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Review

Impact of winter freshwater from tidewater glaciers on fjords in Svalbard and Greenland; A review

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ABSTRACT

This review paper is the first to collect and synthesise the available knowledge, across various disciplines, on the importance of wintertime freshwater inflow from tidewater glaciers into Arctic fjords. While surface melt is limited during winter, tidewater glaciers can continue to deliver freshwater into the marine environment. This can be delivered via subglacial discharge or produced by submarine melt. Subglacial freshwater can be generated all year round through geothermal and frictional heat and delayed release of subglacially-stored freshwater. Submarine melt in Arctic fjords is caused by the presence of warm water such as Atlantic Water and its derivative coastal water masses. The dynamics of the contributing water masses are subject to varying bathymetric barriers, seasonally shifting density fronts, and external forcing such as wind or internal waves. Their impact is variable across different fjord systems. When other terrestrial water influx is limited during winter, any glacier-derived freshwater inflow into the fjords can have pronounced physical and biogeochemical consequences, even at low fluxes. These can include the generation of upwelling, but also increased stratification. The extent of the freshwater influence depends on parameters such as discharge volume flux, water depth, and depth of the glacier termini, which might in turn affect ice algae and phytoplankton production during the early spring bloom. Coupling of winter freshwater discharge from tidewater glaciers with the physical and biogeochemical conditions of the fjord is therefore a dynamic multivariable process. Rapidly changing wintertime conditions in the Arctic may already be impacting the functioning of the Arctic fjord ecosystems and necessitate efforts to understand these processes better. This review highlights the importance of wintertime freshwater by summarising the current state of knowledge about its presence and magnitude, drivers governing its inputs, as well as its potential ecological impact on fjord ecosystems. Our study uncovers knowledge gaps and proposes research directions to better understand the changing Arctic environment.

1. Introduction

This article reviews for the first time the presence, magnitude, and drivers of wintertime (defined as sub-zero air temperatures) freshwater discharge associated with tidewater glaciers. We show the impacts on marine ecosystems in Arctic fjords with a focus on Svalbard and Greenland (Fig. 1). Available case studies and the main winter heat sources for submarine melt and subglacial discharge are discussed. We review the ecological implications of winter freshwater inflow by discussing the dynamics of phytoplankton spring blooms and sea ice algae. In addition, we summarise knowledge about fjord-shelf exchange processes in winter because this exchange is the key heat source in winter, via inflow of warm water masses. We elucidate a variety of potential impacts of climate change on winter freshwater runoff and associated processes. Finally, we identify existing knowledge gaps and propose future research to approach these.

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Winter is classically defined by fixed dates in the calendar as one of four seasons. At high latitudes the transition between seasons could alternatively be defined by light availability or temperature. Winter as defined by a period with fixed calendar dates is warming, due to recent climate change. Winter, defined by weather patterns is becoming less predictable and shorter in duration. Whilst light can be a key driver for biological processes in the Arctic during the polar night, climate change affects light availability only indirectly via cloud coverage. Conversely, air temperature is a key driver for freshwater inputs (e.g., Gokhman and Khodakov, 1986) and the seasonality of freshwater inputs is thus highly impacted by climate change. In the Arctic, this occurs via increased precipitation, and ice melt (glaciers, sea ice, permafrost; Zhu et al., 2021). Because this review focuses on freshwater inputs, we define winter as the time of the year when terrestrial melt is absent due to sustained sub-zero air temperatures (Fig. 2). In Young Sound in East Greenland (G-E-M.dk/data, ClimateBasis Zackenberg) the winter period, defined by air temperature, has already decreased from 264 days (1996–2006) to 256 days (2011–2021), while the winter period in Longyearbyen on Svalbard (Svalbard airport station SN99840, met.no) has decreased from 233 to 203 days in the same period.

Winter freshwater discharge in Arctic fjords is an emerging research field and has only recently been acknowledged following campaigns in several fjords with tidewater glaciers. Winter studies as well as data are still scarce and fragmented across different geographic regions and research disciplines. Both modelling, and *in situ* observational studies are available, but often in disagreement due to high uncertainties. The available studies do however show a potentially important role for tidewater glacier-associated winter freshwater fluxes at least locally and in late winter. Increasing recognition of the importance of glacial discharge, and specifically impacts within fjords across all seasons, is the rationale for this review. Our paper bridges different disciplines and approaches to give a more comprehensive background on available knowledge, to identify the existing knowledge gaps, and to address the potential future research directions. This review serves as a baseline for future research in this emerging field on a process highly impacted by climate change.

1.1. Freshwater sources to the Arctic marine ecosystem

The largest inflow of freshwater to the Arctic Ocean of approximately 4200 km^3 yr^{-1} comes from rivers and groundwater followed by Polar water inflow through the Bering Strait (based on a reference salinity of 34.80) and precipitation (Haine et al., 2015; Carmack et al., 2016). Terrestrial freshwater discharge in the Arctic is generally increasing with climate change (e.g., Carmack et al., 2016; Mouginot et al., 2019; Mankoff et al., 2020, Moreno-Ibáñez et al., 2021; Zhu et al., 2021). Compared to 1989 total terrestrial freshwater runoff 2000–2010 had increased from 3300 km^3 yr^{-1} to 4200 km^3 yr^{-1} (Aagaard and Carmack 1989; Haine et al., 2015; Carmack et al., 2016). While glacial melt is currently only a minor freshwater source to the Arctic Ocean, with a mean freshwater flux of 84 km^3 yr^{-1} (2007–2016) the total flux has increased with climate change (Bamber et al., 2018). At a catchment scale, trends are more variable as in some locations peak-water may have already occurred. For smaller cold-based glaciers (basal glacier temperature below the pressure melting point) which have retreated markedly, decreasing trends have been observed in annual freshwater fluxes (Nowak et al., 2021).

On a global scale glacial runoff leads to sea-level rise (Dowdeswell, 2006). On a regional scale near the coast, glacial runoff can impact circulation and stratification, which are both drivers of primary production (Oliver et al., 2018). On a local scale near glacier outlets, sediment and ion fluxes associated with freshwater have been shown to affect the ecosystem directly (e.g., Nowak and Hodson 2013, Meire et al., 2016; Overeem et al., 2017; Terhaar et al., 2021). In the Arctic, discharge of freshwater to fjord and coastal waters is highly seasonal. In the summer, when air temperatures are mostly positive, runoff is mostly generated by surface ice- and snowmelt (e.g., Carmack et al., 2016; Moon et al., 2018). During winter, surface melt is negligible, but other sources of liquid freshwater are located below the ground, in addition to atmospheric deposition and submarine ice melt (Fig. 3).

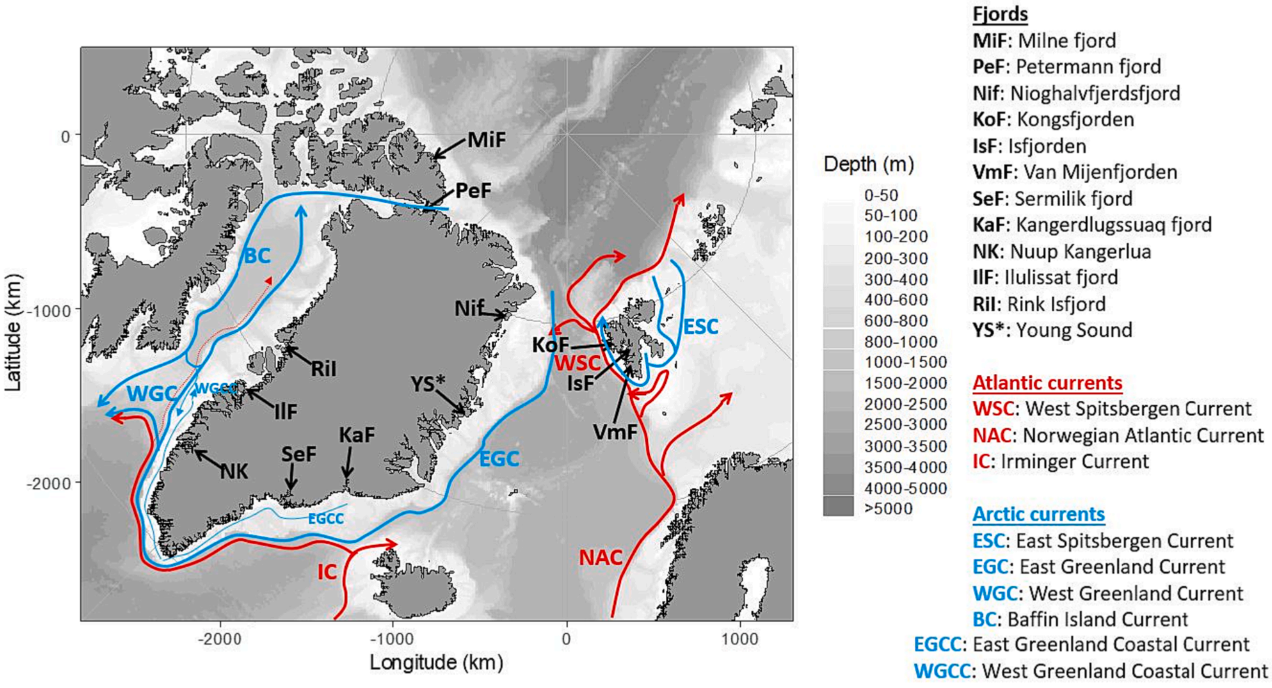

Fig. 1. Map indicating the fjords and major near-coast currents discussed in this Review. Solid arrows show surface currents, and dashed arrows show some important subsurface current extensions. Red arrows show the main sources of warm Atlantic water (AW) masses that may enter the fjords and impact melt. Blue currents originate in the Arctic but are typically subducted by deep AW (not shown in the map) and may be modified by AW mixing. YS* has no tidewater glaciers, but an extensive time series for comparison.

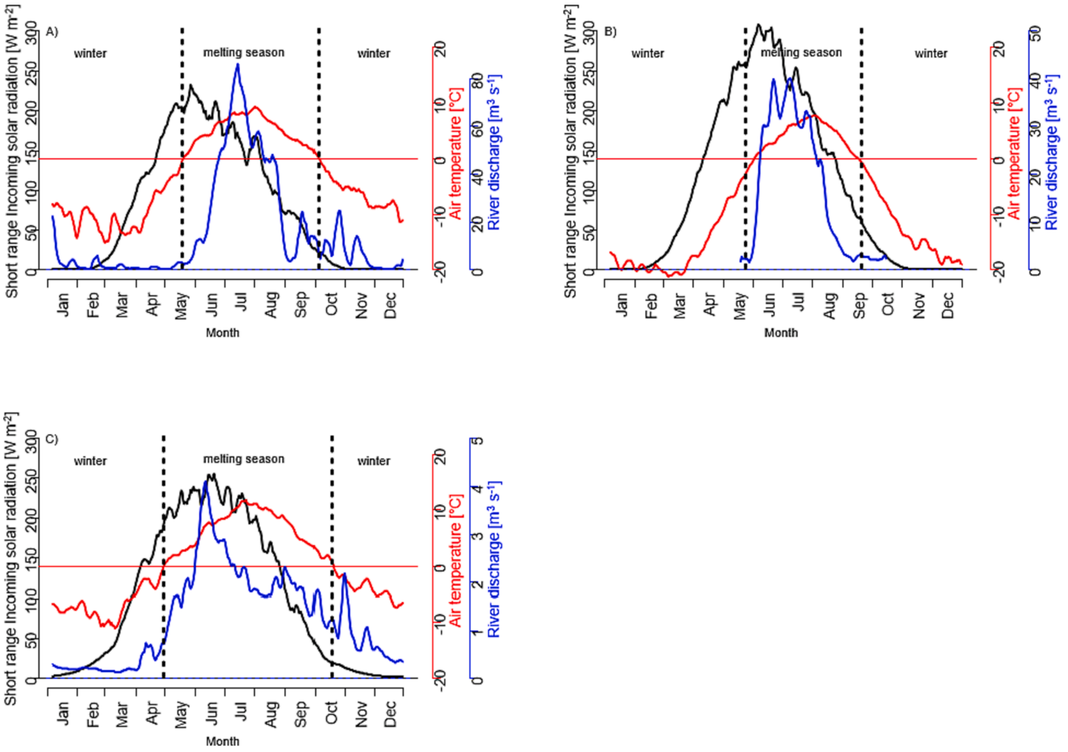

Fig. 2. Seasonality of short-wave incoming radiation (proportional to PAR), air temperature, and discharge from local rivers (7-day moving average of daily mean values) in key fjords discussed in this review. Winter is defined as the time of the year with sub-zero air temperatures A) Data from Adventdalen in Isfjorden (meteorological data by UNIS, the University Centre in Svalbard; https://www.unis.no/resources/weather-stations/) and discharge data modelled by Nowak and Randall (2019), B) Data from ClimateBasis Zackenberg (Air temperature: https://doi.org/10.17897/G5WS-0W04; short range incoming radiation: https://doi.org/10.17897/5T0P-N482; Discharge: https://doi.org/10.17897/A308-6075) in Young Sound representing the climate in East Greenland (Data from G-E-M.dk, 2012–2020) C) Data from ClimateBasis Nuuk (Air temperature: https://doi.org/10.17897/PGN3-7597, short range incoming radiation: https://doi.org/10.17897/AA4G-XC20, Discharge: https://doi.org/10.17897/H2MR-PP28) in Kobbefjord representing the climate in Nuup Kangerlua (Godthåbsfjord) in SW Greenland (Data from G-E-M.dk, 2007–2020,).

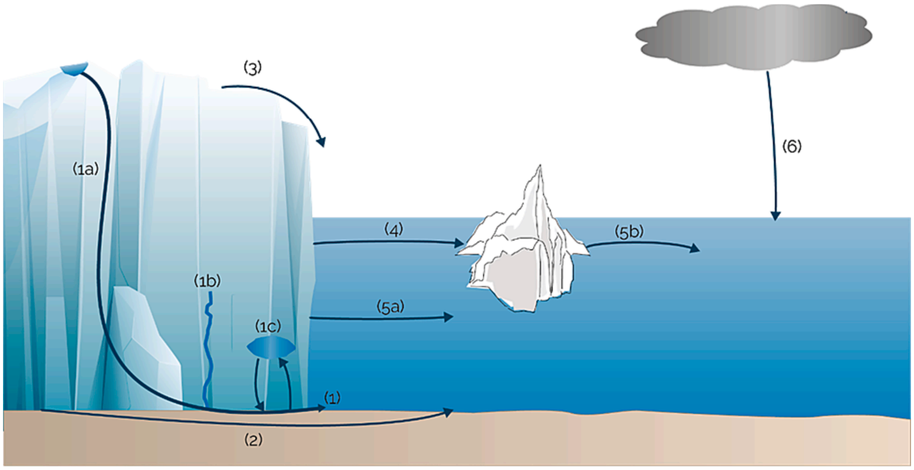

Fig. 3. Potential freshwater inputs in a fjord with a tidewater glacier. 1) subglacial discharge fed by surface melt in summer (1a), basal ice melt (1b) or delayed outflow of internally stored meltwater (1c). 2) Submarine groundwater discharge. 3) surface runoff in summer (glacial ice and snow- melt). 4) solid ice discharge. 5) submarine melt of (5a) the glacier terminus, or (5b) icebergs, including ice melange and potentially sea ice. 6) precipitation.

