

Response to comments by Reviewer 1

We thank Reviewer 1 for the insightful comments, suggestions and detailed scrutiny of our manuscript. We will carefully consider these comments and suggestions, and include them in our updated manuscript. Our responses are shown in black text.

Reviewer comment:

The manuscript by Nicolas et al. provides a valuable contribution to our understanding of ancient carbon mobilization in the Laptev Sea over the last 16,000 years. Through the combination of high-resolution terrigenous biomarkers and compound-specific ^{14}C dating of n-alkanoic fatty acid methyl esters, the authors trace the contribution of pre-aged organic carbon to the marine environment. The comprehensive use of multiple proxies enhances the robustness of their interpretations.

General comments:

1. In the abstract, you provide the following statement: “However, the regional variations, timing and rate of carbon release from thawing permafrost remain elusive, primarily because of the limited number of deglacial records that document carbon mobilization occurrences.” You need to state more clearly and consistently throughout the manuscript, which of these knowledge gaps this study is addressing (timing/rate/mechanisms?).

Reply: Thank you for this valuable feedback. We would like first to replace the phrase “remain elusive” to “are still poorly understood”. We appreciate your suggestion to clarify which specific knowledge gaps our study addresses. We will clarify more explicitly and consistently throughout the revised Discussion section which specific knowledge gaps (timings/magnitude/mechanisms) our study addresses throughout the studied deglacial period.

Reviewer comment:

2. The structure of 3.2 of the methods section is currently quite confusing and missing some significant information. It requires restructuring to make it flow and to clearly explain to the reader which biomarkers were extracted, how they were extracted (which fractions they came from), and then to clearly but briefly explain the use of each biomarker in this study.

Reply: Thank you for this insightful comment with regards to section 3.2. We will include further subdivisions in Section 3.2, to enhance the clarity and readability of the manuscript. Furthermore, in the revised manuscript we will provide additional details to clearly specify which biomarkers were extracted, describe the extraction process and source fractions, and clearly explain the specific use of each biomarker in this study.

Reviewer comment:

3. Some of the language is quite colloquial and would benefit from being changed to more formal terms, and ensure there is consistency i.e. sea ice/sea-ice

Reply: Thank you for this helpful comment regarding the language and terminology used in the manuscript. We will carefully review the text to replace colloquial expressions with more formal language and ensure consistent use of terms throughout the manuscript.

Reviewer comment:

Detailed comments:

Line 25: for clarity and formality, rephrase “from off the Lena River outflow”

Reply: We will revise the phrase for improved clarity and formality to “close to the Lena River outflow”

Line 44: joining the two sentence together will make it flow better - “global average temperatures (Rantanen et al., 2022) **and** future warming”

Reply: Revision will be done

Line 46: change ‘in part’ to ‘partially’

Reply: Change will be done

Line 47-48: change ‘might’ to ‘could’

Reply: Change will be done

Line 51: remove ‘during’

Reply: Revision will be done

Line 56: and the mechanisms are also poorly constrained? Is this not also one of the research areas?

Reply: Yes, “mechanisms” is also one of the research areas and this will be added in the sentence. We will describe the main mechanisms of carbon release from degrading permafrost, such as coastal erosion and river runoff, in the Discussion section of the revised manuscript.

Line 60-63: “Moreover, the degree to which mobilized permafrost OM is remineralized is not well constrained either, and the available estimates differ widely (Bröder et al., 2018; Ruben et al., 2024; Tanski et al., 2019; Vonk et al., 2012)” This statement may be unnecessary as it is outside of the scope of this study?

Reply: Thank you for this comment. We agree that this statement is outside the main scope of our study. We will remove it from the revised manuscript to maintain focus and clarity.

Line 67: **which was amplified**

Reply: Revision will be done

Line 68: Remove “The”

Reply: Revision will be done

Line 70: References needed

Reply: The reference will be added as follows: “The Bølling-Allerød (B/A; ca. 14.7 - 12.9 kyr BP) and the Pre-Boreal (PB; 11.5 – 9.5 kyr BP) (Rasmussen et al., 2006) were periods characterized by abrupt temperature increases in the Northern Hemisphere...”

Line 73: References needed

Reply: References will be added as follows: ... and their onsets coincide with periods of increased sea-level rise referred to as Meltwater Pulse 1A (mwp-1A) (Brendryen et al., 2020; Deschamps et al., 2012) and Meltwater Pulse 1B (mwp-1B) (Bard et al., 1996; Fairbanks, 1989) respectively.

Line 79: There is an abrupt shift from the topic of the last paragraph to this one. The paragraph on the last deglaciation would benefit with a brief conclusion of why this period is important for providing insight into your study aim and you can then use this to flow back to the permafrost topic.

Reply: Thank you for pointing this out. We agree that the transition between the paragraph of the last deglaciation and the subsequent paragraph could be improved for clarity and flow. In response, we will revise the end of the paragraph on the last deglaciation to include a brief concluding statement as follows: “These rapid climate shifts during the last deglaciation profoundly influence permafrost stability and landscape dynamics in the Arctic region. Therefore, this period provides important insights into how permafrost responded to rapid climate change.”

