Chapter 14
Kongsfjorden as Harbinger of the Future Arctic: Knowns, Unknowns and Research Priorities

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Abstract Due to its year-round accessibility and excellent on-site infrastructure, Kongsfjorden and the Ny-Ålesund Research and Monitoring Facility have become established as a primary location to study the impact of environmental change on Arctic coastal ecosystems. Due to its location right at the interface of Arctic and Atlantic oceanic regimes, Kongsfjorden already experiences large amplitudes of variability in physico/chemical conditions and might, thus, be considered as an early warning indicator of future changes, which can then be extrapolated in a pan-Arctic perspective. Already now, Kongsfjorden represents one of the best-studied Arctic fjord systems. However, research conducted to date has concentrated largely on small disciplinary projects, prompting the need for a higher level of integration of future research activities. This contribution, thus, aims at identifying gaps in knowledge and research priorities with respect to ecological and adaptive responses

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to Arctic ecosystem changes. By doing so we aim to provide a stimulus for the initiation of new international and interdisciplinary research initiatives.

Keywords Flagship program · Monitoring · Land-sea-ocean-interaction · Indicator species · Pan-Arctic

14.1 Introduction

Polar systems, and in particular the High Arctic, are environmentally sensitive regions in which the impacts of global climate change will be manifested faster than elsewhere on our planet (Larsen et al. 2014). Arctic marine communities can therefore be regarded as sensitive indicators signalling the onset of environmental change. Kongsfjorden, a fjord located on the west Spitsbergen coast, is one of the northernmost areas influenced by the inflow of warm Atlantic water from the West Spitsbergen Current, and is positioned right at the interface of High Arctic and Atlantic influences. The marine communities of this ecosystem therefore dynamically respond to the variability and changes in environmental conditions occurring today. The Atlantic-Arctic climate signals vary between years, leading to measurable effects on biological processes, such as alterations in benthic and pelagic primary production (Hegseth and Tverberg 2013; Krause-Jensen and Duarte 2014;

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Bartsch et al. 2016; Hegseth et al., Chap. 6), and changes in composition of zooplankton (Beuchel et al. 2006; Willis et al. 2006, 2008; Dalpadado et al. 2016) as well as fish communities (Brand and Fischer 2016), with potential consequential negative implications for seabirds and mammals (Lydersen et al. 2014; Vihtakari et al. 2018). In the current era of global environmental change, documented and projected alterations in the physico-chemical environment in the Kongsfjorden system include changes in atmospheric and seawater temperature, decreases in winter sea–ice cover, changes in the salinity regime ("Atlantification"; Hegseth and Sundfjord 2008), decrease in seawater pH ("ocean acidification"; Fransson et al. 2016; Lou et al. 2016), increased terrestrial run-off potentially altering nutrient, sediment and soil-associated contaminant loadings (Granberg et al. 2017), changes in light climate, particularly ultraviolet B exposure (due to stratospheric ozone depletion; Hanelt et al. 2001), and glacier retreat (Kohler et al. 2007; Blaszczyk et al. 2009). In addition, air- and waterborne pollutants emitted from low latitudes (Gabrielsen 2007; Jæger et al. 2009) as well as originating from local pollution sources such as dumping sites and remains from mining activities (Skei 1994; Szczybelski et al. 2016; Vázquez Alonso 2016) are detected in the Kongsfjorden region, and can impact marine life.

Any of the above-mentioned environmental alterations may impose stress on organisms, and species-specific responses are expected. Grime (1989) and Vinebrooke et al. (2004) basically defined stress as *the impact of any set of abiotic and biotic factors negatively affecting the performance individually, and eventually deteriorating the growth rate of the population through the reduction of individual survival, growth and reproduction.* Thus, stress can be invoked by abiotic or biotic drivers, and both can interact producing combined (additive, synergistic, antagonistic) impacts. In addition, the effects of stress depend on a) its intensity, duration and periodicity, b) the target organism, and c) any interaction between the stressors themselves. Davison and Pearson (1996) proposed that growth rate of a certain organism can be affected by "limiting factors" as well as by "disruptive factors", and among the latter we can consider high irradiance (both PAR and UV), high or low temperature, desiccation, freezing, low pH, osmotic stress and contaminant exposure.

Such widespread and profound environmental changes will provoke species-specific responses, which may further result in new inter-specific interactions, such as competitive or trophic changes and, thus affect ecosystem functions (e.g. Russell et al. 2012; AMAP 2013; Pörtner et al. 2014). At the organism level, responses to environmental changes are often summarised by the simple phrase: 'Move, adapt or die'. This kind of simplistic view, however, neglects the plasticity of organism responses, which may buffer against the stress impacts of environmental changes. Physiological plasticity has evolved along temporal gradients of environmental stability, with organisms from evolutionarily stable habitats generally being less plastic (Peck et al. 2006). However, due to the Arctic's comparatively short cold-water history (compared to Antarctica) we might expect a higher degree of plasticity in the majority of inhabiting organisms (Wiencke and Amsler 2012). When characterising individual *vs.* species responses towards environmental change we should discriminate between the different timescales for expressing such response: the term "regulation" means an immediate response of an individual to varying environmental factors, for instance by activation/up−/down-regulation of existing enzymes. "Acclimation" is a mid-term response (hours or days) and usually involves changes in gene expression. "Adaptation" represents the genetic framework, which sets the limits for acclimation. Adaptation to new environments requires alterations of the genome, drives speciation processes and is, thus, usually active over longer timescales or at least sequentially develops over a number of generations. Future studies on environmental impacts on Arctic coastal ecosystems will thus need to address responses on different timescales and hierarchical levels (molecular/cellular, individual, population, community, ecosystem). An improved understanding of acclimative, interactive and adaptive responses is urgently needed to reduce the level of uncertainty in our predictions on the consequences of climate change.

