



Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL070191

Key Points:

- The Greenland Ice Sheet functions as an important source of silicate for the fjords and surrounding coastal waters
- Glacial meltwater does not directly stimulate phytoplankton productivity due to low nitrate concentrations
- Exported silicate from the Greenland Ice Sheet is taken up by diatoms, suggesting a regulating role in phytoplankton composition

Supporting Information:

- Supporting Information S1

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Citation:

Meire, L., P. Meire, E. Struyf, D. W. Krawczyk, K. E. Arendt, J. C. Yde, T. Juul Pedersen, M. J. Hopwood, S. Rysgaard, and F. J. R. Meysman (2016), High export of dissolved silica from the Greenland Ice Sheet, *Geophys. Res. Lett.*, *43*, 9173–9182, doi:10.1002/2016GL070191.

Received 30 JUN 2016

Accepted 19 AUG 2016

Accepted article online 23 AUG 2016

Published online 14 SEP 2016

High export of dissolved silica from the Greenland Ice Sheet

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Abstract Silica is an essential element for marine life and plays a key role in the biogeochemistry of the ocean. Glacial activity stimulates rock weathering, generating dissolved silica that is exported to coastal areas along with meltwater. The magnitude of the dissolved silica export from large glacial areas such as the Greenland Ice Sheet is presently poorly quantified and not accounted for in global budgets. Here we present data from two fjord systems adjacent to the Greenland Ice Sheet which reveal a large export of dissolved silica by glacial meltwater relative to other macronutrients. Upscaled to the entire Greenland Ice Sheet, the export of dissolved silica equals $22 \pm 10 \text{ Gmol Si yr}^{-1}$. When the silicate-rich meltwater mixes with upwelled deep water, either inside or outside Greenland's fjords, primary production takes place at increased silicate to nitrate ratios. This likely stimulates the growth of diatoms relative to other phytoplankton groups.

1. Introduction

Glacial meltwater forms an important source of freshwater to high-latitude coastal areas [Bamber *et al.*, 2012]. However, the nutrient export accompanying meltwater release from large glacial systems, such as the Greenland Ice Sheet (GrIS), and its effects on high-latitude coastal ecosystems is as yet poorly quantified. Glaciers play potentially an important role in global biogeochemical cycles, as physical and chemical weathering by glaciers releases large quantities of dissolved and particulate matter to the coastal zone [Anderson, 2007; Hawkings *et al.*, 2015]. Still it is presently uncertain whether these nutrient inputs are important for the marine ecosystems surrounding the GrIS, as little data are available on the macronutrient delivery along with these meltwater inputs, let alone their downstream effect on the productivity of fjordic and coastal systems around Greenland.

Among the macronutrients, dissolved silica (DSi) stands out, as it forms the major end product of silicate rock weathering by glaciers. DSi plays an important role in marine biogeochemical cycling, since it is an essential macronutrient for diatoms, a key group of primary producers in marine ecosystems. Riverine input and submarine groundwater discharge are the dominant supply pathways of DSi to the surface ocean [Dürr *et al.*, 2011; Tréguer and De La Rocha, 2011]. This supply of DSi from terrestrial environments is essential to sustain the diatom-fueled carbon pump in the ocean, compensating for the burial of biogenic silica (BSi) on continental shelves and in abyssal plains [Tréguer and De La Rocha, 2011]. In the Arctic region, large rivers that drain the Siberian and Canadian plateaus supply high loads of DSi (around $0.33 \text{ Tmol Si yr}^{-1}$ or $\sim 5\%$ of global riverine DSi input while representing 10% of total riverine discharge), thus leading to elevated silicate concentrations on the inner shelves [Carmack *et al.*, 2004].

Glacial weathering of the GrIS could form another source of DSi to the Arctic marine environment, but presently, the DSi export from the GrIS has not been quantified. As a consequence, the impact of the GrIS on the ecosystem productivity in adjacent coastal areas is presently poorly understood. Here we present hydrographic and geochemical data from two fjord systems adjacent to the GrIS, supplemented with nutrient

