Summary

An ultra-high resolution time series for central/eastern Greenland deuterium variability is presented. After correction for diffusion, 7-15-year variability is considered as represented and and interpreted in terms of temperature variability that changes between Greenland stadials and interstadials. Temperature change at the ice core site on decadal scales is compared to sea-ice and sea surface-temperature change in the North Atlantic, and interpreted as primarily arising from sea-ice variability.

Crucially, the authors suggest that a reduction of decadal temperature variability at the ice core site occurs centuries prior to the interstadial warming, and corroborate this with the analysis of model simulations and one high-resolution marine core.

The study is well-written, and the topic is relevant to Climate of the Past. However, there are a few points were more detail, or more stringent acknowledgement of uncertainties, is important.

Major Points

- Please acknowledge the assumption of the validity of the temperature interpretation of dD at sub-decadal timescales -- as you show, sea-ice variability is highly correlated with temperature, but it is not the only driver.
    - The authors acknowledge uncertainties in translating the water isotope record directly to temperature, especially at decadal and interannual scales. It is also acknowledged that further isotope modeling studies are required, as the current understanding of water isotopes at high-frequency scales is limited. The following lines highlight this:
        - Line 48: "Stable isotopes of hydrogen (δD) and oxygen (δ^{18}O) in polar ice cores provide information about local temperature and atmospheric circulation (Dansgaard, 1964)"
        - Line 303: "It is possible that greater excursions in sea-ice concentration were driven by the enhanced latitudinal range between maximum summer and winter ice extents (Sadatzki et al. 2020), which presumably changed on a year-to-year basis. These seasonal variations would impart volatility in high-frequency temperature fluctuations on annual, interannual, and decadal scales via ice-atmosphere feedbacks. By extension, Rayleigh distillation and the isotopic signature of precipitation at EGRIP would also be impacted. An additional contribution to enhanced isotopic variability during stadial phases may stem from altered source-to-sink pathways. With large seasonal swings in the capping and exposure of the ocean surface by sea ice, evaporative sources upstream of EGRIP would also be altered. As a consequence, variability in both evaporative source signatures and temperature gradients of moisture transport to Northeastern Greenland would increase. An isotope enabled GCM is required to test this hypothesis."

    - One additional concern is that the isotopic signal we document may also be related to non-climate noise at high-frequencies, which changes across climate states (glacial interstadials vs stadials). It has been proposed that shifting accumulation rates may cause such a systematic influence on non-climate noise, as colder periods are associated with lower accumulation and thus greater precipitation intermittency and stratigraphic noise. To refute this, the authors have also now included the coevolution of EGRIP accumulation with 7-15 diffusion corrected variability in Figure A8. It shows that declines in variability lead accumulation shifts by hundreds of years for most D-O events. This suggests local depositional effects during cold stadial phases cannot account for the early shifts in 7-15 year variability, relative to D-O warming.
- Consider, in the Discussion, the robustness of the model-based process interpretation considering a usefulness of model intercomparison (e.g., [1]), in particular given the complexity of sea-ice models. Similarly, the marine record is a (hand-picked) example, there would be potential for targeted synthesis work here.
    - The author is waiting for input from coauthor before addressing this comment.
- The figures need to be reworked. Standard red/green looks grey to quite a few people (Listen, e.g. to these people describing their experience https://www.youtube.com/watch?v=FKSOe5NK_qQ and imagine how distinguishable colors are in most of your figures...)
    - Figures 1, 3 and 4 have been reworked to remove all standard red/green color combinations

Minor Comments

- p1l26/27 This sentence is ambiguously phrased. (Why) should there be a phase offset, and should it be distinguishable? I read this as: "Across stadial/interstadial transitions proxy evidence showed in-phase changes in mean temperature/dust/sea-salt concentration/accumulation rate".
    - The author is stating (not questioning) that proxy evidence (mean temp/dust/sea salt/accumulation) exhibits in-phase shifts across stadial-interstadial transitions consistent with the cited literature (Capron et al., 2021).
- p1l29/30 You write that high-frequency interannual variability surrounding "mean temperature change" has not been investigated -- please clarify that by mean change you mean centennial-to-millennial scales, and by high-frequency interannual variability. From a lower-resolution marine point of view both timescales are "just" variability.
    - This has been rephrased
- p2l71 "tipping-point sea-ice displacement" - The concept of a threshold, below which the ice edge becomes unstable, and fast/complete retreat of perennial sea-ice cover occurs is debated [2,3]. Compared to the ice sheet, sea-ice itself has little memory, but small changes in the ice edge may lead to large impact warming. Please rephrase.
    - The author has removed the phrase “tipping-point”

