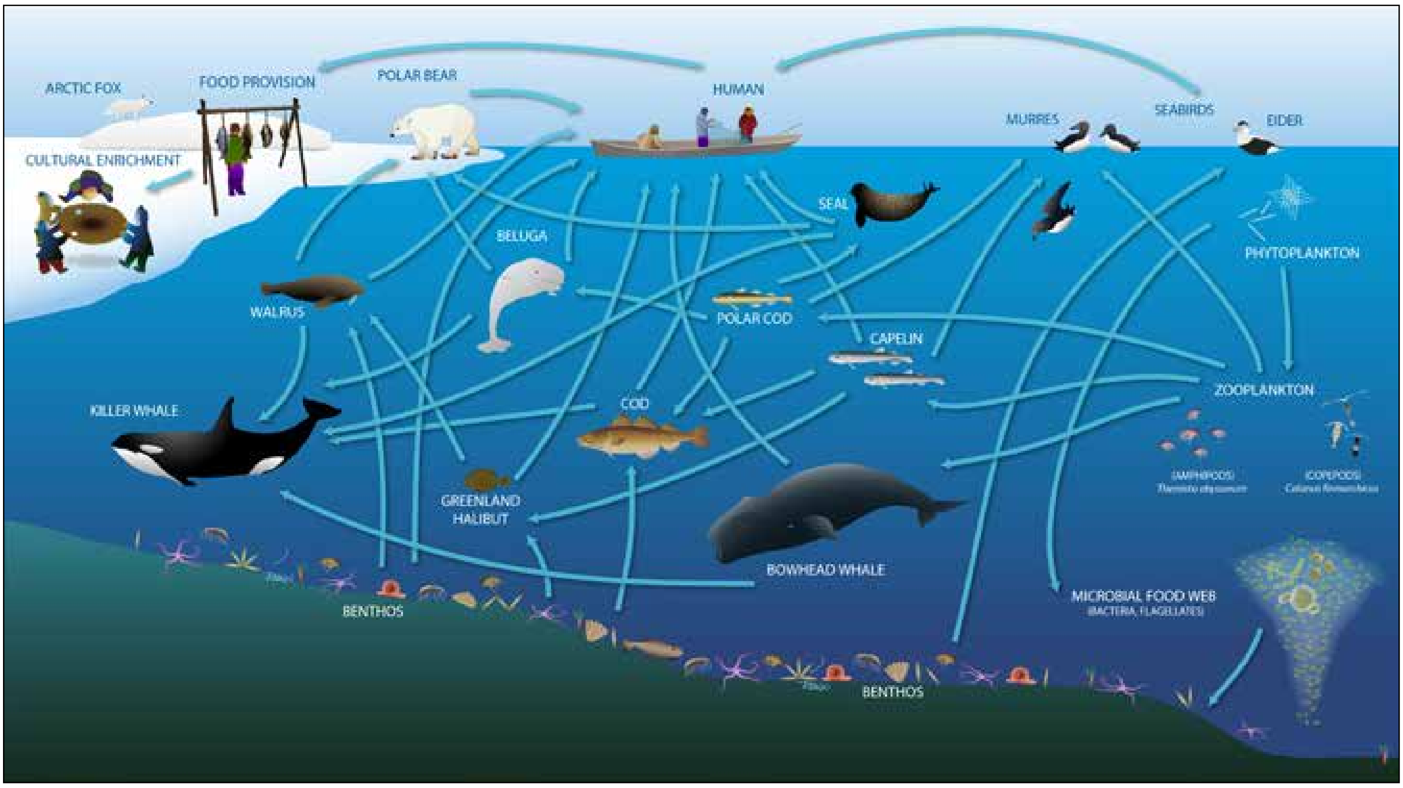


Figure 2.2b: Changes expected or underway in the energy flow in the High Arctic marine environment. The Arctic marine food web includes the exchange of energy and nutrition, and also provides cultural, social and spiritual meaning for human communities. Adapted from Darnis et al. (2012) and the Inuit Circumpolar Council- Alaska (2015).

through the shallow and narrow Bering Strait (Fig. 2.1). Pacific water is less saline and therefore less dense than Atlantic water, and forms a distinct layer on top of the Atlantic water. Furthermore, freshwater enters the Arctic Ocean from river basins and glaciers, mainly from Russia and Canada—countries that contain some of the largest freshwater systems in the world. This input of freshwater contributes to stratification, making the top 45 m or so of the Arctic Ocean less saline than the water below. Warming, combined with increased precipitation, has caused an increase in freshwater discharge into the Arctic Ocean (Dyurgerov et al. 2010), for example, increased melting from the Greenland Ice Sheet has increased freshwater inflow to areas in the North Atlantic.

Alkalinity is a fundamental chemical property of the carbonate system for seawater. Oceans have been increasingly absorbing carbon dioxide (CO_2) because of the rising levels of CO_2 in the atmosphere (Freely et al. 2004, Pelejero et al. 2010, AMAP 2013). The resulting higher concentration of CO_2 in the world's oceans causes ***ocean acidification***, a phenomenon that changes the chemical carbonate balance of the sea water, and thus the living conditions for biota. The Arctic is especially vulnerable to this acidification since CO_2 dissolves more easily in colder water.

