



Review

Future harvest of living resources in the Arctic Ocean north of the Nordic and Barents Seas: A review of possibilities and constraints

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ABSTRACT

Global warming drives changes in oceanographic conditions in the Arctic Ocean and the adjacent continental slopes. This may result in favourable conditions for increased biological production in waters at the northern continental shelves. However, production in the central Arctic Ocean will continue to be limited by the amount of light and by vertical stratification reducing nutrient availability. Upwelling conditions due to topography and inflowing warm and nutrient rich Atlantic Water may result in high production in areas along the shelf breaks. This may particularly influence distribution and abundance of sea mammals, as can be seen from analysis of historical records of hunting. The species composition and biomass of plankton, fish and shellfish may be influenced by acidification due to increased carbon dioxide uptake in the water, thereby reducing the survival of some species. Northwards shift in the distribution of commercial species of fish and shellfish is observed in the Barents Sea, especially in the summer period, and is related to increased inflow of Atlantic Water and reduced ice cover. This implies a northward extension of boreal species and potential displacement of lipid-rich Arctic zooplankton, altering the distribution of organisms that depend on such prey. However, euphausiid stocks expanding northward into the Arctic Ocean may be a valuable food resource as they may benefit from increases in Arctic phytoplankton production and rising water temperatures. Even though no scenario modelling or other prediction analyses have been made, both scientific ecosystem surveys in the northern areas, as well as the fisheries show indications of a recent northern expansion of mackerel (*Scomber scombrus*), cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and capelin (*Mallotus villosus*). These stocks are found as far north as the shelf-break north of Svalbard. Greenland halibut (*Reinhardtius hippoglossoides*), redfish (*Sebastes* spp.) and shrimp (*Pandalus borealis*) are also present in the slope waters between the Barents Sea and the Arctic Ocean. It is assumed that cod and haddock have reached their northernmost limit, whereas capelin and redfish have potential to expand their distribution further into the Arctic Ocean. Common minke whales (*Balaenoptera acutorostrata*) and harp seals (*Pagophilus groenlandicus*) may also be able to expand their distribution into the Arctic Ocean. The abundance and distribution of other species may change as well – to what degree is unknown.

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Contents

1. Introduction.....	39
2. Advection, stratification and nutrients.....	39
3. Ocean acidification.....	41
4. Planktonic and benthic production.....	42
5. Harvestable fish and shellfish stocks.....	43

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5.1. Fisheries	43
5.2. Life history patterns of fish.....	43
6. Marine mammals	44
6.1. Cetaceans endemic to the Arctic	44
6.2. Pinnipeds endemic to the Arctic	46
6.3. Ice-associated harp seals.....	47
6.4. Summer guests in the Arctic	48
7. Discussion.....	48
7.1. Oceanography and plankton	48
7.2. Fish	50
7.3. Marine mammals.....	52
7.4. Summary	53
Acknowledgements.....	53
References	54

1. Introduction

The marine Arctic comprises the Arctic Ocean, including the deep Eurasian and Canadian Basins, and the surrounding continental shelf seas (Barents, Kara, Laptev, East Siberian, Chukchi, and Beaufort Seas and the Canadian Archipelago (Fig. 1)). The Arctic Ocean has a distinct natural climate variability occurring on time scales ranging from seasonal to multi-decadal (Overland et al., 2008). Dramatic reduction in the Arctic sea-ice mass and coverage (Overland, 2011; Comiso, 2012) is observed for the summer period, and growing also in winter. The speed of these changes has been underestimated in global models (Stroeve et al., 2012; IPCC, 2013). The sea-ice changes have resulted in large areas of the Arctic Ocean becoming more accessible, allowing for increased human activity. Other observed environmental changes include warming and freshening of surface waters due to increased river runoff and ice melting. This can alter the Arctic Ocean's stratification, acidification state, light regime, carbon cycle and nutrient availability. The combination of increased human activity and environmental perturbations is likely to affect the Arctic Ocean ecosystems and may pose challenges to their management (ACIA, 2005).

The Fram Strait is the only main deep gateway for the exchange of deeper waters out of the Arctic and warm Atlantic Water and heat into the Arctic Ocean (Schauer et al., 2002). An increase in this heat transfer will have profound implications for the marine environment and the living marine resources. Colonization of new regions by immigrating species is more likely on the Atlantic side of the Arctic Ocean than on the Pacific side (Drinkwater, 2011; Hollowed et al., 2013a,b). But the number of well-documented, climate-related changes in plankton, fish and benthic communities in the Arctic Ocean's marine ecosystems is low, and there is substantial uncertainty regarding current and future productivity (Wassmann et al., 2011).

Large-scale commercial harvesting of mammals (since 1611, see Christensen et al., 1992a; Allen and Keay, 2006) and fish (since the 1870s, see Iversen, 1934) already occurs in the sub-Arctic Barents and Norwegian seas adjacent to the Arctic Ocean. The harvesting potential of marine sub-Arctic regions is predicted to increase with global warming (Cheung et al., 2011). Some species currently targeted in fisheries in these regions may expand into the Arctic Ocean (Hollowed et al., 2013a,b). In addition, currently unexploited species may become harvestable, either in conventional fisheries or in new fisheries, as technology develops (e.g. zooplankton harvest; Grimaldo et al., 2010; Nicol et al., 2012) or because of marine bioprospecting (Svenson, 2012). Also, new species are emerging in these areas, either as a result of artificial introduction or bio-invasion (Ware et al., 2013; Sundet and Hoel 2016). Moreover, due to warming, species that are more southerly may enter Arctic waters, extend their distributional range northwards and

reproduce (Buchholz et al., 2012; Berge et al., 2015a; Fossheim et al., 2015; Misund et al., 2016).

Climate change projection scenarios of how some of the key stocks would respond (e.g. Cheung et al., 2009; Wisz et al., 2015) are often used to evaluate future harvesting opportunities. However, central to such projections are correct predictions of propagation limits of the individual species. Such projections call for suitable physical model forcing as input (Ingvaldsen et al., 2015) as well as real data for understudied Arctic seas (Christiansen et al., 2016). Even more important, climate change affects a multitude of environmental factors that may affect various processes at different levels of biological organization (e.g. Rijnsdorp et al., 2009; Hollowed et al., 2013a,b), and regional-scale variation in climate-demographic functions make range-wide population dynamics challenging to predict (Sydeman et al., 2015). In this paper we review the possibilities and constraints regarding future harvest in the Arctic Ocean north of the Nordic and Barents Seas. We examine how changes in the physical and chemical conditions influence the biological production, and affecting possible future harvesting of marine biological resources on the Northeast Atlantic side of the Arctic Ocean. We will focus on fundamental conditions for harvestable populations to occur: (1) beneficial oceanographic conditions; (2) adequate primary, secondary and benthic production; and (3) plasticity in life cycles, migration and drift patterns of potentially harvestable stocks.

2. Advection, stratification and nutrients

The region west and north of the Svalbard archipelago (>80° N), the northernmost extension of the northern North Atlantic, is of particular interest with regard to the biological production of the Arctic Ocean. Atlantic Water carried northwards brings heat, thereby affecting thermal conditions as well as the sea ice cover (e.g., Beszczynska-Möller et al., 2012; Onarheim et al., 2014). The Atlantic current also supplies the region with nutrients and drifting organisms like zooplankton (Kosobokova and Hirche, 2009) and micronekton (Knutson et al., in press). This advective regime fuels life in the Arctic Ocean (Bluhm et al., 2015; Wassmann et al., 2015; Hunt et al., 2016).

This region is a transition zone between Atlantic and Arctic conditions. Typically, the Arctic Ocean is strongly stratified due to the ice freezing and melting cycle combined with the large volumes of river runoff, and there are horizontal layers of water associated with the large-scale circulation and these local processes (e.g., Rudels, 2012). Biological production in Arctic regions experiencing seasonal ice melt are usually nutrient limited (e.g. Tremblay and Gagnon, 2009), nutrient availability depending on the strength of the stratification and the depth of the surface mixed layer. Comparing the deep Arctic Ocean with the Barents Sea shows substantial

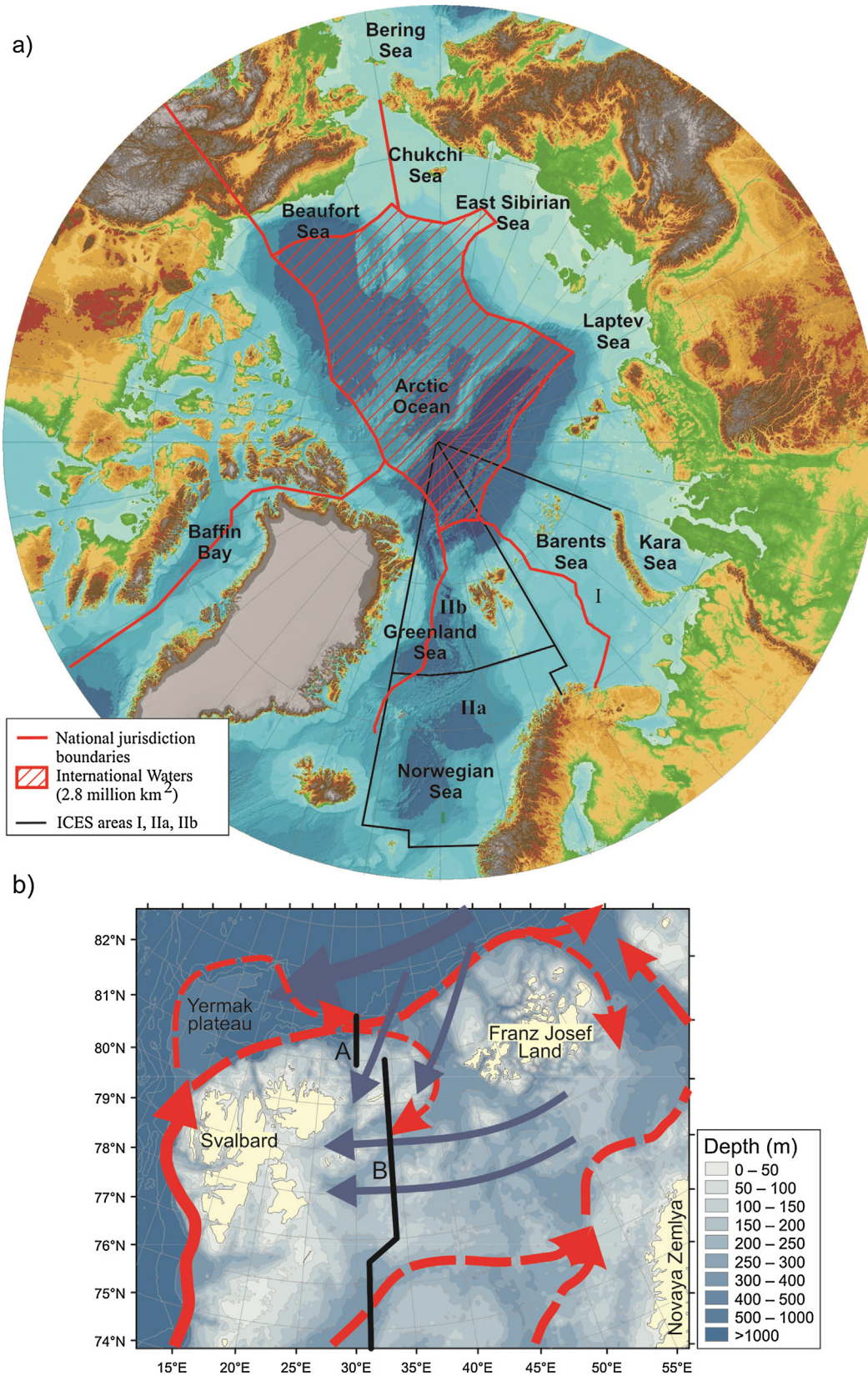


Fig. 1. (a) Bathymetric map showing the Arctic Ocean, the national jurisdiction boundaries and ICES areas relevant for this study. (b) Study area, ocean currents and location of sections. Red arrows denote surface (solid) and subducted (dashed) flow of Atlantic Water while blue arrows denotes flow of Arctic/polar waters.

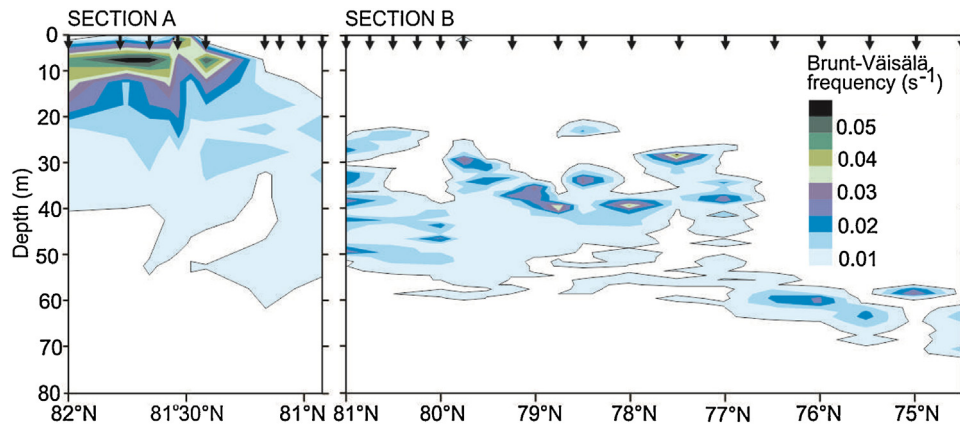


Fig. 2. Example of vertical stratification (or Brunt-Väisälä frequency) in the upper 80 m depth across the continental slope north-east of Svalbard (section A) and in the northern Barents Sea (section B). High values indicate strong stratification. Location of sections A and B are shown in Fig. 1.

south-north gradients in stratification and mixed layer depth at the end of the melting season (Fig. 2). In the Barents Sea which is ice-free year around south of the Polar Front close to 78°N the stratification is weak and the mixed layer relatively deep. Nutrients are therefore available in the beginning of the growth season and there is likely a continuous supply during the growth season providing for high production. On the northern shelf of the Barents Sea the stratification is stronger and the mixed layer shallower, crossing the continental slope northwards into the deep Arctic Ocean (close to 81°N) where the stratification become strong and the surface layer shallow. In this northern region only limited amounts of nutrients are available at the start of the productive season, and little mixing occurs during the melting season to replenish the stock (Fig. 2, section A). This makes the deep Arctic Ocean a low production region compared to the slope region and the continental shelves to the south. A major question determining future harvestable population levels is whether this pattern of stratification will change, providing for sufficient biological production to sustain high biomass concentrations of species of interest to commercial harvest in the deep Arctic Ocean.

During the past decades, there has been substantial warming of the waters in the Fram Strait and the region to the north of Svalbard. The inflowing Atlantic Water has become exceptionally warm, with no analogy since the 1950s, or probably in the history of instrumental observations in the Arctic Ocean (Polyakov et al., 2012). Associated with this warming the winter ice extent in the waters north of Svalbard has declined by about 10% per decade (Onarheim et al., 2014). However, the variability in temperatures in the region is large and occurs on seasonal, inter-annual, multi-annual and multi-decadal time scales (e.g., Polyakov et al., 2012; Lind and Ingvaldsen, 2012; Falk-Petersen et al., 2014; Misund et al., 2016).

3. Ocean acidification

Ocean acidification (OA) refers to the change in carbonate chemistry due to the oceanic uptake of anthropogenic CO₂, which has led to decreased pH and carbonate ion concentration (e.g., Caldeira and Wickett, 2003). This has the consequence that the dissolution potential (Ω) for calcium carbonate (CaCO₃) has increased and may result in limitations for organisms to calcify. Ω is a measure of the chemical dissolution potential and at undersaturation ($\Omega < 1$) calcium carbonate will dissolve. The formation of calcium carbonate is energy demanding and is usually only biologically controlled. This implies that calcifying organisms may require more energy at lower Ω levels than when Ω is oversaturated. The surface waters in areas with long-term observations such as in the Icelandic Sea

show an annual CO₂ increase of about 2 μ atm, which corresponds to the rate of change in the atmosphere (Olafsson et al., 2009). This anthropogenic CO₂ increase converts to a decadal pH decrease of about 0.02. The anthropogenic CO₂ uptake during several centuries has also resulted in a shoaling of the depth of the calcium carbonate saturation horizon (Ω) of about 4 m per year in the Iceland Sea (Olafsson et al., 2009). Since there are no long-term time series stations in the Arctic Ocean we cannot estimate the rates of CO₂ and pH change as yet. OA has been shown to have predominantly negative effects on marine organisms, although it varies considerably between species (Fabry et al., 2008; Kroeker et al., 2010). The cold and relatively fresh Arctic Ocean surface water, with its capacity to dissolve atmospheric CO₂ and low pH and carbonate ion ([CO₃²⁻]) levels, makes these waters particularly vulnerable to the effects of increased oceanic CO₂ (Orr et al., 2005; AMAP, 2013). Recent studies show that CaCO₃ undersaturation in the Arctic Ocean is already occurring on freshwater influenced shelves (Chierici and Fransson, 2009), and substantially sooner than predicted by models (Steinacher et al., 2009).