Line 103: Briefly define Ice Complex Deposits

Reply: A definition of Ice Complex Deposits will be given at Line 105 as follows: "Ice Complex Deposits are characterized by their mainly fine-grained composition and their connection to syngenetic permafrost processes. The substantial ground ice content is primarily found as pore ice and ice wedges that developed together with sediment accumulation (Schirmer et al., 2013)."

Line 106: Remove “were” thawed

Reply: Revision will be done

Line 107-109: This sentence needs rearranging, so it is clear you are referring to the last deglaciation

Reply: The sentence will be revised as: “Different studies from the Arctic and sub-Arctic regions have suggested that the biodegradation and oxidation of the thawed OC from Yedoma deposits during the last deglaciation have led to an increase in atmospheric CO₂ concentrations (Martens et al., 2020; Meyer et al., 2019; Nogarotto et al., 2023; Tesi et al., 2016; Winterfeld et al., 2018).”

112: “well-dated”- mention that it’s 14C dating

Reply: The following phrase will be added at the end of the sentence: “and dated using radiocarbon methods”.

119: More detail on the information you are providing- magnitude/timing/mechanisms?

Reply: The sentence will be revised as follows: “Our results provide additional insights into the mechanisms, timings and magnitude of ancient carbon release from deglacial degradation of permafrost and contribute towards a better understanding of permafrost thaw dynamics and aged carbon release for the projected warming climate and sea level rise.”

133: change probably to likely- less colloquial

Reply: Revision will be done

133: Are there any estimations of regional sea levels during the last deglaciation that can be included?

Reply: The estimates of regional sea level rise reconstructed from core PS2458-4 are based on the work of Klemann et al. (2015). Additionally, the reconstructions of coastline positions for different time periods, as presented in Figure 1, are also derived from Klemann et al. (2015) and are appropriately referenced in the figure caption and main text.

Line 150-152: be clearer about the type of isotope analysis you are referring to here. Is this in reference to the biomarker compound-specific isotope analysis or the analysis conducted for the age model?

Reply: Thank you for this suggestion. The sentence will be updated for more clarity as follows: We used archived sediment samples that were freeze-dried, homogenized and kept in amber glass jars for the terrigenous biomarker, bulk (TOC, TN) and isotopic analyses ($\delta^{13}\text{C}$ and bulk OC radiocarbon analyses).

Line 154: It is unclear in this paragraph that this is a previously published age model. This needs to be explicit in the first sentence, then describe the methods in more detail

Reply: The paragraph will be updated as follows: “The age-model used for core PS2458-4 in this study has already been published by Nicolas et al. (2024). The chronology was established by accelerator mass spectrometry (AMS) ^{14}C dating based on seven mixed benthic foraminifera dates from Spielhagen et al. (2005) and seven mixed foraminifera and bivalve samples (Nicolas et al., 2024) measured at the Mini Carbon Dating System (MICADAS) ^{14}C laboratory facility of the Alfred Wegener Institute (Mollenhauer et al., 2021). The radiocarbon and modelled ages, and species names of foraminifera and bivalve samples used are given in Nicolas et al. (2024). The age-depth model of core PS2458-4 was constructed using the OxCal 4.4 software (Ramsey, 2009). For this, the ^{14}C dates were calibrated with the Marine20 curve (Heaton et al., 2020), and a local marine reservoir correction (ΔR) value of 345 ± 60 ^{14}C years (Nicolas et al., 2024) based on a beryllium-based age model. The sediment interval between 121.5 and 667 cm represents the time between about 6.0 and 13.7 calendar kyr BP. The sediment layer at 0.5 cm represents a modern calendar age of 0, signifying the present-day reference point in the stratigraphic timeline. The base of the core at 800 cm has an extrapolated calendar age of about 15.6 calendar kyr BP.”

Line 175: change to: “apolar and polar (including GDGTs)”

Reply: Revision will be done

Line 202: State what you are using to assess biomarker content- peak area?

Reply: For more clarity, the following sentences will be added to replace the sentence at lines 200-202: “GDGT content was assessed by integrating the peak areas of the respective (M+H)⁺ ions in the SIM chromatograms. Due to the lack of authentic standards for all GDGTs, these values are considered semi-quantitative and are referenced to the C₄₆-GDGT internal standard.”.

204-205: Explain what the BIT index is used for

Reply: This information is given at lines 216-218 and will be shifted to line 204.

Line 205: State briefly why 6-methyl brGDGTs have been included

Reply: This sentence will be added at line 210: “6-methyl brGDGTs have been included in the BIT index calculation to provide a more complete and accurate assessment of terrestrial OM input, as both 5- and 6-methyl brGDGTs are important soil-derived compounds.”

Line 210: Add reference- Sinninghe Damste et al., 2002

Reply: Reference will be added

Line 212-214: Hard to follow the sudden mention of n-alkanoic acids without any reference to their use in this study. Also, when referencing long-chain leaf wax lipids, state which chain-lengths you are referring to.