Less alkaline waters may dissolve the materials that some organisms need to build their skeletons and shells (Orr et al. 2005, AMAP 2013), although organisms in many cases will still be able to construct their skeletons at the cost of increased energy requirements (Browman 2016). Calcium carbonate crystalizes in two forms, calcite and aragonite, which have different solubilities in relation to pH. Organisms using the more soluble form, aragonite, are most sensitive to acidification. Pelagic snails (pteropods) are an important component of zooplankton and experimental studies have shown that they are highly vulnerable to dissolution of their aragonite shells at close to current pH levels (Bednarsek et al. 2014). On the other hand, organisms incorporating the less soluble calcite, such as the abundant planktonic algae belonging to the group coccolithophores, may be better able to adapt to increasing acidity at the cost of expending more energy on constructing their skeletons (Beaufort et al. 2011). Arctic copepods, such as *Calanus glacialis*, are less affected by increased seawater pCO_2, even at the younger life stages (Bailey et al. 2017). However, lowered pH may increase metabolic cost for this species at the expense of growth performance (Thor et al. 2016).

Nutrient-rich areas stimulate growth of ice algae, phytoplankton and invertebrates and serve as important feeding grounds for larger animals such as fish, seals, whales and seabirds (Chapter 2.3). Nutrient-rich waters can be found in areas of sea-ice melt, ice edges, upwelling zones and throughout nutrient-rich currents such as the Anadyr Current, which moves northward into the Arctic Ocean via the Pacific Arctic Bering Strait region (Codispoti et al. 2005). Changes in nutrient supply related to changes in physical parameters, such as sea ice and current alteration, could dramatically alter ocean ecosystems (Meltofte 2013).

Timing, distribution and characteristics of ***sea-ice cover*** define and drive the conditions in many Arctic marine ecosystems, affecting seasonal cycles of light availability, water temperature, nutrients and the flow of energy through the food web. Some of the features of the sea ice environment are illustrated Box 2.1.

Average summer ***sea-ice extent and thickness*** is decreasing (AMAP in press a, b; Fig. 2.4), which can have major impacts on sea-ice dependent species and ice-associated ecosystems.

The presence of sea ice impedes surface water mixing, and influences freshwater and heat fluxes, which, in combination with snow cover, reduces light availability for primary producers. Therefore, snow cover and sea-ice melt/break-up appear to control the timing of ice-associated (i.e., ice algae) and pelagic (i.e., phytoplankton) blooms (Michel et al. 2006, Lavoie et al. 2009).

Most of the Arctic Ocean is projected to be virtually ice-free in summer within 30 years, with multi-year ice persisting mainly in the Arctic Archipelago, the narrow straits between Canada and Greenland, and north of Greenland (Wang and Overland 2012, Eamer et al. 2013, Meltofte 2013). Multi-year ice is very low in the straights between Greenland and Canada, with the high productivity surface water historically in Northern Baffin Bay moving north. The most obvious negative impacts of rapid changes in sea ice are on species that depend on the ice as habitat, such as polar cod (*Boreogadus saida*), ivory gull (*Pagophilia eburnea*), ice seals and polar bear (Chapter 3). Together with more extreme weather events, such as storms, changes in sea ices are also likely to have direct or indirect effects on many other species and on productivity (Meltofte 2013).

Polynyas and leads play an important role in the productivity and biodiversity of Arctic marine ecosystems. Polynyas are pockets of recurrent open water areas amidst ice-cover and are distinguished from leads by being broad openings rather than long, narrow fractures. They occur throughout the Arctic and are associated with circumpolar flaw lead systems that form along the edge of landfast ice areas (where ice is frozen to the coast and does not move with wind or currents). Polynyas can be sites of enhanced or early season productivity, making them important biological hotspots (Bursa 1963, Hirche et al. 1991, Stirling 1997, Moore and Laidre 2006). In summer, the region of the North Water Polynya in Baffin Bay supports some of the largest concentrations of seabirds anywhere in the Arctic and is a critical habitat to several populations of marine mammals (Stirling 1997, Christensen et al. 2012, Heide Jørgensen et al. 2013).

2.3 Human drivers

Many Arctic regions have seen little or no direct human-induced habitat change compared with other parts of the world. Some historical examples can be found in activities such as hunting, commercial fishing, oil spills and others where human-induced impacts have had direct effects on Arctic marine ecosystems (Meltofte 2013). The *CBMP Marine Plan* identifies several important drivers that influence the FECs (Gill et al. 2011).

Overharvest has not only caused depletion of some target populations, but in some cases, it has had cascading ecosystem effects. For example, the elimination of large whales by commercial whaling may have been followed