A recent assessment of Arctic Ocean acidification concluded that Arctic marine waters are undergoing widespread, rapid ocean acidification (AMAP, 2013). Information on biological effects as a response to ocean acidification are generally based on laboratory studies on specific organisms at elevated CO₂ levels and have shown a large variability among species. This requires caution when using data from one species to predict the response of another (Miller et al., 2009). While some marine organisms will respond positively to new conditions associated with ocean acidification, others will respond negatively, possibly resulting in local extinction (Dupont and Pörtner, 2013). Calcifying organisms such as shellfish, echinoderms, and mollusks generally suffer under high CO₂ levels (i.e., low Ω), whereas adult fish seems relatively robust for the projected CO₂ levels. However, a recent study showed increased mortality of Atlantic and Baltic Sea cod larvae at elevated CO₂ levels (Stiasny et al., 2016). Some of the first observations of biological effects due to ocean acidification have been reported from the Pacific side of the Arctic Ocean, where the bottom waters intermittently reach undersaturation with regard to aragonite. Bivalves, which are an important food source for spectacled eiders (*Somateria fisheri*) and walrus (*Odobenus rosmarus*) in the region, show dissolution and thinning of shells under such conditions (Grebmeier et al., 2015). Other studies, found that the pteropod *Limacina helicina*, an important prey for polar cod (*Boreogadus saida*), may already be affected by OA in ocean regions at similar saturation levels as in parts of the Arctic Ocean (Lischka and Riebesell, 2012; Bednaršek et al., 2014). The few studies that have been performed on polar cod shows it to be relatively robust against OA (AMAP, 2013) and

it is more likely that it may be negatively affected through its main prey such as krill and pteropods. In the southern Bering Sea and the Alaska coast, the pH decrease has been pronounced and OA has negatively affected shellfish, crab and salmonids and the Alaskan fisheries show great concern about progressing OA (Mathis et al., 2015).

4. Planktonic and benthic production

Dramatic seasonal changes, low temperatures, extensive permanent and seasonal ice cover, a large supply of freshwater from rivers, and melting ice are key physical factors characterizing the Arctic Ocean ecosystem. Primary production in the Arctic Ocean is influenced by stratification and the timing of sea-ice breakup, which affect both nutrient and light availability (Wassmann et al., 2006) and results in a short production season. These factors largely control the food supply to pelagic and benthic species (Grebmeier et al., 2006). Annual primary production is typically $<30 \text{ g C m}^{-2} \text{ y}^{-1}$ in the central Arctic Ocean where compact perennial sea ice is predominant, whereas it is between 30 and $100 \text{ g C m}^{-2} \text{ y}^{-1}$ in seasonally ice-covered areas (Wassmann, 2011; Reigstad et al., 2011). This compares well with regional values of the Barents Sea (Dalpadado et al., 2012), ranging from $44.1 \text{ g C m}^{-2} \text{ y}^{-1}$ in their northernmost Arctic region (ARC) to $113.4 \text{ g C m}^{-2} \text{ y}^{-1}$ in the southwestern region (CSTW). Comparatively, values for the Norwegian Sea and Norwegian Coastal Current vary from about $80 \text{ g C m}^{-2} \text{ y}^{-1}$ to $90\text{--}120 \text{ g C m}^{-2} \text{ y}^{-1}$ respectively (Rey, 2004).

Variations in physical environment and water mass characteristics along the continental slope north of Svalbard affect the distribution of mesozooplankton and have resulted in the establishment of well-defined communities of Atlantic species, Arctic species and deepwater inhabitants in that area (Blachowiak-Samolyk et al., 2008). Regional variability in total zooplankton biomass in the Eurasian Basin is mainly related to the circulation pattern of the Atlantic current. Local food availability is also important in sustaining local and imported secondary producers (Kosobokova and Hirche, 2009). Key species associated with Atlantic current advection are the copepod *Calanus finmarchicus* and the amphipod *Themisto abyssorum* (Jaschnov, 1966; Mumm et al., 1998; Blachowiak-Samolyk et al., 2008; Kosobokova and Hirche, 2009), whereas *Calanus hyperboreus* and *Metridia longa* are the two predominant large copepods in the central Arctic Ocean. Plankton composition can be an indicator of ocean climate variability and change (Hays et al., 2005). Composition changes have included poleward movement of Boreal species (Beaugrand et al., 2002), changes in species distribution (Greene and Pershing, 2000) and changes in the timing of seasonal cycles (Edwards and Richardson, 2004). Timing of sea-ice breakup is probably the single most important factor affecting recruitment success among the secondary producers (zooplankton) able to reproduce in the Arctic Ocean (Wassmann, 2011). Both early and late sea-ice breakup can affect the relationship between primary and secondary producers, particularly the key Arctic copepod *Calanus glacialis* that depends on the ice algal bloom for its seasonal migration, feeding, and reproduction, while its offspring depends on the subsequent later increase in phytoplankton and microzooplankton abundance. Any mismatch affecting these processes could severely impact the entire lipid-based Arctic marine food web (Leu et al., 2011). Another uncertainty associated with the receding sea-ice cover is the ability of grazers such as ctenophores, scyphomedusae and hydromedusae to take advantage of new habitats and resources (Purcell, 2005; Purcell et al., 2009). Such changes could alter energy pathways and food-web dynamics with subsequent negative impact on production at higher trophic levels.

Planktonic communities are complex as are also their response to external forcing (e.g., Daly and Smith, 1993). Biological interactions are probably equally important to the responses of such communities to external forcing, although far less understood. The classical paradigm of biological quiescence during the Arctic winter has been seriously challenged by recent works: Active raptorial feeding in hyperiid amphipods during Arctic-darkness are documented (Kraft et al., 2013), as are mass-vertical zooplankton migration during Arctic winter driven by moonlight (Last et al., 2016), and unexpected levels of biological activity during the polar night (Berge et al., 2015a). Another study shows that diel vertical migration during the Arctic winter is an important feature of the zooplankton community, especially for copepods in the epipelagic (Berge et al., 2009). The authors particularly stress that diel vertical migration is a critical component of the 'biological pump' crucial for the drawdown of organic carbon and atmospheric CO_2 , a process that could be of increased importance with a reduced Arctic ice cover. It has also recently been shown that the Arctic plankton community displays complex distributional and behavioral patterns, possibly governed both by light conditions and the physical complexity of water masses (Berge et al., 2014), and it is concluded that a continued warming of the Arctic is likely to result in more complex ecotones across the Arctic marine system.

The benthic fauna, an integral component of the Arctic marine food web, has been associated with the overlying primary productivity regime (Tremblay et al., 2011) with observed benthic-pelagic faunal relationships in ice-influenced areas in the Barents Sea (Wassmann et al., 2006; Cochrane et al., 2009; Anisimova et al., 2011). Higher megabenthic secondary production was found in the seasonally ice-covered regions of the Barents Sea than in the permanently ice-free areas (Degen et al., 2016). Ongoing decrease of winter sea ice extent and the associated poleward movement of the seasonal ice edge point towards a distinct decline of benthic secondary production in the northern Barents Sea in the future. A significant portion of the energy flow in Arctic Ocean continental shelf communities may pass through the epibenthos (Piepenburg et al., 1995; Piepenburg and Schmid, 1996). For example, echinoderms, often predominant on Arctic continental shelves, play an important role in the redistribution and remineralisation of the organic carbon that reaches the seabed (Bluhm et al., 2009; Blicher and Sejr, 2011). These organisms contribute significantly to the overall benthic biomass of the Arctic shelves despite their patchy distribution (Ambrose et al., 2001) and are reported as prey for demersal fish (Planque et al., 2014). A shift from an ice-influenced, tightly coupled, pelagic-benthic system to a less-coupled, ice-free system can be expected to result from future reductions in sea-ice cover. This shift would affect the distribution and production of benthic organisms in the Barents Sea, that most probably would also result in a northward shift in biogeographic boundaries (Kiyko and Pogrebov, 1997; Galkin, 1998; Wassmann et al., 2006; Denisenko, 2007). The snow crab (*Chionoecetes opilio*), a commercial fishing resource, is a non-native species (Alvsvåg et al., 2009) currently spreading westward from Russian to Norwegian waters (Jørgensen et al., 2015) as far north as Svalbard. As the snow crab is a benthic predator (Squires and Dawe, 2003), it might compete with other bottom feeding fish and benthic species.

One important question asked is whether benthic consumers, especially the fish, would shift their diet from nutrient-rich benthic prey, capturing zooplankton organisms in the productive waters in the Arctic ice-melting zone (especially brittle stars and crustaceans), to nutrient poor prey organisms adapted to suspension feeding and filtering microbial particles in less productive waters (bristle worms and bivalves). If benthic prey become less nutrient rich, benthic consumers might change prey, foraging areas, or become less abundant. Changes in benthic prey distribution should therefore be monitored regularly together with fish health (growth

rate, condition factor), diet analyses and stomach fullness, parallel to isotopic values and fatty acid measures of prey and predator.

5. Harvestable fish and shellfish stocks

5.1. Fisheries

Several species of fish and shellfish from the Barents Sea and from the shelf around Svalbard have been exploited for centuries (Fig. 3). Among the most important fish species are the Northeast Arctic populations of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). The deep-water species beaked redfish (*Sebastes mentella*), golden redfish (*Sebastes norvegicus*) and Greenland halibut (*Reinhardtius hippoglossoides*), are also economically important, as is the pelagic species capelin (*Mallotus villosus*). Among invertebrates deep sea prawns (*Pandalus borealis*) and Iceland scallop (*Chlamys islandica*) have been the most important commercial species. Red king crab (*Paralithodes camtschaticus*) and snow crab have become important in recent years. In the Northern Barents Sea, including the Svalbard area, cod, haddock, capelin, Greenland halibut, prawn, and Iceland scallop have been important after 1980 (Misund et al., 2016).

There is an increasing trend in the landings from the Svalbard area during the period 1980–2013 Misund et al. (2016). This trend was accompanied by, and probably partly resulted from, a rising trend in temperatures of the Atlantic Water flowing along the west coast of Svalbard (Misund et al., 2016). The rising trend in landings was not continuous when looking at specific species; for instance, the cod showed peaks in the landings around 1986, 1995, and towards the end of the time series. There are reasons to believe that earlier peaks in the cod fishery in the Svalbard area, for instance the rich cod fishery reported by Iversen (1934) for the period 1925–1935, was associated with periods when sea temperatures were high (e.g., Townhill et al., 2015). Cod was also reported to be found (and fished) west of Svalbard during the pioneering Northern Seas expedition in 1876–78 (Sars, 1879). Given this history and the high present fisheries activity in the Barents Sea it is likely that fisheries can expand rapidly into new areas to the north where potential fishing grounds exist (see Figs. 4 and 5). Pre-conditions for fisheries to develop in new areas are discussed by Hollowed et al. (2013a,b), and include *inter alia* bottom topography, water temperatures, salinities, and distance to spawning grounds.

5.2. Life history patterns of fish

Seasonal migrations are widespread among fish. Most of the commercially exploited fish species in the Nordic Seas have substantial migratory ranges. When mapping a shift in the distribution of a particular life stage at a particular time of the year, this does not necessarily mean that this is a permanent shift, involving other life stages as well. In addition, northward species expansions can result from factors other than increased temperatures, such as the size of fish stocks. Large fish stocks require more space and needs more food and therefore tends to expand its geographical distribution. Ingvaldsen and Gjosæter (2013) suggested that capelin distribution is a combined effect of stock size and sea temperatures. Increased availability of suitable prey in the outskirts of a species' temperature preference would possibly be another reason. Regardless of these caveats, it is known that fish in the Barents Sea react to changing climate (Ponomarenko, 1996) and it is believed that a species poleward migration can occur quite rapidly (Fossheim et al., 2015).

The geographical distribution of most fish stocks in the Barents Sea during the main feeding period is closely monitored through annual joint Norwegian-Russian ecosystem surveys (Michalsen et al., 2013). Distribution maps of various life stages

of several species can be found in the annual survey reports referred to by Michalsen et al. (2013)) and at http://www.imr.no/tokt/okosystemtokt_i_barentshavet/utbredelskart/nb-no. During 2010–2013, adult stages of both Atlantic cod and capelin expanded their northern limits of distribution northward in the Barents Sea and in 2013 the northern distribution limits of both species were near the shelf-break facing the Arctic Ocean (Fig. 5) at 81°N. Haddock, Greenland halibut, deep-sea redfish and prawn were also present on the border between the Barents and the Arctic Ocean during the years 2010–2013 (Fig. 6). During the early 1970s polar cod was a significant object for fisheries in the Barents Sea. A small fishery has existed up to recent years, when the stock dwindled and is now only found in the eastern parts of the area. Since the northern limit of the polar cod distribution has never been monitored, the northern and north-eastern extension of the distribution is unknown (Ajiad et al., 2011), and it is unknown whether the observed decline in measured stock size during the annual ecosystem surveys in the Barents Sea until 2015 was a result of a real stock decline or the stock partly withdrawing from the Barents Sea. Contrary to expectation, the 2016 joint Norwegian-Russian ecosystem survey (Prozorkevich and Sunnanå (in press)) revealed an almost fourfold increase in polar cod biomass compared to the three preceding years. This resulted from a rich 2015 year-class and might not be indicative of a changed trend in the future.

For the deep-sea species Greenland halibut, the northern areas of the Barents Sea and the slope towards the Arctic Ocean serve as nursery areas (Albert et al., 2001; Albert and Vollen 2015), while known spawning grounds are at the continental slope between Norway and Svalbard (Høines and Gundersen, 2008). It is possible that the spawning areas and thus also potential fishing grounds can be relocated northward with changes in hydrographic conditions. Alternatively, changes in physical properties of waters might result in spawning at deeper water rather than horizontal northward displacement. However, it is unclear if the present changes in physical conditions seen in the pelagic layers extend into deeper waters. Additionally, any northward displacement of spawning grounds would also need to allow for spawning products to end up in suitable nursery areas.

The same applies to a certain extent to the Atlantic redfishes *S. mentella* and *S. norvegicus*. Both species have larval extrusion along the continental slope from around 62°N up to the Bear Island area at 75°N in May followed by feeding migrations into the Barents Sea. The southwestern Barents Sea and Svalbard areas are primarily nursery areas for redfish (Sorokin, 1961; Saborido-Rey and Nedreaas, 2000; Drevetnyak and Nedreaas, 2009). Adult Atlantic redfishes are found strictly in Atlantic water masses, while juveniles are largely distributed over the Barents Sea shelf. In the case of *S. mentella*, adults distribute in open waters during summer feeding migrations, and given increased pelagic/mesopelagic production might extend the distribution into the Arctic Ocean in a future, warmer scenario (Hollowed et al., 2013a,b).

