Industrial-era decline of subarctic Atlantic productivity

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FAQ

Why are phytoplankton important?

Marine phytoplankton account for roughly half (~46%) of Earth's biological net primary production, despite accounting for less than 1% of the globally-integrated plant biomass[1]. Through the process of photosynthesis, these phytoplankton consume carbon dioxide to produce oxygen (the very stuff we breathe!), as well as "bioavailable" carbon that can be passed up the food chain to higher trophic levels. As such, phytoplankton play a critical role in global climate and ecosystems functioning: through their *net* drawdown of atmospheric carbon dioxide, the most important greenhouse gas, phytoplankton counteract anthropogenic carbon dioxide emissions that are currently warming the Earth's mean surface temperature at rates likely exceeding anything felt on Earth in millions of years[2]. Further, by forming the base of the oceanic food chain, phytoplankton allow life to exist in the ocean at all: phytoplankton and the carbon they produce are consumed by small herbaceous grazers, which in turn are eaten by small fish, that are eaten by yet-larger carnivorous species, and so on up to the top of the food chain (e.g., sharks, dolphins). Indeed, by setting the upper limit on fisheries yields, basin-scale changes in planktonic biomass on a year-to-year basis impart rippling effects that can reach all the way to our dinner tables.

How do we measure planktonic abundance and productivity over time?

Despite the importance of phytoplankton to global ecosystems and climate, little is known about their long-term response to climatic forcing. This lack of knowledge is largely due to limited observations of plankton abundance back in time. Global-scale inferences of phytoplankton abundance extend only as far back as 1997 (albeit intermittently to 1979), with the launch of satellite-based sensors that can monitor the entire globe over the span of a few days. Specifically, by measuring the green wavelength light reflected off of Earth, these satellite sensors provide an indicator of ocean-surface *chlorophyll* concentration (the primary photosynthetic pigment contained in phytoplankton), which is strongly linked to ocean planktonic abundance. By

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[1] Field, C. B., *et al*. Primary production of the biosphere: Integrating terrestrial and oceanic components. Science 281, 237–240 (1998). https://science.sciencemag.org/content/281/5374/237

[2] https://eos.org/scientific-press/carbon-could-soon-reach-levels-not-seen-in-56-million-years

incorporating these satellite *chlorophyll* measurements into empirical mathematical models developed in controlled laboratory- or ship-based settings, scientists can further derive high-resolution estimates of ocean Net Primary Production (i.e. NPP[3]). Yet, prior to the satellite era inferences of plankton abundance must be drawn from sparse (both across space and time) sources such as ship-board ocean transparency measurements, or plankton "counts" from ship-towed particle filtering devices. Although such measurements are critically important in extending inferences of plankton abundance back to the early 20th century[4], it has proved challenging to "upscale" the collection of such measurements onto ocean-basin- or global-scales. Accordingly, prior suggestions of a long-term 20th century decline in phytoplankton across most ocean basins, as inferred from ship-based measurements, have remained a point of contention amongst scientists. In particular, detractors point out that phytoplankton concentrations can vary dramatically (factor 100 or more) over short (~kilometer) spatial scales, such that any given (point-specific) ship-derived measurement is fundamentally unlikely to capture broader-scale trends. Therein, global-planktonic biomass turnover time averages less than a week – much faster than the speed at which a slow-moving ship can traverse and sample an ocean basin.

What did this study find?

This study used ice cores to sidestep several of the deficiencies underlying ship-based measurements to reconstruct past productivity across the northern ("subarctic") Atlantic Ocean, one of the most biologically-productive ocean basins in the world. Specifically, by using high-precision chemical measurements conducted across an array of twelve Greenlandic ice core records, we identified a unique and coherent signal of planktonic-derived biological-aerosol. This ice core signal allowed us to develop the first near-continuous and spatially-integrated "proxy" record of northern Atlantic marine productivity over the last two and a half centuries. Indeed, our results strongly support a prior assessment based on sparse ship-derived data suggesting 20th century declines in Atlantic Ocean phytoplankton[3] and further reveal this decline to be part of a much longer, multicentury trend. In addition, our work provides the following major findings:

1. subarctic Atlantic marine productivity has declined significantly over the industrial-era, by as much as 10 ± 7%;
2. the onset of declining productivity occurred in the early 19th century, coinciding with the onset of regional Arctic surface warming, and also strongly covaries with regional sea surface temperatures and basin-scale gyre circulation strength;
3. there exists significant decadal- to centennial-scale correlation between northern Atlantic productivity variability and declining Atlantic Meridional Overturning Circulation (AMOC) strength, as predicted by a prior modeling study;
4. given finding 3., we speculate that continued atmospheric warming (predicted to contribute to accelerating Greenland Ice Sheet runoff, Atlantic Ocean-surface freshening, stratification, and continued AMOC slowdown) may result in future productivity declines across this globally-relevant region, with important implications for future carbon dioxide drawdown and global fisheries stocks.

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[3] Broadly, NPP estimates the amount of carbon that is passed up the food chain to higher trophic levels. It is defined as the rate of photosynthetically-produced bioavailable-carbon production minus the rate of carbon respiration by autotrophic (energy producing) planktonic communities.

