



**HAL**  
open science

## **Drivers of Change in Arctic Fjord Socio-ecological Systems: Examples from the European Arctic**

Robert Schlegel, Inka Bartsch, Kai Bischof, Lill Rastad Bjørst, Halvor Dannevig, Nora Diehl, Pedro Duarte, Grete Hovelsrud, Thomas Juul-Pedersen, Anaïs Lebrun, et al.

► **To cite this version:**

Robert Schlegel, Inka Bartsch, Kai Bischof, Lill Rastad Bjørst, Halvor Dannevig, et al.. Drivers of Change in Arctic Fjord Socio-ecological Systems: Examples from the European Arctic. Cambridge Prisms: Coastal Futures, 2023, pp.1-49. 10.1017/cft.2023.1 . hal-03959397

**HAL Id: hal-03959397**

**<https://cnrs.hal.science/hal-03959397v1>**

Submitted on 2 Nov 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Review

**Cite this article:** Schlegel R, Bartsch I, Bischof K, Bjørst LR, Dannevig H, Diehl N, Duarte P, Hovelsrud GK, Juul-Pedersen T, Lebrun A, Merillet L, Miller C, Ren C, Sejr M, Søreide JE, Vonnahme TR and Gattuso J-P (2023). Drivers of change in Arctic fjord socio-ecological systems: Examples from the European Arctic. *Cambridge Prisms: Coastal Futures*, 1, e13, 1–18 <https://doi.org/10.1017/cft.2023.1>

Received: 27 October 2022

Revised: 05 January 2023

Accepted: 05 January 2023

### Keywords:

Arctic fjords; climate change; social science; marine science; socio-ecological processes


### Author for correspondence:

Robert Schlegel,  
Email: [robert.schlegel@imev-mer.fr](mailto:robert.schlegel@imev-mer.fr)

© The Author(s), 2023. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.



# Drivers of change in Arctic fjord socio-ecological systems: Examples from the European Arctic

Robert Schlegel<sup>1</sup> , Inka Bartsch<sup>2</sup>, Kai Bischof<sup>3</sup>, Lill Rastad Bjørst<sup>4</sup>, Halvor Dannevig<sup>5</sup>, Nora Diehl<sup>3</sup>, Pedro Duarte<sup>6</sup>, Grete K. Hovelsrud<sup>7</sup>, Thomas Juul-Pedersen<sup>8</sup>, Anaïs Lebrun<sup>1</sup>, Laurène Merillet<sup>9,10,11</sup>, Cale Miller<sup>1,12</sup>, Carina Ren<sup>4</sup>, Mikael Sejr<sup>13</sup>, Janne E. Søreide<sup>14</sup>, Tobias R. Vonnahme<sup>8</sup> and Jean-Pierre Gattuso<sup>1,15</sup>

<sup>1</sup>Laboratoire d'Océanographie de Villefranche, Sorbonne University, CNRS, Villefranche-sur-mer, France; <sup>2</sup>Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany; <sup>3</sup>Marine Botany, University of Bremen & MARUM, Bremen, Germany; <sup>4</sup>Center for Innovation and Research in Culture and Living in the Arctic, Aalborg University, Aalborg, Denmark; <sup>5</sup>Western Norway Research Institute, Sogndal, Norway; <sup>6</sup>Norwegian Polar Institute, Fram Centre, Tromsø, Norway; <sup>7</sup>Nordland Research Institute, Bodø, Norway; <sup>8</sup>Greenland Climate Research Centre, Greenland Institute of Natural Resources, Nuuk, Greenland; <sup>9</sup>Institute of Marine Research, Bergen, Norway; <sup>10</sup>Bjerknes Center for Climate Research, Bergen, Norway; <sup>11</sup>Marine Ecosystems Modelling Group, Collecte Localisation Satellite, Ramonville Saint Agne, France; <sup>12</sup>Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands; <sup>13</sup>National Environmental Research Institute, Aarhus University, Silkeborg, Denmark; <sup>14</sup>The University Centre in Svalbard, Longyearbyen, Norway and <sup>15</sup>Institute for Sustainable Development and International Relations (IDDRI-Sciences Po), Paris, France

## Abstract

Fjord systems are transition zones between land and sea, resulting in complex and dynamic environments. They are of particular interest in the Arctic as they harbour ecosystems inhabited by a rich range of species and provide many societal benefits. The key drivers of change in the European Arctic (i.e., Greenland, Svalbard, and Northern Norway) fjord socio-ecological systems are reviewed here, structured into five categories: cryosphere (sea ice, glacier mass balance, and glacial and riverine discharge), physics (seawater temperature, salinity, and light), chemistry (carbonate system, nutrients), biology (primary production, biomass, and species richness), and social (governance, tourism, and fisheries). The data available for the past and present state of these drivers, as well as future model projections, are analysed in a companion paper. Changes to the two drivers at the base of most interactions within fjords, seawater temperature and glacier mass balance, will have the most significant and profound consequences on the future of European Arctic fjords. This is because even though governance may be effective at mitigating/adapting to local disruptions caused by the changing climate, there is possibly nothing that can be done to halt the melting of glaciers, the warming of fjord waters, and all of the downstream consequences that these two changes will have. This review provides the first transdisciplinary synthesis of the interactions between the drivers of change within Arctic fjord socio-ecological systems. Knowledge of what these drivers of change are, and how they interact with one another, should provide more expedient focus for future research on the needs of adapting to the changing Arctic.

## Impact statement

It is now well documented that the Arctic, the northern polar region of our planet, is changing rapidly. It is likely that as soon as 2050 the Arctic Ocean will be largely ice-free over the summer. The consequences of this are vast and merit our effort to discern how we may best adapt to the coming changes that a melted Arctic cryosphere will mean for human habitation across the globe. Within the European Arctic (i.e., Greenland, Svalbard, and Northern Norway), fjord ecosystems are particularly important because they serve as loci for ecosystem functioning and human settlement. In this transdisciplinary review, we synthesise the knowledge that exists for the socio-ecological systems within European Arctic fjords. It is necessary to review the complete scope of knowledge on these systems for the past, present, and possible future projections because as the climate changes, the interactions within these systems will themselves likely change. Meaning that European Arctic fjords will experience both externally and internally driven pressures. The 14 key drivers of change within European Arctic fjords are identified here and classified into five categories. The scope of these relationships, and how they may change across the European Arctic, are discussed. The aim of this review is to provide future research projects with a more complete foundation upon which they can orient their research questions for how best to adapt Arctic fjord socio-ecological systems to the changing climate.

## Introduction

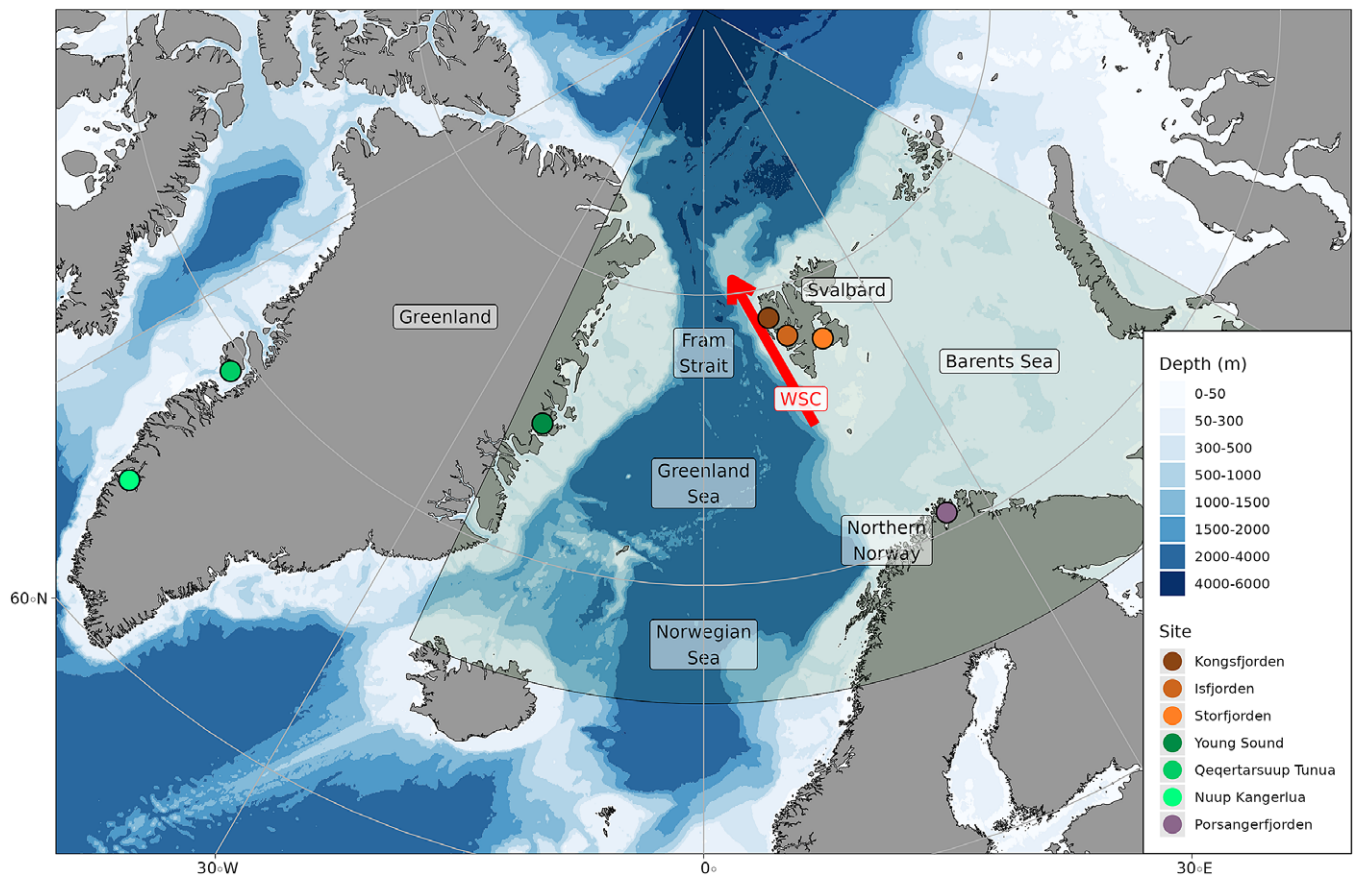
Fjord systems are characterised as deep narrow inlets of water, usually created by glaciers and sometimes harbouring a sill, a physical barrier that creates inner and outer deep areas. These systems are of particular importance in Greenland, Svalbard, and Northern Norway; hereafter referred to as the European Arctic (25°W–60°E and 66°N–90°N; Figure 1), because they host highly productive ecosystems that may be exploited by humans (e.g., aquaculture; Hermansen and Troell, 2012; Aanesen and Mikkelsen, 2020), act as carbon sinks (Smith *et al.*, 2015; Cui *et al.*, 2022), and provide suitable areas for spawning grounds and nurseries (e.g., Spotowitz *et al.*, 2022). These regions are also well studied, with the necessarily large body of attendant literature required for the following review (see also Cottier *et al.*, 2010).

The European Arctic is not one monolithic entity. Indeed, there are many differences between the fjords found throughout the region and therefore a wide range of possible interactions between the forces responsible for the changes therein are possible. The three study regions (and sites therein) focussed on to frame the review of these differences are Greenland (Qeqertarsuup Tunua, Nuup Kangerlua, and Young Sound), Svalbard (Kongsfjorden, Isfjorden, and Storfjorden), and Northern Norway (Porsangerfjorden). Where relevant to the text, additional sites are also mentioned. While all are classified geographically as Arctic, many fjords in Northern Norway lack sea ice and glaciers altogether, and the west coast of Svalbard is in the process of

transitioning from Arctic temperatures to boreal (Hop and Wiencke, 2019). It is the fjords along the east coast of Greenland that have persisted as cold Arctic, for the time being.

The terminology used throughout the literature to describe the processes that cause changes in Arctic fjords is varied; therefore, we have decided to refer to them here as *drivers*: “Any natural- or human-induced factor that directly or indirectly causes a change in a system” (*sensu* Möller *et al.*, 2022). There is a general hierarchy to the scale and directional forcing of these drivers; however, there are many feedback processes between them and many non-linear relationships. For example, warming induces a loss of sea ice, increasing light availability, which stimulates primary production, thereby promoting the progressive abundance of zooplankton to fish to birds, the overall species richness of the fjord, and the ecosystem services that provide to the human settlement(s) along the fjord. Some drivers, especially those in the biology category, tend to drive changes within themselves, rather than impacting drivers in other categories.

The drivers are classified into five categories and separated into sections below: cryosphere, physics, chemistry, biology, and social. Subsections for each driver provide a review of the current state of knowledge, which are followed by a summary of the present and future uncertainties for the category. The focus of the summaries varies between categories, reflecting the differences in the scientific sub-disciplines of the natural and social sciences. Any references within the text to a specific subsection are



**Figure 1.** The extent of the European Arctic (25°W–60°E and 66°N–90°N; *sensu* Copernicus Marine Environment Monitoring Service) highlighted here *via* a polygon, with the seven focal sites for this review paper shown as coloured points grouped into the regions: Svalbard (brown), Greenland (green), and Northern Norway (purple). Areas referenced in the text are indicated with black labels. The general position of the West Spitsbergen Current (WSC) is shown with a red arrow.

made via the name of the section (i.e., section “Seawater temperature”). The review finishes with a discussion of the relationships between the categories and their drivers in the past, present, and future before providing concluding remarks. An analysis of the *in situ* data available for the key drivers reviewed below is available in a companion paper (Schlegel and Gattuso, *in review*).

## Cryosphere drivers

### Sea ice

Sea ice is a globally unique ecosystem that hosts a diversity of endemic flora and fauna, and whose presence in fjords provides an array of services to society (Eamer et al., 2013). Indeed, the presence of sea ice, or lack thereof, forms the basis through which many of the drivers in this review interact with one another.

The primary conditions for the formation of sea ice are air temperature and salinity (Pavlov et al., 2013), but other complex factors also play an important role. Wind stress can fragment forming sea ice and prevent water stratification, freshwater inputs allow freezing at less negative temperatures, and snow cover can insulate against colder air temperatures which prevents further growth (Merkouriadi et al., 2017). The amount of sea ice formation and its location in late winter and spring determines the bottom temperature over the shelf when melted water is mixed with bottom water by storms (Hunt et al., 2011), which has implications for benthic life (see section “Biomass”).

Large pulses of warm and salty Atlantic water (AW) have been increasing in the fjords along the North/West Svalbard Archipelago over the last three decades (Skogseth et al., 2020). The combination of AW with increased air temperatures (e.g., winter trend of  $+3^{\circ}\text{C dec}^{-1}$ ; Maturilli et al., 2019) have severely restricted sea ice formation (Kongsfjorden: Cottier et al., 2007; Tverberg et al., 2019; Isfjorden: Muckenhuber et al., 2016; Skogseth et al., 2020; Gronfjorden: Zhuravskiy et al., 2012). Pronounced warming in the temperature of AW inflow (see section “Seawater temperature”) itself has been recorded during the summer from 1912 to 2019 (Bloszkina et al., 2021).

Unlike North/West Svalbard, most of Greenland is not exposed to rapidly warming ocean currents. The tidewater glaciers (see section “Glacier mass balance”) of Nuup Kangerlua (W Greenland) introduce large amounts of icebergs to the fjord, creating a dense ice melange stretching over several kilometres and freezing together in winter (Mortensen et al., 2020). As of this writing, there was a scarcity of *in situ* time series measuring sea ice cover for West Greenland, but satellite measurements (NSIDC, 2022) from 2006 to 2020 show trends of increasing cover within fjords and embayments (Schlegel and Gattuso, *in review*). The ice-free season in Young Sound (E Greenland) has been increasing, primarily driven by later formation of sea ice in autumn, accompanied by increased interannual variability since 2000 (Middelbo et al., 2019). On the southern border of the Barents Sea, Porsangerfjorden (N Norway) does not freeze over in the winter, with only the very inner reaches of the fjord occasionally covered by seasonal sea ice (Petrich et al., 2017).

### Glacier mass balance

Glaciers are mountainous bodies of land-borne ice that have formed and persisted over millennia. Glaciers have such a dominating downstream effect on fjords that the ecosystems therein are

generally defined by whether there is a glacier present and, if there is, whether it is land-terminating or marine-terminating (Lydersen et al., 2014).

Most of the large reservoirs of glacial ice in the Arctic, including the Greenland ice sheet (GrIS), are losing mass by surface melt, basal ice melt, and solid ice discharge at marine-terminating glacier fronts (Kochtitzky and Copland, 2022). The rate of this loss is projected to double by 2100 (Geyman et al., 2022). While the GrIS gained mass between 1972 and 1980 ( $+47 \pm 21 \text{ Gt yr}^{-1}$ ), since 1980 the GrIS has lost mass at an accelerating rate until a peak of  $286 \pm 20 \text{ Gt yr}^{-1}$  between 2010 and 2018 (Mouginot et al., 2019). This process of ice loss (in both solid and liquid form) has also been well documented for fjord glaciers on Svalbard, such as those in Kongsfjorden (Schuler et al., 2020).