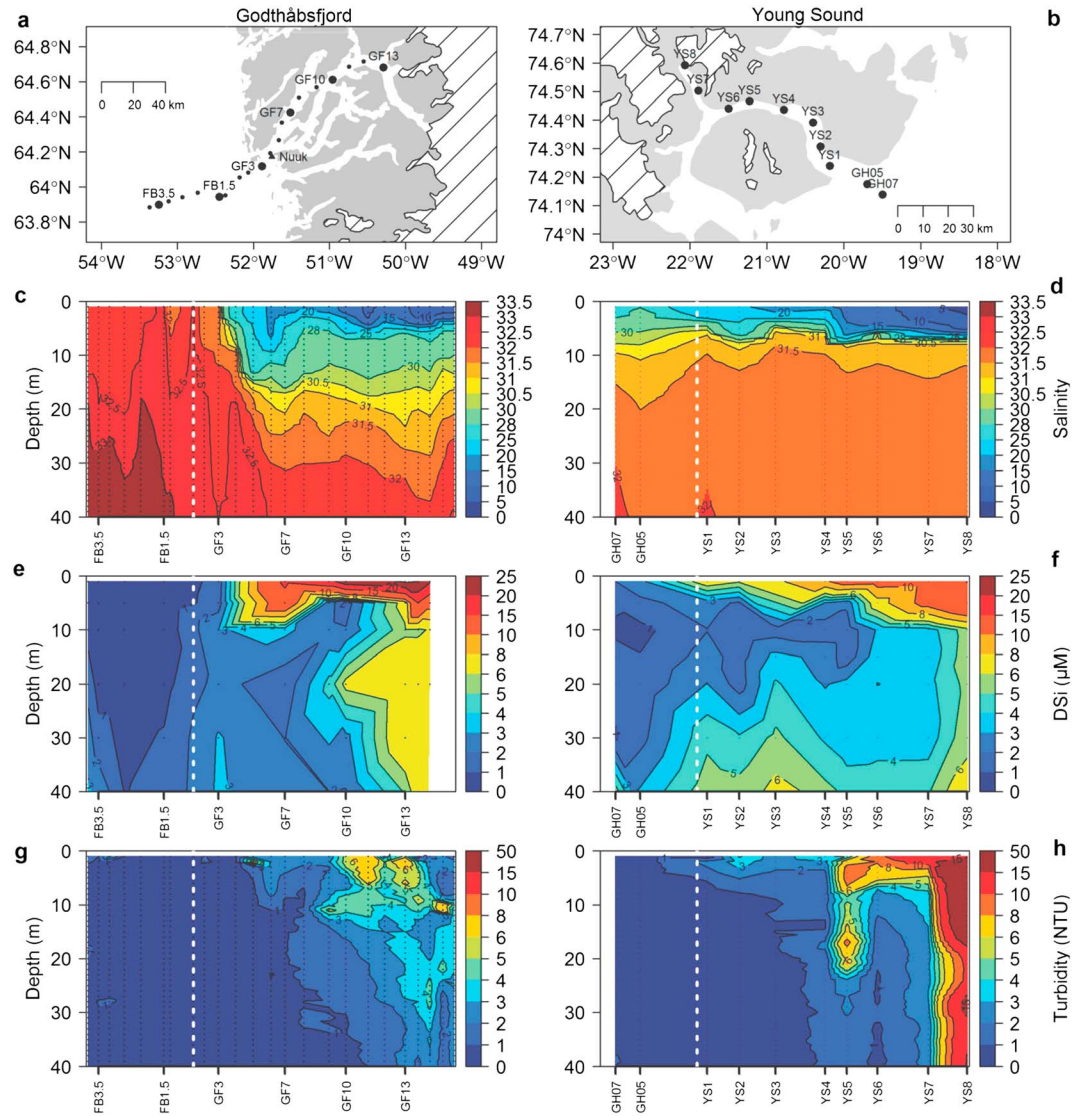


Figure 1. Overview map of (a) Godthåbsfjord, SW Greenland and (b) Young Sound, NE Greenland indicating the location of sampling stations. (c,d) Salinity in the upper 40 m of the water column in (c) Godthåbsfjord and (d) Young Sound along a transect from the glaciers (right) to the shelf area (left). (e, f) The distributions of DSI concentration (μM) in Godthåbsfjord (e) and Young Sound (Figure 1f). (g, h) The turbidity (NTU) in Godthåbsfjord (Figure 1g) and Young Sound (Figure 1h). The white dashed line indicates the mouth of the fjord.

data from meltwater rivers around Greenland. We utilize this data set to quantify the DSI export from the GrIS and to assess the importance of this DSI export for biogeochemical cycling within the downstream fjord ecosystems.

2. Methods

2.1. Sampling Sites

Samples were collected in two fjords in Greenland which have been monitored intensely by the Greenland Ecosystem monitoring program. Godthåbsfjord ($64^{\circ}10'N$, $51^{\circ}44'W$) is a fjord system located in southwest Greenland with a length of ~ 190 km covering an area of 2013 km² (Figure 1). Meltwater input into the fjord originates from three marine-terminating and three land-terminating glaciers from the Greenland Ice Sheet. Recent hydrological simulations estimate the annual freshwater input to Godthåbsfjord to be ~ 25 km³ yr⁻¹ as meltwater runoff and ~ 10 km³ yr⁻¹ as solid ice discharge in the

period 2010–2012 [Mortensen *et al.*, 2013; Van As *et al.*, 2014]. Young Sound (74°18'N, 20°18'W) is a fjord in northeast Greenland with an area of 390 km² and a length of ~90 km (Figure 1). Three major glacial rivers discharge into the fjord with a combined discharge of ~1.0 km³ yr⁻¹ [Rysgaard *et al.*, 2003].

2.2. Sample Collection and Analysis

During an oceanographic cruise in August 2013, samples were collected in Godthåbsfjord at 26 stations along a length transect covering the fjord and shelf area (Figure 1). Combined CTD and Niskin sampling was carried out at 10 stations, while at the other 16 stations only CTD measurements were performed. The presence of a dense ice mélange in August made sampling upstream of station GF15 impossible. The data set was further complemented by monthly sampling at one station in the inner fjord (GF10) from January to December 2013 to describe the seasonal dynamics and the importance of glacial melting. Sampling was conducted in Young Sound in August 2012 at 30 stations covering the fjord and open sea (10 CTD + Niskin and 20 CTD only). The sampling program was identical in both fjords. At each station and time point, a CTD instrument (Seabird SBE19plus) equipped with additional sensors for fluorescence (Chlorophyll Fluorometer, Seapoint) and turbidity (Seapoint) recorded salinity and temperature depth profiles. Water samples from discrete depths were collected using 5 L Niskin bottles (KC Denmark research Equipment) at eight water depths (1, 5, 10, 20, 30, 40, 100, and 400 m) with higher resolution in the upper 40 m where the main biological activity occurs [Juul-Pedersen *et al.*, 2015]. The data set was further supplemented by sampling in glacial rivers in August (Godthåbsfjord, SW Greenland; Hobbs Gletscher, E Greenland). Additionally, solid ice samples were collected in spring and summer (2013–2014) in the inner part of Godthåbsfjord (station GF10 to glacier terminus). Samples for nutrient analysis in solid ice were obtained by sealing small pieces of ice (approximately 1 kg) allowing the ice to melt at room temperature. All water samples (10 mL) for nutrients were filtered through 0.45 µm filters (Q-Max GPF syringe filters) and frozen until further analysis. Nitrate and phosphate concentrations were determined using standard colorimetric methods on a Seal QuAAtro autoanalyzer. DSi concentrations were analyzed on a Thermo iCAP6300 Duo-ICP with a detection limit of 0.03 µM. Samples collected in Young Sound were analyzed using a spectrophotometric approach for phosphate and silicate [Grasshoff *et al.*, 2009] and by vanadium chloride reduction for nitrate and nitrite [Braman and Hendrix, 1989]. Biogenic Silica (BSi) analysis in Godthåbsfjord was performed on 200–500 mL water samples, filtered through 0.45 µm cellulose nitrate filters and air dried at 20°C. Subsequently, concentrations of BSi were analyzed using a wet chemical digestion method, with filters in 0.1 M Na₂CO₃ for 1 h and subsequent analysis of the DSi concentration on a continuous flow analyzer (Skalar SAN CFA). Water samples for chlorophyll *a* analysis (0.5–1 L) were filtered through 25 mm GF/F filters (Whatman, nominal pore size 0.7 µm). Filters were placed in 10 mL 96% ethanol for 18 to 24 h and chlorophyll fluorescence in the filtrate was analyzed using a fluorometer (TD-700, Turner Designs) before and after addition of 200 µL 1 M HCl solution.

