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COMMENTARY
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Key Points:

- A new article by Williams et al. published in *JGR: Biogeosciences* prompts discussion of the role glaciers play in coastal nutrient cycling
- Marine-terminating glaciers play an important role in coastal ecosystems by indirectly supplying macronutrients to surface waters
- Substantial changes to marine nutrient cycling expected in glaciated regions as ice cover wanes in response to atmospheric and oceanic warming

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Trickle and Treat? The Critical Role of Marine-Terminating Glaciers as Icy Macronutrient Pumps in Polar Regions

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Abstract Nutrient supply to the coastal euphotic zone is critical in sustaining the productivity of ecosystems and provides an important feedback on the carbon cycle via stimulating the biological pump. The supply of coastal nutrients is typically thought to be dominated by terrestrial inputs and upwelling of deep ocean waters. Marine-terminating glaciers can provide nutrients via both mechanisms but the relative importance of each is dependent on complex physical–biogeochemical processes ranging from those in the glacier drainage system to the ice–ocean interface. Constraining these glacial nutrient supply processes in a remote part of the Canadian Arctic Archipelago (CAA) is the focus of a new study by Williams et al. (2021, https://doi.org/10.1029/2021JG006289). Their findings advance our understanding of the role glaciers play in polar nutrient cycling by highlighting significant shallow meltwater pumping of macronutrient-replete marine waters by CAA marine-terminating glaciers into the euphotic zone.

Plain Language Summary Glaciers that flow into the ocean supply essential nutrients for life to coastal ecosystems. The glacial meltwater itself provides a direct "trickle" supply. Pumping of macronutrient-rich ocean waters by upwelling of fresh meltwater when it exits the glacier provides an indirect nutrient "treat." These glacially derived nutrients likely help maintain ecosystem health, but the mobilization and delivery processes involved are complex and poorly resolved, in part due to a lack of spatial and temporal data. Recent research, some of which is featured in the current issue of *Journal of Geophysical Research: Biogeosciences*, has helped to highlight the importance of marine-terminating glaciers in indirect nutrient supply by detailing the importance of the meltwater pump. Melting of glaciers under climate warming scenarios is likely to change the balance of and processes contributing to nutrient supply and therefore the health of societally important polar ecosystems.

The delivery of the macronutrients carbon (C), nitrogen (N), phosphorus (P), and silicon (Si) to the euphotic zone of the coastal ocean represents one of the most important biogeochemical processes on Earth (Jickells, 1998; Moore et al., 2013). Macronutrients sustain microbial primary and secondary production, which are vital components of the global carbon cycle (De La Rocha & Passow, 2014). These microscopic organisms form the base of the marine food web and therefore dictate the structure of the marine ecosystem, including the vitality of environmentally and economically important fisheries (Chassot et al., 2010). Both land inputs and the hydrodynamics of coastal waters play critical roles in replenishing surface waters with nutrients for growth (Tseng et al., 2014). The main sources of nutrients transported from land to ocean are rivers (Statham, 2012), groundwater (Santos et al., 2021), and atmospheric aerosols/dust (Jickells et al., 2016). Upwelling waters at continental and island margins bring nutrient-rich deep water to the ocean surface (Bruland et al., 2001; Gove et al., 2016; Watanabe et al., 2017). More recently, glaciers have been identified as potential macronutrient sources to coastal waters (J. Hawkings et al., 2016; Hendry et al., 2019; Vick-Majors et al., 2020). Far from the inhospitable and undynamic systems they are often perceived, glaciers host diverse microbial communities (Anesio et al., 2017) and sustain high rates of biogeochemical activity through the unique combination of liquid water and access to an abundance of finely comminuted and amorphous particles (glacial flour) generated from glacier sliding (Tranter & Wadham, 2014; Wadham et al., 2019). Recently observed and predicted rapid ice mass loss due to climatic warming (Hugonnet et al., 2021; Mouginot et al., 2019) highlights the need to better constrain the role of glaciers as dynamic components of coastal nutrient cycling.

