Impact of a warming Arctic on hydrological flow routing and carbon transport from glaciated environments to the ocean

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The Greenland ice sheet (GrIS) is the largest expanse of glacial ice in the Northern Hemisphere and is capable of contributing significant quantities of meltwater and associated material to the surrounding North Atlantic and Arctic Oceans (IPCC, 2007). The total GrIS freshwater flux is comprised of surface melt, iceberg calving and geothermal bottom melting and is estimated to be close to 800 km^3/yr, with more than half of this contribution coming from surface meltwater runoff. During the record melt year of 2007, the GrIS contributed an estimated 523 km^3/yr surface runoff, equivalent to the combined mean annual discharge from the 5 large North American Arctic rivers.

This meltwater does not take a direct path from the ice sheet surface to the sea. Our recent results suggest a significant quantity of the annual surface melt may drain directly to the base of the ice sheet through hydrofractures and moulins, even through km-scale ice thicknesses (DAS et al., 2008; KRAWCZYNSKI et al., 2009) where it interacts with the underlying subglacial (beneath the ice) environment along long (tens of kms), seasonally-evolving flowpaths. Previous work on mountain glaciers and small ice caps has shown that the interaction of glacial meltwaters with subglacial till and bedrock produces discharge with significant chemical enrichment from its origin as dilute snow- and ice-melt (BROWN, 2002). This meltwater also fuels biogeochemical processes beneath the ice initiated by subglacial microbial communities. Such communities could in turn facilitate the release of additional nutrients or metals, amplify chemical weathering reactions, or utilize the organic carbon present in overridden soils and vegetation (SHARP et al., 1999; WADHAM et al., 2004). The timescale and nature of these water-bed interactions depend heavily on the nature of the subglacial hydrological system, which is poorly constrained for the GrIS. Future climate warming scenarios predict an acceleration of GrIS meltwater runoff, characterized by an increase in both the GrIS surface melt area and melt intensity, and an increase in the proglacial area as the ice sheet margin retreats. This could affect the processing of materials in both the subglacial and proglacial drainage networks, which may be a key driver in material export to the Arctic and North Atlantic Oceans. These activities could in turn affect downstream biological productivity, atmospheric CO_2 levels, or the global organic carbon cycle.

Funds from the Arctic Research Initiative supported a field campaign in 2008 to collect integrated data to constrain the hydrology and resultant nutrient and carbon cycles on the western margin of the GrIS (Figure 1). Meltwater from three land-terminating outlet glaciers (named glaciers 'M', 'N', and 'O' here), drains into a large proglacial lake (Thycho Brahe So Lake) before being released into a fjord. We focused our data collection on the smallest glacial system in this region (N glacier), with some point measurements from the M and O glacier outflow streams, Thycho Brahe So Lake, and the Thycho Brahe So Lake outflow to the fjord.

These data constitute the foundation of a PhD thesis by Maya Bhatia and all results presented below are chapters in her dissertation.

