Summary

The study by Brashear et al. shows how stable water isotope interannual variability on the Greenland ice sheet changes throughout the Last Glacial, being stronger during stadials than interstadials, with peaks preceding D-O events by hundreds of years. They used CFA to measure high-resolution isotope data, spectral estimates for the correction of isotopic diffusion, and for estimating isotopic variance at interannual frequencies. They hypothesize that sea ice variability in the North Atlantic area and the mean temperature on the Greenland plateau are closely related to isotopic variability at the ice core location, underpinning this hypothesis by using HadCM3 models, and comparing ice sheet temperatures to sea ice dynamics. The study is important for advancing our understanding of the climate system, specifically Greenland variability and the North Atlantic Ocean and AMOC in relation to the global mean climate state, as well as the characteristics of abrupt climate changes by assessing sudden shifts of D-O events. They use adequate methods and contextualize their results within previous studies and hypotheses. We believe this paper includes interesting and relevant results suitable for publication in "Climate of the Past." However, we have some major concerns that should be addressed before publication, as well as some minor suggestions.

Major concerns:

- **Contribution of non-climatic noise on the changes of isotope variability:** The authors cautiously interpret isotopes and do not directly translate them to temperature, which aligns well with current knowledge of the uncertainties regarding isotope interpretation and isotope-temperature translations. They discuss altered source-sink pathways and evaporation sources upstream as other possible influences on isotope variability. Based on their thorough analysis of different frequencies (Figures A2, A5), their results should not be sensitive to time uncertainties within this (not layer counted) record.. As the analyzed core is highly influenced by ice flow, the authors could additionally state why they think upstream effects do not influence their results.
  Despite considering all these effects, the fast variability interpreted in this manuscript will still be influenced by non-climate noise. Even nearby ice core isotope records are found to be quite distinct from each other, especially at high frequencies (Münch & Laepple 2018). Estimates of the Signal to Noise Ratio (SNR) in the Greenland NGT stack (Hörhold et al. Extended Data Fig. 1b) suggest an SNR of 3-5 in this frequency band for a stack of 12 records; resulting in an SNR of around 0.3-0.4 for a single record such as EastGRIP. This in turn shows that the majority of the interpreted variance will likely be due to local depositional effects. Such noise components likely differ across climate states (e.g., GI vs. GS) and introduce isotope variability changes unrelated to climate. One characteristic that could hint towards such systematic influence could be a change in accumulation rates, which is strongly reduced in the cold phases compared to the Holocene. Lower accumulation rates in the last glacial coincide with more precipitation intermittency and stratigraphic noise. We, therefore, suggest that the authors show the accumulation history of the record, how it coevolves with the variability changes, and

discuss the possibility of state-dependent noise influencing the discovered changes in variability.

- Ice flow at the EGRIP location causes the glacial portion of the water isotope record to originate ~200 km upstream near the ice divide (Gerber et al., 2021). A consequence of this may be thinning of interannual to decadal layers which could affect variability interpretations. Currently, we do not have a method to quantify this. One future possibility is to compare our results with those of a mm-scale water isotope record that is retrieved near the ice divide and not subject to ice flow/upstream effects. Still, we do not think the potential affect would change the primary message of our paper.
- Accumulation rates in Greenland have been shown to move in phase with water isotopes during the LGP (Capron et al., 2021; Guillevic et al., 2013) where warm interstadials are associated with greater accumulation, and vice versa. We show in Figure A8 how EGRIP accumulation rates (Gerber et al., 2021) coevolve with high-resolution (i.e. 50 year timestep) 7-15 year variability. As expected, declines in variability lead accumulation shifts by hundreds of years for most D-O events. This suggests precipitation intermittency and stratigraphic noise during cold stadial phases cannot account for the early shifts in 7-15 year variability, relative to D-O warming. Additionally, we show in Figure A3 that diffusion length (which is significantly influenced by accumulation), also moves in sync with the water isotope record. Specifically, diffusion lengths in the time domain are lower during warm interstadials when accumulation is enhanced. Effects of accumulation on diffusion or the diffusion correction therefore also cannot account for the centennial-scale lead lag that we document. This further shows a robust result which is not overwhelming influenced by local depositional effects.
- Hörhold et al., (2023) shows SNR for a stack of 12 records in the last 1000 years of the Holocene. Our record includes glacial stadials and interstadials, wherein the Hörhold analysis likely does not hold. Additional high-resolution analysis of deep ice cores would provide proof that the signal is repeatable across regions of Greenland, eliminating the concern that noise is causing much of the signal.

- **Uncertainty of the diffusion correction:** The authors estimate the diffusion length in the spectral domain. As shown by Jones et al., 2017 and by Kahle et al. 2018, in CFA systems, some noise is added to the isotopic signal on the preparation side of the system that, after the smoothing of the CFA system, leads to red noise at the higher frequency end (which would, with discrete measurements, be white), as visible in Appendix Figure A4. This red noise can interfere with the diffusion length estimate as it is difficult to distinguish from a diffused signal. Therefore techniques to account for this have been developed (Kahle et al., 2018, Improved methodologies for continuous-flow analysis of stable water isotopes in ice cores, most authors from this paper are also on this new manuscript). The red noise might also influence the analyzed frequencies and the diffusion correction possibly amplifies this high frequency noise.
  We suggest that the authors use or at least discuss the diffusion length estimation method they introduced in Kahle et al., 2018 for CFA measured data. Further, the authors could

show that their results are robust by elaborating on how the variability changes are also detectable on the diffused record (Figure 1c).