### Terrestrial runoff

The Arctic Ocean holds ca. 1% of the world’s seawater, but receives 11% of global freshwater runoff (Shiklomanov, 1997). Meltwater from land-terminating glaciers enters the fjord at the surface, resulting in strong stratification that drives estuarine circulation. This also increases turbidity (Konik et al., 2021), which may have consequences for benthic life (see section “Biomass”). At marine-terminating glaciers, freshwater input comes mostly from below as subglacial discharge, often several hundred metres below the sea surface (Hopwood et al., 2020). Due to its low density, the subglacial meltwater can drive upwelling, thereby resupplying nutrient-rich but potentially warmer deep water to shallower depths (Meire et al., 2016; Hopwood et al., 2020) and stimulating primary production (see section “Primary production”; Hopwood et al., 2020). Icebergs, which originate from the calving of marine-terminating glaciers, can add freshwater at the surface, increasing stratification. As the cryosphere warms, glaciers do not melt at a linearly increasing rate, rather the melt rate eventually slows as they lose mass (Huss and Hock, 2018). On Svalbard, glacial meltwater is already decreasing due to mass loss below a critical tipping point (Nowak et al., 2021).

In addition to the melting of glaciers, river runoff is a major input of freshwater into Arctic fjords. River runoff is similar to land-terminating glacier melt in that it decreases the penetration of light, surface heating, stratification, oxygen content, nutrient input, and finally primary production (Wassmann et al., 1996; Aksnes et al., 2009). However, it differs in that the content of terrigenous material in Arctic rivers is highly variable and depends on the catchment type (Slagstad et al., 2015; Frigstad et al., 2020). Glaciers and ice sheets can dominate catchments in Greenland, Canada, Alaska, and archipelagoes such as Svalbard and Franz Joseph Land, but tundra dominates on the Eurasian and American continents, where catchments extend beyond the Arctic region. The organic carbon content in the large Eurasian rivers can be 10-fold higher than in glacial meltwater, partly reflecting thawing permafrost (Wild et al., 2019). The nitrogen input (see section “Nutrients”) from land (rivers and eroding coasts combined) is also substantial and has been estimated to sustain a third of the net primary production (see section “Primary production”) of the Arctic Ocean (Terhaar et al., 2021).

### Summary

The cryosphere, a defining characteristic of the Arctic (Pavlova et al., 2019), is vanishing at an alarming rate (Meredith et al., 2019), driven primarily by warming air and seawater temperatures (see section “Seawater temperature”; Isaksen et al., 2022). There is also a



robust linear relationship between the increase in atmospheric CO<sub>2</sub> and the decrease in sea ice extent (Stroeve and Notz, 2018). Many West Svalbard fjords are already experiencing increasingly longer sea ice-free periods (Dahlke *et al.*, 2020), and given the current emissions trajectory most Arctic fjords will very likely follow this trend in the near future (Meredith *et al.*, 2019). Sea ice volume over the entire Arctic has already diminished by 75% (Overland *et al.*, 2019). Within the Svalbard fjords, sea ice has reduced by 50% on average from the periods 1973–2000 to 2005–2019, with a further reduction down to ca. 90% in the next 10 to 20 years (Urbański and Litwicka, 2022).

Marine-terminating glaciers in the northern hemisphere have been losing mass at such unprecedented rates that 7% of them have transitioned to land-terminating over the last 20 years (Kochtitzky and Copland, 2022). Such a change in glacier status restructures the entire local ecosystem and its services. Moreover, it is worth noting that rapid glacial melt may also be driving further increases in atmospheric CO<sub>2</sub> (Wadhwa *et al.*, 2019; Christiansen *et al.*, 2021).

Precipitation rates in the Arctic have been increasing, and are projected to continue to increase, and by the end of the century (except Greenland) the majority of this precipitation is projected to be rain rather than snow (Bintanja and Andry, 2017). Indeed, from 1979 to 2009, the average trend throughout the Arctic for snow days per year has been  $-2.49$  days per decade (Liston and Hiemstra, 2011). This has resulted in increases of river runoff (Mankoff *et al.*, 2020), associated with a peak date occurring earlier in the calendar year (Holmes *et al.*, 2018). This increasing discharge intensifies the freshwater cycle and increases the connectivity between land and sea (Hernes *et al.*, 2021) through the increased delivery of nutrients, organic matter, sediments, and contaminants. This is especially pronounced for Eurasian rivers (Shiklomanov *et al.*, 2021). Within Arctic fjords specifically, we see that this process is beginning to affect the surface waters in Greenland fjords (Paulsen *et al.*, 2017), and has a larger impact on Svalbard fjords (Wiedmann *et al.*, 2016; Santos-Garcia *et al.*, 2022) and their adjacent ecosystems (Delpech *et al.*, 2021), with an even greater effect on northern Norwegian fjords (McGovern *et al.*, 2020).

## Physics drivers

### Seawater temperature

One of the primary controlling factors of the extent of the Arctic cryosphere is the earth's temperature (Meredith *et al.*, 2019). This also has a dominating effect on the presence of species thriving in a given location (see section "Species richness"; Willis *et al.*, 2006; Vihtakari *et al.*, 2018). It has been established that the rate of warming in the air is four times more rapid in the Arctic than elsewhere (Rantanen *et al.*, 2022). However, changes in seawater temperature are not always linear, nor are they uniform in scale temporally or spatially. Rather, disturbances may materialise as non-linear phenomena, such as shifts of ocean currents or the ephemeral appearance of extreme ocean temperature events.

AW, which is warmer and more nutrient-rich than Arctic waters, is circulated to Svalbard via the Fram Strait as part of the West Spitsbergen Current (WSC) where it forms much of the bottom layer of the West Svalbard fjords in summer. However, starting in 2006, AW has begun occupying much more of the water column (Tverberg *et al.*, 2019; Skogseth *et al.*, 2020), a process referred to as "Atlantification". This occurs in part due to changes to patterns of the wind stress field in the area (Pavlov *et al.*, 2013) and the wandering of large-scale ocean currents. In addition to

increasing temperatures, changes to the inflow of AW are so critical because this water body is the main nutrient contributor (see section "Nutrients") to the European Arctic (Duarte *et al.*, 2021).

In contrast to the warming in Western Svalbard, driven largely by increased AW temperature, Hanna and Cappelen (2003) observed a significant cooling trend in southern Greenland seawater surface temperatures in eight meteorological stations from 1958 to 2001 ( $-1.22^{\circ}\text{C}$  in 44 years), while the rest of the world was warming ( $+0.55^{\circ}\text{C}$  in 44 years). They suggested that this cooling could be attributed to a positive phase in the North Atlantic Oscillation (NAO), which leads to northerly winds over Greenland pushing cold air masses down to the south, and was highly positively correlated ( $r = 0.76$ ) to the historic seawater temperature trend (Hanna and Cappelen, 2003). However, after 2001, southern Greenland air and seawater temperatures began increasing and a more recent study by Jiang *et al.* (2020) found that in addition to climate indices, such as the NAO, that greenhouse gas concentrations are key drivers for seawater temperature changes in Greenland.

### Salinity

The salinity of seawater creates bounding limits for the presence of many, but not all, marine species found throughout the Arctic (see section "Species richness"; Węśławski *et al.*, 2011) and salinity changes can have impacts on the trophic structure of local fjord ecosystems (Bridier *et al.*, 2021). Changes in salinity also induce changes in total alkalinity, a key parameter of the carbonate system (see section "Carbonate system"). In general, fjords have three distinct strongly stratified water masses (Stigebrandt, 2012):

- 1) *Surface water*: generally, the lowest salinity due to local freshwater supply.
- 2) *Intermediate water*: mirrors the stratification of adjacent coastal waters but with some phase delay.
- 3) *Basin water*: rests below the sill level and contains the densest waters, which may enter from outside the fjord (*NB*: not all fjords have a sill).

The increasing rates of rainfall, glacial melt, and river discharge into fjords (see section "Terrestrial runoff") may hypothetically impact the thickness and extent of the low-salinity layer in their inner regions so greatly that it slows the rate of the overturning circulation and deep-water renewal (Bianchi *et al.*, 2020). High precipitation in temperate fjords can create a persistent low-salinity layer in surface waters (Gillibrand *et al.*, 1995; Gibbs, 2001) that accentuates salinity stratification and limits phytoplankton access to nutrient-rich saline bottom waters (see section "Primary production"), except during wind-induced mixing episodes (Sakshaug and Mykkestad, 1973; Goebel *et al.*, 2005; Bianchi *et al.*, 2020). A decrease in salinity of the surface water (0–50 m) in Young Sound (E Greenland) and on the adjacent shelf has been observed (Sejr *et al.*, 2017). The lower density of the freshening surface means that bottom water in the deeper part of the fjord is isolated from exchange with shelf water (Boone *et al.*, 2018).

### Light (PAR and UV)

The light available throughout the water column, here specifically photosynthetically active radiation (PAR), is a key driver of the presence and composition of benthic and pelagic phototrophic communities due to their need to photosynthesise (see section "Biomass"). Assuming the availability of necessary nutrients

(see section “Nutrients”), this means that light plays a major role in the global carbon cycle by controlling the geographical and depth distributions of primary producers (see section “Primary production”; Gattuso et al., 2020). In the Arctic, three processes linked to climate change that affect the penetration of light into the water column have been well researched:

- 1) Current and future projected sea ice loss (see section “Sea ice”) creates longer sea ice free periods that allow for greater penetration of light (Pavlov et al., 2019).
- 2) Projected increases in freshwater input (see section “Terrestrial runoff”) reduce light penetration in the coastal zone by increasing turbidity via the delivery of particulate and dissolved organic matter (DOM; Frigstad et al., 2020; Nowak et al., 2021).
- 3) If summer cloudiness increases as the Arctic warms, it will decrease incident PAR above the sea surface (Bélangier et al., 2013).

Largely due to increased freshwater inputs, most fjords in Western Svalbard (1997–2019; Konik et al., 2021), and many fjords on mainland Norway (1935–2007; Aksnes et al., 2009) have experienced a regime shift towards darker water, a phenomenon referred to as “darkening” or “browning”. It is hypothesised that this darkening of water may cause a reduction in primary production (see section “Primary production”; Aksnes et al., 2009). Areas distant from sources of freshwater input (e.g., glaciers and rivers; section “Terrestrial runoff”) could, however, experience an increase in light penetration as is occurring in the open Arctic Ocean where reduced sea ice leads to increased PAR and thereby primary production (see section “Primary production”; Arrigo and van Dijken, 2011).

For atmospheric radiation conditions, further stratospheric ozone loss will result in a higher UV-B burden in the Arctic (Manney et al., 2011). The impact of UV-B on benthic communities in Arctic fjords has been extensively studied; however, the results with respect to the ecological implications are still somewhat inconclusive (see Bischof and Steinhoff, 2012, for review). UV-B may negatively affect biological processes in shallow waters, as experimentally tested for the germination of seaweed spores (Wiencke et al., 2006). However, under natural field conditions, kelp spores germinating under parental canopies might not be exposed to harmful UV-B, and it remains questionable to what extent biologically significant UV-B fluxes will propagate into subtidal communities (i.e., deeper than 10 m; Laeseke et al., 2019).

## Summary

Models show that a global temperature rise of +2°C will translate to +4°C of warming in the air temperature of the Arctic (Overland et al., 2019), with the worst-case scenario showing +15°C of winter air warming by 2100 (Overland et al., 2019). One must also consider the disproportionately larger surface heat fluxes into the Arctic (Bischof et al., 2019) that may inhibit the stabilisation of the global climate even if an effective emissions reduction strategy is implemented (Overland et al., 2019). There is therefore a high level of certainty that the rate of increasing seawater temperature will further accelerate in the future (Meredith et al., 2019).

Rapidly increasing seawater temperatures appear to be accelerating the phenomenon of Atlantification, a process that will potentially decrease the density differences between polar surface water and the AW that rest below, which in turn may lead to more mixing and larger ocean heat fluxes towards the surface (Polyakov et al., 2020). The changes to the salinity itself may also cause trophic

restructuring of the ecosystems throughout many Arctic fjords (see section “Biomass”), with inherent knock-on effects to the human societies that are structured around present ecosystem services (see section “Fisheries”).

Less clear than the increases in temperature and changes in salinity are the changes to light penetration in Arctic fjords. While it appears evident that light penetration in the open Arctic Ocean will increase over time (Pavlov et al., 2019), it is still unclear whether or not this will hold true within fjords. While sea ice is melting rapidly within most fjords, there is also an increased rate of turbid water runoff. So while there is a longer period in which light may contact the sea surface, it is becoming more difficult for light to penetrate these waters. This is an area of investigation that still requires much research (e.g., Walch et al., 2022).

## Chemistry drivers

### Carbonate system

Increased atmospheric carbon dioxide (CO<sub>2</sub>) globally raises the partial pressure of CO<sub>2</sub> in seawater (*p*CO<sub>2</sub>). The ocean has absorbed >25% of anthropogenic CO<sub>2</sub> emissions since the industrial revolution (Friedlingstein et al., 2022), which moderates climate change at the cost of ocean acidification, a process that describes the increase in dissolved inorganic carbon (DIC), the concomitant decline of pH, and the saturation state of calcium carbonate (CaCO<sub>3</sub>; Gattuso and Hansson, 2011). The projected decrease in pH and CaCO<sub>3</sub> saturation state will lead to undersaturation of surface waters with respect to aragonite-type CaCO<sub>3</sub> in the entire Arctic Ocean by 2040 (Steinacher et al., 2009). This undersaturation has already been observed *in situ* throughout many Arctic Seas from 2008 onwards (e.g., Zhang et al., 2020; Fransner et al., 2022). This is due in part to the decrease of salinity (see section “Salinity”), which lowers the buffering capacity of these systems (Qi et al., 2022). Aragonite undersaturation has negative consequences on ecologically important aragonite-shelled organisms in Arctic fjords (see section “Biomass”; Comeau et al., 2012), which may have large knock-on consequences for a number of other taxa (see section “Species richness”; Bednaršek et al., 2021; Niemi et al., 2021).

### Nutrients

Besides light, macronutrients (e.g., nitrate [NO<sub>3</sub>], nitrite [NO<sub>2</sub>], ammonium [NH<sub>4</sub>], phosphate [PO<sub>4</sub>], silicate [SiO<sub>4</sub>], and iron [Fe]) are the key drivers of primary production (see section “Primary production”). Within the euphotic zone, the shallower depths where light levels are sufficient for photosynthesis, nutrients are typically the limiting factor for primary production (generally used up by algae, depending on the season). Organic matter sinking out of the euphotic zone is slowly degraded and nutrients are regenerated; however, these nutrients stay at depth, unavailable for primary production, unless deep water is mixed up to the surface (see section “Salinity”; Valiela, 2015). The process of deep water mixing is particularly important because nitrogen may enter fjords via organic matter that is not directly available to primary producers (see section “Primary production”) and must be degraded by bacteria and archaea into bioavailable forms while at depth (e.g., NO<sub>3</sub> and/or NH<sub>4</sub>; Valiela, 2015).

Four well-studied processes that can bring deep nutrient-rich water masses to the euphotic zone are the following (Cottier et al., 2010):

- 1) melting at the marine-terminating face of glaciers that drives local upwelling (see section “Glacier mass balance”),
- 2) reduced stratification of the water column in winter, typically weakened by decreased meltwater runoff (see section “Terrestrial runoff”), allows deeper mixing of the water column by physical forces (e.g., winds and tides),
- 3) surface currents exiting fjords over steep slopes (e.g., shelf breaks), and
- 4) icebergs melt from below driving local upwelling similar to marine-terminating glacier fronts (Moon *et al.*, 2018).

Glacial meltwater is one of the primary sources of nutrient input into fjords and may be rich in  $\text{SiO}_4$  and Fe depending on bedrock geochemistry (Halbach *et al.*, 2019; Hopwood *et al.*, 2020).  $\text{PO}_4$  may also be introduced by meltwater where it is quickly scavenged (Hopwood *et al.*, 2020). Land-terminating glaciers may provide even higher levels of nutrients and organic matter in systems with high levels of snowmelt and/or soil/permafrost leaching, which has large implications for local fjord ecology and adjacent coastal communities (Harris *et al.*, 2018; Kotwicki *et al.*, 2018; McGovern *et al.*, 2020; Delpech *et al.*, 2021).

River runoff is another primary input, with nutrient and organic loads that tend to be similar to neighbouring glaciers. A consideration for riverine inputs that differ from glacial is the increased nutrient load attributed to wastewater from human activities (Tuholske *et al.*, 2021). In Isfjorden, for example, where one may find the largest human settlement on Svalbard, nutrient concentrations in river runoff (i.e.,  $\text{NO}_2 + \text{NO}_3$ ) can be 12-fold higher than in the uninhabited regions of the fjord (McGovern *et al.*, 2020). Very rapid and sudden precipitation events may also lead to high-nutrient freshwater plumes in fjords, but whose effects on local ecosystems tend to remain very localised (McGovern *et al.*, 2020).