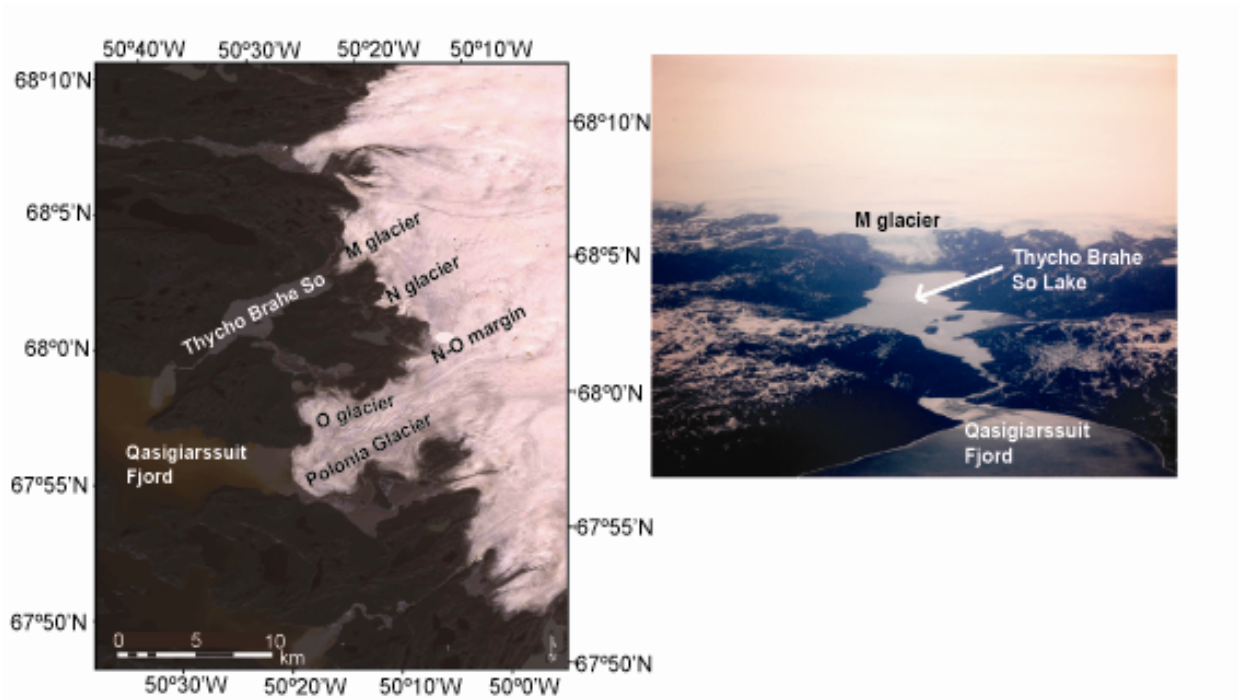

Figure 1. Landsat image and photo of proposed study site on the southwestern margin of the Greenland ice sheet.

The data analyzed to date falls into three broad categories. First, we assessed the contribution of each meltwater end-member to the overall discharge as a function of time. Second, we quantified nutrients and trace metals in all our samples in order to estimate nutrient and metal delivery from the glacier to downstream ecosystems. Third, we measured bulk carbon concentrations, radiocarbon (^{14}C) content and molecular-level composition of dissolved organic matter in order to examine sources and sinks of reactive reduced carbon in this system.

In the first category, we have combined results from three radioactive and stable isotopes (^{222}Rn, ^{18}O, D) as unique end-member tracers and developed a numerical model to calculate the relative contribution of each end-member. Through this model, we see a clear contrast between the relative contributions of each end-member in the early and late melt-seasons (Figure 2). In early May, the overall flow is low and water is comprised of a mixture of snow melt, ice melt and basal melt. As the flow increases throughout May and into July, the contribution from snow melt vanishes and the substantial increase in ice melt dilutes the relatively constant basal melt contribution. These results are interesting and novel because they are the first attempt to include a non-reactive tracer such as ^{222}Rn in hydrological models of glacier systems. This is an improvement over models that use chemical ions such as sulfate which can react or be produced within the subglacial system. This model will be used to interpret our chemical data.