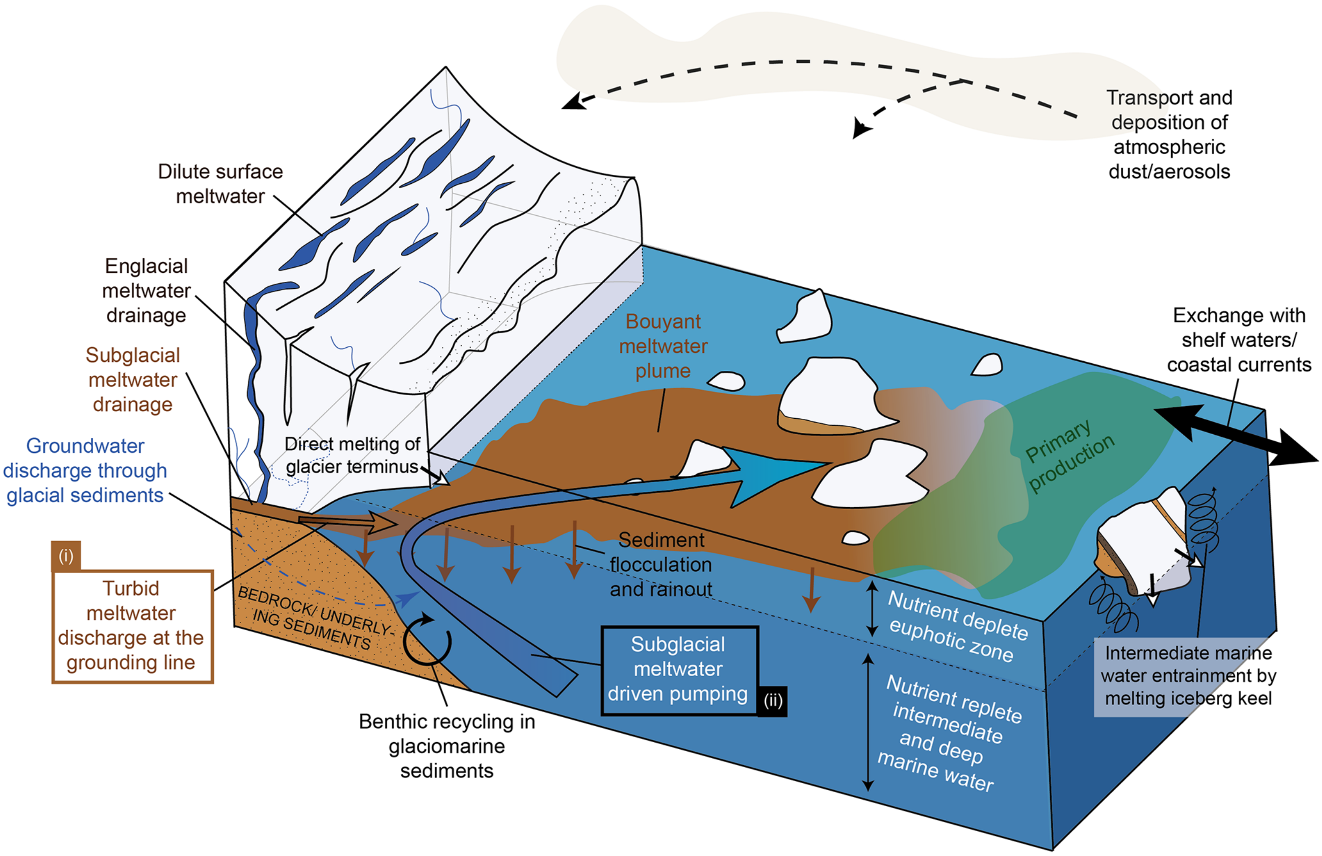

Figure 1. A schematic of the current hypothesized physiochemical processes occurring at the ice–ocean aquatic critical zone. Two main nutrient delivery pathways are identified: (i) direct input of dissolved macronutrients from subglacial meltwater and (ii) indirect macronutrient-replete deep ocean water entrainment in the upwelling meltwater plume. The size of the arrows indicates approximate dissolved macronutrient flux terms. Other processes are also likely to imprint on the main two delivery pathways, but these remain poorly constrained. Figure adapted from Chu (2014).

