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Supplementary information

Reply to: No freshwater-filled glacial Arctic Ocean

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Supplementary material for the reply to Spielhagen et al.'s comment "No freshwater-filled glacial Arctic Ocean"

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Discussion of individual cores from our Fig.1

For core GIK23259, the original age models[1,2] place the clearly detectable $^{230}Th_{ex}$ minima at the end of MIS4 and MIS6, respectively, therefore fully supporting our view, in agreement with a $\delta^{18}O$-based age model by Henrich (doi:10.1594/PANGAEA.319945). Uncorrected $^{230}Th_{ex}$ data were retrieved from the Pangaea data base (doi:10.1594/PANGAEA.107737).

Core GIK23065-3 is located west of the Vøring Plateau in 2802 m depth. The available age estimates are in virtual agreement that the $^{230}Th_{ex}$ minima belong to MIS4/3 boundary and late MIS6[2]. Several studies confirmed the absence of calcium carbonate in the respective intervals [3-5], with the corresponding datasets available online, e.g. doi: 10.1594/PANGAEA.107736. These data are in line with our proposed freshwater Arctic Ocean, and the absence of carbonate in these intervals casts doubt on the availability of sufficiently preserved foraminiferal tests to base a reliable $\delta^{18}O$ constraints on them, similar to PS1535-8, discussed later.

GIK23059-3, located east of the Jan Mayen microcontinent in 2281 m depth, has very low carbonate contents for the presumed end of MIS6 too (doi:10.1594/PANGAEA.107734), but only slightly reduced contents for the presumed MIS4. The same is true for ^{230}Th in the respective intervals: MIS6 is cleary seen, MIS4 not so clearly. Planktic foraminifera $\delta^{18}O$ (doi: 10.1594/PANGAEA.89205) shows heavy and variable values in what must be MIS6, followed by very light $\delta^{18}O$ in conjunction with the re-emerging ^{230}Th. There is an anomaly for $\delta^{18}O$ in MIS4 in the documented records (doi: 10.1594/PANGAEA.89205). The change in sedimentation patterns with the onset of the last interglacial is remarkable and could point to a substantial change in seafloor topography due to glacial erosion, as documented for nearby Jan Mayen microcontinent[6]. Regarding the relatively short MIS4 freshwater interval (8 ka according to core PS1533-3[7]), we run here into the issue of bioturbation that affects sediment records from the Nordic Seas[8], especially the southern parts near Vøring Plateau, down to 25 cm. This would obscure thin layers from previous glacial periods in subsequent interglacials. Together with the integration of 10 cm slices for ^{230}Th sampling, the short MIS4 signal was probably lost by mixing of sediment of different ages.

The age correction of $^{230}Th_{ex}$ for core M17728 in the original reference[1] is based on the assumption that there is no $^{230}Th_{ex}$ below the sampled core length. This can be misleading in Arctic cores due to the strong local $^{230}Th_{ex}$ minima. An adapted slope based on the uncorrected data (doi:

10.1594/PANGAEA.107733) would suggest a somewhat younger age, bringing the core more in line with the neighbouring cores with respect to sedimentation rate, thorium inventories and its $^{230}Th_{ex}$ pattern. We note that we see again a combined low^{230}Th/low carbonate for MIS 6 (doi: 10.1594/PANGAEA.107733), but only a dip for MIS4, presumably again due to low temporal resolution and/or bioturbation.