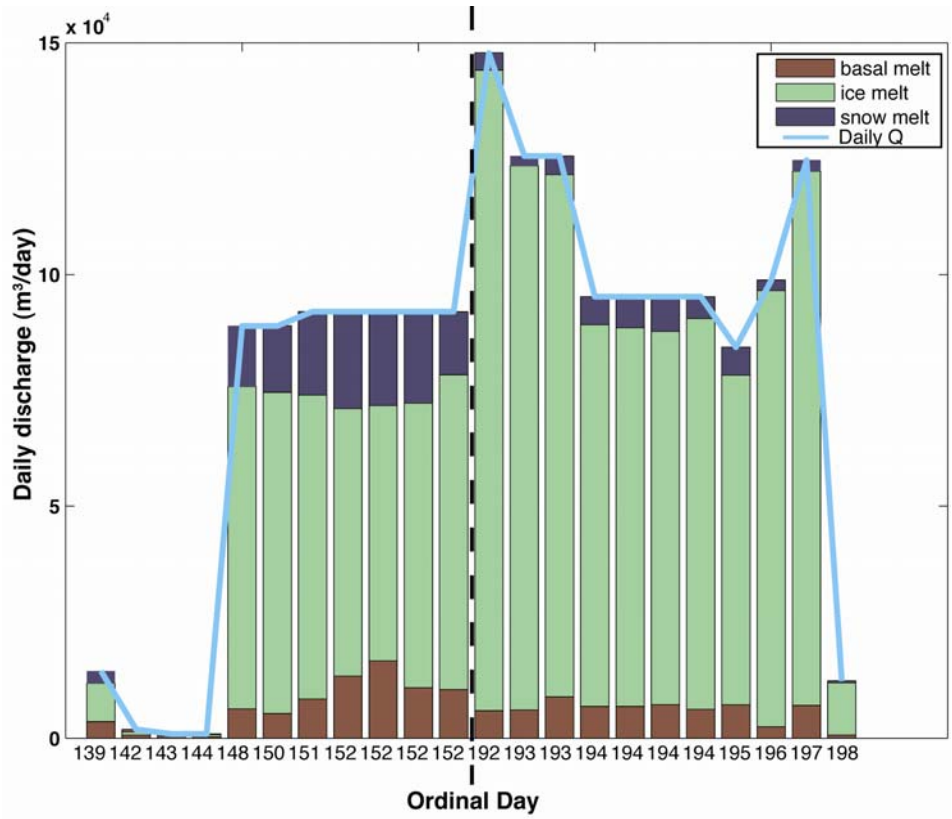

Figure 2. Relative contributions of snow melt, ice melt and basal melt to the total discharge measured at the mouth of the N glacier. The blue line shows the total discharge volume. The dashed line indicates the break in our data between the beginning of June and the beginning of July.

In the second category, our preliminary results indicate that glacial meltwater discharge can contain high iron (Fe) concentrations. Specifically, in May the N and O glacier subglacial streams had concentrations as high as ~10 μM. The subglacial outflow Fe concentration appears to scale with glacier catchment size: the much smaller M glacier system (Figure 1) had 3 times less Fe than the O glacier outflow. Furthermore, it appears that reactions in downstream Thycho Brahe So Lake amplified concentrations prior to release into the fjord (Figure 3A). The iron concentrations reported in the Thycho Brache So lake outflow in May to the fjord (~17 μM) are much higher than average river (~0.7 μM) and open ocean (~0.0007 μM) concentrations (SARMIENTO and GRUBER, 2006). Enhanced lake Fe outputs relative to the measured input concentrations may reflect overwinter build up in the lake due to permanent or seasonal anoxia. Lastly, in terms of mass flux, Fe export from the glacier N system was approximately constant from early season to steady-state summertime discharge: ~2-fold higher Fe concentrations during May were offset by ~2-fold lower water fluxes during this time period (Figure 3B). Hence, although we cannot draw a conclusion about which period within the melting season is most important in terms of mass flux for trace metals like Fe based on our preliminary data set, the importance of this system for iron delivery to the downstream fjord (and possibly North Atlantic Ocean) is clear.