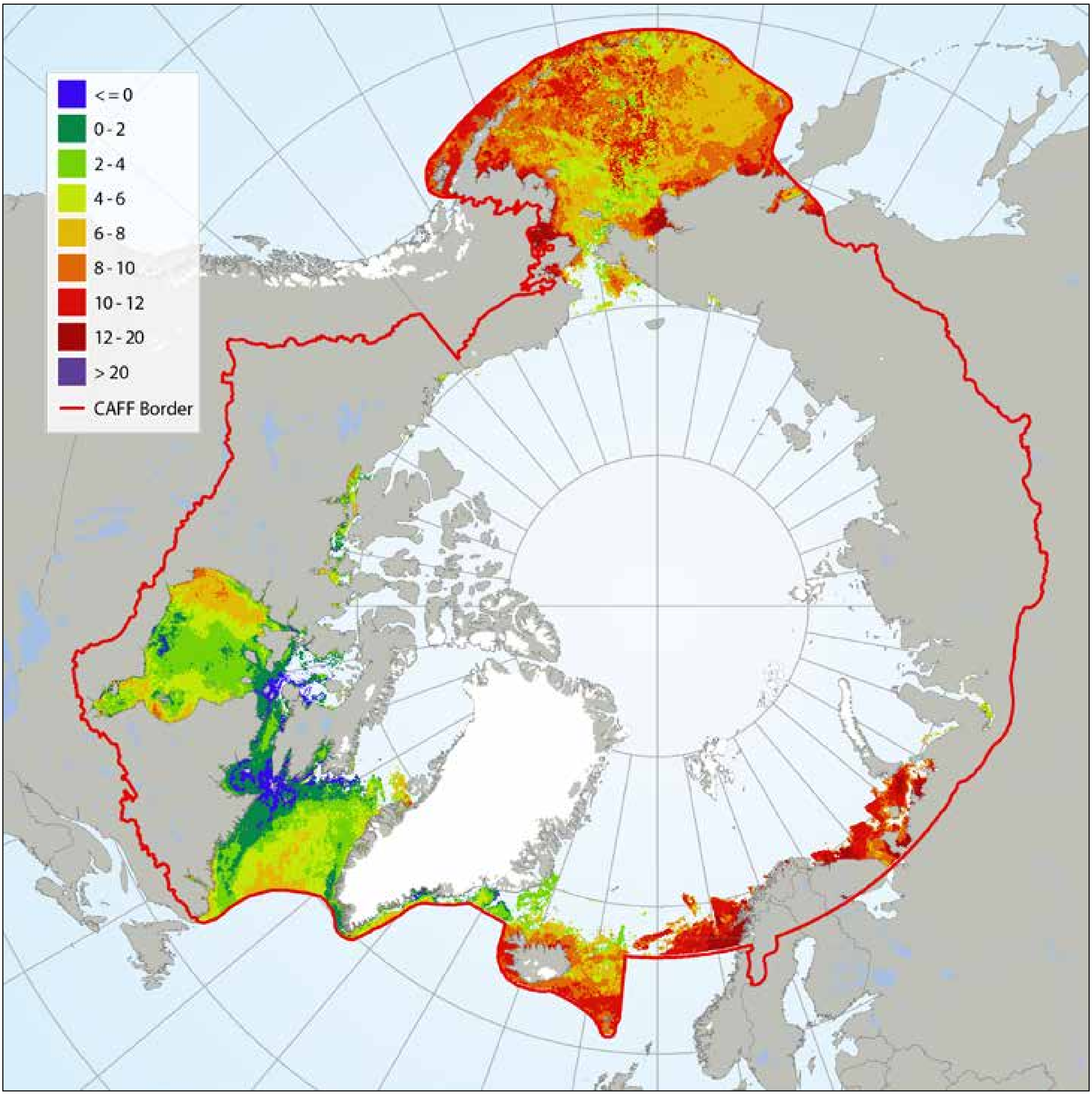


Figure 2.3: It has not been possible to identify available trend data for Arctic Ocean sea surface temperatures because there is not enough data to calculate reliable long-term trends for much of the Arctic marine environment (IPCC 2013, NOAA 2015). Here, sea surface temperature for July 2015 is shown from CAFF's Land Cover Change Index. MODIS Sea Surface Temperature (SST) provided a 4 kms spatial resolution monthly composite snapshot made from night-time measurements from the NASA Aqua Satellite. The night-time measurements are used to collect a consistent temperature measurement that is unaffected by the warming of the top layer of water by the sun.

by increasing populations of smaller marine mammals together with some seabirds (Springer et al. 2003). Another example is the depletion of large populations of predatory fish (Smetacek and Nicol 2005) that may have resulted in reduced genetic variability of some species (Meltofte 2013). The impact of historical harvest of marine mammals, fish and seabirds on current structure and function of Arctic marine ecosystems is not well documented, but the removal of such a large biomass of targeted species would have affected the flow of energy and trophic interactions. Overharvest was historically the primary human impact on many Arctic species, but sound management has successfully addressed this problem in most, but not all, cases. However, there have been management failures and high harvest pressure continues for some fish stocks and seabird populations (Meltofte 2013).

Fisheries in some Arctic regions play a significant role in the economy (AMAP in press a). For example, Greenlandic commercial fisheries produce over half of the total service and goods export value for the country, amounting to 57% in 2011 (AMAP in press a). Commercial fisheries are also rapidly expanding in the waters off Nunavut, Canada, with an increase in total value from 38 million to 86 million CAD during the period 2006-2014 (AMAP in press a). Up to 1,600 vessels may be active at times in the ice-free sections of the Barents Sea (PAME 2009).

Conventional ***bottom trawl*** fisheries for groundfishes are highly efficient, but can be damaging to the environment, as they can change the composition of benthic communities. Fishing practices such as bottom trawling may pose serious threats to benthic communities and remain an important stressor in some areas (Thurstan et al. 2010, Meltofte 2013). The most harmful effects of trawling have been demonstrated for hard-bottom habitats dominated by large sessile (immobile) fauna (Lyubin et al. 2011, Jørgensen et al. 2015, AMAP in press a).

The recent levels of ***mercury*** and ***persistent organic pollutants*** (POPs) in some areas are believed to exceed the threshold for biological effects in some species, in particular, top predators in Davis Strait-Baffin Bay, East Greenland and Svalbard (Letcher et al. 2010, AMAP 2011, Fauchald et al. 2015). It is anticipated that mercury concentration will increase in the environment and wildlife, while legacy POPs controlled by or subject to national and international regulations will likely decrease (AMAP in press a). However, new and emerging compounds (such as such as brominated and fluorinated compounds and siloxanes) with unknown effects on biodiversity will likely continue to be found in the environment.