The large migratory pelagic fish stocks in the Nordic seas, i.e. Norwegian spring spawning herring (*Clupea harengus*), mackerel (*Scomber scombrus*) and blue whiting (*Micromesistius poutassou*) in the Greenland, Norwegian, and Iceland seas, are found in the Atlantic water masses. They are at their northernmost distribution in summer and autumn when on feeding migration (Iversen, 2004; Belikov et al., 2011; Krysov and Røttingen, 2011). Their spawning areas are south in the temperate region along the European shelf edge. The main spawning areas for herring are located along the Norwegian coast and the most important nursery area is the southern Barents Sea. Adult herring have a feeding migration to the western and northern Norwegian Sea in summer and autumn. After spawning along the European shelf, the mackerel gradually moves northwards, as far north as the northern Norwegian Sea and Svalbard area (Uriarte et al., 2001; Iversen, 2004; Berge et al., 2015b;

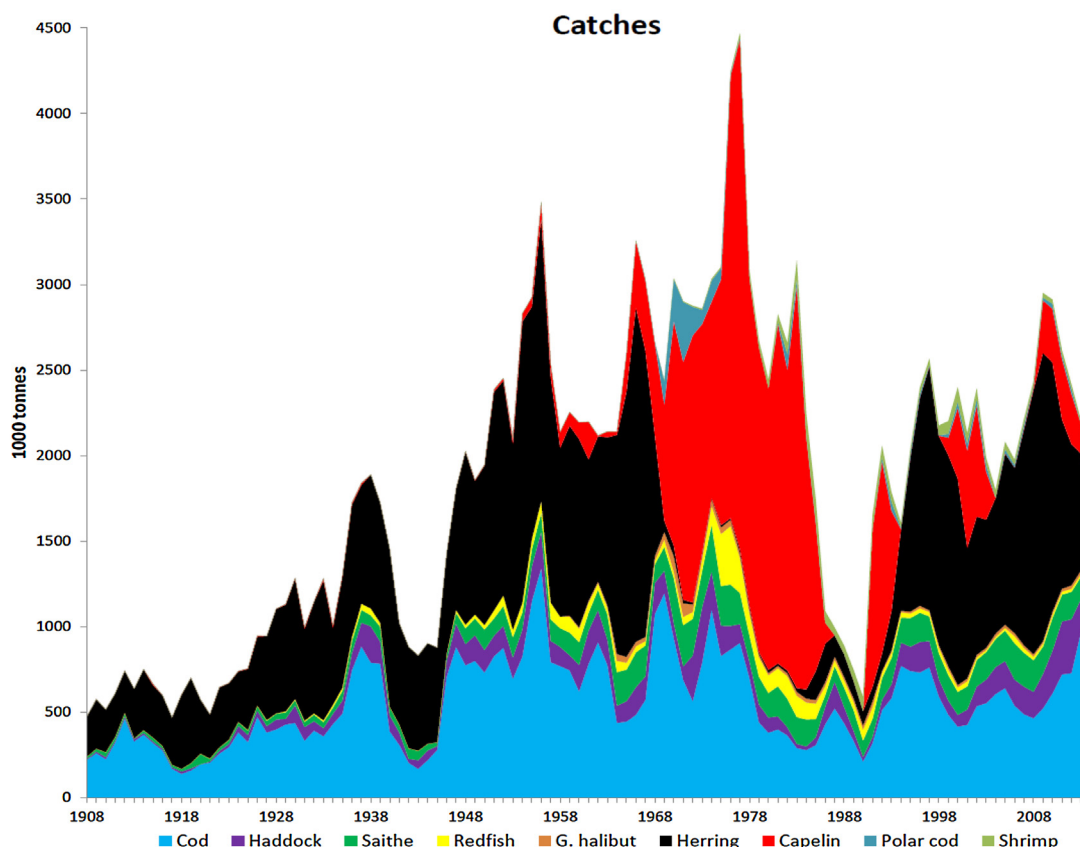


Fig. 3. Catches of main stocks in the Barents and Norwegian Seas 1908–2014. Historically, the catch reached a level between 2 and 3 million tonnes in the 1950s and has since mostly been within this range. A peak in the 1970s was due to large capelin catches, and a dip in the late 1980s was caused by low catches of all stocks. Data are taken from ICES (ICES, 2015a,b,c; Lassen et al., 2012). The catches include all catches of the species in ICES areas I, IIa and IIb (Fig. 1 for ICES areas). For herring, all catches of Norwegian spring-spawning herring are included, also those outside the mentioned ICES areas.

Nøttestad et al., 2016). Most of the spawning of blue whiting takes place between March and April, along the shelf edge and banks west of the British Isles. The eggs and larvae that drift northwards spread the major part of the juvenile blue whiting to the warmer parts of the Norwegian Sea and adjacent areas from Iceland to the Barents Sea. Adult blue whiting carries out active feeding and spawning migrations in the same area as herring.

If increased temperatures result in higher plankton production or plankton production further to the north, and the stock size of these pelagic stocks results in food limitations, there is reason to believe that they will expand their feeding areas northwards. A more permanent displacement, including changes in spawning areas are less probable in the short term, in particular for the herring, which has demersal spawning at sand and gravel substrate that is unlikely to be found offshore and at greater depths. Blue whiting and mackerel, spawning pelagically, may more easily extend or move their spawning areas northwards. Where to spawn for these stocks is closely linked to the current system, since the passive drift of eggs and larvae need to take them where it is likely to find suitable food and the risk of predation is lowered.

6. Marine mammals

Marine mammal species endemic to the Arctic have been and remain an important resource for many of the indigenous and nonindigenous people of the north (Hovelsrud et al., 2008). Traditionally, the core target species for the hunt in the circumpolar Arctic are bowhead whales (*Balaena mysticetus*), belugas (*Delphinapterus leucas*), narwhals (*Monodon monoceros*), walrus, ringed seals (*Phoca hispida*) and bearded seals (*Erignathus barba-*

tus). Changes in climate are likely to bring about changes to the environment in which these animals live and subsequently to the hunting practices and livelihoods of the people that hunt them. Reductions in ice extent and thickness with subsequent increase in shipping and oil and gas activities is also a challenge for the Arctic species (Hovelsrud et al., 2008; Reeves et al., 2014).

6.1. Cetaceans endemic to the Arctic

While the indigenous Arctic hunt generally has been confined to northern areas in Greenland, Canada, Alaska (USA), and Russia (Hovelsrud et al., 2008), the Northeast Atlantic areas have previously been dominated by nonindigenous hunters coming from more southern areas. The intensive commercial hunting that nearly exterminated bowhead whales in Svalbard waters from 1611 to 1911 is a typical example as it was an effort performed by Dutch, German and British whalers (Allen and Keay, 2006). The Spitsbergen stock of bowhead whales is confined to the north-east Atlantic where they have been observed in areas between Greenland and Svalbard, and eastwards past the Barents and Kara Sea and Franz Josef Land, well into the Russian Arctic (see Christensen et al., 1992a).

Narwhals occur only occasionally in Svalbard waters and is too rare to be of any ecological significance or of interest for hunters (Heide-Jørgensen, 2002). The third endemic Arctic whale, the beluga or white whale, was hunted during summer in Svalbard nearshore waters, first by Russians from 1715 to 1720 on, thereafter by Norwegians in the period 1866–1960 (Lønø and Øynes, 1961). Belugas generally prefer to overwinter in shallow or coastal areas with light or highly moveable ice cover (see Laidre et al., 2008).

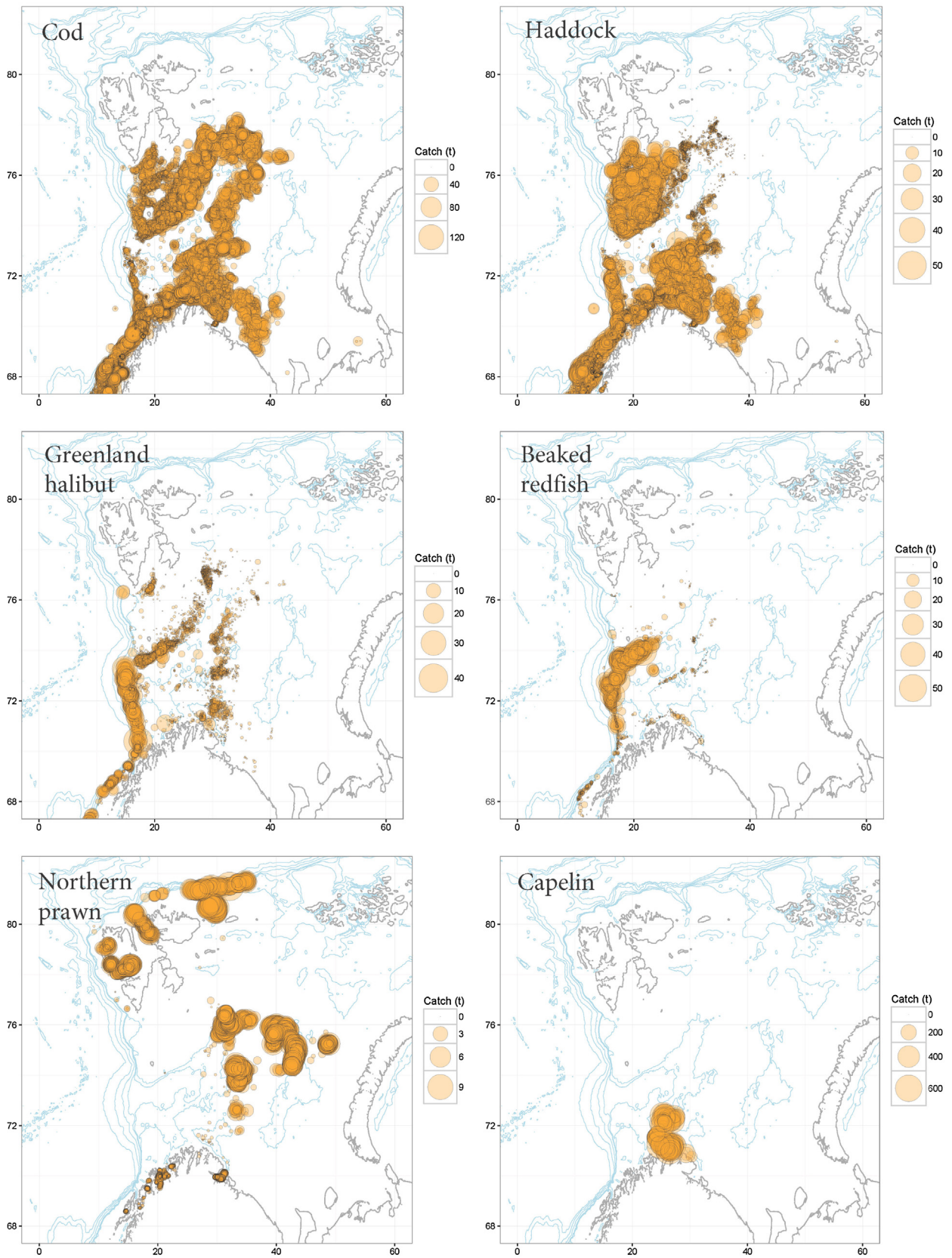


Fig. 4. Catch positions in Norwegian fisheries in the Barents Sea 2014, as registered in Logbooks, for species of most relevance for the Arctic Ocean. Each circle represents one fishing operation and the size of the circles reflects catch weight (note different scales in bubble size due to variation in catch amounts per fishing operation for different species).

Source: Directorate of Fisheries, Norway.

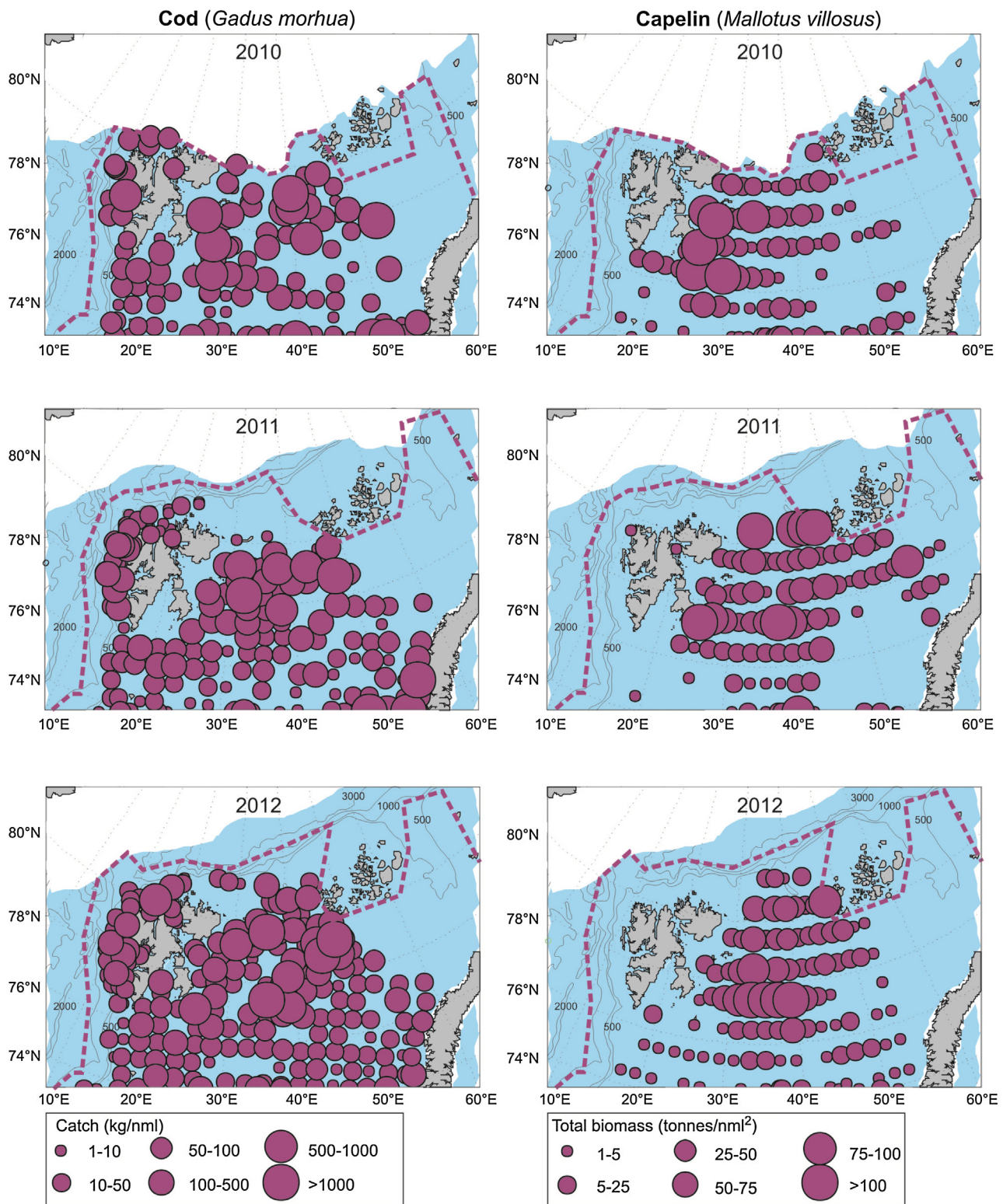


Fig. 5. Distribution of cod (a) and capelin (b) in the northern Barents Sea in August–September 2010 (top), 2011 (middle) and 2012 (bottom). Dashed line indicates the survey area coverage. Data from the annual joint Russian–Norwegian Ecosystem survey (Michalsen et al., 2013). Black lines show bottom contours (500, 1000, 2000 and 3000 m). Blue shading indicate open water while white shading show ice cover (>20% concentration). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Recent satellite track studies have revealed that white whales tagged in Svalbard spent most of the summer and autumn in Svalbard waters, often in association with glacier fronts (Lydersen et al., 2001). Current exploitation of cetaceans in this region is carried out by Norwegian fishers hunting minke whales.

6.2. Pinnipeds endemic to the Arctic

Four seal species are year round residents at the Svalbard archipelago: Walrus, harbour seals, ringed seals and bearded seals. Walruses were once very abundant in Svalbard, but were hunted

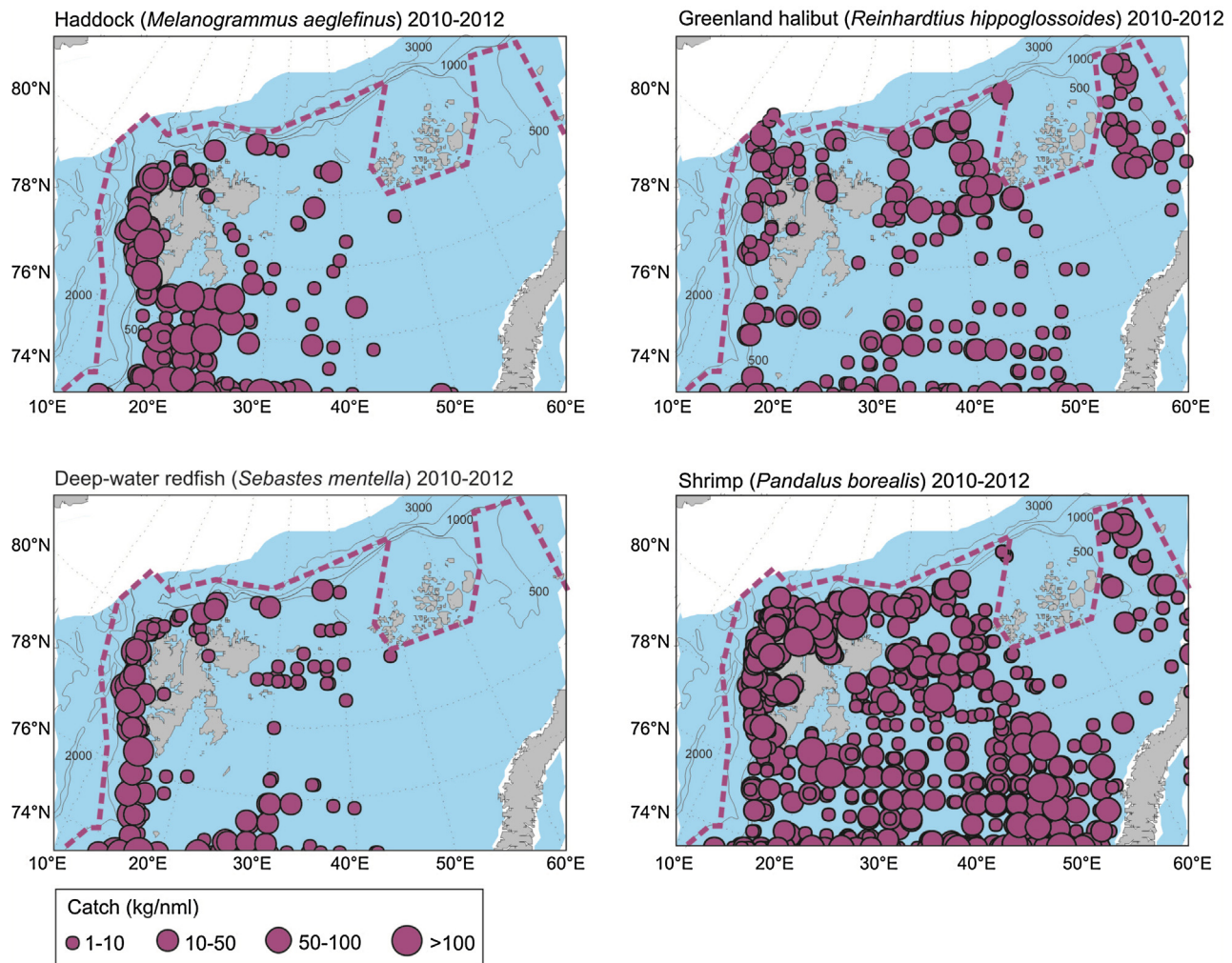


Fig. 6. Distribution of haddock (a), Greenland halibut (b), redfish (c) and shrimp (d) in August–September the northern Barents Sea and Arctic Ocean based on aggregated data from 2010 to 2012. Dashed line indicates the survey area coverage in 2012. Data from the annual joint Russian–Norwegian Ecosystem survey (Michalsen et al., 2013). Black lines show bottom contours (500, 1000, 2000 and 3000 m). Blue shading indicate open water while white shading show ice cover (>20% concentration). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

virtually to extinction during 350 years of heavy commercial exploitation. The species became protected in 1952, and is now recovering slowly (Born et al., 1995; Lydersen et al., 2008). Harbour seals (common only on the west coast of the Spitsbergen island) are protected from hunting (Lydersen and Kovacs, 2010), whereas ringed seals and bearded seals can be hunted by licensed hunters (Kovacs et al., 2004).