Submarine groundwater discharge (SBGD) can supply freshwater throughout the year (DeFoor et al., 2011). Precipitation can deliver freshwater as snow in winter. If tidewater glaciers are present, additional freshwater sources can be submarine glacial melt, and subglacial discharge. Submarine melt can occur either at glacier fronts or from icebergs, in both cases driven by warm seawater (Slater et al., 2017). Subglacial discharge on the other hand originates from the subglacial system and can be sustained by geothermal heat, frictional energy, or delayed discharge from the prior melting season (Karlsson et al., 2021). We hypothesise that these winter freshwater sources could play a key role in winter for physical and biogeochemical processes as we will evaluate in this review.

Submarine groundwater discharge (SMGD) is estimated to represent only up to 1–4% of the total annual Greenland ice sheet melt (DeFoor et al., 2011). SMGD may enter the sea at large distances (100 km) from the glacier. Ice sheet thickness plays an important role in driving SMGD, and with thinning glaciers SMGD is predicted to decrease (Liljedahl et al., 2021). While net winter precipitation (precipitation – evaporation) over seawater is the third most important freshwater source for the Arctic Ocean (2200 km^3 yr^{-1} or 23%, Carmack et al., 2016; Haine et al., 2015) it appears to have a relatively minor role in fjords (e.g., <5% for Nuup Kangerlua; Langen et al., 2015) due to the small surface area: volume ratio and the much larger freshwater fluxes from glacial sources. The quantitative inputs of submarine melt and subglacial discharge have only recently been considered in modelling, oceanographical, and ecological studies and are discussed in greater detail herein.

A key feature of freshwater derived from submarine melt or subglacial discharge is its high sediment load. Glacial runoff carries suspended sediments produced by physical and chemical erosion. These sediments can inhibit light penetration for primary production (e.g., Halbach et al., 2019), especially if the runoff enters a fjord in the surface layer via streams and rivers. Dissolved constituents in the meltwater include nutrients (such as silica, nitrate and phosphate), organic material (carbon, nitrogen and phosphorus), major ions, and trace metals (Hopwood et al., 2021). The amount and composition of the dissolved constituents depend largely on bedrock composition in the catchment area (e.g., Halbach et al., 2019). Whilst the labile fraction of most elements in runoff is low compared to coastal inflow, glacially derived dissolved organic carbon (DOC) in high latitude systems may be relatively more labile than carbon from coastal inflow (Paulsen et al., 2017). However, compared to the organic carbon produced *in situ* in the marine environment it is typically less important at the fjord scale (Hood et al., 2009; Paulsen et al., 2017).

Whilst circulation is a key influence on ice melt via the inflow of warm water masses, subglacial upwelling can also be a major driver for fjord circulation (e.g., Mortensen et al., 2014; Straneo & Cenedese, 2015; Carroll et al., 2017; Mortensen et al., 2020). Subsurface nutrients transported to the euphotic zone via subglacial upwelling are often a more important source of nutrients to biota than solutes in meltwater (Hopwood et al., 2020, Meire et al., 2016). At tidewater glacier fronts, subglacial freshwater released at depth rises towards the surface, entraining nutrient-rich deep waters in a buoyant plume referred to as 'subglacial upwelling' (e.g., Drewry, 1986; Carroll et al., 2015; Meire et al., 2017). Studies suggest that this process is responsible for significantly higher summer primary production in fjords where tidewater glaciers are present compared to those with land-terminating systems (e.g., Juul-Pedersen et al., 2015; Meire et al., 2017; Halbach et al., 2019; Hopwood et al., 2020). Other processes such as thermohaline convection (Cottier et al., 2010), katabatic winds (Spall et al., 2017), and intermediary tidal-induced circulation can mix the water column on the same scale (Mortensen et al., 2011) and also thereby affect nutrient availability on seasonal timescales. Collectively, those processes are also crucial for oxygenating the bottom water (Cottier et al., 2010).

While subglacial upwelling-fueled primary production is the main driver for higher secondary production in fjords with tidewater glaciers (Meire et al., 2017), tidewater glacier plumes can also sustain locally high secondary production close to the glacier termini via other mechanisms. Locally increased secondary productivity is attributed to increased zooplankton availability in the vicinity of meltwater plumes. This is because mixing transports zooplankton towards the surface. At the same time, a combination of high sediment load and low-salinity water may stun zooplankton and make them easier prey, especially during stronger upwelling or sudden glacial lakes drainage events (e.g., Lydersen et al., 2014; Arendt et al., 2016; Urbanski et al., 2017). Regions where these plumes occur are considered good feeding grounds for fish, seabirds, and marine mammals (Lydersen et al., 2014; Urbanski et al., 2017).

Freshwater dynamics in the marine environment, during winter and especially during the dark part of winter, are rarely studied. This knowledge is severely limited due to a strong bias towards summer data collection, when sampling campaigns are easier to perform and processes associated with freshwater outflow occurring in the environment are much easier to detect. Harsh winter conditions in the Arctic, especially during the polar night, make fieldwork challenging. Many sampling sites are simply not easily accessible in winter due to sea ice coverage and local regulations restricting access to fjord ice via icebreakers or snowmobiles. While the use of autonomous instrumentation may provide year-round data collection, these types of data collection remain spatially and temporally limited due to the cost of deploying and recovering the equipment and data. Finally, and maybe most importantly, the dark part of the winter period 'the polar night' has for a very long time been perceived as biologically inactive, therefore out of focus for many biogeochemical investigations.

2. Winter discharge

2.1. Winter discharge: River and glacial discharge

Winter supply of freshwater into Arctic fjords is mostly restricted to subglacial discharge, submarine glacial melt, and to a lesser extent groundwater seeps (Fig. 3, Walvoord and Striegl, 2007; Charkin et al., 2017; Liljedahl et al., 2021). In fjords with tidewater glaciers most of the freshwater originates from subglacial discharge or submarine glacial melt, and solid ice discharge. With sub-zero air temperatures, surface discharge is limited, especially in higher latitudes and late winter (>2 months after the melting season, Fig. 2). A Greenland river near Nuup Kangerlua with a mean winter length of 6.5 months has a mean winter discharge of 0.27 m^3 s^{-1} (14% of summer discharge), compared to 2 m^3 s^{-1} in summer (Fig. 2C, GEM). In a river near Longyearbyen with a winter length of 7.4 months the mean modelled winter discharge was estimated to be 3 m^3 s^{-1} (9% of summer discharge), compared to 33 m^3 s^{-1} in summer (Fig. 2, Nowak and Randall, 2019). At the Zackenberg station in East Greenland with a mean winter length of 8 months, winter discharge in May is 1.5 m^3 s^{-1} (7% of summer discharge), compared to 20.7 m^3 s^{-1} in summer (Fig. 2, GEM). In a river system in inner Isfjorden on Svalbard with a winter length of 9 months, winter discharge was not detectable (Gokhman and Khodakov, 1986).

While direct winter measurements are almost universally lacking, modelling studies estimate that submarine glacial meltwater fluxes (subglacial discharge + submarine glacial melt) in winter can be quite substantial, especially in colder regions. However, model estimates of the same system can differ by several orders of magnitudes (e.g., Rignot et al., 2016; Cook et al., 2020; Schulz et al., 2022; Sommers et al., 2022). In five West Greenland fjords winter subglacial meltwater fluxes were initially estimated to range between 0.4 m^3 s^{-1} at Kangilerngata Sermia, 0.8 m^3 s^{-1} at Store Glacier, and 1.1 m^3 s^{-1} at Rink Isbræ (ca 1–4% of yearly discharge and 0.1% of summer peak discharge, Rignot et al., 2016). Later modelling studies that included more detailed plume dynamics estimated higher winter fluxes of 9.4 m^3 s^{-1} at Store glacier (Cook et al., 2020). In Sermilik fjord in East Greenland, submarine glacial meltwater fluxes are dominated by submarine iceberg melt which is estimated to be a considerable freshwater flux of approximately 200–400 m^3 s^{-1} meltwater in winter. This is about one third of summer iceberg melt discharge (Moon et al., 2018). While Moon et al. assumed subglacial discharge to be absent in winter, a more recent modelling study focussing on frictional heat estimated winter discharge up to 131 m^3 s^{-1} at Helheim glacier (Sermilik fjord; Sommers et al., 2022). Similarly, in Northeast Greenland fjords basal ice melt is the main (approximately 80%) annual freshwater source supplying approximately 327 m^3 s^{-1} meltwater to the system (Johnson et al., 2011). While comparable hydrological modelling studies on Svalbard are lacking, a simple estimate based on nutrient supply and uptake estimated winter subglacial discharge of up to 2 m^3 s^{-1} in Billefjorden (Vonnahme et al., 2021).

2.2. Winter discharge: Active subglacial discharge

Wintertime subglacial discharge is typically assumed to be negligible due to the assumption that the main source of subglacial meltwater is the supply of surface melt. This supply stops at the end of the ablation season (Fig. 3, Moon et al., 2018). However, subglacial meltwater can continue to be produced by basal melt which is independent of surface atmospheric conditions. Basal melt occurs mainly through generation of frictional (e.g., Sommers et al., 2022) and geothermal (Rysgaard et al., 2018) heat (contributing between 64% and 82% of the energy for basal melt in addition to the heat energy coming with warm surface meltwater; Karlsson et al., 2021). It is estimated that basal melt can contribute up to about 8% of the Greenland Ice sheet's mass balance (Fig. 3, Karlsson et al., 2021). In Svalbard, estimates of the volume of basal melt beneath tidewater glaciers could possibly be calculated from available models, but this had to our knowledge not been done in prior literature.

Heat for glacier melt during winter can also be supplied with surface meltwater that is stored in englacial and subglacial conduits, or subglacial lakes, but these are considered minor contributions compared to basal melt (Fig. 3, Pattyn, 2008; Cook et al., 2020 Karlsson et al., 2021). Discharge events releasing stored meltwater may happen in pulses following glacial movements and are thus difficult to detect via sampling at a specific time point (Wadham et al., 2000). Submarine discharge can fluctuate through changes in the subglacial hydrological networks which can undergo reconfiguration even at the timescale of one melt season (e.g., How et al., 2017, Slater et al., 2017) further complicating outflow patterns and confounding monitoring efforts. Finally, atmospheric changes are leading towards a more rain dominated Arctic (McCrystall et al., 2021) and may also play an important role in increasing subglacial discharge outside summer melt season (Decaux et al., 2022). Intense rainfall at the end of the melting season can reactivate subglacial drainage systems and cause water storage at the glacier base and even promote glacier movement throughout winter (How et al., 2017 or Vallot et al., 2017).

While glaciological studies of land-terminating glaciers commonly describe active subglacial wintertime drainage systems under polythermal glaciers, albeit at much lower rates than in summer (e.g., Wadham et al., 2000, Cauche et al., Cook et al., 2020; Karlsson et al., 2021, Nowak et al., 2021), similar studies at tidewater glacier fronts only emerged recently and are still limited. On Svalbard, a few studies found evidence of winter subglacial discharge at tidewater glaciers in various fjords via salinity and solute measurements very close to tidewater glacier termini (e.g., Marchenko et al., 2017; Vonnahme et al., 2021). In Greenland, such direct observations are lacking. The lack of such studies is largely due to the challenges of studying these often limited and discrete winter discharge processes near glacier termini, which are often inaccessible due to glacial ice and ice melange. However, Greenland modelling studies increasingly recognize subglacial discharge as a potentially important winter freshwater source and attempted to quantify this source (Cook et al., 2020; Sommers et al., 2022).

2.3. Winter discharge: Submarine glacial ice melt

In contrast to limited case studies and evidence of winter subglacial upwelling, submarine ice melt is better understood and comparatively well documented. However, there is bias in the published studies in both winter and summer towards larger fjord systems in Greenland and Atlantic-influenced fjords in western Svalbard (e.g., Monteban et al., 2020). Available case studies include the largest Greenland tidewater glaciers with respect to the total solid ice discharge. In 2020/2021, 14 out of 171 Greenland tidewater systems accounted for 32% of all Greenland tidewater glacier discharge (Mankoff and Solgaard, 2021). Since the majority of glaciers along the Greenland coastline are small, these data could be misrepresentative from a process perspective because larger systems may have water column structures which are not representative of smaller systems particularly with respect to sill depths and freshwater driven stratification- the effectiveness of which can vary with fjord geometry and freshwater discharge volume.

The research that is available allowed us to separate investigated fjords into two main types (e.g., Table 1). Those are: i) isolated fjords with a shallow sill inhibiting winter AW inflow (Cottier et al., 2010; Vonnahme et al., 2021) more common in Svalbard, and ii) open fjords with no or only deeper sills allowing seasonal or periodic inflow of warm water masses from outside the fjord often found in Greenland (Cottier et al., 2007; Mortensen et al., 2011, Skogseth et al., 2020).

For isolated fjords in Svalbard, winter circulation is mainly driven by thermal convection and wind mixing at the beginning of winter. During sea ice formation, haline convection can additionally contribute to the mixing (Cottier et al., 2010). Eventually, these fjords are well mixed with local winter water masses close to the freezing point of seawater and below the freezing point of glacial ice (Vonnahme et al., 2021). Submarine glacial ice melt during winter is thereby insignificant, but subglacial discharge may still play a role for nutrient supply and low salinity frazil sea ice formation (Marchenko et al., 2017; Vonnahme et al., 2021). Tidewater glaciers (like Kronebreen, Tunabreen, or Aavatsmarkbreen) usually modestly advance during the winter and rapidly retreat during summer and autumn (Luckman et al., 2015). Systems in other parts of the Arctic with small to medium sized, valley-confined tidewater glaciers may be subjected to similar processes.

In fjords with absent or deeper sills, warm external water masses (CW, AW, TAW, or SPMW) provide the key heat source for winter melting. Understanding the drivers of this warm water inflow requires a thorough understanding of the drivers of winter fjord-shelf exchange. In many Arctic fjords, winter is the main season of fjord-shelf exchange of bottom water. Heat and nutrients can enter the fjords with inflows (AW/TAW/SPMW) from outside the fjords (e.g., Nuup Kangerlua, Mortensen et al., 2011, 2018; Kongsfjorden, Cottier et al., 2005).

Warm water masses of Atlantic origin are present throughout the Arctic Basin (e.g., Pnyushkov et al., 2015), but the depth and heat content vary along the flow path. The AW masses underlie a layer of fresher and colder surface water (SW) and enter the fjords at depth (Straneo and Cenedese, 2015). The depth of inflow is variable and dependent on the density of the fjord water (e.g., Skogseth et al., 2005; Tverberg et al., 2019; Skogseth et al., 2020). The warm water masses of the case studies in this review originate initially from the Atlantic (AW) but are often modified in some way along or across the shelf (TAW, CW, or SPMW). TAW/SPMW inflow fluxes and the TAW/SPMW-SW interface depth experience strong spatial, interannual and seasonal variations (Cottier et al., 2010, Mortensen et al., 2018, Hamilton et al., 2021).