The extraction and use of ***oil, gas and minerals*** is probably the single most important human-induced contributor to pollution, both locally in the form of release of toxic compounds and accidents (AMAP 2009, Meltofte 2013) and globally in the form of greenhouse gases, black carbon and mercury emitted when fossil fuels are combusted. This is particularly relevant for the Arctic, not only because the region potentially holds one-fifth of the world's yet undiscovered hydrocarbon resources, but also because it experiences globally disproportionate and amplified effects of warming (Bird et al. 2008, Meltofte 2013).

Box 2.3. Key anthropogenic drivers of change

- Harvest and fisheries
  - direct impacts: mortality, population demographic shifts
  - indirect impacts: bycatch, habitat loss, disturbance (displacement from important habitats; some hunting activities, alteration (trawling) and changes/reduction of prey availability and size.
- Persistent, bio-accumulative and toxic contaminants: impact of persistent organic pollutants (POPs) and toxic metals (e.g., methylmercury), originating primarily from non-Arctic sources.
- Industrial development: habitat loss, alteration, disturbance, seismic activity, oil spills, pollution, garbage, noise, etc.
- Shipping: oil spills, chemical discharges, waste, noise over and under the water, collisions with marine mammals, introduction of invasive alien species, etc.
- Invasive alien species

Environmental impacts from exploring and extracting raw materials may change with a changing climate, requiring a call for flexible and adaptive management actions (AMAP in press a). Overall, warming will increase access to resources and this may increasingly expose vulnerable areas to resource exploration activities.

Projected losses of Arctic sea ice are likely to influence future ***shipping activities*** as natural resource development, regional trade, transportation of goods, tourism and research activities are developing in relation to climate change. Climate change and resulting changes in sea ice extent are recognised as important drivers for future shipping in the Arctic (PAME 2009, AMAP, in press a). In relation to transit shipping, the Northeast Passage will likely be an important gateway from the Pacific to the Atlantic in the future. However, other drivers outside the Arctic such as market constraints, as well as geopolitics, including the deepening of the Panama Canal and Suez Canal will also affect the transit and destinational shipping in the Arctic, and are therefore important drivers for future Arctic shipping activities.

If not regulated properly, ***shipping and industrial development activities*** are likely to have serious consequences for the Arctic environment (Reeves et al. 2014) and for those living in the region that continue to rely on the environment for food security and livelihoods. Impacts include accidental or regular discharge of oil, noise, air emissions, garbage discharge, invasive species introduction, light disturbance, whale strikes and more. However, a large oil spill is probably the most serious hazard to the Arctic marine environment (Skjoldal et al. 2009) and is a major concern to communities, fishers and hunters, politicians, environmentalists, and the scientific community.

Figure 2.4. Average September sea ice extent in 1979 (blue) compared with 2016 (white) and the median sea ice extent (yellow line) from 1981 to 2010 (Data: NSDIC 2016).

Invasive alien species have been recognized as one of the greatest biological threats to the planet's ecological and economic well-being (McNeely et al. 2001) and the adverse impacts of invasive alien species recognised as constituting one of the most significant stressors facing Arctic biodiversity (CAFF 2017).

2.4 Cumulative effects

A single driver may put relatively little pressure on the environment, but in combination, multiple repeated drivers can create cumulative effects in the environment with surprising and hard-to-predict results. Different drivers act on different elements within the ecosystem and different pressures may have either synergistic or antagonistic effects on particular ecosystem components. Drivers may also have direct and indirect effects on the ecosystem, further complicating relationships between drivers and change. Worldwide there is an increasing awareness of cumulative effects and the need to take a holistic and integrated approach to management to ensure the sustainability of marine ecosystems (ICC-Alaska 2015, Ottersen et al. 2011, O'Boyle and Jamieson 2006). Little is known about the patterns of cumulative effects and the changes these effects may cause. There currently exists no method or standardized approach for determining the impacts of cumulative effects. However, knowledge about causalities in the ecosystem, spatial data on important areas for species and ecosystems, and data on the distribution and intensity of human activities in marine areas are all essential in establishing a more adaptive and ecosystem-based approach to marine environmental management (Halpern et al. 2008, 2015, Ottersen et al. 2011).

Figure 2.5 Circumpolar map of known polynyas. Note that polynyas are dynamic systems and some may no longer exist in the form known from their recent history. Adapted from Meltofte (2013) and based on Barber and Massom (2007).

Inuit understanding of the environment also places strong recognition and consideration on the need to monitor connections between components of the ecosystem and how systems interlink (ICC-Alaska 2015). This approach is important to contribute towards a better understanding of cumulative effects (ICC-Alaska 2015). For example, Inuit walrus hunters consider not just the walrus, but also the connections between the animal and sea ice thickness, benthic food supply, ocean currents and more, as these drivers shape the appearance, location and health of the walrus (ICC-Alaska 2015). Collaboration and co-production of knowledge between scientists and Traditional Knowledge (TK) holders can foster important relationships, meaningful engagement and understanding, thus increasing collective knowledge about cumulative effects and points of resilience and vulnerability (ICC-Alaska 2015).