## Summary

If the concentration of  $\text{CO}_2$  in the atmosphere keeps increasing as it has done in past decades (IPCC, 2021), the impacts of the seawater  $\text{CO}_2$  system on shell-forming organisms will almost certainly become more severe. The weakening or possible local extinction of these organisms may lead to an entire trophic restructuring of ecosystems both within and adjacent to fjords due to the trophic importance of these organisms to small pelagic fish and birds (see section “Biomass”; Bednaršek *et al.*, 2021).

Nutrient loading of Arctic fjord waters is likely to increase in the future due to higher rates of river runoff, glacial melt (see section “Terrestrial runoff”; Santos-Garcia *et al.*, 2022), and precipitation (Frigstad *et al.*, 2020), in combination with increased human activities. Therefore, the biogeochemical properties of fjords are projected to change apace with the climate (McGovern *et al.*, 2020). As more glaciers transition from marine- to land-terminating, their fjords will have fewer methods through which deep water mixing resupplies nutrients to the surface. The loss of icebergs caused by the change in a glacier’s status may reduce the transport of nutrients further out towards its mouth, resulting in a tighter concentration at the points of entry for freshwater runoff. These reductions to nutrient input may be offset by increased rates of terrestrial runoff, another point of research whose future outcome remains uncertain.

Lastly, and perhaps most dramatically, future warming may result in a winter melt, thereby preventing the normal seasonal recirculation of nutrients from deep waters and creating a situation where the nutrients in sinking biological matter are no longer

resupplied to fjord ecosystems in the euphotic zone. Taken all together, the dramatic warming in the Arctic will likely lead to many fjords losing three of their four primary processes of deep water recirculation. The remaining process, surface currents exiting fjords, may become stronger due to increased river runoff.

## Biology drivers

### Primary production

Primary productivity in Arctic fjord ecosystems is a foundational measure of the trophic energy available in an ecosystem and has extreme interannual variability due to the multitude of non-linear interactions between physicochemical processes in nearshore systems (Hopwood *et al.*, 2020). Increasingly frequent warm water intrusions and glacial melt are affecting the inter-annual duration and stability of the pycnocline (i.e., surface salinity; section “Salinity”) and biological pump (i.e., deep water upwelling; section “Nutrients”), thereby modifying phytoplankton bloom periods and their species composition (see section “Species richness”; Piwosz *et al.*, 2009; Wiencke and Hop, 2016).

Arctic fjord primary production is heavily seasonal, with the highest levels typically reached during phytoplankton bloom events in spring and occasionally autumn. The spring bloom occurs when the nutrients supplied by the deep mixing in winter (see section “Nutrients”) are joined by the sufficient light availability of the spring (see the section “Light (PAR and UV)”). A second bloom may develop in late summer when upwelling driven by marine-terminating glacial melt (see section “Nutrients”) supplies enough additional nutrients to the euphotic zone (Juil-Pedersen *et al.*, 2015). The separate autumn bloom is driven by the seasonal weakening of water column stratification that leads to an increased deep water mixing while light is still sufficient for photosynthesis (e.g., Eilertsen *et al.*, 1989).

Even though primary production is undoubtedly an important ecological factor in the shallow margins of Arctic fjord systems, with only a few exceptions, it has not been comprehensively quantified. In Kongsfjorden (W Spitsbergen), the loss of sea ice (see section “Sea ice”) has led to changes in spring bloom dynamics, with higher light levels in the water column (see section “Light (PAR and UV)”) earlier in the year driving earlier spring blooms with higher biomass and diversity (see section “Species richness”; Hegseth and Tverberg, 2013). Pelagic primary productivity in this fjord has been estimated across multiple studies conducted over a 20-year period (1979–1999) and ranges from 4 to  $180 \text{ mg C m}^{-2} \text{ yr}^{-1}$  with no clear predictive trend or continuity (Hop *et al.*, 2002 and references therein; Duarte *et al.*, 2019). Primary production in Nuup Kangerlua (W Greenland) follows a recurring seasonal pattern with the highest production and biomass during the spring bloom or late summer (Juil-Pedersen *et al.*, 2015; Krawczyk *et al.*, 2018). Primary production in Godthåbsfjorden (Nuup Kangerlua, W Greenland) has smaller interannual variability with ranges between 84.6 and  $139.1 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Juil-Pedersen *et al.*, 2015).

### Biomass

Phytoplankton biomass is directly related to primary production (see section “Primary production”); however, loss of this biomass can be related to grazing, viral or fungal lysis (e.g., Hassett *et al.*, 2019), or sedimentation. Thus, high primary production does not necessarily lead to high phytoplankton biomass. Due largely to Atlantification (see section “Salinity”), a significant northward



advance of temperate phytoplankton and changes of the planktonic organism size distribution towards smaller organisms (i.e., pico- and nanoplankton) have been observed (Oziel et al., 2017; Neukermans et al., 2018; Konik et al., 2021). This means that climate change may be mediating trophic shifts in fjord ecosystems, a process referred to as “borealisation”.

The biomass of zooplankton communities in Arctic fjords relies heavily on the seasonal availability of highly productive phytoplankton (Vereide, 2019), making zooplankton one of the main pathways connecting pelagic primary production (see section “Primary production”) to larger predators. Zooplankton biomass is also affected by local scale perturbations in temperature (see section “Seawater temperature”), salinity (see section “Salinity”), and light availability (see section “Light (PAR and UV)”), all of which are in flux due to the changing climate. The borealisation of West Svalbard fjords, due to Atlantification, is already affecting seabirds via its impacts on zooplankton (Descamps et al., 2022).

The shifting of the large ocean currents in the Arctic will have widespread effects on pelagic macrozooplankton (i.e., copepods, euphausiids, and amphipods). It was found that the warming occurring in the Kongsfjorden ecosystem (W Svalbard), largely due to increased AW inflow (see section “Seawater temperature”), is having a positive effect on the abundance of euphausiids and amphipods (Dalpadado et al., 2016), which are key prey for target fishery species (see section “Fisheries”) such as capelin and polar cod (Dalpadado et al., 2016). As the borealisation of the fjords along Western Svalbard continues, it may alter the population dynamics of key prey macrozooplankton species so dramatically that the changes may be tracked by monitoring the diets of local black-legged kittiwakes (Vihtakari et al., 2018).

Although macrophytobenthos (seaweeds and seagrass) are mostly restricted to a narrow spatial stretch along fjords, being dependent on either rocky substrate (seaweeds) or light-flooded sandy sediments (seagrass), their local biomass can be considerable. The vertical structures they create as ecosystem engineers also translate into a strong bottom-up effect in Arctic fjords. Increases in the biomass of these communities over time have been observed (Kędra et al., 2010; Bartsch et al., 2016), and even though the *in situ* sampling in the study was spatially limited, the findings were striking enough to conclude that a regime shift of the rocky-bottom community occurred via a sharp increase in macroalgae cover in 1995 (Kortsch et al., 2012). Indeed, a pan-Arctic study of 38 sites showed a general increase in abundance, productivity, and/or biodiversity, with a poleward migration rate of 18–23 km per decade (Krause-Jensen et al., 2020). An *in situ* study in Kongsfjorden (W Svalbard), which compared macroalgae biomass records from 2012 to 2014 against those from 1996 to 1998, found that biomass at the 2.5 m depth had increased by 8.2-fold, and that the community had shifted to shallower waters (Bartsch et al., 2016). The two forces driving shallower shifts in macrophytobenthos biomass are

- 1) decreases in sea ice cover (see section “Sea ice”) mean less ice scour and more PAR penetration at the shallow depths macroalgae like to inhabit (Fredriksen et al., 2019 and citations therein) and
- 2) increased turbidity, which inhibits PAR penetration (see section “Light (PAR and UV)”) to the historically deeper range where macroalgae have been found (Bartsch et al., 2016).

Demersal fish have a strong top-down effect on fjord ecosystems via predation, and their distribution in fjords is strongly driven by along fjord salinity and temperature gradients (Mérillet et al., 2022).

Fjords with a sill (i.e., physical barrier) that guard the inner waters from external oceanic forces create very cold habitats that harbour specific communities (Kędra et al., 2010; Węśławski et al., 2011). These are hypothesised to offer a refuge for Arctic endemic species against increasing seawater temperatures (see section “Seawater temperature”; Węśławski et al., 2011; Drewnik et al., 2017). This may be particularly important as continuing poleward expansion of boreal communities and corresponding decreases in dominance of Arctic communities is being observed (see section “Species richness”; Jørgensen et al., 2019), which will likely have widespread impacts on the established fisheries in the Arctic (see “Summary” of “Social drivers” section).

### Species richness

In addition to the primary production of an ecosystem and the biomass therein, the richness of species, their diversity, and evenness are critically important for stable functioning (Diaz and Cabido, 2001; Gamfeldt et al., 2015; Isbell et al., 2018). Meaning that the more diverse the assemblage of species in an ecosystem is, the more likely that system will be able to withstand a range of external stressors, based on the insurance hypothesis that some species will have redundant characteristics (i.e., biological traits) and that the ones that will survive will be able to maintain the ecosystem functions performed (Yachi and Loreau, 1999; Lamy et al., 2019). A consideration of paramount importance given the massive and rapid impacts that climate change and other human activities are having on Arctic fjords.

The first impacts of climate change on flora or fauna within the European Arctic (i.e., Greenland, Svalbard, and Northern Norway) were noted by Blacker (1957), followed by a long pause until research on the species richness of rocky shore communities within European Arctic and sub-Arctic fjords showed that they had increased (Hansen and Ingólfsson, 1993; Włodarska-Kowalczyk et al., 2012; Fredriksen et al., 2019 and references therein). Due primarily to warming seawater (see section “Seawater temperature”), an increase in species richness of rocky littoral microorganisms has also been recorded on Svalbard (Węśławski et al., 2010). Similarly, fish species richness has significantly increased in Porsangerfjorden (N Norway) over 2007–2019, facilitated by reductions in sea ice cover (see section “Sea ice”) and the freshening of water (see section “Salinity”; Mérillet et al., 2022).

While seawater temperatures in Arctic fjords remain below the present mean of 3°C, rising temperatures are projected to decrease species richness; however, upon passing that 3°C threshold, species richness is projected to begin to increase (Benedetti et al., 2021). Plankton species richness in particular is expected to see an overall increase with global warming as species shift poleward (see section “Biomass”; Benedetti et al., 2021). However, most decreases are expected in East and Southwest Greenland and West Svalbard (Benedetti et al., 2021). The temperature of seawater (see section “Seawater temperature”) is described as the primary cause of the overall increase to species richness in the Arctic, with nutrients (see section “Nutrients”) playing an additional role in some areas (Benedetti et al., 2021). Due to the almost certain continued increases to both of these drivers, it is likely that while species richness in fjords may decrease in the short term, on a multi-decadal scale it is likely that borealisation of fjord species (see section “Biomass”) will lead to an overall increase in species richness (with the possible exception of plankton). Unfortunately, this will not necessarily equate to a more resilient ecosystem because the incoming boreal species may lack the same diversity of functional



traits found in Arctic species (Kędra et al., 2015; McGovern et al., 2020).

Climate change and increased anthropogenic activities are expected to contribute to the potential increases to species richness largely by elevating the potential for the introduction of non-indigenous species (NIS; Chan et al., 2019), which when established in novel ecosystems are often able to outcompete local species (Wood et al., 2011). There is a particular risk of this along the coasts of Northern Norway and West Svalbard, where warming water masses and high potential for advection via the North Atlantic Current and WSC are good preconditions for the introduction of NIS (Węśławski et al., 2011; Tarling et al., 2022). In the Greenland Sea/East Greenland area, three known NIS have already been introduced (among them the Pacific diatom *Neodenticula seminae*) and five in the Barents Sea/Svalbard area. Among those, the following have become established: the Japanese skeleton shrimp *Caprella mutica*, the copepod *Eurytemora americana*, the Chinese mitten crab *Eriocheir sinensis*, and the red king crab *Paralithodes camtschaticus* (Chan et al., 2019). Of these, king crabs were intentionally introduced to the east of Porsangerfjorden (N Norway) in the 1960s to establish a commercial fishery (see “Summary” of “Social drivers” section), and are now spreading west over the north of Norway, causing widespread trophic perturbations (Dvoretzky and Dvoretzky, 2015).

### Summary

Decreases of sea ice cover (see section “Sea ice”) in the open Arctic Ocean have been associated with increased primary productivity (Ardyna and Arrigo, 2020), but this relationship has not yet been conclusively measured in fjords. It is, however, hypothesised that this will eventually become a measurable relationship because further warming of seawater (see section “Seawater temperature”) within fjords will almost certainly result in prolonged sea ice-free periods and larger volumes of meltwater (see section “Terrestrial runoff”), which will provide more nutrients that fuel primary productivity (Piquet et al., 2014).

It is generally agreed that most Arctic fjords ecosystems will experience radical community changes, with many going through stable state shifts from Arctic to boreal (Kortsch et al., 2012; Fossheim et al., 2015; Pecuchet et al., 2020), though how these changes will look remains unclear. For example, it is known that demersal fish communities have an inherent adaptive capacity to survive long periods of seasonally low food availability (Sun et al., 2009), which in combination with their opportunistic feeding strategy (Iken et al., 2010; Węśławski et al., 2011) might translate to some degree of stability in the face of the climate-driven changes to fjord ecosystems. Modelling efforts to predict the impact of potential warming and acidification scenarios by 2100 on demersal fish showed that habitat loss would be small (0–11%), with no appreciable difference between losses for Arctic and Arctic-boreal species (Renaud et al., 2019). The extent of marine forests (macrophytobenthos) within the Arctic basin is also predicted to remain stable (Bringloe et al., 2022), if not increase due to the changing climate (Krause-Jensen et al., 2020). The depth structure of these forests, however, is likely to shift to shallower waters (Bartsch et al., 2016).

Until recently, the climatic conditions around Svalbard acted as a barrier to the spread of NIS, but the Atlantification (see section “Salinity”) of the marine environment has partly removed this (Øian and Kaltenborn, 2020). The encroachment of NIS, due to borealisation, is currently squeezing Arctic species further

northward (Fossheim et al., 2015; Kortsch et al., 2015). A process that will almost certainly continue into the future (Filbee-Dexter et al., 2019). It has been noted, however, that assemblages in Svalbard will likely remain different from those in Northern Norway due to the greater direct human influence on the continent (Kujawa et al., 2021).

## Social drivers

### Governance

There are many ways that changes to the drivers detailed above may affect Arctic livelihoods, culture, identity, economy, health, and security, especially for Indigenous Peoples (IPCC, 2021); however, these are not the only drivers of change in the Arctic. Through its top-down control of human societies, governance may have broader impacts on Arctic fjord socio-ecological systems than nearly all other aspects of climate change by controlling the rapid and dramatic direct local impacts that human actions may have on the natural world (Tyler et al., 2007; Hovelsrud and Smit, 2010).

Self-determination in managing climate change impacts has inspired Greenlandic politicians to contemplate joining the Paris Agreement and to look for investors to expand the hydro-power resource enabling the storage and export of green energy within a decade (Bjørst, 2022). In parallel, the national strategy for oil and gas exploration has been abandoned. As another way to grow and diversify its economy, Greenland is in the process of building two international airports to improve transport and connectivity, specifically around tourism (see section “Tourism”). These two examples showcase how the Government of Greenland is managing the right to resources, subsurface and hydropower installation, and how regional governments are becoming key players for domestic development that are increasingly empowered to act on negative trends affecting the regional population, but in ways that may have negative ecological consequences.

In 2018, the Norwegian government decided to close most of its coal mines on Svalbard (the primary original reason for human settlements there) and identified tourism (see section “Tourism”) as a new cornerstone industry (NMJ, 2016). Concurrent with this recent shift is the goal for Svalbard to ensure the best wilderness management in the world (MoCE, 2020). Strict regulations have been followed, and currently underway is a major overhaul and tightening of the environmental protections and tourism management for the archipelago (Granberg et al., 2017; NEA, 2022).

### Tourism

In recent decades (until the onset of COVID-19 countermeasures in early 2020), there has been an increasing global interest in the Arctic as a tourist destination, particularly fjords. Promoting this increase in tourism has been an intentional governance choice (see section “Governance”), with the stated goal being the development and diversification of the economies of the sparsely populated peripheral regions of Nordic countries (Ren et al., 2021a). This has, however, led to growing human impacts on small and remote destinations where signs of human activities had yet been scarce, and where these anthropogenic disturbances may have wide-ranging consequences.

Ironically, the changing climate is currently serving as a net benefit to Arctic tourism, with tourist arrivals via cruise ship in Longyearbyen (W Svalbard) doubling from 2010 to 2018 (Port of Longyearbyen, 2018; Epinion, 2019). This has led to calls for

opportunity-based adaptations to the cruise tourism influx (Dawson et al., 2016) because the warming Arctic and its melting sea ice (see section “Sea ice”) will ensure that coastal destinations remain the most accessible. This is an important consideration because in addition to the impacts of the humans themselves, the ships they use for transport to and from the Arctic may drive changes in a number of different ways. Some of these may be more apparent, like the introduction of nutrients (i.e., via human waste; section “Nutrients”) and pollutants (Øian and Kaltenborn, 2020), but some less so, like the introduction of NIS (see section “Species richness”; Hellmann et al., 2008; Goldsmit et al., 2018). These are transported on the hulls of ships, via the emptying of ballast water (Chan et al., 2013), or by the tourists themselves. Weaver and Lawton (2017) argue that the potential economic benefits of cruise tourism in small coastal communities may be outweighed by their social and environmental stressors, and Ren et al. (2021b) stress the need for more locally based management of Arctic cruise tourism.