How physiological and molecular responses translate into structural and functional ecosystem processes is almost completely unexplored for most species inhabiting the Kongsfjorden system. Without this knowledge, predicting or modelling climate change effects on biota becomes an impossible task. Improved understanding of general mechanistic principles applying to a wide range of organisms and the overall adaptive capacity ("thresholds, tipping points") of the system has yet to be established for any environmental stressor, either in isolation or in combination with other abiotic and biotic drivers (Wassmann and Lenton 2012; AMAP 2013).

The Kongsfjorden area (Fig. 14.1) has a rich history of scientific research and monitoring focused on the research station at Ny-Ålesund, and is ideally suited to play a leading role in establishing such in-depth knowledge on Arctic change. Given the high degree of complementary expertise in the international community conducting science at Kongsfjorden, greater integration of research activities would provide the opportunity to accelerate development of mechanistic understanding of adaptation processes, life-cycle control of key organisms, and ecosystem structure, function and services. A compilation of the current state of knowledge is provided by this book. Starting from an improved topical research focus on the Kongsfjord marine ecosystem, principles found should be addressed and compared across systems and across phyla (e.g. by identifying common principles across marine and terrestrial systems, or connectivity between atmosphere-land-ocean) and within a pan-Arctic perspective.

In the light of this complex changing environmental scenario, a set of key scientific questions have been formulated by the Kongsfjord ecosystem research community. They provide a framework for future integrative research applied to the Kongsfjorden system.

1. Is Kongsfjorden a suitable model system to project the future of marine ecosystems on Svalbard and beyond? Are contemporary changes harbingers of the future in other fjords?
2. What consequences will 'Atlantification' have for ecosystem processes and services such as carbon uptake and storage, sources/sinks of nutrients, or dynamics of contaminants in the food webs?
3. Can effects of climate change be mitigated by acclimation and adaptation, and, if so, what will those responses be? What is the timescale of responses towards

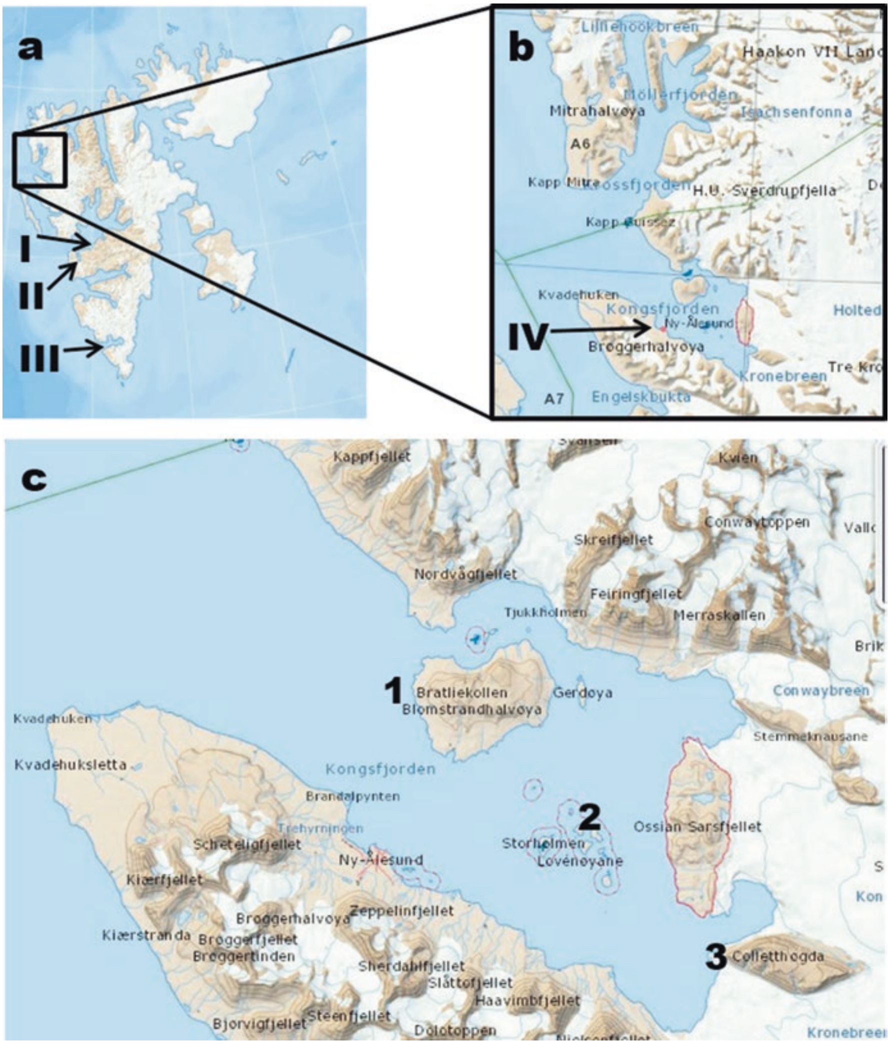

Fig. 14.1 (**a**) Map of the Svalbard archipelago; location of **I**: Longyearbyen, **II**: Barentsburg, **III**: Hornsund. (**b**) Map of the Kongsfjorden and neighboring Krossfjorden system, **IV** location of Ny-Ålesund. **c**: map of Kongsfjorden, indicating important study sites for marine research along the fjord axis; **1**: Hansneset, **2**: Juttaholmen, **3**: Collethøgda. (Map retrieved from Topo Svalbard, Norwegian Polar Institute)

different and interacting environmental drivers and can they help sustain ecosystem services?

