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Arctic River Chemistry: A Changing Climate's Imprint

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Winning article

Recent trends in the chemistry of major northern rivers signal widespread Arctic change
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> The integrative power of these large, northern rivers provides a striking reminder of the primacy of climate change and that warming and changing precipitation have far-reaching, often unexpected, results.

Earth's north is one of its key planetary commons, with expansive permafrost and boreal forests that sequester vast quantities of carbon and play a critical role in climate control for all of Earth's inhabitants. This region also brings together a broad range of stakeholders from varied nation states to diverse Indigenous governance structures, to a multitude of non-governmental and local community organizations. Therefore, although our planet's north is a critical linchpin in our quest to maintain Earth's position within its planetary boundaries, these geopolitical considerations also make it uniquely challenging to study and manage from a systems perspective. It was with this awareness of challenge, coupled with necessity, that the Arctic Great Rivers Observatory (originally founded as the PARTNERS project, Pan-Arctic River Transport of Nutrients, Organic Matter, and Suspended Sediments) was established in 2002: at a time when Russian-North American scientific collaboration was ascendant, investment in Arctic research was growing, and key, positive, developments that have come to shape our context for work in the north were either recently established, or gaining steam (e.g., the Inuvialuit Final Agreement and establishment of Nunavut in Canada; establishment of the Arctic Council internationally).

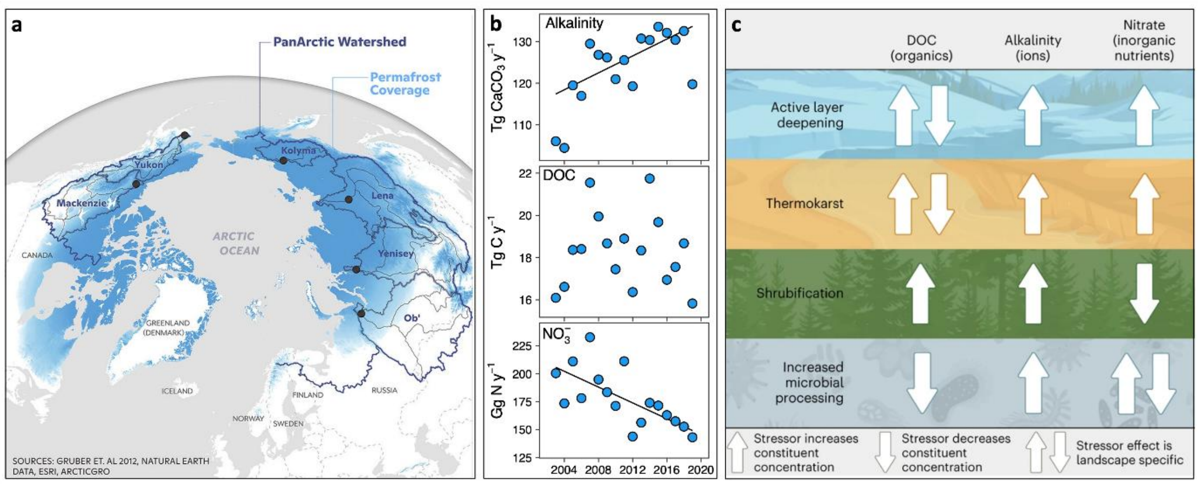

Figure 1: (a) The Pan-Arctic watershed (dark blue) and the six great Arctic rivers, with sampling points indicated with black dots. (b) Trends in land-ocean transport of alkalinity, dissolved organic carbon (DOC), and nitrate (NO3) over the Arctic Great Rivers sampling period, and (c) the effect of varied stressors of change on each of these constituents.

At its core, the Arctic Great Rivers Observatory takes advantage of the fact that six large rivers in Canada, Russia, and the US (Alaska) drain over two-thirds of the Arctic Ocean's watershed (**Figure 1a**). When measured at their outflow, the chemistry of large rivers provides a "fingerprint" that integrates a multitude of processes occurring over vast spatial scales. The water flowing from land to rivers carries with it the chemical signature it acquires in transit. Therefore, just like the concentration of atmospheric CO_2 captured by the iconic Keeling curve, the changing chemical signature of large river outflows describes systems-scale change occurring across broad swaths of Earth's landmass. At the same time, this riverine diagnostic of landscape function is transported to Earth's coastal oceans, where it shapes processes such as photosynthesis and organic matter decomposition. Our multi-national team has worked together to measure the chemistry of these six large rivers for over two decades. This long-standing, cross-jurisdictional collaboration has built a time series that has provided critical insight into the functioning of the land-ocean Arctic system, while also amassing a sample archive that enables retrospective analyses as important new questions emerge.

