REVIEWER 2

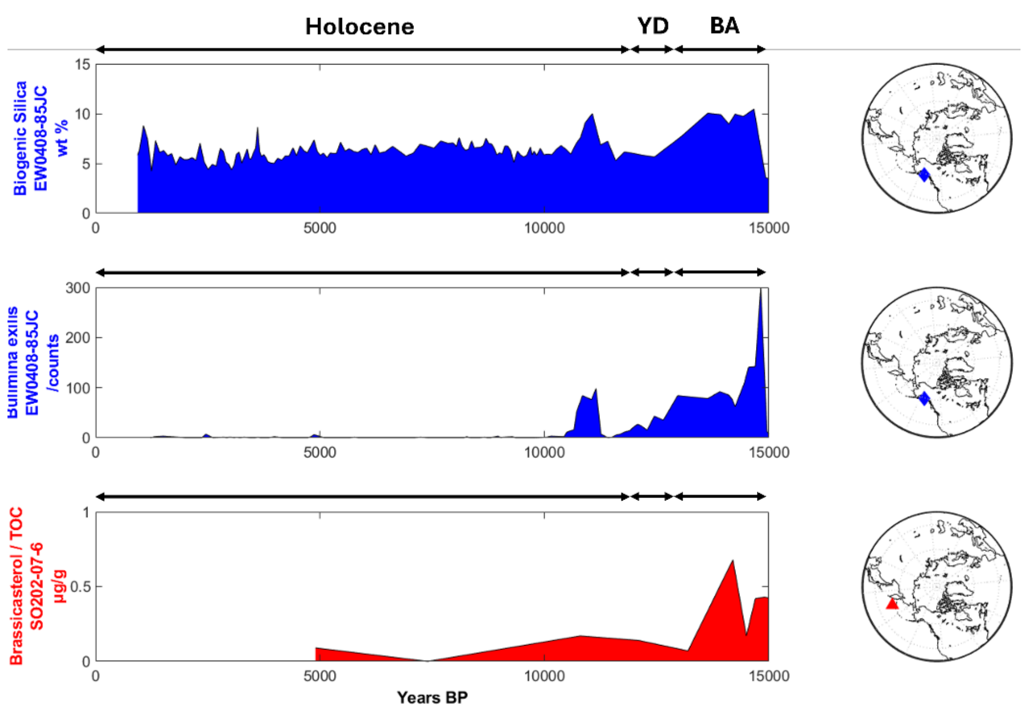
This manuscript reports high-resolution records of Fe_{ICP} and DFe from the EGRIP ice core in Greenland, covering the Pleistocene-Holocene transition (10.3–13.0 ka). The study demonstrates that while total iron concentrations increased 17-fold during the YD compared to the Early Holocene, the biologically active DFe fraction increased by only 29%. By integrating ice-core chemistry with marine productivity records from the North Pacific HNLC region, the authors effectively argue that aerosol alkalinity, rather than total dust flux, acted as a critical limit on iron fertilization during this climatic transition. The data are of high quality, utilizing CFA coupled with spICP-MS, and the findings provide significant new insights into the biogeochemical cycling of iron in the Northern Hemisphere. The manuscript is well-written and deserving of publication in Climate of the Past after addressing the following comments.

We thank the reviewer for the feedback

General comments

Comment 1: The manuscript effectively argues that aerosol alkalinity controls the iron solubility, however, the connection to marine primary productivity remains largely theoretical. The manuscript lacks a direct comparison with existing productivity records from the North Pacific HNLC region.

We agree with the reviewer. In the current version, we primarily refer to Burgay et al. (2021) and Kienast et al. (2004) for marine productivity proxy records; however, we acknowledge that including this information more explicitly in the main text would improve clarity. We added a reference to a new Figure (in the supplementary) reporting biogenic silica, *bulimina exilis* and brassicasterol records from the EW0408-85JC and the SO202-07-6 sediment cores from the Western and Eastern North Pacific Ocean covering the Holocene, Younger Dryas and Bolling-Allerod (Meheust et al., 2018, Praetorius et al., 2015, Davies et al., 2011). From this figure it appears clear ho productivity is higher during the BA than during the YD.