The coastal regions proximal to significant ice cover harbor economically important ecosystems (Long & Jones, 2021). Circumstantial evidence elucidating the importance of glacially derived nutrients for these ecosystems has existed for over 50 years (Apolloni, 1973; Burton & Liss, 1973), including early observations of enhanced biological activity in marine waters proximal to glacier meltwater outflow dating to the 1930s (Hartley & Dunbar, 1938), and more recent studies identifying marine-terminating glacier fronts as foraging hotspots and refugia for marine life (Laidre et al., 2016; Lydersen et al., 2014; Nishizawa et al., 2019; Urbanski et al., 2017). Glaciers deliver macronutrients to the euphotic zone of coastal waters via two broad mechanisms (Figure 1). First, the direct input of dissolved and labile particulate nutrients carried by meltwaters (J. R. Hawkings et al., 2015; Hood & Scott, 2008; J. B. Martin et al., 2020) and icebergs (Smith et al., 2013; Wadham et al., 2019). Second, indirect nutrient-rich deep ocean water entrainment in buoyant fresh meltwater plumes emerging from the subglacial hydrological system of marine-terminating glaciers (also commonly referred to as tidewater glaciers) and melting keel of icebergs ("meltwater pumping"; e.g., Cape, Straneo, et al., 2019; Cape, Vernet, et al., 2019; Greisman, 1979; Halbach et al., 2019; Hopwood et al., 2018; Kanna et al., 2018; Meire et al., 2017; Moon et al., 2018). Grounding line depth, that is, depth in the water column at which the glacier separates from the bedrock beneath it and where the majority of meltwater exits the glacier, is argued to be critical in determining the effectiveness of this meltwater pump (Hopwood et al., 2018). The impacts of these two delivery mechanisms are spatially and temporally complex and a topic of healthy debate in the literature.

There are very few studies linking land and marine measurements in an ice-to-ocean gradient, which has made accurately quantifying direct versus indirect macronutrient inputs from glaciers difficult. In this issue of *Journal of Geophysical Research: Biogeosciences*, Williams et al. (2021) present macronutrient concentration data over a gradient from the marine-terminating Sverdrup Glacier to coastal waters up to ~25 km from the glacier terminus. The study highlights the impact of direct meltwater macronutrient export versus indirect meltwater entrainment of marine waters. The authors conducted their work in the heavily glaciated Canadian Arctic Archipelago (CAA) where no data have been collected since the early 1970s (Apolloni, 1973), apart from that in a companion article published concurrently in *Global Biogeochemical Cycles* (Bhatia et al., 2021). The study is one of the first to use an ice-to-ocean biogeochemical data set to provide evidence of significant nutrient entrainment from a shallow (approximately tens of meters depth) marine-terminating glacier (e.g., Figure 1). These data are highly valuable in constraining flows and fluxes of macronutrients to coastal ecosystems in glaciated regions and can be used to infer how these interface zones are likely to respond to future glacier retreat and melt in a warming climate.

The ice-to-ocean biogeochemical gradient sampled by Williams et al. (2021) provides several important insights into the role of marine-terminating glaciers in regional macronutrient cycling. The authors found dissolved nutrient concentrations (inorganic N as $NO_3^- + NH_4^+$, soluble reactive phosphorus [SRP], dissolved silicon, and dissolved organic carbon [DOC]) indicative of oligotrophic conditions in glacial meltwaters sampled at ice margin and surface locations (supraglacial ice, snow, and fresh surface melt). Nutrient concentrations suggested a depleted glacial meltwater endmember consistent with inputs predominantly from atmospheric deposition onto the ice surface (e.g., J. Hawkings et al., 2016; McCutcheon et al., 2021; Wadham et al., 2016). These low dissolved nutrient concentrations are inferred to be representative of the bulk meltwater discharge and impart a dilution effect upon mixing with marine waters at the ice–ocean interface.