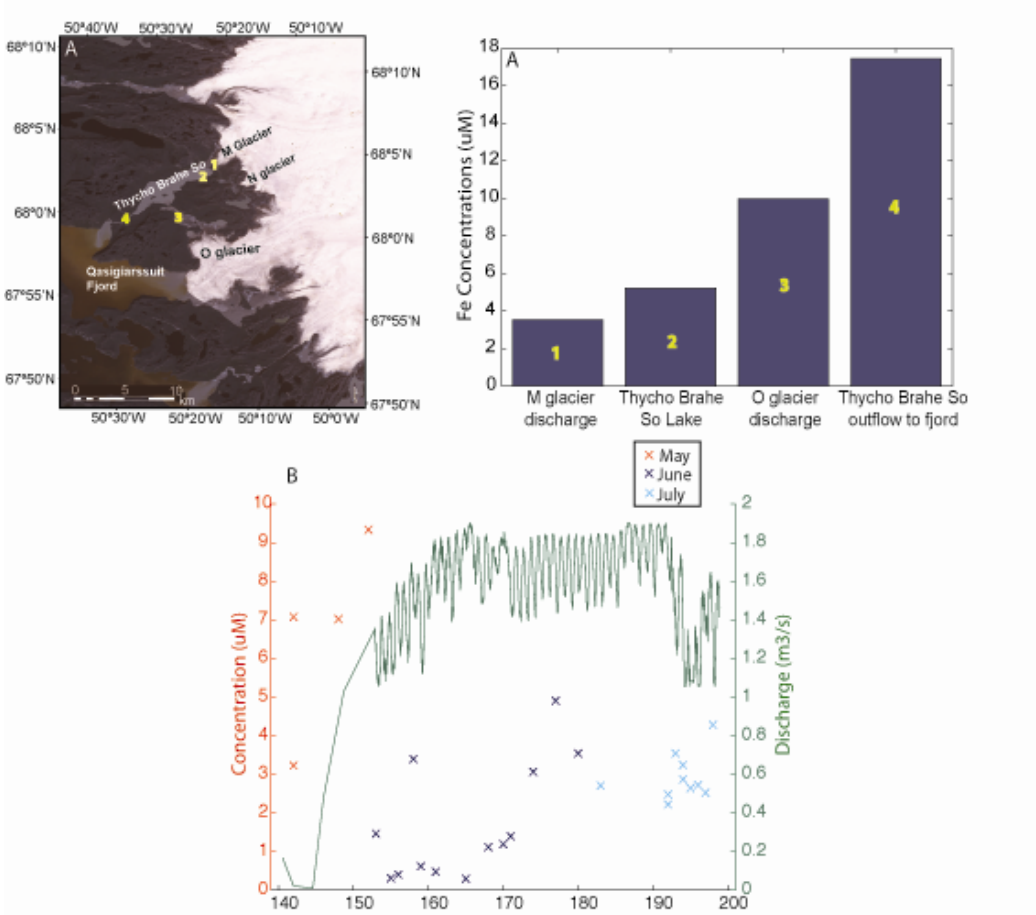

Figure 3. (A) Iron concentrations at four proglacial sites measured during May 2008. Iron concentration increases with distace from the glacier edge; overall concentrations are serveral orders of magnitude higher than North Atlantic surface water. (B) Iron concentrations and discharge measurements at N glacier from May to July 2008. May 2008 discharge values are confined to daily point measurements only.

Lastly, we have examined the carbon cycle in this system with a combination of bulk and molecular-level analyses. Bulk dissolved organic carbon (DOC) concentrations in the outflow stream exiting N glacier were variable over 1-2 orders of magnitude over the melt season. Radiocarbon content also varied over the melt season with progressively older carbon emerging in the later melt season. Using ultrahigh resolution mass spectrometry, we also observed a shift in DOC composition from microbial-derived materials to terrestrial-derived materials. Using these data in combination, we are developing a conceptual model for the organic carbon cycle in this system (Figure 4). Over winter, active microbial communities at the base of the glacier produce new reduced carbon as well as convert carbon left from the previous melt-season into biomass, leaving a microbial signature in the DOC. When melt begins, this water is flushed out first, producing high bulk concentrations with an intermediate radiocarbon signature. At the height of the melt season, ice melt from the surface dilutes this basal material and liberates a small amount of overridden carbon from the glacier bed. The discharge is thus characterized by low bulk DOC concentrations with an old radiocarbon signature and a more terrestrial composition.