These research questions are based on the following hypotheses:

1. Warming and acidification in Arctic coastal waters will continue and develop beyond the range of current natural variability.

2. Tidewater glaciers will disappear, with major consequences for seawater circulation and associated biological systems in Arctic fjord systems.
3. "Atlantification" will continue, leading to local extinction of endemic species and/or the colonization by and establishment of temperate species in Arctic marine ecosystems.

This contribution aims to provide a research framework or catalyst for addressing climate-related changes in Kongsfjorden, and the Arctic generally, with respect to productivity, ecosystem functions and biodiversity, regime shifts, and ecosystem services. Gaps in knowledge and research priorities identified by the community of marine researchers working in Kongsfjorden are summarized and discussed. This summary represents the outcome of discussions held in a workshop funded by the Svalbard Science Forum and the Norwegian Polar Institute and focused on "Adaptation to environmental changes in the Arctic" that took place in Tromsø, Norway, in October 2016. Its results are presented here as a starting point to stimulate further discussion and development of research.

14.2 Assessment of the status of marine research in Kongsfjorden

The 'Ny-Ålesund Science Plan' adopted by the Svalbard Science Forum in 2010 states that Ny-Ålesund shall be developed as a premier international Arctic research and monitoring facility. Research at this globally unique facility is organised in four topical research flagships (Atmosphere Research, Glaciology Research, Terrestrial Ecosystem, Kongsfjorden System; see http://nysmac.npolar.no/research/flagships/). Due to its location right at the interface of Arctic and Atlantic systems, Kongsfjorden is a crucial site for the detection of environmental changes. At the Ny-Ålesund research facility, a large number of individual monitoring and research activities are clustered around the central topic of the changing Arctic environment, its ecosystems and their components. Ongoing research activities on response patterns in organisms related to the marine environment include studies on all taxonomic and functional levels, from bacteria to vertebrates, and from primary producers to top predators (Hop et al. 2002a, Berge et al. 2015a, b). Amongst others, the ecophysiology of phyto- and zooplankton, seaweeds, benthic invertebrates, the local fish fauna, and seabird communities are studied in the context of changes in the degree of Atlantification, UV-radiation, ocean acidification or with respect to their trophic interactions. However, as yet research and data management have failed to achieve a higher level of integration of data, holding back the identification of common (or contrasting) principles in the response patterns across phyla.

The small settlement of Ny-Ålesund hosts 14 permanent research stations operated by 10 different nations. Scientists from all over the world visit Ny-Ålesund to conduct research, with approximately 13,000 research days being registered annually. Logistical support is provided by Kings Bay AS and the Norwegian Polar

Institute, including a marine laboratory and a research vessel. The multitude of technological infrastructure available on site further comprises, amongst others, a wide range of observation platforms with focus on physical and chemical oceanography, including various mooring systems (e.g. Cottier et al. 2007; Venkatesan et al. 2016), an underwater observatory fitted with radiation sensors, a Ferry Box system for the assessment of sea water chemistry and which is now delivering the first Arctic time series for the seawater carbonate system (Fischer et al. 2016), and sediment traps along the fjord axis, in addition to long-standing time series of CTD data.

Oceanographic processes observed in Kongsfjorden can be closely linked to long-term time series of atmospheric data recorded in Ny-Ålesund, comprising records of temperature, precipitation, radiation transfer including UV-radiation (Maturilli et al. 2013). The coupling with physical data from atmospheric and oceanographic records also facilitates research with respect to the movement patterns of the higher vertebrate fauna (birds, seals, whales, polar bears) in the system (Lydersen et al. 2014; Goutte et al. 2014; Hanssen et al. 2016) or the distribution and deposition patterns of anthropogenic and non-anthropogenic contaminants (Gabrielsen 2007). Such monitoring efforts have already allowed for deeper understanding of the functionality of the Kongsfjorden system and its adjacent environments (Svendsen et al. 2002). Amongst others, models on the glacial mass balances and their discharge rates to Kongsfjorden, as well as an oceanographic circulation model for the Kongsfjorden, and adjacent Krossfjorden system have either already been implemented or will soon become available (Ingvaldsen et al. 2001; Cottier et al. 2007; Tverberg and Nøst 2009; Aas et al. 2016; Duarte et al., Chap. 12). The world-class infrastructure hosted in Ny-Ålesund now also supports an increasing number of research projects during the winter season, which is of utmost importance to complete our understanding of marine ecosystem functionality (e.g. Berge et al. 2015a, b). With this foundation, and in order to provide a basis for a more structured and integrative approach to studying the Kongsfjord ecosystem in an interdisciplinary manner, we will now discuss some important gaps in knowledge.

14.3 The Abiotic Environment

In order to gain a better understanding of ecosystem functionality, improved and integrated monitoring of a number of physical drivers is of utmost importance, including ice and glacial regimes, air and water temperatures, oceanographic forcing, light and nutrient regimes (including nearshore areas), as well as the discharge dynamics and chemical characteristics of the freshwater sources (glaciers and streams).