An important precondition for deep water intrusions into fjords is water masses of low density in the fjord basin, often coupled with changing offshore density fields (Cottier et al., 2007; Mortensen et al., 2011). Different drivers allowing periodic, or continuous inflow in winter have been proposed with varying importance in different fjords. These mechanisms include: a) wind-induced Ekman upwelling and transport which can bring AW onto and over relatively shallow shelves or sills (Cottier et al., 2007), b) periodically alternating strong offshore winds which can create coastal trapped internal waves that together with the Coriolis force can drive a circulation mode introducing SPMW into the fjord (Fraser et al., 2018, Fraser and Inall, 2018), c) tidal induced internal waves or periodic AW shoaling which may contribute to AW/SPMW spilling over a sill (Hamilton et al., 2021), d) katabatic winds pushing surface water out of the fjord, which is then replaced by deep water inflow (Spall et al., 2017), and e) buoyant meltwater of an ice tongue in contact with AW can result in near-surface outflow and deeper AW inflow (Schaffer et al., 2020).

The most extensively studied fjords are open fjords with sills deep enough to allow warm water intrusions (e.g., Sermilik, Nuup Kangerlua, Ilulissat Icefjord, Bowdoin, Isfjorden, Kongsfjorden). Thus, AW masses can enter the fjords, once density barriers (e.g., fjords in western

Table 1
Example fjords of different regions and types discussed herein. Type 1 - isolated fjords with a shallow sill inhibiting winter AW inflow, Type 2 – open fjords with a deeper -or no– sill allowing inflow of warm water masses from outside the fjord at least periodically if not year-round. Fjord abbreviations are explained in Fig. 1. a) fjords having a sill shallower or close to the Atlantic water (AW)/ SPMW- Polar water (PW)/ coastal water (CW) interface, b) fjords lacking a sill, and c) fjords with an ice tongue or ice shelf. The main season for Atlantic water intrusions and the dominant drivers of fjord-shelf exchange are described. When data are available, the contribution of winter submarine melt of glacial ice compared to summer values is given (in %) alongside the dominant freshwater (FW) source to the fjord (either subglacial discharge, submarine melt, or no clear dominance subglacial = submarine melt).

Fjord		AW inflow (season)	Main AW inflow driver in winter	winter submarine melt [% of summer]	Dominant annual FW source	References
isolated Svalbard (BF, TF)	1	none	sill protected	Negligible	subglacial	Fransson et al., 2015; Marchenko et al., 2017; Fransson et al., 2020; Vonnahme et al., 2021; Pogojeva et al., 2022
open W Svalbard (KoF)	2a	mostly summer	Meridional (N) winds (Ekman upwelling)	no data	subglacial (90%)	Cottier et Al., 2005; Nilsen et al., 2006; Cottier et al., 2007; Tverberg & Nøst, 2009; Cottier et al., 2010; Darlington, 2015; Luckman et al., 2015; Sundfjord et al., 2017; Cantoni et al., 2020
SW Greenland (NK)	2b	winter	Dense CW inflow	no data	subglacial	Mortensen et al., 2011; Mortensen et al., 2013; Mortensen et al., 2018; Meire et al., 2015
SE Greenland (KaF, SF)	2c	more in winter	changes in strong wind directions (coastal trapped internal waves,)	ca 30% (SeF)	submarine melt (67% SeF)	Moon et al., 2018; Fraser et al., 2018; Fraser and Inall, 2018
N Greenland (NF, PF)	2e	year-round	hydraulic control (Ice tongue melt, subglacial upwelling, tides)	ca 50% (NiF)	submarine melt (89%, NiF; 80% PeF)	Washam et al., 2018; Schaffer et al., 2020; Washam et al., 2020; Johnson et al., 2011
Ellesmere Island (MF)	2f	year-round	AW shoaling, tides	no data	subglacial	Hamilton et al., 2021

Svalbard, Cottier et al., 2005; Nuup Kangerlua, Mortensen et al., 2011) weaken or are overcome by external forcing.

Warm SPMW water masses entering fjords can contribute substantially to the heat budget for the melting of deeper parts of icebergs, glacier tongues, and glacier termini (Moon et al., 2018; Schaffer et al., 2020). The importance of the different processes depends on the fjord and glacier topography (e.g., fjord width; sill depth; basin volume; presence of an ice tongue, ice shelf, or ice melange; glacier grounding line depth; presence of troughs on the shelf), the depth of the AW/ SPMW-PW/SW interface outside the fjord, local and regional wind direction and strength, basin water density, and water column stratification within the fjord. In the following chapters we discuss the main drivers of fjord-shelf exchange in different Arctic fjord case studies and its effects on winter freshwater production (summarised in Table 1).

2.4. Winter discharge in Fjord-Ocean models

A variety of modelling approaches have been used to understand glacier-fjord-ocean interaction. It is important to note that in most cases fjords are sub-grid with respect to global or even regional model resolution. Consequently, most coupled biogeochemical-physical ocean models investigating regional or global processes cannot be used to gain detailed insight into glacier-fjord-ocean exchange. Most ocean models also lack an ice sheet interface and so it is mainly small, fjord-scale, models specifically constructed to investigate fjord dynamics that are of relevance to the research questions discussed herein.

A key feature of glacier fjord circulation (and biogeochemistry) is the influence of buoyant plumes, and this has been utilised in a variety of studies to describe fjord dynamics (Jenkins, 2011), including in winter (Cook et al., 2020). One example is the Regional Ocean Modelling System (ROMS) by Oliver et al. (2020). They use fjord geometries loosely based on Sermilik Fjord, water masses representative of SE Greenland, and subglacial discharge at daily resolution from a surface elevation model. Fjord dynamics are modelled from May until the end of November and produce modelled water column distributions of nitrate and silicate that resemble those measured *in situ* where only summertime observations are available (Cape et al., 2018). A discernible influence of runoff on the nitrate anomaly attributable to the buoyant plume is found in model results at the fjord mouth from mid-June until the end of October (Oliver et al., 2020). Similarly, Torsvik et al. (2019) use a ROMS setup, but with a bathymetry grid specifically for Kongsfjorden and Krossfjorden focusing on the time period May-September. Modelled snow and runoff distributions are used to represent freshwater at daily resolution but this configuration does not include a buoyant plume model, plume-driven melt, or biogeochemical components (e.g., Sciascia et al., 2013). Neither of these models include the effects of icebergs as in both cases freshwater is released as a point source of runoff. With respect to over-winter effects, iceberg processes are likely to be relatively more important (e.g., Moon et al., 2018) and so models designed mainly to understand peak meltwater season processes may be poorly suited to understanding wintertime dynamics. More recent work has begun to explore the combined effects of icebergs and runoff in model simulations. Kajanto et al. (2023) use the Massachusetts Institute of Technology general circulation model (MITgcm), including a buoyant plume and iceberg representation. The model is a representation of the Ilulissat Icefjord where iceberg density is high year-round and does, perhaps unsurprisingly, suggest an influence of icebergs on fjord water column profiles throughout the year (results are discussed for March, June, August and October).

3. Svalbard case studies

3.1. Active subglacial drainage in winter

Svalbard tidewater glaciers are characterised by shallow grounding lines, seasonally oscillating glacier fronts (advancing during winter and spring, retreating in the summer and autumn) and turbid subglacial discharge. Svalbard fjords with tidewater glaciers often have sills shallower than the depth of the Atlantic Water (AW) in the water column with consequently limited AW inflow. However, recent observations show that conditions in Svalbard fjords are changing and warm AW masses flow into fjords at increasing volumes (e.g., Cottier et al., 2007, Sundfjord et al., 2017). Increased AW inflow can have serious implications for tidewater glaciers as fjord water temperature is a key driver controlling frontal ablation (Luckman et al., 2015).

The limited case studies of winter subglacial discharge to date were mainly located in Tempelfjorden, Billefjorden, Van Mijenfjorden and Kongsfjorden (Fig. 1), and were usually focused upon fjord biogeochemistry or sea ice formation. Water chemistry, in particular silicate concentration or silicate concentration relative to nitrate, is often used to determine the presence of subglacial discharge. Silicate is predominantly produced by chemical weathering of glacial flour (Fransson et al., 2020). While dissolution of diatom frustules may be an additional Si source, it is likely quantitatively less important compared to glacial flour at tidewater glacier fronts. Silicate concentrations can become enriched in freshwater over winter, due to the prolonged contact of subglacial freshwater with the bedrock (Wadham et al., 2000). In Tempelfjorden, high concentrations of silicate were observed entering the fjord via glacial discharge in late winter (Fransson et al., 2015, 2020). Although other studies did not find elevated silicate concentrations in spring subglacial outflow (Vonnahme et al., 2021), this likely reflects the dependence of freshwater chemistry on catchment bedrock. Subglacially derived silicate can consequently, in some cases, also affect the Si:N ratio in saline waters, especially in winter waters when light is limited or absent. At this time of year sea-ice protects the water column from wind induced mixing, and silicate upwelling via water circulation is generally less pronounced than in summer. Winter discharge of silicate can therefore lead to silicate accumulation, even if its source is relatively small. A high Si:N ratio may then facilitate diatom over haptophyte blooms in spring. While a few examples of haptophyte blooms in silicate-rich environments exist, they occur in later stages of the spring bloom (Krawczyk et al., 2015a).

Subglacial discharge can also deliver other nutrients like dissolved iron and manganese due to elevated concentrations within meltwater, or ammonia and nitrate from subglacial upwelling. These nutrients inputs in winter appear to be highly localised, despite no or very low uptake by biota, and are therefore rarely detected. One study in Billefjorden (Fig. 4; Svalbard; Vonnahme et al.; 2021), found elevated nutrient concentrations localised to only a few hundred metres from the glacier front. As a result, it was suggested that other processes, such as wind mixing and thermohaline convection, rather than subglacial upwelling, could be generally more important in nutrient redistribution during winter (Cottier et al., 2010). In Billefjorden (Vonnahme et al., 2021) heavy sea ice likely blocked wind mixing and low tidal currents made it possible for even small subglacially produced nutrient fluxes to increase surface nutrient concentrations close to the glacier (Vonnahme et al., 2021). In systems with stronger tidal and wind induced mixing, it is likely that nutrient anomalies associated with low freshwater fluxes are too dilute to detect in seawater.

Another tracer of subglacial discharge could be the concentration of suspended sediments (SS; i.e., turbidity). Svalbard subglacial discharge is known for its high SS load (e.g., Schild et al., 2017). However, distinguishing the source of the SS in marine waters from subglacial discharge, or sediment re-suspension is challenging. Glacially derived SS have been shown to have strong impacts on local light regimes and phytoplankton growth in summer (e.g., Schild et al., 2017; Halbach et al., 2019). Studies in winter found that SS inputs are much lower even in the same location (Moskalik et al., 2018; Vonnahme et al., 2021), indicating a minor role for light limitation and suggesting a limited role for glacier derived particles in over-winter biogeochemistry.

Indirect studies of subglacial discharge have also been performed through investigations of the formation of frazil ice, which can be formed by supercooling of subglacial meltwater in Svalbard fjords. Its presence has been detected in direct proximity (10 m) of a shallow (15 m) Svalbard tidewater glacier in Van Mijenfjorden (Marchenko et al., 2017) indicating the presence of active subglacial drainage. Low salinity sea ice associated with subglacial discharge was also found in Tempelfjorden (Fransson et al., 2015, 2020) and Billefjorden (Vonnahme et al., 2021), while reference sites nearby lacking tidewater glaciers had more typical salinity sea ice conditions.

Several studies in Svalbard show strong evidence that wintertime freshwater has a profound impact on the local sea ice physics, chemistry, and biogeochemistry in various fjords (Marchenko et al., 2017; Fransson et al., 2020; Vonnahme et al., 2021; Pogojeva et al., 2022). The only winter subglacial discharge estimate is based on nutrient demand calculations in Billefjorden (Fig. 4), estimating subglacial winter discharge of up to 2 m^3 s^{-1}. Hydrological modelling studies of wintertime subglacial discharge from tidewater glaciers have not been performed in Svalbard to date.

3.2. *Fjord-shelf exchange: West Svalbard Atlantification*

West Svalbard fjords are in close proximity to warm and saline AW transported in the West Spitsbergen current (WSC). The warm core of the barotropic branch of the WSC resides at rather shallow depths on the upper continental slope (Fig. 1; Aagaard et al., 1987; Cottier et al., 2010). During summer, a three-layer arrangement of the water masses can be observed in Svalbard; a fresher surface layer that extends to about 40 m, an intermediate layer comprised of advected AW and WSC down to about 100 m and more saline winter water at near-freezing point from sea-ice formation and brine release down to the bottom (Cottier et al., 2005; Nilsen et al., 2008).

While the WSC is the main heat source to the Arctic Ocean (Aagaard and Greisman, 1975; Schauer et al., 2004), Svalbard fjords are to a certain degree protected from direct contact via fresh and cold Arctic coastal waters (CWs) on the shelf, originating from the Barents Sea and

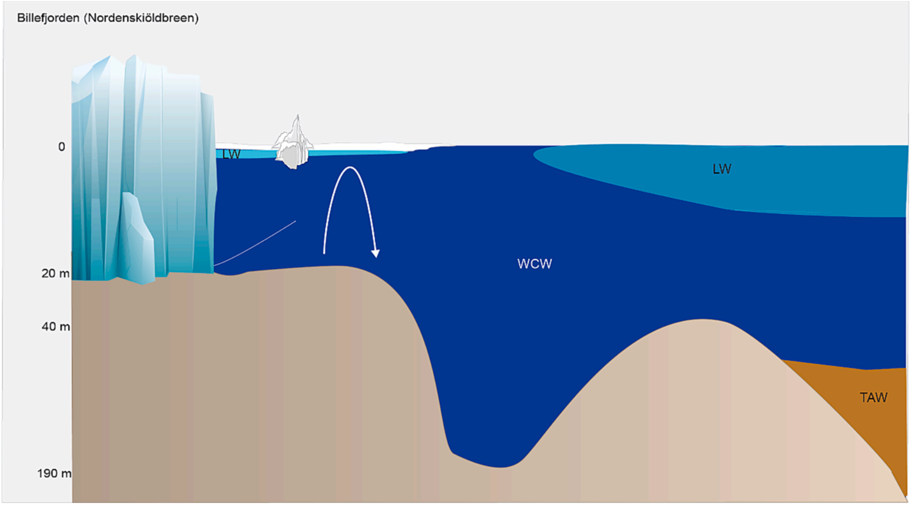

Fig. 4. Illustration of winter processes in Billefjorden (Svalbard), showing water mass distributions (LW: Local water, WCW: Winter-cooled water < -0.5 °C, TAW: Transformed Atlantic water; Skogseth et al., 2021), subglacial discharge of up to 2 m^3 s^{-1}, and major water circulation via thermohaline convection (Vonnahme et al., 2021).

Storfjorden and transported by the East Spitsbergen current (ESC; Fig. 1), building the Arctic front west of Spitsbergen (Saloranta and Svendsen, 2001; Cottier et al., 2010).