- p3l85 and following: Investigating leads and lags, as well as interannual to multicentennial variability across the LGP and for different timescales ("mean" vs. "variability") and attributing it primarily to local temperature change assumes that dD is faithfully representing local EGRIP site temperature. This is not explicitly mentioned, but is permeating the study, and should be acknowledged explicitly. Sea-ice variability, independently of temperature change at the EGRIP site, can induce d18O variability [4], and, as the authors themselves show with the model-based correlations these variables are colinear. Isotope-enabled simulations could allow, to some extent, to disentangle these relationships.
    - See comment under first bullet point of "Major Points". The authors do not intend to assume dD faithfully represents local EGRIP site temperature and present multiple arguments backed by their results on why the water isotope record at interannual and decadal scales is largely uncertain at present. The authors suggest isotope enabled modeling in future work.
- p4l141 timestep of 50-200 years -- presumably these are the shifts for the moving windows? Unclear.
    - Yes, this has been clarified in the manuscript on Line 144: "We spectrally analyze the EGRIP δD record in 400-year windows with a timestep (i.e. stepwise shift between adjacent windows) of 50 to 200 years, depending on desired temporal resolution"
- p5l154 correct: preserved
    - This has been corrected
- p6l204: instead of "spectrum of change" suggest rephrasing
    - This has been rephrased. Line 206 now reads: "The freshwater hosing and pinned sea-ice simulations give a range of mean temperatures at the location of EGRIP that represent a spectrum of possible mean LGP climate states. By including a spectrum, we reduce the bias that could arise from defining a single stadial or interstadial state with only one forcing mechanism."
- p7l217 increased depletion
    - This has been corrected
- p8l251 clarify "mean" timescale (see above)
    - This has been addressed. Line 259 now reads: "Thus, there is clear evidence that 7-15 year variability for D-O Events 2.2, 3, 4, 5.2, 6, 7, 8, 10, 12 and 13 leads centennial-scale mean temperature change at the onset of GI phases.

- p8l255 and following: How long are the simulations? How are the degrees of freedom and a significance for the correlations calculated? Are these step-wise simulations, and is the mean change then subtracted prior to correlation? The magnitude of the correlation is surprisingly high. To what extent are these correlations representative for other models (given the fairly simple sea-ice model in HadCM3)?

- All simulations are run for 500 years, branched from a control simulation (Pre-industrial/LGM) that has been run for many 1000s of model years. Climatologies are computed from the last 100 years. All simulations are self contained, independent, simulations and branch from the same control simulation at the same time - they are not "step-wise" in the sense that the simulation with the sea ice edge at 55N feeds the simulation with the sea ice edge at 50N etc. In fig 5 (a) and (b) no means are subtracted as the correlation is between the variability (variance) in sea ice concentration and temperature. In figs 6(b) and (c) the abscissae do not have the control mean temperature removed: we wish to establish the relationship between cold and warm states and variability, therefore must include the overall colder conditions that arise from the LGM climate. The correlations in fig 5(a) are indeed high as in this figure we are correlating temperature variability with itself - over EGRIP this is by definition 1. This map gives a sense of the spatial autocorrelation for 7-15 year variability over the North Atlantic. Unsurprisingly over Greenland this is high. The correlations with sea ice are maximum at around 0.6, so sea ice variability can explain ~30% of the variance at EGRIP, thus the majority of the variance arises from other sources. Since no other model has been run across such a range of different forcings, it is impossible to say to what extent the results arise from HadCM3's quirks. However, over the 7-15 year timescale the atmosphere has little memory so coherent changes are driven by the ocean/ice system. Therefore, the magnitude of the correlations that we see arise from the dynamics of the atmosphere. Thus the relatively simple sea ice model in HadCM3 is not likely to bias the results.