While human activities in the permanent settlements of Svalbard do have an environmental footprint, this is easily rivalled by that of tourism, where residents are outnumbered by tourists during the high season (Hovelsrud et al., 2021). Tourists arriving in Isfjorden (W Svalbard) tend to spend less than 3 days on the archipelago (Hovelsrud et al., 2021), but the increase in tourist arrivals has meant a doubling of total tourist nights per year (Visit Svalbard, 2020). Management decisions (see section “Governance”) to deal with this issue are ongoing (Hovelsrud et al., 2020). Of the cruise ships arriving on the archipelago, the average number of overseas arrivals per year has decreased (Stocker et al., 2020), most likely due to a ban on heavy oil fuel in most of the coastal waters of Svalbard. This is endemic to a shift towards smaller expedition cruises and pleasure craft vessels, which have increased by 42% from 2008 to 2018 (NEA, 2022). These smaller vessels benefit more from the retreating sea ice edge (Palma et al., 2019; Hovelsrud et al., 2020) due to their ability to sail closer to the ice-edge and glaciers, a demand for which has become a recent market trend (Hovelsrud et al., 2021).

Accounting for about a third of all foreign visitors, cruises have for many years been a central part of tourism in Greenland. The country has previously set annual growth targets for cruises as a whole. However, Visit Greenland announced in late 2022 that it will abstain from marketing to conventional cruises after a summer with cruise tourism numbers matching the record year of 2019 (Visit Greenland, 2022). Whether this may actually enable a move from conventional cruises to cleaner and socially less impactful expedition cruise tourism remains to be seen but will have crucial implications for the fjord systems of Greenland as a return to mass tourism will mean greater anthropogenic impact in the future.

### Fisheries

Besides adding nutrients (see section “Nutrients”) and pollutants, humans also engage in extractive behaviours that can upset natural trophic balance. These disturbances are generally monitored via target species and regulated by the management of fisheries (see section “Governance”). However, fishing also affects non-targeted species as well as the structure of the habitats, such as the use of bottom trawls (Gray et al., 2006; Kaiser et al., 2006). While the impacts of tourists are generally inferred via head counts at ports of call, the proxy for tracking the impacts of fishing vessels in the Arctic is by monitoring ship mileage. This value has been increasing in the waters around Svalbard as the ice edge steadily retreats (see section “Sea ice”; Stocker et al., 2020), and the duration of the

operational season extends (i.e., longer sea ice-free period per year). Unsurprisingly then the overall number of ships in the Arctic increased by 25% from just 2013 to 2019 (Stocker et al., 2020).

In Porsangerfjorden (N Norway), the shrimp fishery, which used the ecologically damaging method of bottom trawling, was closed in the early 1970s after intensive fishing caused the over-exploitation of cod as well as small and young fishes (Søvik et al., 2020). This fishery was, however, opened again in 2021 for trial with only a few boats allowed to fish in the outer part of the fjord (G. Søvik, pers. comm.), a demonstration of the direct impact that governance (see section “Governance”) can have on a local ecosystem. Fishing for cod (*Gadus morhua*), saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), and red king crab (*P. camtschaticus*) had always been allowed in the fjord with other less damaging gear. Red king crab in particular has become an important commercial fishery with 921 t landed in 2018 (Søvik et al., 2020). Originally a NIS (see section “Species richness”), the adaptation of a fishery for red king crab (Sundet and Hoel, 2016), has potentially aided the recovery of kelp forests in Northern Norway by reducing sea urchin grazing pressure (Christie et al., 2019), and is a good example of how governance can help to adapt to the inevitable changes that Arctic fjord ecosystems will experience.

The largest city of Greenland lies at the mouth of Nuup Kangerlua, where hunting for seals and seabirds, as well as fishing for cod, halibut, and redfish is common. Humpback whales have been protected inside the fjord since 2021, while other species remain open for hunting. As of today, fishing is the main economic sector for the country (Grønlands Økonomiske Råd, 2021). And while fisheries are affected by the changing climate, government regulations (see section “Governance”) and changes to the international prices on fish and shrimp likely have a greater impact. In 2021, for example, (because of COVID-19) the prices for cod dropped suddenly compared to previous years, leading to widely felt economic hardships (Andersen, 2022). To limit this reoccurrence, development in the formal economy is seen as important by decision-makers and business owners. However, fishing, hunting, and gathering activities remain a key part of the region’s mixed economy and hold great cultural and social value. This means that it is particularly difficult for the government of Greenland to tightly regulate the extractive behaviour of its citizens, and thereby the ecological impacts they may have. It is in part to address issues like this that many governments of Arctic nations have been leaning away from extractive economic strategies in favour of tourism (see section “Tourism”).

The northernmost fisheries on the planet, found in the fjords and waters around Svalbard, have been strictly regulated since 1977 when Norway claimed the right to regulate fishing 200 nautical miles around Svalbard under the Norwegian Economic Zone Act (reduced slightly in 2010 when a final dividing line agreement with Russia was made). Since 1980, the Directorate of Fisheries has collected detailed information on landings from Norwegian fishers in the Svalbard zone (Misund et al., 2016), and the main fisheries are Atlantic cod *G. morhua* with close to 75 million tonnes fished in 2021 with an estimated value of 1.2 billion NOK (or 114.2 million €), followed by shrimp (*Pandalus borealis*; 27.3 million tonnes; 550 million NOK or 52.3 million €), haddock (*M. aeglefinus*; 22.1 million tonnes; 331 million NOK or 31.5 million €) and snow crab (*Chionoecetes opilio*; 6.3 million tonnes; 586 million NOK or 55.7 million €; Fiskeridirektoratet, 2022). Within the coastal zone/fjords of Svalbard, the core areas for fishing (mostly for shrimp) are Isfjorden, Krossfjorden, and Hinlopen. At present, it is not possible

to deliver landings directly to local communities on Svalbard, with most going to mainland Norway. While there is interest to develop the necessary local infrastructure, it has been inhibited by strict environmental regulations (see section “Governance”). A few local hunters provide seal meat and Atlantic cod to restaurants in Longyearbyen, and it is popular for the locals to fish cod and hunt seals for their own use.

### Summary

It is very difficult to predict what the future social structure of Arctic communities will look like. One can, however, seek to understand how and why these societies have changed in the past and present (AMAP, 2017). Future policies that may be developed in order to adapt to the changing personal decisions of the inhabitants of the Arctic will in turn have top-down impacts on many of the drivers detailed in previous sections. One must also remember that the results of climate change research do not automatically translate into adaptive human behaviour (Hovelsrud *et al.*, 2015). Indeed, the many international climate meetings (e.g., Conference of the Parties [COPs]) and IPCC projections on the changing climate have had seemingly little impact when introduced into national politics and everyday lives. The need for economic growth and the development of new infrastructure in Arctic communities may very well lead to an increase in CO<sub>2</sub> emissions, rather than a reduction, meaning that social drivers may negatively impact the Arctic climate system even more in years to come. For example, the increase in local pollution in the form of CO<sub>2</sub>, sulphur, black carbon emissions, and nutrient runoff are directly affected by how northern communities decide to manage the tourism industry (see section “Tourism”). The failure (or success) of local ecosystems and key taxa are also directly influenced by choices in how to manage northern fisheries (see section “Fisheries”) and the potential expansion of aquaculture endeavours (Heath *et al.*, 2022), such as the farming of kelp forests.

Social drivers of change are generally perceived first and foremost to have local impacts, but they too are capable of having widespread feedback on the other categories of drivers. For example, while various aspects of climate change will likely have the largest impact on ecosystems and species in the future (Thierry *et al.*, 2022), the greatest impacts historically have come from human overexploitation of species and destruction of their habitats (Caro *et al.*, 2022). The melting Arctic will allow for even greater exploitation of the resources therein, which will have entirely new impacts that until present had not been possible.

### Conclusions

Arctic fjords are changing rapidly at nearly every measurable level. Therefore, a clear understanding of the relationships of these drivers with each other in the past, present, and how they may change in the future is necessary for designing effective adaptation strategies (Søreide *et al.*, 2021). Some of these changes, such as the increase in sea ice-free days, are easier to project than others, such as whether governance decisions to create economic growth will focus on developing industry over ecological protection. In this review, we have provided a summary of the knowledge of the key drivers of change in socio-ecological Arctic fjord systems (Table 1), and how those drivers interact with one another (Figure 2). Below, we provide a discussion on the choice of the drivers, gaps in knowledge, future changes, and concluding remarks.

The list of drivers in this review was very carefully considered. A much longer list of drivers was initially constructed, but many were cut when no literature supporting their importance within Arctic fjords was found. An illustrative example is dissolved oxygen in fjord waters. The general global trend shows oxygen levels are decreasing and will continue to do so in a changing climate (Breitburg *et al.*, 2018). There is, however, very little research on this issue in the Arctic, leading the IPCC to give medium confidence

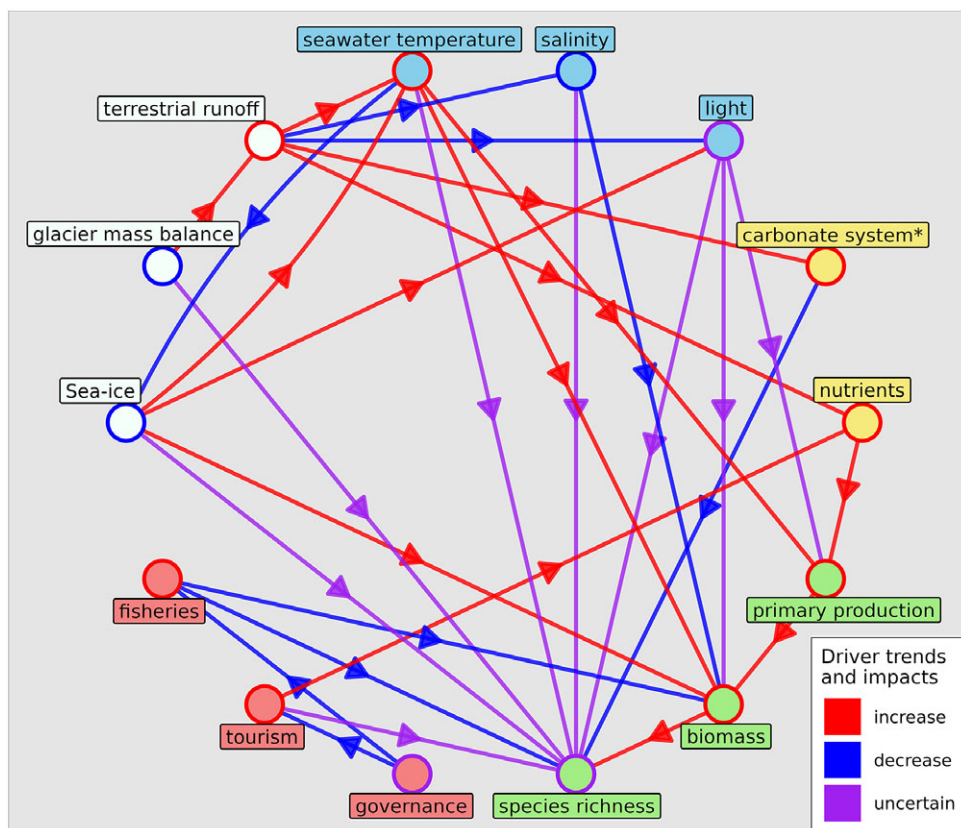
**Table 1.** The main point to consider for each driver of change, and the summary per category

Category	Driver	Main point
Cryosphere	Sea ice	Sea ice is melting so rapidly that ice-free periods are lasting for most if not all year long.
	Glacier mass balance	Glacier melt is so advanced that many are beginning to transition from marine-terminating to land-terminating.
	Terrestrial runoff	The increased rate of runoff from glaciers and rivers is increasing surface nutrients, turbidity, and stratification.
	Summary	<i>The Arctic cryosphere as a unique ecosystem may completely disappear.</i>
Physics	Seawater temperature	The temperature of seawater is increasing at the surface and depth much more rapidly almost anywhere else on Earth.
	Salinity	Changes of large ocean currents is causing the “Atlantification” (increased salinity and nutrients) of many W Svalbard fjords, which will likely increase in the future.
	Light	The loss of sea ice increases the potential for more light to enter the water, but increases in turbidity are counteracting this to an uncertain degree.
	Summary	<i>The rate of climate change to the physical environment will not abate and can only be reduced and perhaps stopped by implementing the Paris Agreement in a full and timely manner.</i>
Chemistry	Carbonate system	The waters of Arctic fjords will continue to acidify apace with, or more rapid than, global CO <sub>2</sub> emissions.
	Nutrients	Increasing terrestrial runoff and continued human development/tourism mean an almost certain increasing trend in nutrient inputs to Arctic fjords.
	Summary	<i>The chemical composition of seawater will continue to alter rapidly, likely having ecological impacts on the mid to lower trophic ranges.</i>

(Continued)

Table 1. (Continued)

Category	Driver	Main point
Biology	Primary production	Primary production will likely increase apace with rising temperatures, glacial melt, and nutrient inputs, even though surface waters will darken.
	Biomass	The low to mid-range trophic levels of many ecosystems will likely see extreme borealisation (i.e., replacement by species from the south), but the macrobenthos may remain relatively stable (e.g., demersal fish) or even increase (e.g., kelps).
	Species richness	Non-indigenous species (NIS) will likely outcompete Arctic endemics, causing short-term decreases to species richness, but this trend will likely reverse as ecosystems shift to a stable boreal state.
	Summary	While some Arctic species may remain, future ecosystems will likely have mostly boreal characteristics, potentially weakening their overall resilience.
Social	Governance	Because the need for economic development is large for most human communities, it is not clear whether ecologically responsible governance choices will be made.
	Tourism	Tourism and its impact will continue to increase, but a strong trend towards ecological responsibility is emerging.
	Fisheries	The shift towards tourism creates economic opportunities that may alleviate pressure from fisheries practices, which is a positive signal for increased ecological protection.
	Summary	Governance can have greater impacts on local taxa/ecosystems than climate change, and it appears the future may be tipped more towards ecological choices rather than industry.



**Figure 2.** Network chart of the interactions between the drivers of change in Arctic fjord socio-ecological systems as determined from a review of the literature. The trend in the change of each driver (i.e., increasing, decreasing, or uncertain) is shown via the coloured borders of the labelled points. The impacts that the drivers have on each other are shown with coloured arrows. The categories of the drivers are shown with the internal colour of the points and their labels. Note that “positive” governance is assumed here to be choices in favour of environmental protection rather than exploitation. It is for this reason that governance is shown here to have a negative impact on fisheries and tourism. The asterisk on the carbonate system is to note that it consists of several variables, including pCO<sub>2</sub>, DIC, TA, pH, and CaCO<sub>3</sub> saturation state (see section “Carbonate system”), which do not vary in synchrony. The positive effect of increasing terrestrial runoff on the carbonate system refers to pCO<sub>2</sub> and DIC, whereas the negative effect on calcifying organisms refers to pH and CaCO<sub>3</sub> saturation state.



to the past trend (Arias et al., 2021). While decreasing oxygen levels will likely be deleterious for multicellular life in the global ocean (Storch et al., 2014), initial research in Arctic fjords shows they may be partially exempt (Kempf, 2020).

The melting Arctic will fundamentally reshuffle the biotic interactions within fjords, but will also increase the opportunity for fisheries and maritime traffic. For example, as multi-year sea ice becomes scarce to the north of Russia it will become an important arterial for shipping (e.g., Shanghai to Hamburg is 30% shorter than the Suez Canal route, saving 14 days of travel time/cost). Will Arctic communities adapt to these new logistical opportunities? Will they continue to exploit and extract from the natural world, or will the recent trends towards more ecologically responsible practices take root? One must also consider that once the Arctic cryosphere is mostly gone, tourism will almost certainly decrease. The main research gap then that persists in the social sciences is, in the face of the changing climate and the potential draw-down of tourism as a viable economic pathway, how can Arctic communities achieve sustainability given their need for long-distance travel and the increasing energy requirements to match economic development. In the natural sciences, a key unknown is how the light regime within Arctic fjord surface waters will change in the future, and how it will impact the borealisation of coastal communities.

Given that a range of data is collected in the Arctic via *in situ* measurements and remote sensing, it is possible to discern the numeric relationships for many of the drivers detailed above, and to project those relationships forward into the future based on different climate projections (Schlegel and Gattuso, *in review*). It is therefore possible to see where in the Arctic these historic relationships differ, and where the future projections may likewise diverge. Using the interplay of sea ice cover and seawater temperature as an example, while most fjords experience similar decreases in sea ice cover as fjord waters warm, the relationship at depth (>200 m) differs between Greenland and Svalbard due to the lack of Atlantification of fjord waters in the former (see section “Seawater temperature”; Schlegel and Gattuso, *in review*). It must be noted, however, that while the Arctic is becoming increasingly well sampled, data within most fjords remain scarce. The more thorough sampling of fjords, particularly for the 14 drivers covered in this review, should be an area of concerted future effort.