Northeast Atlantic walrus are distributed in shallow coastal areas of Greenland, Svalbard and Franz Josef Land. They use both sea ice and terrestrial haul-outs as a hub for feeding excursions on shallow nearshore banks with substantial bivalve mollusk production (Born et al., 1995). Sea ice declines will most likely decrease the duration of the walrus sea ice season, with subsequent increase in the use of terrestrial haul-out grounds and their adjacent feeding areas (Kovacs et al., 2011). Also bearded seals prey on benthic organisms (Hjelset et al., 1999), and hence prefer to reside in drifting pack ice in areas over shallow water shelves. Their distribution is largely coastal, although over shallow waters (e.g., in the Barents Sea) they can be found quite far from shore on the drifting pack ice (Kovacs et al., 2011).

Ringed seals are extremely dependent on sea ice, as their exclusive breeding and haul out platform. The preferred breeding habitat for ringed seals is usually described as land-fast ice in fjords that has good snow cover, but relatively stable, drifting pack ice can

also serve as breeding habitat for this species (Finley et al., 1983; Wiig et al., 1999). As the summer position of the marginal ice zone in Svalbard has shifted from a position over the continental shelf, northward to the deep Arctic Ocean basin, ringed seals seems to have followed the ice edge. Hamilton et al. (2015) suggested that the behavioural changes involved in this move requires increased energetic costs in finding food, and continued declines in sea-ice are likely to result in distributional changes, range reductions and population declines in this keystone Arctic species.

6.3. Ice-associated harp seals

Harp seals (*Pagophilus groenlandicus*) are pagophilic and prefer to be near sea ice at virtually all times of the year. They congregate in large concentrations within relatively predictable, limited areas on drift ice during the spring period (March–May) of breeding and moult (Fig. 7). This has facilitated commercial hunt both in the Greenland Sea (the West Ice, located east of Greenland) and in the White Sea and the southeastern Barents Sea (the East Ice) (Sergeant, 1991; Øigård et al., 2014).

Harp seals are migratory and wide ranging, and in May–September, most northeast Atlantic harp seals are distributed in central and northern parts of the Barents Sea (Haug et al., 1994; Folkow et al., 2004; Nordøy et al., 2008). They use the sea ice edge

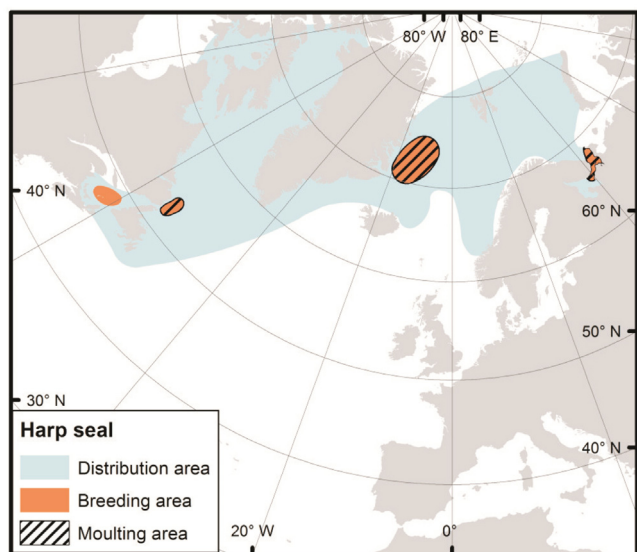


Fig. 7. Distribution, breeding and moulting areas of harp seal (*Pagophilus groenlandicus*).

as a platform from which they conduct extended foraging trips into open waters. Availability of high-energetic food such as krill in the northern areas in spring and summer presumably provide the energetic advantage necessary to account for the long migrations of harp seals from their more sub-Arctic winter distributions (Lindstrøm et al., 2013).

6.4. Summer guests in the Arctic

While northward range expansions have limited the geographic scope for endemic Arctic marine mammals, leaving them vulnerable to the effects of climate change within their current ranges, temperate area marine mammal species such as harbour porpoise (*Phocoena phocoena*), killer whale (*Orcinus orca*) and several baleen whale species are expanding their ranges northward (Skaug et al., 2004; Øien, 2009; Pike et al., 2009; Kovacs et al., 2011). Such northward range expansions of temperate marine mammal species are likely to result in competitive pressure on some endemic Arctic species, presumably also increased predation, disease, and parasite infection risks. There has been a Norwegian commercial hunt for both the large baleen whales in 1864–1971 (Christensen et al., 1992a) and for common minke whales (*Balaenoptera acutorostrata*) from the late 1920s to date (see Haug et al., 2011). The hunting areas have included areas to the west of and, in case of minke whales, also to the north of Svalbard (Fig. 8).

When minke whales and other summering baleen whales arrive on their northern feeding grounds in spring they are extremely lean, but during their stay they gain considerable fat reserves that they deposit in the blubber layer, particularly during late summer and autumn (July–September; Næss et al., 1998). Feeding is the reason why these whales migrate northwards every spring, attracted by the good availability of particularly high energetic food in the northern areas. The whales exploit a variety of species and sizes of fish and crustaceans, but in general, they selectively forage on capelin, herring and krill (Christensen et al., 1992b; Haug et al., 2002). Observations made throughout the most recent decade during autumn have shown that minke, fin (*Balaenoptera physalus*) and humpback (*Megaptera novaeangliae*) whales inhabited both Arctic and Atlantic waters, with highest densities in Arctic waters north of the Polar Front (Skern-Mauritzen et al., 2011; Ressler et al., 2015). Blue whales (*Balaenoptera musculus*) are among other large baleen

whales that occur seasonally, but more occasionally, in the northern areas, are (Pike et al., 2009).

7. Discussion

7.1. Oceanography and plankton

Possible future changes in the region include a general warming due to higher air and ocean temperatures, as well as changes in the amount (volume flux) of the inflowing Atlantic Water (e.g. Polyakov et al., 2012; Wassmann et al., 2015). In addition to warming of the water masses, this can also cause sea ice retreat through reduced ice freezing and/or enhanced melting (Sandø et al., 2014; Ivanov et al., 2016). Other likely future changes include upper layer freshening and altered stratification due to increased ice melt and possibly an altered hydrological cycle as well as changes in local wind forcing due to shifts in storm tracks and polar jet streams (Carmack and McLaughlin, 2011).

Projection of future changes in pH from 1998 to 2065 shows the largest pH decrease of 0.3 in the Central Arctic Ocean and decreases of about 0.25 in waters surrounding Svalbard (Skogen et al., 2014). There is a need to establish models to predict the combined consequences of climate change, fishing pressure and ocean acidification for the Arctic Ocean. Ocean acidification was identified as one of several factors that may affect the abundance and geographical distribution of important fish stocks in Arctic fisheries, but the magnitude and direction of those changes are uncertain (AMAP, 2013). Given the potential ecological consequences, studies of processes that affect the natural variability of CaCO_3 saturation levels in the Arctic Ocean are important when attempting to predict the effects of increased atmospheric CO_2 levels on vulnerable ecosystem components and on the carbon cycle in the Arctic Ocean (Kawaguchi et al., 2013; regarding Antarctic krill).

Of special interest in the region north of Svalbard is the combination of sea ice cover, a continental shelf and slope, and the warm Atlantic boundary current flowing along the slope. Wind over water moves the surface waters and might create horizontal gradients (differences) in sea surface level. This can in turn drive large-scale vertical movements in the ocean, far below the surface where the wind acts. For example cyclones, which frequently enter the region from the North Atlantic (Sorteberg and Kvingsedal, 2006) can cause upwelling (Fig. 9–upper). Regions with bottom slopes, or other obstacles to flow in the ocean interior, will be more affected than regions with a flatter sea floor. Because of this, wind fields creating differences in sea level along the slope north of Svalbard can cause upwelling (upward motion) or downwelling (downward motion) of the Atlantic Water along the slope. If the sea ice retreats north beyond the slope, thus exposing the slope region and the Atlantic boundary current to more cyclones and/or other stronger wind forcing creating differences in sea level, this process is likely to be enhanced (Fig. 9–lower). The Atlantic Water will be brought higher in the water column, enhancing its potential for ice melting and nutrient fueling as well as increasing the inflow over the deeper parts of the northern Barents Sea shelf.

The Eurasian perimeter of the Arctic Ocean has been found to be warming, showing the greatest increases in primary production along the Atlantic Water inflow (Slagstad et al., 2015). Another issue is relocation of ocean fronts. For the region north of Svalbard, this might not be a big issue, but for the Polar Front in the central Barents Sea large changes can be anticipated. A northward shift of this front is already observed, and simulations of future changes indicate that by the end of this century this front might be completely pushed out of the shallow Barents Sea, instead following the slope north of Svalbard (Wassmann et al., 2015).

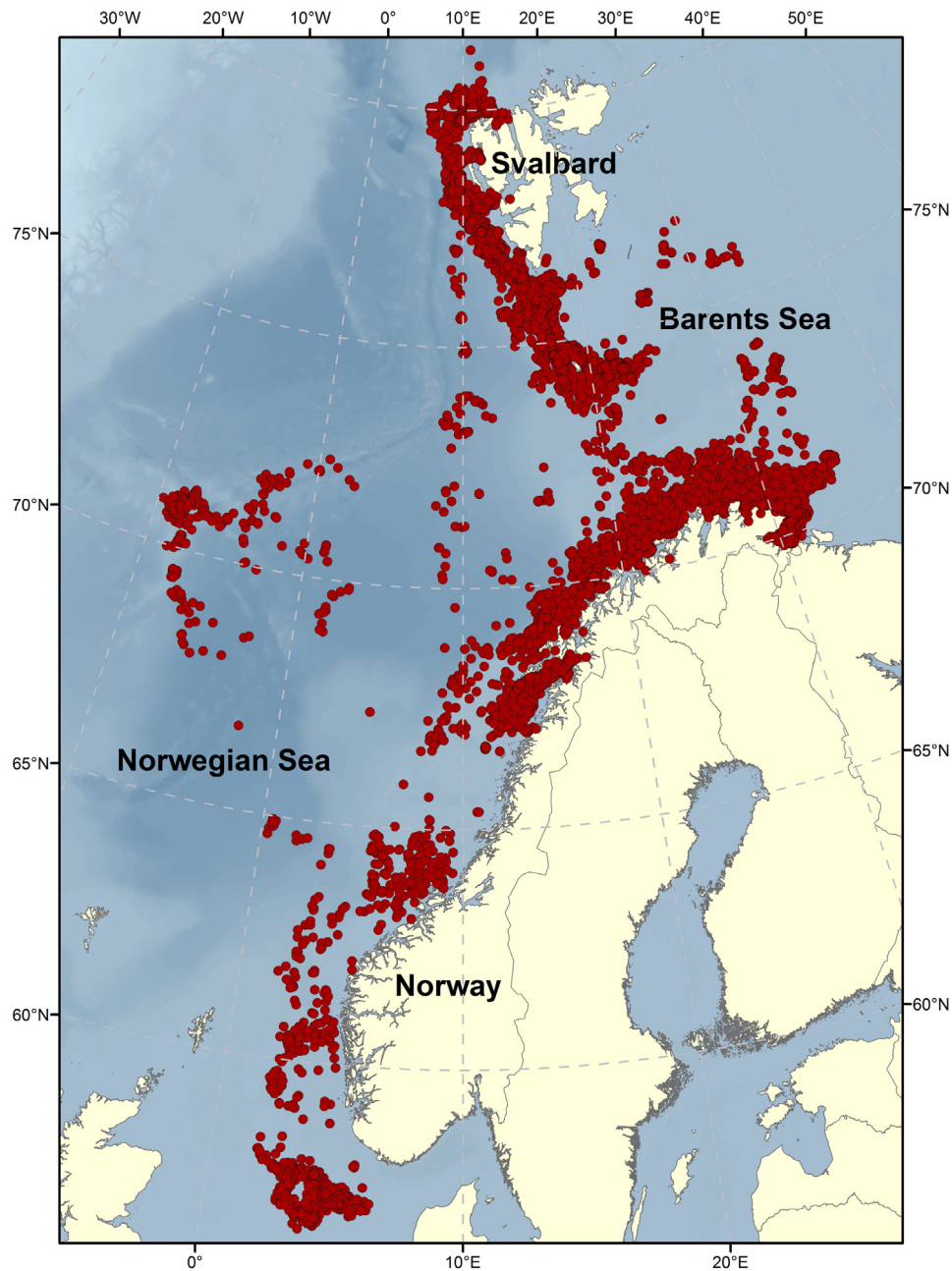


Fig. 8. Distribution of catch positions for common minke whales (*Balaenoptera acutorostrata*) taken in the Norwegian commercial hunting operations in 1993–2015.

With less and thinner sea-ice cover in the Arctic Ocean, the productive period will possibly be prolonged and result in a moderate increase in total yearly primary production (Slagstad et al., 2011). However, the existing strong vertical stratification limits nutrient availability and is likely to do so in the future (Tremblay and Gagnon, 2009); hence, the central Arctic Ocean may remain a low production region (Wassmann, 2011). In contrast, along the continental shelf and slope adjacent to the deep central Arctic Ocean, the productivity response will depend on regional conditions. For example, an increased inflow of Atlantic Water may enhance sea-ice melt and such sea-ice reduction beyond the shelf-break can enhance wind- and ice-forced shelf-break upwelling. This will result in increases in carbon and nutrient availability, thereby increasing biological productivity (Carmack and McLaughlin, 2011; Tremblay et al., 2011).