In fjords with a shallow bathymetric sill, the sill will act as a physical barrier against inflow of water masses from the shelf (e.g., Jakobsson et al., 2020; Vonnahme et al., 2021). The exchange in this case is controlled by hydraulics (Stigebrandt, 1980; Nilsen et al., 2008). In open fjords or in fjords with deeper sills, however, alongshore winds on the shelf outside the fjord can affect the fjord circulation and control the inflow of water masses from the shelf through geostrophic control (Klinck et al., 1981). Alongshore winds on the shelf west of Spitsbergen induce up- or downwelling conditions and a geostrophically balanced alongshore current system (Nilsen et al., 2008). The displacement of the free surface and the pycnocline at the fjord mouth results in pressure gradients within the fjord, which again drive the circulation. The induced current across the fjord entrance maintains the offshore slopes of the sea surface and the pycnocline even after the wind has ceased and thereby maintains the control mechanism (Klinck et al., 1981; Nilsen et al., 2008).

Alongshore winds can also be important drivers of inflow to the fjords and can affect which water masses are present on the shelf in the first place. Strong and persistent northerly winds along the West-Spitsbergen shelf have been shown to set up upwelling conditions which could lift AW from the core of the WSC (Cottier et al., 2007), making AW available to advect across the shelf towards the fjords on the west coast of Svalbard. Northerly winds along the West-Spitsbergen shelf are among several other processes important for cross-front exchange of AW near the shelf edge (Sundfjord et al., 2017) as they tend to flatten the front between the WSC and the coastal current. Other processes important for the area near the shelf edge are barotropic (Nilsen et al., 2006; Teigen et al., 2010) and baroclinic (Teigen et al., 2010) instabilities on topographic vorticity waves along the continental slope, and eddy activity generated by instabilities due to density differences between the water masses (Tverberg and Nøst, 2009).

Southerly winds can also drive inflow of water masses in the lower layer through first setting up an offshore pressure gradient force as a response to the wind. When the wind ceases, the upper layer is moved offshore, driving a compensating onshore lower layer transport (Cottier et al., 2007). In these flooding events connected to alongshore winds, AW can reach the surface and turn previously Arctic fjords along the west coast into ice-free Atlantic-influenced fjords (Cottier et al., 2007, Sundfjord et al., 2017). Continued increases of this inflow of heat will lead to increased submarine glacier ice melt (Luckman et al., 2015) and then a further reduction in sea ice.

In order to understand fjord-shelf exchange in the winter it is important to also understand the summertime process as they often precondition the water column for the following season. For example, barotropic instabilities via freshening of fjord water columns are important for AW intrusions (Cottier et al., 2005). Thereby, freshwater is a key driver of horizontal density gradients. Summer storm events can also suddenly replenish fjord waters, weakening density gradients, thus the intensity of strong wind events should also be considered alongside changes to mean wind conditions. In 2016 for example, a single modest strong wind event (8.3 m s^{-1}) at the end of July was sufficient to reduce the depth integrated freshwater content of Kongsfjorden by 40% (Cantoni et al., 2020). Such events in winter would have less absolute impact on the density gradient and stratification because both would be weak in general, but shifts in storm intensity may either impede or promote the onset of seasonal stratification.

Since the grounding lines of marine-terminating glaciers in Svalbard are shallow, given present rates of retreat and shoaling, some of them are likely to become land-terminating on a decadal timescale (Blaszczyk et al., 2009). It needs to be noted that this is not the case for all tidewater glaciers in Svalbard as their extent can vary due to surging cycles (rapid advance). We suspect however that the future fractional and absolute importance of AW induced glacial ice melt will slowly decline with continuous glacier recession. This will profoundly affect freshwater fluxes over winter as a dominant component of the over-winter freshwater input will be lost entirely when marine-terminating systems retreat inland.

4. Greenland case studies

4.1. Active subglacial drainage in winter

The first studies describing subglacial discharge in winter in Greenland were based on hydrological modelling, describing active subglacial discharge at various Greenland tidewater glaciers. The modelled fluxes are typically one to two orders of magnitude lower than in summer, but sufficient for submarine ice melt at the glacier front, driving subglacial upwelling and influencing fjord circulation (Cauche et al., 2016; Cook et al., 2020). However, the model outputs are highly variable and very sensitive to the processes included in the parameterization (Sommers et al., 2022). An early modelling study from Store Glacier in West Greenland found only limited subglacial discharge of 0.8 $m^3 s^{-1}$, which is about 50% of the winter 1.5 $m^3 s^{-1}$ submarine melt rate (Rignot et al., 2016). A more recent study from the same glacier included more detailed plume dynamics and estimated a total winter discharge of 9.4 $m^3 s^{-1}$ (Cook et al., 2020). In Sermilik fjord in East Greenland an early modelling study assumed 0 $m^3 s^{-1}$ subglacial discharge in winter due to the assumption of surface melt as the sole source of subglacial meltwater. However, a recent study at Helheim glacier in Sermilik fjord estimated winter subglacial discharge between 2.7 $m^3 s^{-1}$ and 131 $m^3 s^{-1}$ depending on the processes included in the model and the parametrization for basal shear stress (Sommers et al., 2022). With no frictional heat the estimated discharge was 2.7 $m^3 s^{-1}$, while frictional heat increased the estimate to 10.2 $m^3 s^{-1}$. In turn, frictional heat estimates are very sensitive to basal shear stress estimates, leading to estimates of winter subglacial discharge of up to 131 $m^3 s^{-1}$ if the basal shear stress is equal to the driving stress (Sommers et al., 2022).

Despite the importance of subglacial discharge in modelling studies, *in-situ* observations of winter discharge in Greenland are lacking. In Greenland, fjords are much deeper than Svalbard and so are the mean grounding lines of tidewater glaciers thus making low volume subglacial discharge even more difficult to detect. Subglacial discharge at deeper grounding lines theoretically leads to a larger entrainment of bottom water (e.g., 1:1.6 in Billefjorden, 1:6–30 in Greenland), resulting in a low freshwater content in the entrained plume (Hopwood et al., 2020; Vonnahme et al., 2021). In addition, active glacier fronts are often preceded with a several kilometres wide, dense and non-navigable ice mélange, making them logistically challenging locations to sample, which means there is a lack of data close to glacier fronts, especially during winter.

At the deep grounding lines of large marine-terminating glaciers (several hundred metres below sea level) any freshwater is theoretically highly diluted by ambient seawater during upwelling and near surface advection (Jenkins, 2011; Hopwood et al., 2018). Small freshwater fluxes will thus achieve neutral buoyancy at depth (e.g., as hypothesised for iceberg melt: Moon et al., 2018; Hopwood et al., 2019). At the same time, warm coastal Atlantic origin water masses may mask any signal of other minor freshwater sources as they can enter fjords in winter and cause direct melt of the glacier terminus and any icebergs, if present (Moon et al., 2018). In most Greenland fjords, Atlantic origin or coastal water inflow is, in fact, most dominant in winter (Mortensen et al., 2011). No winter subglacial discharge was detected during a winter field campaign in Nuup Kangerlua using a thermodynamic model (Mortensen et al., 2014). But, as noted, this may simply reflect the dilute nature of a small signal at a considerable distance from the calving front (profiles obtained >45 km from the source glacier).

4.2. Fjord-shelf exchange in large Greenland fjords

Greenland fjords are heterogeneous with respect to climate, hydrography, bathymetry, and glacier morphology. Thus, different processes drive fjord-shelf exchange and glacial ice melt in different fjords (Straneo and Cenedese, 2015). This makes investigation of fjord-shelf exchange challenging in a Greenlandic perspective. The case studies presented here should be considered examples of larger fjords with large tidewater glaciers, while we suggest that Svalbard fjords may be more representative for smaller and shallower fjords with smaller tidewater glaciers.

In large Greenland fjords, glacial ice melt makes a larger contribution to freshwater discharge compared to Svalbard fjords. This is because of the comparatively larger ice-seawater interface (e.g., Moon et al., 2018). In Petermannsfjord, for example, an ice shelf provides a large ocean-glacier interface leading to a submarine glacial meltwater contribution of 80% to total freshwater discharge (Johnson et al., 2011). In the Sermilik fjord system, about two times as much freshwater originates from submarine glacier and iceberg melt (515 $m^3 s^{-1}$), compared to subglacial runoff (260 $m^3 s^{-1}$, Moon et al., 2018). While the iceberg melt flux is estimated to be 3 times higher in summer than in winter, winter melt is still substantial contributing approx. 200–400 $m^3 s^{-1}$ meltwater in winter (Moon et al., 2018, Fig. 3, Table 1). In contrast, in the Svalbard fjord Kongsfjorden about 90% of freshwater is estimated to originate from subglacial discharge (Darlington, 2015).

Due to the lateral dispersion of icebergs, the fractional importance of ice melt to freshwater outflow depends on the flux gate used (Mankoff et al., 2020). Meltwater can either originate from the calving face at the glacier terminus, or from calved icebergs progressively melting and disintegrating while moving down-fjord. From the few studies available in Nuup Kangerlua and Sermilik fjord it can be estimated that roughly 50% of calved ice melts in inner-fjord environments (Bendtsen et al., 2015, Moon et al., 2018) and a large fraction, ~70–90%, melts within the fjord (Moyer 2019) in both winter and summer. The absolute and fractional importance of ice melt as a freshwater source therefore increases with distance from the ice calving faces.

A critical difference compared to the smaller Svalbard systems is that SPMW inflow is often most dominant in winter, with warmer inflows dominating in later winter and colder inflows in early winter (e.g., Mortensen et al., 2011). We suggest that besides the size of the fjords and glaciers, also the location and the water mass properties outside the fjord may explain the different timing of SPMW inflow. The winter SPMW inflow can lead to high heat influx and winter glacial meltwater fractions comparable to summer values in East Greenland (Motyka et al., 2017; Schaffer et al., 2020). In Nioghalvfjerdsfjord (NE Greenland), submarine glacier melt of an ice tongue is highest in winter, as found in year-round mooring data between 2016 and 2017 (Schaffer et al., 2020).

4.3. Fjord- shelf exchange: West Greenland case studies of dense coastal water inflow

The Southwest and West Greenland Current (WGC) flowing northwards along the shelf (Fig. 1) is characterised by three different water masses: i) a thin local summer water layer on the surface (SW), impacted from local terrestrial runoff, ii) rather cold and fresh coastal water (CW) extending from the East Greenland Current (EGC), and iii) underlying warm and saline subpolar mode water (SPMW) originating from the warm and saline Atlantic-sourced Irminger Current water (IC) submersed via winter cooling (Mortensen et al., 2011, 2022). Concurrently, cold Baffin Bay Polar water (BBPW) can reach the West Greenland shelf via a counter-current extension from the Baffin Island Current (Myers and Ribergaard, 2013; Rysgaard et al., 2020; Mortensen et al., 2022). The BBPW has been shown to reach both southward (Rysgaard et al., 2020), and northwards of the Davis Strait (Myers and Ribergaard, 2013). SPMW can be a major heat source for submarine glacial ice melt, as also observed in West Svalbard. In contrast to Svalbard however, geostrophic controls play a minor role for CW or SPMW intrusions in SW Greenland (Cottier et al., 2010).

For Nuup Kangerlua, the seasonal development of water masses is relatively well studied (Fig. 5). When meltwater runoff ceases in winter, surface salinity and density inside the fjord increases, and stratification consequently weakens (Stuart-Lee et al., 2021). Outside the fjord, the coastal pycnocline becomes shallower in autumn due to meridional winds driving Ekman upwelling (Carroll et al., 2018). Eventually, the density difference is low enough to allow dense CW/SPMW inflow over the rather shallow (170 m) sill (Mortensen et al., 2011). Consequently, dense CW/SPMW inflow is the dominant circulation mode in winter, with SPMW as a major source of heat (Mortensen et al., 2011, 2013, 2018). The CW/SPMW can replace the basin water over 1–2 winter periods with episodes of 1–3 months each winter (Mortensen et al., 2011, 2013). The depth of the SPMW underlies interannual variations leading to differences in the amount of CW vs SPMW entering the fjord (Mortensen et al., 2011, 2018). Local temperatures in the outer fjord also appear to determine the timing of the CW/SPMW inflow (Mortensen et al., 2018) (Fig. 6, Fig. 7).

In the neighbouring Ameralik fjord, which lacks a tidewater glacier, a complete breakdown of stratification was observed in 2019, leading to an earlier and complete bottom water renewal. In the same year in Nuup Kangerlua some weak stratification, blocking bottom water renewal, remained over-winter (Stuart-Lee et al., 2021). Sea ice blocking wind-driven circulation in the inner fjord and continuous summer accumulated freshwater outflow have been discussed as potential drivers (Stuart-Lee et al., 2021). Winter submarine and perhaps to a lesser extent subglacial freshwater discharge could also be drivers of the sustained winter stratification observed by Stuart-Lee et al. (2021).

Dense coastal water inflow underlies strong interannual variability (Mortensen et al., 2018). During cold years, colder coastal water may fill the water column in the outer fjord, blocking further CW/SPMW inflow. This blockage leads to later CW inflow further into the fjord, which is typically colder, leading to a colder local climate and less heat available for glacial melt. In warm years, CW/SPMW enters the fjord earlier, introducing more heat to the marine-glacier interface (Mortensen et al., 2018). An example for a warm year was 2009/2010, when high amounts of SPMW were able to enter Nuup Kangerlua. In Autumn 2009, SPMW on the shelf was only 150 m deep, which is above the sill depth (ca 170 m) and was therefore able to flood the fjord basin (Mortensen et al., 2011, 2018). The high inflow of SPMW reached the glacier termini in the inner fjord and led to record high summer temperatures in 2010 (Mortensen et al., 2018). The intrusion of SPMW in 2009/2010 contributed to winter glacial ice melt leading to a surface water freshwater fraction of about 1% in the inner basin, which is equivalent to 0.1–0.4 m of melted ice per m^2. (Mortensen et al., 2013). The winter SPMW inflow also led to summer glacial melt and retreat in 2010 being two times higher than in 2009 demonstrating the important role of over-winter processes for pre-determining dynamics of the following summer.

Dense coastal water inflow can drive upwelling in the inner fjord, and drive submarine glacier terminus and iceberg melt (Fig. 5; Mortensen et al., 2011, 2013). Processes described in Nuup Kangerlua are also observed in other West Greenland fjords, indicating that they may be common in large fjord systems across the area. In contrast, other West Greenland fjords have rather deep sills (e.g., 400 m at Kangerdlugssuaq Sermersua, Carroll et al., 2018; 250 m at Ilulissat Icefjord; Gladish et al., 2015) and troughs connecting the fjord to the Baffin Bay, but even there, dense coastal water inflow is still the main source of SPMW influx over the sill driving basin water renewal. As with the case of Svalbard fjords, processes in summer strongly influence turnover the following winter. In the case of West Greenland fjords, summertime mixing of deep fjord water (e.g., tidal mixing, diffusion) with overlying water is thought to be the key in-fjord process influencing winter dynamics (Carroll et al., 2015; Moon et al., 2018).