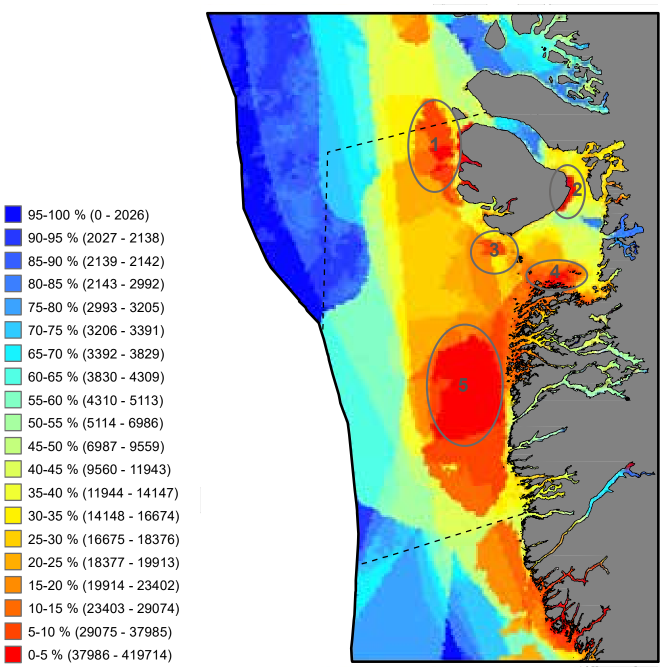
Ecosystem-based management (EBM) has been identified by Arctic States as key to an adaptive way to sustainably manage Arctic ecosystems. Its interdisciplinary approach considers the political, regional and cultural contexts of an area and provides a flexible means to manage the effects of multiple pressures on Arctic ecosystems (Arctic Council 2013). An important goal of EBM is to consider the cumulative environmental effects of important pressures and impacts on the environment.

Box 2.4 Looking at cumulative effects and ecosystem-based management

Critical to the successful implementation of ecosystem-based mangement (EBM) in the Arctic is the existence of a cohesive circumpolar approach to the collection and management of data and the application of compatible frameworks, standards and protocols that this entails.

Many examples demonstrate how more intensive use of spatial data has been applied in a national context to implement a marine spatial planning exercise in support of marine EBM. For instance, EBM regimes are introduced for Norwegian Sea areas. These can be regarded as large-scale spatial management tools and are coordinated by a management forum led by the Norwegian Environment Agency, and an advisory forum for monitoring, led by the Institute of Marine Research. EBM also requires an ecosystem-based approach to the monitoring of effects. One example is the plan for the Barents Sea (Olsen et al. 2007). In the Barents Sea example, monitoring effects is a stepwise process. Firstly, information on environmental conditions, commercial activities in the sea areas and value creation are compiled to provide a common factual basis for impact assessments. Secondly, impact assessments are carried out for all main activities that may affect the environment and relevant indicators to monitor are identified. An inter-ministerial steering committee carries out the environmental targets, based on the scientific advice. The monitoring program is regularly updated according to new knowledge and research (Ottersen et al. 2011).

Another recent example from Greenland demonstrates how different parameters, including species and ecosystem distribution, and human induced effects, were compared spatially to identify areas in need of special management attention. In response to the potential impacts from shipping and other activities in Disko Bay and Store Hellefiskebanke, the Danish Ministry of Environment conducted an extensive spatial analysis and modelling exercise to inform the development of appropriate management initiatives (Christensen et al. 2015). Abundance, occurrence and migration routes for over 65 species in the region were mapped focusing on the spatial distribution of important marine species and ecosystem components. These map layers were then combined to identify the most biologically important areas according to a set of criteria informed by the Convention on Biological Diversity to identify Ecologically and Biological Sensitive Areas (EBSAs) and by the International Maritime Organization (IMO) to identify Particular Sensitive Sea Areas (PSSA). This method was inspired by impact-mapping approaches used in marine regions outside the Arctic, as described by Halpern et al. (2008). Each of the biological features was assessed and ranked according to its specific sensitivity to potential environmental effects caused by shipping. This analysis found that several smaller areas around Disko Bay and Store Hellefiskebanke are sensitive or very sensitive to the environmental impacts that shipping may cause. Five sub-areas were identified (Box Fig. 2.2) where heightened awareness is needed in relation to impacts from shipping.



Box figure 2.2. Relative environmental sensitivity of areas in Disko Bay and Store Hellefiskebanke, western Greenland including five sub-areas (1 – 5) where there may be need for heightened awareness in relation to shipping. The colours indicate sensitivity in 2.5 x 2.5 km² grids, based on an assessment of existing species and ecosystem-component sensitivity to environmental impacts from shipping (oil, noise/ disturbance, organic garbage). Grids are divided into 5% fractiles with the relatively most sensitive in red. Adapted from Christensen et al. (2015).

References

Arctic Council. 2013. Ecosystem Based Management in the Arctic: Report submitted to Senior Arctic Officials by the Expert Group on Ecosystem-Based Management. Arctic Council, Tromsø, Norway.

Arctic Monitoring and Assessment Programme (AMAP). 2009. Arctic Pollution 2009: Persistent Organic Pollutants, Radioactivity, Human Health. Arctic Monitoring and Assessment Programme, Oslo, Norway.

Arctic Monitoring and Assessment Programme (AMAP). 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme, Oslo, Norway.

Arctic Monitoring and Assessment Programme (AMAP). 2013. Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme, Oslo, Norway.

Arctic Monitoring and Assessment Programme (AMAP). In press a. Adaptation Actions for a Changing Arctic (AACA): Baffin Bay-Davis Strait (BBDS). Arctic Monitoring and Assessment Programme, Oslo, Norway.

Arctic Monitoring and Assessment Programme (AMAP). In press b. Arctic Cryosphere Change: Snow, Water, Ice and Permafrost in the Arctic (SWIPA). Arctic Monitoring and Assessment Programme, Oslo, Norway.

