Section 4

Subchapter 5R

Fjord systems

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Key points

- Fjords are ecologically carbon organic-rich regions and home to Indigenous Peoples and local communities.
- Global warming is already affecting both northern and southern hemisphere fjords (through warming, deoxygenation and acidification).
- The loss of glacier ice and the changing seasonality of the hydrological cycle is affecting physical and chemical factors and processes in fjord systems.

1. Introduction

The fjord systems of the world are characterized by a deep basin connecting directly or indirectly with the open sea at the mouth (Matthews and Heimdal, 1980). Fjords are often long, narrow, deep and steep-sided inlets, frequently branched and sinuous, or straight, and may contain one or more submarine sills (a shallow dome of bedrock that forms at the mouth of a fjord). The presence and size of these sills at the fjord's mouth can restrict the exchange of water between the fjord and the coastal ocean, often leading to highly stratified conditions that result in low-oxygen bottom waters. Main fjord regions occur along the coasts of North and South America (above 42° latitude); many sub-Antarctic islands; the southwest coast of New Zealand's South Island; Antarctica;[1] the Russian and Canadian Arctic Archipelagos; Svalbard,[2] Norway; Iceland; Greenland; and northern Europe, including the west coast of Scotland (Pickard, 1961, 1973; Syvitski and others, 1987; Cottier and others, 2010) (see figure I). Fjord systems are large transitional coastal zones, encompassing many distinct climate-hydrological-oceanographic interconnected systems, that are strongly influenced by interactions with mountain ranges, freshwater input, local to hemispheric-scale atmospheric weather patterns, glacier ice fields and the open ocean (i.e. Pacific, Atlantic) (Bianchi and others, 2020; Hunt and others, 2024). These transitional coastal zones are characterized by a complex geography including the presence of several marine habitats such as bays, estuaries, gulfs, islands, fjords and channels. Inner coastal waters are influenced by freshwater flux from rivers, which are fed from precipitation, as well as snow, glacier and sea ice melting. The interaction of this freshwater with oceanic waters can generate strong horizontal and vertical salinity, density and nutrient gradients (see sect. 4, chap. 3). Fjords are also

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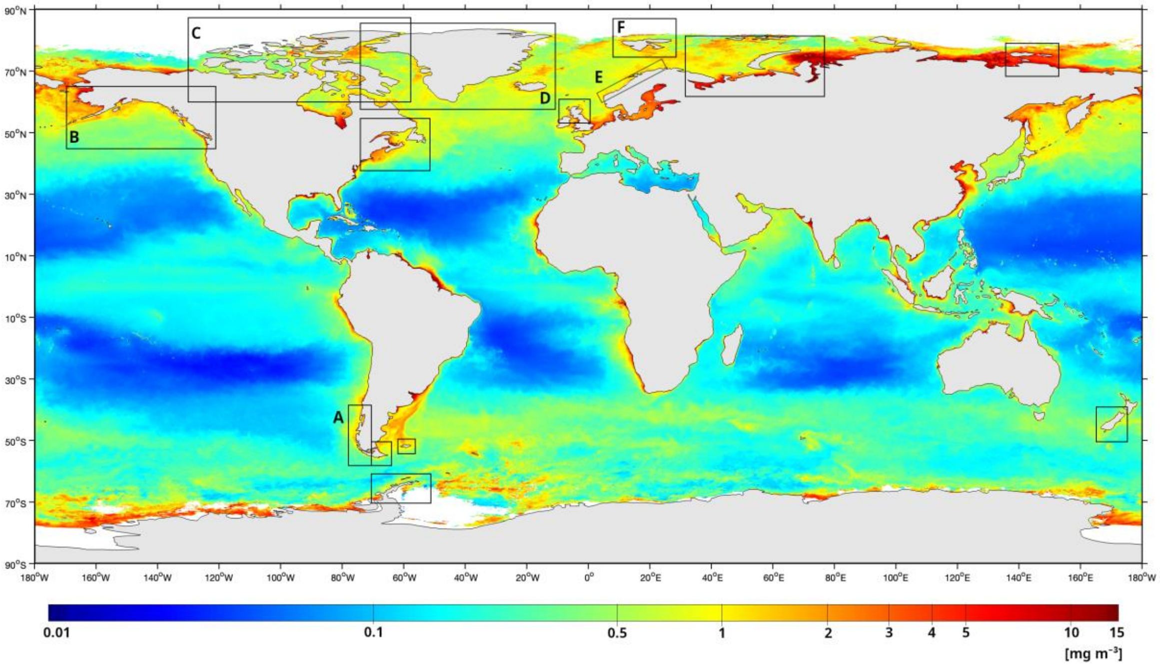
[1] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/antarctic-region" \o "Learn more about Antarctica from ScienceDirect's AI-generated Topic Pages.