The authors highlight a potential role for glacial DOC, in contrast to inorganic N, P, and Si. The glacially derived dissolved organic matter (DOM) exhibits fluorophores characteristic of microbially produced highly labile compounds (at least ~20% more protein-like fluorescence than marine samples; Dubnick et al., 2020), despite low overall concentrations of DOC (mostly <20 μM), compared to more recalcitrant marine organic matter dominated by humic-like florescence. Bioavailable glacial DOM is consistent with findings on Arctic land terminating glacier systems (Fellman et al., 2010; Kellerman et al., 2020; Pain et al., 2020), but this is the first demonstration of labile DOM delivery from a marine-terminating glacier. Distinctive DOM fluorescence in glacially modified coastal waters around southwestern Greenland has also been reported recently and may be linked to glacier DOM delivery across boundary currents, although the ultimate source is unclear (Hendry et al., 2021). It is interesting to speculate how large the impact of glacial DOM might be versus other local sources (e.g., primary production, upwelling, and nonglacial terrestrial inputs) and how rapidly each may be consumed by heterotrophic organisms in the marine environment, given the low export flux may be balanced by high bioavailability.

The nutrient concentrations in the study by Williams et al. (2021) are generally lower (up to more than an order of magnitude for lithogenic nutrients) than those reported in glacial meltwaters elsewhere. These low nutrient concentrations indicate limited interaction of meltwater with sediments beneath the glacier, highlighting the importance of the subglacial hydrological regime in nutrient mobilization (Irvine-Fynn et al., 2011). Sverdrup Glacier is a slow moving polythermal glacier, likely with extensive regions of cold-based ice (Wyatt & Sharp, 2015). In cold-based regions, the glacier is frozen to the bedrock and production of glacial flour is significantly lower than glaciers with extensive regions of fast flowing warm-based ice (e.g., southwest Greenland; Nienow et al., 2017). Sverdrup Glacier likely lacks the widespread subglacial drainage networks that promote water–rock interaction, biogeochemical weathering, and higher nutrient concentrations, particularly rock-derived nutrients like Si (e.g., J. R. Hawkings et al., 2017; Meire et al., 2016, where dissolved Si concentrations can exceed 50 μM in glacial meltwaters vs. ~detection in this study). Even with these differences, glacial meltwater in all systems studied appears mostly to provide a "trickle" of direct dissolved macronutrients to coastal ecosystems that can only sustain a small portion of the observed primary productivity.

The real "treat" from marine-terminating glaciers comes indirectly from meltwater-driven upwelling of nutrient-rich marine waters. Williams et al. (2021) corroborate a range of studies from the Arctic where likely >90% of NO_3^- and SRP in the euphotic zone is sourced from indirect meltwater pumping (Cape, Straneo, et al., 2019; Halbach et al., 2019; Kanna et al., 2018; Meire et al., 2017). Large marine-terminating glaciers in Greenland are estimated to provide a flux of dissolved macronutrients to the coastal euphotic zone that rivals the major Arctic river inputs in magnitude (Cape, Straneo, et al., 2019), while even smaller marine-terminating glaciers provide a significant nutrient addition to coastal surface waters (e.g., Bowdoin Glacier, Kanna et al., 2018). These large glacier dissolved macronutrient subsidies are linked to enhanced proximal summertime productivity, and likely impact higher trophic levels (e.g., higher observed catch in coastal systems with significant marine-terminating glacier inputs; Meire et al., 2017) with clear relevance for ecosystem services.