Méheust, M., Stein, R., Fahl, K., and Gersonde, R.: Sea-ice variability in the subarctic North Pacific and adjacent Bering Sea during the past 25 ka: new insights from IP 25 and U k' 37 proxy records, Arktos, 4, 1–19, 2018

Praetorius SK, Mix AC, Walczak MH, Wolhowe MD, Addison JA, Prahl FG. North Pacific deglacial hypoxic events linked to abrupt ocean warming. Nature. 2015 Nov 19;527(7578):362-6.

Davies, M., Mix, A., Stoner, J., Addison, J., Jaeger, J., Finney, B., and Wiest, J.: The deglacial transition on the southeastern Alaska Margin: Meltwater input, sea level rise, marine productivity, and sedimentary anoxia, Paleoceanography, 26, 2011.

Comment 2: L12-15: The manuscript excludes the correlation between atmospheric Fe deposition and productivity due to alkalinity constraints, while implies DFe is the key driver. However, this does not confirm that other factors (stratification, sea-ice, etc.) were more relevant without direct evidence. Additionally, the manuscript lack of the comparison between DFe and productivity records.

We agree with the reviewer and we expanded the Discussion section to include a more detailed consideration of the role of sea-ice (Méheust et al., 2016; Méheust et al., 2018) and enhanced water-column stratification (Ren et al., 2015) in regulating marine productivity. We add a more detailed discussion at the end of paragraph 3.2 (i.e., when we state that "[…] other players such as water stratification, iron remobilization from sediments, and sea-ice extent having a stronger contribution in modulating NPP" and we removed the following paragraph from section 3.1 (to avoid redundancy):

This pattern has been linked to ocean warming, which expanded the subsurface oxygen minimum zone and promoted seafloor hypoxia. Under these low-oxygen conditions, iron is remobilized from sediments, providing a source of bioavailable Fe that further stimulated marine productivity. An additional explanation for why NPP was higher during the BA warm period in the subarctic North Pacific is associated with an increase in sea level that inundated previously exposed lands, which in turn entrained iron and other nutrients to the marine ecosystems (Davies et al., 2011). Conversely, during the colder and dustier YD, either enhanced water stratification, which led to the consumption of major nutrients in surface waters, or a more extensive sea-ice cover, acting as a physical barrier between the atmosphere and ocean surface limiting aeolian iron deposition, played a more dominant role (Méheust et al., 2018; Kienast et al., 2004). In addition, atmospheric aerosol was more alkaline during the YD, potentially reducing Fe solubility (Delmas, 1994; Wolff et al., 1997).

Added in paragraph 3.2

Sea-ice has been proposed as one of the key factors controlling productivity, as it can act as a physical barrier between the atmosphere and the ocean, reducing both light availability and the direct deposition of bioavailable iron to surface waters. Marine sediment records from the eastern and western Subarctic North Pacific, as well as the Bering Sea, indicate extended spring sea-ice cover during the Last Glacial Maximum, coinciding with maximum iron fluxes (Burgay et al., 2021). The subsequent decline in perennial sea-ice coverage following the LGM is associated with an increase in marine productivity, which reached a maximum during the BA when prevalently ice-free conditions were recorded, and decreased during the YD, when variable sea-ice conditions were present (Figure S2) (Méheust et al., 2018).

Enhanced water stratification provides an additional mechanism to explain the decoupling between iron supply and productivity. Reconstructions based on foraminifera-bound $\delta^{15}N$, i.e., a proxy for

nitrate consumption, show that nitrate utilization was more complete during the Younger Dryas, despite low productivity, than during warmer periods (Ren et al., 2015). This apparent contradiction can be explained by stronger stratification during cold and dusty periods, which reduced vertical mixing and upwelling. As a result, nutrient-rich deep waters remained isolated from the surface, while nutrient-depleted, well-ventilated waters dominated the upper ocean (Kohfeld and Chase, 2017). This led to reduced nutrient supply to the euphotic zone and, consequently, to lower marine productivity despite elevated iron inputs.

Ren, H., Studer, A. S., Serno, S., Sigman, D. M., Winckler, G., Anderson, R. F., Oleynik, S., Gersonde, R., and Haug, G. H.: Glacial-to-interglacial changes in nitrate supply and consumption in the subarctic North Pacific from microfossil-bound N isotopes at two trophic levels, Paleoceanography, 30, 1217–1232, 2015.

Kohfeld, K. E. and Chase, Z.: Temporal evolution of mechanisms controlling ocean carbon uptake during the last glacial cycle, Earth Planet. Sci. Lett., 472, 206–215, 2017.