Samples for phytoplankton community composition analysis were collected from Niskin bottles at 5, 10, 20, and 30 m in Godthåbsfjord and at 5, 20, and 30 m depth (determined by chlorophyll maximum) in Young Sound. Additionally, at station GF3 in Godthåbsfjord, triplicate vertical hauls were taken monthly from 2007 to 2013 from 60 m to the surface using a 20 µm mesh net as part of the Greenland Ecosystem monitoring program. All samples were stored in amber glass bottles and preserved with Lugol's iodine to a final concentration of 1%. Subsamples were studied using plate-counting chambers using an inverted microscope. The samples were routinely rinsed, cleansed of organic material (using hydrogen peroxide), and mounted in Naphrax[®] for an accurate identification of species using a light microscope and scanning electron microscope. To eliminate observer bias the same person always identified cells to species level. Cell counts were converted into carbon biomass density using biovolume estimates based on species composition and cell sizes [Leblanc *et al.*, 2012].

All processing of data was done in the open-source programming language R [R Core Team, 2013]. In order to investigate the effect of DSi fluxes to the inner part of Godthåbsfjord, we calculate fluxes derived from melt-water runoff, subglacial meltwater, and melting calved icebergs. Calculation of DSi fluxes is provided in the supporting information. The freshwater inventory in upper 40 m of the water column was calculated as

$$\text{FW content} = \sum_{z=0\text{m}}^{40\text{m}} \frac{S_{\text{ref}} - S}{S_{\text{ref}}}$$
 using the reference salinity (S_{ref}) of 35.

3. Results and Discussion

Young Sound (NE Greenland) is a sill fjord system affected by meltwater inflow solely derived from land-terminating glaciers, while Godthåbsfjord (SW Greenland) receives meltwater from both land-terminating and marine-terminating glaciers (Figures 1a and 1b). Oceanographic surveys carried out in summer, when glacial meltwater runoff is strongest, reveal a shallow surface layer of low salinity and a strong halocline between 5 and 10 m water depth (Figures 1c and 1d), confirming the substantial imprint of glacial meltwater on both fjord systems during the summer months [Mortensen *et al.*, 2013; Bendtsen *et al.*, 2014]. Alongside this input of freshwater, a plume with elevated DSi concentrations is apparent in the surface waters of both fjord systems (Figures 1e and 1f). In Young Sound, DSi concentrations are highest within the inner part of the fjord where glacial meltwater enters the fjord system (DSi $\sim 15 \mu\text{M}$ at salinity < 5). DSi concentrations gradually diminish downstream but remain elevated until the surface water reaches the sill region (Figure 1e). In contrast, high DSi concentrations at depth are only observed at the innermost station of Young Sound (YS8), which receives highly turbid waters from glacial rivers, thus suggesting DSi release from settling sediment of glacial origin (Figures 1f and 1h). A similar pattern is observed in the surface waters of Godthåbsfjord, where surface DSi concentrations reach $\sim 30 \mu\text{M}$ at salinity < 5 in the inner part of the fjord. Yet, while Young Sound is only subject to surface meltwater runoff from land-terminating glaciers, Godthåbsfjord is also characterized by subglacial meltwater discharge from marine-terminating glaciers. This subglacial meltwater discharge explains the secondary increase in DSi ($\sim 6\text{--}8 \mu\text{M}$) at 20–40 m depth, which forms a subsurface DSi plume that extends far into the fjord ($\sim 50 \text{ km}$, Figure 1e). Buoyant meltwater plumes entrain large volumes of deep fjord water, typically 10 to 30 times the volume of the rising meltwater plume [Mortensen *et al.*, 2013]. These subglacial meltwater plumes form a second supply route of both silicate and other macronutrients (nitrate and phosphate) to the surface layer, as bottom water is upwelled close to the glacier termini [Bendtsen *et al.*, 2015]. The upwelling of clear, deep fjord water also explains why the subsurface DSi plume in Godthåbsfjord is not correlated with increased turbidity levels (Figure 1g). Finally, melting icebergs, calved from the marine-terminating glaciers, form a third supply route for DSi in Godthåbsfjord. Melting of icebergs represents around 22% of the total meltwater input into Godthåbsfjord [Van As *et al.*, 2014]. Nutrient samples collected from icebergs in Godthåbsfjord reveal large variability in DSi concentrations, ranging from below the detection limit in clear ice samples up to $18 \mu\text{M}$ in debris-rich ice samples. A two-end-member mixing model yields a mean DSi concentration of $13 \mu\text{M}$ for the bulk ice (supporting information). To assess the importance of these three pathways, we constructed a silicate budget for the surface layer in the inner part of Godthåbsfjord (supporting information). This shows that surface meltwater runoff forms the main source of silicate contributing 79%, while solid ice discharge and subglacial freshwater discharge only account for, respectively, 9 and 12% to the total DSi input into Godthåbsfjord. It should be noted that surface and subglacial discharge provide direct inputs of DSi near the glacier termini, while the DSi that is locked in icebergs can be transported over large distances.

Elevated silicate concentrations, reflecting meltwater derived silicate input, are not restricted to the two fjords examined here but can be observed in glacial rivers all around the GrIS. A compilation of data from different meltwater rivers in Greenland (Table 1) shows a range of DSi concentrations in glacial rivers from 5 to $280 \mu\text{M}$, where rivers draining granitic and gneissic rocks have lower concentrations ($5\text{--}50 \mu\text{M}$) and basaltic rocks, such as those at Kuannersuit Kuussuat (Disko Bay), are associated with far higher DSi loadings ($\sim 280 \mu\text{M}$) [Yde *et al.*, 2005]. Hence, DSi concentrations in glacial meltwater strongly depend on source rock lithology and the interaction time between ice or subglacial water and bedrock [Aciego *et al.*, 2015]. Based on our data compilation (Table 1), we were able to derive a DSi budget for the GrIS. The largest fraction of the meltwater flux from the GrIS ($\sim 600 \text{ km}^3 \text{ yr}^{-1}$) derives from calving of icebergs and the remaining part ($\sim 400 \text{ km}^3 \text{ yr}^{-1}$) is due to subglacial and surface runoff [Bamber *et al.*, 2012]. Using these discharge estimates and employing the DSi concentrations for each of the supply routes as resulting from our data compilation, we estimate a total DSi export of $22 \pm 10 \text{ Gmol Si yr}^{-1}$ from the GrIS (Table 1 and supporting information). Given the GrIS area of $1.710.000 \text{ km}^2$, this translates into a DSi yield of $7\text{--}17 \text{ mmol Si m}^{-2} \text{ yr}^{-1}$, which is similar to yields from the Siberian Arctic [Dürr *et al.*, 2011]. Note that these are conservative estimates as the GrIS drains large areas with basaltic rock formations that are likely associated with higher DSi concentrations [Yde *et al.*, 2005; Henriksen *et al.*, 2009]. Our export estimate of $22 \text{ Gmol Si yr}^{-1}$ represents around 7% of