There is a high level of uncertainty with respect to the future radiation environment in Kongsfjorden (Hanelt et al. 2001). Sea ice cover in Kongsfjorden will be reduced, with presumably drastic negative effects to higher ice-associated biota (seals, polar bears), but with a likely promotion of pelagic and benthic primary producers. Reducing impacts of sea-ice may allow for earlier and deeper penetration of solar radiation into the water column, eventually stimulating primary production. However, increased terrestrial run-off will also increase the discharge of sediments to near-shore ecosystems, conversely resulting in increased water turbidity and decreased light availability (Svendsen et al. 2002). The consequences for the phenology and productivity of the phytoplankton and phytobenthos communities need to be evaluated. Intensified monitoring and, eventually, modelling of radiation and nutrient environments may allow prediction of the phenology, primary productivity and species composition of phytoplankton blooms (Hegseth et al., Chap. 6) and changes in the distribution of seaweeds with water depth (Bartsch et al. 2016). Increased spectral resolution of underwater radiation will allow quantifying the role of sediments for sun-screening, i.e. as a UV-protectant. An expanded mooring system with photosynthetically active radiation (PAR) sensors determining turbidity by beam attenuation in different water depths along the fjord gradient (e.g. at Hansneset, Juttaholmen, Colletthøgda; Fig. 14.1) would be a valuable approach.

The inflow of Atlantic and Arctic water masses into the fjord has been identified as a key driver for water column stability and, furthermore, represents an important source of inorganic nutrients, contaminants, and seeding populations of planktonic organisms (van de Poll et al. 2016; Hunt et al. 2016; Hegseth et al., Chap. 6). Thus, characterizing patterns of, and changes in, advection dynamics will become the key for understanding the environmental controls of the Kongsfjorden marine ecosystem. Here, closer connections with monitoring data from the Fram Strait (see: https://www.pangaea.de/?count=10&q= project%3Ahausgarten) may provide valuable insight into community composition of local *vs.* advected organisms.

The extent to which remote sensing might offer improved tools for monitoring the Kongsfjord environment, for instance with respect to sea ice and ocean color at high spatial, temporal and spectral resolutions, should be investigated. Glacial influences, phytoplankton bloom events and sediment discharge rates in time and space should be evaluated further.

14.4 Land-Sea-Atmosphere-Interactions

The coupling of atmosphere, land and sea has been largely overlooked in the research conducted in the Kongsfjorden area to date, although being of primary importance to coastal processes. Changes in glacial discharge, as well as increased terrestrial sediment run off caused by melting snow or increased precipitation, will affect the Kongsfjorden ecosystem along a spatial gradient from glacial fronts and shores to the open water (Fig. 14.2, Svendsen et al. 2002; van de Poll et al. 2016). Apart from changes with respect to radiation transfer from the atmosphere into pelagic and benthic systems, increased sediment load may result in a smothering of benthic substrates and thus impact associated community structure and function (Roleda and Dethleff 2011). However, benefits of increased sediment loads have also been reported, such as a screening function against harmful short-wavelength radiation, which contributes to UV-protection of kelps (Roleda et al. 2008). Glacial

Fig. 14.2 Interface of a sediment-laden river plume and saline fjord water in front of the Bayelva river mouth, Kongsfjorden. (Photo: K. Bischof)

and terrestrial meltwater discharge will alter the in-fjord salinity regime. How the shallow-water communities present in Kongsfjorden may adapt to the changing spatial gradients in light, sediment load and desalination along the fjord axis is as yet poorly understood (Wiencke et al. 2006; Karsten 2007; Fredersdorf et al. 2009). Increasing run-off events also have the potential to alter the input of nutrients from the terrestrial system into Kongsfjorden, in particular with respect to different forms of inorganic N and P along with dissolved organic carbon from the soil. Under elevated temperature, soils from northern latitudes may achieve mineralization rates similar to those found in soils that undergo annual thawing processes (i.e. periglacial or discontinuous permafrost soils). We hypothesise that increased contribution to the N and P content in the fjord in summer may affect growth and metabolic performances of both pelagic and benthic primary producers. Some preliminary data indicate that several species of macrophytes benefit from N and P enrichment in summer (Gordillo et al. 2004, 2006). However, conclusive data on the effects on growth and physiological performance of primary producers are still lacking. Quantifying loads of freshwater and associated dissolved and suspended substances may be particularly challenging when most of the freshwater pathways have a diffuse nature through a complex seasonal network. Therefore, one possible approach is to define a sampling program in selected water pathways and model the overall hydrographic network with a hydrological model [e.g. SWAT (Soil Water Assessment Tool), Neitsch et al. 2002]. The model may be calibrated and validated with the help of available measurements. Thereafter, it may be used to quantify the loads mentioned above. Similarly, glacier water discharges may be simulated based on the glacier energy balance (Aas et al. 2016).

There are several tidewater glaciers in Kongsfjorden, as is also typical in many other Arctic coastal regions. The fronts of these glaciers have been identified as "ecological hotspots" due to their importance as feeding areas for seabirds and mammals (Fig. 14.3). The ice calving from these glaciers may provide suitable platforms for seal species, for resting, moulting, birthing and nursing. They may then also become important hunting areas for polar bears (Lydersen et al. 2014). The freshwater plumes from these glaciers transport a large load of suspended matter, contributing to the extremely high water turbidity near the glacier fronts, with direct implications for primary production and benthic deposition processes. The full extent of the contribution of these plumes to fjord biogeochemistry in terms of nutrients and organic matter is yet unknown. Tidewater glaciers in Svalbard are retreating but it is difficult to predict how long it will take for the glaciers in Kongsfjorden to retreat onto land and what consequences this will have on the fjord ecosystem (Kohler et al. 2007).

Furthermore, the transport, deposition and biological impact of pollutants are also dictated by the closely coupled continuum of atmosphere-land-sea. With respect to the deposition and bioaccumulation of contaminants, the relative importance of local sources (where there are or have been human activities) *vs.* distant transport has yet to be evaluated.