In West Greenland fjords other than Nuup Kangerlua, CW enters the fjords in shorter pulses following a more intermittent sub-annual pattern

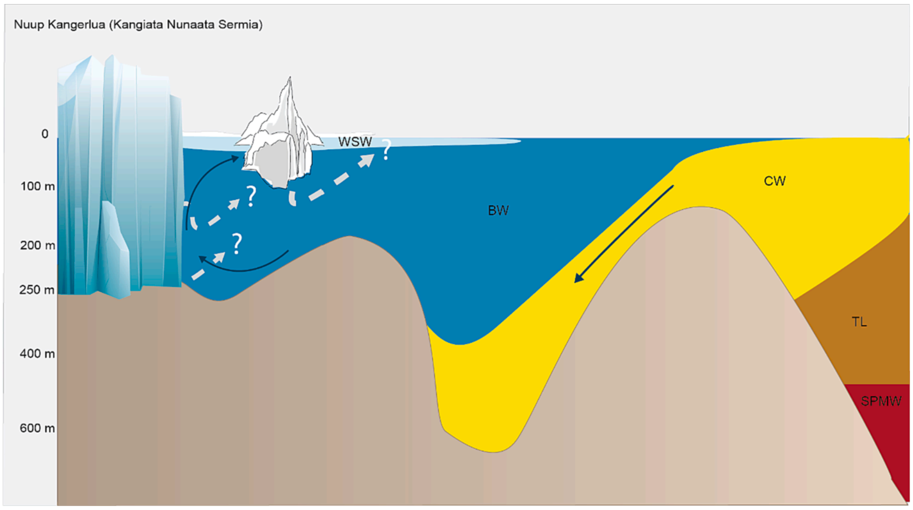

Fig. 5. Illustration of winter processes in Nuup Kangerlua, showing the water mass distributions in the water column (SPMW: Subpolar mode water, TL: Transition layer, CW: Coastal water, BW: basin water, wSW: Winter surface water, Mortensen et al., 2018) and main circulation modes (Coastal water inflow, upwelling). Data on subglacial discharge and submarine melt are presently unknown.

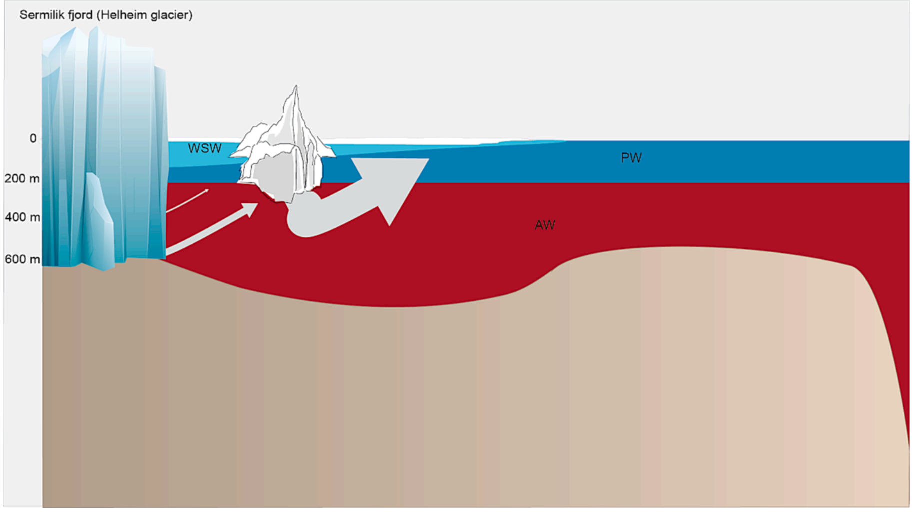

Fig. 6. Illustration of winter processes in Sermilik fjord (Helheim glacier), showing the main water masses (wSW: Winter surface water, PW: Polar water, AW: Atlantic water; Fraser et al., 2018), and proportional estimates of subglacial discharge (Sommers et al., 2022) and submarine melt (Moon et al. 2018).

(e.g., Ilulissat Icefjord: Gladish et al., 2015; Kangerdlugssuaq Sermerssua and Rink Isbræ: Carroll et al., 2018). The residence time of the water is dependent on preconditioning of the fjord basin water but also on topographic features, such as the sill depth, the presence of a trough and the volume of the fjord basin (Carroll et al., 2018). Residence times of water in Greenland fjords have yet to be established, but likely range from months to, at most, a few years (Slater et al., 2022).

4.4. *Fjord- shelf exchange: Southeast Greenland barrier winds and iceberg upwelling*

In Southeast Greenland, the EGC flows along the shelf with the Irminger Current containing warm AW outside the shelf (Fig. 1). Part of the AW submerges below polar water (PW) in the EGC and may enter fjords with deep sills and troughs over the continental shelf (e.g., Sermilik, Straneo et al., 2011). The depth of the PW/AW interface is variable over the season with the shallowest PW layer after the melting season in autumn, before the PW layer thickens gradually over winter (Harden et al., 2014). The largest and best studied fjords are Sermilik fjord (SF) and Kangerdlugssuaq fjord (KF), both with deep sills (550 m) below the AW/PW interface. The glacier termini are deep (>600 m), and solid iceberg production is the main source of glacial meltwater to the fjords, exceeding subglacial discharge (Jackson et al., 2014; Moon et al., 2018; Fraser et al., 2018). AW masses are present throughout the year contributing to substantial subglacial melt (Straneo et al., 2010).

Whilst AW intrusions are present throughout the year, stronger barrier winds make it a more viable process in winter (Straneo et al., 2010; Spall et al., 2017). Fjord-shelf exchange mainly occurs during winter in both West and Southeast Greenland. Barrier winds are substantially stronger in Southeast Greenland and act as the main driver for fjord-shelf exchange (Harden and Renfrew, 2012). Winter AW intrusions can drive submarine melt rates reaching approximately 60% of summer values in Sermilik (Jackson et al., 2014; Fraser et al., 2018). Unlike Nuup Kangerlua, iceberg production and submarine melt keeps Sermilik fjord stratified throughout the year (Jackson et al., 2014; Fraser et al., 2018). Up to 50% of glacial meltwater in Sermilik originates from iceberg melt, with the largest fractional contribution occurring in early winter (Moon et al., 2018; Moyer et al., 2019).

During periods of strong meridional winds, Ekman transport towards the coast leads to downwelling, causing a deepening pycnocline and the

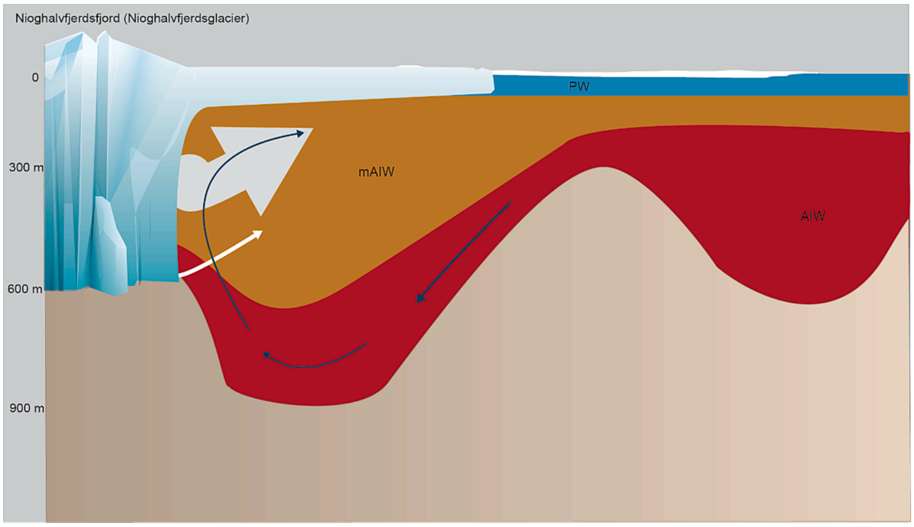

Fig. 7. Illustration of winter processes in Nioghalvfjerdsfjord, showing the main fjord water mass distributions (AIW: Atlantic intermediate water, mAIW: modified Atlantic intermediate water, PW: Polar water; Schaffer et al., 2020) in the water column, main circulation modes, and subglacial discharge and submarine melt.

build-up of a density gradient. Once the wind relaxes, the surface water flows along the density gradient out of the fjord leading to a compensating inflow of deep AW (Fraser et al., 2018). These periodically changing density gradients lead to coastal trapped internal waves periodically mixing fjord and shelf waters. The coastal trapped waves propagate in the fjord with the coastal boundary to its right and mediate baroclinic exchange induced by the along-shelf winds (Fraser et al., 2018). Baroclinic exchange after strong meridional winds is described as the main driver of fjord-shelf exchange (intermediary circulation, Klinck et al., 1981; Jackson et al., 2014; Fraser et al., 2018). The processes in SF and KF are specific to fjords where the width exceeds the internal Rossby radius of deformation (Coriolis forces play a role), and a shallow sill is lacking.

In addition, strong katabatic winds in winter have been described as a driver of fjord-shelf exchange in SF. In SF, katabatic winds can push about 10% of the surface waters out of the fjord during a single event, which is then compensated by deeper water inflows leading to an estuarine-like circulation. Katabatic winds also drive the export of icebergs and sea ice, thereby destabilising the glacier terminus (Spall et al., 2017; Carroll et al., 2017).

The year-round AW inflow and large input of icebergs at SF and KF leads to a strongly stratified low salinity surface layer throughout the year (Moon et al., 2018). Deep iceberg melt introduces freshwater at depth which partly mixes with the surrounding seawater and can also drive buoyant meltwater plumes and upwelling of nutrient-rich AW (Moon et al., 2018). Typically, the water column is most strongly stratified in winter, but with a mixed layer depth of about 170 m, allowing submarine meltwater released above 170 m to reach the surface (Moon et al., 2018). In summer a second pycnocline at about 20 m is present, blocking meltwater from depths below 20 m from reaching the surface (Moon et al., 2018). Unlike subglacial discharge which is well characterised by buoyant plume models, iceberg derived meltwater may be distributed over a broad depth range. There is some uncertainty concerning how to parameterise iceberg melt, particularly wave-induced melt (Wagner et al., 2014; Moon et al., 2018), although this melt component is likely much less prominent in winter when icebergs are trapped in ice mélange. The resulting upwelling is therefore, theoretically, better described as a series of stacked melt-driven convection cells up the ice face rather than as a single buoyant meltwater plume (Hopwood et al., 2019). While winter appears to be a crucial time for iceberg induced upwelling of deep nutrient-rich AW, this is also the time of year when the water column is most homogenous meaning that the entrainment of nutrients within buoyant plumes has less effect on vertical nutrient flux anomalies than it would with a steeper nutricline in spring or summer.

4.5. Fjord- shelf exchange: North Greenland ice tongues

In Northern Greenland, Atlantic Intermediate Water (AIW) masses can originate from Fram Strait or the Arctic Ocean (Fig. 1) and are observed below a thick (ca 100 m) layer of Polar water masses (Schaffer et al., 2020). At the largest tidewater glaciers, deep sills (>200 m depth) and troughs across the NE Greenland shelf allow the warm AIW masses to enter the fjords, contributing to substantial glacial ice melt.

The northernmost tidewater glaciers are often characterised by extensive floating ice tongues (80 km long at Nioghalvfjerdsfjord, Schaffer et al., 2020; 70 km at Petermann glacier, Johnson et al., 2011; 20 km at Flade isbrink icecap, Bendtsen et al., 2017) often extending 500 m below the sea surface, which is well below the PW/AW interface. The ice tongues are typically preceded by sea ice, which may last for multiple years. Due to their large contact area with the deep fjord waters, direct glacial ice melt is an important process contributing meltwater throughout the year (at least in the innermost 20 km of the ice tongues, Washam et al., 2018). Submarine melting of Greenland ice tongues due to increasing deep sea water temperatures is described as the main driver for ice tongue thinning and destabilisation (Motyka et al., 2011; Choi et al., 2017). Sedimentary records from the NE Greenland shelf are consistent with basal ice melt, driven by strong AW inflow, having been responsible for past contraction of the ice shelves during the Holocene (Syring et al., 2020).

At Nioghalvfjerdsfjord, AIW inflow originating from Fram Strait (Fig. 1), is mostly controlled hydraulically. Overturning of the seawater cavity beneath the floating ice tongue is relatively insensitive to freshwater discharge which is estimated to drive only 1.4% of the overturning (Schaffer et al., 2020). Once AIW gets into contact with the ice, the ice tongue melts gradually leading to AIW freshening. AIW thereby decreases in density and shoals. The shoaling then draws denser AIW into the fjord. The deep AIW inflow is then compensated by a surface outflow (Schaffer et al., 2020). Compared to this basal melt-induced circulation mode, subglacial discharge at Nioghalvfjerdsfjord contributes only ~11% of the meltwater and is insignificant for driving the circulation (Fig. 8).

Climate change is expected to change this important circulation system. A major control for periodic variabilities is the depth of the PW/AIW interface (Schaffer et al., 2020; Gjelstrup et al., 2022). With a thickening thermocline (the AIW layer defined by a 1.2 °C threshold),

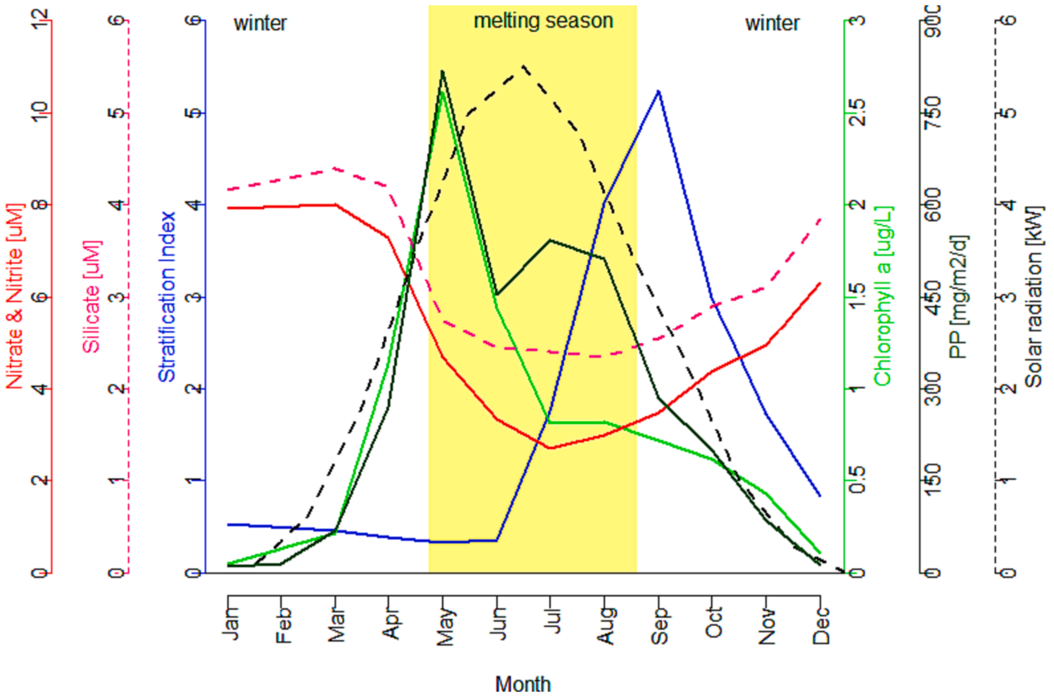

Fig. 8. Average seasonal cycle in Nuup Kangerlua (Godthåbsfjord) (Data retrieved from G-E-M.dk MarineBasis Nuuk, https://doi.org/10.17897/PGN3-7597) and monthly average calculated over the time series period from 2005 to 2020). Nutrients (Nitrate, Nitrite, Silicate) are supplied via winter mixing (Cottier et al., 2010), consumed by primary producers during the spring bloom and partly resupplied via subglacial upwelling in later summer. The water column is mixed in winter, but increased freshwater runoff leads to a strongly salinity stratified water column in summer. Chlorophyll biomass is highest in the spring bloom, while solar radiation and nutrient concentrations are high, declines to lower levels in summer due to nutrient limitation and presumably grazing, and further declines to very low levels due to light limitations in winter. Primary production follows a similar trend to Chlorophyll, but shows a distinctive second peak in summer, driven by subglacial upwelling (Detailed description at Juul-Pedersen et al., 2015).

more AIW can penetrate the fjord over the sill leading to increased submarine melt (Schaffer et al., 2020). In fact, shoaling of the AW layer is one major consequence of climate change in the European sector of the Arctic and has already led to an estimated 141% increase in overturning of the Nioghalvfjerdsfjord basin water in 2013–2017, compared to estimates prior to 2008 (Schaffer et al., 2020). In East Greenland the depth of the AW mass experienced an upward displacement of 76–134 m from the 1990 s to 2017/2018 (Gjelstrup et al., 2022). At the same time, AW warmed by 1 °C (Gjelstrup et al., 2022).