[2] See https://www.sciencedirect.com/topics/earth-and-planetary-sciences/svalbard" \o "Learn more about Svalbard from ScienceDirect's AI-generated Topic Pages.

carbon cycle[3] hotspots where the largest amount of organic carbon[4] per unit area is buried in sediments, making them key ecosystems for carbon cycle regulation over time (Smith and others, 2015; Faust and Knies, 2019; Cui and others, 2022; Smeaton and Austin, 2022; Watts and others, 2024; Bertrand, 2025). At present, coastal fjord regions are increasingly experiencing anthropogenic impacts due to global processes (e.g. climate change) and regional activities (e.g. eutrophication) in inshore waters. Under the framework established in the third *World Ocean Assessment*, the present subchapter focuses for the first time on several fjord systems of the world (see figure I), with particular emphasis on recent studies in mainland Norway, Svalbard, Greenland, Patagonia and Pacific North America.

Figure I

Map showing the global distribution of fjord systems overlaid with map showing chlorophyll-a concentrations. Fjord systems of the world, with particular emphasis on recent studies in Patagonia (A), Pacific North America (B), Canadian Arctic Archipelago (C), Greenland margins (D), mainland Norway (E) and Svalbard (F).



Source: Jose L. Iriarte.

2. Descriptions of the overall status

Mainland Norway

Mainland Norway has thousands of fjords along the coast (58°-72°N). Fjords on the west coast are influenced by two distinct water masses: the low-salinity Norwegian Coastal Water in the upper layer and the high-salinity Atlantic Water in the lower layer beneath. The vertical structure and horizontal extent of

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[3] See https://www.sciencedirect.com/topics/earth-and-planetary-sciences/carbon-cycle" \o "Learn more about carbon cycle from ScienceDirect's AI-generated Topic Pages.

[4] See https://www.sciencedirect.com/topics/earth-and-planetary-sciences/organic-carbon" \o "Learn more about organic carbon from ScienceDirect's AI-generated Topic Pages.

coastal water show seasonal oscillations due to prevailing wind conditions, where alongshore northerly (southerly) winds can cause coastal upwelling (downwelling) (Sætre and others, 1988; Skarðhamar and Svendsen, 2005). Norwegian fjords are affected by land-fjord-shelf interactions such as river water input carrying organic matter and nutrients to the fjords and further to the shelf and some glaciated fjords have meltwater runoff. Some fjords have a shallow sill that prevents frequent renewal of the deep water due to the low salinity (low density) surface layer. Strong stratification and limited vertical mixing can result in long residence times of deep-water masses, which can lead to a decrease in oxygen levels and create challenging environments for local ecosystems (Aksnes and others, 2019; Darelius, 2020; Johnsen and others, 2024).

Fjords are productive due to nutrient-rich freshwater runoff from rivers and land promoting primary and secondary production. Diatom-spring blooms are most common in Norwegian fjords and as food for zooplankton. Periodically, spring blooms of the calcium carbonate forming coccolithophore have been reported in several Norwegian fjords (Kristiansenet and others, 2014), observed from space (NASA; Modis). Large copepods are an important food source for fish (e.g. Atlantic coastal cod) and shrimps (Zimmermann and others, 2023). Some fjords have unique cold-water corals (Ruggeberg and others, 2011). Fixation of CO_2 by phytoplankton is a significant factor controlling the partial pressure of CO_2 (pCO_2), with the development of spring blooms in northernmost fjords. Decreased CO_2 uptake is observed in autumn due to a combined reduction of the mixed layer with the entrainment of high-CO_2 subsurface water, reduced biological production and increased surface water temperatures (Aalto and others, 2021). Time-series data reveal that the North Atlantic Oscillation significantly influences river discharge, temperature and precipitation in central Norway, making terrigenous input and erosional processes in the fjord hinterland highly sensitive to atmospheric variability. In addition, marine carbonate productivity is the primary source of calcite and calcium in all three fjords (Faust and others, 2014, 2017).