Fig. 14.3 Glacier fronts as ecological hotspots – Kittiwakes feeding in front of the Kongsvegen glacier, Kongsfjorden. (Photo: G.W. Gabrielsen)

Currently, also the trophic coupling of land and sea (and *vice versa*) is poorly understood. Climate change is not only likely to impact the terrestrial and marine ecosystems separately, but also their interaction (Stempniewicz et al. 2007). For example, seabirds nesting in the Kongsfjorden area may have to change their diet in response to potential shifts in the pelagic prey communities, with unknown consequences for pollutant uptake and energetics of birds (Hop et al. 2002b, Guzzo et al. 2014; Blévin et al. 2017). Reindeer, which can become deprived of terrestrial food sources after ice formation on the ground surface following more frequently occurring rain-on-snow events, may increasingly depend on access to marine shoreline food sources such as seaweeds (Hansen and Aanes 2012).

14.5 Primary Production

Primary production is one of the key processes for ecosystem function, but its utilization by the food web and its temporal trends are unresolved key questions in the face of environmental change. Furthermore, research on changes in primary production forms the basis of an understanding of environmental effects on higher trophic levels and food-web structure. As outlined above, there is large uncertainty with respect to the future radiation climate in Kongsfjorden, as a result of the balance between sea ice loss and sediment input. How the annually accumulated dose of photosynthetically active radiation and the distribution of light availability over the year may affect the timing of primary production and the community composition of primary producers needs to be evaluated. To tackle this question, coordinated plankton time series must be expanded further, in particular over seasonal cycles, for instance through weekly autonomous water sampling on moorings or regular sampling by station personnel. The timing of blooms is important to ecosystem function in Kongsfjorden. On the one hand, ongoing Atlantification may imply a reset of bloom initiation in the transition from an Arctic to a temperate regime and plankton succession patterns, with an earlier spring bloom and the potential for the occurrence of autumn blooms (Kahru et al. 2011; Ardyna et al. 2014). Alternatively, changes in advection patterns may delay re-seeding from the sediment, thus delaying spring bloom initiation (Hegseth and Tverberg 2013; Hegseth et al., Chap. 6). As, overall, the availability of macronutrients such as nitrate may limit primary production earlier in the season (Tremblay et al. 2015), the future balance between stronger surface stratification caused by warming and glacial melt with the increased input of nutrients from external sources (e.g. terrestrial run-off, advection of Atlantic water) could have beneficial or detrimental effects on annual net primary production. Thus, closer integration between physical, chemical and biological monitoring efforts will be the key to resolving questions of future primary production trends in Kongsfjorden. Furthermore, interactive effects between multiple drivers, including ocean acidification and warming, need to be considered (AMAP 2013; Riebesell and Gattuso 2015).

14.6 Indicator Species

Changes in the physical environment will alter the performance of individual species in an ecosystem. Physiological fitness will affect reproduction and competitive strength in interactions with co-occurring species. Here, it is crucial to focus research on carefully selected species, either because of their ecological significance, for instance as ecosystem engineers, or because of their particular sensitivity or adaptive capacity to environmental changes. Such species have good potential as indicator species, and may be characterized by strict threshold levels for acclimation or adaptation. The following species and/or taxonomic and functional groups have been identified as being of specific interest in the evaluation of change in the Kongsfjorden system (and hence to extrapolate to changes across the Arctic):

First, it is striking that the significance of the entire microbial community to ecosystem function in Kongsfjorden has been largely neglected, although some studies have involved the microbial loop and production of microphytobenthos (Rokkan Iversen and Seuthe 2011; Seuthe et al. 2011; Karsten et al., Chap. 8). Changes in land runoff are likely to affect the efficiency, relative roles and identity of actors of microbial processes such as carbon, nitrogen and organic contaminant turnover (Dunton et al. 2006). New research activities in the fields of microbial ecology, biogeochemical cycling and contaminant biodegradation are desirable in the land-water interface associated with shallower marine areas. Soft sediment systems form the basis for the transfer of carbon, energy and persistent contaminant along benthic food chains, and hitherto monitoring in Kongsfjorden has largely focused on the deeper areas (below 20 m), which are readily accessible by larger research vessels (e.g. Miløovervåking Svalbard og Jan Mayen; www.MOSJ.no). This approach has left the sedimentary littoral and sublittoral zones largely unexplored regarding both biological and ecotoxicological processes. Coastal shallow waters represent areas of high productivity and are naturally intimately connected with biological and biogeochemical processes on land. Thus, in order to detect and understand the impact of climate change on Arctic systems, shallow water ecosystems need to be included.

In the hard-bottom benthic littoral and sub-littoral systems, the functional group of kelps (large brown seaweeds) comprises keystone species of great ecological significance to the overall system (Hop et al. 2016; Bartsch et al. 2016). Here the changing performance of polar (*Laminaria solidungula*) *versus* boreal-Arctic (*Saccharina latissima*) and boreal (*Laminaria hyperborea*) species should be compared.

With respect to benthic invertebrates, the group of amphipods has been proposed as key invertebrates to study in the intertidal/shallow subtidal fringe. *Gammarus setosus*, *Onissimus litoralis* and *Anonyx sarsi* represent commonly occurring species with different life strategies (Węsławski and Legeżyńska 2002). Amphipods are consumed by fish, seabirds and seals in the Arctic and therefore constitute a trophic link between water- and air breathers. Ecotoxicological assays related to reproductive success have for example already been developed both for temperate and Arctic amphipod species (Sundelin and Eriksson 1998; Bach et al. 2009).