- p10l350 Arguably, this is a single core site for which a reduction of sea-ice occurs prior to Greenland isotopic/temperature change, and a single climate model. The correlation patterns of sea-ice variability with EGRIP temperature in other models would be interesting. What is the age model of MD95-2010 based on, and what is the corresponding age uncertainty? Hopefully (or perhaps, evidently, from the results) not tie-points to GICC05. Perhaps this is an age model issue?
    - The authors acknowledge further isotope-enabled modeling and high-resolution sea ice reconstructions are critical (Line 383): “Additionally, future isotope-enabled GCM studies may benefit from utilizing the high-frequency EGRIP variability timeseries, presented here, to constrain boundary conditions or benchmark model output. We suggest targeted tests aimed at temporally reconciling the centennial-scale offset with sea-ice behavior to better understand regional North Atlantic climate change within the context of abrupt D-O warming. Analysis of high-resolution sediment proxy records from critical locations identified in this study may also clarify uncertainties.”
    - Text regarding sediment core age model taken directly from Sadatzki et al., 2020:
        - “Accordingly, the age model of MD99-2284 is based on alignment of near-surface temperature signals and D-O climate transitions, independently verified and constrained by four distinct cryptotephra layers that were identified before and after the GS6GI5 transition as well as during GI6 and GI8 in both core MD992284 and the NGRIP (North Greenland Ice Core Project) ice core with a consistent geochemistry (33)

(SI Appendix, Materials and Methods and Fig. S2). Moreover, the glacial sediment sections in both cores MD95-2010 and MD99-2284 reveal a very consistent variability in anhysteretic remanent magnetization (ARM), reflecting deep ocean circulation changes in the Nordic Seas (13, 34, 35), which closely resemble the D-O climate fluctuations recorded by the δ18O of the NGRIP ice core. This enables development of an age model for core MD95-2010 by stratigraphic alignment of its ARM record to that of MD99-2284 and the δ18O of the NGRIP ice core (SI Appendix, Materials and Methods and Fig. S2). Thereby, our sedimentary sea ice records are placed on the Greenland ice core chronology GICC05 (36) and can thus be directly compared with the RECAP sea ice record, which also has been transferred to the GICC05 chronology by alignment of the RECAP dust record to NGRIP δ18O".

    - The above text has now been summarized in the manuscript on Line 355: "In this study, sediment core age models are tied to GICC05 using stratigraphic alignment of ARM (anhysteretic remanent magnetization), near-surface temperature, and cryotephra layers with NGRIP δ^{18}O."

- Fig. 3, 4, 6, 7 please avoid red/orange and green as dominant colors in figures (not colorblind friendly)
    - This has been addressed
- Fig. 5, perhaps add the mean position of the sea-ice edge in these figures for the LGM to aid interpretation.
    - The author does not think this information would significantly aid interpretation as ice extent can be inferred from mean temperature in Figures A6 and A7, which are used to create the plots in Figure 5. Further, we use ~20 simulations over a spectrum of LGP climate states and including 20 mean sea-ice edges might distract from the primary message of the plot.
- Data availability: The DOI points to a lower-resolution (5cm) version of the dataset. As such the study is, therefore, not (yet) reproducible.
    - The mm-scale data set is currently being uploaded to the Arctic Data Center

References

[1] Malmierca-Vallet, I., Sime, L. C., and the D–O community members: Dansgaard–Oeschger events in climate models: review and baseline Marine Isotope Stage 3 (MIS3) protocol, Clim. Past, 19, 915–942, https://doi.org/10.5194/cp-19-915-2023, 2023.
[2] Serreze, M. Rethinking the sea-ice tipping point. Nature 471, 47–48 (2011). https://doi.org/10.1038/471047a

[3] Livina, V. N. and Lenton, T. M.: A recent tipping point in the Arctic sea-ice cover: abrupt and persistent increase in the seasonal cycle since 2007, The Cryosphere, 7, 275–286, https://doi.org/10.5194/tc-7-275-2013, 2013.

[4] Rhines, Andrew, and Peter J. Huybers. "Sea ice and dynamical controls on preindustrial and last glacial maximum accumulation in central Greenland." Journal of Climate 27.23 (2014): 8902-8917.

Citation: https://doi.org/10.5194/egusphere-2024-1003-RC1