[4] Boyce, D. G., Lewis, M. R. & Worm, B. Global phytoplankton decline over the past century. *Nature* 466, 591–596 (2010). https://www.nature.com/articles/nature09268

How does our ice core productivity "proxy" work?
The productivity proxy our study used is an organic compound known as methanesulfonic acid, or "MSA". MSA can be measured at trace concentrations (i.e., parts per billion by mass) in cylindrical cores of polar ice (i.e, an "ice core") drilled from the surface of an ice sheet. At high latitudes, MSA is *solely* produced as an oxidative byproduct from oceanic dimethylsulfide (DMS) emissions. DMS, in turn, is linked to naturally-occurring planktonic life-cycle processes[5]. Importantly, because MSA is solely produced from DMS-producing plankton, we know that any MSA measured in an ice core must have its initial source from a planktonic bloom. Because of its potential climatic importance, independent researchers have sought to measure the concentration and emissions rate of DMS across global oceans since the early 1970's. Using this data, which has been compiled and publically archived by the National Oceanic and Atmospheric Administration[6], we were able to show that in the subarctic Atlantic Ocean DMS production and emissions strongly correlate with satellite and ship-derived ocean color and planktonic abundance measurements. This suggests that the magnitude of DMS emissions from this region also serve as an indicator of phytoplankton abundance, such that a greater amount of productivity in a given year will have correspondingly greater emissions of DMS from the ocean, and hence greater atmospheric MSA formation. Independently, by modeling the atmospheric circulation patterns that bring MSA to our Greenland ice core sites, we found the most likely source region to be the subarctic Atlantic. Thus, our analyses suggest that the amount, or concentration, of MSA deposited atop the Greenland Ice Sheet and archived within annual layers of snowfall back in time provide a strong indicator of changes in past productivity.

How does this advance our understanding of how ocean phytoplankton respond to climate?
Satellite-derived inferences of planktonic abundance and productivity – the current "gold standard" – extend back only about two decades. Ship-based measurements, which can extend this limited timescale, become exceedingly sparse by the mid-20th century. Our ice core based productivity index extends these ship and satellite records by factors of ~5 and 12, respectively. Further, while a limited number of studies to date have previously attempted to use ocean-derived proxies (e.g., coralline algae, sea-floor sediments) to infer productivity at single locations in the ocean, our ice core-derived productivity index represents the first basin-scale, annual-resolution reconstruction spanning the pre- to post-Industrial Era (c. mid-19th century) transition. Our productivity index thus allows us to explore climatic and non-climatic (e.g., anthropogenic) influences on productivity across a much broader range of time and spatial scales than previously possible. This is especially useful, given we know that the northern Atlantic region has undergone numerous climatic perturbations during the Industrial Era outside the range of "naturally forced" variability. This has been manifested through widespread surface warming, AMOC slowdown, sea ice decline, and accelerating Greenland Ice Sheet (GrIS) meltwater runoff. Our study suggests a particularly close correspondence between productivity and ocean circulation across multiple

[5] The processes leading to the production, transport, and deposition of MSA onto an ice sheet are complex. The process begins (typically) with a compound known as dimethylsulfoniopropionate, or DMSP, which is produced by certain marine phytoplankton assemblages (dinoflagellates, coccolithophores, and, to a lesser extent, diatoms, chrysophytes, and prasinophytes) and used as an osmotic regulator. Planktonic life cycle processes ultimately release DMSP to the water column, whereupon fast-acting bacterial-mediated breakdown of the compound promotes the formation of dimethylsulfide, or DMS, a gas. Once freed to the atmosphere, DMS is rapidly oxidized (broken down), branching to form either sulfate aerosol or, to a lesser extent, MSA. Importantly, unlike sulfate, DMS production appears to be the exclusive source of MSA.
[6] https://saga.pmel.noaa.gov/dms/

decades to centuries, underscoring relationships that have previously been strongly predicted by models but so far unconfirmed from observations.

What is the exact linkage between AMOC and subarctic Atlantic productivity?
By just measuring the chemical end product of marine productivity (i.e., MSA) in polar ice, our study is not able to discriminate the *exact* underlying causal mechanism(s) linking AMOC to productivity. Based on the mechanisms offered by prior modeling studies[7] which our observations corroborate, we can, however, offer the following hypotheses. That is, given a decline in AMOC:

1. a steady shoaling of subarctic Atlantic mixed layer depth *could* limit the wintertime exchange of nutrients from intermediate ocean depths to surface waters, thus progressively depleting the upper-ocean nutrient supply needed for productivity during the spring/summer; meanwhile,
2. a progressive and anomalous cooling of subarctic Atlantic surface waters – driven by a decreased northward transport of warm, equatorial waters from the south – may decrease the ambient thermal energy available to drive productivity.

How will ocean productivity change in the future?
That **is** the big question! While our study cannot predict the future, our study **does** provide previously-unprecedented high-resolution temporal context for climatic drivers of subarctic Atlantic productivity, and highlights the sensitivity of marine-based autotrophic ecosystems to climate. Our analysis suggests a marked decline in productivity (~10 ± 7%) has ensued over the Industrial-era, coincident with greenhouse-gas induced surface temperature increases. In response to this warming, models and observations alike suggest a nonlinear response in Greenland Ice Sheet melt and runoff, which in turn will perpetuate subarctic Atlantic freshening, mixed layer depth shoaling, and AMOC slowdown over the coming decades to centuries. Thus, we *speculate* that declining subarctic Atlantic productivity will continue to characterize the coming decades **if** humans continue down the path of unabated greenhouse gas emissions. This will in turn have important implications on future atmospheric carbon drawdown and northern Atlantic fisheries.

[7] Schmittner, A. Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation. *Nature* 434, 628–633 (2005). https://www.nature.com/articles/nature03476