Enhanced Arctic Amplification Began at the Mid-Brunhes Event ~400,000 years ago

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Online Content: Methods, Extended Data and Appendix.

Methods
Seven piston and gravity cores from the Northwind Ridge and Mendeleev Ridge in the Arctic Ocean (water depths 700-1470 meters) were used to extend the 50 kyr record from Cronin et al. (ref 6), which was based on 31 short box and multicores, back to 1.5 Ma. (Fig. 1). Chronology combined radiocarbon dating10, bio- and lithostratigraphy13,31,32, and orbital tuning9 (Figure S1)

Adult ostracode shells were picked using fine brushes from the >150μm dry fraction and assigned VPI values. Three species of Krithe inhabit the Arctic: K. hunti (formerly called K. glacialis33,34), which is the most common species in the last 400 kyr, K. minima, and K. aquilonia, which inhabits the pre-Brunhes interval32. Prior to Mg/Ca analysis, adult specimens of Krithe were soaked in ~5% NaOCl for 16-24 h to oxidize organic matter and remove adhering particles. Shells were triple-rinsed in deionized water, inspected under a light microscope for the remaining adhering particles, and twice more rinsed with deionized water under light sonication. Shells were then dissolved in 3-30mL of 0.05N nitric acid and the resulting aqueous solution analyzed for Mg, Sr, and Ca on a Fisons Instruments Spectraspan 7 direct current plasma atomic emission spectrometer (DCP) at Duke University using ultra-pure plasma-grade SPEX standard solutions. Analytical precision is approximately 2% based on replicate analysis of samples and standards.

Extended Data
Ostracode shell chemistry and paleothermometry
Previous studies indicate that Krithe shell Mg/Ca ratios are predominantly controlled by water temperature at the time of shell growth and that post-depositional diagenetic factors such as dissolution, have negligible impact on original shell Mg/Ca ratios\textsuperscript{35,36,37,38,11}. Carbonate ion effects, which are thought to influence deep-sea benthic foraminifera Mg/Ca ratios\textsuperscript{37,38}, do not appear to influence Krithe Mg/Ca, especially in Arctic Ocean sediments\textsuperscript{11}. Finally, although dissolution can affect ostracode shells, dissolution has negligible impact on ostracode Mg/Ca ratios\textsuperscript{38}, but we nevertheless assess dissolution using a visual inspection index (VPI) that quantifies preservation state using VPI values of 1 [clear, translucent, pristine] to 7 [partially dissolved, chalky]. In our reconstruction we use well-preserved specimens (VPI – 1-5) that additionally show no signs of secondary calcite.

The Mg/Ca-temperature relationship for the main Arctic species of Krithe, K. hunti, is based on Arctic-Nordic Sea coretop material from 50 sites (50 to 3500m water depth, temperatures from -1.6° to 1°C) and is expressed in the equation BWT (°C) = (0.438 x Mg/Ca\textsubscript{Krithe}) – 5.14 (r\textsuperscript{2} = 0.5). This calibration has a 1σ prediction error of ±1.0°C and a temperature sensitivity is ~2.3 mmol mol\textsuperscript{-1} °C\textsuperscript{-1} \textsuperscript{6,11}. This sensitivity is nearly double that of Krithe species from the North Atlantic (temperature range of 2° to 14°C)\textsuperscript{37} but similar to that from Coral Sea Krithe Mg/Ca (temperatures 2° to 6°C). We point out one caveat that some Mg/Ca values fall outside the calibration range (up to 13 mmol/mol), so there is additional uncertainty with the actual BWTs they represent. Krithe minima is used in some Mg/Ca paleothermometry in the Arctic with a species vital effect correction based on consistent offset\textsuperscript{11}. Although no modern calibration is available for the other Arctic species K. aquilonia, paired samples of K. hunti and K. aquilonia in the pre-Brunhes sediments from core P23 show indistinguishable Mg/Ca ratios for the two species.

In addition to temperature, we considered other potential factors that may have influenced Mg/Ca variability at the MBE. Although coretop Arctic Krithe Mg/Ca values show no carbonate ion sensitivity\textsuperscript{11}, we cannot totally rule out some effect
given the apparent magnitude of the biogeochemical changes in the Arctic Ocean across the MBE transition, as well as those over orbital and suborbital timescales. However, we note that our Mg/Ca results are inconsistent with the direction of a carbonate ion effect. If the Mg/Ca increase after the MBE were due to carbonate ion instead of temperature, this would require that AIW became enriched in carbonate ion after the MBE, and should be reflected in enhanced CaCO₃ preservation in both the Arctic and Nordic Seas. Though available records are limited, CaCO₃ preservation in the Nordic Seas does not support a preservation spike around the MBE⁴¹.

Another possibility is that there was at certain times higher seawater Mg in the Arctic Ocean due to land-sea transport of dolomite, although it is difficult to imagine how this would affect bottom water dissolved ion chemistry, ostracode shell secretion, and the chemistry of molting fluids. This scenario is implausible for numerous reasons, including: (1) Ostracode Mg/Ca peaks in the record (TME’s), including pre- and post-peak lower Mg/Ca values, occur stratigraphically outside dolomitic IRD layers, which are used as stratigraphic markers in the Arctic Ocean; (2) Dolomite is less soluble than calcite; thus water corrosive enough to dissolve dolomite and release Mg would likely dissolve all calcitic ostracode shells leaving sediment barren of ostracode shells; (3) Dissolution of dolomite would release Mg and Ca in 1:1 proportion thereby decreasing the seawater Mg/Ca ratio (~5:1), which in turn should actually lead to lower Mg/Ca ratios in ostracode shells, not higher.