Svalbard (Spitsbergen)

Most fjords on the west coast of Svalbard exhibit a typical fjord circulation associated with a three-layer structure: a fresh surface layer in summer; a layer of intermediate water, transformed Atlantic Water in the middle to outer part; and local fjord water in the deeper part of the fjord (Hop and others, 2006; Cottier and others, 2005; Nilsen and others, 2008; Skogseth and others, 2020). The summer surface layer is mainly formed by freshwater from glacial meltwater and river runoff (Svendsen and others, 2002). East coast fjords are mostly impacted by cold Arctic water and thicker sea ice than are found in the west coast fjords. Due to the sill depth, some fjords with a shallow sill depth such as Billefjorden have limited inflow of water from outside the fjord to renew the bottom water and creates arctic conditions in the inner parts (Søreide and others, 2008, 2022).

Mountains surrounding the fjords have different bedrock compositions where weathering supplies minerals and ions to the fjord (Dragańska-Deja, 2024), which impacts the marine chemistry (alkalinity) and carbonate system (ocean CO_2 uptake) (Fransson and others, 2015; 2016; Ericson and others, 2019). Glacier runoff contributes to surface stratification and nutrient supply. Sub-glacial melting affects the presence and supply of nutrients and other bio-essential substances (iron) derived from the bedrock/sediment at the bottom and transported by vertical mixing (Hopwood and others, 2020). High primary production blooms in Kongsfjorden (usually in April-June) are initiated due to shallow surface stratification and are often dominated by diatoms (e.g. Hegseth and others, 2019) and when the surface layer becomes more mixed and warmer the blooms are dominated by other species such as *Phaeocystis pouchetii* (e.g. Hoppe and others, 2024). Submarine melt in Arctic/Svalbard fjords is typically driven by the presence of warm water such as Atlantic Water and its derivative coastal water masses (Svendsen and others, 2002; Straneo and others, 2012). This melting causes low-density water to rise to the surface in the inner fjord, with positive responses on phytoplankton growth (diatoms), zooplankton (large copepods), fish, birds and sea mammals (Søreide and others, 2008; Lydersen and others, 2014; Halbach and others, 2019; Assmy and others, 2023). On the other hand, sediments carried by glacial meltwater can lead light availability, thereby limiting primary production (Hopwood and others, 2020; Dragańska-Deja and others, 2024). Sea ice is important for ice algae (mainly diatoms) which play an important role as an early food source for many marine invertebrates such as polychaetae and roundworms (*Nematoda*) that are known to reside within sea ice (Søreide and others, 2008). Glacial surface melt is largest in summer and limited during winter, while subglacial freshwater generated all year round through geothermal and frictional heat and delayed release of subglacially-stored freshwater (Vonnahme and others, 2023). Recent research in Kongsfjorden, Svalbard, reveals how freshwater runoff from marine- and land-terminating glaciers affects the biogeochemical cycles of carbon, nutrients and trace elements in the Arctic fjord system. The data show that intense carbonate weathering in proglacial catchments adds dissolved carbonates to fjord waters, mitigating the reduced buffering capacity from glacial runoff (Schmidt and others., 2025). Also observed in other west-Spitsbergen fjords such as Tempelfjorden (Fransson and others, 2015; 2020). Work in Smeerenburgfjorden, Kongsfjorden and Van Keulenfjorden, of Western Svalbard, revealed that benthic recycling of glacially derived dissolved iron into seawater, followed by partial re-oxidation and deposition, facilitates iron transport across the fjords and potentially into adjacent shelf waters. This new data on biogeochemical processes and carbon cycling in a climate-sensitive, high-latitude fjord region, aids in predictions of future Arctic ecosystem changes (Wehrmann and others, 2014).

