


Reply to ‘Challenging the hypothesis of an arctic ocean lake during recent glacial episodes’ by Hillaire-Marcel, *et al*

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ABSTRACT: Hillaire-Marcel *et al.* bring forward several physical and geochemical arguments against our finding of an Arctic glaciolacustrine system in the past. In brief, we find that a physical approach to further test our hypothesis should additionally consider the actual bathymetry of the Greenland–Scotland Ridge (GSR), the density maximum of freshwater at 3–4°C, the sensible heat flux from rivers, and the actual volumes that are being mixed and advected. Their geochemical considerations acknowledge our original argument, but they also add a number of assumptions that are neither required to explain the observations, nor do they correspond to the lithology of the sediments. Rather than being additive in nature, their arguments of high particle flux, low particle flux, export of ²³⁰Th and accumulation of ²³⁰Th, are mutually exclusive. We first address the arguments above, before commenting on some misunderstandings of our original claim in their contribution, especially regarding our dating approach.

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The physical viewpoint

We include here a complete map of the Greenland–Scotland Ridge (GSR, Fig. 1), based on modern bathymetry. It shows that the majority of the GSR is shallower than 500 m (ca. 400–420 m in peak glacials). Only small parts of the Denmark Strait, the Iceland–Faroe Gap and Faroe Bank Channel are deeper than 500 m, up to approximately 750 m (ca. 650–670 m in peak glacials). Consequently, it is not necessary to cover the entire GSR with an 800 m ice shelf to restrict saline water inflow; already icebergs of more than 450 m thickness had to strand on the GSR. Once a couple of larger icebergs also block the Faroe Bank Channel and the Faroe–Shetland Channel, the GSR is blocked almost entirely. There is evidence for sufficiently thick grounded ice in the Nordic Seas (NS): iceberg scourmarks of 800 m and more are known from both north (Blischke *et al.*, 2019) and south (Kuijpers and Werner, 2007) of the GSR (Fig. 1), which is no surprise because the Greenland, Iceland and the Scandinavian ice sheets were calving into the NS, presumably creating an iceberg armada retained by the sill, immobilised by falling sea levels, and waiting for sea-level rise, their slow melting, or a salinity increase that modified iceberg freeboard, for their release.

Hillaire-Marcel *et al.* state that it was necessary to block all inflow of saline water at the GSR to turn the Arctic Ocean (AO) and NS fresh. We would think that it is simply necessary that more salt is exported than imported over a prolonged period. If saline water entering the NS at the GSR is diluted by the freshwater leaving the system, as commonly seen in fjords with a series of sills (Edwards and Edelman, 1977), no fully saline water is available to replenish NS waters and the AO. Stärz *et al.* (2017), found that already free depths of around 50 m across the entire width of the GSR lead to a freshening of the AO, when other gateways are closed, although in much warmer periods.

We also disagree with the statement that there is no evidence of non-marine periods in the NS, as there are carbonate-free, ²³⁰Th_{ex}-free intervals at least for MIS6 documented throughout the NS (Geibert *et al.*, 2022). The occurrence of foraminifera and consequently reliable $\delta^{18}\text{O}$ signals in the NS is discontinuous.

Regarding the removal of salt from the AO, we do not debate the correctness of the calculations of Hillaire-Marcel *et al.* for a saline, remote ocean, but we consider them to be incomplete for an almost enclosed system consisting of thick meteoric ice, freshwater and (initially) saline water, fed by rivers and glaciers. We start our consideration regarding the removal of salt from the AO at Fram Strait. When Fram Strait was blocked at the surface by ice of a certain thickness during glacial sea-level lowstands, freshwater from the East Siberian rivers had to accumulate in the AO, filling it from the surface down to the depth of the ice barrier, be it 100 or 1000 m. Arndt *et al.* (2014) report iceberg scourmarks down to 1200 m just south of Fram Strait. A surface ice barrier here would lead to an initial (glacio) lacustrine circulation in an upper part of the AO by simple replacement of seawater, with no mixing required.