It is the region's potential with regard to primary and secondary productivity that forms the basis for the production at higher trophic levels, and upwelling regions are among the most productive marine ecosystems known (Carr and Kearns, 2003). According to historic records (see Vinje, 1999; Falk-Petersen et al., 2014), there are reasons to believe that the current situation with a significant reduced ice-cover north of Svalbard during autumn is a situation that is not new and unique. Based on logbooks from whalers and early explorers that frequented these waters in late summer and autumn (Vinje, 1999), it is clear that there was a considerable northward retreat of the ice edge between Svalbard and Franz Josef Land (20–45°E) during the years 1680–1790, coinciding with the peak of early European whaling. Falk-Petersen et al. (2014) report on massive upwelling of Atlantic Water during winter 2012 north of Svalbard, being consistent with modeling results

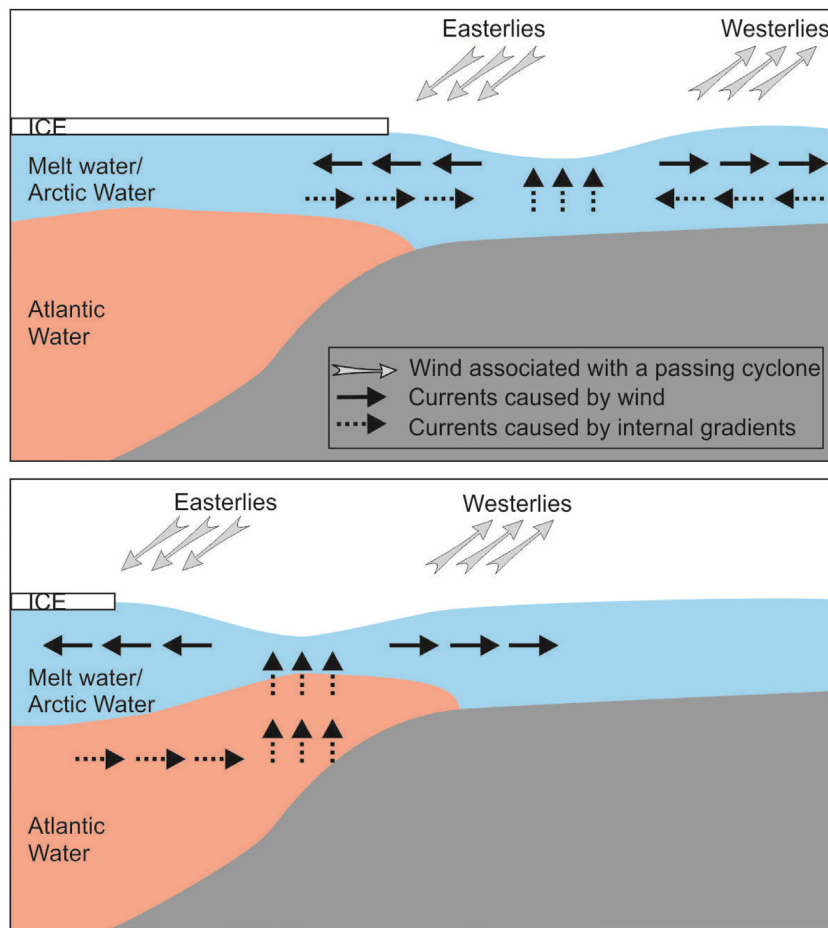


Fig. 9. Schematics illustrating upwelling associated with a passing cyclone. On the top is the situation with sea ice covering the slope and the cyclone passing in the shallow northern Barents Sea. The lower panel shows the situation with sea ice retreating northward and the cyclone passing the slope with the Atlantic boundary current.

of Lind and Ingvaldsen (2012) that winter upwelling will be important when ice retreats on the northern Svalbard shelf. Falk-Petersen et al. (2014) argues, based on the upwelling potential, that there must have been a high primary productivity that likely fueled a high *Calanus* production that sustained the historical stocks of the bowhead whales which were exploited nearly to extinction during the 16–1700s. These hypotheses are supported by the high biomass of lipid-rich zooplankton recorded ($10\text{--}60\text{ DW m}^{-2}$) in the Fram Strait and in the northern Svalbard shelf and slope region in recent years (Søreide et al., 2008; Knutsen et al., in press).

7.2. Fish

Predicting the responses of stocks of commercial fish species to future climate change in the Arctic Ocean is relevant to scientists, managers, and fishers (see Table 1). Previous studies have predicted shifts in bio-climatic habitats of marine fish species and concluded that new species will colonize polar ecosystems at an accelerated rate relative to other regions of the globe (Cheung et al., 2009). Recent assessments of the potential for fish and/or shellfish stocks to move from sub-Arctic areas into the Arctic Ocean reveal that life history traits should be considered when assessing the potential of species displacement in response to changing climate conditions (Hollowed et al., 2013a,b; Hop and Gjøvsæter, 2013).

However, when modelling future expansion or displacement of fish stock caused by climate change, caution should be exercised. In a recent publication, Wisz et al. (2015) predicted that Atlantic cod, according to the EC-Earth RCP8.5 scenario would find suitable

living conditions in the central and northern Barents Sea near the end of this century. This is a rather imprecise prediction knowing that Atlantic cod has occupied these areas and has been heavily fished there for centuries already (Bogstad et al., 2015; Ingvaldsen et al., 2015).

Compared to changes in fish feeding areas, the location of spawning areas and the migration patterns between spawning, feeding and wintering areas are more resistant to change (Hop and Gjøvsæter, 2013). A migration pattern with a closed life cycle is a prerequisite for a fish stock to stay within a defined geographical area for a period of generations (e.g., Rijnsdorp et al., 2009). In many species, such a migration pattern implies an upstream spawning migration, a passive drift of larvae to a nursery area that does not overlap the feeding area of adults, and an adult feeding migration that depends on locations where food conditions are optimal (Fig. 10). A potential movement of fish into the central Arctic Ocean may require changes in various migration types. For instance, if feeding conditions improve due to changes in oceanographic conditions, resulting in increased primary and secondary production, the present northward feeding migrations common to fish in the Barents Sea may expand northwards into the Arctic Ocean. However, permanent residence in the Arctic Ocean may be unlikely in the short and medium term, as it may be constrained by the distance to a southern spawning area or by winter conditions such as ice cover. If a persistent, significant rise in temperatures forces a species to abandon its present spawning area and established migration pattern, its continued existence would depend on whether it could establish new, northern spawning areas and new nursery,

Table 1

How some commercial species found in the Greenland, Norwegian and Barents Seas today are likely to act in case of a warming Arctic. * Herring and blue whiting are at present only found in the Barents Sea as juveniles and are not fished there. (Modified from [Hollowed et al., 2013a,b](#)).

Species	Demersal/Pelagic	Temperature preferences (°C)	Likelihood of moving into the Arctic Ocean	How far?
Cod (<i>Gadus morhua</i>)	Demersal	>0	Moderate	To shelf edge
Haddock (<i>Melanogrammus aeglefinus</i>)	Demersal	>2	Moderate	To shelf edge
Redfish (<i>Sebastes mentella</i>)	Demersal/deep water	>2	High	Unlimited
Greenland halibut (<i>Reinhardtius hippoglossoides</i>)	Demersal/deep water	>0	Moderate	Beyond shelf edge
Shrimp (<i>Pandalus borealis</i>)	Demersal	>0	High	To shelf edge
Capelin (<i>Mallotus villosus</i>)	Pelagic	>0	Moderate	Unlimited
Polar cod (<i>Boreogadus saida</i>)	Pelagic	>-1	High	Unlimited
Herring* (<i>Clupea harengus</i> L.)	Pelagic	>1	Moderate	Unlimited
Blue whiting* (<i>Micromesistius poutassou</i>)	Pelagic	>3	Low	Unlimited
Minke whale (<i>Balaenoptera acutorostrata</i>)	Pelagic	>1	High	To ice edge
Harp seal (<i>Pagophilus groenlandicus</i>)	Pelagic	>0	High	To ice edge

feeding and wintering areas closer to the Arctic Ocean. Such changes would depend on a range of other factors, e.g., topographic and hydrographic features, water mass dynamics such as water column stratification and ocean currents and, for bottom-spawning species such as capelin, on a suitable bottom substrate. Similarly, whether the change implies an expansion of the species distribution area or its displacement into a new distribution area would depend on its preferred temperature range and its tolerance to non-preferred temperatures.

Apparently, cod and haddock have expanded their northern limit of distribution northward during 2010–2012 ([Figs. 5 and 6](#)). This is probably a result of the large stock size ([ICES, 2015b](#)) expanding over a large area with favourable oceanographic conditions during the feeding season. Further spatial expansions of cod and haddock are more likely to proceed eastward than northward because those species are demersal and would avoid the deep basins in the Arctic Ocean ([Hollowed et al., 2013a,b](#)). Cod and haddock are therefore very unlikely candidate species for future harvest in the deep Arctic Ocean.

Capelin did not exhibit a northward expansion during 2010–2012 ([Fig. 5](#)). Although capelin tended to follow the receding sea-ice edge in the northern Barents Sea ([Ingvaldsen and Gjørseter, 2013](#)) it did not follow the ice edge into the Arctic Ocean, probably due to vertical stratification ([Fig. 2](#)) limiting production and lower food abundance. Further northward expansion of capelin into the Arctic Ocean may occur in the future, but it will depend on a sufficient increase in production and food availability and possibly on

shifts in capelin spawning areas as spawning migration distances may be a limiting factor ([Hop and Gjørseter, 2013](#)).

Polar cod has in recent years mostly been found in scattered concentrations in the eastern Barents Sea. As already mentioned, 2016 was an exception to the trend seen in recent years, but it is unknown whether this was a one-time event or whether it is signalling a new trend. The low abundance of polar cod seen in the recent period up to the current year contrasts with the situation in the previous 40-years-period, when this stock played an important role as forage fish and in short periods also as a fisheries object. With its circumpolar distribution this species is probably already the most widespread fish species in the Arctic Ocean, but its distribution and biomass in the areas north and east of the Barents Sea are poorly known. An expansion into this area has probably taken place and could continue in the future.

Greenland halibut, redfish and shrimp are present on the slope adjacent to the Arctic Ocean ([Fig. 6](#)). Redfish are pelagic and present above great depths in the Norwegian Sea and Irminger Sea southwest of Iceland. Greenland halibut is a deepwater species and live along continental slopes. Currently the slope and shelf areas north of Svalbard, and between Svalbard and the northern Kara Sea serve as nursing areas for Greenland halibut. Further expansion of the species in fishable sizes would imply north- and eastwards displacement of spawning grounds, which success in turn will depend on drift of spawning products into suitable nursing areas, presumably further east. An eastward expansion has already been reported for shrimp, but a northward expansion toward the Arctic Ocean is less likely. In contrast, redfish is a semi-benthic species that could expand into the deeper parts of the Arctic Ocean in the future ([Nedreaas et al., 2011; Hollowed et al., 2013a,b](#)) and could therefore be a candidate for possible future fisheries in the deep Arctic Ocean to the north of the continental shelves.

The large pelagic stocks in the Nordic Seas are found in warmer Atlantic water masses, but they might extend their feeding migration into colder waters. The migration patterns of these stocks in the Nordic Seas are influenced by different factors, e.g. abundance, changing food availability and increasing sea temperature. In recent years the mackerel has increased the feeding migration in summer westwards to Greenland and northwards to the western Svalbard area ([Berge et al., 2015b; Nøttestad et al., 2016](#)). With an even warmer scenario this species is capable to utilize new feeding areas in the border regions to the Arctic Ocean. It is likely that the mackerel in the future could be a common species in summer in the Barents Sea. Blue whiting follows the Atlantic water masses and are found well into the warmer and deeper parts of the Barents Sea and a possible extension of the distribution into the slope area north of Svalbard and into the Arctic Ocean in a future warmer scenario is likely.

No scenario projections for future stock levels for the main stocks such as cod, haddock, capelin and herring have been made. Although an increased feeding area implies a larger carrying

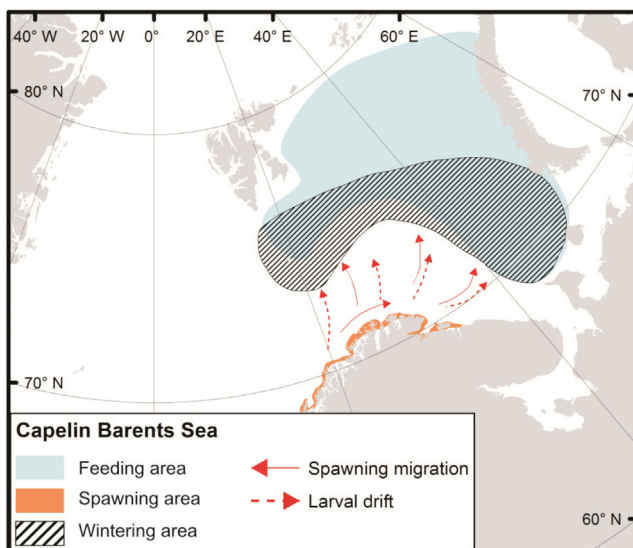


Fig. 10. Migration pattern with a closed life cycle as exemplified by capelin (*Mallotus villosus*).

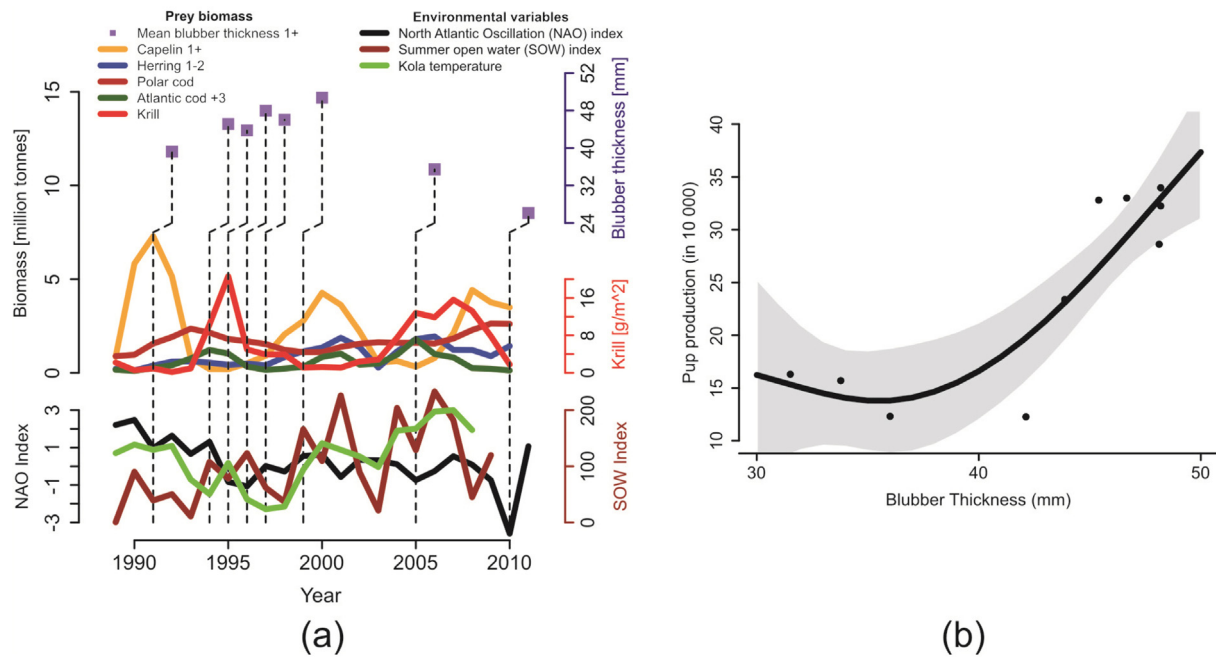


Fig. 11. Harp seal (*Pagophilus groenlandicus*). (a) Mean blubber thickness along with abundance estimates (biomass) of key prey species and environmental variables. (b) Estimated non-linear relationship between the predicted blubber thickness of the 1+ group and the pup production estimates. Figures are taken from Øigård et al. (2013) with permission.

capacity, the effects of changes in the ecosystem on the stock dynamics, in particular on the recruitment are hard to predict. Although cod, haddock and herring recruitment is positively associated with temperature in some periods (Bogstad et al., 2015), this does not necessarily mean that a further increase in temperature would improve recruitment even more. Match/mismatch of larvae and their prey could change in unpredictable ways, as can composition of zooplankton species (see discussion in Dalpadado et al., 2012) that in turn could affect the fish stocks.

Reference points and harvest control rules in the management of the fish stocks are updated with relatively short intervals (~5–10 years), in that way effects of climate change on stock dynamics (including species interactions) will be taken into account and only cause gradual changes. If, however, it is considered that some kind of 'regime shift' has taken place, then larger changes in the basis for management could take place following a change of the historic period used as a basis for reference points and harvest control rules. In practice, one would be well into a regime shift before it actually can be distinguished from normal variability.

Based on the descriptions above about effects of warming on geographical distribution of fish, the commercial fish stocks will likely stay within the 200 nm zones north of the countries on the NE Atlantic side of the Arctic Ocean and around Svalbard (Fig. 1) in the coming decades. Thus, management of fish stocks could continue to be handled by RFMOs such as The Joint Norwegian-Russian Fisheries Commission in the same way as today. And even if the tail of the distribution should stretch into international waters, there is a considerable difference between finding a few stray fish in international waters vs. finding fishable concentrations.

7.3. Marine mammals

Arctic marine mammals are large, highly mobile, warm-blooded animals that experience significant variation in their environments. They have physiological capacities that are unlikely to be affected directly by climate change. However, predicted reductions in sea ice are likely to affect them directly by reducing or eliminating the

current breeding habitats of many Arctic pinnipeds and by shifting the location and timing of productivity in Arctic shelf seas (Kovacs and Lydersen, 2008; Kovacs et al., 2011; Stenson and Hammill, 2014). It has been suggested that sea ice provides protection for some Arctic marine mammals from predators; for example, an increased presence of killer whales could affect endemic Arctic whales and seals under reduced sea-ice conditions (Kovacs and Lydersen, 2008). Changes in ocean circulation patterns could cause shifts in the locations of ocean fronts and the overall productivity of large areas. Such large-scale changes are likely to affect the distribution and abundance of marine mammals that often forage at ocean fronts and other areas where upwelling results in high productivity. Water warming has already resulted in a more poleward distribution of arctic boreal and boreal species (Poloczanska et al., 2013; Fosheim et al., 2015). Such oceanographic and biological changes are assumed to have contributed to observed changes in distribution and abundance of several cetacean species in the north-east Atlantic during the past 30 years (Vikingsson et al., 2015). Also, species endemic to the Arctic may face increasing competition from seasonally migrant species (e.g., large baleen whales), which will likely infiltrate Arctic habitats (Moore and Huntington, 2008).