- Using the methods presented in this paper (Jones et al., 2018), we apply a correction to the diffused interval, which generally exists between the 2-20 year band. In the EGRIP record, analytical/red noise exists at higher frequencies (<1 year) which is orders of magnitude lower in its power density and therefore does not significantly influence the diffusion correction or subsequent calculations of high-frequency variability. We also use equally-spaced logarithmic bins to avoid weighing the correction towards higher frequencies which are more likely to be affected by analytical noise. This can be seen in Figure A4.
- The Kahle et al. (2018) and Jones et al., (2018) methods result in very similar estimations for diffusion length. Even if small variations exist, this is a moot point because the raw signal and the corrected signal in the 7-15 year band yield the same temporal evolution, just at varying magnitudes. In other words, the lead-lag relationship we document is a robust feature of the climate system and unrelated to the diffusion correction. The manuscript has been edited to make the above point clear on:
    - Line 227: "Another important detail is that the raw (i.e. non-diffusion corrected) 7-15 year variability record exhibits lower amplitudes, yet simultaneous shifts with the corrected record (Fig 1c). This demonstrates the ability of our correction to target signal attenuation by diffusion without incorporating uncertainty into the temporal evolution of the record. In other words, the signal we document is a robust feature of the climate system and not an artifact of the diffusion correction or laboratory analysis."

- **Variability leading abrupt change or variability just depending on the mean state?** We suggest that the authors interpret their results on the variability 'leading' abrupt climate change with more caution. They write, 'Such a large phase offset between two climate parameters in a Greenland ice core has never been documented for D-O cycles' (Lines 34ff). To play devil's advocate, at least visually, the minima in δD also seem to lead the onset of the interstadial periods (their Fig. 3). This may be due to the definition of the onsets, which is set at a certain magnitude of change in the proxy records over time (Rasmussen et al. 2014), combined with the typical shape of the isotope changes. The counter-hypothesis would thus be that the variability depends on the mean isotope value (their Figure 1b), and this dependency (which is interesting in itself) already explains the time-lag. We therefore suggest that the authors either refute this simpler counter-hypothesis, or if this is not possible, one down their interpretation of their results
    - To refute the counter-hypothesis, Figure 1b demonstrates a general relationship between 7-15 variability and mean Greenland climate (e.g. Holocene, Interstadial, Stadial), though there is significant overlap in the data for Interstadials and Stadials. A closer look at Figure 3 shows a substantial centennial-scale offset between shifts in variability and the following onset of abrupt warming, which partly explains the overlap. Though δD may reach an absolute minimum earlier in the stadial phase, the overwhelming interest in D-O Events is the rate and

magnitude of change that occurs at a GI-GS transition which is well studied and defined according to Rasmussen et al., 2014. Between Figures 3 and 4, we show that 50% or more of the abrupt change in 7-15 year variability occurs prior to the onset of D-O Events (Line 259), indicating a decoupling between the two variables. The authors feel it is reasonable to state "Such a large phase offset between two climate parameters in a Greenland ice core has never been documented for D-O cycles"

- The author also states that there are large swings in variability between 27-14 ka b2k when D-O cycling does not occur, further strengthening the argument that Greenland isotope mean and variability are decoupled (for reasons that must be further researched to fully understand).
  - Line 242: "It is important to note that we document multi-millennial excursions in variability occurring between 27-15 ka b2k wherein cold GS conditions persist uninterrupted by abrupt warming, with the exception of D-O Events 5.1 and 5.2 around 23 ka b2k which do not appear to be associated with a detectable change in 7-15 year variability. The excursions are comparable, yet generally smaller in magnitude than those occurring between 50-27 ka b2k when D-O cycling is relatively consistent."
  - Line 371: "Lastly, an inexplicable component of this study is the continuation of large excursions in high-frequency isotopic variability even when D-O cycling is turned off for long stretches (i.e. 27-15 ka b2k). In some cases, the fluctuations are comparable in magnitude to those occurring across prior GS-GI transitions. It seems a climate variability oscillation is inherent to the LGP background state, yet does not result in abrupt mean climate change (i.e. D-O Events) based on certain boundary conditions which remain to be seen. Due to the simultaneous occurrence of the Last Glacial Maximum during this timeframe, an obvious factor to test in future studies is the height and extent of the Laurentide and Scandinavian Ice Sheets and their effects on climate variability."