Without an immediate and massive reduction in anthropogenic emissions, accompanied by the rapid development and implementation of atmospheric CO<sub>2</sub> extraction technologies to limit global warming to 1.5°C by 2100, the Arctic cryosphere will be altered significantly (Meredith et al., 2019). Considering that the UN has concluded this is no longer possible, the work now is projecting when exactly massive significant shifts will occur (e.g., Wei et al., 2020). Of the published models for Arctic Ocean sea ice, the soonest predicted ice-free summer period over the North Pole is 2030, though most err towards 2050 (Wei et al., 2020). Taking into account the relationships between all of the drivers detailed in this review, and considering that the time scale of human governance only extends to 2050, we may conclude that many Arctic fjords will become entirely and irrevocably borealised in the coming decades. They may, however, continue functioning in some way resembling their current state, meaning that human strategies for adaptation will have to continue to change rapidly, but will likely not need to be fundamentally overhauled to match the types of ecosystems that are found below the Arctic circle. Taken all together, the drivers of change in socio-ecological systems weave a complex web of interaction, with no one driver or category being necessarily more or less important than another, and certainly, none of them can be

excluded when one’s aim is to create effective adaptation strategies for a changing future Arctic.

**Open peer review.** To view the open peer review materials for this article, please visit <http://doi.org/10.1017/cft.2023.1>.

**Data availability statement.** No data were generated or analysed for this review, however, this paper is accompanied by a sister paper (Schlegel and Gattuso, *in review*) that describes and analyses a data product whose compilation was directed by the knowledge generated during this review process. The data product itself is openly available on PANGAEA at: <https://doi.org/10.1594/PANGAEA.953115>.

**Acknowledgements.** This study is a contribution to the project FACE-IT (The Future of Arctic Coastal Ecosystems – Identifying Transitions in Fjord Systems and Adjacent Coastal Areas). We thank D. Storch (AWI) for providing information on oxygen deficiency in the Arctic. Figure 1 was created in large part thanks to the R package “ggoceanmaps” (Vihtakari, 2022).

**Author contributions.** R.S. and J.-P.G. defined the concept and frame of the paper. R.S. prepared a first draft of the manuscript, figures, tables, and coordinated the discussion rounds. All authors revised, commented, and edited the manuscript during multiple revision rounds and approved the final version for publication.

**Financial support.** FACE-IT has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 869154.

**Competing interest.** The authors declare no competing interests exist.

## References

- Aanesen M and Mikkelsen E (2020) Cost-benefit analysis of aquaculture expansion in Arctic Norway. *Aquaculture Economics & Management* **24** (1), 20–42. <https://doi.org/10.1080/13657305.2019.1641570>.
- Aksnes D, Dupont N, Staby A, Fiksen Ø, Kaartvedt S and Aure J (2009) Coastal water darkening and implications for mesopelagic regime shifts in Norwegian fjords. *Marine Ecology Progress Series* **387**, 39–49. <https://doi.org/10.3354/meps08120>.
- AMAP (2017). *Adaptation Actions for a Changing Arctic (AACA)—Barents Area Overview Report*. Arctic Monitoring and Assessment Programme (AMAP). Available at <https://oarchive.arctic-council.org/handle/11374/1960>. (Accessed 14 October 2022)
- Andersen TM (2022) Grønland, en selvberende økonomi – Krav og muligheder. *Samfundsøkonomen* **2021**(4), 4–18. <https://doi.org/10.7146/samfundsoekonomen.v2021i4.132055>.
- Ardaya M and Arrigo KR (2020) Phytoplankton dynamics in a changing Arctic Ocean. *Nature Climate Change* **10**(10), 892–903. <https://doi.org/10.1038/s41558-020-0905-y>.
- Arias PA, Bellouin N, Coppola E, Jones RG, Krinner G, Marotzke J, Naik V, Palmer MD, Plattner G-K and Rogelj J (2021) Technical summary. In Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R and Zhou B (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change: Vol. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 33–144.
- Arrigo KR and van Dijken GL (2011) Secular trends in Arctic Ocean net primary production. *Journal of Geophysical Research* **116**(C9), C09011. <https://doi.org/10.1029/2011JC007151>.
- Bartsch I, Paar M, Fredriksen S, Schwanitz M, Daniel C, Hop H and Wiencke C (2016) Changes in kelp forest biomass and depth distribution in Kongsfjorden, Svalbard, between 1996–1998 and 2012–2014 reflect Arctic warming. *Polar Biology* **39**(11), 2021–2036. <https://doi.org/10.1007/s00300-015-1870-1>.

- Bednaršek N, Naish K-A, Feely RA, Hauri C, Kimoto K, Hermann AJ, Michel C, Niemi A and Pilcher D (2021) Integrated assessment of ocean acidification risks to pteropods in the northern high latitudes: Regional comparison of exposure, sensitivity and adaptive capacity. *Frontiers in Marine Science* 8, 671497. <https://doi.org/10.3389/fmars.2021.671497>.
- Bélanger S, Babin M and Tremblay J-É (2013) Increasing cloudiness in Arctic dampens the increase in phytoplankton primary production due to sea ice receding. *Biogeosciences* 10(6), 4087–4101. <https://doi.org/10.5194/bg-10-4087-2013>.
- Benedetti F, Vogt M, Elizondo UH, Righetti D, Zimmermann NE and Gruber N (2021) Major restructuring of marine plankton assemblages under global warming. *Nature Communications* 12(1), 5226. <https://doi.org/10.1038/s41467-021-25385-x>.
- Bianchi TS, Arndt S, Austin WEN, Benn DI, Bertrand S, Cui X, Faust JC, Koziarowska-Makuch K, Moy CM, Savage C, Smeaton C, Smith RW and Syvitski J (2020) Fjords as aquatic critical zones (ACZs). *Earth-Science Reviews* 203, 103145. <https://doi.org/10.1016/j.earscirev.2020.103145>.
- Bintanja R and Andry O (2017) Towards a rain-dominated Arctic. *Nature Climate Change* 7(4), 263–267. <https://doi.org/10.1038/nclimate3240>.
- Bischof K, Convey P, Duarte P, Gattuso J-P, Granberg M, Hop H, Hoppe C, Jiménez C, Lisitsyn L, Martínez B, Roleda MY, Thor P, Wiktor JM and Gabrielsen GW (2019) Kongsfjorden as harbinger of the future Arctic: Known, unknowns and research priorities. In Hop H and Wiencke C (eds), *The Ecosystem of Kongsfjorden, Svalbard*. Cham: Springer International Publishing, pp. 537–562. [https://doi.org/10.1007/978-3-319-46425-1\\_14](https://doi.org/10.1007/978-3-319-46425-1_14).
- Bischof K and Steinhoff FS (2012) Impacts of ozone stratospheric depletion and solar UVB radiation on seaweeds. In Wiencke C and Bischof K (eds), *Seaweed Biology*, Vol. 219. Berlin, Heidelberg: Springer, pp. 433–448. [https://doi.org/10.1007/978-3-642-28451-9\\_20](https://doi.org/10.1007/978-3-642-28451-9_20).
- Björst L (2022) To live up to our name “Greenland”: Politics of comparison in Greenland’s green transition. In Heininen (ed), *Arctic Yearbook 2022*. Lapland: Thematic Network on Geopolitics and Security, pp. 1–19.
- Blacker RW (1957) *Benthic animals as indicators of hydrographic conditions and climatic change in Svalbard waters*. Her Majesty’s Stationery Office.
- Bloshkina EV, Pavlov AK and Filchuk K (2021) Warming of Atlantic water in three West Spitsbergen fjords: Recent patterns and century-long trends. *Polar Research* 40, 1–11. <https://doi.org/10.33265/polar.v40.5392>.
- Boone W, Rysgaard S, Carlson DF, Meire L, Kirillov S, Mortensen J, Dmitrenko I, Vergeynst L and Sejr MK (2018) Coastal freshening prevents Fjord bottom water renewal in Northeast Greenland: A mooring study from 2003 to 2015. *Geophysical Research Letters* 45(6), 2726–2733. <https://doi.org/10.1002/2017GL076591>.
- Breitburg D, Levin LA, Oschlies A, Grégoire M, Chavez FP, Conley DJ, Garçon V, Gilbert D, Gutiérrez D, Isensee K, Jacinto GS, Limburg KE, Montes I, Naqvi SWA, Pitcher GC, Rabalais NN, Roman MR, Rose KA, Seibel BA, Telszewski M, Yasuhara M and Zhang J (2018) Declining oxygen in the global ocean and coastal waters. *Science* 359(6371), eaam7240. <https://doi.org/10.1126/science.aam7240>.
- Bridier G, Olivier F, Chauvaud L, Sejr MK and Grall J (2021) Food source diversity, trophic plasticity, and omnivory enhance the stability of a shallow benthic food web from a high-Arctic fjord exposed to freshwater inputs. *Limnology and Oceanography* 66(S1), S259–S272. <https://doi.org/10.1002/lno.11688>.
- Bringloe TT, Wilkinson DP, Goldsmit J, Savoie AM, Filbee-Dexter K, Macgregor KA, Howland KL, McKindsey CW and Verbruggen H (2022) Arctic marine forest distribution models showcase potentially severe habitat losses for cryophilic species under climate change. *Global Change Biology* 28(11), 3711–3727. <https://doi.org/10.1111/gcb.16142>.
- Caro T, Rowe Z, Berger J, Wholey P and Dobson A (2022) An inconvenient misconception: Climate change is not the principal driver of biodiversity loss. *Conservation Letters* 15(3), e12868. <https://doi.org/10.1111/conl.12868>.
- Chan FT, Bailey SA, Wiley CJ and MacIsaac HJ (2013) Relative risk assessment for ballast-mediated invasions at Canadian Arctic ports. *Biological Invasions* 15(2), 295–308. <https://doi.org/10.1007/s10530-012-0284-z>.
- Chan FT, Stanislawczyk K, Sneekes AC, Dvoretzky A, Gollasch S, Minchin D, David M, Jelmert A, Albreten J and Bailey SA (2019) Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. *Global Change Biology* 25(1), 25–38. <https://doi.org/10.1111/gcb.14469>.
- Christiansen JR, Röckmann T, Popa ME, Sapart CJ and Jørgensen CJ (2021) Carbon emissions from the edge of the Greenland ice sheet reveal subglacial processes of methane and carbon dioxide turnover. *Journal of Geophysical Research: Biogeosciences* 126(11), e2021JG006308. <https://doi.org/10.1029/2021JG006308>.
- Christie H, Gundersen H, Rinde E, Filbee-Dexter K, Norderhaug KM, Pedersen T, Bekkby T, Gitmark JK and Fagerli CW (2019) Can multitrophic interactions and ocean warming influence large-scale kelp recovery? *Ecology and Evolution* 9(5), 2847–2862. <https://doi.org/10.1002/ece3.4963>.
- Comeau S, Gattuso J-P, Nisumaa A-M and Orr J (2012) Impact of aragonite saturation state changes on migratory pteropods. *Proceedings of the Royal Society B: Biological Sciences* 279(1729), 732–738. <https://doi.org/10.1098/rspb.2011.0910>.
- Cottier FR, Nilsen F, Inall ME, Gerland S, Tverberg V and Svendsen H (2007) Wintertime warming of an Arctic shelf in response to large-scale atmospheric circulation. *Geophysical Research Letters* 34(10), L10607. <https://doi.org/10.1029/2007GL029948>.
- Cottier FR, Nilsen F, Skogseth R, Tverberg V, Skarðhamar J and Svendsen H (2010) Arctic fjords: A review of the oceanographic environment and dominant physical processes. *Geological Society, London, Special Publications* 344(1), 35–50. <https://doi.org/10.1144/SP344.4>.
- Cui X, Mucci A, Bianchi TS, He D, Vaughn D, Williams EK, Wang C, Smeaton C, Koziarowska-Makuch K, Faust JC, Plante AF and Rosenheim BE (2022) Global fjords as transitory reservoirs of labile organic carbon modulated by organo-mineral interactions. *Science Advances* 8(46), eadd0610. <https://doi.org/10.1126/sciadv.add0610>.
- Dahlke S, Hughes NE, Wagner PM, Gerland S, Wawrzyniak T, Ivanov B and Maturilli M (2020) The observed recent surface air temperature development across Svalbard and concurring footprints in local sea ice cover. *International Journal of Climatology* 40(12), 5246–5265. <https://doi.org/10.1002/joc.6517>.
- Dalpadado P, Hop H, Rønning J, Pavlov V, Sperfeld E, Buchholz F, Rey A and Wold A (2016) Distribution and abundance of euphausiids and pelagic amphipods in Kongsfjorden, Isfjorden and Rijpfjorden (Svalbard) and changes in their relative importance as key prey in a warming marine ecosystem. *Polar Biology* 39(10), 1765–1784. <https://doi.org/10.1007/s00300-015-1874-x>.
- Dawson J, Stewart EJ, Johnston ME and Lemieux CJ (2016) Identifying and evaluating adaptation strategies for cruise tourism in Arctic Canada. *Journal of Sustainable Tourism* 24(10), 1425–1441. <https://doi.org/10.1080/09669582.2015.1125358>.
- Delpech L-M, Vonnahme TR, McGovern M, Gradinger R, Præbel K and Poste AE (2021) Terrestrial inputs shape coastal bacterial and archaeal communities in a high Arctic fjord (Isfjorden, Svalbard). *Frontiers in Microbiology* 12, 614634. <https://doi.org/10.3389/fmicb.2021.614634>.
- Descamps S, Wojczulanis-Jakubas K, Jakubas D, Vihtakari M, Steen H, Karnovsky NJ, Welcker J, Hovinen J, Bertrand P, Strzelewiec A, Skogseth R, Kidawa D, Boehnke R and Blachowiak-Samołyk K (2022) Consequences of atlantification on a zooplanktivorous Arctic seabird. *Frontiers in Marine Science* 9, 878746. <https://doi.org/10.3389/fmars.2022.878746>.
- Diaz S and Cabido M (2001) Vive la différence: Plant functional diversity matters to ecosystem processes. *Trends in Ecology & Evolution* 16(11), 646–655. [https://doi.org/10.1016/S0169-5347\(01\)02283-2](https://doi.org/10.1016/S0169-5347(01)02283-2).
- Drewnik A, Weślowski JM and Włodarska-Kowalczyk M (2017) Benthic Crustacea and Mollusca distribution in Arctic fjord – Case study of patterns in Hornsund, Svalbard. *Oceanologia* 59(4), 565–575. <https://doi.org/10.1016/j.oceano.2017.01.005>.
- Duarte P, Meyer A and Moreau S (2021) Nutrients in water masses in the Atlantic sector of the Arctic Ocean: Temporal trends. Mixing and links with primary production. *Journal of Geophysical Research: Oceans* 126(8), e2021JC017413. <https://doi.org/10.1029/2021JC017413>.
- Duarte P, Weslawski JM and Hop H (2019) Outline of an Arctic fjord ecosystem model for Kongsfjorden-Krossfjorden, Svalbard. In Hop H and Wiencke C (eds), *The Ecosystem of Kongsfjorden, Svalbard*, Vol. 2. Cham: Springer International Publishing, pp. 485–514. [https://doi.org/10.1007/978-3-319-46425-1\\_12](https://doi.org/10.1007/978-3-319-46425-1_12).