Bailey, A., Thor, P., Browman, H.I., Fields, D.M., Runge, J., Vermont, A., Bjelland, R., Thompson, C., Shema, S., Durif, C.M.F. and Hop, H. 2017. Early life stages of the Arctic copepod *Calanus glacialis* are unaffected by increased seawater pCO_2. ICES Journal of Marine Science, fsw066.

Barber, D.G. and Massom, R.A. 2007. Chapter 1: The role of sea ice in Arctic and Antarctic polynyas. *In:* W.O. Smith Jr. and D.G. Barber (eds.). Polynyas: Windows to the world, Elsevier Oceanography Series, 74, Elsevier Science, pp 1-54.

Beaufort L., Probert, I., de Garidel-Thoron, T., Bendif, E.M., Ruiz-Pino, D., Metzl, N., Goyet, C., Buchet, N., Coupel, P., Grelaud, M., Rost, B., Rickaby, R.E.M. and de Vargas, C. 2011. Sensitivity of coccolithophores to carbonate chemistry and ocean acidification. Nature. 476: 80-83.

Bednarsek N., Tarling, G.A., Bakker, D.C.E., Fielding S. and Feely, R.A. 2014. Dissolution dominating calcification process in polar pteropods close to the point of aragonite undersaturation. PLoS One 9: 1-14.

Bird, K.J., Carpentier, R.R., Gautier, D.L., Houseknecht, D.W., Klett, T.R., Pitman, J.K., Moore, T.E., Schenk, C.J., Tennyson, M.E. and Wandrey, C.J. 2008. Circum-Arctic resource appraisal: estimates of undiscovered oil and gas north of the Arctic Circle. United States Geological Survey Fact Sheet, 2008-3049.

Browman, H.I. 2016. Applying organized scepticism to ocean acidification research. ICES Journal of Marine Science, 73(3): 529-536.

Bursa, A.S. 1963. Phytoplankton in coastal waters of the Arctic Ocean at Point Barrow. Arctic, 16: 239-262.

Conservation of Arctic Flora and Fauna (CAFF). 2017. The Arctic Invasive Alien Species (ARIAS) Strategy and Action Plan. Conservation of Arctic Flora and Fauna, Akureyri, Iceland.

Carmack, E. and Wassmann, P. 2006. Food webs and physical-biological coupling on pan-Arctic shelves: Unifying concepts and comprehensive perspectives. Progress in Oceanography, 71 (2-4): 446-477.

Christensen, T., Falk, K., Boye, T., Ugarte, F., Boertmann, D. and Mosbech, A. 2012. Identifikation af sårbare marine områder i den grønlandske/danske del af Arktis. Scientific Report from DCE – Danish Centre for Environment and Energy No. 43. Aarhus University, Danish Centre for Environment and Energy.

Christensen, T., Mosbech, A., Geertz-Hansen, O., Johansen, K.L., Wegeberg, S., Boertmann, D., Clausen, D.S., Zinglersen, K.B. and Linnebjerg, J.F. 2015. Analyse af mulig økosystembaseret tilgang til forvaltning af skibstrafik i Disko Bugt og Store Hellefiskebanke. Aarhus University, Technical Report from DCE – Danish Centre for Environment and Energy No. 61. Aarhus University, Danish Centre for Environment and Energy.

Codispoti, L.A., Flagg, C., Kelly, V. and Swift, J.H. 2005. Hydrographic conditions during the 2002 SBI process experiments. Deep-Sea Research Part II, 52 (24-26): 3199-3226.

Darnis, G., Robert, D., Pomerleau, C., Link, H., Archambault, P., Nelson, R.J., Geoffroy, M., Tremblay, J.E., Lovejoy, C., Ferguson, S.H., Hunt, B.P.V. and Fortier, L. 2012. Current state and trends in Canadian Arctic marine ecosystems: II. Heterotrophic food web, pelagic-benthic coupling, and biodiversity. Climatic Change, 115(1): 179-205.

Dyurgerov, M., Bring, A. and Destouni, G. 2010. Integrated assessment of changes in freshwater inflow to the Arctic Ocean. Journal of Geophysical Research Atmospheres, 115 (D12): 116.

Eamer, J., Donaldson, G.M., Gaston, A.J., Kosobokova, K.N., Lárusson, K.F., Melnikov, I.A., Reist, J.D., Richardson, E., Staples, L. and von Quillfeldt, C.H. 2013. Life Linked to Ice: A guide to sea-ice-associated biodiversity in this time of rapid change. CAFF Assessment Series No. 10. Conservation of Arctic Flora and Fauna, Akureyri, Iceland.

Einarsson, N., Beach, H. and van Ginkel, R. 2011. Culture, Conflict and Crises in the Icelandic Fisheries: An Anthropological Study of People, Policy and Marine Resources in the North Atlantic Arctic. Uppsala University, Humanities and Social Sciences, Faculty of Arts, Department of Cultural Anthropology and Ethnology.

Falk-Petersen, S., Mayzaud, P., Kattner, G. and Sargent, J.R. 2009. Lipids and life strategy of Arctic *Calanus*. Marine Biology Research, 5(1): 18-39.

Fauchald, P., Anker-Nilssen, T., Barrett, R.T., Bustnes, J.O., Bårdsen, B.J., Christensen-Dalsgaard, S., Descamps, S., Engen, S., Erikstad, K.E., Hanssen, S.A., Lorentsen, S.-H., Moe, B., Reiertsen, T.K., Strøm H. and Systad, G.H. 2015. The status and trends of seabirds breeding in Norway and Svalbard. NINA Report 1151, Norwegian Institute for Nature Research, Tromsø, Norway.