Regarding the results from the North Atlantic[9], which Spielhagen et al. cite as an example for dilution of ^{230}Th during Heinrich events - implying this was the reason for low $^{230}Th_{ex}$ in the Arctic Ocean and in the Nordic Seas- it is noteworthy that the mentioned core V28-82 from south of the GSR shows a pattern that is inverse to the cores from north of the GSR. Heinrich event (H1-H5) associated $^{230}Th_{ex}$ minima, which are most pronounced south of the GSR, are basically not seen North of the GSR. H6, which marks the end of MIS4, is not seen south of the GSR, while $^{230}Th_{ex}$ drops to zero in two of the cores from the Nordic Seas north of the GSR, and all of the cores in the Arctic Ocean. Low $^{230}Th_{ex}$ due to dilution south of the GSR is associated with extremely thick IRD layers**.**

In summary, we disagree with the statement that the low ^{230}Th intervals are not seen in the Nordic Seas, and that dilution can be the cause. We find a MIS6 $^{230}Th_{ex}$ absence in all four cores shown in Fig. 1, and a MIS4 absence in the two cores with higher temporal resolution. We explain the missing MIS4 intervals in two cores by insufficient resolution due to bioturbation and the sampling technique that integrates over 10 cm.

Discussion of individual cores from Spielhagen et al.'s Fig. 1

Core PS1535-8 from the compilation in their figure 1 was selected as proof for the absence of an ice shelf in Fram Strait. Its δ^{18}O record as shown in Spielhagen et al.'s Figure 1 shows several spikes and a high variability around the presumed MIS4, just like GIK23352. However, a complete lack of planktic foraminifera has been documented for these extended intervals[10] (https://doi.org/10.1594/PANGAEA.713814), just like for the thoroughly studied neighbouring core PS93/006-1[11], as would be expected for coverage by an ice shelf. Nevertheless, Spielhagen et al. report planktic foraminiferal δ^{18}O for PS1535-8 as continuous. We conclude that the picked specimens must have been excessively rare, and sensitive to cross-contamination and bioturbation due to the extreme differences in abundance. Their preservation state is not documented.

For GIK23065, we encounter the same problem with the absence of carbonate in key sections of the record. It had zero carbonate recorded in MIS4 (doi:10.1594/PANGAEA.316034), and a reference from 1996 [3] consequently shows no foraminiferal carbonate δ^{18}O value for this isotope stage. In figure 2, however, there is a single δ^{18}O value for the presumed MIS4 shown. The source of this value, in particular any age constraints, remain unclear.

Additionally, we are shown core GIK23352. A related reference[12] notes in their figure captions the poor availability and high variability in (carbonate) ostracod and *C. wuellerstorfi* stable isotopes for these samples.

The uncertainty of fitting an age based on foraminifera $\delta^{18}O$ values, and consequently assigning $\delta^{18}O$ values to an age for glacial periods north of the GSR also can be underlined with a highly resolving core close to ODP644 shown in Spielhagen et al.'s Figure 2, MD95-2010[13]. For the transition from MIS6 to MIS5, this core shows a large scatter in benthic $\delta^{18}O$ during MIS6, then a brief gap in data, followed by an offset for MIS5 (see figure S1).