- Dvoretzky AG and Dvoretzky VG (2015) Commercial fish and shellfish in the Barents Sea: Have introduced crab species affected the population trajectories of commercial fish? *Reviews in Fish Biology and Fisheries* 25(2), 297–322. <https://doi.org/10.1007/s11160-015-9382-1>.
- Eamer J, Donaldson G, Gaston A, Kosobokova K, Lárusson K, Melnikov I, Reist J, Richardson E, Staples L and von Quillfeldt C (2013) *Life Linked to Ice. A Guide to Sea-Ice-Associated Biodiversity in this Time of Rapid Change*. Conservation of Arctic Flora and Fauna (CAFF).
- Eilertsen HC, Taasen JP and Weslawski JM (1989) Phytoplankton studies in the fjords of West Spitzbergen: Physical environment and production in spring and summer. *Journal of Plankton Research* 11(6), 1245–1260. <https://doi.org/10.1093/plankt/11.6.1245>.
- Epinion (2019) Cruise Study Svalbard. An Examination of the Economical Impact of Cruise Tourism (Expedition- and Conventional Cruise) in Svalbard. Available at <https://www.aeco.no/wp-content/uploads/2019/09/2019-Epinion-Cruise-Study-AECO-and-VisitSvalbard-Final-report.pdf>. (Accessed 14 October 2022)
- Filbee-Dexter K, Wernberg T, Fredriksen S, Norderhaug KM and Pedersen MF (2019) Arctic kelp forests: Diversity, resilience and future. *Global and Planetary Change* 172, 1–14. <https://doi.org/10.1016/j.gloplacha.2018.09.005>.
- Fiskeridirektoratet (2022) *Norwegian Directorate of Fisheries Database*. Available at <https://www.fiskeridir.no/>. (Accessed 14 October 2022)
- Fosheim M, Primicerio R, Johannessen E, Ingvaldsen RB, Aschan MM and Dolgov AV (2015) Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature Climate Change* 5(7), Article 7. <https://doi.org/10.1038/nclimate2647>.
- Franser F, Frøb F, Tjiputra J, Goris N, Lauvset SK, Skjelvan I, Jeansson E, Omar A, Chierici M, Jones E, Fransson A, Ólafsdóttir SR, Johannessen T and Olsen A (2022) Acidification of the Nordic seas. *Biogeosciences* 19(3), 979–1012. <https://doi.org/10.5194/bg-19-979-2022>.
- Fredriksen S, Karsten U, Bartsch I, Woelfel J, Koblowsky M, Schumann R, Moy SR, Steneck RS, Wiktor JM, Hop H and Wiencke C (2019) Biodiversity of benthic macro- and microalgae from Svalbard with special focus on Kongsfjorden. In Hop H and Wiencke C (eds), *The Ecosystem of Kongsfjorden, Svalbard*. Cham: Springer International Publishing, pp. 331–371. [https://doi.org/10.1007/978-3-319-46425-1\\_9](https://doi.org/10.1007/978-3-319-46425-1_9).
- Frey KE, Comiso JC, Cooper LW, Grebmeier JM, Stock LV (2018) Arctic Ocean Primary Productivity: The Response of Marine Algae to Climate Warming and Sea Ice Decline. *NOAA Arctic Report Card 2021*. Available at <https://repository.library.noaa.gov/view/noaa/34197>. (Accessed 14 October 2022)
- Friedlingstein P, Jones MW, O’Sullivan M, Andrew RM, Bakker DCE, Hauck J, Le Quéré C, Peters GP, Peters W, Pongratz J, Sitch S, Canadell JG, Ciais P, Jackson RB, Alin SR, Anthoni P, Bates NR, Becker M, Bellouin N, Bopp L, Chau TTT, Chevallier F, Chini LP, Cronin M, Currie KI, Decharme B, Djeutchouang LM, Dou X, Evans W, Feely RA, Feng L, Gasser T, Gilfillan D, Gkritzalis T, Grassi G, Gregor L, Gruber N, Gürses Ö, Harris I, Houghton RA, Hurtt GC, Iida Y, Ilyina T, Luijkx IT, Jain A, Jones SD, Kato E, Kennedy D, Goldewijk KK, Knauer J, Korsbakken JI, Körtzinger A, Landschützer P, Lauvset SK, Lefèvre N, Lienert S, Liu J, Marland G, McGuire PC, Melton JR, Munro DR, Nabel JEMS, Nakaoka SI, Niwa Y, Ono T, Pierrot D, Poulter B, Rehder G, Resplandy L, Robertson E, Rödenbeck C, Rosan TM, Schwinger J, Schwingshackl C, Séférian R, Sutton AJ, Sweeney C, Tanhua T, Tans PP, Tian H, Tilbrook B, Tubiello F, Van Der Werf GR, Vuichard N, Wada C, Wanninkhof R, Watson AJ, Willis D, Wiltshire AJ, Yuan W, Yue C, Yue X, Zaehle S and Zeng J (2022) Global carbon budget 2021. *Earth System Science Data* 14(4), 1917–2005. <https://doi.org/10.5194/essd-14-1917-2022>.
- Frigstad H, Kaste Ø, Deininger A, Kvalsund K, Christensen G, Bellerby RGJ, Sørensen K, Norli M and King AL (2020) Influence of riverine input on Norwegian coastal systems. *Frontiers in Marine Science* 7, 332. <https://doi.org/10.3389/fmars.2020.00332>.
- Gamfeldt L, Lefcheck JS, Byrnes JEK, Cardinale BJ, Duffy JE and Griffin JN (2015) Marine biodiversity and ecosystem functioning: What’s known and what’s next? *Oikos* 124(3), 252–265. <https://doi.org/10.1111/oik.01549>.
- Gattuso J-P, Gentili B, Antoine D and Doxaran D (2020) Global distribution of photosynthetically available radiation on the seafloor. *Earth System Science Data* 12(3), 1697–1709. <https://doi.org/10.5194/essd-12-1697-2020>.
- Gattuso J-P and Hansson L (2011) Ocean acidification: Background and history. In Gattuso J-P and Hansson L (eds), *Ocean Acidification: Vol. Ocean Acidification*. Oxford: Oxford University Press, pp. 1–20.
- Geyman EC, van Pelt WJJ, Maloof AC, Aas HF and Kohler J (2022) Historical glacier change on Svalbard predicts doubling of mass loss by 2100. *Nature* 601(7893), Article 7893. <https://doi.org/10.1038/s41586-021-04314-4>.
- Gibbs MT (2001) Aspects of the structure and variability of the low-salinity-layer in doubtful sound, a New Zealand fiord. *New Zealand Journal of Marine and Freshwater Research* 35(1), 59–72. <https://doi.org/10.1080/00288330.2001.9516978>.
- Gillibrand PA, Turrell WR and Elliott AJ (1995) Deep-water renewal in the Upper Basin of loch Sunart, a Scottish fjord. *Journal of Physical Oceanography* 25(6), 1488–1503. [https://doi.org/10.1175/1520-0485\(1995\)025<1488:DWRI>2.0.CO;2](https://doi.org/10.1175/1520-0485(1995)025<1488:DWRI>2.0.CO;2).
- Goebel NL, Wing SR and Boyd PW (2005) A mechanism for onset of diatom blooms in a fjord with persistent salinity stratification. *Estuarine, Coastal and Shelf Science* 64(2), 546–560. <https://doi.org/10.1016/j.ecss.2005.03.015>.
- Goldsmith J, Archambault P, Chust G, Villarino E, Liu G, Lukovich JV, Barber DG and Howland KL (2018) Projecting present and future habitat suitability of ship-mediated aquatic invasive species in the Canadian Arctic. *Biological Invasions* 20(2), 501–517. <https://doi.org/10.1007/s10530-017-1553-7>.
- Granberg ME, Ask A and Gabrielsen GW (2017) *Local Contamination in Svalbard. Overview and Suggestions for Remediation Actions*. Brief Report No. 044. Tromsø: Norsk Polarinstittutt.
- Gray JS, Dayton P, Thrush S and Kaiser MJ (2006) On effects of trawling, benthos and sampling design. *Marine Pollution Bulletin* 52(8), 840–843. <https://doi.org/10.1016/j.marpolbul.2006.07.003>.
- Grønlands Økonomiske Råd (2021) Grønlands økonomi Forår 2021. Available at [https://pure.au.dk/portal/files/230707343/G\\_R\\_F2021\\_210519\\_final.pdf](https://pure.au.dk/portal/files/230707343/G_R_F2021_210519_final.pdf). (Accessed 14 October 2022)
- Halbach L, Vihtakari M, Duarte P, Everett A, Granskog MA, Hop H, Kauko HM, Kristiansen S, Myhre PI, Pavlov AK, Pramanik A, Tatarek A, Torsvik T, Wiktor JM, Wold A, Wulff A, Steen H and Assmy P (2019) Tidewater glaciers and bedrock characteristics control the phytoplankton growth environment in a fjord in the Arctic. *Frontiers in Marine Science* 6, 254. <https://www.frontiersin.org/articles/10.3389/fmars.2019.00254>.
- Hanna E and Cappelen J (2003) Recent cooling in coastal southern Greenland and relation with the North Atlantic oscillation. *Geophysical Research Letters* 30(3), 1132. <https://doi.org/10.1029/2002GL015797>.
- Hansen JR and Ingólfsson A (1993) Patterns in species composition of rocky shore communities in sub-Arctic fjords of eastern Iceland. *Marine Biology* 117(3), 469–481. <https://doi.org/10.1007/BF00349323>.
- Harris PT, Macmillan-Lawler M, Kullerud L and Rice JC (2018) Arctic marine conservation is not prepared for the coming melt. *ICES Journal of Marine Science* 75(1), 61–71. <https://doi.org/10.1093/icesjms/fsx153>.
- Hassett BT, Borrego EJ, Vonnahme TR, Rämä T, Kolomiets MV and Gradinger R (2019) Arctic marine fungi: Biomass, functional genes, and putative ecological roles. *The ISME Journal* 13(6), Article 6. <https://doi.org/10.1038/s41396-019-0368-1>.
- Heath MR, Benkort D, Brierley AS, Daewel U, Laverick JH, Proud R and Speirs DC (2022) Ecosystem approach to harvesting in the Arctic: Walking the tightrope between exploitation and conservation in the Barents Sea. *Ambio* 51(2), 456–470. <https://doi.org/10.1007/s13280-021-01616-9>.
- Hegseth EN and Tverberg V (2013) Effect of Atlantic water inflow on timing of the phytoplankton spring bloom in a high Arctic fjord (Kongsfjorden, Svalbard). *Journal of Marine Systems* 113–114, 94–105. <https://doi.org/10.1016/j.jmarsys.2013.01.003>.
- Hellmann JJ, Byers JE, Bierwagen BG and Dukes JS (2008) Five potential consequences of climate change for invasive species. *Conservation Biology* 22(3), 534–543. <https://doi.org/10.1111/j.1523-1739.2008.00951.x>.
- Hermansen Ø and Troell M (2012) *Aquaculture in the Arctic – A Review (No. 36/2012)*. Nofima rapportserie. Available at <https://nofima.no/publikasjon/1154618/>. (Accessed 14 October 2022)



- Hernes PJ, Tank SE, Sejr MK and Glud RN (2021) Element cycling and aquatic function in a changing Arctic. *Limnology and Oceanography* **66**(S1), S1–S16. <https://doi.org/10.1002/lno.11717>.
- Holmes RM, Shiklomanov AI, Suslova A, Tretiakov M, McClelland JW, Spencer RGM and Tank SE (2018) River Discharge. Arctic Report Card: Update for 2018. Available at <https://www.arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/786/River-Discharge>. (Accessed 14 October 2022)
- Hop H, Pearson T, Hegseth EN, Kovacs KM, Wiencke C, Kwasniewski S, Eiane K, Mehlum F, Gulliksen B, Włodarska-Kowalczyk M, Lydersen C, Weslawski JM, Cochrane S, Gabrielsen GW, Leakey RJG, Lønne OJ, Zajaczkowski M, Falk-Petersen S, Kendall M, Wängberg S-Å, Bischof K, Voronkov AY, Kovaltchouk NA, Wiktor J, Poltermann M, di Prisco G, Papucci C and Gerland S (2002) The marine ecosystem of Kongsfjorden, Svalbard. *Polar Research* **21**(1), 167–208. <https://doi.org/10.3402/polar.v21i1.6480>.
- Hop H and Wiencke C (2019) The ecosystem of Kongsfjorden, Svalbard. In Hop H and Wiencke C (eds), *The Ecosystem of Kongsfjorden, Svalbard*. Cham: Springer International Publishing, pp. 1–20. [https://doi.org/10.1007/978-3-319-46425-1\\_1](https://doi.org/10.1007/978-3-319-46425-1_1).
- Hopwood MJ, Carroll D, Dunse T, Hodson A, Holding JM, Iriarte JL, Ribeiro S, Achterberg EP, Cantoni C, Carlson DF, Chierici M, Clarke JS, Cozzi S, Fransson A, Juul-Pedersen T, Winding MHS and Meire L (2020) Review article: How does glacier discharge affect marine biogeochemistry and primary production in the Arctic? *The Cryosphere* **14**(4), 1347–1383. <https://doi.org/10.5194/tc-14-1347-2020>.
- Hovelsrud GK, Kaltenborn BP and Olsen J (2020) Svalbard in transition: Adaptation to cross-scale changes in Longyearbyen. *The Polar Journal* **10**(2), 420–442. <https://doi.org/10.1080/2154896X.2020.1819016>.
- Hovelsrud GK and Smit B (eds) (2010) *In Community Adaptation and Vulnerability in Arctic Regions*. Cham: Springer Netherlands. <https://doi.org/10.1007/978-90-481-9174-1>.
- Hovelsrud GK, Veland S, Kaltenborn B, Olsen J and Dannevig H (2021) Sustainable tourism in Svalbard: Balancing economic growth, sustainability, and environmental governance. *Polar Record* **57**, e47. <https://doi.org/10.1017/S00322474211000668>.
- Hovelsrud GK, West J and Dannevig H (2015) Exploring vulnerability and adaptation narratives among fishers, farmers and municipal planners in Northern Norway. In *The Adaptive Challenge of Climate Change*, pp. 194–212.
- Hunt GL, Coyle KO, Eisner LB, Farley EV, Heintz RA, Mueter F, Napp JM, Overland JE, Ressler PH, Salo S and Stabeno PJ (2011) Climate impacts on eastern Bering Sea foodwebs: A synthesis of new data and an assessment of the oscillating control hypothesis. *ICES Journal of Marine Science* **68**(6), 1230–1243. <https://doi.org/10.1093/icesjms/fsr036>.
- Huss M and Hock R (2018) Global-scale hydrological response to future glacier mass loss. *Nature Climate Change* **8**(2), Article 2. <https://doi.org/10.1038/s41558-017-0049-x>.
- Iken K, Bluhm B and Dunton K (2010) Benthic food-web structure under differing water mass properties in the southern Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography* **57**(1), 71–85. <https://doi.org/10.1016/j.dsr2.2009.08.007>.
- IPCC (2021) Summary for policymakers. In (Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R and B Zhou (eds), *Climate Change 2021: The Physical Science Basis*. Cambridge: Cambridge University Press.
- Isaksen K, Nordli Ø, Ivanov B, Koltzow MAØ, Aaboe S, Gjeltén HM, Mezghani A, Eastwood S, Forland E, Benestad RE, Hanssen-Bauer I, Brækkan R, Sviashchennikov P, Demin V, Revina A and Karandasheva T (2022) Exceptional warming over the Barents area. *Scientific Reports* **12**(1), 9371. <https://doi.org/10.1038/s41598-022-13568-5>.
- Isbell F, Cowles J, Dee LE, Loreau M, Reich PB, Gonzalez A, Hector A and Schmid B (2018) Quantifying effects of biodiversity on ecosystem functioning across times and places. *Ecology Letters* **21**(6), 763–778. <https://doi.org/10.1111/ele.12928>.
- Jiang S, Ye A and Xiao C (2020) The temperature increase in Greenland has accelerated in the past five years. *Global and Planetary Change* **194**, 103297. <https://doi.org/10.1016/j.gloplacha.2020.103297>.
- Jørgensen LL, Primicerio R, Ingvaldsen RB, Fossheim M, Strelkova N, Thangstad TH, Manushin I and Zakharov D (2019) Impact of multiple stressors on sea bed fauna in a warming Arctic. *Marine Ecology Progress Series* **608**, 1–12. <https://doi.org/10.3354/meps12803>.
- Juul-Pedersen T, Arendt KE, Mortensen J, Blicher ME, Søgaard DH and Rysgaard S (2015) Seasonal and interannual phytoplankton production in a sub-Arctic tidewater outlet glacier fjord, SW Greenland. *Marine Ecology Progress Series* **524**, 27–38. <https://doi.org/10.3354/meps11174>.
- Kaiser MJ, Clarke KR, Hinz H, Austen MCV, Somerfield PJ and Karakassis I (2006) Global analysis of response and recovery of benthic biota to fishing. *Marine Ecology Progress Series* **311**, 1–14. <https://doi.org/10.3354/meps311001>.
- Kędra M, Moritz C, Choy ES, David C, Degen R, Duerksen S, Ellingsen I, Górka B, Grebmeier JM, Kirievskaya D, van Oevelen D, Piwosz K, Samuelsen A and Węślawski JM (2015) Status and trends in the structure of Arctic benthic food webs. *Polar Research* **34**(1), 23775. <https://doi.org/10.3402/polar.v34.23775>.
- Kędra M, Włodarska-Kowalczyk M and Węślawski JM (2010) Decadal change in macrobenthic soft-bottom community structure in a high Arctic fjord (Kongsfjorden, Svalbard). *Polar Biology* **33**(1), 1–11. <https://doi.org/10.1007/s00300-009-0679-1>.
- Kempf S (2020) The Physiological Response of an Arctic Key Species Polar Cod, *Boreogadus saida*, to Environmental Hypoxia: Critical Oxygen Level and Swimming Performance. Master thesis, Universität Bremen.
- Kochtitzky W and Copland L (2022) Retreat of northern hemisphere marine-terminating glaciers, 2000–2020. *Geophysical Research Letters* **49**(3), e2021GL096501. <https://doi.org/10.1029/2021GL096501>.
- Konik M, Darecki M, Pavlov AK, Sagan S and Kowalczyk P (2021) Darkening of the Svalbard fjords waters observed with Satellite Ocean color imagery in 1997–2019. *Frontiers in Marine Science* **8**, 699318. <https://www.frontiersin.org/articles/10.3389/fmars.2021.699318>.
- Kortsch S, Primicerio R, Beuchel F, Renaud PE, Rodrigues J, Lønne OJ and Gulliksen B (2012) Climate-driven regime shifts in Arctic marine benthos. *Proceedings of the National Academy of Sciences* **109**(35), 14052–14057. <https://doi.org/10.1073/pnas.1207509109>.
- Kortsch S, Primicerio R, Fossheim M, Dolgov AV and Aschan M (2015) Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. *Proceedings of the Royal Society B: Biological Sciences* **282**(1814), 20151546. <https://doi.org/10.1098/rspb.2015.1546>.
- Kotwicki L, Grzelak K, Opaliński K and Węślawski JM (2018) Total benthic oxygen uptake in two Arctic fjords (Spitsbergen) with different hydrological regimes. *Oceanologia* **60**(2), 107–113. <https://doi.org/10.1016/j.oceano.2017.11.005>.
- Krause-Jensen D, Archambault P, Assis J, Bartsch I, Bischof K, Filbee-Dexter K, Dunton KH, Maximova O, Ragnarsdóttir SB, Sejr MK, Simakova U, Spiridonov V, Wegeberg S, Winding MHS and Duarte CM (2020) Imprint of climate change on pan-Arctic marine vegetation. *Frontiers in Marine Science* **7**, 617324. <https://doi.org/10.3389/fmars.2020.617324>.
- Krawczyk DW, Meire L, Lopes C, Juul-Pedersen T, Mortensen J, Li CL and Krogh T (2018) Seasonal succession, distribution, and diversity of planktonic protists in relation to hydrography of the Godthåbsfjord system (SW Greenland). *Polar Biology* **41**(10), 2033–2052. <https://doi.org/10.1007/s00300-018-2343-0>.
- Kujawa A, Łącka M, Szymańska N, Pawłowska J, Telesiński MM and Zajaczkowski M (2021) Could Norwegian fjords serve as an analogue for the future of the Svalbard fjords? State and fate of high latitude fjords in the face of progressive “atlantification”. *Polar Biology* **44**(12), 2217–2233. <https://doi.org/10.1007/s00300-021-02951-z>.
- Laeseke P, Bartsch I and Bischof K (2019) Effects of kelp canopy on underwater light climate and viability of brown algal spores in Kongsfjorden (Spitsbergen). *Polar Biology* **42**(8), 1511–1527. <https://doi.org/10.1007/s00300-019-02537-w>.