Comment 3: The manuscript suggest that volcanic eruptions can drive DFe atmospheric iron solubility. However, the ice core record primarily reflects local deposition near the EGRIP site. It remains unclear to what extent these volcanic events influenced the productivity in the North Pacific, which need more sedimentary record in the North Pacific. I suggest add a figure comparing the DFe of 10 volcanic eruptions with a productivity record in the North Pacific.

The identified volcanic eruptions caused sulphate deposition over the Greenland plateau larger than 30 kg km^{-2} yr^{-1} (up to 272 kg km^{-2} yr^{-1}). This indicates that these volcanic eruptions were exceptionally intense and they might have influenced the entire northern hemisphere. Three, occurring at 10 481, 12 917 and 13 028, were also observed in Antarctic ice cores (Lin et al. 2022), with an estimate stratospheric aerosol loading ranging between 150 and 220 Tg, proving a global deposition of sulfate (and also volcanic dust, including iron). Nevertheless, we agree with the reviewer that, for other volcanic eruptions, we don't know if the volcanic aerosol was also deposited in the Subarctic Pacific Ocean (SNP), because we do not know the location of the volcanos. Unfortunately, due to the coarse resolution of marine sediments, it is impossible to observe marine productivity blooms as consequence of volcanic eruptions, as already stated in the manuscript. We added a sentence:

Enhanced labile iron concentrations may have triggered local phytoplankton blooms in the HNLC North Pacific Ocean, in line with modern satellite observations (Olgun et al., 2011; Langmann et al., 2010). This can be particularly true for at least three interhemispheric eruptions occurring at 10481, 12917 and 13028 BP. However, due to the short time during which these bloom events develop, it is not possible to track them in sediment cores and their effect on biological productivity would be limited to a few years after the eruption.

Comment 4: There is a geographic distance between the study site and the North Pacific. Therefore, the manuscript should to discuss whether the characteristic (concentration and solubility) of DFe at the study site are truly representative of the aerosol deposition over the North Pacific, given the chemical evolution during long-range transport.

We thank the reviewer for this comment and we paste here the answer we gave to Rev. 1 who raised a similar concern.

The representativeness of the LFe ice-core record presented here with the amount of labile iron deposited in the North Pacific Ocean is supported by the comparison of dust fluxes from sediment core SO202-7-6 (Subarctic North Pacific Ocean), with the high-resolution dust flux record from the NGRIP ice core (Serno et al., 2015). The comparison shows a good coherence in temporal dust deposition changes in Greenland and the Subarctic North Pacific and therefore that atmospheric deposition of iron-bearing particles deposited in Greenland are representative of what has been deposited over the Subarctic North Pacific Ocean. What differs between marine sediments and ice cores is the amplitude of the observed changes, with NGRIP showing a much larger variability in dust fluxes. This enhanced amplitude has been attributed to more efficient dust transport to Greenland and extended atmospheric residence time, driven by climate-related shifts in atmospheric circulation and wet deposition en route. While concentration and flux values from Greenland ice cores are not directly representative of the absolute amount of iron deposited in the Subarctic North Pacific Ocean, they still provide a robust record of relative changes in atmospheric dust (and iron) input in this HNLC region.

Specific comments

Comment 1: L213-215: I suggest adding panel labels (a, b and c) to the Figure 2 and captions.

Ok

Comment 2: Move Figure S1 to the main text to better introduce the location of these three ice cores in the text.

We agree with the reviewer and will move Figure S1 to the main text. To better introduce the location of the ice cores, we will add the following sentence to Section 2.1:

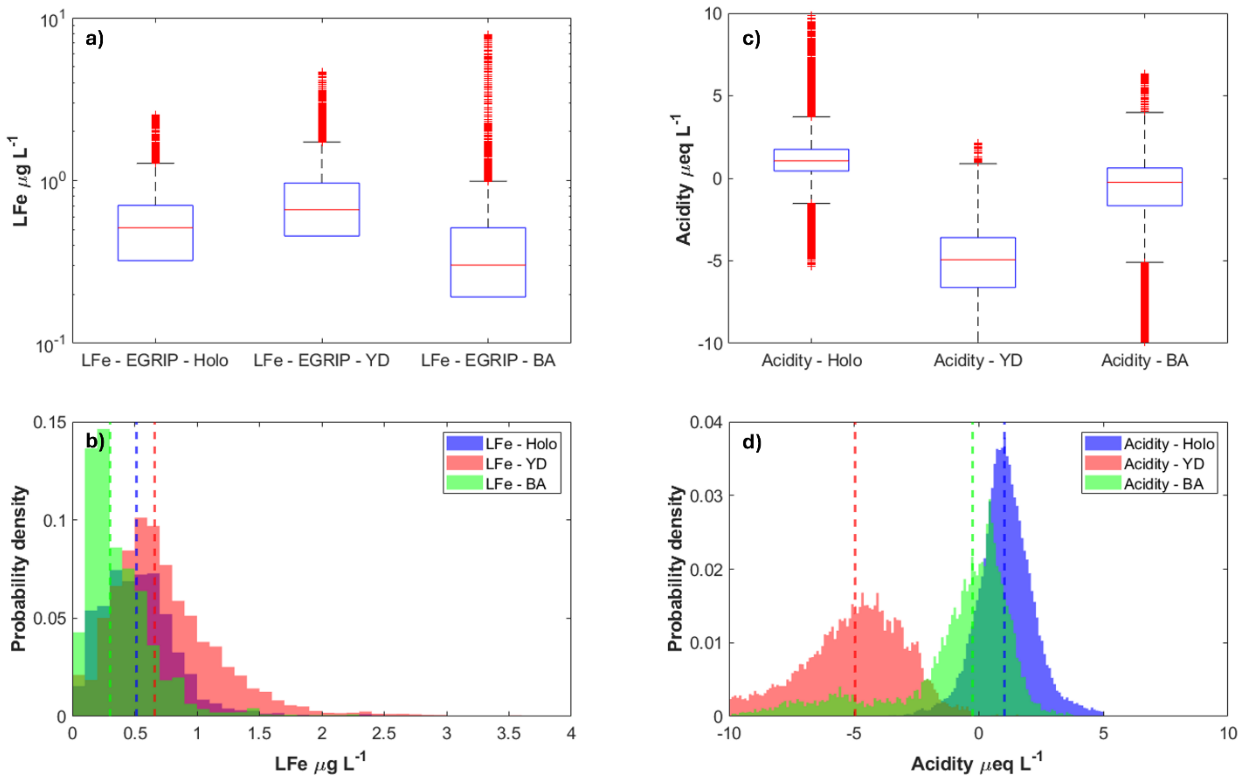
LFe and FeICP data from EGRIP are compared with other Greenland ice-core iron records, including NEEM (77.45°N, 51,06°W, blue star in Figure 1; Burgay et al., 2018) and GRIP (72.35°N, 37.38°W; green star in Figure 1; Hiscock et al., 2013). NEEM and GRIP are both located on the Greenland plateau at 2540 and 3230 m a.s.l., respectively, with modern accumulation rates of 22 and 23 cm ice equivalent per year (Schüpbach et al., 2018; Andersen et al., 2006). All three sites are predominantly influenced by dust originating from Asian deserts during the investigated time period.

To provide a comprehensive and inter-hemispherical comparison, the Fe records from Greenland were compared with an ice core from Antarctica (Epica Dome C, EDC96, 75°06'S; 123°21'E) (Traversi et al., 2004). EDC96 is located in the Antarctic Plateau at 3233 m. a.s.l., with a modern accumulation rate of 2.9 cm ice equivalent per year (Udisti et al., 2004).

Andersen KK, Ditlevsen PD, Rasmussen SO, Clausen HB, Vinther BM, Johnsen SJ, Steffensen JP. Retrieving a common accumulation record from Greenland ice cores for the past 1800 years. Journal of Geophysical Research: Atmospheres. 2006 Aug 16;111(D15).

Comment 3: The relationship between the acidity and DFe is important evidence of the argument. I suggest (1) moving Figure S3 and S4 to the main text, (2) combining these two penal into one figure, which can better compare the correspondence across the different periods.

Ok, we produced a single 2x2 picture merging both LFe and acidity data (see below).



Comment 4: Add one figure superimposing the volcanic LFe and acidity data onto the records of the 8 selected periods, to provide further supporting evidence for the limiting effects of aerosol alkalinity on Fe solubility.

We believe that the effect of acidity in enhancing LFe is already quite clear from Figure S5 (now in the main text) and the Figure above (now Figure 4).