METHODS

BERYLLIUM SAMPLE PREPARATION AND PURIFICATION

A total of 84 samples and 10 procedure blanks were prepared at the Alfred Wegener Institute, in Bremerhaven (Germany). The samples were collected from the same sediment cores as those used in Geibert et al. (2021). More specifically, identical sample splits were used for cores PS87/030-1, PS72/396-5, and PS51/038-4. For the remaining cores, samples were taken manually and do not represent aliquots of the material previously used for Geibert et al. (2021)'s $^{230}Th_{xs}$ analyses. All sediment samples were freeze-dried, manually softly ground to disaggregate and homogenize prior to leaching (sample list in Suppl. 1). About 1.5 g of sediment underwent a two-step leaching process. First, carbonates were removed using 1 M NaOAc and 1 M AcOH (52:48) at room temperature for 2 hours. The residue was then leached to extract the Fe-Mn phase [1], the main authigenic Be host [2], omitting the exchangeable fraction, as this was shown to not contain significant quantities of Be [3]. This step used 0.04 M NH_2OH-HCl in 15% AcOH, buffered to pH 4 with NH_3, for 24 hours at room temperature. The supernatant was oxidized with HCl, HNO_3, and H_2O_2, then evaporated. The leachate was re-dissolved in HNO_3 and split: one aliquot for ICP-OES total Be measurement, the other for ^{10}Be analysis. The ^{10}Be fraction was spiked with 0.5 mL of a ^{9}Be carrier (1000 mg/L, LGC 998969–73, $^{10}Be/^{9}Be = (3.74 \pm 0.30) \times 10^{-15}$ – value determined at the DREAMS facility - Helmholtz-Zentrum Dresden-Rossendorf. ^{10}Be purification followed the precipitation protocol of Loftfield et al. (2024) [4] for AMS measurements. After purification, samples were dried, calcined to BeO, mixed with Niobium powder, and pressed into copper-cathodes. ^{9}Be OES measurements at AWI also followed Loftfield et al. (2024), with ^{9}Be concentrations calculated via standard addition [5]. ^{10}Be was measured at the DREAMS facility [6,7]. Data were normalized relative to the "SMD-Be-12" standard, with a weighted mean of $(1.704 \pm 0.030) \times 10^{-12}$ [8]. Results and associated uncertainties are shown in Supplements 1.

RADIOISOTOPE MEASUREMENTS AND $^{230}TH_{XS}$ CALCULATION

The analytical work was carried out at the Alfred Wegener Institute in Bremerhaven (Germany), following procedures comparable to those described by Geibert et al., (2019, 2021). A total of 35 sediment samples from core GIK23065-3 were freeze-dried and homogenized into a fine powder. Approximately 75 mg of each sample was weighed and combined with isotopic tracers (^{236}U and ^{229}Th) and a mixture of acids (HNO_3, HCl, and HF). Complete digestion was achieved using a microwave digestion system (Mars Xpress, CEM). Each analytical batch consisted of 24 positions, including two procedural blanks spiked with isotopic tracers, as well as two certified reference materials: one radionuclide reference material (IAEA-385 from the Irish Sea) [11] and one reference material for elemental composition (MESS-4). Following digestion, the solutions were evaporated using a CEM MARS XpressVap system and subsequently re-dissolved in nitric acid via microwave treatment. Final solutions were diluted to a total volume of 20 ml. Aliquots were then taken for elemental analysis by ICP-OES and ICP-MS, following Geibert et al. (2019). The fraction designated for radionuclide analysis underwent additional chemical separation to isolate thorium and uranium using an ESI PrepFAST system equipped with TRU resin. The separated fractions were evaporated to near dryness and re-dissolved in 1 M HNO_3 prior to measurement. Radionuclide concentrations were determined using an ICP-MS (Thermo Scientific Element2 with Jet interface). Acid blanks and standards containing uranium with natural isotopic composition were included in each analytical run to monitor instrumental background and mass bias. Concentrations of ^{238}U were derived from measured ^{235}U assuming a natural isotopic ratio of 137.88. Results and subsequent recoveries obtained for the reference materials are provided in Supplement 2. For elemental analyses (e.g., S and Mn presented in Extended Data Figure 4), a separate aliquot from the same digestion solution was diluted (1:3) and analyzed using a dual-view ICP-OES system (Thermo iCAP), with yttrium used as an internal standard.

Excess ^{230}Th ($^{230}Th_{xs}$) was calculated following the methodology outlined in Geibert et al. (2019). This approach involves subtracting the supported ^{230}Th component ($^{230}Th_{supp}$) from the sediment, from the total measured ^{230}Th to isolate the water-column-derived fraction. The supported component was estimated based on the activity of ^{234}U. Elevated authigenic uranium concentrations were observed in the deeper section of the core (474.5 - 504.5 cm). However, this interval lies below the depth range of primary interest for this study (~300 cm). Therefore, no additional correction to the calculated $^{230}Th_{xs}$ values was applied.