- Lamy T, Wang S, Renard D, Lafferty KD, Reed DC and Miller RJ (2019) Species insurance trumps spatial insurance in stabilizing biomass of a marine macroalgal metacommunity. *Ecology* **100**(7), e02719. <https://doi.org/10.1002/ecy.2719>.
- Liston GE and Hiemstra CA (2011) The changing cryosphere: Pan-Arctic snow trends (1979–2009). *Journal of Climate* **24**(21), 5691–5712. <https://doi.org/10.1175/JCLI-D-11-00081.1>.
- Lydersen C, Assmy P, Falk-Petersen S, Kohler J, Kovacs KM, Reigstad M, Steen H, Strøm H, Sundfjord A, Varpe Ø, Walczowski W, Weslawski JM and Zajaczkowski M (2014) The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. *Journal of Marine Systems* **129**, 452–471. <https://doi.org/10.1016/j.jmarsys.2013.09.006>.
- Mankoff KD, Noël B, Fettweis X, Ahlstrøm AP, Colgan W, Kondo K, Langley K, Sugiyama S, van As D and Fausto RS (2020) Greenland liquid water discharge from 1958 through 2019. *Earth System Science Data* **12**(4), 2811–2841. <https://doi.org/10.5194/essd-12-2811-2020>.
- Manney GL, Santee ML, Rex M, Livesey NJ, Pitts MC, Veefkind P, Nash ER, Wohltmann I, Lehmann R, Froidevaux L, Poole LR, Schoeberl MR, Haffner DP, Davies J, Dorokhov V, Gernandt H, Johnson B, Kivi R, Kyrö E, Larsen N, Levelt PF, Makshtas A, McElroy CT, Nakajima H, Parrondo MC, Tarasick DW, von der Gathen P, Walker KA and Zinoviev NS (2011) Unprecedented Arctic ozone loss in 2011. *Nature* **478**(7370), Article 7370. <https://doi.org/10.1038/nature10556>.
- Maturilli M, Hanssen-Bauer I, Neuber R, Rex M and Edvardsen K (2019) The atmosphere above Ny-Ålesund: Climate and global warming, ozone and surface UV radiation. In Hop H and Wiencke C (eds), *The Ecosystem of Kongsfjorden, Svalbard*. Cham: Springer International Publishing, pp. 23–46. [https://doi.org/10.1007/978-3-319-46425-1\\_2](https://doi.org/10.1007/978-3-319-46425-1_2).
- McGovern M, Pavlov AK, Deininger A, Granskog MA, Leu E, Søreide JE and Poste AE (2020) Terrestrial inputs drive seasonality in organic matter and nutrient biogeochemistry in a high Arctic fjord system (Isfjorden, Svalbard). *Frontiers in Marine Science* **7**, 542563. <https://www.frontiersin.org/articles/10.3389/fmars.2020.542563>.
- Meire L, Mortensen J, Rysgaard S, Bendtsen J, Boone W, Meire P and Meysman FJR (2016) Spring bloom dynamics in a subarctic fjord influenced by tidewater outlet glaciers (Godthåbsfjord, SW Greenland). *Journal of Geophysical Research: Biogeosciences* **121**(6), 1581–1592. <https://doi.org/10.1002/2015JG003240>.
- Meredith M, Sommerkorn M, Cassotta S, Derksen C, Ekaykin A, Hollowed A, Kofinas G, Mackintosh, Melbourne-Thomas J, Muelbert M, Ottersen G, Pritchard H and Schuur E (2019) Polar regions. In Pörtner H-O, Roberts D, Masson-Delmotte V and Zhai P (eds), *Special Report on Ocean and Cryosphere in a Changing Climate: Vol. Special Report on Ocean and Cryosphere in a Changing Climate*. Cambridge: Cambridge University Press, pp. 73–129.
- Mérlillet L, Skogen MD, Vikebø F and Jørgensen LL (2022) Fish assemblages of a sub-Arctic fjord show early signals of climate change response contrary to the benthic assemblages. *Frontiers in Marine Science* **9**, 822979. <https://www.frontiersin.org/articles/10.3389/fmars.2022.822979>.
- Merkouriadi I, Cheng B, Graham RM, Rösel A and Granskog MA (2017) Critical role of snow on sea ice growth in the Atlantic sector of the Arctic Ocean. *Geophysical Research Letters* **44**(20), 10,479–10,485. <https://doi.org/10.1002/2017GL075494>.
- Middelbo AB, Møller EF, Arendt KE, Thyrring J and Sejr MK (2019) Spatial, seasonal and inter-annual variation in abundance and carbon turnover of small copepods in young sound, Northeast Greenland. *Polar Biology* **42**(1), 179–193. <https://doi.org/10.1007/s00300-018-2416-0>.
- Misund OA, Heggland K, Skogseth R, Falck E, Gjosæter H, Sundet J, Watne J and Lønne OJ (2016) Norwegian fisheries in the Svalbard zone since 1980. Regulations, profitability and warming waters affect landings. *Polar Science* **10**(3), 312–322. <https://doi.org/10.1016/j.polar.2016.02.001>.
- MoCE (2020) *Green Paper from the Ministry of Climate and Environment (MoCE) on Policies for the High North, (Mld. St. 9 2020–2021)*. (Stortingsmelding). Regjeringen.no. November 27. Available at <https://www.regjeringen.no/no/dokumenter/meld.-st.-9-20202021/id2787429/>. (Accessed 14 October 2022)
- Møller V, van Diemen R, Matthews J, Méndez C, Semenov S, Fuglestedt J and Reisinger A (2022) Annex II: Glossary. In Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Lösche S, Möller V, Okem A and Rama B (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 2897–2930.
- Moon T, Sutherland DA, Carroll D, Felikson D, Kehrl L and Straneo F (2018) Subsurface iceberg melt key to Greenland fjord freshwater budget. *Nature Geoscience* **11**(1), Article 1. <https://doi.org/10.1038/s41561-017-0018-z>.
- Mortensen J, Rysgaard S, Bendtsen J, Lennert K, Kanzow T, Lund H and Meire L (2020) Subglacial discharge and its Down-Fjord transformation in West Greenland fjords with an ice Mélange. *Journal of Geophysical Research: Oceans* **125**(9), e2020JC016301. <https://doi.org/10.1029/2020JC016301>.
- Mouginot J, Rignot E, Bjørk AA, van den Broeke M, Millan R, Morlighem M, Noël B, Scheuchl B and Wood M (2019) Forty-six years of Greenland ice sheet mass balance from 1972 to 2018. *Proceedings of the National Academy of Sciences* **116**(19), 9239–9244. <https://doi.org/10.1073/pnas.1904242116>.
- Muckenhuber S, Nilsen F, Korosov A and Sandven S (2016) Sea ice cover in Isfjorden and Hornsund, Svalbard (2000–2014) from remote sensing data. *The Cryosphere* **10**(1), 149–158. <https://doi.org/10.5194/tc-10-149-2016>.
- NEA (2022) *Høringsuttalelse: Endringer i svalbardmiljøloven og tilhørende forskrifter om naturvernområder, otorferdsel, leiropphold og om områdefredning og ferdselsregulering i Virgohamna*. Miljødirektoratet (Norwegian Environmental Agency, Oslo, Norway).
- Neukermans G, Oziel L and Babin M (2018) Increased intrusion of warming Atlantic water leads to rapid expansion of temperate phytoplankton in the Arctic. *Global Change Biology* **24**(6), 2545–2553. <https://doi.org/10.1111/gcb.14075>.
- Niemi A, Bednarek N, Michel C, Feely RA, Williams W, Azetsu-Scott K, Walkusz W and Reist JD (2021) Biological impact of ocean acidification in the Canadian Arctic: Widespread severe pteropod shell dissolution in Amundsen Gulf. *Frontiers in Marine Science* **8**, 600184. <https://www.frontiersin.org/articles/10.3389/fmars.2021.600184>.
- NMJ (2016) *Svalbard—Meld.St. 32. 2015–2016. White Paper to the Norwegian Parliament from the Ministry of Justice*. (Stortingsmelding). Regjeringen.no. May 11. Available at <https://www.regjeringen.no/en/dokumenter/meld.-st.-32-20152016/id2499962/>. (Accessed 14 October 2022)
- Nowak A, Hodgkins R, Nikulina A, Osuch M, Wazryniak T, Kavan J, Łepkowska E, Majerska M, Romashova K, Vasilevich I, Sobota I and Rachlewicz G (2021) *From Land to Fjords: The Review of Svalbard Hydrology from 1970 to 2019 (SvalHydro)*. Leicestershire, UK: Loughborough University. <https://doi.org/10.5281/ZENODO.4294063>.
- NSIDC (2022) U.S. National Ice Center and National Snow and Ice Data Center. Compiled by F Fetterer, M Savoie, S Helfrich and P Clemente-Colón. 2010, updated daily. *Multisensor Analyzed Sea Ice Extent—Northern Hemisphere (MASIE-NH), Version 1. 4km resolution*. Boulder, CO, USA: National Snow and Ice Data Center. <https://doi.org/10.7265/N5GT5K3K>.
- Øian H and Kaltenborn B (2020) *Turisme på Svalbard og i Arktis. Effekter på naturmiljø, kulturminner og samfunn med hovedvekt på cruiseturisme*. Trondheim, Norway: Norsk institutt for naturforskning (NINA). <https://brage.nina.no/nina-xmlui/handle/11250/2643245>.
- Overland J, Dunlea E, Box JE, Corell R, Forsius M, Kattsov V, Olsen MS, Pawlak J, Reiersen L-O and Wang M (2019) The urgency of Arctic change. *Polar Science* **21**, 6–13. <https://doi.org/10.1016/j.polar.2018.11.008>.
- Oziel L, Neukermans G, Ardyna M, Lancelot C, Tison J-L, Wassmann P, Sirven J, Ruiz-Pino D and Gascard J-C (2017) Role for Atlantic inflows and sea ice loss on shifting phytoplankton blooms in the Barents Sea. *Journal of Geophysical Research: Oceans* **122**(6), 5121–5139. <https://doi.org/10.1002/2016JC012582>.
- Palma D, Varnajot A, Dalen K, Basaran IK, Brunette C, Bystrowska M, Korablina AD, Nowicki RC and Ronge TA (2019) Cruising the marginal ice zone: Climate change and Arctic tourism. *Polar Geography* **42**(4), 215–235. <https://doi.org/10.1080/1088937X.2019.1648585>.
- Paulsen ML, Nielsen SEB, Müller O, Møller EF, Stedmon CA, Juul-Pedersen T, Markager S, Sejr MK, Delgado Huertas A, Larsen A and Middelboe M (2017) Carbon bioavailability in a high Arctic fjord influenced by glacial meltwater, NE Greenland. *Frontiers in Marine Science* **4**, 176. <https://www.frontiersin.org/articles/10.3389/fmars.2017.00176>.
- Pavlov AK, Leu E, Hanelt D, Bartsch I, Karsten U, Hudson SR, Gallet J-C, Cottier F, Cohen JH, Berge J, Johnsen G, Maturilli M, Kowalczyk P, Sagan