Bowhead whales are endemic Arctic whales with an assumed potential to succeed in the northeast Arctic Ocean also in the future. Falk-Petersen et al. (2014) have suggested that current reduction in sea ice, in combination with observed mid-winter upwelling of nutrient-rich waters may result in enhanced primary and secondary production of diatoms and *Calanus* spp., which may be beneficial for the bowhead whale stock near Svalbard. This view is further supported by observations made of another severely depleted bowhead stock, the Bering-Chukchi-Beaufort population which has increased substantially in numbers since the end of commercial American whaling in 1910 (George et al., 2015). Today, this bowhead stock remains an important, well-managed subsistence species for many coastal native communities in Russia, USA (Alaska), and Canada. The summer and fall habitats of the stock have seen dramatic reductions in sea ice. Associated with this, an overall increase in bowhead whale body condition has occurred,

thus indicating that the sea ice loss has had positive effects on the secondary trophic production within the summer feeding region of these whales (George et al., 2015).

Several boreal whale species, including minke whales, are regular seasonal migrants to the Northeast Atlantic side of the Arctic Ocean where they take advantage of the summer peak in productivity as the sea-ice recedes northward (Skaug et al., 2004; Øien, 2009; Pike et al., 2009; Skern-Mauritzen et al., 2011). During the spring to autumn period, most harp seals on the Northeast Atlantic side of the Arctic are found in the central and northern parts of the Barents Sea where sea-ice edge is a platform from which they make foraging trips into open waters (Folkow et al., 2004; Nordøy et al., 2008; Lindstrøm et al., 2013). Both migrant cetaceans and harp seals are likely to follow any further receding of the sea-ice edge, if sufficient food resources become available in the region. Current harvesting of minke whales already occurs to the west and north of Svalbard (Haug et al., 2011). Harp seals are traditionally only hunted when they congregate for breeding and moult on drifting pack ice at lower latitudes. A more northwards localisation of their feeding areas is not likely to alter this unless the ice melt destroys their breeding and moulting habitats to such an extent that they will have to move to other geographic sites areas also in this period.

Barents Sea harp seal body condition has exhibited a significant decrease in the last decade, apparently with associated declines in pup production (Fig. 11). A time series of minke whale blubber measurements in the period 1992–2013, shows a significant negative trend over the entire period for this species as well (Solvang et al., 2016), and it has been suggested that the two mammal stocks may have been outperformed by the now record-large cod stock in the area (Bogstad et al., 2015). For harp seals, also longer migration routes with increased energy expenditure between the breeding/moulting areas and feeding areas along the ice edge may certainly have contributed to the reduced recent body condition. Furthermore, poor ice conditions are known to increase pup mortality (Stenson and Hammill, 2014), and Stenson et al. (2015) have also observed that climate changes may impact indirectly through changes in prey and subsequent decrease in reproduction rates. Harp seals are long lived, so the loss of one or two cohorts will not have a major impact on the population, but if severe negative ice conditions increase in frequency, then the impact on future population trends may become significant (Hammill et al., 2015).

7.4. Summary

Due to the expected continuation of a low rate of primary production in the Arctic Ocean, large commercial harvests in future accessible areas of the Arctic Ocean are not likely, at least not in the next 10–20 years. However, a northward expansion of existing fishing and hunting activities in adjacent areas is possible and may result in future harvesting in the Arctic Ocean, primarily in areas under the jurisdiction of the coastal states there. Moreover, the development of fisheries for hitherto unexploited species such as cephalopods, plankton organisms, shellfish and deep-water fish species (e.g. grenadiers) cannot be ruled out. As sea ice continues to recede, large areas will become available for various types of exploitation.

In preparing for these future opportunities of harvesting and possible constraints, the following road map may be considered useful:

- There is a high probability that increasing temperatures in the Atlantic Water will persist, although with large variations, leading to potential good conditions for biomass growth during peak conditions of the variability. This will particularly be the case in the

slope areas where upwelling situations may create production hotspots.

- However, there is also a probability that there will be an increased stratification between the upper cold and less saline water masses originating from river outlets and ice melt, and the Atlantic Water below, being cooled down and becoming denser. This may lead to less nutrient water in the productive zone and may counteract the positive effects of inflowing warm waters.
- All predictions points towards reduced areas of ice coverage and this gives a high probability that the potential area of distribution for many species will increase. The distribution of fast winter ice seems to be a boundary for boreal fish distribution, as seen for Atlantic cod. There is a high probability that this border will retreat to the abyssal parts of the Arctic Ocean, leaving the continental slope to be populated by boreal species.
- With the assumed reductions in ice cover, pagophilic seal species will experience marked breeding-habitat loss in traditional breeding areas and will certainly undergo distributional changes, presumably also abundance reductions, with subsequent consequences for traditional harvest.
- There is a high probability that the waters in the Arctic Ocean will have lower pH in the years to come, and that ocean acidification may affect plankton biomasses and change the relative species abundance of vital prey biomasses in the Arctic ocean and the slope areas at its borders.
- There is a certain probability that some combinations of the above mentioned hydrographical conditions may cause favorable conditions for fish species migrating into more northern areas than they today are found in, as is indicated by historical records.
- As boreal species migrate northwards for feeding, the question of relocating spawning grounds and egg, larval and juvenile distribution becomes vital for predicting the future. Summer and autumn spawners are found among several species, even if the dominant spawning time is spring. This may indicate a certain probability of expanding spawning grounds to the shelf areas of Svalbard and Franz Josef Land, as the production blooms are later in these areas. Observed settlement of young ages of several species on the northern shelves of these archipelagoes may indicate a certain probability of a northern movement of the full life cycle of some species.
- Combining the above paths of the roadmap there seem to be a high probability of increased northern movement of several commercial fish species, however not further north than the shelf slope for the demersal species. This would also indicate a high probability of increased fishing activity in these northern areas, however well within the 200 nm zones and the present management system, although such activity may not represent any increase in the total effort applied in the fisheries.
- Temperate marine mammal species, including the exploited minke whale, are showing northward expansions of their ranges, which are likely to cause competitive pressure on some endemic Arctic species, as well as putting them at risk of predation and diseases.

Altogether, the prospects of future harvest in the Arctic Ocean are not very prosperous, as it is believed that most of the changes will take place at the continental shelf and the slopes down to the deeper basins. It means that the constraints are more dominating than the prospects.

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References

- Øien, N., 2009. Distribution and abundance of large whales in Norwegian and adjacent waters based on ship surveys 1995–2001. *NAMMCO Sci. Publ.* 7, 31–47.
- Øigård, T.A., Lindstrøm, U., Haug, T., Nilssen, K.T., Smout, S., 2013. Functional relationship between harp seal body condition and available prey in the Barents Sea. *Mar. Ecol. Prog. Ser.* 484, 287–301.
- Øigård, T.A., Haug, T., Nilssen, K.T., 2014. From pup production to quotas: current status of harp seals in the Greenland Sea. *ICES J. Mar. Sci.* 71, 537–545.
- ACIA, 2005. Arctic Climate Impact Assessment: Scientific Report. Oxford: Cambridge University Press, New York.
- AMAP, 2013. Arctic Monitoring and Assessment Programme, Arctic Ocean Acidification Assessment: Key Findings, Visited 27 May, 2013 <http://www.imr.no/filarkiv/2013/05/aoa/key-findings.4pp-lr.pdf/nb-no>.
- Ajiad, A.M., Oganin, I.A., Gjøsæter, H., 2011. Polar cod. In: Jakobsen, T., Ozhigin, V.K. (Eds.), *The Barents Sea. Ecosystem, Resources, Management. Half a Century of Russian-Norwegian Cooperation*. Tapir Academic Press, Trondheim, pp. 315–328.
- Albert, O.T., Vollen, T., 2015. A major nursery area around the Svalbard archipelago provides recruits for the stocks in both Greenland halibut management areas in the Northeast Atlantic. *ICES J. Mar. Sci.* 72, 872–879.
- Albert, O.T., Nilssen, E.M., Nedreaas, K.H., Gundersen, A.C., 2001. Distribution and abundance of juvenile Northeast Arctic Greenland halibut (*Reinhardtius hippoglossoides*) in relation to survey coverage and the physical environment. *ICES J. Mar. Sci.* 58, 1053–1062.
- Allen, R.C., Keay, I., 2006. Bowhead whales in the eastern Arctic, 1611–1911: population reconstruction with historical whaling records. *Environ. Hist.* 12, 89–113.
- Alvsvåg, J., Agnalt, A.L., Jørstad, K., 2009. Evidence for a permanent establishment of the snow crab (*Chionoecetes opilio*) in the Barents Sea. *Biol. Invasion* 11, 587–595.
- Ambrose Jr., W.G., Clough, L., Tilney, P., Beer, L., 2001. Role of echinoderms in benthic remineralization in the Chukchi Sea. *Mar. Biol.* 139, 937–949.
- Anisimova, N.A., Jørgensen, L.L., Lubin, P., Manushin, I., 2011. Benthos. In: Jakobsen, T., Ozhigin, V.K. (Eds.), *The Barents Sea. Ecosystem, Resources, Management. Half a Century of Russian-Norwegian Cooperation*. Tapir Academic Press, Trondheim, pp. 121–159.
- Beaugrand, G., Reid, P.C., Ibañez, F., Lindley, J.A., Edwards, M., 2002. Reorganisation of North Atlantic marine copepod biodiversity and climate. *Science* 296, 1692–1694.
- Bednaršek, N., Tarling, G.A., Bakker, D.C.E., Fielding, S., Feely, R.A., 2014. Dissolution dominating calcification process in polar pteropods close to the point of aragonite undersaturation. *PLoS One* 9 (10), <http://dx.doi.org/10.1371/journal.pone.0109183>, e109183.
- Belikov, S.V., Oganin, I.A., Høines, Å.S., 2011. Blue whiting. In: Jakobsen, T., Ozhigin, V.K. (Eds.), *The Barents Sea. Ecosystem, Resources, Management. Half a Century of Russian-Norwegian Cooperation*. Tapir Academic Press, Trondheim, pp. 355–362.
- Berge, J., Cottier, F., Last, K.S., Varpe, Ø., Leu, E., Søreide, J., Eiane, K., Falk-Petersen, S., Willis, K., Nygård, H., Vogedes, D., Griffiths, C., Johnsen, G., Lorentzen, D., Brierley, A.S., 2009. Diel vertical migration of Arctic zooplankton during the polar night. *Biol. Lett.* 5, 69–72.
- Berge, J., Cottier, F., Varpe, Ø., Renaud, P.E., Falk-Petersen, S., Kwasniewski, S., Griffiths, C., Søreide, J.E., Johnsen, G., Aubert, A., Bjærke, O., Hovinen, J., Jung-Madsen, S., Tveit, M., Majaneva, S., 2014. Arctic complexity: a case study on diel vertical migration of zooplankton. *J. Plankton Res.* 36, 1279–1297, <http://dx.doi.org/10.1093/plankt/fbu059>.
- Berge, J., Daase, M., Renaud, P.E., Ambrose Jr., W.G., Darnis, G., Last, K.S., Leu, E., Cohen, J.H., Johnsen, G., Moline, M.A., Cottier, F., Varpe, Ø., Shunatova, N., Balazy, P., Morata, N., Massabuau, J.C., Falk-Petersen, S., Kosobokova, K., Hoppe, C.J.M., Weslawski, J.M., Kuklinski, P., Legezynska, J., Nikishina, D., Cusa, M., Kedra, M., Włodarska-Kowalczyk, M., Vogedes, D., Camus, L., Tran, D., Michaud, E., Gabrielsen, T.M., Granovitch, A., Gonchar, A., Krapp, R., Callesen, T.A., 2015a. Unexpected levels of biological activity during the polar night offer new perspectives on a warming arctic. *Curr. Biol.* 25, 1–7.
- Berge, J., Heggland, K., Lønne, O.J., Cottier, F., Hop, H., Gabrielsen, G.W., Nøttestad, L., Misund, O.A., 2015b. First records of Atlantic mackerel (*Scomber scombrus*) from the Svalbard archipelago, Norway, with possible explanations for the extension of its distribution. *Arctic* 68, 54–61.
- Beszczynska-Möller, A., Fahrbach, E., Schauer, U., Hansen, E., 2012. Variability in Atlantic water temperature and transport at the entrance to the Arctic Ocean, 1997–2010. *ICES J. Mar. Sci.* 69, 852–863, <http://dx.doi.org/10.1093/icesjms/ffs056>.
- Blachowiak-Samolyk, K., Søreide, J.E., Kwasniewski, S., Sundfjord, A., Hop, H., Falk-Petersen, S., Hegseth, E.N., 2008. Hydrodynamic control of Mesozooplankton abundance and biomass in northern Svalbard waters (79–81°N). *Deep-Sea Res. II* 55, 2210–2224.
- Blicher, M.E., Sejr, M.K., 2011. Abundance, oxygen consumption and carbon demand of brittle stars in Young Sound and the NE Greenland shelf. *Mar. Ecol. Prog. Ser.* 422, 139–144.
- Bluhm, B.A., Iken, K., Mincks, H.S., Sirenko, B.I., Holladay, B.A., 2009. Community structure of epibenthic megafauna in the Chukchi Sea. *Aquat. Biol.* 7, 269–293.
- Bluhm, B.A., Kosobokova, K.N., Carmack, E.C., 2015. A tale of two basins: an integrated physical and biological perspective of the deep Arctic Ocean. *Progr. Oceanogr.* 139, 89–121.
- Bogstad, B., Gjøsæter, H., Haug, T., Lindstrøm, U., 2015. A review of the battle for food in the Barents Sea: cod vs marine mammals. *Front. Ecol. Evol.* 3 (29), <http://dx.doi.org/10.3389/fevo.2015.00029>.
- Born, E., Gjert, I., Reeves, R.R., 1995. Population Assessment of Atlantic Walrus (*Odobenus rosmarus* L.), 138. *Polarinstitutt Meddr. Norsk*, pp. 100.
- Buchholz, F., Werner, T., Buchholz, C., 2012. First observation of krill spawning in the high Arctic Kongsfjorden, west Spitsbergen. *Polar Biol.* 35, 1273–1279.
- Caldeira, K., Wickett, M.E., 2003. Anthropogenic carbon and oceanic pH. *Nature* 425, 365.
- Carmack, E., McLaughlin, F., 2011. Towards recognition of physical and geochemical change in Subarctic and Arctic Seas. *Progr. Oceanogr.* 90, 90–104.
- Carr, M.E., Kearns, E.J., 2003. Production regimes in four eastern boundary current systems. *Deep-Sea Res. II* 50, 3199–3221.
- Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Pauly, D., 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish. Fish.* 10, 235–251, <http://dx.doi.org/10.1111/j.1467-2979.2008.00315.x>.
- Cheung, W.W.L., Dunne, J., Sarmiento, J.L., Pauly, D., 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. *ICES J. Mar. Sci.* 68, 1008–1018, <http://dx.doi.org/10.1093/icesjms/fsr012>.
- Chierici, M., Fransson, A., 2009. CaCO₂ saturation in the surface water of the Arctic Ocean: undersaturation in freshwater influenced shelves. *Biogeosciences* 6, 2421–2432.
- Christensen, I., Haug, T., Øien, N., 1992a. Seasonal distribution, exploitation and present abundance of stocks of large baleen whales (Mysticeti) and sperm whales (*Physeter macrocephalus*) in Norwegian and adjacent waters. *ICES J. Mar. Sci.* 49, 341–355.
- Christensen, I., Haug, T., Øien, N., 1992b. A review of feeding and reproduction in large baleen whales (Mysticeti) and sperm whales *Physeter macrocephalus* in Norwegian and adjacent waters. *Fauna Norv. Ser. A* 13, 39–48.
- Christiansen, J.S., Bonsdorff, E., Byrkjedal, I., Fevolden, S.E., Karamushko, O.V., Lynghammar, A., Mecklenburg, C.W., Møller, P.D.R., Nielsen, J., Nordström, M.C., Præbel, K., Wienerroither, R.M., 2016. Novel biodiversity baselines outpace models of fish distribution in Arctic waters. *Sci. Nat.* 103, 8, <http://dx.doi.org/10.1007/s00114-016-1332-9>.
- Cochrane, S.K.J., Denisenko, S.G., Renaud, P.E., Emblow, C.S., Ambrose Jr., W.G., Ellingsen, I.H., Skarðhamar, J., 2009. Benthic macrofauna and productivity regimes in the Barents Sea – ecological implications in a changing Arctic. *J. Sea Res.* 61, 222–233.
- Comiso, J.C., 2012. Large decadal decline of the arctic multiyear ice cover. *J. Clim.* 25, 1176–1193.
- Dalpadado, P., Ingvaldsen, R.B., Stige, L.C., Bogstad, B., Knutsen, T., Ottersen, G., Ellertsen, B., 2012. Climate effects on the Barents Sea ecosystem dynamics. *ICES J. Mar. Sci.* 69, 1303–1316.
- Daly, K.L., Smith Jr., W.O., 1993. Physical-biological interactions influencing marine plankton production. *Ann. Rev. Ecol. Syst.* 24, 555–585.
- Degen, R., Jørgensen, L.L., Ljubin, P., Ellingsen, I.H., Pahlke, H., Brey, T., 2016. Patterns and drivers of megabenthic secondary production on the Barents Sea shelf. *Mar. Ecol. Prog. Ser.* 546, 1–16, <http://dx.doi.org/10.3354/meps11662>.
- Denisenko, S.G., 2007. Zoobenthos of the Barents Sea in the conditions of the variable climate and anthropogenic influence. In: Tarasov, V.G. (Ed.), *Dynamics of Marine Ecosystem and Modern Problem of Conservation of Biological Resources of the Russian Seas*. Dalnauka, Vladivostok, pp. 418–511, In Russian.
- Drevetnyak, K., Nedreaas, K.H., 2009. Historical movement pattern of juvenile beaked redfish (*Sebastes mentella* Travin) in the Barents Sea as inferred from long-term research survey series. *Mar. Biol. Res.* 5, 86–100.
- Drinkwater, K.F., 2011. The influence of climate variability and change on the ecosystems of the Barents Sea and adjacent waters: review and synthesis of recent studies from the NESSAR project. *Progr. Oceanogr.* 90, 47–61.
- Dupont, S., Pörtner, H.O., 2013. A snapshot of ocean acidification research. *Mar. Biol.* 160, 1765–1771, <http://dx.doi.org/10.1007/s00227-013-2282-9>.
- Edwards, M., Richardson, A.J., 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* 430, 881–884.
- Fabry, V.J., Seibel, B.A., Feely, R.A., Orr, J.C., 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES J. Mar. Sci.* 65, 414–432.
- Falk-Petersen, S., Pavlov, V., Berge, J., Cottier, F., Kovacs, K.M., Lydersen, C., 2014. At the rainbow's end: high productivity fueled by winter upwelling along an Arctic shelf. *Polar Biol.* 38, 5–11, <http://dx.doi.org/10.1007/s00300-014-1482-1>.
- Finley, K.J., Miller, G.W., Davis, R.A., Koski, W.R., 1983. A distinctive large breeding population of ringed seals (*Phoca hispida*) inhabiting the Baffin Bay pack ice. *Arctic* 36, 162–173.
- Folkow, L.P., Nordøy, E., Blix, A.S., 2004. Distribution and diving behaviour of harp seals *Pagophilus groenlandica* from the Greenland Sea stock. *Polar Biol.* 27, 281–298.