Minor comments:

- 42 "Thus, both paleoclimate proxy evidence and model simulations suggest that sea ice plays a substantial role in high-frequency climate variability prior to D-O warming." - Argument unclear. You mean paleoclimate proxy evidence including the ice core records as well as the open ocean biomarkers? The ice cores alone do not evidence that, so maybe mention the biomarkers as being part of the "paleoclimate proxy evidence" you are referring to, or delete "Thus" as: "Both paleoclimate proxy evidence as well as these model simulations suggest…"
  - "Thus" has been removed and Line 43 has been rephrased to: "Together, paleoclimate proxy evidence and model simulations suggest that sea ice plays a substantial role in high-frequency climate variability prior to D-O warming."
- 63 References unclear. Which literature explains D-O warming events being related to sea ice and which literature just generally associates sea ice with abrupt warming? Do all of the studies do both? Then maybe add a : between the two sentences?

- All references provide evidence of DO events being related to sea ice behavior
- 134 “On average, temporal differences in adjacent data points range from sub-weekly in the Holocene to sub-monthly during the LGP”. Can you clarify what you mean by “adjacent”? Temporally closest together?
  - “Adjacent” meaning data points which are next to one another
- 151 pore “close-off”
  - This has been corrected
- 139 Can you state why you choose not to include lower frequencies - e.g., because of prior expectations regarding sea ice variability?
  - High-frequency variability is stated as the focus of our study beginning on Line 92: “Though studies assessing decadal-scale variability during the LGP exist (Boers et al., 2018; Ditlevsen et al., 2002), the data sets used were discretely sampled at cm-scale resolutions which may diminish or conceal important high-frequency climatic information (Fig. A1). Developments in continuous-flow sampling techniques have recently allowed for high-frequency analysis of water isotope variability in Antarctic ice cores during the LGP by preserving the amplitude of interannual-scale signals (Jones et al., 2017a; Jones et al., 2018). In the case of West Antarctica, a shift in LGP interannual isotopic variability was linked to broad changes in Pacific Basin teleconnection strength driven by reductions in Laurentide Ice Sheet topography and changing albedo (Jones et al., 2018). This study demonstrated that the drivers of high-frequency climate variability can temporally decouple from the drivers of mean local climate (e.g. temperature, accumulation, etc.), providing new insights about paleoclimate dynamics. In the northern high latitudes, sea ice varies substantially on multi-year and multi-decade bases, imparting variability into the climate system on similar timescales. The Greenland water isotope variability record may therefore provide clues about high-frequency sea-ice variations as such shifts would affect the isotopic signature of precipitation via influences on both moisture source and atmospheric circulation.”
- 154: persevered or better “preserved”?
  - This has been corrected
- 185: The method description is too short to be reproducible. If I understand it right, it needs to assume / assumes that 1.) P0(f) is not frequency dependent and the fit takes only place on frequencies lower than a manually chosen fc to ensure that the spectrum is dominated by the diffusion signal in this range of frequencies and measurement noise can be ignored.
  - The authors feel the description accurately and succinctly describes the methods used in this study and is consistent with prior studies (Jones et al., 2017b; Jones et al., 2018; Jones et al., 2023; Kahle et al., 2021)
    - Po(f) is still frequency dependent based on its definition in equation 3
    - It is unclear what the variable ‘fc’ is in reviewer comment, but it is correct that the correction fit is placed on frequencies affected by diffusion and not analytical noise
- Event 2.2 is mentioned for the first time, please define what that is. It’s not in the table.
  - The following text has been added to table caption: “Due to the brief duration of D-O Events 2.1 and 2.2 (collectively referred to as D-O 2 in Table), one 400-year

window is placed at the onset of D-O 2.2 (i.e. 23.34 ka b2k), which encompasses the entirety of D-O 2.2, a majority of D-O 2.1, and the short-lived stadial phase between each interstadial"

- F2: Please define 2.1 and 2.2 events
  - This has been addressed in captions of Figure 2 and Table 1
- F2 and F3: Could you please put the names/numbers of the D-O events into the graphic to make it easier to follow? Right now, if you write about a specific event, one has to check the table for the D-O event's time and then search for it in the graph.
  - This has been addressed on Figures 2 and 3

Literature

Hörhold, M., Münch, T., Weißbach, S., Kipfstuhl, S., Freitag, J., Sasgen, I., Lohmann, G., Vinther, B., Laepple, T., 2023. Modern temperatures in central–north Greenland warmest in past millennium. Nature 613, 503–507. https://doi.org/10.1038/s41586-022-05517-z

Jones, T.R., White, J.W.C., Steig, E.J., Vaughn, B.H., Morris, V., Gkinis, V., Markle, B.R., Schoenemann, S.W., 2017. Improved methodologies for continuous-flow analysis of stable water isotopes in ice cores. Atmos. Meas. Tech. 10, 617–632. https://doi.org/10.5194/amt-10-617-2017

Kahle, E. C., Holme, C., Jones, T. R., Gkinis, V., & Steig, E. J. (2018). A generalized approach to estimating diffusion length of stable water isotopes from ice-core data. *Journal of Geophysical Research: Earth Surface*, *123*(10), 2377-2391.

Münch, T., & Laepple, T. (2018). What climate signal is contained in decadal-to centennial-scale isotope variations from Antarctic ice cores?. *Climate of the Past*, *14*(12), 2053-2070.

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., ... & Winstrup, M. (2014). A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quaternary science reviews*, *106*, 14-28.

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