- S, Meler J and Granskog MA (2019) The underwater light climate in Kongsfjorden and its ecological implications. In Hop H and Wiencke C (eds), *The Ecosystem of Kongsfjorden, Svalbard*. Cham: Springer International Publishing, pp. 137–170. [https://doi.org/10.1007/978-3-319-46425-1\\_5](https://doi.org/10.1007/978-3-319-46425-1_5).
- Pavlov AK, Tverberg V, Ivanov BV, Nilsen F, Falk-Petersen S and Granskog MA (2013) Warming of Atlantic water in two West Spitsbergen fjords over the last century (1912–2009). *Polar Research* 32(1), 11206. <https://doi.org/10.3402/polar.v32i0.11206>.
- Pavlova O, Gerland S and Hop H (2019) Changes in sea-ice extent and thickness in Kongsfjorden, Svalbard (2003–2016). In Hop H and Wiencke C (eds), *The Ecosystem of Kongsfjorden, Svalbard*. Cham: Springer International Publishing, pp. 105–136. [https://doi.org/10.1007/978-3-319-46425-1\\_4](https://doi.org/10.1007/978-3-319-46425-1_4).
- Pecuchet L, Blanchet M-A, Frainer A, Husson B, Jørgensen LL, Kortsch S and Primicerio R (2020) Novel feeding interactions amplify the impact of species redistribution on an Arctic food web. *Global Change Biology* 26(9), 4894–4906. <https://doi.org/10.1111/gcb.15196>.
- Petrich C, O'Sadnick ME and Dale L (2017) Recent Ice Conditions in North-Norwegian Porsangerfjorden. Available at: <https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2640259>. (Accessed 14 October 2022)
- Piquet AM-T, van de Poll WH, Visser RJW, Wiencke C, Bolhuis H and Buma AGJ (2014) Springtime phytoplankton dynamics in Arctic Krossfjorden and Kongsfjorden (Spitsbergen) as a function of glacier proximity. *Biogeosciences* 11(8), 2263–2279. <https://doi.org/10.5194/bg-11-2263-2014>.
- Piwosz K, Walkusz W, Hapter R, Wieczorek P, Hop H and Wiktor J (2009) Comparison of productivity and phytoplankton in a warm (Kongsfjorden) and a cold (Hornsund) Spitsbergen fjord in mid-summer 2002. *Polar Biology* 32(4), 549–559. <https://doi.org/10.1007/s00300-008-0549-2>.
- Polyakov IV, Alkire MB, Bluhm BA, Brown KA, Carmack EC, Chierici M, Danielson SL, Ellingsen I, Ershova EA, Gårdfeldt K, Ingvaldsen RB, Pnyushkov AV, Slagstad D and Wassmann P (2020) Borealization of the Arctic Ocean in response to anomalous advection from sub-Arctic seas. *Frontiers in Marine Science* 7, 491. <https://www.frontiersin.org/articles/10.3389/fmars.2020.00491>.
- Port of Longyearbyen (2018) *Statistics Port of Longyearbyen 2006–2017 (Statistics)*. Port of Longyearbyen. Available at [https://portlongyear.no/wp-content/uploads/2017/02/Statistics\\_2006-2017.pdf](https://portlongyear.no/wp-content/uploads/2017/02/Statistics_2006-2017.pdf). (Accessed 14 October 2022)
- Qi D, Ouyang Z, Chen L, Wu Y, Lei R, Chen B, Feely RA, Anderson LG, Zhong W, Lin H, Polukhin A, Zhang Y, Zhang Y, Bi H, Lin X, Luo Y, Zhuang Y, He J, Chen J and Cai W-J (2022) Climate change drives rapid decadal acidification in the Arctic Ocean from 1994 to 2020. *Science* 377(6614), 1544–1550. <https://doi.org/10.1126/science.abo0383>.
- Rantanen M, Karpechko AY, Lipponen A, Nordling K, Hyvärinen O, Ruosteenoja K, Vihma T and Laaksonen A (2022) The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment* 3(1), Article 1. <https://doi.org/10.1038/s43247-022-00498-3>.
- Ren C, James L, Pashkevich A and Hoarau-Heemstra H (2021a) Cruise trouble. A practice-based approach to studying Arctic cruise tourism. *Tourism Management Perspectives* 40, 100901. <https://doi.org/10.1016/j.tmp.2021.100901>.
- Ren C, Jóhannesson GT, Kramvig B, Pashkevich A and Höckert E (2021b) 20 years of research on Arctic and indigenous cultures in Nordic tourism: A review and future research agenda. *Scandinavian Journal of Hospitality and Tourism* 21(1), 111–121. <https://doi.org/10.1080/15022250.2020.1830433>.
- Renaud PE, Wallhead P, Kotta J, Włodarska-Kowalczyk M, Bellerby RGJ, Rätsep M, Slagstad D and Kukliński P (2019) Arctic sensitivity? Suitable habitat for benthic taxa is surprisingly robust to climate change. *Frontiers in Marine Science* 6, 538. <https://www.frontiersin.org/articles/10.3389/fmars.2019.00538>.
- Sakshaug E and Myklestad S (1973) Studies on the phytoplankton ecology of the trondheimsfjord. III. Dynamics of phytoplankton blooms in relation to environmental factors, bioassay experiments and parameters for the physiological state of the populations. *Journal of Experimental Marine Biology and Ecology* 11(2), 157–188. [https://doi.org/10.1016/0022-0981\(73\)90053-1](https://doi.org/10.1016/0022-0981(73)90053-1).
- Santos-Garcia M, Ganeshram RS, Tuerena RE, Debyser MCF, Husum K, Assmy P and Hop H (2022) Nitrate isotope investigations reveal future impacts of climate change on nitrogen inputs and cycling in Arctic fjords: Kongsfjorden and Rijpfjorden (Svalbard). *Biogeosciences* 19(24), 5973–6002. <https://doi.org/10.5194/bg-19-5973-2022>.
- Schlegel RW and Gattuso J-P (in review, 2023) *The Changing Fjords of the European Arctic: What Do the Data Say?* Earth System Science Data. <https://doi.org/10.5194/essd-2022-455>
- Schuler TV, Kohler J, Elagina N, Hagen JOM, Hodson AJ, Jania JA, Käab AM, Luks B, Małecki J, Moholdt G, Pohjola VA, Sobota I and Van Pelt WJJ (2020) Reconciling Svalbard glacier mass balance. *Frontiers in Earth Science* 8, 156. <https://www.frontiersin.org/articles/10.3389/feart.2020.00156>.
- Sejr MK, Stedmon CA, Bendtsen J, Abermann J, Juul-Pedersen T, Mortensen J and Rysgaard S (2017) Evidence of local and regional freshening of North-east Greenland coastal waters. *Scientific Reports* 7(1), Article 1. <https://doi.org/10.1038/s41598-017-10610-9>.
- Shiklomanov A, Déry S, Tretiakov M, Yang D, Magritsky D, Georgiadi A and Tang W (2021) River freshwater flux to the Arctic Ocean. In Yang D and Kane DL (eds), *Arctic Hydrology, Permafrost and Ecosystems*. Cham: Springer International Publishing, pp. 703–738. [https://doi.org/10.1007/978-3-030-50930-9\\_24](https://doi.org/10.1007/978-3-030-50930-9_24).
- Shiklomanov IA (1997) *Assessment of Water Resources and Water Availability in the World* (Comprehensive Assessment of the Freshwater Re-Sources of the World). World Meteorological Organization. Available at <https://digitallibrary.un.org/record/261669>. (Accessed 14 October 2022)
- Skogseth R, Olivier LLA, Nilsen F, Falck E, Fraser N, Tverberg V, Ledang AB, Vader A, Jonassen MO, Søreide J, Cottier F, Berge J, Ivanov BV and Falk-Petersen S (2020) Variability and decadal trends in the Isfjorden (Svalbard) ocean climate and circulation – An indicator for climate change in the European Arctic. *Progress in Oceanography* 187, 102394. <https://doi.org/10.1016/j.pocean.2020.102394>.
- Slagstad D, Wassmann PFJ and Ellingsen I (2015) Physical constrains and productivity in the future Arctic Ocean. *Frontiers in Marine Science* 2, 85. <https://www.frontiersin.org/articles/10.3389/fmars.2015.00085>.
- Smith RW, Bianchi TS, Allison M, Savage C and Galy V (2015) High rates of organic carbon burial in fjord sediments globally. *Nature Geoscience* 8(6), Article 6. <https://doi.org/10.1038/ngeo2421>.
- Søreide JE, Pituis V, Vader A, Damsgård B, Nilsen F, Skogseth R, Poste A, Bailey A, Kovacs KM, Lydersen C, Gerland S, Descamps S, Strom H, Renaud PE, Christensen G, Arvnes MP, Moiseev D, Singh RK, Bélanger S, Elster J, Urbański J, Moskalik M, Wiktor J and Węśławski JM (2021) Environmental status of Svalbard coastal waters: Coastscapes and focal ecosystem components. In Moreno-Ibáñez M, Hagen JOM, Hübner C, Lihavainen H, Zaborska A (eds), *SESS report 2020: summary for stakeholders: the State of Environmental Science in Svalbard: an annual report*. Longyearbyen, Norway: Svalbard Integrated Arctic Earth Observing System (SIOS), pp. 142–174. <https://doi.org/10.5281/ZENODO.4293849>.
- Søvik G, Nedreaas K, Zimmermann F, Husson B, Strand HK, Jørgensen LL, Strand M, Thangstad TH, Hansen A, Båtevik T, Albreten J and Staby A (2020) *Kartlegging av fjordøkosystemene i Tana- og Porsangerfjorden*. Havforskning sinstituttet. Available at <https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2020-39>. (Accessed 14 October 2022)
- Spotowitz L, Johansen T, Hansen A, Berg E, Stransky C and Fischer P (2022) New evidence for the establishment of coastal cod *Gadus morhua* in Svalbard fjords. *Marine Ecology Progress Series* 696, 119–133. <https://doi.org/10.3354/meps14126>.
- Steinacher M, Joos F, Frölicher TL, Plattner G-K and Doney SC (2009) Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. *Biogeosciences* 6(4), 515–533. <https://doi.org/10.5194/bg-6-515-2009>.
- Stigebrandt A (2012) Hydrodynamics and circulation of fjords. In Bengtsson L, Herschy RW and Fairbridge RW (eds), *Encyclopedia of Lakes and Reservoirs*. Cham: Springer Netherlands, pp. 327–344. [https://doi.org/10.1007/978-1-4020-4410-6\\_247](https://doi.org/10.1007/978-1-4020-4410-6_247).
- Stocker AN, Renner AHH and Knol-Kauffman M (2020) Sea ice variability and maritime activity around Svalbard in the period 2012–2019. *Scientific Reports* 10(1), Article 1. <https://doi.org/10.1038/s41598-020-74064-2>.
- Storch D, Menzel L, Frickenhaus S and Pörtner H-O (2014) Climate sensitivity across marine domains of life: Limits to evolutionary adaptation shape species interactions. *Global Change Biology* 20(10), 3059–3067. <https://doi.org/10.1111/gcb.12645>.



- Stroeve J and Notz D** (2018) Changing state of Arctic Sea ice across all seasons. *Environmental Research Letters* **13**(10), 103001. <https://doi.org/10.1088/1748-9326/aade56>.
- Sun M-Y, Clough LM, Carroll ML, Dai J, Ambrose WG and Lopez GR** (2009) Different responses of two common Arctic macrobenthic species (*Macoma balthica* and *Monoporeia affinis*) to phytoplankton and ice algae: Will climate change impacts be species specific? *Journal of Experimental Marine Biology and Ecology* **376**(2), 110–121. <https://doi.org/10.1016/j.jembe.2009.06.018>.
- Sundet JH and Hoel AH** (2016) The Norwegian management of an introduced species: The Arctic red king crab fishery. *Marine Policy* **72**, 278–284. <https://doi.org/10.1016/j.marpol.2016.04.041>.
- Tarling GA, Freer JJ, Banas NS, Belcher A, Blackwell M, Castellani C, Cook KB, Cottier FR, Daase M, Johnson ML, Last KS, Lindeque PK, Mayor DJ, Mitchell E, Parry HE, Speirs DC, Stowasser G and Wootton M** (2022) Can a key boreal *Calanus* copepod species now complete its life-cycle in the Arctic? Evidence and implications for Arctic food-webs. *Ambio* **51**(2), 333–344. <https://doi.org/10.1007/s13280-021-01667-y>.
- Terhaar J, Lauerwald R, Regnier P, Gruber N and Bopp L** (2021) Around one third of current Arctic Ocean primary production sustained by rivers and coastal erosion. *Nature Communications* **12**(1), Article 1. <https://doi.org/10.1038/s41467-020-20470-z>.
- Thierry A, Bullock JM and Gardner CJ** (2022) The recent past is not a reliable guide to future climate impacts: Response to Caro et al. (2022). *Conservation Letters* **15**, e12915. <https://doi.org/10.1111/conl.12915>.
- Tuholske C, Halpern BS, Blasco G, Villaseñor JC, Frazier M and Caylor K** (2021) Mapping global inputs and impacts from of human sewage in coastal ecosystems. *PLoS One* **16**(11), e0258898. <https://doi.org/10.1371/journal.pone.0258898>.
- Tverberg V, Skogseth R, Cottier F, Sundfjord A, Walczowski W, Inall ME, Falck E, Pavlova O and Nilsen F** (2019) The Kongsfjorden transect: Seasonal and inter-annual variability in hydrography. In Hop H and Wiencke C (eds), *The Ecosystem of Kongsfjorden, Svalbard*. Cham: Springer International Publishing, pp. 49–104. [https://doi.org/10.1007/978-3-319-46425-1\\_3](https://doi.org/10.1007/978-3-319-46425-1_3).
- Tyler NJC, Turi JM, Sundset MA, Strom Bull K, Sara MN, Reinert E, Oskal N, Nellemann C, McCarthy JJ, Mathiesen SD, Martello ML, Magga OH, Hovelsrud GK, Hanssen-Bauer I, Eira NI, Eira IMG and Corell WR** (2007) Saami reindeer pastoralism under climate change: Applying a generalized framework for vulnerability studies to a sub-arctic social-ecological system. *Global Environmental Change* **17**(2), 191–206. <https://doi.org/10.1016/j.gloenvcha.2006.06.001>.
- Urbański JA and Litwicka D** (2022) The decline of Svalbard land-fast sea ice extent as a result of climate change. *Oceanologia* **64**(3), 535–545. <https://doi.org/10.1016/j.oceano.2022.03.008>.
- Valiela I** (2015) *Marine Ecological Processes*. New York City, NY, USA: Springer-Verlag. <https://link.springer.com/book/10.1007/978-0-387-79070-1>.
- Vereide EH** (2019) Seasonal Zooplankton Community Patterns along a Gradient from Land to Sea in Isfjorden, Svalbard. Master thesis. Available at <https://www.duo.uio.no/handle/10852/74253>. (Accessed 14 October 2022)
- Vihitakari M** (2022) ggOceanMaps: Plot data on oceanographic maps using “ggplot2” (1.3.4) (R). Available at <https://CRAN.R-project.org/package=ggOceanMaps>. (Accessed 14 October 2022)
- Vihitakari M, Welcker J, Moe B, Chastel O, Tartu S, Hop H, Bech C, Descamps S and Gabrielsen GW** (2018) Black-legged kittiwakes as messengers of atlantification in the Arctic. *Scientific Reports* **8**(1), Article 1. <https://doi.org/10.1038/s41598-017-19118-8>.
- Visit Greenland** (2022) Visit Greenland Wants to Highlight the Challenges and Potentials in Cruise Tourism. Available at <https://traveltrade.visitgreenland.com/latest-news/visit-greenland-wants-to-highlight-the-challenges-and-potentials-in-cruise-tourism/>. (Accessed 14 October 2022)
- Visit Svalbard** (2020) Statistikk fra Visit Svalbard AS. Available at <https://www.visitsvalbard.com/dbimms/Statistikk%20gjester%20Svalbard%202007-2018%20%20per%20august.pdf>. (Accessed 14 October 2022)
- Wadham JL, Hawkings JR, Tarasov L, Gregoire LJ, Spencer RGM, Gutjahr M, Ridgwell A and Kohfeld KE** (2019) Ice sheets matter for the global carbon cycle. *Nature Communications* **10**(1), Article 1. <https://doi.org/10.1038/s41467-019-11394-4>.
- Walch DMR, Singh RK, Søreide JE, Lantuit H and Poste A** (2022) Spatio-temporal variability of suspended particulate matter in a high-Arctic estuary (Adventfjorden, Svalbard) using Sentinel-2 time-series. *Remote Sensing* **14**(13), Article 13. <https://doi.org/10.3390/rs14133123>.
- Wassmann P, Svendsen H, Keck A and Reigstad M** (1996) Selected aspects of the physical oceanography and particle fluxes in fjords of northern Norway. *Journal of Marine Systems* **8**(1), 53–71. [https://doi.org/10.1016/0924-7963\(95\)00037-2](https://doi.org/10.1016/0924-7963(95)00037-2).
- Weaver DB and Lawton LJ** (2017) A new visitation paradigm for protected areas. *Tourism Management* **60**, 140–146. <https://doi.org/10.1016/j.tourman.2016.11.018>.
- Wei T, Yan Q, Qi W, Ding M and Wang C** (2020) Projections of Arctic Sea ice conditions and shipping routes in the twenty-first century using CMIP6 forcing scenarios. *Environmental Research Letters* **15**(10), 104079. <https://doi.org/10.1088/1748-9326/abb2c8>.
- Węśławski JM, Kendall MA, Włodarska-Kowalczyk M, Iken K, Kędra M, Legezyska J and Sejr MK** (2011) Climate change effects on Arctic fjord and coastal macrobenthic diversity—Observations and predictions. *Marine Biodiversity* **41**(1), 71–85. <https://doi.org/10.1007/s12526-010-0073-9>.
- Węśławski JM, Wiktor J and Kotwicki L** (2010) Increase in biodiversity in the arctic rocky littoral, Sorkapland, Svalbard, after 20 years of climate warming. *Marine Biodiversity* **40**(2), 123–130. <https://doi.org/10.1007/s12526-010-0038-z>.
- Wiedmann I, Reigstad M, Marquardt M, Vader A and Gabrielsen TM** (2016) Seasonality of vertical flux and sinking particle characteristics in an ice-free high Arctic fjord—Different from subarctic fjords? *Journal of Marine Systems* **154**, 192–205. <https://doi.org/10.1016/j.jmarsys.2015.10.003>.
- Wiencke C and Hop H** (2016) Ecosystem Kongsfjorden: New views after more than a decade of research. *Polar Biology* **39**(10), 1679–1687. <https://doi.org/10.1007/s00300-016-2032-9>.
- Wiencke C, Roleda MY, Gruber A, Clayton MN and Bischof K** (2006) Susceptibility of zoospores to UV radiation determines upper depth distribution limit of Arctic kelps: Evidence through field experiments. *Journal of Ecology* **94**(2), 455–463.
- Wild B, Andersson A, Bröder L, Vonk J, Hugelius G, McClelland JW, Song W, Raymond PA and Gustafsson Ö** (2019) Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing permafrost. *Proceedings of the National Academy of Sciences* **116**(21), 10280–10285. <https://doi.org/10.1073/pnas.1811797116>.
- Willis K, Cottier F, Kwasniewski S, Wold A and Falk-Petersen S** (2006) The influence of advection on zooplankton community composition in an Arctic fjord (Kongsfjorden, Svalbard). *Journal of Marine Systems* **61**(1), 39–54. <https://doi.org/10.1016/j.jmarsys.2005.11.013>.
- Włodarska-Kowalczyk M, Renaud PE, Węśławski JM, Cochrane SKJ and Denisenko SG** (2012) Species diversity, functional complexity and rarity in Arctic fjordic versus open shelf benthic systems. *Marine Ecology Progress Series* **463**, 73–87. <https://doi.org/10.3354/meps09858>.
- Wood HL, Spicer JI, Kendall MA, Lowe DM and Widdicombe S** (2011) Ocean warming and acidification; implications for the Arctic brittlestar *Ophiocten sericeum*. *Polar Biology* **34**(7), 1033–1044. <https://doi.org/10.1007/s00300-011-0963-8>.
- Yachi S and Loreau M** (1999) Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. *Proceedings of the National Academy of Sciences* **96**(4), 1463–1468. <https://doi.org/10.1073/pnas.96.4.1463>.
- Zhang Y, Yamamoto-Kawai M and Williams Wj** (2020) Two decades of ocean acidification in the surface waters of the Beaufort gyre, Arctic Ocean: Effects of sea ice melt and retreat from 1997–2016. *Geophysical Research Letters* **47**(3), e60119. <https://doi.org/10.1029/2019GL086421>.
- Zhuravskiy D, Ivanov B and Pavlov A** (2012) Ice conditions at Gronfjorden Bay, Svalbard, from 1974 to 2008. *Polar Geography* **35**(2), 169–176. <https://doi.org/10.1080/1088937X.2012.662535>.