Whenever low-salinity meltwater gets transported into seawater below the freezing point of the meltwater, frazil ice may be expected to appear. A part of the meltwater released each year can refreeze under ice tongues (Johnson et al., 2017), or contribute to the preceding sea ice in a similar fashion to the processes occurring along Antarctic ice shelves (e.g., Hoppmann et al., 2020). In Antarctica, frazil ice formation under ice shelves is well described and known to have a profound impact on sea ice formation by resulting in a highly porous platelet ice layer (Hoppmann et al., 2020). However, in the Arctic refreezing of glacial meltwater (Marchenko et al., 2017, Johnson et al., 2017) and platelet ice (Kirillov et al., 2018) has only been observed sparsely due to limited field investigations. Thus, any biological implications of refreezing are unknown here. However, platelet ice formation requires sub-zero water temperatures and is likely only feasible at high latitudes.

The best studied ice tongue in the Northeast is Petermann glacier where the relative importance of different freshwater sources appears similar to Nioghalvfjerdsfjord. At Petermann glacier, basal ice melt has been estimated to be the main (80%) meltwater source to the fjord, contributing 280 to 340 $m^3 s^{-1}$ meltwater (Johnson et al., 2011). The sill at 290 m is deep enough for AW intrusions (which can occur at 200 m depth). A geostrophic flow is driven by basal ice meltwater exiting the fjord at the surface, compensated for by AIW inflow at depth, and is described as the main driver of fjord-shelf water exchange (Washam et al., 2018). Due to the fjord width of ~20 km, the flow is affected by the Coriolis force leading to an inflow in the south and an outflow in the north (Washam et al., 2018). Subglacial discharge and upwelling can increase the flow, making it a more important process in late summer (Washam et al., 2020).

Basal ice melt and circulation at ice tongues appears to be seasonally more buffered than in fjords with more vertical tidewater glaciers, with the main glacial ice melt (>80%) coming from basal melt. Thus, winter meltwater fluxes may be considerably larger than in other fjords (Schaffer et al., 2020) which implies that the associated lateral export of any meltwater, or sedimentary derived nutrients (e.g., silicic acid or iron) may also occur over-winter (Krisch et al., 2021), although this is yet to be explicitly demonstrated. In the context of ice-tongue retreat and loss, this also implies a long-term shift in the seasonal supply of these nutrients associated with the transition towards a lower fractional importance of basal ice melt to annual freshwater release. Due to the depth of these tongues, nutrient upwelling plays an additional role. While primary production is light limited below the ice tongues, the preceding sea ice and nutrient rich and stratified surface water may theoretically fuel primary production along seasonally retreating sea ice edges. However, paleo-oceanographic studies at Nioghalvfjerdsfjord investigating Holocene dynamics suggest the highest algae biomass at times of long-term ice tongue and sea ice retreat and very low biomass at times with more extensive sea ice coverage, indicating a negative local effect of ice coverage on local primary production (Syring et al., 2020).

5. Other (sub-)Arctic fjords with tidewater glaciers

While published information about winter freshwater discharge from tidewater glaciers is so far only available from Svalbard (mostly observations) and Greenland (mostly modelling), there are other regions with similar systems. Tidewater glacier influenced fjords are also dominant features in the Canadian Arctic (e.g., Ellesmere Island, Hamilton et al., 2021), Alaska (e.g., Glacier Bay, Matthews, 1981), and the Russian archipelagos (e.g., Severnaya Zemlya, Franz-Josef Land, Gavrilo et al., 2020). These sites share similar complexities to their Greenland counterparts in terms of the likelihood of detecting winter subglacial outflow due to deep glacier termina, warm water inflow allowing direct ice melt, and ice mélange or shelves limiting access. A recent seasonal study at LeConte glacier on Northern Ellesmere Island detected strong impacts of AW inflow leading to a direct melt of the glacier tongue but did not find any evidence for winter subglacial discharge (Hamilton et al., 2021). However, considering the findings of the four Svalbard (Vonnahme et al., 2021; Fransson et al., 2015, 2020; Marchenko et al., 2017) and two Greenland case studies (Cauche et al., 2016; Cook et al., 2020), an active subglacial drainage in winter is also likely to be present in other tidewater glaciers.

At Northern Ellesmere Island some of the last ice shelves remain in front of tidewater glaciers, but only the hydrography in Milnes fjord, a fjord with a tidewater glacier and ice shelf, has been described in detail (Hamilton, 2016; Hamilton et al., 2021). AW masses can enter the fjord due to a deep (260 m) bathymetric sill and contribute to substantial (2.5 $m^3\ s^{-1}$) submarine glacial ice melt throughout the year (Hamilton et al., 2021). Compared to North Greenland glaciers, the submarine melt rate is one to two orders of magnitude lower (Hamilton et al., 2021; Bamber et al., 2018). External processes such as periodic Arctic thermocline shoaling, tidal oscillations, and the position of the Atlantic/Pacific front are described as drivers of the hydraulic inflow of this AW mass (Hamilton et al., 2021) into the deep basin. (Sub-)glacial discharge in summer is trapped in the epishelf lake and surface layer by the preceding thick ice shelf, keeping the fjord strongly stratified throughout the year. This stratification also limits winter submarine meltwater upwelling to only about 25 m before the meltwater becomes neutrally buoyant after mixing with the surrounding seawater (Hamilton et al., 2021). Other Canadian fjord systems likely have similar dynamics but lack sufficient winter measurements.

Tidewater glaciers of Glacier Bay (Alaska) are relatively well observed. Oceanographic processes in Glacier Bay are profoundly affected by the presence of a sill at ~25 m depth which acts as a barrier to saline inflow into the Bay (Matthews 1981). Glacier Bay is an interesting case study as there is documented evidence of glacier retreat since the Little Ice Age, and a trend towards increasing precipitation across the region; a 10% increase in precipitation was reported from 1949 to 2005. Some evidence of historical change in the fjord may also be evident with the intra-annual seasonal change in salinity reduced in the 1990s compared to the 1960s and surface waters >2 °C warmer year-round (Hooge and Hooge 2002). Around 8 glaciers within Glacier Bay can be considered tidewater systems, but a number of these have grounding lines close to sea-level and are poised to transition to land-terminating systems. Winter waters within the bay are relatively warm (2.5–6 °C) and well mixed (Reisdorph and Mathis, 2014). Snowmelt and precipitation stratify the bay in spring creating a barrier to inflow over the shallow sill. Inflow is thus most viable over-winter but may occur year-round (Matthews 1981). Whilst total freshwater discharge shows a broad peak from July to September, freshwater discharge remains >300 $m^3\ s^{-1}$ year-round (Hill et al., 2009), and thus no time period strictly conforms to the criteria for 'winter' as defined herein. The freshwater content of the bay declines from ~40% in June-August to <10% in January-March (Reisdorph and Mathis, 2014) but remains high compared to many Greenland and Svalbard systems at the same time of year likely due to a combination of high precipitation and the retention of some freshwater within the fjord from summer. Future projections suggest an increase in runoff over winter primarily due to increased snowmelt and precipitation (Crumley et al., 2019).

Fjord systems in subarctic Alaska are unlike Svalbard and Greenland as there is no cold sub-zero surface water layer (e.g., PW; Matthews, 1981; Etherington et al., 2007). Fjord-shelf exchange can be blocked by a brackish surface layer originating from terrestrial runoff in summer (baroclinic barrier) until the pycnocline erodes, similar to what is observed in Nuup Kangerlua. Low surface freshwater discharge is also present in winter, leading to a continuous estuarine circulation (Matthews, 1981). At LeConte glacier submarine melting has recently been described as an important process leading to meltwater intrusions, contributing to 65% of the total melt budget in summer (Sutherland et al., 2019; Jackson et al., 2020). This finding is in contrast with earlier model assumptions of negligible ambient melt compared to subglacial discharge at tidewater glaciers with a near vertical terminus (Jackson et al., 2020), and opens the question if submarine melt may also be a more important process than previously recognized in Greenland (Jackson et al., 2020).

6. Winter freshwater and primary producers

6.1. Freshwater quality for biological production

The freshwater that is released from tidewater glaciers either by submarine melting or subglacial discharge often carries high concentration suspended sediments, and associated minerals and nutrients (such as iron and silica) from surrounding bedrock of the drainage basin (e.g., Hopwood et al., 2020). More importantly, freshwater released at depth can rise towards the surface entraining nutrient-rich bottom water into the euphotic zone (subglacial upwelling). Increased nutrient concentrations have been shown to promote primary production in summer near the fronts of the marine-terminating glaciers both in Svalbard and Greenland (e.g., Fransson et al., 2016, Meire et al., 2017, Hopwood et al., 2020). Mixing between freshwater and saline water also results in increased drawdown of atmospheric CO_2 via a purely chemical process due the resulting changes to the carbonate system (i.e. carbonate equilibrium). In winter, these processes are both assumed to be negligible due to low freshwater fluxes. However, on Svalbard even freshwater release at low fluxes in winter has been shown to promote subglacial upwelling and increase late winter primary production (Vonnahme et al., 2021). Yet, in contrast to Svalbard where both grounding lines and fjords are shallower, at the deeper Greenland tidewater glacier termini, slow release of freshwater theoretically achieves neutral buoyancy at depth such that no change in the depth distribution of entrained nutrients would be observed, and any direct additions (e.g., of iron or silica) would remain at depth (Hopwood et al., 2020). Monthly resolution data for Nuup Kangerlua shows that nutrients in the fjord mouth reach maximum concentrations in February and March because of vertical mixing and low productivity, pre-conditioning the water column for the spring bloom in late April or May. While winter vertical mixing is common in most high latitude systems, glacial derived freshwater may play an additional role via upwelling, or early stratification (e.g., Vonnahme et al., 2021). A detailed representation of seasonal dynamics of the key drivers for phytoplankton production and biomass is given in Fig. 8 and discussed by Juul-Pedersen et al. (2015) for Nuup Kangerlua (SW Greenland).

Carbonate chemistry is important for the shells of calcifying phytoplankton (e.g., coccolithophores). Glacial meltwater may contain relatively high total alkalinity (concentration of bicarbonate HCO_3^- and carbonate ions CO_3^{2-}; Fransson et al., 2015, 2016), due to carbonate dissolution in the glacial catchment. However, on average glacier discharge has a lower total alkalinity than seawater and consequently dilutes total alkalinity in the marine environment. Aragonite is a common proxy for carbonate ion concentration. When aragonite is undersaturated (aragonite saturation <1), calcifying phytoplankton taxa cannot easily produce their calcite shells. In fjords, aragonite is typically undersaturated due to high freshwater contents (Fransson et al., 2015). A lower freshwater content in winter may lead to higher aragonite saturation, but patchy aragonite undersaturation is still common in tidewater-glacier influenced fjords (e.g., Reisdorph and Mathis, 2014). Low aragonite saturation wintertime values, likely driven by ice melt, in fjord enclosed regions could be a stressor for calcifying phytoplankton and might influence the viability of primary producers at a critical time of year for bloom onset (Etherington et al., 2007). In productive fjords primary production, rather than freshwater derived ions, causes the largest change in CO_2, making productive glacial fjords predominantly a sink for CO_2 (e.g., Meire et al., 2015; Ericson et al., 2019). However, regional variability is large and dynamics in less productive fjords are likely very different. In fjords, with high winter freshwater discharge comparable to summer discharge (e.g., Northern Greenland), aragonite undersaturation may be a common feature year-round. In contrast, in fjords that lack winter freshwater discharge, aragonite may become supersaturated.

6.2. Phytoplankton dynamics

In summer freshwater is known as a key driver for Arctic phytoplankton dynamics and primary production by affecting stratification, light availability, grazing pressure, and nutrient availability (e.g., Sverdrup, 1953; Behrenfeld, 2010; Hegseth et al., 2019, Vonnahme et al., 2022). Yet, these dynamics have been neglected in winter studies due to the perceived absence of freshwater inputs.

To our knowledge, there are no studies specific to the role of tidewater glaciers in influencing polar night biological dynamics (e.g., via submarine melt, or subglacial discharge). Although, primary producers during the light-limited winter and polar night and their strategies to withstand prolonged periods of darkness have been well studied in recent years (Zhang et al., 1998; Vader et al., 2015, Søgaard et al., 2021). Overwintering phytoplankton populations have been found to be diverse (Krawczyk et al., 2015a; Marquardt et al., 2016), viable (Vader et al., 2015; Van De Poll et al., 2020), and photosynthetically active too (Kvernvik et al., 2018; Randelhoff et al., 2020). We expect that the tidewater glaciers have very little direct impacts, and that light limitation is overwhelmingly responsible for limiting primary production throughout the Arctic. Despite the low phytoplankton abundance and biomass typically observed in the polar night, compared to later winter (e.g., Dabrowska et al., 2021), it does however play a key role as seeding material for the following spring bloom (Krawczyk et al., 2015a; Hegseth et al., 2019). Thus, it is important to understand the effects of overwinter processes on polar night phytoplankton dynamics, particularly in the context of the lengthening of the meltwater season.