The impact of meltwater-induced oceanic water entrainment on dissolved macronutrient availability (nitrogen and phosphorus) has been modeled by Hopwood et al. (2018) and is expected to be approximately 2 orders of magnitude greater than the "trickle" from direct meltwater input. The same study hypothesized that retreat of marine-terminating glaciers into shallower waters would suppress nutrient entrainment (the "productivity continuum"), as pumping theoretically occurs above the hypothesized nutricline. The anticipated net effect is that shallow meltwater pumping has a minimal impact on euphotic zone primary productivity.

Marine-terminating glaciers in the CAA have shallow grounding lines with subglacial meltwater discharging at depths of approximately tens meters. The study of Williams et al. (2021) therefore provides an ideal testing ground for the hypothesis that shallow meltwater pumping (~30 m) of intermediate oceanic waters is relatively unimportant for marine ecosystem productivity. Williams et al. (2021) found that meltwater pumping at Sverdrup Glacier still drives significant nutrient entrainment, similar to the findings from Halbach et al. (2019) in Kongsfjorden, Svalbard, with turbid plumes positively correlated to higher chlorophyll *a* concentration. The nutrient enrichment is more modest than deeply ground marine-terminating glaciers (e.g., ~5 μM of NO_3^- compared to ~10 μM in Nuup Kangerlua, Sermilik Fjord, and Bowdoin Fjord; Cape, Straneo et al., 2019; Kanna et al., 2018; Meire et al., 2017) but is somewhat surprising considering the expected productivity decline with decreasing grounding line depth. Indeed, shallow grounded marine-terminating glaciers in the remote CAA have the capacity to pump oceanic nutrient-rich water to the surface at a scale that rivals direct nutrient inputs from the largest Arctic river in North America (Mackenzie River; Williams et al., 2021). Glaciers in the CAA can therefore maintain a significant nutrient pump to surface waters at the ice–ocean interface, with importance for regional coastal ecosystem health.

Despite the progress in understanding the ice–ocean biogeochemical critical zone, there are still multiple uncertainties that exist. Even though the direct input of dissolved macronutrients from glaciers into the marine environment appears minor, glaciers may play an important role in micronutrient (trace elements essential for life) input. Glacial meltwaters in both polar regions appear enriched in particulate and filterable micronutrients (e.g., Fe, Mn, and Co), particularly where an extensive subglacial drainage system exists (Aciego et al., 2015; Bhatia et al., 2013; J. R. Hawkings et al., 2020). Evidence also suggests that glacially derived micronutrients are exported into the euphotic zone of coastal waters, where they are important in maintaining elevated concentrations, particularly of Fe (e.g., Arrigo et al., 2017; Bhatia et al., 2021; Cape, Straneo, et al., 2019; Herraiz-Borreguero et al., 2016; Hopwood et al., 2016; Kanna et al., 2020; Krisch et al., 2021). This glacier micronutrient "treat" is likely have disproportionate biogeochemical effects in the Arctic and Antarctic due to the differences in marine nutrient limitation patterns (Hopwood et al., 2020; Moore et al., 2013). For example, Southern Ocean waters are mostly Fe (and possibly Mn) limited (Browning et al., 2021; J. H. Martin et al., 1990), while most Arctic Ocean waters are believed to be largely N limited, with pockets of seasonal Fe limitation (Arrigo et al., 2017; Nielsdottir et al., 2009). The biogeochemical impact of direct micronutrient enrichment and indirect macronutrient enrichment is therefore complex and spatially variable, requiring more holistic studies in the future.

The meltwater pump provides a direct link between the benthic environment and the surface yet the role of benthic–pelagic coupling is poorly quantified but likely important. Diagenetic recycling of nutrients in coastal sediments with a high input of reactive glaciogenic sediment and organic matter is likely to be significant (e.g., Halbach et al., 2019; Hendry et al., 2019; Laufer-Meiser et al., 2021; Wehrmann et al., 2014), and the input of submarine groundwater in regions that are heavily glaciated is virtually unknown (Ó Dochartaigh et al., 2019). Sediment diagenesis and submarine groundwater discharge is potentially already imprinted on the biogeochemical data sets of previous studies yet is very hard to account for without direct observations of benthic processes in coastal sediments (Ng et al., 2020) coupled to numerical models (e.g., Hülse et al., 2018).