Once a surface freshwater layer is in place, a different mechanism comes into play, which has been overlooked by Hillaire-Marcel *et al.*: lakes have a fundamentally different circulation from marine systems because freshwater is densest at 4°C (at atmospheric pressure), not at the temperature minimum. In temperate and polar freshwater systems this is known to cause seasonal vertical turnover events, with a collapsing stratification when water warmer than 4°C is cooled. In very deep lake systems like Lake Baikal (1642 m depth), water density peaks around 3.2°C at depth, due to pressure effects. There, already subtle differences in particulate or dissolved solids, even variations in Si(OH)₄, lead to riverine inputs reaching depths >1000 m within weeks (Hohmann *et al.*, 1997). Therefore, river discharge, once cooled to 3–4°C by melting ice, will inject freshwater and sensible heat at the bottom of a colder freshwater column. For comparison, just

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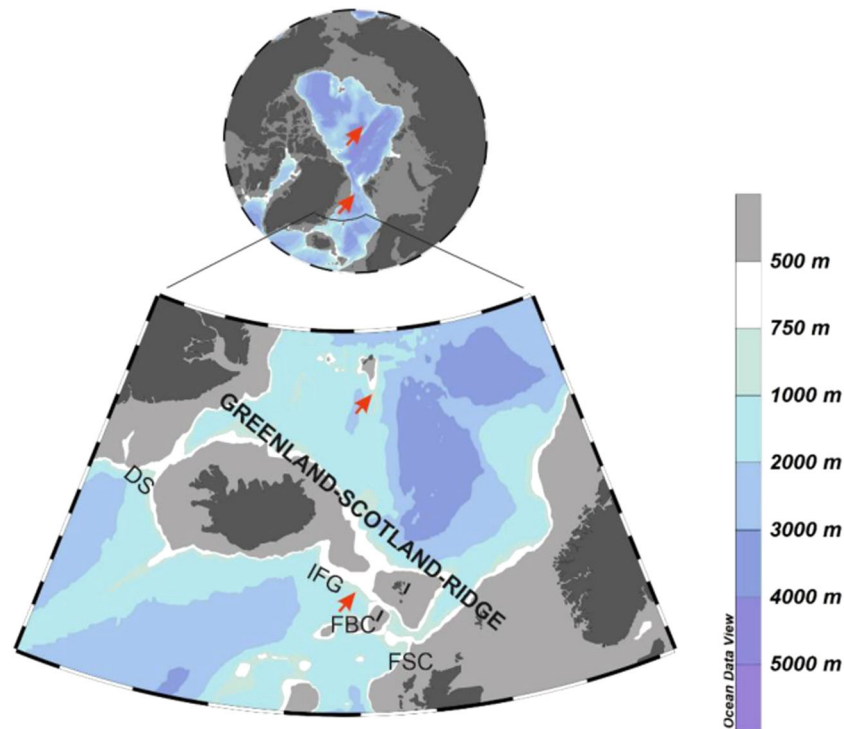


Figure 1. The (modern) Arctic Ocean and Nordic Seas in Polar map projection for orientation (top), and the Greenland–Scotland Ridge, with shallow depths highlighted in grey (bottom). DS: Denmark Strait; FBC: Faroe Bank Channel; FSC: Faroe–Shetland Channel; IFG: Iceland–Faroe Gap. Areas depicted in grey could not be passed by icebergs of >470 m total thickness, areas in white were blocked by any ice thicker than 720 m. Ice sheets from Greenland, Iceland and Scandinavia calved into this region. Red arrows indicate examples of deep iceberg scourmarks (800–1200 m water depth) or ice shelf traces (Lomonossov Ridge, close to 1000 m) [Color figure can be viewed at wileyonlinelibrary.com].