Table 1. Nutrient Concentrations in Glacial Rivers and Iceberg Samples in Greenland's Fjord Systems^a

Area Code	Location	Type	Latitude (°N)	Longitude (°W)	Discharge (km ³ yr ⁻¹)	NO ₃ (μM)	PO ₄ ³⁻ (μM)	DSi (μM)			DSi Flux (10 ⁶ mol yr ⁻¹)	Reference Chemistry	Reference Discharge
								Min	Max	Mean			
1	Kuannersuit Kuussuat	Glacial river	69°45'	53°18'	0.65	<1.5		71	540	280	182	Yde et al. [2005]	Yde et al. [2005]
2	Arferiorfik fjord	Glacial river	68°02'	50°16'	0.0064	2.3	0.12	3.4	40	14	0.09	Bhatia [2012]	Bhatia [2012]
3	Kangerlussuaq	Watson glacial River	67°00'	50°41'	3	2.5		25	98	51	153	Yde et al. [2014]	Yde et al. [2014]
3	Kangerlussuaq	Glacial river	67°08'	50°03'	3		0.13	4.7	7	5.5	16.5	Aciego et al. [2015]	Yde et al. [2014]
3	Kangerlussuaq	Leverett glacier	67°06'	50°17'	1.5	1.6	0.2			4.2	6.3	Hawkings et al. [2015]	Hawkings et al. [2015]
4	Godthåbsfjord	Saqqaq Sermersuaq glacial river	64°10'	51°44'	20	2.5	0.3			33	660	This study	Van As et al. [2014]
5	Ameralik	Glacial river	64°06'	49°57'			0.1	17.6	19.3	18.3		Aciego et al. [2015]	
6	Narsarsuaq	Glacial river	61°12'	45°20'			0.7	19.8	36	26.6		Aciego et al. [2015]	
7	Kulusuk	Glacial river	65°42'	38°27'			0.34	5.5	8.9	6.8		Aciego et al. [2015]	
8	Sermilik fjord	Mittivakkat Gletscher	65°41'	37°50'	0.04	<1.5		36	45	28	1.1	Hagedorn and Hasholt [2004]	Mernild et al. [2010]
8	Sermilik fjord	Hobbs Glacier	65°46'	38°11'		<1.5		22	40	31		This study	
9	Kangerdlugssuaq	Fjord	68°07'	31°51'						>10		Azetsu-Scott and Syvitski [1999]	Azetsu-Scott and Syvitski [1999]
10	Young Sound	Glacial river	74°18'	20°18'	1.5	2.5		11	61	30	45	Hasholt and Hagedorn [2000]/This study	Rysgaard et al. [2003]
4	Godthåbsfjord	Icebergs August	64°10'	51°44'	10	0.5	0.1	0.1	18	4.7	47	This study	Van As et al. [2014]
4	Godthåbsfjord	Icebergs May 2014	64°10'	51°44'	10	2.2	0.05			<0.02		Hopwood et al. [2016]	Van As et al. [2014]
9	Kangerdlugssuaq	Iceberg	68°07'	31°51'	15	1.4	0.5			9.1	137	Azetsu-Scott and Syvitski [1999]	Azetsu-Scott and Syvitski [1999]

^aThe area code refers to the different locations shown in Figure S5

riverine DSi flux to the Arctic [Holmes *et al.*, 2012] and corresponds to 0.3% of the global DSi input to the ocean [Tréguer and De La Rocha, 2011]. Overall, the DSi export from the GrIS is comparable to some large Arctic rivers (Yukon, Mackenzie) [Holmes *et al.*, 2012].

Unlike large Canadian and Siberian rivers, which discharge onto wide continental shelves, the silicate input from the GrIS is delivered into confined fjords. Accordingly, the question arises whether the DSi input from glacial meltwater has any effect on the primary production and/or phytoplankton composition in the fjords and coastal waters around Greenland? It has been speculated that glaciers may export significant quantities of nutrients to the Arctic Ocean, thus potentially stimulating primary production in the downstream ecosystems [Hawkings *et al.*, 2015, 2016]. The majority of nitrogen and phosphorus input is however associated with particulate matter rather than dissolved phases, and so the bioavailability is likely not high [Hodson *et al.*, 2004]. Our measurements from the Saqqap Sermersua glacially fed river in Godthåbsfjord reveal maximum concentrations of $0.31 \mu\text{M PO}_4^{3-}$ and $2.5 \mu\text{M NO}_3^-$, thus providing a Si:N:P ratio of 112:8:1, which deviates strongly from the standard stoichiometry (Si:N:P = 15:16:1) of diatoms. Data from other meltwater rivers (Table 1) suggest a similar imbalanced input of macronutrients. This imbalanced input of nutrients is further confirmed by the surface water chemistry of the inner fjords in summer. While surface DSi concentrations were elevated near the glacier termini ($\sim 30 \mu\text{M}$ in Godthåbsfjord and $\sim 15 \mu\text{M}$ in Young Sound), nitrate concentrations were low in the surface waters close to glacial discharge points ($< 1.0 \mu\text{M}$ in Godthåbsfjord and $< 0.1 \mu\text{M}$ in Young Sound). Moreover, compared to upwelled coastal seawater, the concentrations of phosphate (PO_4^{3-}) and nitrate (NO_3^-) are low in glacial meltwater, so meltwater cannot be an important source of nitrate and phosphate to coastal ecosystems [Hopwood *et al.*, 2016].