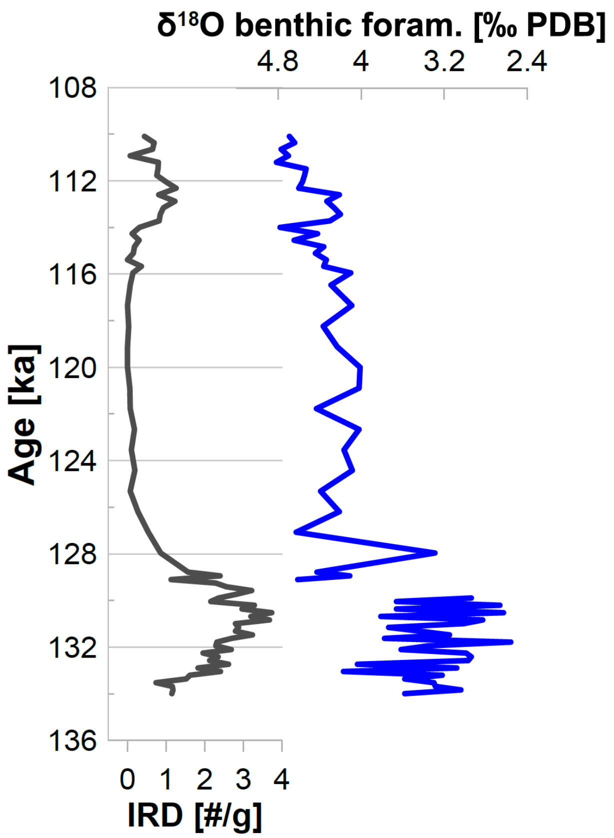

Figure S1: Ice-rafted debris (IRD) and the oxygen isotope composition of benthic foraminifera from core MD95-2010 [13] (near ODP 644) at the MIS6/5 transition.

The (un)suitability of *N. pachyderma* stable oxygen isotopes to detect a thick freshwater lens

We note that the largest part of the huge volume of freshwater bound in Northern Hemisphere ice sheets in peak glacials, including in MIS4[14], had to pass through the North Atlantic anyway during the very short deglaciation periods, irrespective of whether it was previously stored in liquid or solid form. Even when liquid, the stored water mass cannot have discharged instantaneously due to the narrow passages, but spread over years to decades (substantially reducing the 200 m freshwater lens that Spielhagen et al. calculate assuming an instantaneous release). Even when solid, melting must have been very fast: At the end of MIS6, the main part of the >100 m global (not only Atlantic) sea level equivalent seems to have been added in much less than 1000 years, if we follow the isotope change in high-resolution speleothem records[15] and high-resolution marine records (e.g. U1302/U1303 in Spielhagen's figure S3). The corresponding required meltwater signal is hardly seen in the deep-sea records shown in Figure S3. This observation should raise concerns if planktic foraminifera are actually the right tool to trace large meltwater inputs. This has previously been hypothesized due to the ecological requirements of *N. pachyderma* growth[16]. A comparison of $\delta^{18}O$ from a surface-dwelling *Coscinodiscus* diatom with the more subsurface *N. pachyderma* $\delta^{18}O$ signal from the North Pacific (Fig. 2)[17] confirms that *N. pachyderma* has limited capabilities to detect large meltwater inputs.

How rapidly was freshwater released during terminations?

For a true record of the velocity of isotopic change at the end of MIS6, which is also key to understanding freshwater water release, an archive without bioturbation is required. Such an archive is available in speleothems[15]. For the end of MIS6, we see –with small offsets in absolute dates- a virtually instantaneous change on the Northern Hemisphere to lighter $\delta^{18}O$ that is delivered via precipitation (which originates in large parts from the sea surface). While we are admittedly no experts on the physics of the melting of glaciers, we find it difficult to explain such a sudden offset with only the melting of ice on land. Even under intense anthropogenic forcing, the melting of the Greenland ice sheet is assumed to take hundreds or thousands of years.

Marine records usually do not have the resolution to show an event of this velocity. As the authors state, the usual proxy organisms would be missing, which is an observation that is easily overlooked, obscured by bioturbation, or often not resolved in insufficient sampling resolution. The highly resolving Iberian Margin sediment core MD95-2044 in Spielhagen et al.'s figure S3 does display some stepwise rapid oxygen isotope events that would be compatible with a release of the Arctic Ocean freshwater pool in several instalments, together with Northern Hemisphere Ice Sheets. Cores U1302/U1302 or ODP 983 (Spielhagen's figure S3) also show an almost instantaneous full glacial-interglacial change of the isotopic signature of sub-surface $\delta^{18}O$.

The speed of the MIS6/MIS5 transition is truly astonishing. This instantaneous response to a merely gradual change in insolation at the terminations would be much easier to explain with our scenario that provides a clear tipping point. We believe that the amplification by the discharge of liquid freshwater into the North Atlantic south of the GSR, and the resulting sudden introduction of large amounts of heat to the Nordic Seas and the Arctic Ocean North of the GSR, remaining there for decades, can help to explain this phenomenon.

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