In the pelagic realm, Atlantification may promote haptophytes such as *Phaeocystis* and coccolithophores, reducing the abundance of the currently dominant diatoms in the spring bloom phytoplankton assemblages (Hegseth and Tverberg 2013; Nöthig et al. 2015). The effects of changes in nutrient availability in Kongsfjorden may be best monitored by observing the abundance of picoeukaryotes (e.g. *Micromonas pusilla*) and dinoflagellates, which are indicators of nutrient-limited conditions and become increasingly important in nutrient-limited Arctic waters (Assmy and Smetacek 2009; Li et al. 2009). In terms of zooplankton community structure, the changing abundance of Arctic to boreal zooplankton species should be addressed by following the development of the plankton community composition, for example comparing abundances of the copepods *Calanus glacialis* and *C. hyperboreus vs. C. finmarchicus* (Kwasniewski et al. 2003, 2013; Walkusz et al. 2009).

Ocean acidification is an emerging driver of environmental change and affects many pH sensitive extra- and intracellular physiological functions (Pörtner 2008), and keystone Arctic species are shown to be affected (Thor and Oliva 2015; Thor et al. 2016). At present there are no suitable indicators of biological effects of ocean acidification, but the exposure to potential ocean acidification effects can be monitored by studies of pteropod shell degradation (Gannefors et al. 2005; Comeau et al. 2009, 2010; Lischka and Riebesell 2012; Fransson et al. 2016; Fig. 14.4). Future research on higher trophic levels needs to address species shifts in the fish fauna of Kongsfjorden, and the abundance of polar cod *versus* Atlantic fish species such as capelin and herring (Hop and Gjøsæter 2013; Dalpadado et al. 2016). Kittiwakes have been proposed as a representative bird species affected by climate change and pollutant impacts (Goutte et al. 2015; Tartu et al. 2015; Bustnes et al. 2017).

Globally, a "jellification" of coastal systems (an increased abundance of jellyfish species and other gelatinous zooplankton) is observed (see Gibbons and Richardson 2013), and this has also been noted in Kongsfjorden (Falk-Petersen et al. 2002; Lundberg et al. 2006). Research on the ecological functions of jellyfish (e.g. the genera *Cyanea*, *Mertensia*, *Beroë*) is urgently required, in particular with respect to their contribution to the trophic web through their impact on zooplankton standing stock and/or in providing food to the benthos.

For the indicator species mentioned, the assessment whether their responses (comprising regulatory, acclimatory or adaptive traits) can keep up with the pace of environmental change will be crucial to predictions of the future trajectory of the Kongsfjorden ecosystem. As a baseline for such studies, extended habitat and species distribution mapping are vital to improving data coverage for Kongsfjorden and enhancing the valuable information already provided by the Mareano database (www.mareano.no).

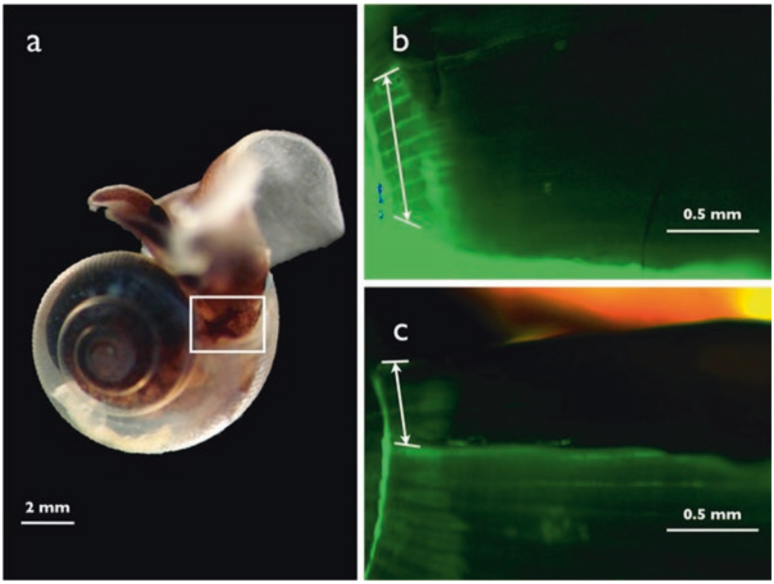

Fig. 14.4 The Arctic pteropod *Limacina helicina* **(a)**, stained with calcein (staining calcium carbonate depositions) and subsequently maintained at pH 8.09 **(b)** and 7.78 **(c)**, illustrating reduced calcification under reduced pH. The arrow indicates the linear extent of the shell over an incubation period of 5 days. (Figure from Comeau et al. 2009)

14.7 Trophic Interactions

Trophic interactions within Kongsfjorden have been characterized by Hop et al. (2002a), and divided into a benthic and pelagic food web, however, with a hitherto only fragmented understanding of their interactions (bentho-pelagic coupling processes). Research on trophic interactions needs to move towards the quantification of energy budgets and flows between the different nodes within the trophic web (Paar et al. 2016; Duarte et al., Chap. 12). In particular, the top-down control of the system with respect to the impacts of seabirds and mammals has only been addressed to a limited extent in Kongsfjorden (but see estimates in Hop et al. 2002a). With progressing Atlantification, large predators could enter the system and cause cascading effects (e.g. tuna, dolphins, killer whales, baleen whales, and Atlantic cod) with potential interaction with the Greenland shark, which is already a significant, large predator in the system (Lydersen et al. 2016). Furthermore, there is only very fragmentary knowledge about predator-parasite/pathogen-relationships (Maat and Brussard 2016). Microbial pathogens and the significance of marine viruses have been largely overlooked. As previously mentioned, our understanding of the microbial ecology and biogeochemical cycling is still in its infancy, and those need to be further explored in order to understand the effects of anticipated environmental changes on nutrient- and contaminant cycling related to ecosystem services.