Greenland glacial fjords

Kalaallit Nunaat (Greenland) is characterized by hundreds of glacial fjords, distributed around its perimeter, that connect the ocean with the ice sheet. Many of these fjords are associated with marine-terminating glaciers that discharge icebergs that move through the fjords and into the coastal ocean. Meltwater released into the fjords from glacier melt, iceberg melt and tundra runoff constitute a significant freshwater export into the coastal ocean (Bamber and others, 2018). One key feature of Greenland's glacial fjords is the release of large volumes of summer surface melt at the grounding zone of marine terminating glaciers, hundreds of meters below sea-level (Moon and others, 2017; Beaird and others, 2018). The large density difference between this freshwater and the ocean water gives rise to turbulent, rising plumes, which play a key role in driving the fjord circulation, increase melting of the glacier face and upwell deep nutrients (Slater and others, 2015; Meire and others, 2017; Hopwood and others, 2018; Cape and others, 2019). Estimating the dissolved silica (dSi) flux from the Greenland Ice Sheet has been difficult, with existing estimates differing by an order of magnitude. A new study indicates a modest dissolve Si flux from runoff, with smaller contributions from melting icebergs and suspended particles (Hopwood and others, 2025). The confluence of Arctic and Atlantic- origin waters flow along-side with the Arctic waters inshore and the Atlantic waters on the continental slope (Straneo and others, 2012). Greenland fjords are characterized by seasonal sea-ice coverage varying significantly with latitude and between east and west Greenland. Sea ice plays a vital role for Indigenous Peoples and local communities, supporting traditional livelihoods such as fishing and hunting (Krupnik and others, 2010).

Large phytoplankton blooms occur in spring as solar radiation increases and sea-ice retreats (Vernet and others, 2021). The mixing of different water types and nutrient upwelling associated with glacial plumes contributes to a continued high productivity in the fjords with marine-terminating glaciers during summer (Meire and others, 2023; Juul-Pedersen and others, 2015). These high primary production blooms, often dominated by diatoms, provide a valuable food source for attracting large zooplankton communities and consequently for lower trophic level forage fish species such as capelin (Grønkjær and others, 2019, Laidre and others, 2008). These rich marine ecosystems are not only of ecological importance but also of socio-economic importance for commercial fisheries (Boje and others, 2014; Meire and others, 2017) as well as local fishing and hunting activities (Schiøtt and others, 2022, Straneo and others, 2022).

Patagonian fjords

Along the Chilean Patagonia (41 – 54°S), the coast is characterized by a complex geography including the presence of fjords and channels. Northern Patagonia (41 – 47°S) showed high freshwater input by large rivers (up to 600 $m^3 s^{-1}$) along the coast characterized by waters of low salinity and high silicic acid concentration (Jacob and others, 2014; Cuevas and others, 2019). Such discharges affect the nutrient content and their stoichiometric ratio (N:P:Si), as well as the water column structure showing a strong haline stratification (León-Muñoz and others, 2024). Their interaction with the Subantarctic Water (SAAW), generate strong horizontal and vertical salinity (and density) gradients (Saldías and others, 2019) that contribute to maintain the phytoplankton community under high nutrient availability within the euphotic zone (Iriarte and others, 2014). The interplay between river discharges and oceanic water masses, as the principal nutrient sources, leads the maximum peak of chlorophyll-a to occur in the inner coastal waters during the austral spring-summer months (Iriarte and others, 2007). The pronounced salinity gradient by the riverine freshwater input can be extended to the offshore region, reaching as far as approximately 80°W, generating a strong relationship between stratification, nutrient content and surface total chlorophyll *a* biomass (Galán and others, 2021). In contrast, southern Patagonia (47 – 54□S) is strongly affected by western winds (which have maximum intensity during summer) and the fluvial influence is lower compared to snow and glacial melting processes (Garreaud and others, 2009; Aguayo and others, 2024). These conditions promote a deeper mixed layer, low silicic acid and nitrate concentrations (Cuevas and others, 2014) and high content of suspended sediments, which affect the light availability in the upper layer, mainly in the inner waters (González and others, 2013; Jacob and others, 2014). The biogeochemistry of Patagonia's fjords is shaped by complex, changing factors, including fjord geomorphology, local climate, interactions of multiple water masses and atmospheric modes (Crosswell and others, 2022; Linford and others, 2023; Rebolledo and others, 2015; Sepúlveda and others, 2009). Despite this complexity, studies of water columns, surface sediments and downcore organic carbon emphasize the heterogeneity of carbon inputs and fate (González and others, 2019; Rojas and Silva, 2005; Sepúlveda and others, 2011; Silva and others, 2011).