- Fossheim, M., Primicerio, R., Johannessen, E., Ingvaldsen, R.B., Aschan, M.A., Dolgov, A.V., 2015. Recent warming leads to rapid borealization of fish communities in the Arctic. *Nat. Clim. Change* 5, 673–678.
- Galkin, Y.I., 1998. Long-term changes in the distribution of mollusks in the Barents Sea related to the climate. *Ber. Polarforsch.* 287, 100–143.
- George, J.C., Druckenmiller, M.L., Laidre, K.L., Suydam, R., Person, B., 2015. Bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea. *Progr. Oceanogr.* 136, 250–262.
- Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E.V., Carmack, E.C., Cooper, L.W., Frey, K.E., Helle, J.E., McLaughlin, F.A., McNutt, S.L., 2006. A Major ecosystem shift observed in the northern Bering Sea. *Science* 311, 1461–1464.
- Grebmeier, J.M., Bluhm, B.A., Cooper, L.W., Danielson, S., Arrigo, K.R., Blanchard, A.M., Clarke, J.T., Day, R.H., Frey, K.E., Gradinger, R.R., Kedra, M., Konar, B., Kulev, K.J., Lee, S.H., Lovvorn, J.R., Norcross, B.L., Okkonen, S.R., 2015. Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. *Prog. Oceanogr.* 136, 92–114.
- Greene, C.H., Pershing, A.J., 2000. The response of *Calanus finmarchicus* populations to climate variability in the Northwest Atlantic: basin-scale forcing associated with the North Atlantic Oscillation. *ICES J. Mar. Sci.* 57, 1536–1544.
- Grimaldo, E., Leifer, I., Gjøsvund, S.H., Larsen, R.B., Jeuthe, H., Basedow, S., 2010. Field demonstration of a novel towed: area bubble-plume zooplankton (*Calanus* sp.) harvester. *Fish. Res.* 107, 147–158.
- Høines, Å.S., Gundersen, A.C., 2008. Rebuilding the stock of northeast arctic Greenland halibut (*Reinhardtius hippoglossoides*). *J. Northw. Atl. Fish. Sci.* 41, 107–117.
- Hamilton, C.D., Lydersen, C., Ims, R.A., Kovacs, K.M., 2015. Predictions replaced by facts: a keystone species' behavioural responses to declining Arctic sea-ice. *Biol. Lett.* 11, 20150803, <http://dx.doi.org/10.1098/rsbl.2015.0803>.
- Hammill, M.O., Stenson, G.B., Doniol-Valcroze, T., Mosnier, A., 2015. Conservation of northwestern Atlantic harp seals: past success, future uncertainty? *Biol. Conserv.* 192, 181–191.
- Haug, T., Nilssen, K.T., Øien, N., Potelov, V., 1994. Seasonal distribution of harp seals (*Phoca groenlandica*) in the Barents Sea. *Polar Res.* 13, 161–172.
- Haug, T., Lindstrøm, U., Nilssen, K.T., 2002. Variations in minke whale *Balaenoptera acutorostrata* diet and body condition in response to ecosystem changes in the Barents Sea. *Sarsia* 87, 409–422.
- Haug, T., Bjørge, A., Øien, N., Ziryanov, S.V., 2011. Marine mammals of the barents sea. In: Jakobsen, T., Ozhigin, V.K. (Eds.), *The Barents Sea. Ecosystem, Resources, Management. Half a Century of Russian-Norwegian Cooperation*. Tapir Academic Press, Trondheim, pp. 395–430.
- Hays, G.C., Richardson, A.J., Robinson, C., 2005. Climate change and marine plankton. *Trends Ecol. Evol.* 20, 337–344.
- Heide-Jørgensen, M.P., 2002. Narwhal *Monodon monoceros*. In: Perrin, W.F., Würsig, B., Theewissen, J.G.M. (Eds.), *Encyclopedia of Marine Mammals*. Acad. Press, San Diego, pp. 783–787.
- Hjelset, A.M., Andersen, M., Gjert, I., Lydersen, C., Gulliksen, B., 1999. Feeding habits of bearded seals (*Erignathus barbatus*) from the Svalbard area, Norway. *Polar Biol.* 21, 186–193.
- Hollowed, A.B., Barange, M., Beamish, R.J., Brander, K., Cochrane, K., Drinkwater, K., Foreman, M.G.G., Hare, J.A., Holt, J., Ito, S.-i., Kim, S., King, J.R., Loeng, H., MacKenzie, B.R., Mueter, F.J., Okey, T.A., Peck, M.A., Radchenko, V.I., Rice, J.C., Schirripa, M.J., Yatsu, A., Yamanaka, Y., 2013a. Projected impacts of climate change on marine fish and fisheries. *ICES J. Mar. Sci.* 70, 1023–1037, <http://dx.doi.org/10.1093/icesjms/fst081>.
- Hollowed, A., Planque, B., Loeng, H., 2013b. Potential movement of fish and shellfish stocks from the sub-Arctic to the Arctic. *Fish. Oceanogr.* 22, 355–370, <http://dx.doi.org/10.1111/fog.12027>.
- Hop, H., Gjøsvæter, H., 2013. Polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) as key species in marine food webs of the Arctic and the Barents Sea. *Mar. Biol. Res.* 9, 878–894.
- Hovelsrud, G.K., McKenna, M., Huntington, H.P., 2008. Marine mammal harvests and other interactions with humans. *Ecol. Appl.* 18, S135–S147.
- Hunt, G.L., Drinkwater, K.F., Arrigo, K., Berge, J., Daly, K.L., Danielson, S., Daase, M., Hop, H., Isla, E., Karnovsky, N., Laidre, K., Mueter, F.J., Murphy, E.J., Renaud, P.E., Smith Jr, W.O., Trathan, P., Turner, J., Wolf-Gladrow, D., 2016. Advection in polar and sub-polar environments: impacts on high latitude marine ecosystems. *Progr. Oceanogr.* 149, 40–81.
- ICES, 2015. Report of the NAFO/ICES Pandalus Assessment Group (NIPAG), 9–16 September 2015, St. John's, Newfoundland, Canada. ICES CM 2015/ACOM: 14. 85 pp.
- ICES, 2015. Report of the Arctic Fisheries Working Group, Hamburg, 23–29 April 2015. ICES C.M. 2015/ACOM:05, 590 pp.
- ICES, 2015. Report of the Working Group on Widely Distributed Stocks (WGWDSE), 25 August – 31 August 2015, Pasaia, Spain. ICES CM 2015/ACOM:15. 57 pp.
- IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, <http://dx.doi.org/10.1017/CBO9781107415324>, 1535 pp.
- Ingvaldsen, R., Gjøsvæter, H., 2013. Impact of marine climate variability on the spatial distribution of Barents Sea capelin. *Mar. Biol. Res.* 9, 867–877.
- Ingvaldsen, R.B., Bogstad, B., Dolgov, A.V., Ellingsen, K.E., Gjøsvæter, H., Gradinger, R., Johannessen, E., Tveraa, T., Yoccoz, N.G., 2015. Sources of uncertainties in cod distribution models. *Nat. Clim. Change* 5, 788–789, <http://dx.doi.org/10.1038/nclimate2761>.
- Ivanov, V., Alexeev, V., Koldunov, N., Repina, I., Sandø, A.B., Smedsrud, L., Smirnov, A., 2016. Arctic Ocean heat impact on regional ice decay – a suggested positive feedback. *J. Phys. Oceanogr.* 46, 1437–1456, <http://dx.doi.org/10.1175/JPO-D-15-0144.1>, in press.
- Iversen, T., 1934. Some observations on cod in northern waters. preliminary report. *Fiskeridir. Skr. Ser. Havunders* 48, 1–4.
- Iversen, S., 2004. Mackerel and horse mackerel. In: Skjoldal, H.R. (Ed.), *The Norwegian Sea Ecosystem*. Tapir Academic Press, Trondheim, Norway, pp. 289–300.
- Jørgensen, L.L., Ljubin, P., Skjoldal, H.R., Ingvaldsen, R.B., Anisimova, N., Manushin, I., 2015. Distribution of benthic megafauna in the Barents Sea: baseline for an ecosystem approach to management. *ICES J. Mar. Sci.* 72, 595–613.
- Jaschnov, V.A., 1966. Water masses and plankton. *Calanus finmarchicus* and *Dimophyes arctica* as indicators of Atlantic waters in the Polar Basin. *Oceanology* 6, 493–503 (In Russian).
- Kawaguchi, S.A., Ishida, A., King, R., Raymond, B., Waller, N., Constable, A., Nicol, S., Wakita, M., Ishimatsu, A., 2013. Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nat. Clim. Change* 3, 843–847, <http://dx.doi.org/10.1038/nclimate1937>.
- Kiyko, O.A., Pogrebov, V.B., 1997. Long-term benthic population changes (1920–1930s-present) in the Barents and Kara Sea. *Mar. Poll. Bull.* 35, 322–332.
- Knutsen, T., Wiebe, P., Gjøsvæter, H., Ingvaldsen, R., Lien, G., 2016. High latitude acoustic scattering structures – a reference for future arctic ecosystem change. *Mar. Ecol. Prog. Ser.*, in press.
- Kosobokova, K., Hirche, H.-J., 2009. Biomass of zooplankton in the eastern Arctic Ocean – a base line study. *Prog. Oceanogr.* 82, 265–208.
- Kovacs, K.M., Lydersen, C., 2008. Climate change impacts on seals and whales in the North Atlantic Arctic and adjacent shelf areas. *Sci. Progr.* 91, 117–150.
- Kovacs, K.M., Gjert, I., Lydersen, C., 2004. *Marine Mammals of Svalbard*. Norwegian Polar Institute, Tromsø, Norway, 64 pp.
- Kovacs, K.M., Lydersen, C., Overland, J.E., Moore, S.E., 2011. Impacts of changing sea ice conditions on Arctic marine mammals. *Mar. Biodivers.* 41, 181–194.
- Kraft, A., Bauerfeind, E., Nöthig, E.-M., Klages, M., Beszczynska-Möller, A., Bathmann, U., 2013. Amphipods in sediment traps of the eastern Fram Strait with focus on the life-history of the lysianassoid *Cyclocaris guillelmi*. *Deep Sea Res.* 173, 62–72, <http://dx.doi.org/10.1016/j.dsr.2012.11.012>.
- Kroecker, K.J., Kordas, R.L., Crim, R.N., Singh, G.G., 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecol. Lett.* 13, 1419–1434.
- Krysov, A.I., Røttingen, I., 2011. Herring. In: Jakobsen, T., Ozhigin, V.K. (Eds.), *The Barents Sea. Ecosystem, Resources, Management. Half a Century of Russian-Norwegian Cooperation*. Tapir Academic Press, Trondheim, pp. 215–224.
- Lønø, O., Øynes, P., 1961. White whale fishery at Spitzbergen. *Norsk Hvalfangst-Tid.* 50, 267–286.
- Laidre, K.L., Stirling, I., Lowry, L.F., Wiig, Ø., Heide-Jørgensen, M.P., Ferguson, S.H., 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol. Appl.* 18, S97–S125.
- Lassen, H., Cross, D., Christiansen, E., 2012. One hundred years of catch statistics for the Northeast Atlantic. *ICES Coop. Res. Rep.* 311, 21.
- Last, K.S., Hobbs, L., Berge, J., Brierley, A.S., Cottier, F., 2016. Moonlight drives ocean-scale mass vertical migration of zooplankton during the arctic winter. *Curr. Biol.* 26, 1–8, <http://dx.doi.org/10.1016/j.cub.2015.11.038>.
- Leu, E., Søreide, J.E., Hessen, D.O., Falk-Petersen, S., Berge, J., 2011. Consequences of changing sea-ice cover for primary and secondary producers in the European Arctic shelf seas: Timing, quantity, and quality. *Prog. Oceanogr.* 90, 18–32.
- Lind, S., Ingvaldsen, R., 2012. Variability and impacts of Atlantic Water entering the Barents Sea from the north. *Deep-Sea Res.* 162, 70–88.
- Lindstrøm, U., Nilssen, K.T., Pettersen, L.M.S., Haug, T., 2013. Harp seal foraging behaviour during summer around Svalbard in the northern Barents Sea: diet composition and the selection of prey. *Polar Biol.* 36, 305–320.
- Lischka, S., Riebesell, U., 2012. Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. *Global Change Biol.* 18, 3517–3528, <http://dx.doi.org/10.1111/gcb.12020>.
- Lydersen, C., Kovacs, K.M., 2010. Status of harbour seals (*Phoca vitulina*) in Svalbard. *NAMMCO Sci. Publ.* 8, 47–60.
- Lydersen, C., Martin, A.R., Kovacs, K.M., Gjert, I., 2001. Summer and autumn movements of white whales *Delphinapterus leucas* in Svalbard, Norway. *Mar. Ecol. Prog. Ser.* 219, 265–274.
- Lydersen, C., Aars, J., Kovacs, K.M., 2008. Estimating the number of walrus in Svalbard from aerial surveys and behavioural data from satellite telemetry. *Arctic* 61, 119–128.
- Mathis, J.T., Cooley, S.R., Lucey, M., Colt, S., Ekstrom, J., Hurst, T., Hauri, C., Evans, W., Cross, J.N., Feely, R.A., 2015. Ocean acidification risk assessment for Alaska's fishery sector. *Progr. Oceanogr.* 136, 71–91.
- Michelsen, K., Dalpadado, P., Eriksen, E., Gjøsvæter, H., Ingvaldsen, R., Johannessen, E., Jørgensen, L.L., Knutsen, T., Skern-Mauritzen, M., Prozorkevich, D.D., 2013. Marine living resources of the Barents Sea – ecosystem understanding and monitoring in a climate change perspective. *Mar. Biol. Res.* 9, 932–947.
- Miller, A.W., Reynolds, A.C., Sobrino, C., Riedel, G.F., 2009. Shellfish face uncertain future in high CO2 world: influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS One* 4, e5661.
- Misund, O.A., Heggland, K., Skogseth, R., Falck, E., Gjøsvæter, H., Sundet, J., Watne, J., Lønne, O.J., 2016. Norwegian fisheries in the Svalbard zone since 1980