These low nitrate concentrations indicate nitrogen limitation of primary production and suggest that the summer meltwater discharge will not stimulate primary production within the surface layer of the fjords. This hypothesis is corroborated by our biogeochemical field data from Young Sound. The inner part of the Young Sound fjord showed high DSi and low NO_3^- concentrations accompanied by low chlorophyll *a* values in the meltwater-impacted surface layer (Figures 2d and 2f), indicating that phytoplankton productivity was low. The DSi concentration gradually diminished downstream coinciding with the decrease in freshwater content of the surface layer (Figure 2d), suggesting that DSi enriched meltwater was conservatively mixed with DSi depleted saline water, and biological uptake of DSi was marginal in the inner fjord [Rysgaard *et al.*, 1999]. As a result, the utilization of DSi by phytoplankton occurs further downstream where the outflowing surface water reaches the entrance of the fjord, where higher chlorophyll *a* values indicated elevated primary production (Stations YS1 to YS3, Figure 2f). Strong tidal mixing near the sill region brings up bottom water that is low in silicate but high in nitrate (Si:N:P = 9:11:1). This increased availability of DSi in the surface layer resulting from glacial meltwater input could compensate for the DSi deficit of bottom water, thus potentially explaining the observed dominance of diatoms over other primary producers (Stations YS1 to YS3, Figure 2f). Hence, by enriching the surface water of Greenland fjords with silicate relative to nitrate, DSi export from the GrIS appears to favor diatom growth relative to other phytoplankton taxa, when nitrate-rich but low-silicate deep water is upwelled. In contrast to Young Sound, summer chlorophyll *a* values were high close to the tidewater glaciers in Godthåbsfjord. Upwelling of nutrient-rich water due to subglacial freshwater discharge fuels a sustained intense phytoplankton bloom within the inner fjord [Arendt *et al.*, 2011], as seen in the Chl*a* and BSi concentrations (Figures 2a, 2c, and 2e). Deep fjord water upwelled through subglacial discharge was high in nitrate but low in DSi (Si:N:P = 10:15:1), while DSi was highly enriched in surface water (Si:N:P = 112:8:1). Diatoms accounted for up to 95% of the biomass close to the glaciers (Figure 2e) [Calbet *et al.*, 2011], and production occurred at the interface between the surface and upwelled water masses, at elevated Si:N ratios (between 1 and 20), which is relatively high compared to the Si:N ratio (0.67) of the upwelling deep fjord water (supporting information). The nonconservative behavior of DSi from the surface layer indicates DSi uptake by diatoms, which suggests that meltwater derived DSi is utilized and thus could play a regulating role in the phytoplankton composition.

Although the DSi of the upwelled deep fjord water is low (Si:N ~ 0.67), one cannot conclude a priori that this concentration is insufficient to sustain diatoms. Future experiments are needed to verify the hypothesis that summer blooms of diatoms are indeed reliant on meltwater derived DSi. However, the likely importance of glacial meltwater as a DSi source for diatoms is illustrated by seasonal data of Godthåbsfjord (Figure 3) recorded at stations GF10 (in the inner fjord close to the glaciers) and GF3 (in the mouth). The start of the spring bloom in April invokes a rapid consumption of nutrients in surface waters mainly by diatoms

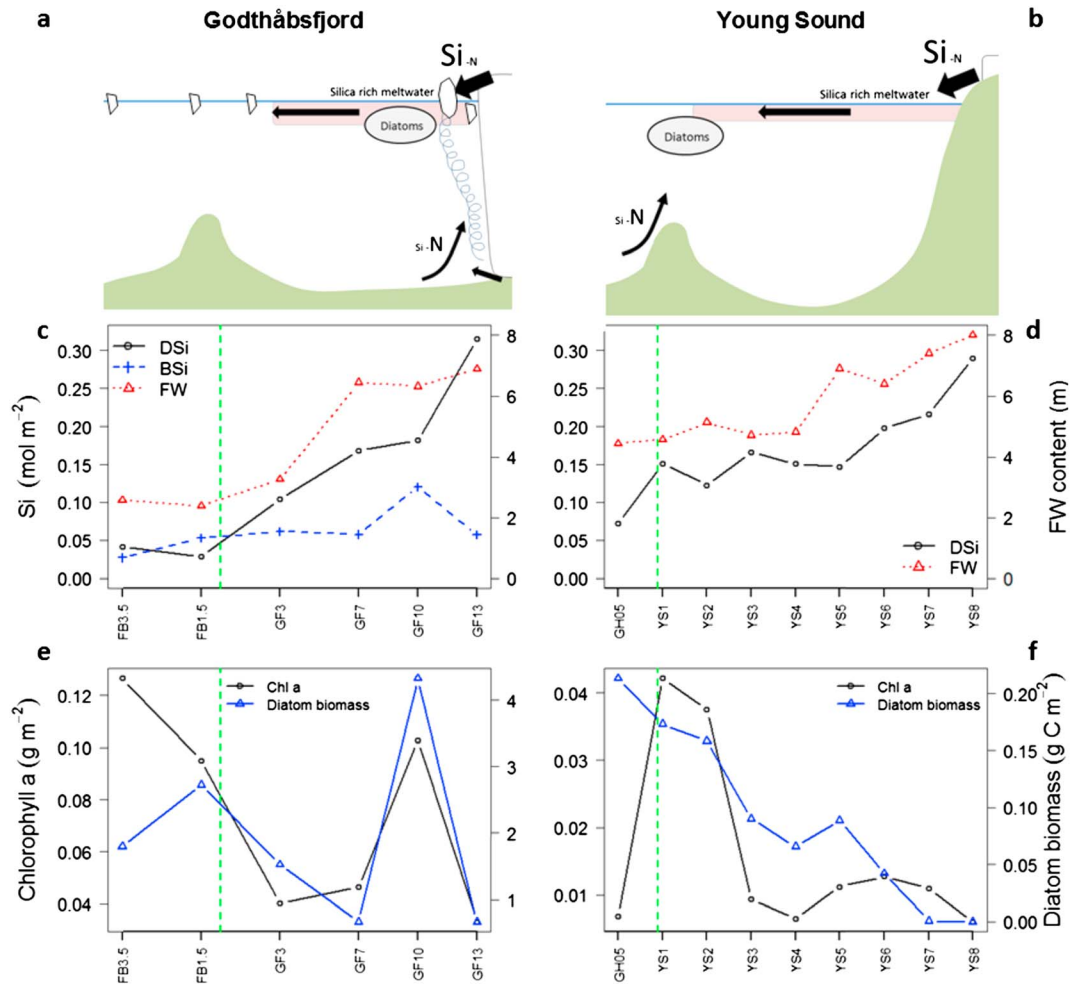


Figure 2. (a, b) Conceptual model on the link between meltwater runoff rich in silicate and diatom blooms in a fjord system impacted by marine- and land-terminating glaciers. (c,d) Integrated concentrations in the upper 40 m along a length transect in August from the inner fjord (right) to the open shelf area (left) in (c) Godthåbsfjord and (d) Young Sound. For Godthåbsfjord both dissolved silica (DSi, black) and biogenic silica (BSi, blue) are shown alongside the freshwater content (FW, red). The green dashed line indicates the mouth of the fjord. (e, f) The integrated chlorophyll *a* concentration (in g m⁻²) and diatom biomass (in g C m⁻²) in the upper 40 m for Godthåbsfjord (Figure 2e) and Young Sound (Figure 2f). Note the different scaling for chlorophyll and diatoms biomass between Young Sound and Godthåbsfjord.