**Ostracode ecology and indicator species**

Two indicator ostracode groups are used to reconstruct Arctic Ocean sea ice and productivity. The species *Acetabulastoma arcticum* has been used as a sea-ice proxy because it is a parasitic species living in the epipelagic, sea-ice dwelling amphipod *Gammarus* and its shells are commonly preserved in Arctic sediments⁴². The benthic genus *Polycope*, an opportunistic group that signifies high local surface ocean productivity⁴¹, often reaches 80% of total assemblages in late Quaternary
sediments\textsuperscript{10}. Prior study of \textit{A. arcticum} and \textit{Polycope} from many box and multicores shows large variability related to surface sea ice and productivity throughout most of the central Arctic\textsuperscript{10}. These two ostracode taxa were studied in core HLY0503-6 from the Mendeleev Ridge indicating a sharp increase in both sea-ice and local productivity proxies between 400 and 350 ka\textsuperscript{15, 32}. The near absence of \textit{Polycope} spp. and associated species in pre-MBE sediments likely reflects its migration into the Arctic Ocean only when appropriate habitat, with local and pulsed surface productivity providing surface-to-bottom food for opportunistic genus. In addition, the sustained lack of summer sea ice and competition with a more diverse benthic ostracode fauna were likely factors influencing the pre-MBE benthic assemblages\textsuperscript{32}. A major environmental change near the MBE is also indicated by benthic foraminiferal assemblages\textsuperscript{13}.

**Revisionist views on Arctic Ice Cover during Glacials**

There is growing evidence that the Arctic Ocean was at least partially covered with thick ice shelves up to 1-km thick and thicker-than-modern sea-ice cover during recent glacial periods. Evidence comes from geophysical and sediment records from the Hovgaard Ridge–Arctic Ocean\textsuperscript{44}, the Chukchi Borderland (including the Northwind Ridge and Chukchi Plateau\textsuperscript{45, 46, 47}, the Beaufort Sea\textsuperscript{48} and East Siberian Sea\textsuperscript{49} margins, the Lomonosov Ridge, the Arlis Plateau and the slope off the Herald Canyon, E. Siberian Sea\textsuperscript{50, 51, 7}. Age estimates vary but include the last few major glacial maxima including MIS 2, 4, and 6. Laurentide Ice Sheet ice streams also exhibited complex behavior during periods of deglaciation\textsuperscript{52}, which may have contributed to large ice discharges during Heinrich Events.

**Continuous Mid-Brunhes Records**

Previously published continuous records across the MBE include deep-sea temperature\textsuperscript{53}, ice volume derived from deep-sea $\delta^{18}$O\textsuperscript{17}, sea level\textsuperscript{54}, global sea-surface temperature\textsuperscript{55}, atmospheric CO$_2$\textsuperscript{22, 56}, and East Asian Monsoon strength\textsuperscript{57}. They generally show gradual, progressive change in the pattern of glacial-interglacial cycles with increasing amplitude over the last 5 cycles.
Caption. Figure S1. Age-depth plots for Arctic cores used in paleothermometry. An age model for each core was developed using tiepoints for segments of the core from reference # 9 (Marzen et al. 2016). All cores used $^{14}$C dates for the first age tie point, except P21, which has no $^{14}$C dates. Estimates of glacial terminations determined by ostracode and foraminiferal density and local stratigraphic markers tuned to the deep-sea oxygen isotope stratigraphy (reference # 17, Lisiecki and Raymo 2005) were used for other tie points. Age models for HLY-6 and P23 back to 900 ka were taken from reference # 15 (Cronin et al. 2010) and reference # 13 (Polyak et al. 2013), ages older than 900 ka in P23 were extrapolated from the age model of Polyak et al. (2013) and are considered preliminary.

Table S1

| Core | $B. aculeata$ zone mid-depth (cm) | $T. egelida$ zone mid-depth (cm) | pink white layer 1 mid-depth (cm) | pink white layer 2 mid-depth (cm) |
|------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| P9   | 163.25-181.75                    | 413.75-427.25                    | N/A                              | N/A                              |
| P40  | 86.5-114                         | 342.5-403                       | N/A                              | N/A                              |
| P39  | 105.5-119.5                      | 288.5-332                       | 210.5                            | 145.5                            |
| P30  | 140-186                          | 586-624                         | 164                              | 418                              |
| P21  | 34.5-55.5                        | 204.5-224.5                     | 179.5                            | 103                              |

Table S1 Caption

The following tie points were used to correlate among the cores and develop age models

- MIS 1- RC
- MIS5a- *Bulimina aculeata* benthic foraminiferal zone
• MIS 11- *Turborotalia egelida* planктic foraminiferal zone
• MIS 8--7- pink white layer 1 (when applicable)
• MIS 5 (early) - pink white layer 2 (when applicable)

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