Yukon and McKenzie today, both in catchment areas with average annual air temperatures below 0°C and mostly permafrost, deliver peak discharge around 15–17°C, together supplying >5.3 PWh (Petawatt hours) per year to the AO (Yang *et al.*, 2014). East Siberian rivers have similar peak temperatures (Lammers *et al.*, 2007). The AO is therefore not a closed system with respect to energy, especially if one allows—in good agreement with our previous conservative estimate—an annual liquid freshwater input of 2700 km³ per year.

Assuming very conservatively that the rivers delivered (on average) water with a temperature difference of 4°C compared with dense saline waters to depth, we already calculate more than 12 PWh energy as sensible heat that is annually introduced to the system. This equates to >1379 GW, as compared with the 25 GW Hillaire-Marcel *et al.* allow for tidal mixing. Freshwater of 3–4°C must have been delivered quickly to depth, protected from further energy loss to the atmosphere, then flowing or accumulating along the deep freshwater/seawater boundary. This aspect stands in contrast to Hillaire-Marcel's statement, 'After isolation of the AO&NS basins, freshwater water input, which would necessarily be near the water column surface, would result in even more stratified water masses, ...'.

Upon contact with colder seawater, the densest freshwater would expand and, counter-intuitively, rise when cooled, unless salinity is entrained, creating an efficient energy and salt transfer at the boundary, accompanied by mixing. It is also worth noting that if deep mixing happens at any site within the AO to great depth, most likely at the ocean margin, baroclinic exchange will supply salt laterally from the central parts. It is therefore not only the mixing in the centre that controls the events, but the mixing and advection at the boundaries.

Furthermore, a glaciolacustrine system, in contrast to a lake, is constrained by rough topography not just at its bottom, but also at the upper boundary of the liquid water phase, with

strong currents evolving along glacier fronts, episodic surges of water masses from below the glacier and strong tidal currents (Makinson and Nicholls, 1999). The situation only gets more complex when estuarine aspects, as present here, are to be considered as well. A further simplification of their model concerns the volumes mixed during freshening. Most of the fresh upper water column will not interact with the saline layer below, making the incremental full water column mixing an unsuitable mathematical approach. In addition, advective transport would need to be taken into account for this system with a directed flow.

For all the reasons outlined above, we believe that transferring diapycnal mixing values from the deep open ocean with smooth topography to a glaciolacustrine (and partly estuarine system), surrounded by near margins, with relatively warm riverine freshwater input flowing at depth, is inappropriate. Given that the physical considerations neglect such important sources of energy and processes for the system, it is reassuring that Hillaire-Marcel *et al.* come up with estimates for mixing of the entire AO basin that are already not too far from what we proposed.

Regarding the potential sources of freshwater, the direction of the arguments is not entirely clear to us. First, the authors introduce a refined estimate of the precipitation that may reach the AO in glacials, all of which needs to be removed via the GSR: 6320 km³/year, and they give an upper limit of 2700 km³/year liquid water input (compared with 3220 km³/year today). Below, however, they indirectly also dispute significant riverine inputs – due to summer temperatures below freezing point, citing 'Kageyama *et al.*' – a statement which we find neither supported there, nor by modern river equivalents. For detailed calculations of the substantial riverine input from East Siberia and Beringia we refer to Alkama *et al.* (2006). Summer air temperatures were typically just 0–4°C lower than today in peak glacials at this latitude band (Kageyama *et al.*, 2019), as confirmed in the