Reply: Thank you for this insightful comment. We will revise the manuscript to clarify how n-alkanoic acids were used in our analysis and specify the chain-lengths considered as long-chain leaf wax lipids. Specifically, we will now state that in this study, long-chain *n*-alkanoic acids (C₂₆–C₃₀) were analyzed as biomarkers for terrestrial higher plant input. These details will be incorporated into the revised paragraph to improve clarity and coherence. The revised paragraph now reads: “Long-chain *n*-alkanoic acids (C₂₆–C₃₀), derived from the leaf wax lipids of higher land plants (Eglinton & Hamilton, 1967), were analyzed in this study as biomarkers for terrestrial OM. In higher plants, the predominant *n*-alkanoic acids are high-molecular-weight saturated fatty acids with even-numbered carbon chains (Bianchi and Canuel, 2011).”

Line 214: The information on brGDGTs here is confusing- this part needs to go before the BIT index calculation.

Reply: Thank you for this comment. We agree that providing information on brGDGTs prior to describing the BIT index calculation will improve the clarity and logical flow of the manuscript. Accordingly, we will move the relevant information on brGDGTs (originally at line 214) to precede the description of the BIT index calculation (line 204).

Line 223: There needs to be a clear explanation of what RI-OH is- mention that it is based on hydroxylated isoprenoid glycerol dialkyl glycerol tetraethers, their source, and refer to other key references.

Reply: Thank you for this helpful comment. The revised paragraph will read as follows: “The ring index of hydroxylated tetraethers (RI-OH’) is a proxy based on the relative abundance of hydroxylated isoprenoid glycerol dialkyl glycerol tetraethers (OH-GDGTs), which are membrane lipids primarily produced by marine Thaumarchaeota (Lü et al., 2015). OH-GDGTs have been shown to be sensitive to sea surface temperature (SST), and the RI-OH’ and its derived SST are calculated using the following equations (Lü et al., 2015):”

Line 300: State the laboratory where this was conducted

Reply: The sentence will be updated as follows: Radiocarbon content analysis was performed using an Ionplus MICADAS accelerator mass spectrometer (Synal et al., 2007; Wacker et al., 2010b) at the Alfred Wegener Institute in Bremerhaven, Germany.

Lines 375-381: References to regional SLR

Reply: We will incorporate the reference (Klemann et al., 2015) into the relevant paragraph as appropriate.

Line 386: The BIT index does not follow the pattern of your other terrestrial markers during the YD. It might be beneficial to explore the potential of in situ production of brGDGTs complicating this signal- either here or in the discussion (i.e. Sinninghe Damsté et al., 2009, GCA; De Jonge et al., 2024, GCA).

Reply: Thank you for raising this point. We agree that the BIT index deviation from other terrestrial markers during the YD calls for further exploration of in situ brGDGT production. We will add a small paragraph in the Discussion section at line 553 to elaborate more on the BIT index deviation during the YD. The additional references (Sinninghe Damsté et al., (2009); De Jonge et al., (2024)) will be included. The revised paragraph will be written as follows: “During the YD, the BIT index does not show the same pattern as other terrestrial biomarkers, such as long-chain *n*-alkanoic acids, brGDGTs and lignin phenols. This discrepancy may reflect the potential for in situ production of brGDGTs within the marine environment, as has been documented in previous studies (De Jonge et al., 2014; Sinninghe Damsté et al., 2009).”

Line 469: Change similarly to similar

Reply: Revision will be done. “features” will be replaced to “featured”.

Line 480: Check spelling

Reply: Revision will be done.

Line 552: It is good to see the Fahl & Stein, 2012 sea-ice record in your supplementary figures, but it might be worth showing some of the other records that are frequently mentioned throughout the discussion

Reply: Thank you for this comment. The terrestrial biomarker records from Fahl and Stein (2012); Hörner et al. (2016); Lin et al. (2024); Meyer et al. (2016); Winterfeld et al. (2018); (Wu et al., 2020) will be added in the separate Fig. S2 in Supplementary information. These records were frequently mentioned throughout the Discussion section.

Line 506 and 587: Reference figure S1

Reply: (Fig. S1) will be added as reference.

Line 595: Especially

Reply: “Specially” will be changed to “Especially” in the revised manuscript.

Line 657: References to regional SLR

Reply: References for regional SLR (Klemann et al., (2015)) will be added in the revised manuscript.

Line 692: Here you refer to it as ICD, but in the introduction you primarily use *Yedoma*- try to make it consistent throughout

Reply: Thank you for this comment. We will ensure that the term *Yedoma* is used consistently throughout the manuscript to maintain clarity and uniformity.

Figures 2 & 3: Really clear and well-produced figures

Reply: We will make sure to add all relevant references in the caption.

General Reply:

We appreciate the detailed comments provided by the Reviewer. All comments, suggestions and concerns raised will be carefully addressed and incorporated in the revised manuscript.

References

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