Linked to the benthic reprocessing of glacial flour is also the role of particle-bound phases in coastal nutrient cycling. Glacial meltwaters carry an abundance of reactive minerals that could supply macronutrients to biota after further biogeochemical processing (Hendry et al., 2019). Particle-bound nutrients are found at concentrations often over an order of magnitude higher than dissolved macronutrients in glacial meltwater rivers (J. R. Hawkings et al., 2015; Pryer et al., 2020), yet the fate of this material could be anywhere from burial/loss to remobilization, is temporally and spatial variable, and dependent on a range of external factors (e.g., organic matter reactivity and sedimentation rates). Glacial flour is highly bioavailable when used to relieve nutrient limitation in microcosm experiments (e.g., Shoenfelt et al., 2017) and particulate phases are dissolvable in seawater under lab conditions (e.g., J. R. Hawkings et al., 2017). However, the lability of these phases in the marine water column is not thought to be significant based on dissolved macronutrient data (Hopwood et al., 2020) and particles are unlikely to supply nitrogen, the primary limiting nutrient in Arctic marine systems (Bhatia et al., 2021; Randelhoff et al., 2020), in any significant quantity (Wadham et al., 2016). Much of the particulate flux is lost at low salinities as seawater-induced particle aggregation and flocculation accelerates sedimentation, and some evidence suggests adsorption of SRP onto reactive iron phases during seawater–freshwater mixing (Cape, Straneo, et al., 2019). Highly turbid waters also limit light penetration into the water column and provide a challenging environment for some eukaryotic organisms (Giesecke et al., 2019). The impact of particulate material (as nutriment and as a light modulator) is likely to be heavily dependent on the source geology (Halbach et al., 2019), which varies widely across glacially covered regions. The role of glacial flour on nutrient inventories therefore remains heavily debated.

Marine-terminating glaciers in the Arctic are rapidly retreating in response to atmospheric and/or oceanic warming (Cook et al., 2019; Wood et al., 2021). Glacier grounding lines are likely to retreat into shallower depths or onto a retrograde slope (and therefore deeper depths; e.g., in Greenland and Antarctica; Gudmundsson et al., 2012; King et al., 2020), the glacier may transition to a land-based system, and/or the subglacial hydrological system may expand or contract in response to external effects (e.g., meltwater input, ice thickness, and mean annual temperature). A transition from marine to land terminating system will almost certainly impact proximal ecosystems by eliminating the meltwater pump and increasing the discharge of turbid meltwater into the euphotic zone. Perhaps the ultimate question to pursue is therefore how glacial nutrient fluxes (direct and indirect) are likely to change under these different confounding scenarios.

The work of Williams et al. (2021) in the CAA highlights some of the nuances associated with understanding biogeochemical cycling at the ice–ocean interface. Studies of coastal polar processes need to acknowledge the complex interplay of physiochemical processes at this emerging critical zone (Oliver et al., 2018), with both known unknowns (e.g., benthic fluxes) and unknown unknowns. Collecting data in these environments is challenging due to the remoteness and associated logistical complexity, as well as the unpredictability of rapidly evolving landscapes. However, additional temporal and spatial coverage is needed to understand the evolution of these interfaces. Only with a better physical and biogeochemical understanding of these systems will we be able to accurately predict future changes to glaciomarine macronutrient cycling. Knowledge of the coupling between glacier nutrient supply and marine productivity in polar regions is essential because of the tight linkages with ocean–atmosphere CO_2 exchange and the health of marine ecosystems, both of which are highly relevant to society. The challenge is open to integrate observational data over ice to ocean gradients with more realistic numerical models that can be used to predict future response of these vulnerable systems in a warmer world.

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Data Availability Statement

No new data was produced in this commentary.

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