Freely, R.A., Sabine, C.L., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J. and Milero, F.J. 2004. Impact of Anthropognic CO_2 on the $CaCO_3$ System in the Ocean. Science, 305(5682): 362-366.

Gill, M.J., Crane, K., Hindrum, R., Arneberg, P., Bysveen, I., Denisenko, N.V., Gofman, V., Grant-Friedman, A., Guðmundsson, G., Hopcroft, R.R., Iken, K., Labansen, A., Liubina, O.S., Melnikov, I.A., Moore, S.E., Reist, J.D., Sirenko, B.I., Stow, J., Ugarte, F., Vongraven, D. and Watkins, J. 2011. Arctic Marine Biodiversity Monitoring Plan. CAFF Monitoring Series Report No. 3, Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland.

Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Stewart Lowndes, J., Cotton Rockwood, R., Selig, E.R., Selkoe, K.A. and Walbridge, S. 2015. Spatial and temporal changes in cumulative human impacts on the world's oceans. Nature Communications, 6(7615).

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R. and Watson, R. 2008. A Global Map of Human Impact on Marine Ecosystems. Science, 319(5865): 948-952.

Heide-Jørgensen, M.P., Burt, M.L., Hansen, R.G., Nielsen, N.H., Rasmussen, M., Stern, H. and Fossette, S. 2013. The significance of the North Water Polynya to Arctic top predators. Ambio, 42(5): 596-610.

Hirche, H-J., Baumann, M.E.M., Kattner, G. and Gradinger, R. 1991. Plankton distribution and the impact of copepod grazing on primary production in Fram Strait, Greenland Sea. Journal of Marine Systems, 2(3-4): 477-494.

Hunt Jr., G.L., Drinkwater, K.F., Arrigo, K., Berge, J., Daly, K.L., Danielson, S., Daase, M., Hop, H., Isla, E., Karnovsky, N., Laidre, K., Murphy, E.J., Mueter, F.J., Renaud, P.E., Smith Jr., W.O., Trathan, P., Turner J. and Wolf-Gladrow, D. 2016. Advection in polar and sub-polar environments: Impacts on high latitude marine ecosystems. Progress in Oceanography, 149: 40-81.

Intergovernmental Panel on Climate Change (IPCC). 2013. Climate change 2013: The physical science basis. Working Group, I contribution to the IPCC Fifth Assessment Report. *In:* T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Intergovernmental Panel on Climate Change. Cambridge University Press, New York, U.S.A.

Inuit Circumpolar Council-Alaska (ICC-Alaska). 2015. Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic from an Inuit Perspective. Technical Report, Inuit Circumpolar Council-Alaska, Anchorage, U.S.A.

Jakobsson, M., Mayer, L.A., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.-W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O.B., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S V., Pedrosa, M.T., Travaglini, P.G. and Weatherall P. 2012. The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0. Geophysical Research Letters, 39(L1209): 1-6.

Johannesen, E., Ingvaldsen, R.B., Bogstad, B., Dalpadado, P., Eriksen, E., Gjøsæter, H., Knutsen, T. and Skern-Mauritzen, M. 2012. Changes in Barents Sea ecosystem state, 1970–2009: climate fluctuations, human impact, and trophic interactions. ICES Journal of Marine Science, 69: 880-889.

Jørgensen, L.L., Planque, B., Thangstad, T.H. and Certain, G. 2015. Vulnerability of megabenthic species to trawling in the Barents Sea. ICES Journal of Marine Science, 73(suppl. 1): i84-i97.

Lavoie, D., Macdonald R.W. and Denman K.L. 2009. Primary productivity and export fluxes on the Canadian shelf of the Beaufort Sea: A modelling study. Journal of Marine Systems, 75(1-2): 17-32.

Letcher, R.J., Bustnes, J.O., Dietz, R., Jenssen, B.M., Jørgensen, E.H., Sonne, C., Verreault, J., Vijayan, M.M. and Gabrielsen, G.W. 2010. Exposure and effects assessment of persistent organohalogen contaminants in arctic wildlife and fish. Science of the Total Environment, 408(15): 2995-3043.

Lyubin, P.A., Anisimova, N.A., and Manushin, I.E. 2011. Chapter 14.6 Long-term effects on benthos of the use of bottom fishing gears. *In:* T. Jakobsen and V.K. Ozhigin (eds.). The Barents Sea - ecosystem, resources and management. Half a century of Russian-Norwegian cooperation. Tapir Acadmeic Press, Trondheim, Norway, pp 768-775.

McNeely, J.A., Mooney, H.A., Neville, L.E., Schei, P.J., and Waage J.K. (eds.). 2001. A Global Strategy on Invasive Alien Species. IUCN Gland, Switzerland, and Cambridge, UK.

Meltofte, H. (ed.). 2013. Arctic Biodiversity Assessment Status and Trends in Arctic Biodiversity. Conservation of Arctic Flora and Fauna, Akureyri, Iceland.

Michel, C., Ingram, R.G. and Harris, L. 2006. Variability of oceanographic and ecological processes in the Canadian Arctic Archipelago. Progress in Oceanography, 71(2-4): 379-401.

Moore, S.E. and Laidre, K. 2006. Trends in sea ice cover within habitats used by bowhead whales in the Western Arctic. Ecological Applications, 16(3): 932-944.