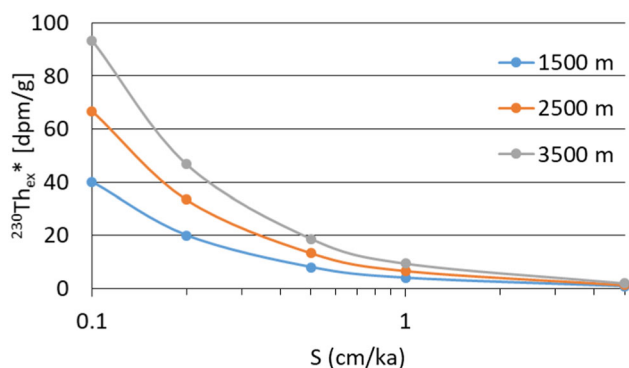


Figure 2. Modelled expected initial $^{230}\text{Th}_{\text{ex}}$ activity in sediments for selected (saline) water depths, assuming a ^{230}Th production rate of $0.0267 \text{ dpm m}^{-3} \text{ a}^{-1}$, and a dry bulk density of 1 g cm^{-3} . Maximum $^{230}\text{Th}_{\text{ex}}$ seen in the Arctic Ocean is well within the expected range and does not indicate excessive accumulation of ^{230}Th in the Arctic Ocean. The $^{230}\text{Th}_{\text{ex}}$ minima $<0.1 \text{ dpm g}^{-1}$, however, cannot be explained with dilution as they would require excessive sedimentation rates.

palaeobotanical records from Lake El'gygytyn (Melles *et al.*, 2012). Today, substantial liquid (and warm) discharge is seen even for subzero annual mean temperatures (Yang *et al.*, 2014). In addition, extensive subglacial sources need to be considered (Montelli *et al.*, 2020). Taking the total input of liquid meteoric water as described here and ice together, because both displace saline water, the mean residence time of water in the AO is around just 2000 years.

The geochemical viewpoint

Hillaire-Marcel *et al.* include in their explanations for low $^{230}\text{Th}_{\text{ex}}$, 'Under full glacial conditions with a $\sim 800 \text{ m}$ -thick ice shelf, as estimated above, possibly underlain by a low salinity layer, $^{230}\text{Th}_{\text{xs}}$ was close to nil at such sites.' This is exactly our original argument, so we find the physical plausibility of our finding in principle supported by their comment. The debate then would condense to a discussion about the possible thickness of a freshwater layer under an ice shelf in the glacial AO.

Yet, they also introduce a number of other arguments. In brief, we argued in the original publication that:

- (1) Sufficient dilution to suppress $^{230}\text{Th}_{\text{ex}}$ to nil would require much higher sedimentation rates.
- (2) Low sedimentation rates as seen in the AO are globally associated with the highest $^{230}\text{Th}_{\text{ex}}$ signals in saline systems (Yang *et al.*, 1986), even for sedimentation rates lower than in the AO.

Figure 2 illustrates the expected $^{230}\text{Th}_{\text{ex}}$ activities from production in a saline water column, for variable water depths and sedimentation rates. These values agree well with surface sediment data from the Pacific Ocean (Yang *et al.*, 1986). Hillaire-Marcel *et al.* now invoke a scenario in which both high and extremely low particle fluxes occur during low $^{230}\text{Th}_{\text{ex}}$ intervals, pulsed and regionally distributed. We consider this scenario to be inconsistent with the lithology of the $^{230}\text{Th}_{\text{ex}}$ -free intervals, which are characterised by a mixture of coarse and fine particles. Even a short particle pulse would be enough to remove ^{230}Th from the water column. Even fine particle fluxes generating sedimentation rates $<1 \text{ mm}/1000 \text{ years}$ lead to >100 -fold ^{230}Th concentrations elsewhere (Yang *et al.*, 1986). Even an absence of sedimentation – a hiatus – would not be visible as an absence of $^{230}\text{Th}_{\text{ex}}$ activities in sediment because then no sediment was deposited at all. Another possibility to lose ^{230}Th would be water export from the

AO down, limited by the sill depth of Fram Strait; or one could also build it up in the water column of the AO and remove it later by particle flux. Again, both cannot happen simultaneously as Hillaire-Marcel *et al.* suggest in their conceptual figure.