Pacific North American fjords

In North America, fjords are located on all three ocean coasts - the Atlantic, Arctic and Pacific Oceans but here the focus is on Pacific North American fjords, which span Washington State (United States of America), British Columbia (Canada) and Alaska (United States of America). These fjords are part of the Northeast Pacific Coastal Temperate Rainforest Ecoregion, which includes prehumid and seasonal rainforests (Bidlack and others, 2021; Hunt and others, 2024). The Pacific North American fjords are fringed by mountain ranges: the Olympic range in western Washington and the coast mountain range (also known as the Cascade Range) that runs throughout Washington, British Columbia and Alaska. Freshwater flows from the coastal mountains to the coast via thousands of small coastal rivers and five large continental rivers (Giesbrecht and others, 2021). Rivers are observed at the heads of most fjords and the seasonality of the river depends on whether the source of the freshwater is rain, snow or glacial melt (Morrison and others, 2012). In British Columbia, there are 42 fjords that are longer than 18.5 km and of these, the outer sill depth ranges from 6 to 490 m, the maximum depth ranges from 75 to 730 m, and the length ranges from 33 to 130 km (Pickard, 1961). In most cases there are three water types in fjords: deep water (greater than sill depth), that in most fjords is seasonally modified by deep water renewal (Farmer and Freeland, 1983); intermediate water (above sill and below surface water), that can be modified by wind-driven or advective processes (Jackson and others, 2022); and surface water that is driven by estuarine circulation (Pickard, 1961).In recent research it has been pointed out that the ecosystem within fjords is different than surrounding waters, with high phytoplankton concentrations (Marchese and others, 2022) that are dominated year-round by diatoms (Johannessen and others, 2019; Del Bel Belluz and others, 2024) and very abundant and diverse zooplankton populations (Pata and others, 2022).

3. Region-specific changes

Mainland Norway

Freshwater input is increasing to the coastal zone which is an important area for fisheries (cod, salmon, shrimp) and aquaculture. Cod egg dispersion models show negative impacts of increased low-density water with low oxygen (Stenevik and others, 2008). There is recent evidence that coastal waters in mainland Norway are becoming lighter due to climate change, resulting in a stronger stratification in the fjord basins with reduced mixing and consequent deoxygenation in fjords (Johnsen and others, 2024). An estimated increase of 0.6°C in temperature in the fjord basins after 1990 showed that basin water renewal occurred less frequently in most fjord basins along the Norwegian coast (Johnson and others, 2024). Masfjorden in southern Norway is one of the fjords showing recent oxygen-depleted basin water (Pitcher and others, 2021). Impacts of ocean acidification: some glaciated fjords have meltwater runoff that dilutes buffering ions (and alkalinity), increases CO_2-uptake and increases ocean acidification (Aalto and others, 2021; Jones and others, 2020). Human activities such as shipping, aquaculture (see subsect. 5A, subchap. 1D), fishing and pollution (e.g. mining waste; see sect. 4, chap. 6) and climate stressors such as ocean warming and acidification, negatively impacting the fjords. Because of the unique and diverse environment, several such fjords (i.e. Ytre Hardangerfjorden fjord) have recently become marine protected areas (MPAs).

Svalbard

Ocean warming of 0.7° C per year in winter and 0.6° C per year in summer is observed on the shelf of western Spitsbergen and Isfjorden (Skogseth and others, 2020) and a decline in sea ice is reported in Kongsfjorden (Pavlova and others, 2019; Gerland and others, 2020). Glaciers in Svalbard are melting and retreating and freshwater input to the coastal zone is increasing (Kohler and others, 2007; Geyman and others, 2022) due to warming (e.g. Foss and others, 2024). Fjords in Svalbard experience increased ocean acidification due to increased glacial discharge and meltwater-induced CO_2 uptake (e.g. Fransson and others, 2016; Cantoni and others, 2020). These waters are further modified by accumulated dissolved inorganic carbon from sea-ice brine rejection and respiration of organic matter which further contributes to acidification (Ericson and others, 2019; Fransson and others, 2016, 2015). Studies in Kongsfjorden (west Spitsbergen) showed inter-annual variability in biogeochemical properties with lower aragonite saturation