Arctic phytoplankton spring blooms typically start when sunlight returns, but may also depend on, or benefit from a stratified surface layer (e.g., Hegseth et al., 2019). The onset of the spring bloom is almost always still within the freezing season (winter). Below the Arctic circle (e.g., Nuup Kangerlua in SW Greenland) sunlight is present throughout winter, but light may still be limiting due to shorter days, a lower angle of the sun, and ice cover (Long et al., 2012). A stratified surface layer keeping phytoplankton in the euphotic zone has traditionally been described as crucial for the start of the spring bloom (Critical Depth hypothesis, Sverdrup, 1953). However, more recent studies found spring blooms in fully mixed water columns (Eilertsen, 1993), suggesting reduced turbulence (net heat gain) to be sufficient for the bloom initiation (Critical Turbulence Hypothesis, Huisman et al., 1999; Hegseth et al., 2019). In some systems, a fully mixed water column has been described to benefit phytoplankton biomass production due to dilution of grazers (Dilution Recoupling Hypothesis, Behrenfeld, 2010). In any case, stratification, which can be controlled by submarine glacial melt in the freezing season, still appears to be a key driver of spring bloom dynamics, either via increased light availability, or reduced grazing pressure.

With increasing AW intrusions at shallower depth in Svalbard fjords, sea ice formation and thereby sea ice melt mediated stratification is reduced (Skogseth et al., 2020). However, in Kongsfjord, the loss of sea-ice melt induced stratification can be locally compensated by increased submarine glacial ice melt in late winter (van De Poll et al., 2016). In fact, AW mediated submarine ice melt can lead to earlier and increased freshwater influx and stratification, while air temperatures are still below the freezing point (van De Poll et al., 2016). However, in contrast to large-scale sea ice or snowmelt, the effects of submarine glacial melt are highly localised to within a few kilometres from the glacier front (van de Poll et al., 2016). At the same time, the fully mixed water column further out in the fjord still has low biomass dominated by small flagellates (nano- picophytoplankton), typical for winter (Piquet et al., 2014; van De Poll et al., 2016). Whilst these studies contrast stations close to and distant from glacier fronts, it is important to note these systems may have a patchy distribution of stratification in winter. Patchiness in stratification may be a general feature of any glacier system at time of year when discharge is weak or diffuse, a situation which may represent both winter and spring. In Ameralik for example the diffuse nature of snowmelt in spring compared to the approximate point-source nature of glacier discharge in summer was speculated to drive patchiness in the stratification index (Stuart-Lee et al., 2021).

The key driver for the spring bloom in Nuup Kangerlua appears to be incident solar radiation with a bloom developing in a still weakly stratified water column before the onset of snowmelt. Soon after, a weak stratification of the water column due to the onset of early snow and ice melt can strengthen the bloom. Primary production can be high throughout the fjord. Phytoplankton biomass often starts accumulating inside the fjord, but also on the shelf outside the fjord in April/May (e.g., Juul-Pedersen et al., 2015; Meire et al., 2016). In the inner part of the fjord, an early stratification driven by the melting sea ice and ice melange is a likely driver for the early biomass accumulation. Advection, partly related to the tidewater glacier (katabatic winds), is one of the drivers for the location of the bloom (Meire et al., 2016). Meire et al. (2016) found katabatic winds, together with dense CW inflow to drive the in-fjord upwelling in late winter, which pushed the euphotic surface water layer out of the fjord, displacing the phytoplankton bloom during its development. Later in the season the wind direction reversed, pushing them towards the glacier (Meire et al., 2016).

Besides incident solar radiation and submarine meltwater, subglacial discharge may also have a role in spring bloom dynamics. A recent study by Vonnahme et al. (2021) found a moderate under-ice phytoplankton bloom at a Svalbard glacier front in Billefjorden. Subglacial upwelling of nutrients, increased light due to snow removal, and a highly stratified surface layer keeping phytoplankton in the euphotic zone, were the main drivers allowing high phytoplankton production and biomass (Vonnahme et al., 2021). However, the effect was very localised (inner km of the fjord) and might be a unique case due to the shallow grounding line depth (20 m) and stagnant conditions in the fjord permitting a weak subglacial discharge plume to influence nutrient distribution within the photic zone. At deeper grounding lines thermohaline convection, or wind will likely play a more important role than subglacial upwelling. In a well-mixed water column, upwelling would have no discernible effect on nutrient concentrations.

Seeding material for the spring bloom can be suspended algae cells in the water column that survived the winter (Krawczyk et al., 2015a, 2018), supplemented by resuspended resting spores from the sediment (Hegseth and Tverberg, 2013; Hegseth et al., 2019). While a low biomass of seeding material may be present in the water column throughout winter (Krawczyk et al., 2015a, 2018), Hegseth et al. (2019) argued that winter mixing and resupply of sediment resting spores can still be important for supplying a higher seeding biomass. On Svalbard, deep thermohaline convection over winter is described as the major winter mixing process (Cottier et al., 2010). In Greenland fjords, such as Nuup Kangerlua, dense coastal water inflow is more important for fjord water renewal and winter circulation potentially resupplying phytoplankton seeding material from both, deep water masses and offshore coastal water masses (Mortensen et al., 2011; Krawczyk et al., 2015a). In contrast to Svalbard, subglacial upwelling has not been described as important in spring, but an inshore upwelling, driven by katabatic winds and dense coastal inflows may have a similar localised effect (Meire et al., 2016).

Winter mixing and resupply of nutrients to the surface by either wind mixing and thermohaline convection (cold and salty water sinking through the water column) on Svalbard (Cottier et al., 2010), or dense coastal water inflow in Greenland (Mortensen et al., 2011), is independent of the presence of a tidewater glacier (Cottier et al., 2010). Direct glacial ice melt can add additional silicate and iron (Bhatia et al., 2013; Meire et al., 2016; Hawkings et al., 2017), which would however be localized to the inner ice melange. While these nutrients are unlikely to be limiting in Arctic fjords, and certainly not during the initial spring bloom, an increased Si:N ratio could be important for the dominance of silicifying algae (e.g., diatoms) over other taxa (e.g., haptophytes) towards the end of the spring bloom (Krawczyk et al., 2015a, Juul-Pedersen et al., 2015, Meire et al., 2016) because silicate tend to be depleted prior to nitrate (Krause et al., 2019). Yet, some systems show nitrogen depletion before silicate depletion (Fig. 8). The extent to which over-winter processes affect nutrient stoichiometry within fjords is unclear. The Si:N ratio in Nuup Kangerlua appears to be maximised during the melting season, and minimal over winter (Fig. 8). This is consistent with meltwater directly driving the silicate excess (Meire et al., 2016) and saline inflow reducing Si:N ratios towards the source water mass ratio. A sedimentary, or particle associated release of silicate from glacial flour would be expected to operate year-round (Hawkings et al., 2017) and thus might be especially evident in water masses such as WCW which remain trapped in inner fjord environments. In Kongsfjorden however, WCW (also referred to as ‘local water’ LW) conversely appears to show preferential remineralisation of nitrate with a Si:N ratio of 1:8 observed prior to renewal, far below the 2:1 ratio in glacier discharge from the same catchment and even lower than AW (1:2; Cantoni et al., 2020). The underlying mechanism for such shifts is unclear, but this suggests that stagnant basins facilitate higher over-winter nutrient concentrations from remineralisation of plankton-derived material from the prior summer, and that this re-supply is sufficiently large to mask glacier inputs on this spatial scale (~10 km from the glacier front).

In most Arctic systems snowmelt is the largest source of meltwater during the year, initiating a strongly stratified water column. Where sea ice is present, sea ice melt, which can start before the snow melt, is important for initiating a stratified surface layer in spring, leading to pronounced ice edge blooms both in offshore pack-ice and inshore land-fast ice (Wu et al., 2007). Under-ice phytoplankton blooms can already develop while the sea ice is still present once the surface layer is stratified and the snow on the ice melted (Ardyna et al., 2020). With sea ice break-up, light availability and stratification increases even more, making it a common trigger for the development of more pronounced spring phytoplankton blooms (e.g., Hegseth and Tverberg, 2013).

6.3. Phytoplankton communities

Despite the severe light limitation during a large part of winter, diverse phytoplankton communities have been found (Krawczyk et al., 2015a; Marquardt et al., 2016). Communities in the light-limited winter and polar night are often dominated by flagellates, such as auto- or mixotrophic dinoflagellates, silicoflagellates, and green algae (i.e., chlorophytes) (Krawczyk et al., 2015a; Vader et al., 2015; Marquardt et al., 2016; Joli et al., 2017; Dabrowska et al., 2021). While freshwater inflow is often a key driver for phytoplankton communities in spring and summer (e.g., van de Poll et al., 2016) studies on the effects of winter freshwater discharge on the diverse dark winter communities are lacking.

Time series of phytoplankton community structures and potential environmental drivers allow some discussion about the role of tidewater glaciers on phytoplankton communities (Table 2). Monitoring efforts in Nuup Kangerlua (Greenland Ecosystem Monitoring programme; g-e-m.dk) show that winter communities are dominated by centric diatoms (i.e., genera *Chaetoceros* and *Thalassiosira*), which are also dominant during the spring bloom, together with the haptophyte *Phaeocystis* cf. *pouchetii* (Krawczyk et al., 2018). Diatoms in this fjord appear to be associated with cold and less saline water, while more oceanic water masses showed higher abundances of *Phaeocystis* (Krawczyk et al., 2015a, 2018). These findings are comparable to studies in Svalbard fjords, where AW masses are often associated with a dominance of *Phaeocystis* and local water masses with a dominance of centric diatoms (e.g., Dabrowska et al., 2021).

Table 2
Summary of recorded phytoplankton associated with AW, fjord water, or tidewater glaciers in Nuup Kangerlua and Kongsfjorden.

Taxa	AW	Fjord	Glacier	Reference: Nuup Kangerlua	Reference: Kongsfjorden
Diatoms		X		Krawczyk et al., 2015a, 2018	
Phaocystis sp.	X			Krawczyk et al., 2015a, 2018	Hegseth et al., 2019
Cyanobacteria			X		van de Poll et al., 2016
Cryptophytes			X		van de Poll et al., 2016
Gedaniella boltonii			X	Krawczyk et al., 2018	

The dominance of *Phaeocystis* is not certain at all times as it seems it might be dependent on AW inflow. Conversely, a delayed onset of the spring stratification has been proposed to promote a *Phaeocystis*-dominated spring bloom. A study in Kongsfjorden found lower abundance of *Phaeocystis* in years when AW ingress was high and the onset of stratification late. In that case, AW intrusions lead to creation of sea ice-free conditions in the fjord and an earlier bloom, favouring diatoms (Hegseth et al., 2019). Similarly, an unusually long period of winter inflow of dense coastal water in Nuup Kangerlua, was stipulated to be responsible for the absence of haptophytes, and instead a mass occurrence of centric diatoms (Krawczyk et al., 2015a). Overall, water masses like AW, local freshwater, and sea ice conditions, seem to determine whether diatoms or *Phaeocystis* become dominant. While AW intrusions are mostly independent of the presence of a tidewater glacier, meltwater intrusions in winter are unique to tidewater glacier influenced fjords and we hypothesise that they play an important role in driving phytoplankton community structure.

Communities in direct proximity to glacier fronts have been described to be very different from typical coastal phytoplankton communities (Table 2). Close to the glacier in Kongsfjorden the community is dominated by cyanophytes and cryptophytes throughout the year (Piquet et al., 2014). Both organisms are typically rare in Arctic waters and could originate from freshwater runoff or AW advection from temperate regions (Piquet et al., 2014). At some distance from the glaciers, the salinity stratified surface layer facilitated a diatom dominated spring bloom which is typical for glaciated fjords (van De Poll et al., 2016). With meltwater extending outwards away from the glaciers over time, the diatom bloom followed. In Nuup Kangerlua, the diatom *Gedaniella boltonii* was dominant near the tidewater glacier front during the spring bloom (Krawczyk et al., 2018). Similarly to Svalbard, also *Gedaniella boltonii* may be associated with brackish water as it has only been found in Nuup Kangerlua and an Arctic river (Krawczyk et al., 2018; Selivanova et al., 2019). Freshwater itself may deliver diverse algae into the marine environment, but algae adapted to freshwater environments are unlikely to survive in seawater, somewhat questioning the hypothesis that runoff may be an important source of algae inoculum.

6.4. Sea ice algae

Studies on sea ice algae close to tidewater glaciers are common on Svalbard but absent in Greenland. In most sea ice case studies in Svalbard, the ice was sampled a few kilometres from the glacier front and showed physical characteristics typical for Arctic sea ice with respect to salinity and temperature as well as communities (e.g., *Nitzschia frigida* dominance; Leu et al., 2015). Here, sea ice algae are usually concentrated in the bottom skeletal layer (Leu et al., 2015). While sea ice algae studies at the tidewater glacier branch of Nuup Kangerlua are lacking, studies in neighbouring fjords and fjord branches also showed typical Arctic ice species succession from flagellate dominance (dinoflagellates and cryptophytes) in December to February, followed by centric diatoms (*Chaetoceros simplex*) in March and pennate diatoms in May (*Navicula*, *Nitzschia*) (Mikkelsen et al., 2008). In contrast to typical Arctic sea ice, bulk salinities in Greenland were lower (<1–4 PSU) than ice salinities observed elsewhere in the Arctic (4–8 PSU, e.g., Vonnahme et al., 2021) and the algae were distributed throughout the sea ice and not only in the bottom skeleton layer (Mikkelsen et al., 2008; Søgaard et al., 2010, 2013; Lund-Hansen et al., 2020). Brackish sea ice has a more stratified brine network with low brine space fractions, which might limit algae brine mobility and prevent convective exchange of nutrients and CO_2 (Crabeck et al., 2014; Vonnahme et al., 2021).

Closer to the glacier fronts studied on Svalbard (<500 m), sea ice becomes thicker and more brackish with decreasing brine volume (Marchenko et al., 2017; Vonnahme et al., 2021). One recent study in this brackish sea ice found a unique, low biomass sea ice algae community dominated by cryptophyte flagellates and a frozen-in layer of the centric diatom *Leptocylindrus* sp. (Persson, 2020; Vonnahme et al., 2021). These algae are typically not dominant in Arctic sea ice, but may be found in other brackish sea ice systems, such as the Baltic Sea and northern Norway (Ikävalko, 1998; Persson, 2020; Vonnahme et al., 2021). Cryptophytes are also common in phytoplankton communities close to glacier termini in the Arctic and Antarctic (e.g., Piquet et al., 2014; Pan et al., 2020).

While sea ice algae close to glaciers have not been sampled directly in Greenland to date, samples of phytoplankton or sediment traps adjacent to sea ice cover and close to glaciers were able to capture potential sea ice algae, thus allowing the first insight into the potential community structure of these sympagic environments (Table 3). Pelagic time series in Nuup Kangerlua found high abundances of *Nitzschia frigida* in late winter, suggesting a typical ice algae community in the inner fjord (Krawczyk et al., 2015a). *N. frigida* were not found in earlier winter sediment traps, but several other potential sea ice-associated algae, such as *Fragilariopsis* spp. were present (Luostarinen et al., 2020). Interestingly, the ice associated algae *Pauliella taeniata* was abundant in Nuup Kangerlua sediment traps, but absent in a parallel study in Young Sound, which lacks a tidewater glacier (Luostarinen et al., 2020). However, a study on a longer time frame did find *P. taeniata* in the outer parts of Young Sound (Krawczyk et al., 2015b). This local variability may be depended upon physical conditions within the fjords as *Pauliella taeniata* is typically associated with low-salinity environments, such as the Baltic Sea, and may be adapted to winter freshwater inputs in tidewater glacier fjords either due to brackish sea ice and/or a low-salinity water layer under the ice (Luostarinen et al., 2020). In contrast, *Melosira arctica*, a sea ice algae often associated with multiyear sea ice, was found abundant in inner Young Sound, but very scarce in Nuup Kangerlua (Krawczyk et al., 2015b). The brackish water mixotrophic haptophytes (*Chrysochromulina*) were also observed in sea ice in a fjord near Nuup Kangerlua (Mikkelsen et al., 2008) and in sea ice and under-ice waters in Young Sound (Søgaard et al., 2021).