We find that Hillaire-Marcel *et al.* combined all theoretically possible explanations for reduced ^{230}Th fluxes (high particle fluxes, low particle fluxes, export from the Arctic water column, build-up in the Arctic water column, and a speculation on the role of organic compounds) into one scenario, irrespective of internal consistency. None of the proposed processes has the potential to reduce ^{230}Th to nil, as actually observed, for the observed lithology, and in total, the proposed effects are not additive, but they neutralise each other. We also point to recent studies highlighting the role of terrigenous material and hydrothermal particles for ^{230}Th scavenging in the AO (Gdaniec *et al.*, 2020, Valk *et al.*, 2018, 2019).

Misunderstandings of our study

Right in the title, Hillaire-Marcel *et al.* introduce our finding of a largely freshwater-filled AO&NS basin as the 'Arctic lake' hypothesis—a term we never used. Instead, we called it a 'glaciolacustrine system which has no modern equivalent' for good reason, as outlined above. This is not the only example of a deviation from the original description. The authors summarise our dating approach inadequately when stating, 'This [broad interpolation from $^{230}\text{Th}_{\text{ex}}$ decay] has been the approach used by Geibert and colleagues (2021)...'. In fact, we transferred the age model from core PS1533 dated by a variety of constraints (Spielhagen *et al.* (2004) and references therein) to other cores for which only radiocarbon or $^{230}\text{Th}_{\text{ex}}$ were available (Geibert *et al.*, 2021). Interpolation played no important role for our age boundaries, but correlation of similar $^{230}\text{Th}_{\text{ex}}$ profiles between cores to a well-dated core. We also took oxygen isotope curves from outside the Arctic into account. It is also worth noting that in the original paper, we had restricted the definitive occurrence of freshwater to 2500 m, the deepest cores investigated, when we noted, '...its almost complete absence, even below 2500 m water depth. This implies that the water mass underlying the ice shelf was fresh, not saline, at least to this depth.'

Conclusions

'Occam's razor' favours simple explanations over complicated ones. We need just one simple factor – the temporary absence of sea salt – to allow a synthesis of many seemingly contrasting observations from different disciplines within and outside the Arctic. The alternative scenario of Hillaire-Marcel *et al.* adds several mutually counteracting mechanisms, and it neglects evidence from within and beyond the Arctic sedimentary record. Adopting our explanation, the behaviour of thorium in the Arctic is no longer peculiar.

In summary, we therefore believe it would be premature to close the discussion about a hypothesis that can offer additional aspects to some long-standing problems of Quaternary science like the origin of Heinrich events, Dansgaard-Oeschger events, or the tipping points for rapid melting at terminations, just based on the simplified physical model of Hillaire-Marcel *et al.*

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Ethics statement

We state that questions of data availability, conflicts of interest, ethics approval, patient consent, permission to reproduce material from other sources and clinical trial registration do not apply here. Only public funding was received.

Abbreviations. ^{230}Th , thorium-230; $^{230}\text{Th}_{\text{ex}}$ (synonymous to $^{230}\text{Th}_{\text{xs}}$), excess of the radioisotope thorium-230 over its progenitor ^{234}U ; AO, Arctic Ocean; DS, Denmark Strait; FBC, Faroe Bank Channel; FSC, Faroe–Shetland Channel; GSR, Greenland–Scotland Ridge; IFG, Iceland–Faroe Gap; NS, Nordic Seas; PWh, Petawatt hours.