Müller, J., Massé, G., Stein, R. and Belt, S.T. 2009. Variability of sea-ice conditions in the Fram Strait over the past 30,000 years. Nature Geoscience, 2: 772-776.

National Oceanic and Atmospheric Administration (NOAA). 2015. Merged Land–Ocean Surface Temperature Analysis: Global Gridded 5° x 5° Data. National Centers for Environmental Information, National Oceanic and Atmospheric Administration.

National Snow and Ice Data Center (NSDIC). 2016. Monthly Sea Ice Extent Images. National Snow and Ice Data Center.

O'Boyle, R. and Jamieson, G. 2006. Observations on the implementation of ecosystem-based management: experiences on Canada's east and west coasts. Fisheries Research, 79: 1-12.

Olsen E., Gjøsæter, H., Røttingen, I., Dommasnes, A., Fossum, P. and Sandberg, P. 2007. The Norwegian ecosystem-based management plan for the Barents Sea. ICES Journal of Marine Science, 64: 599-602.

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.F., Yamanaka, Y. and Yool, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437: 681-686.

Ottersen, G., Olsen, E., van der Meeren, G.I., Dommasnes, A. and Loeng, H. 2011. The Norwegian plan for integrated ecosystem-based management of the marine environment in the Norwegian Sea. Marine Policy, 35(3): 389-398.

Protection of the Arctic Marine Environment (PAME). 2009. Arctic Marine Shipping Assessment Report. Protection of the Arctic Marine Environment, Akureyri, Iceland.

Pelejero C., Calvo, E. and Hoegh-Guldberg, O. 2010. Paleo-perspectives on ocean acidification. Trends in Ecology & Evolution 25(6): 332-344.

Raymond-Yakoubian, B., Kaplan, L., Topkok, M. and Raymond-Yakoubian, J. 2014. "The World has Changed": Inalit Traditional Knowledge of Walrus in the Bering Strait. North Pacific Research Board Project Final Report. Revised 2015. Kawerak, Inc. Social Science Program, Nome, Alaska.

Reeves, R.R., Ewins, P.J., Agbayani, S., Heidi-Jorgensen, M.P., Kovacs, K.M., Lydersen, C., Suydam, R., Elliott, W., Polet, G., van Dijk, Y. and Blijleven, R. 2014. Distribution of endemic cetaceans in relation to hydrocarbon development and commercial shipping in a warming Arctic. Marine Policy, 44: 375-389.

Schweitzer, P. 2014. Cultures and identities. *In:* J. Nymand Larsen and G. Fondahl (eds.). Arctic Human Development Report, regional processes and global linkages, pp 105-150, Nordic Council of Ministers, Copenhagen, Denmark.

Skjoldal, H.R., Cobb, D., Corbett, J., Gold, M., Harder, S., Low, L.L., Noblin, R., Robertson, G., Scholik-Schlomer, R., Sheard, W., Silber, G., Southall, B., Wiley, C., Wilson, B. and Winebrake, J. 2009. Arctic Marine Shipping Assessment. Background Research Report on Potential Environmental Impacts from Shipping in the Arctic. Protection of the Arctic Marine Environment, Tromsø, Norway.

Slavik, D. 2015. Inuvialuit Knowledge of Nanuq: Community and Traditional Knowledge of Polar Bears in the Inuvialuit Settlement Region. Inuvialuit Settlement Region Hunters and Trappers Committees, the Wildlife Management Advisory Councils for the North Slope and Northwest Territories and the Inuvialuit Game Council.

Smedsrud, L.H., Esau, I., Ingvaldsen, R.B., Eldevik, T., Haugan, P.M., Li, C., Lien, V.S., Olsen, A., Omar, A.M., Otterå, O.H., Risebrobakken, B., Sandø, A.B., Semenov, V.A. and Sorokina, S.A. 2013. The role of the Barents Sea in the Arctic climate system. Reviews of Geophysics, 51(3): 415-449.

Smetacek, V. and Nicol, S. 2005. Polar ocean ecosystems in a changing world. Nature, 437: 362-368.

Springer, A.M., Estes, J.A., van Vliet, G.B., Williams, T.M., Doak, D.F., Danner, E.M., Forney, K.A. and Pfister, B. 2003. Sequential megafaunal collapse in the North Pacific Ocean: An ongoing legacy of industrial whaling? PNAS, 100(21): 12223-12228.

Stirling, I. 1997. The importance of polynyas, ice edges, and leads to marine mammals and birds. Journal of Marine Systems, 10(1-4): 9-21.

Søreide, J.E., Carroll, M.L., Hop, H., Ambrose Jr., W.G., Hegseth, E.N. and Falk-Petersen, S. 2013. Sympagic-pelagic-benthic coupling in Arctic and Atlantic waters around Svalbard revealed by stable isotopic and fatty acid tracers. Marine Biology Research, 9(9): 831-850.

Thor, P., Bailey, A., Halsband, C., Guschelli, E., Gorokhova, E. and Fransson, A. 2016. Seawater pH predicted for the year 2100 affects the metabolic response to feeding in copepodites of the Arctic copepod *Calanus glacialis*. PLoS ONE, 11(12): e0168735.

Thurstan, R.H., Brockington, S. and Roberts, C.M. 2010. The effect of 118 years of industrial fishing on UK bottom trawl fisheries. Nature Communications, 1(15).

Wang, M. and Overland, J.E. 2012. A sea ice free summer Arctic within 30 years: An update from CMIP5 models. Geophysical Research Letters, 39(L18501).

Ice associated algae.
Photo: Eric Collins, University of Alaska, Fairbanks