Approaches in metagenomics indicate that there are many – currently unidentified – organisms that may be important in the system and which should be studied with high priority, such as viruses and fungi that infect phytoplankton, or prokaryotes that facilitate nutrient recycling (Piquet et al. 2016). Here, adaptive processes may occur through an arms race between host and pathogen, and be further modulated by environmental changes. Furthermore, classical questions in biological oceanography remain to be answered for the Kongsfjorden system (and for most other Arctic coastal systems) concerning match-mismatch situations in the dynamics of phytoplankton blooms *versus* grazer abundance (Søreide et al. 2010). Loss rates of primary producers and the fate of the organic carbon have only been determined to a limited extent for Kongsfjorden (Hop et al. 2006). This approach has to be applied for the pelagic and benthic realms, and their connections, including vertical flux of both phytoplankton and faecal pellets. The energy flow within food webs depends on how much of the organic matter is retained in the pelagic system relative to sinking to the benthos. With ocean warming and acidification, it is expected that more organic matter will be retained in the pelagic system, particularly above the mixed layer depth, because of smaller phytoplankton species, increased activity of the microbial loop, and more intense grazing by zooplankton (Wassmann et al. 2006; Riebesell et al. 2013). The complex trophic web might become rearranged as the environment changes, for instance due to key species becoming rarer (e.g. pteropods) and the arrival of new predators and grazers or their increased abundance, such as sea urchins grazing down kelp forests, and increased predation on sea urchins by eiders. A thorough analysis of current ecosystem structure and functions is thus central to facilitate ecosystem modelling, prediction of future conditions and extrapolation in a pan-Arctic perspective.

Changes in food web structure directly affect the fate of contaminants and thus their concentrations in higher organisms (Rasmussen et al. 1990; Borgå et al. 2001; Hallanger et al. 2011). Intricate equilibria exist between environmental contaminant concentrations, transport patterns, biodegradation, bioavailability, bioaccumulation and biomagnification, which are partly determined by thermodynamic principles (Mackay and Fraser 2000). Thermodynamics is therefore one key to understanding the fate and effects of contaminants, driven primarily by temperature and contaminant affinities to environmental matrixes such as sediment, water, air, ice, organisms and tissues within organisms. Climate change is thus predicted to act directly on these dynamics.

In the Arctic, higher trophic levels are dominated by migrating species, which move seasonally across large distances and inhabit different geographical regions. This means that species like seabirds, marine mammals and polar bears are only temporarily connected to a specific geographical location such as Kongsfjorden or a certain area within Kongsfjorden. These populations are consequently also only temporarily exposed to the environmental conditions or stressors specific to that location, which makes adaptive responses to local contamination unlikely. Increased release of contaminants from local land based sources (e.g. old dumps and industrial sites) to coastal waters is predicted in a warmer Arctic (Noyes et al. 2009). Several such sources have been identified on Svalbard and some in the Kongsfjord area (Granberg et al. 2017 and references therein). Lower trophic level populations including planktonic species have shown rapid adaptation to local conditions related to both contaminant and climate change factors despite a potential for extensive distribution of pelagic larvae and thus genetic exchange (Vidal and Horne 2003; Whitehead et al. 2012; Peijnenburg and Goetze 2013; Thor and Dupont 2015; De Wit et al. 2016). When a population adapts the trophic link represented by the particular species remains intact. This prevents food chains from being disrupted, but it also allows for continued food chain transfer of contaminants to higher trophic levels at polluted sites. Likewise, when populations fail to adapt the link is broken and contaminant transfer is stopped. It is thus important to understand adaptive responses on several trophic levels and to a multitude of stressors in concert. Integrated approaches where ecological and ecotoxicological aspects are considered simultaneously are needed in order to fully comprehend the impact of climate change on Arctic biological systems.

14.8 Ecosystem Modelling

Modelling will be one of the primary tools to address the impact of environmental change on the structure and function of Arctic marine ecosystems and the performance of their component species, again by using Kongsfjorden as a model site. Overall, there is a multitude of potential goals that can be achieved through modelling. These include evaluating the effects of Atlantification and glacier retreat on fjord circulation, on primary and secondary production, on potential shifts in species distribution and abundance and on community composition. Future modelling efforts should build on existing, or currently developing, models for meteorology, ice mass balance, hydrology, hydrodynamics and biogeochemistry. Ideally, a coupled physical-biogeochemical modeling platform should be built integrating most of these models/processes to properly take into account the feedbacks between the physical and the biogeochemical realms (Duarte et al., Chap. 12).

Different modeling approaches should be developed in parallel, aiming at their integration once the adequate level of maturity is reached. A powerful tool to quantify how species ranges will be altered under different climatic change scenarios are species distribution models (SDM), that statistically link spatial data of environmental variables to species presence/absence or abundance data. These models are now widely used to forecast the effects of climatic change on biodiversity (Pearson and Dawson 2003; Araujo et al. 2005; Buckley et al. 2010; Elith et al. 2010) and to guide management policies, such as to track the invasion of alien species (e.g. Kearney et al. 2008). SDMs are typically based on correlations between distributional and environmental data and, thus, they do not explore the physiological and biotic causal mechanisms underlying species distributions. This potentially limits the accuracy of predictions for species at non-equilibrium state with the physical environment, in particular non-indigenous spreading organisms. In this context, the potential applicability of physiological limits to increase the robustness of SDM projections has been suggested, as well as the need to include biological factors, but both approaches have been rarely performed to date (but see Martínez et al. 2015). These major gaps should be addressed by developing new tools to integrate knowledge on the physical and biotic mechanisms underlying species biogeography. This may partly be achieved by integrating the predictions of coupled physical-biogeochemical models (see above) with the physiology and population dynamics of target species: changes in the physical and the biogeochemical environment forecasted by the former will drive changes in species abundances and distributions.