Two decades after first embarking on the Arctic Great Rivers endeavour, we are finding changes across the land-ocean Arctic system that far surpass the 9.5% increase in atmospheric CO_2 measured over the period of our dataset. As just a few examples, land-ocean transport of inorganic nutrients has declined (nitrate by 32%), while alkalinity (buffering capacity) has increased by 18%. Dissolved organic carbon (DOC) has shown no net change, despite known increases in OC mobilization from land to river networks because of permafrost thaw. This latter result strongly suggests escalating in-watershed decomposition of OC (organic carbon) to CO_2. These divergent trends (**Figure 1b**) indicate that a suite of climate-driven processes – including permafrost thaw and changing rates of primary production and microbial activity – are simultaneously altering the pan-Arctic land-ocean system (**Figure 1c**). In a region minimally affected by human settlement, the integrative power of these large, northern rivers provides a striking reminder of the primacy of climate change and that warming and changing precipitation have far-reaching, often unexpected, results.

In addition to diagnosing profound systems-level change, knowledge provided by the chemical signature of large Arctic rivers directly informs the development and implementation of strategies to enable Earth's return to a safe operating space. When considering the core boundary of Earth's climate, for example, this return requires that we first understand the future trajectory of Earth's land and ocean carbon sinks, and second, use this knowledge to shape and effectively achieve carbon emission and sequestration (i.e., carbon capture) targets. The Arctic system is critical to both endeavours.

Effectively accomplishing the first objective requires us to determine the Arctic's ability to hold on to its vast carbon stocks and to continue to act as negative feedback to climate change by taking up some portion of anthropogenic carbon. The chemical fingerprint of large Arctic rivers provides crucial knowledge on both fronts. For example, measuring the molecular composition of organic matter, which is one of the Observatory's core outputs, allows us to track the transport of permafrost carbon from its frozen repository through large river systems. Similarly, measuring the ionic composition of river water (including alkalinity) enables us to monitor whether the inorganic carbon that has been sequestered in rock over geologic time is increasingly being released (a positive feedback to climate change), or reacting with CO_2 in soils to sequester inorganic carbon as bicarbonate (a negative feedback to climate change).

Nutrient trends may be particularly helpful for understanding the degree to which the Arctic system will continue to act as a negative feedback to climate change. On land, declining inorganic nitrogen suggests that increasing air temperatures and "fertilization" of photosynthesis by atmospheric CO_2 may be causing photosynthetic carbon uptake to outpace the supply of nutrients in these northern watersheds. In the Arctic coastal ocean, declining inorganic nitrogen inputs combined with known, long-term increases in water discharge can directly limit carbon uptake by primary production, because nitrogen is the limiting nutrient for photosynthesis in this region, and oceanic freshwater inputs strengthen water column stratification, inhibiting the delivery of deep, nutrient-rich water to the ocean surface.

Effectively accomplishing the second objective requires that carbon capture strategies like alkalinity addition to the world's oceans, or incorporation of easily weatherable material (rock flour) to Earth's soils, are designed with the insight of long-term data that constrains the trajectory of effect. The evolution of Arctic riverine chemistry provides this insight in both cases because it can be used to measure how long-term increases in alkalinity delivery to the coastal ocean play out over time and to assess the effect of broad-scale increases in weathering as permafrost thaw unearths previously frozen inorganic sediments.

Tracking the land-ocean Arctic system directly enables a series of planetary boundary solutions. Our time series is an essential input to recent and ongoing regionally constrained Earth system modelling efforts that assess controls on, and effects of, changing carbon and nutrient flux from land to ocean. The outputs of these efforts, undertaken both by our extended collaborative team and by the broader scientific community are collectively suggesting that net carbon uptake within the Arctic system may be relaxing. The changes that we diagnose can immediately inform Earth system justice frameworks, which are particularly pressing in our planet's north, given the reliance of Indigenous and other local communities on robust, predictably functioning ecosystems. Our outputs can also feed directly to regular planetary boundary updates, as proposed to enable stakeholders to monitor common progress towards sustainability goals.

Most importantly, however, the profound, systems-scale perturbation that our program uncovers provides a clarion call for decarbonisation. Our work's Arctic lens is a lever for policy action, given that the Arctic has the potential to unite geopolitically diverse stakeholders around the common cause of systems-level sustainability and security. Ongoing use of our program's outputs in key policy fora (e.g., Intergovernmental Panel on Climate Change, Arctic Monitoring and Assessment Program) illustrates capacity on this front. Given our current global context, inciting political will for action may be our most pressing priority for solving the global sustainability crisis.

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Figure 2: Top row: the current Arctic Great Rivers Observatory leadership team. Subsequent rows: the co-authorship team for our winning paper.