(Figure 3). High silicate concentrations in the early phase of the spring bloom allowed diatoms to dominate, but as the bloom progressed, DSi decreased below 2 μM, which is a typical threshold value for Si limitation of diatom growth [Egge and Aksnes, 1992]. Concurrent with the depletion of nutrients (DSi and nitrate) in the upper water layer, a shift in the species composition occurred and diatoms became less abundant (Figure 3). The same temporal pattern is observed in the interannual phytoplankton succession at station GF3 (Figure 3) which consistently shows a succession from diatoms to haptophytes in spring, coinciding with a decrease of DSi in surface water [Juul-Pedersen et al., 2015; Krawczyk et al., 2015] (Figure 3). In summer, new nutrients are resupplied to the surface layer through subglacial freshwater discharge (Figure 3). Concurrent with the high input of DSi from surface runoff, a second diatom bloom is stimulated close to the tidewater glaciers, and diatoms remain the dominant species throughout the summer (Figure 3).

4. Conclusion

With an estimated total meltwater discharge of ~1000 km³ yr⁻¹ (including both runoff and solid ice discharge) released in a narrow time span of only a few months, the coastal areas around Greenland are strongly impacted by the input of glacial meltwater [Bamber et al., 2012]. This large meltwater runoff strongly enriches

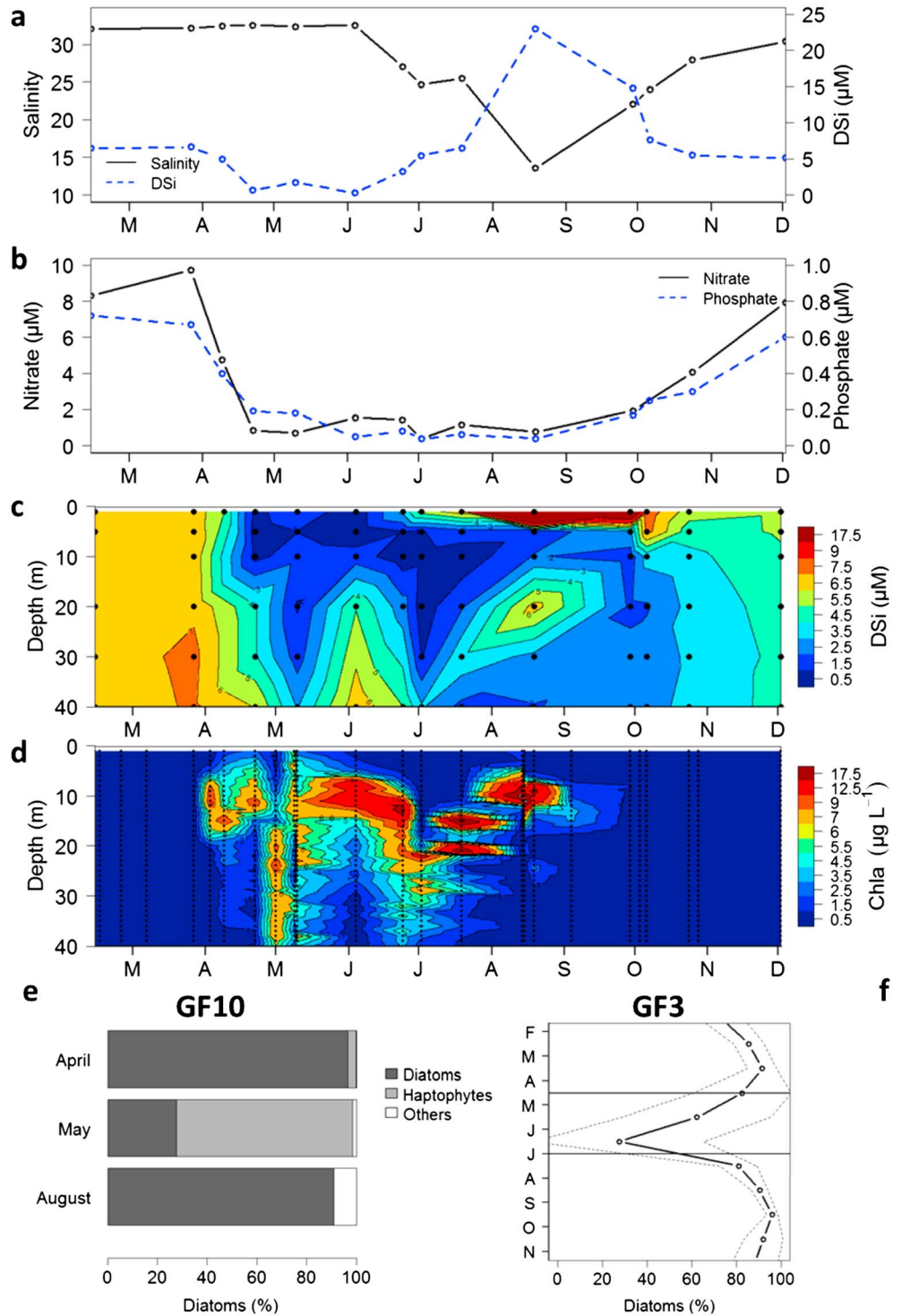


Figure 3. (a) Surface (at 1 m depth) salinity and silicate (μM), (b) surface nitrate and phosphate concentration (in μM), (c) DSi (in μM), and (d) chlorophyll *a* (in $\mu\text{g L}^{-1}$) based on regular sampling during the year 2013 in station GF10 located near to the glaciers in Godthåbsfjord. (e) Species composition during early spring (March–April), late spring (May–June), and summer (July–August) at station GF10 during 2013 and (f) the evolution of the contribution of diatoms to the phytoplankton (relative abundances) averaged over the period 2007–2011 from station GF3 in the mouth of Godthåbsfjord.