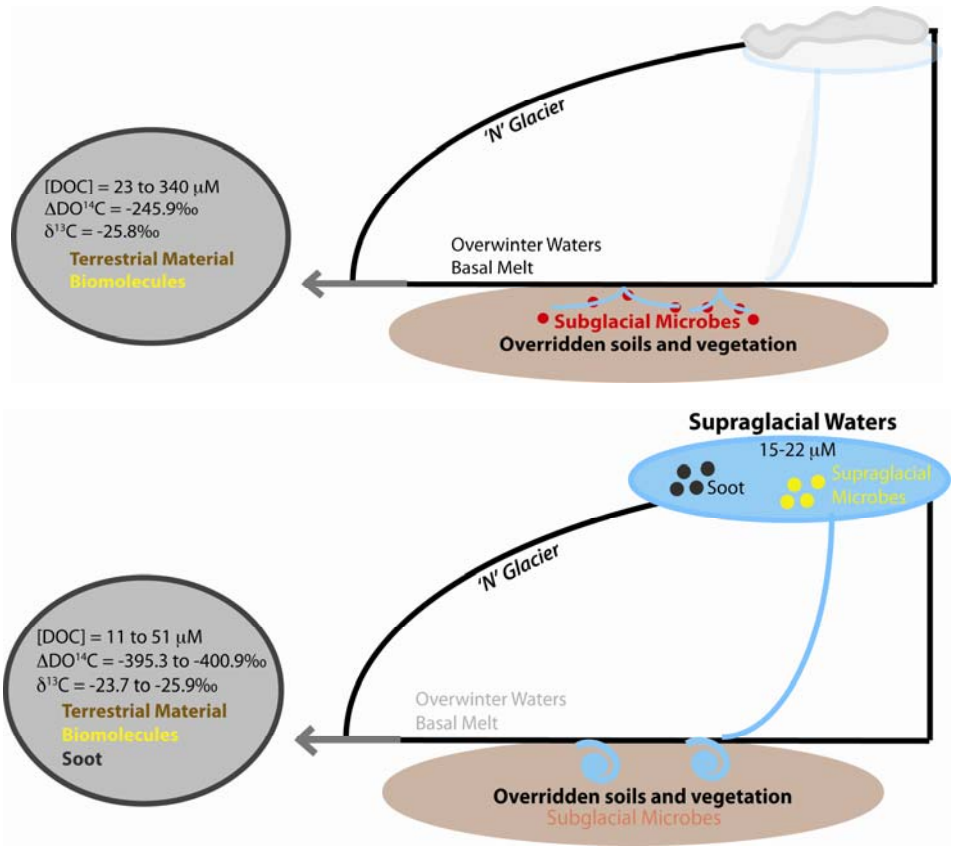

Figure 4. A conceptual model of the organic carbon cycle on the Greenland Ice Sheet. In the top figure, we show the early melt-season schematic (early / mid-May). At this time, the flow is a mixture of melt from snow, ice, and basal regimes (see Figure 2). In the bottom figure, we show the late melt-season schematic (mid-July). At this time, the flow is dominated by ice melt from the glacier surface.

In summary, funds from the Arctic Research Initiative have allowed the three PIs and our graduate student to collect a unique data set and to develop new models for an integrated view of the hydrological, nutrient, and carbon cycles of the Greenland Ice Sheet. Results from this work constitute the PhD thesis of Maya Bhatia and have been used as preliminary data for a $1.8M proposal to the National Science Foundation (pending as of June 2010). We have published one paper from this work to date (BHATIA et al., 2010) and Maya is preparing three other manuscripts for submission prior to her anticipated PhD defense in June 2011. Lastly, these funds have provided the impetus for the expansion of three research programs through the initiation of new research collaborations. We appreciate the generosity of the Arctic Research Initiative in making these connections and research results possible.

Citations

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