(Ω_{ar}) and pH (indicators of ocean acidification) in cold years with extensive sea-ice cover, relative to warm years with a greater influence from warm and saline Atlantic Water inflow (Fransson and others, 2016). Differences in phytoplankton spring bloom composition in Kongsfjorden were observed in contrasting years where in a cold year with more sea ice the spring bloom was dominated by diatoms and in a warm year, with less sea ice, the spring bloom was dominated by haptophyte (Søreide and others, 2010; Assmy and others, 2023). In years with less surface stratification, warmer water and deeper mixed layer the blooms were dominated by species such as *Phaeocystis pouchetii* (Hoppe and others, 2024). Moreover, the reported decreased sea ice presence in Svalbard fjords (Pavlova and others, 2019) will lead to less ice algae and earlier phytoplankton blooms (Søreide and others, 2008), resulting in changes in the diversity of sea-ice protist (e.g. diatoms) and ice-associated fauna (Hop and others, 2020). In sediments of Kongsfjorden in Svalbard benthic remineralization could increase nutrient sources like iron (Fe). Interannual variations in primary productivity, expected to intensify with global warming and changes in glacial sediment delivery will affect benthic iron and sulfur cycling. Over time, this may lead to decreased benthic Fe fluxes. With glacial retreat and shifts in productivity, fjords like Kongsfjorden may become less efficient carbon sinks, burying less organic matter in deep sediments (Herbert and others, 2022). Seepage of methane is reported in most Svalbard fjords and natural gas below the permafrost, with methane flares measured in Isfjorden, Kongsfjorden and VanMijenfjorden (Hodson and others, 2024). With warming, permafrost thawing and methane release into the fjords will likely increase with impacts on carbon cycling in the fjords and shelves. Knowledge gaps on the methane dynamics in Svalbard still exist (Hodson and others, 2024).

Greenland's margins

Climate change, including the rapid warming of the Arctic, is resulting in significant changes over Greenland and along its coastal margins. These changes include the retreat of glaciers, increased surface melt (Mankoff and others, 2021, 2020), reduced sea ice (Cooley and others, 2020) and warming air temperatures (Box and others, 2009). These trends are superimposed with long-term modes of variability, such as the Arctic and North Atlantic Oscillations and the Atlantic Multidecadal Oscillation, that account for a significant fraction of the variability in this region (Hanna and others, 2021). Records of physical and chemical properties and of ecosystem and fisheries variability, in the fjords and in the coastal region are, however, scarce – making it challenging to quantify change that has already occurred. Proxy records derived from fjord sediment archives offer valuable insights into past changes beyond the instrumental era (Heikkilä and others, 2022). Fjord sediments simultaneously record changes in sea ice, ice-sheet discharge, ice-ocean interactions and associated ecosystem responses (Ribeiro and others, 2017, Vermassen and others, 2019). Proxy-data studies from Greenland fjords from both West and East Greenland have revealed multi-decadal changes in the inflow of Atlantic-derived warm water and its relationship with glacier dynamics (Andresen and others, 2012, Vermassen and others, 2019b). They also have revealed that present-day impacts of freshwater discharge on fjord productivity are unprecedented in centuries to millennia (Oksman and others, 2022, Oksman and others, 2024). The increase in the upwelling of nutrients associated with subglacial discharge may be partly offset by the retreat of glaciers into shallower water – thus reducing the ability to upwell deep nutrients (Meire and others, 2017; Hopwood and others, 2020). Sea-ice decrease is impacting wintertime travel and fishing, which Indigenous Peoples and local communities rely on for sustenance and threatens the future viability of key polynya ecosystems (Ribeiro and others, 2021). Sea-ice cover serves as winter refuges for marine mammal species that are harvested by Indigenous People in Greenland fjords (Heide-Jørgensen and others, 2013). At the same time, reduced sea-ice resulted in increased primary productivity as light limitations are reduced and wind-induced mixing increased (e.g. Baffin Bay and the Arctic Ocean) (York and others, 2020; Frey and others, 2020).