the surface waters of Greenland's fjords with silicate. Until now large ice sheets and glaciers have been considered inactive in global silicate cycle budgets [Dürr *et al.*, 2011], but accelerated mass loss of the GrIS is currently occurring and is predicted to further increase in coming decades. Research at the Leverett glacier (West Greenland) shows that DSi fluxes scale with meltwater discharge [Hawkings *et al.*, 2015]. Consequently, based on model projections of mass loss from the GrIS, we project an increase in DSi supply to coastal areas of 20 to 160% by the end of the 21st century, which is higher compared to nonglaciated areas in the Canadian Arctic [Moosdorf *et al.*, 2011] (supporting information). As an essential nutrient for diatom growth, our data suggest that this DSi export impacts coastal biogeochemistry. Bottom water measurements indicate that DSi concentrations are limiting for diatom growth in Greenland coastal waters [Jensen *et al.*, 1999], and consequently, an increased DSi input may induce changes in the phytoplankton community structure, with an anticipated trend toward increased diatom abundance which can impact carbon cycling and sequestration in coastal areas adjacent to the GrIS.

Acknowledgments

This research was supported by the Research Foundation Flanders (FWO aspirant grant to L.M.). S.R. was funded by the Canada Excellence Research Chair program. F.J.R.M. received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) via ERC grant agreement (306933). This study was conducted in collaboration with the marine monitoring program MarineBasis, part of the Greenland Ecosystem Monitoring (GEM) and the Danish Ministry of the Environment (project- PETAX). Supporting data are provided in the figures and included in Table 1 and are available from the authors upon request (lome@natur.gl). This work is a contribution to the Arctic Science Partnership (ASP) and the ArcticNet Networks of Centers of Excellence programs. We would like to thank Flemming Heinrich, Tom van der Spriet, Anne Cools, and the crew of RV SANNA for laboratory and field assistance.

References

- Aciego, S. M., E. I. Stevenson, and C. A. Arendt (2015), Climate versus geological controls on glacial meltwater micronutrient production in southern Greenland, *Earth Planet. Sci. Lett.*, *424*, 51–58, doi:10.1016/j.epsl.2015.05.017.
- Anderson, S. P. (2007), Biogeochemistry of glacial landscape systems, *Annu. Rev. Earth Planet. Sci.*, *35*(1), 375–399, doi:10.1146/annurev.earth.35.031306.140033.
- Arendt, K. E., J. Dutz, S. H. Jonasdottir, S. Jung-Madsen, J. Mortensen, E. F. Moller, and T. G. Nielsen (2011), Effects of suspended sediments on copepods feeding in a glacial influenced sub-Arctic fjord, *J. Plankton Res.*, *33*(10), 1526–1537, doi:10.1093/plankt/fbr054.
- Azetsu-Scott, K., and J. P. M. Syvitski (1999), Influence of melting icebergs on distribution, characteristics and transport of marine particles in an East Greenland fjord, *J. Geophys. Res.*, *104*(C3), 5321–5328, doi:10.1029/1998JC900083.
- Bamber, J., M. van den Broeke, J. Ettema, J. Lenaerts, and E. Rignot (2012), Recent large increases in freshwater fluxes from Greenland into the North Atlantic, *Geophys. Res. Lett.*, *39*, L19501, doi:10.1029/2012GL052552.
- Bendtsen, J., J. Mortensen, and S. Rysgaard (2014), Seasonal surface layer dynamics and sensitivity to runoff in a high Arctic fjord (Young Sound/Tyrolerfjord, 74°N), *J. Geophys. Res. Oceans*, *119*, 6461–6478, doi:10.1002/2014JC010077.
- Bendtsen, J., J. Mortensen, K. Lennert, and S. Rysgaard (2015), Heat sources for glacial ice melt in a west Greenland tidewater outlet glacier fjord: The role of subglacial freshwater discharge, *Geophys. Res. Lett.*, *42*, 4089–4095, doi:10.1002/2015GL063846.
- Bhatia, M. P. (2012), Hydrological and biogeochemical cycling along the Greenland ice sheet margin.
- Braman, R. S., and S. A. Hendrix (1989), Nanogram nitrite and nitrate determination in environmental and biological materials by vanadium (III) reduction with chemiluminescence detection, *Anal. Chem.*, *61*(24), 2715–2718, doi:10.1021/ac00199a007.
- Calbet, A., K. Riisgaard, E. Saiz, S. Zamora, C. Stedmon, and T. Nielsen (2011), Phytoplankton growth and microzooplankton grazing along a sub-Arctic fjord (Godthåbsfjord, west Greenland), *Mar. Ecol. Prog. Ser.*, *442*, 11–22, doi:10.3354/meps09343.
- Carmack, E., R. Macdonald, and S. Jasper (2004), Phytoplankton productivity on the Canadian Shelf of the Beaufort Sea, *Mar. Ecol. Prog. Ser.*, *277*, 37–50, doi:10.3354/meps277037.
- Dürr, H. H., M. Meybeck, J. Hartmann, G. G. Laruelle, and V. Roubeix (2011), Global spatial distribution of natural riverine silica inputs to the coastal zone, *Biogeosciences*, *8*(3), 597–620, doi:10.5194/bg-8-597-2011.
- Egge, J. K., and D. L. Aksnes (1992), Silicate as regulating nutrient in phytoplankton competition, *Mar. Ecol. Prog. Ser.*, *83*(2-3), 281–289, doi:10.3354/meps083281.
- Grasshoff, K., K. Kremling, and M. Ehrhardt (Eds) (2009), *Methods of Seawater Analysis*, John Wiley, New York.
- Hagedorn, B., and B. Hasholt (2004), Hydrology, geochemistry and Sr isotopes in solids and solutes of the meltwater from Mittivakkat Gletscher, SE Greenland, *Nord. Hydrol.*, *35*(4-5), 25–29.
- Hasholt, B., and B. Hagedorn (2000), Hydrology and geochemistry of river-borne material in a high arctic drainage system, Zackenberg, Northeast Greenland, *Arctic Antarct. Alp. Res.*, *32*, 84–94.
- Hawkings, J. R., et al. (2015), The effect of warming climate on nutrient and solute export from the Greenland Ice Sheet, *Geochem. Perspect. Lett.*, 94–104, doi:10.7185/geochemlet.1510.
- Hawkings, J., J. Wadham, M. Tranter, J. Telling, E. Bagshaw, A. Beaton, S. Simmons, D. Chandler, A. Tedstone, and P. Nienow (2016), The Greenland Ice Sheet as a hotspot of phosphorus weathering and export in the Arctic, *Global Biogeochem. Cycles*, *30*, 191–210, doi:10.1002/2015GB005237.
- Henriksen, N., A. K. Higgins, F. Kalsbeek, and T. C. R. Pulvertaft (2009), Greenland from Archaean to Quaternary: Descriptive text to the 1995 geological map of Greenland, 1:2 500 000. 2nd edition, *Geol. Surv. Denmark Greenl. Bull.*, *18*, 126.
- Hodson, A., P. Mumford, and D. Lister (2004), Suspended sediment and phosphorus in proglacial rivers: Bioavailability and potential impacts upon the P status of ice-marginal receiving waters, *Hydrol. Process.*, *18*(13), 2409–2422, doi:10.1002/hyp.1471.
- Holmes, R. M., et al. (2012), Seasonal and annual fluxes of nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas, *Estuaries Coasts*, *35*, 369–382, doi:10.1007/s12237-011-9386-6.
- Hopwood, M. J., D. P. Connelly, K. E. Arendt, T. Juul-Pedersen, M. C. Stinchcombe, L. Meire, M. Esposito, and R. Krishna (2016), Seasonal changes in Fe along a glaciated Greenlandic fjord, *Front. Earth Sci.*, *4*(15), doi:10.3389/feart.2016.00015.
- Jensen, H. M., L. Pedersen, A. Burmeister, and B. Winding Hansen (1999), Pelagic primary production during summer along 65 to 72 N off West Greenland, *Polar Biol.*, *21*(5), 269–278, doi:10.1007/s003000050362.
- Juul-Pedersen, T., K. Arendt, J. Mortensen, M. Blicher, D. Sogaard, and S. Rysgaard (2015), Seasonal and interannual phytoplankton production in a sub-Arctic tidewater outlet glacier fjord, west Greenland, *Mar. Ecol. Prog. Ser.*, *524*, 27–38, doi:10.3354/meps11174.
- Krawczyk, D. W., A. Witkowski, T. Juul-Pedersen, K. E. Arendt, J. Mortensen, and S. Rysgaard (2015), Microplankton succession in a SW Greenland tidewater glacial fjord influenced by coastal inflows and run-off from the Greenland Ice Sheet, *Polar Biol.*, doi:10.1007/s00300-015-1715-y.
- Kristiansen, S. M., J. C. Yde, T. G. Bärçena, B. H. Jakobsen, J. Olsen, and N. T. Knudsen (2013), Geochemistry of groundwater in front of a warm-based glacier in Southeast Greenland, *Geogr. Ann. Ser. A Phys. Geogr.*, *95*, 97–108, doi:10.1111/geoa.12003.