Other approaches that may be developed in parallel and possibly feedback to those described include dynamic energy budget (DEB) models of selected species, potentially allowing prediction of changes in physiological traits in response to a changing environment and/or different pollutant loads. The coupled models mentioned above focus on biogeochemistry and lower trophic level interactions. However, there is growing interest in end-to-end models, combining physicochemical oceanographic descriptors and organisms across all trophic levels in a single modeling framework. End-to-end models result from the need to have quantitative tools for ecosystem-based management, dealing with bottom-up and top-down controls, varying in time and space as a result of global climate change among other possible environmental changes (Fulton 2010; Rose et al. 2010). Another argument in favor of this type of model is the need to properly account for the feedbacks between high trophic level organisms and biogeochemical cycles (Duarte et al., Chap. 12).

14.9 Upscaling and Comparison in a Pan-Arctic Perspective

From the foregoing, it is apparent that research conducted in the marine Kongsfjord Flagship program needs to become more integrated by also involving expertise from the other Flagship programs (Atmosphere, Cryosphere, Terrestrial Ecology). Furthermore, research conducted in Kongsfjorden must be placed in a broader geographic perspective. Identifying exchange processes between Kongsfjorden, neighboring fjords (Krossfjorden) and the open ocean will be a key task for further monitoring programs. However, the scope of research conducted in Kongsfjorden and the Ny-Ålesund Research and Monitoring facility should not be limited to the environmental setting of West Spitsbergen, but has to be placed in perspective of the entire Svalbard Archipelago and the Arctic as a whole. Thus, in a first step, research conducted at Ny-Ålesund and the other research facilities on and around Spitsbergen (Longyearbyen, Hornsund, Barentsburg, Hausgarten observatory in Fram Strait) should become more integrated, and up-scaling modelling is needed. The impacts of environmental changes are already being observed on western Svalbard. It therefore seems to be justified to regard Kongsfjorden as a harbinger for environmental changes of Arctic fjord systems in general. However, in order to enable more comprehensive predictions, comparative research on fjord systems that are currently less dramatically impacted than Kongsfjorden yet needs to be considered, for instance in northern and eastern Svalbard, Greenland, and also Hornsund (Piwosz et al. 2009). It is therefore recommended that options for establishing some research infrastructure at such sites with significantly lower Atlantic signals are evaluated.

14.10 Outlook

The Kongsfjorden system is one of the best-studied fjord systems across the entire Arctic region, with cutting-edge science being conducted at the highest international level. However, there remain important gaps in knowledge, which need to be addressed with high priority in order to give robust foundation for predictions on the future trajectory of Arctic coastal ecosystems in the face of environmental change. In addition to the above-mentioned and more specific research topics, some overarching fields for improvement have been identified. Overall, the links between the physical environment and key ecological processes need to be strengthened, in particular with respect to the drivers of primary and secondary production. The overriding factor of seasonality needs to be addressed by increasing research activity throughout the year (including winter observations and experiments) and reducing the emphasis on research at the height of summer. Perturbation experiments need to be up-scaled from individuals to consider integrated community responses, from short- to long-term incubations and manipulations, and from single to incorporate multiple drivers. Such experiments could be performed in large-scale mesocosm systems (Fig. 14.5).

It will further be crucial to expand research activities in the field of microbiology to address the fundamental role of microbes in ecological processes. These aspects are crucial to identify the losers and winners of environmental change, and how community composition and ecosystem functions will be affected. Furthermore, revealing the mechanisms of adaptation in key organisms will require intensified efforts in the rapidly developing molecular field, including population genetics, epigenetics and transcriptomics. In the longer term, consideration is required as to if and how the on-site infrastructure in Ny-Ålesund could be upgraded to facilitate such future research activities.

The diverse monitoring activities already underway generate extensive but often independent databases, and greater integration is required. A first, but critical, step forward would be to provide a facilitated and integrated accessibility to existing knowledge, to allow available data and information to be obtained more easily through a single source, rather than being scattered in various data repositories. Future research on the links between the physical and chemical environment and key ecological processes will benefit from improved access to existing datasets.

Ny-Ålesund and its surrounding area provide a unique study site to document and understand ongoing changes and to predict future Arctic ecosystem trajectories. The long research background across multiple systems (atmosphere, glaciers,

Fig. 14.5 One of the large-scale pelagic mesocosms of the EPOCA (European Project on Ocean Acidification) experiment 2010 deployed in Kongsfjorden. (Photo: J.-P. Gattuso)

tundra ecosystems) and multidisciplinary knowledge on Kongsfjorden and adjacent marine systems is a great strength and resource that is available nowhere else in the Arctic. It is important and increasingly urgent to use this knowledge to give foundation to robust and reliable predictions. The research carried out here must become increasingly multidisciplinary, encompassing climate, physics, chemistry and response of the biota. The approach must be integrative, including key polar and boreal species, populations and communities in order to make predictions about the continued delivery of ecosystem services. This special edition of studies on the Kongsfjorden ecosystem represents an important contribution towards the achievement of this goal.

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