References

- Alkama R, Kageyama M, Ramstein G. 2006. Freshwater discharges in a simulation of the Last Glacial Maximum climate using improved river routing. *Geophysical research letters* **33**: L21709.
- Arndt JE, Niessen F, Jokat W *et al.* 2014. Deep water paleo-iceberg scouring on top of Hovgaard Ridge–Arctic Ocean. *Geophysical Research Letters* **41**: 5068–5074.
- Blischke A, Stoker MS, Brandsdóttir B *et al.* 2019. The Jan Mayen microcontinent's Cenozoic stratigraphic succession and structural evolution within the NE-Atlantic. *Marine and Petroleum Geology* **103**: 702–737.
- Edwards A, Edelsten DJ. 1977. Deep water renewal of Loch Etive: A three basin Scottish fjord. *Estuarine and Coastal Marine Science* **5**: 575–595.
- Gdaniec S, Roy-Barman M, Levier M *et al.* 2020. ^{231}Pa and ^{230}Th in the Arctic Ocean: Implications for boundary scavenging and $^{231}\text{Pa}/^{230}\text{Th}$ fractionation in the Eurasian Basin. *Chemical Geology* **532**: 119380.
- Geibert W, Matthiessen J, Stimac I *et al.* 2021. Glacial episodes of a freshwater Arctic Ocean covered by a thick ice shelf. *Nature* **590**: 97–102.
- Geibert W, Matthiessen J, Wollenburg J *et al.* 2022. Reply to: No freshwater-filled glacial Arctic Ocean. *Nature* **602**: E4–E6.
- Hohmann R, Kipfer R, Peeters F *et al.* 1997. Processes of deep-water renewal in Lake Baikal. *Limnology and Oceanography* **42**: 841–855.
- Kageyama M, Harrison SP, Kapsch ML *et al.* 2019. The PMIP4-CMIP6 Last Glacial Maximum experiments: Preliminary results and comparison with the PMIP3 simulations. *Climate of the Past Discussions*. <https://doi.org/10.5194/cp-2019-169>
- Kuijpers A, Werner F. 2007. Extremely deep-draft iceberg scouring in the glacial North Atlantic Ocean. *Geo-Marine Letters* **27**: 383–389.
- Lammers RB, Pundsack JW, Shiklomanov AI. 2007. Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass. *Journal of Geophysical Research: Biogeosciences* **112**: 1–15.
- Makinson K, Nicholls KW. 1999. Modeling tidal currents beneath Filchner-Ronne Ice Shelf and on the adjacent continental shelf: Their effect on mixing and transport. *Journal of Geophysical Research: Oceans* **104**: 13449–13465.
- Melles M, Brigham-Grette J, Minyuk PS *et al.* 2012. 2.8 million years of Arctic climate change from Lake El'gygytyn, NE Russia. *Science* **337**: 315–320.
- Montelli A, Dowdeswell JA, Pirogova A *et al.* 2020. Deep and extensive meltwater system beneath the former Eurasian Ice Sheet in the Kara Sea. *Geology* **48**: 179–183.
- Spielhagen RF, Baumann K-H, Erlenkeuser H *et al.* 2004. Arctic Ocean deep-sea record of northern Eurasian ice sheet history. *Quaternary Science Reviews* **23**: 1455–1483.
- Stärz M, Jokat W, Knorr G *et al.* 2017. Threshold in North Atlantic–Arctic Ocean circulation controlled by the subsidence of the Greenland–Scotland Ridge. *Nature Communications* **8**: 15681.
- Valk O, Rutgers van der Loeff M, Geibert W *et al.* 2018. Importance of hydrothermal vents in scavenging removal of ^{230}Th in the Nansen Basin. *Geophysical Research Letters* **45**: 10,539–10,548.
- Valk O, Rutgers van der Loeff MM, Geibert W *et al.* 2019. Circulation changes in the Amundsen Basin from 1991 to 2015 revealed from distributions of dissolved ^{230}Th . *Ocean Science Discussions*. <https://doi.org/10.5194/os-2019-49>
- Yang D, Marsh P, Ge S. 2014. Heat flux calculations for Mackenzie and Yukon Rivers. *Polar Science* **8**: 232–241.
- Yang HS, Nozaki Y, Sakai H *et al.* 1986. The distribution of ^{230}Th and ^{231}Pa in the deep-sea surface sediments of the Pacific Ocean. *Geochimica et Cosmochimica Acta* **50**: 81–89.