- Leblanc, K., et al. (2012), A global diatom database – abundance, biovolume and biomass in the world ocean, *Earth Syst. Sci. Data*, 4(1), 149–165, doi:10.5194/essd-4-149-2012.
- Mernild, S. H., I. M. Howat, Y. Ahn, G. E. Liston, K. Steffen, B. H. Jakobsen, B. Hasholt, B. Fog, and D. Van As (2010), Freshwater flux to Sermilik Fjord, SE Greenland, *Cryosphere*, 4(4), 453–465, doi:10.5194/tc-4-453-2010.
- Moosdorf, N., J. Hartmann, and R. Lauerwald (2011), Changes in dissolved silica mobilization into river systems draining North America until the period 2081 – 2100, *J. Geochem. Explor.*, 110(1), 31–39, doi:10.1016/j.gexplo.2010.09.001.
- Mortensen, J., J. Bendtsen, R. J. Motyka, K. Lennert, M. Truffer, M. Fahnestock, and S. Rysgaard (2013), On the seasonal freshwater stratification in the proximity of fast-flowing tidewater outlet glaciers in a sub-Arctic sill fjord, *J. Geophys. Res. Oceans*, 118, 1382–1395, doi:10.1002/jgrc.20134.
- R Core Team (2013), *R A Lang. Environ. Stat. Comput*, R Foundation for Statistical Computing, Vienna, Austria.
- Rysgaard, S., T. G. Nielsen, and B. W. Hansen (1999), Seasonal variation in nutrients, pelagic primary production and grazing in a high-Arctic coastal marine ecosystem, Young Sound, Northeast Greenland, *Mar. Ecol. Prog. Ser.*, 179(Digby 1953), 13–25, doi:10.3354/meps179013.
- Rysgaard, S., T. Vang, M. Stjernholm, B. Rasmussen, A. Windelin, and S. Kiilsholm (2003), Physical conditions, carbon transport, and climate change impacts in a Northeast Greenland fjord, *Arctic Antarct. Alp. Res.*, 35(3), 301–312, doi:10.1657/1523-0430(2003)035[0301:PCCTAC]2.0.CO;2.
- Tréguer, P. J., and C. L. De La Rocha (2011), The world ocean silica cycle, *Annu. Rev. Mar. Sci.*, 5, 120725114348000, doi:10.1146/annurev-marine-121211-172346.
- Van As, D., et al. (2014), Increasing meltwater discharge from the Nuuk region of the Greenland ice sheet and implications for mass balance (1960–2012), *J. Glaciol.*, 60(220), 314–322, doi:10.3189/2014JoG13J065.
- Yde, J. C., N. Tvis Knudsen, and O. B. Nielsen (2005), Glacier hydrochemistry, solute provenance, and chemical denudation at a surge-type glacier in Kuannersuit Kuussuat, Disko Island, West Greenland, *J. Hydrol.*, 300, 172–187, doi:10.1016/j.jhydrol.2004.06.008.
- Yde, J. C., N. T. Knudsen, B. Hasholt, and A. B. Mikkelsen (2014), Meltwater chemistry and solute export from a Greenland Ice Sheet catchment, Watson River, West Greenland, *J. Hydrol.*, 519, 2165–2179, doi:10.1016/j.jhydrol.2014.10.018.