Patagonia

The Patagonia region is undergoing an increasing anthropogenic affectation due to global phenomena, including hydrological anomalies, glacier retreatment, climatological shifts (Aguayo and others, 2019; 2024; Garreaud and others, 2009) and regional productive activities such as large-scale aquaculture farms (salmon and mussels) allocated along inshore waters (Navedo and Vargas, 2021). In northern Patagonia (41 – 44°S), climate change projections forecast 20% less rainfall in the next decade (Aguayo and others, 2019), which affect negatively the annual dynamics of large river streamflows, water chemistry (silicic acid) and pelagic (mollusk larvae) and benthic organisms inhabiting fjords systems (van Leeuwen and others, 2021) as well as the physical support (weakening of haline stratification and increase of sea surface temperature; Leon-Muñoz and others, 2024). Recurrent harmful microorganisms' events observed in coastal and oceanic regions off northern Patagonia since 2016, coincided with the synergy of remote climatic phenomena (El Niño) and global warming that led to very dry conditions, higher than normal solar radiation, high sea surface temperatures, and reduced wind velocities (León-Muñoz and others, 2018; Mardones and others, 2023). Significant mass loss (65%) in the Patagonia icefields (47 – 55°S) may continue in the future (Minowa and others, 2022; Aguayo and others, 2024), where ocean-terminating and land-terminating fjords are likely exposed to increasing freshwater runoff (freshening effect) and increasing rain precipitation (Garreaud and others, 2013). Patagonian fjords and inner seas are affected by human-induced global changes, including climate-ocean events, altered freshwater inputs, harmful algal blooms, settlement, aquaculture, glacial melt and coastal hypoxia (Dussaillant and others, 2019; González and others, 2019; Iriarte, 2018; Linford and others, 2024; Quiñones and others, 2019).

Pacific North America

Data of temperature, salinity and oxygen have been collected since 1951 in British Columbia fjords. Recent work found that deep water warmed by 1.2 to 1.4°C and lost 0.4 to 0.7 mL L^{-1} of oxygen from 1951 to 2020 (Jackson and others, 2021). These changes are explained by the upwelling of offshore water that was warmed by the 2014-2016 marine heatwave to fjords via deep water renewal (Jackson and others, 2018; Alin and others, 2024); the 2014–2016 marine heat wave water lingered in deep fjord water until 2020 (Jackson and others, 2021). Waters in fjords are often acidic (Hare and others, 2020) and impacted by random events (Alin and others, 2024).

Glaciers in British Columbia are melting rapidly and it is predicted that the volume of glacial ice will shrink by approximately 70% by 2100 relative to 2005 (Clarke and others, 2015). In addition to altering the amount of freshwater transported to the ocean, as the glaciers melt, they cause extreme events such as the 2020 outburst flood that destroyed salmon habitat and advected tons of inorganic and organic sediments into Bute Inlet (Geertsma and others, 2022). There is evidence that these changes to the seasonality and amount of freshwater that enters fjords are impacting the timing of the spring bloom (Wolfe and others, 2015; Hunt and others, 2024; Del Bel Belluz and others, 2024), as well as zooplankton dynamics (Tommasi and others, 2013).

4. Outlook

General awareness of fjords and the key ecosystem services offered by them are essential to determine actions on management under natural disturbances as well as present and projected climate change scenarios. Linking physical-ecological and socioeconomic structures and their ecosystems functions are key to propose and incorporate both mitigation and adaptation processes such as nature-based solutions and climate refugees. Long-term monitoring approaches designed and coordinated by scientists and stakeholders must be undertaken in existing and future marine and terrestrial protected areas located in fjord systems. In the present subchapter as well as others, such as cold-water corals and sponges (CWCS) (sect. 4, subchap. 5E), estuaries and deltas (sect. 4, subchap. 5F) and small-scale aquaculture (subsect. 5A, subchap. 1D), it has been pointed out that fjord regions are under threat from intensive human activities (including land-use, aquaculture, dams, tourism) and the effects of climate change (including warming, freshening, ice loss, permafrost thawing, erosion and sea level rise).

5. Remaining key knowledge and capacity changes and any new gaps

- A critical knowledge gap exists for fjords habitats, as only a small percentage of the world's fjords have been studied.
- Change from marine-terminating glaciers to land-terminating glaciers would determine changes in surface and sub-glacial melt, sediment supply that limits light, stronger stratification and nutrient limitation for primary production, changes in species composition and, ultimately, the dynamic of carbon flux.
- The contribution to the global carbon cycle of methane emissions from melting ice sheets and glaciers in the Arctic unknown.
- The resilience of fjord systems to changes in hydrologic (precipitation, melting, runoff) and oceanographic (water masses, stratification, nutrient stoichiometry) to present conditions remain a major gap.
- Advances in modelling research, such as in relation to the impacts of freshening, coastal acidification, sea surface warming, and deoxygenation processes, are lacking and need to be compared with in situ studies approaches.

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