BERYLLIUM MASS-BALANCE

To quantify the relative contributions of different water masses and atmospheric inputs to the Arctic Ocean's $^{10}Be/^{9}Be$ ratio, we applied a steady-state mass-balance model under a modern setting. The objective was to estimate the resulting $^{10}Be/^{9}Be$ ratio of the Arctic Ocean as a function of the end-member contributions.

The dissolved ^{10}Be and ^{9}Be concentrations of the different endmembers were compiled from Frank et al. (2009) for the major inflows (North Atlantic and Pacific) and for the main Arctic rivers (Ob, Yenisei, Lena, and Mackenzie). Atmospheric ^{10}Be deposition was estimated from GEOS-Chem simulations [12], averaged for 2005 - 2013 and covering latitudes from 77°N (Fram Strait) to the North Pole, yielding a ^{10}Be flux of 8.43×10^{14} atoms per second. To estimate atmospheric ^{9}Be deposition, we adopted the $^{10}Be/^{9}Be$ ratio of 4×10^{-7} reported for marine rain over the North Pacific [13], resulting in a global ^{9}Be flux of approximately 2.11×10^{21} atoms per second. The true ^{9}Be flux is probably somewhat larger, as the marine rain samples were filtered after collection – removing particulate dust.

Water fluxes from each source were calculated as:

$$Flux(Be) = Flux_{water} \times [Be]$$

where $Flux_{water}$ is the volume flux (m^3/s), [Be] stands for the isotope concentration (See Extended Data Table 1). The basin-wide $^{10}Be/^{9}Be$ ratio was then obtained by dividing the sum of ^{10}Be fluxes by the sum of ^{9}Be fluxes.

Modern water volume fluxes were adopted from Aksenov et al. (2010) and Holmes et al. (2002):
- Rivers: Ob (1.28×10^4 m^3/s), Yenisei (1.97×10^4 m^3/s), Lena (1.68×10^4 m^3/s), and Mackenzie (9.73×10^3 m^3/s).
- North Atlantic inflow: 2.1 Sv through Fram Strait and 1.7 Sv through the Barents Sea, consistent with literature estimates though uncertain due to recirculation via the East Greenland Current (EGC).
- Pacific inflow: 1 Sv through Bering Strait.

References:

1. Bourlès, D., Raisbeck, G. M. & Yiou, F. ^{10}Be and ^{9}Be in marine sediments and their potential for dating. *Geochim. Cosmochim. Acta* **53**, 443–452 (1989).

2. Gutjahr, M. *et al.* Reliable extraction of a deepwater trace metal isotope signal from Fe-Mn oxyhydroxide coatings of marine sediments. *Chem. Geol.* **242**, 351–370 (2007).

3. Loftfield, J., Lachner, J., Malter, M., Stübner, K. & Adolphi, F. A simple method of purifying authigenic ^{10}Be from sediments for AMS-analysis. *Nucl. Instrum. Methods Phys. Res. B* **547**, (2024).

4. Lachner, J. *et al.* Optimization of ^{10}Be measurements at the 6 MV AMS facility DREAMS. *Nucl. Instrum. Methods Phys. Res. B* **535**, 29–33 (2023).

5. Rugel, G. *et al.* The first four years of the AMS-facility DREAMS: Status and developments for more accurate radionuclide data. *Nucl. Instrum. Methods Phys. Res. B* **370**, 94–100 (2016).

6. Akhmadaliev, S., Heller, R., Hanf, D., Rugel, G. & Merchel, S. The new 6 MV AMS-facility DREAMS at Dresden. *Nucl. Instrum. Methods Phys. Res. B* **294**, 5–10 (2013).

7. Geibert, W., Matthiessen, J., Stimac, I., Wollenburg, J. & Stein, R. Glacial episodes of a freshwater Arctic Ocean covered by a thick ice shelf. *Nature* **590**, 97–102 (2021).

8. Geibert, W., Stimac, I., Rutgers van der Loeff, M. M. & Kuhn, G. Dating Deep-Sea Sediments With ^{230}Th Excess Using a Constant Rate of Supply Model. *Paleoceanogr. Paleoclimatol.* **34**, 1895–1912 (2019).

9. Zheng, M. *et al.* Modeling Atmospheric Transport of Cosmogenic Radionuclide ^{10}Be Using GEOS-Chem 14.1.1 and ECHAM6.3-HAM2.3: Implications for Solar and Geomagnetic Reconstructions. *Geophys. Res. Lett.* **51**, (2024).

10. Xu, X. *Geochemical Studies of Beryllium Isotopes in Marine and Continental Natural Water Systems*. (University of Southern California, 1994).

11. Aksenov, Y., Bacon, S., Coward, A. C. & Nurser, A. J. G. The North Atlantic inflow to the Arctic Ocean: High-resolution model study. *Journal of Marine Systems* **79**, 1–22 (2010).

12. Holmes, R. M. *et al.* A circumpolar perspective on fluvial sediment flux to the Arctic Ocean. *Global Biogeochem. Cycles* **16**, 41–45 (2002).