Besides the winter freshwater contribution, the high density of icebergs in the ice melange may act as ridges, known as productive and heterogeneous habitats in the central Arctic (Fernández-Méndez et al., 2018). Iceberg-mediated openings in the sea ice may allow more light to penetrate the ice, either via formation of cracks, or due the lack of snow on exposed glacial ice. Icebergs can thereby channel light into surface waters potentially driving further differences between tidewater and non-tidewater glacier systems' sea ice environments. Frazil ice and iceberg borne sediments could further complicate the ice melange light environment, but have not been investigated to date.

Table 3

Summary of recorded Greenland sea ice-associated algae in a fjord with a tidewater glacier (Nuup Kangerlua) compared to a fjord lacking a tidewater glacier (Young Sound) and a Svalbard fjord with a tidewater glacier (Billefjorden). + indicates present and abundant (>1% taxa) and '–' indicates present, but rare (<1%) taxa.

Fjord	Sample	*Nitzschia frigida*	*Fragillariopsis* spp.	*Fossula arctica*	*Pauliella taeniata*	*Melosira arctica*	*Chrysochromulina*	*Entomoneis*	*Gyrosigma/ Pleurosigma*	*Leptocylindrus minimus*	*Haslea* sp.	Reference
Nuup Kangerlua	Pelagic											Krawczyk et al., 2015b
	Phytoplankton nets	+	+		–	–		–	–	–		Krawczyk et al., 2015b; Krawczyk et al., 2015a
	Sediment traps		+	+	+							Luostarinen et al., 2020
Young Sound	Pelagic	+	+									Krawczyk et al., 2015b
	Phytoplankton nets		+		+	+						Krawczyk et al., 2015b
	Sediment traps		+	+		–						Luostarinen et al., 2020
	Sea ice						+					Søgaard et al., 2021
Billefjorden	Pelagic	+	+					–	–		–	Vonnahme et al., 2021; Persson et al., 2020
	Phytoplankton nets	+	+					–	–	–	–	Vonnahme et al., 2021; Persson et al., 2020
	Sea ice	+	+					+	–	+	+	Vonnahme et al., 2021; Persson et al., 2020

7. Winter runoff and climate change

While processes occurring outside the melting season in fjords influenced by a tidewater glacier are still poorly understood, they are already subjected to change as a result of the rapidly warming climate (e.g., Karlsson et al., 2021; Decaux et al., 2022). Our lack of knowledge on pre-Anthropocene conditions for many areas means that current and future detection of climatically driven shifts, and more importantly, prediction of future changes is extremely challenging.

Many of the processes discussed in this review will have been affected by a dramatic change in precipitation as the Arctic is shifting towards being rainfall dominated (e.g., McCrystall et al., 2021). Similarly, most processes will be affected by a shift in the duration of the melting season as spring melting is occurring earlier and winter freeze-up later (IPPC 2021, Climate2100, McCrystall et al., 2021; Nowak et al., 2021). These environmental changes are no longer restricted to sporadic locations but have started to affect the entire Arctic (McCrystall et al., 2021). From the limited available time-series in glacier fjords, it is evident that only a narrow window during winter is static with respect to water column conditions. In Nuup Kangerlua (Fig. 4), for example, prior to January the water column inventory of nutrients is still being replenished from primary production the prior summer, and after March there is drawdown of nutrients from plankton growth in the subsequent spring. How ongoing lengthening of the meltwater season will affect these seasonal trends remains unclear, but it is certain that winter is critical for preconditioning the fjord prior to the subsequent spring bloom. Freshwater induced broadening of the seasonal stratification peak, and a reduced time for replenishment of high nutrient conditions over winter could thereby directly feedback into changing the following spring bloom. An earlier start of freshwater runoff occurring across the entire Arctic has the capacity to affect the timing of the spring bloom on a much larger scale than it occurs at present. This process is akin to better constrained shifts in offshore regions where climate change has already led to earlier spring blooms, due to an earlier onset of sea-ice melt (Kahru et al., 2011).

In the sub-Arctic, where light is not a limiting factor during winter, spring blooms may simply start earlier due to an earlier onset of stratification (Yamaguchi et al., 2022). Consequently, the winter processes described in this review (i.e., submarine glacial ice melt driving an early stratification) would become less important for the initiation of the spring bloom. We are yet to discover the consequences of an earlier bloom, but we hypothesise that earlier spring blooms will have an influence on the seasonal pattern of productivity and ultimately the food web. Research already suggests that earlier spring bloom events may pose problems for higher trophic levels currently adapted to a later spring bloom (Winder and Schindler, 2004; Durant et al., 2007).

In currently sea ice covered systems, a loss of sea ice can increase wind mixing in winter and delay the onset of spring stratification (Singh et al., 2020). In these systems, winter submarine meltwater inputs have been shown to be crucial for sustaining an early stratification and spring bloom by mimicking the role of sea ice melt (van de Poll et al., 2016), but on a smaller spatial scale. The effects of ongoing atmospheric changes and their feedback mechanisms are therefore complex and difficult to theorise as multiple changes are concurrently affecting water column dynamics.

Rapid glacial retreat across much of the Arctic has already caused changes to glacial hydrology, runoff and oceanography (IPPC 2021, Nowak et al., 2021) and potentially also ecology- although this is less well substantiated than physical shifts. Increased surface melt leads to increased glacial discharge; recession leads not only to transformation of glacier thermal regimes but also changes in the glacier groundwater coupling system (Nowak et al., 2021; Decaux et al., 2022). The timescale of hydrological changes for individual glaciers will depend on their size and location; smaller glaciers will respond quicker losing their subglacial drainage system while they transform to cold based systems, and thus losing their potential for winter discharge. Larger glaciers have a longer delay in their response and thus may be able to produce, store and then release more internal freshwater (e.g., Wadham et al., 2000, Nowak et al., 2021), which will also increase winter subglacial discharge. Eventually though, under sustained global warming, glaciers will lose so much mass that annual glacial solid and liquid discharge decreases (Huss and Rock, 2018), a point that is called 'peak-water'. In the case of smaller glaciers in Svalbard (Nowak et al., 2021) and some subArctic glaciers (Huss and Hock, 2018) peak-water has already been passed, although this is now largely only realised through model studies.

Glacial discharge in Greenland appears to be in a transition period with an overall steady state since 2005 and regional trends varying (Mankoff et al., 2020). Sources of subglacial discharge under polythermal glaciers can be geothermal or frictional heat (Karlsson et al., 2021), which are both present throughout the year. While geothermal heat is not affected by climate change, glaciers are moving faster with climate change leading to increasing frictional heat (Rysgaard et al., 2018, Karlsson et al., 2021) and consequently increased subglacial runoff, also in winter. Increased rainfall can also act as an additional lubricant for the movement of tidewater glaciers which then in turn will have an effect on basal sliding and subglacial freshwater delivery (Decaux et al., 2022). In some cases in Svalbard, this can even speed up the surging (rapid advance) cycle (Nowak et al., 2021).

Basal freezing first happens near the glacier front, while the base may still be warm at higher altitudes (Nuth et al., 2019). Basal freezing of patches near the front of tidewater glaciers has been described to increase friction, triggering a glacier surge at Nathorstbreen on Svalbard (Nuth et al., 2019). With a surging glacier, ice tongues may temporarily develop, and large amounts of icebergs can enter the fjords reducing light availability and possibly inducing local upwelling with an increased input of glacial ice as the main freshwater source, more like Southeast Greenland glaciers. This contrasts with the general expectation that the fractional importance of iceberg melt decreases with prolonged glacier retreat as tidewater glaciers transition to land-terminating systems. Changes to the ratio of runoff:iceberg melt may affect multiple biogeochemical processes as runoff is generally associated with higher concentrations of total alkalinity, and dissolved nutrients such as silicic acid and iron, than ice melt which has had less bedrock exposure (Wadham et al., 2000; Cantoni et al., 2020).

As tidewater glaciers retreat, the glacier fronts can deepen or shoal depending on the underlying bedrock geometry (e.g., Matthews, 1981). A change in glacier depth will directly affect the upwelling of nutrient-rich saline waters in multiple ways; the depths from which nutrients are entrained but also the neutral buoyancy depth of the resulting plume will shoal (Hopwood et al., 2018). Eventually, tidewater glaciers will retreat on land, which will cease any subglacial discharge or submarine glacier ice melt reaching the fjords in winter. Once the glaciers retreat to land, the fjord will change from a system where freshwater is introduced throughout the year, to a system where freshwater inputs are limited to summer.

From an oceanographic perspective, the European Arctic is experiencing increased AW inflow at shallower depths (Atlantification; Asbjørnsen et al., 2020; Skogseth et al., 2020; Gjelstrup et al., 2022). In Svalbard, coastal winter wind speeds are increasing, with increasingly meridional winds (Pilguj et al., 2019), which may lead to increased winter AW flooding events (Cottier et al., 2006; Skogseth et al., 2020) and thus accelerate Atlantification. At the same time, the AW is warming and shoaling, and sea ice is thinning or disappearing (Skogseth et al., 2020). In Isfjorden, this has already led to increased AW inflow in early winter at shallower depths (Skogseth et al., 2020). Most of the AW does not reach the tidewater glacier at the end of Isfjorden, but the heat flux is sufficient to inhibit sea ice formation and affects the local climate and following summer hydrography (Skogseth et al., 2020). Similarly, outside Nuup Kangerlua, a very shallow (110 m) AW layer was already sufficient to clear the sill in 2019, leading to increased bottom water temperatures (Gjelstrup et al., 2022). In more open fjords, the AW can reach the tidewater glaciers (e.g., Kongsfjorden, Cottier et al., 2010;

Milne fjord, Hamilton et al., 2021), which may lead to increased glacial ice melt. However, with retreating tidewater glaciers, the glacial ice masses may become too shallow to be in contact with the warm water masses. Especially in Greenland, the SPMW masses are often several hundred metres below the surface (e.g., Schaffer et al., 2019, Moon et al., 2019, Mortensen et al., 2018). When shallower glaciers lose their contact with the warm SPMW, future solid discharge may decrease.

It is clear that presently we can only theorise about the possible changes that will happen in Arctic and sub-Arctic fjords with glacially affected drainage systems. It is even more clear that our lack of knowledge, combined with an intricate network of dependencies of physical and biological processes, precludes constraints on the uncertainty concerning how accurate our predictions can be. One thing that is certain is that to gain a comprehensive understanding and to start predicting with high probability how the Arctic fjords will look in the near to distant future, we must address knowledge gaps and increase our efforts to maintain effective long-term monitoring systems.

8. Main knowledge gaps and recommendations for future research

It is a fundamental challenge that winter processes in fjords influenced by tidewater glaciers are poorly studied. These knowledge gaps are mainly caused by a lack of accessibility and the harsh polar environment, but also a lack of scientific focus on the Arctic winter period. Until recently, the light-limited winter and polar night was considered a biologically inactive season (Berge et al., 2015). As with subglacial environments, recent studies increasingly focus on polar night biology in the Arctic providing insight into oceanographic processes in some key fjords through long-term moorings, field work and modelling approaches (e.g., Mortensen et al., 2011, 2014, 2018, 2020; Moon et al., 2018; Hamilton et al., 2021).

Because interest in wintertime physical and biogeochemical processes is just emerging, most studies have still a bias towards large fjords in summer with large glacier systems and relatively little is known about smaller (Svalbard like) fjords and glacier systems, potentially isolated from AW/TAW inflow during winter. Six of the glacier systems discussed in this review are part of the largest seven systems regarding solid ice discharge (Mankoff and Solgaard, 2021) consistent with the general bias in literature coverage. Thus, it is vital that ecological research in other parts of the Arctic be carried out, providing important information on the functioning of glacier-shelf-fjord coupling. These should include budgets constraining the quality and quantity of freshwater being released during winter from glaciers and sea ice, quantification of suspended sediment dynamics, nutrient dynamics close to glacier fronts and investigations of the physical properties of fjords influenced by glacier melt (e.g., calving and submarine melt). We should favour interdisciplinary studies that connect physical, biogeochemical, and ecological processes across different fields (e.g., a study coupling tidewater glaciers and fjord systems of various sizes during the polar night) that are well integrated into sustained time series (Straneo et al., 2019). A specific knowledge gap concerns processes occurring close to the glacier termini, where released freshwater has the largest impact on the marine ecosystem, as no such research in Greenland or Svalbard fjords exists to date. However, hazards of calving glaciers for boats, and icebergs for navigation and moorings, make sampling technically challenging.

While helicopter-based sampling close (<500 m) to tidewater glaciers and in the plumes is a feasible approach in summer, in winter sea ice blocks direct access to the water. Remotely-operated vehicles (ROV) or Automated underwater vehicles (AUV) deployed from a safe distance have already facilitated observations close to the glacier calving fronts in Alaska and the Antarctic (e.g., Dowdeswell and Powell, 1996; Powell et al., 1996; Bono et al., 1999; Meister et al., 2020), and would very likely also allow water sampling and oceanographic data collection in winter at Arctic tidewater glaciers. Moorings could also supply winter data under sea ice but are subjected to damage or loss related to iceberg scouring. In Greenland, community-based research together with local hunters and fishermen may overcome navigational challenges and facilitate more sustainable methods of sea ice and water sample collection.

A specific research question that should be answered concerns spring blooms and how they are now/and will be in the future affected by glacial meltwater. Studies on ice mélange biology are lacking, although it is clear from existing work this environment represents a unique habitat of heterogeneous glacial-sea ice distinct from Arctic sea ice and more similar to other brackish systems. Studies focusing on the inner part of tidewater glacier influenced fjords during winter may reveal specialised algae communities adapted to low salinities. We should start asking questions about the coupling of salinity changes in the sea ice/ice vicinity as well as brine channels to the composition of phytoplankton blooms.

Future research should continue to include long time series which are powerful tools for understanding climate change. Comparisons of offshore regions, fjords with tidewater glaciers, and fjords with land-terminating glaciers could allow testing for the importance of TAW/AW for spring bloom community structures. Our attention should also be devoted to regional differences. For example, almost nothing is known about fjords in the Russian Arctic archipelagos. Some remote sensing studies show quickly retreating tidewater glaciers, ice shelf breakup, and large amounts of iceberg production (e.g., Williams and Dowdeswell, 2001; Tarasov et al., 2019), but studies on processes below the ice or sea surface are lacking.

From this review it is clear that too many knowledge gaps exist in this field, and even more questions need to be answered before we begin to understand the direction in which the Arctic and sub-Arctic environment is heading at the interface between winter and spring.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used for Figures 2 and 4 are available under G-E-M.dk and Unis.no.

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