- Regulations, profitability and warming waters affect landings. *Polar Sci.* 10, in press.
- Moore, S.E., Huntington, H.P., 2008. Arctic marine mammals and climate change impact and resilience. *Ecol. Appl.* 18, S157–S165.
- Mumm, N., Auel, H., Hanssen, H., Hagen, W., Richter, C., Hirche, H.J., 1998. Breaking the ice: large-scale distribution of mesozooplankton after a decade of Arctic and transpolar cruises. *Polar Biol.* 20, 189–197.
- Næss, A., Haug, T., Nilssen, E.M., 1998. Seasonal variation in body condition and muscular lipid contents in northeast Atlantic minke whales *Balaenoptera acutorostrata*. *Sarsia* 83, 211–218.
- Nøttestad, L., Utne, K.R., Øskarsson, G.J., Jónsson, S.T., Jacobsen, J.A., Tangen, Ø., Anthonypillai, V., Aanes, S., Vølstad, J.H., Bernasconi, M., Debes, H., Smith, L., Sveinbjørnsson, S., Holst, J.C., Jansen, T., Slotte, A., 2016. Quantifying changes in abundance, biomass, and spatial distribution of Northeast Atlantic mackerel (*Scomber scombrus*) in the Nordic seas from 2007 to 2014. *ICES J. Mar. Sci.* 73, 359–373.
- Nedreaas, K.H., Drevetnyak, K.V., Planque, B., 2011. Redfish. In: Jakobsen, T., Ozhigin, V.K. (Eds.), *The Barents Sea. Ecosystem, Resources, Management. Half a Century of Russian-Norwegian Cooperation*. Tapir Academic Press, Trondheim, pp. 292–307430.
- Nicol, S., Foster, J., Kawaguchi, S., 2012. The fishery for Antarctic krill – recent developments. *Fish. Fish.* 13, 30–40.
- Nordøy, E.S., Folkow, L.P., Potelov, V., Prischemikhin, V., Blix, A.S., 2008. Seasonal distribution and dive behaviour of harp seals (*Pagophilus groenlandicus*) of the White Sea – Barents Sea stock. *Polar Biol.* 31, 1119–1135.
- Olafsson, J., Olafsdóttir, S.R., Benoit-Cattin, A., Danielsen, M., Arnarson, T.S., Takahashi, T., 2009. Rate of Iceland Sea acidification from time series measurements. *Biogeosciences* 6, 2661–2668 www.biogeosciences.net/6/2661/2009/.
- Onarheim, I.H., Smedsrud, L.H., Ingvaldsen, R., Nilsen, F., 2014. Loss of sea ice during winter north of Svalbard. *Tellus* 66A, 23933, <http://dx.doi.org/10.3402/tellusa.v66.23933>.
- 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., Yool, A., 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437, 681–686, <http://dx.doi.org/10.1038/nature04095>.
- Overland, J.E., Wang, M., Salo, S., 2008. The recent Arctic warm period. *Tellus* 60A, 589–597.
- Overland, J., 2011. Potential arctic change through climate amplification processes. *Oceanography* 24, 176–185.
- Piepenburg, D., Schmid, M.K., 1996. Brittle star fauna (Echinodermata Ophiuroidea) of the Arctic northwestern Barents Sea: composition, abundance, biomass and spatial distribution. *Polar Biol.* 16, 383–392.
- Piepenburg, D., Blackburn, T.H., Dorrien, C.F., Gutt, J., Hall, P.O.J., Hulth, S., Kendall, M.A., Opalinski, K.W., Rachor, E., Schmid, M.K., 1995. Partitioning of benthic community respiration in the Arctic (northwestern Barents Sea). *Mar. Ecol. Progr. Ser.* 118, 199–213.
- Pike, D.G., Vikingsson, G.A., Gunnlaugsson, T., Øien, N., 2009. A note on the distribution and abundance of blue whales (*Balaenoptera musculus*) in the Central and Northeast North Atlantic. *NAMMCO Sci. Publ.* 7, 19–30.
- Planque, B., Primicerio, R., Michalsen, K., Aschan, M., Certain, G., Dalpadado, P., Gjøseter, H., Hansen, C., Johannessen, E., Jørgensen, L.L., Kolsum, I., Kortsch, S., Leclerc, L.M., Omli, L., Skern-Mauritzen, M., Wiedmann, M., 2014. Who eats whom in the Barents Sea: a food web topology from plankton to whales. *Ecology* 95, 1430.
- Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F., Thompson, S.A., Richardson, A.J., 2013. Global imprint of climate change on marine life. *Nat. Clim. Change*, <http://dx.doi.org/10.1038/NCLIMATE1958>.
- Polyakov, I.V., Pnyushkov, A.W., Timokhov, L.A., 2012. Warming of the intermediate atlantic water of the arctic ocean in the 2000. *J. Clim.* 23, 8362–8370, <http://dx.doi.org/10.1175/JCLI-D-12-00266.1>.
- Ponomarenko, V.P., 1996. Fish migrations in the Barents Sea on the basis of marking. *Oceanology* 35, 819–826 (English translation, Russian Edition: NOVEMBER – DECEMBER 1995).
- Prozorkevich D., Sunnanå, K. (in press) (Eds.) Survey report from the joint Norwegian/Russian ecosystem survey in the Barents Sea and adjacent waters, August–October 2016. IMR/PINRO Joint Report Series, No. 1/2017.
- Purcell, J.E., Hopcroft, R.R., Kosobokova, K.N., Whitedge, T.E., 2009. Distribution, abundance and predation effects of epipelagic ctenophores and jellyfish in the western Arctic Ocean. *Deep-Sea Res.* II 57, 127–135.
- Purcell, J.E., 2005. Climate effects on formation of jellyfish and ctenophores: a review. *J. Mar. Biol. Ass. U.K.* 85, 461–476.
- Reeves, R.R., Ewins, P.J., Agbayani, S., Heide-Jørgensen, M.P., Kovacs, K.M., Lydersen, C., Suydam, R., Elliott, W., Polet, G., van Dijk, Y., Blijleven, R., 2014. Distribution of endemic cetaceans in relation to hydrocarbon development and commercial shipping in a warming Arctic. *Mar. Pol.* 44, 375–389.
- Reigstad, M., Carroll, J., Slagstad, D., Ellingsen, I., Wassmann, P., 2011. Intra-regional comparison of productivity, carbon flux and ecosystem composition within the northern Barents Sea. *Progr. Oceanogr.* 90, 33–46.
- Ressler, P.H., Dalpadado, P., Macaulay, G.J., Handegård, N., Skern-Mauritzen, M., 2015. Acoustic survey of euphausiids and models of baleen whale distribution in the Barents Sea. *Mar. Ecol. Progr. Ser.* 527, 13–29.
- Rey, F., 2004. Phytoplankton: the grass of the sea. In: Skjoldal, H.R. (Ed.), *The Norwegian Sea Ecosystem*. Tapir Academic Press, Trondheim, Norway, pp. 97–136.
- Rijnsdorp, A., Peck, M.A., Engelhard, G.H., Möllmann Pinnegar, J.K., 2009. Resolving the effect of climate change on fish populations. *ICES J. Mar. Sci.* 66, 1570–1583.
- Rudels, B., 2012. Arctic Ocean circulation and variability – advection and external forcing encounter constraints and local processes. *Ocean Sci.* 8, 261–286.
- Søreide, J.E., Falk-Petersen, S., Hegseth, E.N., Hop, H., Carroll, M.L., Hobson, K.A., Blachowiak Samolyk, K., 2008. Seasonal feeding strategies of *Calanus* in the high-Arctic Svalbard region. *Deep Sea Res.* II 55, 2225–2244.
- Saborido-Rey, F., Nedreaas, K.H., 2000. Geographic variation of *Sebastes mentella* in the Northeast Arctic derived from a morphometric approach. *ICES J. Mar. Sci.* 57, 965–975.
- Sandø, A.B., Gao, Y., Langehaug, H.R., 2014. Poleward heat transports, sea ice processed, and Arctic sea ice variability in NorESM1-M simulations. *J. Geophys. Res.* Oceans 119, 2095–2108, <http://dx.doi.org/10.1002/2013JC009435>.
- Sars, G.O., 1879. Indberetning til Departementet for det Indre om de af ham i Aarene 1864–1878 anstillede Undersegelser angaaende Saltvanns-fiskerierne (Report on the investigations on the seawater fisheries from 1864 to 1878) (in Norwegian). Bergh & Ellefsens Bogtrykkeri, Kristiania.
- Schauer, U., Loeng, H., Rudels, B., Ozhigin, V.K., Dieck, W., 2002. Atlantic water flow through the Barents and Kara seas. *Deep-Sea Res.* I 49, 2281–2298.
- Sergeant, D.E., 1991. Harp seal, man and ice. *Can. Fish. Aquat. Sci. Spec. Publ.* 114, 153.
- Skaug, H.J., Øien, N., Schweder, T., Bothun, G., 2004. Abundance of minke whales (*Balaenoptera acutorostrata*) in the Northeastern Atlantic. *Can. J. Fish. Aquat. Sci.* 61, 870–886.
- Skern-Mauritzen, M., Johannesen, E., Bjørge, A., Øien, N., 2011. Baleen whale distributions and prey associations in the Barents Sea. *Mar. Ecol. Progr. Ser.* 426, 289–301, <http://dx.doi.org/10.3354/meps09027>.
- Skogen, M.D., Olsen, A., Børsheim, K.-Y., Sandø, A.B., Skjelvan, I., 2014. Modelling ocean acidification in the Nordic and Barents Seas in present and future climate. *J. Mar. Syst.* 131, 10–20.
- Slagstad, D., Ellingsen, I.H., Wassmann, P., 2011. Evaluating primary and secondary production in an Arctic Ocean void of summer sea ice: an experimental simulation approach. *Prog. Oceanogr.* 90, 117–131.
- Slagstad, D., Wassmann, P., Ellingsen, E., 2015. Physical constraints and productivity in the future Arctic Ocean. *Front. Mar. Sci.* 2, 85, <http://dx.doi.org/10.3389/fmars.2015.0085>.
- Solvang, H.K., Yangihara, H., Øien, N., Haug, T., 2016. Temporal and geographical variation in body condition of common minke whales (*Balaenoptera acutorostrata*) in the Northeast Atlantic. *Polar Biol.* 39, <http://dx.doi.org/10.1007/s00300-016-1992-0> (in press).
- Sorokin, V.P., 1961. The redfish; gametogenesis and migrations of the *Sebastes marinus* (L.) and *Sebastes mentella* Travin. *ICNAF Spec. Publ.* 3, 245–250.
- Sorteberg, A., Kvingsdal, B., 2006. Atmospheric forcing on the Barents sea winter ice extent. *J. Clim.* 19, 4772–4784.
- Squires, H.J., Dawe, E.G., 2003. Stomach contents of snow crab (*Chionoecetes opilio*, decapoda, brachyura) from the northeast newfoundland shelf. *J. Northw. Atl. Fish. Sci.* 32, 27–38.
- Steinacher, M., Joos, F., Frölicher, T.L., Plattner, G.-K., Doney, S.C., 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. *Biogeosciences* 6, 515–533.
- Stenson, G.B., Hammill, M.O., 2014. Can ice breeding seals adapt to habitat loss in a time of climate change? *ICES J. Mar. Sci.* 71, 1977–1986, <http://dx.doi.org/10.1093/icesjms/fsu074>.
- Stenson, G.B., Buren, A.D., Koen-Alonso, M., 2015. The impact of changing climate and abundance on reproduction in ice-dependent species, the Northwest Atlantic harp seal *Pagophilus groenlandicus*. *ICES J. Mar. Sci.* 72, 250–262, <http://dx.doi.org/10.1093/icesjms/fsv202>.
- Stiasny, M.H., Mittermayer, F.H., Swat, M., Voss, R., Jutfelt, F., Chierici, M., Puvanendran, V., Mortensen, A., Reusch, T.B.H., Clemmesen, C., 2016. Ocean acidification effects on Atlantic cod larval survival and recruitment to the fished population. *PLoS One* 11 (8), <http://dx.doi.org/10.1371/journal.pone.0155448>.
- Stroeve, J., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., Meier, W.N., 2012. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophys. Res. Lett.* 39, L16502.
- Sundet, J.H., Hoel, A.H., 2016. The Norwegian management of an introduced species: the Arctic red king crab fishery. *Mar. Policy*, <http://dx.doi.org/10.1016/j.marpol.2016.04.041>.
- Svenson, J., 2012. MabCent: arctic marine bioprospecting in Norway. *Phytochem. Rev.* 12, 567–578, <http://dx.doi.org/10.1007/s11101-012-9239-3>.
- Sydeman, W.J., Poloczanska, E., Reed, T.E., Thomson, S.A., 2015. Climate change and marine vertebrates. *Science* 350, 6262.
- Townhill, B.L., Maxwell, D., Engelhard, G.H., Simpson, S.D., Pinnegar, J.K., 2015. Historical Arctic logbooks provide insights into past diets and climatic responses of cod. *PLoS One* 10 (9), e0135418, <http://dx.doi.org/10.1371/journal.pone.0135418>.
- Tremblay, J.E., Gagnon, J., 2009. The effects of irradiance and nutrient supply on the productivity of Arctic waters: a perspective on climate change. In: Nihoul, C.J., Kostianoy, A.G. (Eds.), *Influence of Climate Change on the Changing Arctic and Subarctic Conditions*. Springer Science, pp. 73–92.

- Tremblay, J.E., Belanger, S., Barber, D.G., Asplin, M., Martin, J., Darnis, G., Fortier, L., Gratton, Y., Link, Y., Archambault, P., Sallon, A., Michel, C., Williams, W.J., Philippe, B., Gosselin, M., 2011. Climate forcing multiplies biological productivity in the coastal Arctic Ocean. *Geophys. Res. Lett.* 38, L18604, <http://dx.doi.org/10.1029/2011GL048825>.
- Uriarte, A., Alvarez, P., Iversen, S.A., Molloy, J., Villamor, B., Martins, M.M., Myklevoll, S., 2001. *Spatial pattern of migration and recruitment of Northeast Atlantic mackerel*. ICES, C.M. 2001/O :17, 40 pp.
- Vikingsson, G.A., Pike, D.G., valdimarsson, H., Schleimer, A., Gunnlaugsson, T., Silva, T., Elvarsson, B.P., Mikkelsen, B., Øien, N., Desportes, G., Bogason, V., Hammond, P.S., 2015. Distribution, abundance, and feeding ecology of baleen whales in Icelandic waters: have recent environmental changes had an effect? *Front. Ecol. Evol.* 3, 6, <http://dx.doi.org/10.3389/fevo.2015.0006>.
- Vinje, T., 1999. *Barents Sea Ice Edge Variation over the Past 400 Years*. Extended Abstract, Workshop on Sea-ice Charts of the Arctic, Seattle, WA. World meteorological Organization, WMO/TD No. 949, 4-6.
- Ware, C., Berge, J., Sundet, J.H., Kirkpatrick, J.B., Coutts, A.D.M., Jelmert, A., Olsen, S.M., Floerl, O., Wisz, M.S., Alsos, I.G., 2013. Climate change, non-indigenous species and shipping: assessing the risk of species introduction to a high-Arctic archipelago. *Divers. Distrib.* 20, 10–19, <http://dx.doi.org/10.1111/ddi.12117>.
- Wassmann, P., Reigstad, M., Haug, T., Rudels, B., Carroll, M.L., Hop, H., Gabrielsen, G.W., Falk-Petersen, S., Denisenko, S.G., Arashkevich, E., Slagstad, D., Pavlova, O., 2006. *Food webs and carbon flux in the Barents Sea*. *Prog. Oceanogr.* 71, 232–287.
- Wassmann, P., Duarte, C.M., Agusti, S., Sejr, M.K., 2011. Footprints of climate change in the Arctic marine ecosystem. *Glob. Change Biol.* 17, 1235–1249, <http://dx.doi.org/10.1111/j.1365-2486.2010.02311.x>.
- Wassmann, P., Kosobokova, K.N., Slagstad, D., Drinkwater, K.F., Hopcroft, R.R., Moore, S.E., Ellingsen, I., Nelson, R.J., Carmack, E., Popova, E., Berge, J., 2015. *The contiguous domain of Arctic Ocean advection: trails of life and death*. *Prog. Oceanogr.* 139, 42–65.
- Wassmann, P., 2011. *Arctic marine ecosystems in an era of rapid climate change*. *Prog. Oceanogr.* 90, 1–132.
- Wiig, Ø., Derocher, A.E., Belikov, S.E., 1999. Ringed seal (*Phoca hispida*) breeding in the drifting pack ice of the Barents Sea. *Mar. Mamm. Sci.* 15, 595–598.
- Wisz, M.S., Broennimann, O., Grønkjær, P., Møller, P.R., Olsen, S.M., Swingedouw, D., Hedeholm, R.B., Nielsen, E.E., Guisan, A., Pellissier, L., 2015. Arctic warming will promote Atlantic–Pacific fish interchange. *Nat. Clim. Change* 5, 261–265, <http://dx.doi.org/10.1038/nclimate2500>.