

Dear Editor

Thank you very much for suggestions. We have revised the manuscript in accordance with the reviewers' comments.

- As noted by Reviewer 1, the manuscript states that two new sediment cores (U1304 and U1308) were analyzed. However, in the current version, the Results and Discussion primarily present and interpret data from U1304, while the presentation and role of U1308 remain unclear. Please ensure that the SST reconstruction from U1308 is clearly presented and described in the revised manuscript, including appropriate figures, description of the results, and discussion of its implications, or clarify explicitly its role in the study.

U1308 was not included initially due to the absence of foraminifera data at this site, as it was solely used for SST gradient calculations. In the revised version, we have explicitly incorporated U1308 into the updated plot. We also include new discussion on this site in the Results section.

- Please ensure that the structure of the manuscript clearly separates Methods, Results, and Discussion, as noted by Reviewer 1. Improving this structure will enhance clarity and readability.

We have improved the structure of the manuscript as suggested.

- Reviewer 2 raised important points regarding the interpretation of your results in the context of previously published Holocene SST reconstructions. Because your manuscript proposes a zonal asymmetry in Holocene SST evolution in the North Atlantic, it is important that your findings are more explicitly discussed in the context of existing reconstructions and considered within a broader geographic framework.

We included a new paragraph in the introduction to address this concern (line 47-56).

- Reviewer 2 also raised an important point regarding the seasonal bias of alkenone-derived SST, as illustrated in Figure S1, and its comparison with previous studies that report different seasonal signatures. Because your interpretation relies on the seasonal significance of SST-alk, please clarify the implications of the seasonal bias shown in your data and discuss possible mechanisms explaining similarities or differences with previous reconstructions.

Revisions have been made between lines 142 and 162 to discuss the seasonal context in relation to previous studies.

- More generally, please ensure that all reviewer comments are fully addressed in the revised manuscript.

I look forward to receiving your revised manuscript.

This manuscript by Si et al., titled "Late Holocene cooling and increased zonal asymmetry in the mid-latitude North Atlantic," presents new records of alkenone-based sea surface temperature (SST) estimates and planktonic foraminiferal analyses from two sediment cores in the North Atlantic. The authors integrated these new data with a suite of paleoreconstructions to examine the spatiotemporal trends of SSTs in the North Atlantic inter-gyre zone from the early to late Holocene. The study addresses an important topic related to the discrepancy between model simulations and proxy data, an important and still-debated "Holocene conundrum", and it has the potential to make a useful contribution to the field. However, in its current form, the manuscript requires revision before it can be considered for publication, specifically regarding the overall structure and flow of the manuscript.

Below I outline several concerns and suggestions that require the authors' attention.

Specific comments

Title: I think "Middle to late Holocene cooling" will be more appropriate.

Revised

Abstract: The authors should first present the results from their own cores (as it currently reads more like a synthesis of previously published data) and then demonstrate how these new data are integrated at the regional scale (mid-latitude North Atlantic) to support their findings regarding an increased zonal SST gradient in relation to inter-gyre circulation.

We have revised the abstract, with emphasis on what has been done in this study.

Introduction: The introduction is well written; however, in my opinion, the authors should better summarize previous studies in the North Atlantic and further discuss the current understanding of the mid- to late-Holocene cooling trend recorded by proxies in this region in order to more clearly identify the existing gaps.

We have revised the introduction to include a more comprehensive discussion of Holocene climate variability in the North Atlantic. Given the extensive literature on this topic, we focus primarily on studies that employ similar analytical methods and proxy types to those used in our work.

Sections 2 and 3: While Section 2 can be accepted as a regional setting, except for the last paragraph, which should be moved to the Materials and Methods section, Section 3 is

problematic and, in its current form, makes the manuscript more difficult to read. This section describes some of the methods adopted by the authors, namely the calculation of productivity-weighted SSTs and their comparison with (i) annual-mean SSTs to compute the differences and (ii) core-top SSTalk, and it also presents the results of these calculations. To improve the overall structure and flow of the manuscript, I suggest that the authors split this section between the Materials and Methods and Results sections, after first presenting their own reconstructions from the two IODP cores.

We have revised the manuscript structure by relocating Section 3 to the Materials and Methods section, where it is now designated as Section 3.4: "Estimation of Δ SST-alk and Seasonality in the North Atlantic."

We prefer to retain Section 2 as it provides essential background on the concept of inter-gyre circulation. While this information may be familiar to reviewers with expertise in North Atlantic climate, it may help readers who are broadly interested in Holocene climate but may not be familiar with these specific oceanographic processes.

Materials and methods section:

As highlighted above, a large part of the content currently included in the previous two sections should be moved here. I also recommend organizing this section into subsections to improve clarity and readability.

We have included titles for each subsection to help organize the text.

Age models: It is unclear why the authors used the Marine13 calibration curve rather than Marine20. The authors should also explain why the ^{14}C dates of the other cores included in their compilation were not recalibrated. Given that some of these records have low temporal resolution, it is not clear whether this choice could influence the calculation of mean SSTalk over the two selected time intervals.

Heaton, T. J., Köhler, P., Butzin, M., Bard, E., Reimer, R. W., Austin, W. E., ... & Skinner, L. C. (2020). Marine20—the marine radiocarbon age calibration curve (0–55,000 cal BP). Radiocarbon, 62(4), 779-820.

We did not re-calibrate previously published records. One of the records we used (MD95-2042; Darfeuil et al., 2016) is based on a fine-tuned age model aligned with speleothem records. For ODP Site 658, the original publication provides ^{14}C dates only in figures, limiting direct recalibration.

For our own records, we followed the reviewer's suggestion to generate new ^{14}C dates using the Marine20 calibration curve and updated the sample ages accordingly. We find that the resulting age differences are small. At Site U1304, this adjustment revises the ΔSST estimate to $1.65\text{ }^{\circ}\text{C}$; at Site U1308, the revised ΔSST is $0.04\text{ }^{\circ}\text{C}$. These updates have been incorporated into the revised figures.

We also identified an error in our initial estimation of $\Delta\text{SST-alk}$ at Site U1313 and nearby coretop records, caused by a typo in longitude that led to the extraction of data from an incorrect location. We have corrected this mistake. The revised $\Delta\text{SST-alk}$ is $-2.26\text{ }^{\circ}\text{C}$, which aligns consistent with the observed zonal pattern.

Results: Please present your new reconstructions first and then the result of your compilation as I suggested before. Why only SST-alk from core U1304 are presented here and in figure 2? I couldn't find those from U1308! Also, for paragraph 165, it's not clear from which core the alkenone concentrations are. This section should be substantially revised to make it clearer for the readers.

We present our results upfront. Initially, we included only Site U1304, as it was the sole site where we conducted foraminiferal assemblage analysis for direct comparison with our SST estimates. In this revised version, we have added SST data from Site U1308.

Discussion and conclusions: Overall, I found these two sections well written, except for some typos, which I have listed below.

Figures: The figures are of high quality; however, in general, their captions lack sufficient detail.

Figure 1: Please mark your two cores with different color. I also suggest to move Figure 1b to a new Figure 3.

Revised. Thanks for the suggestion.

Figure 2: Please add the name of the core for 2d and move the legend for foraminiferal assemblage to be in parallel.

Revised

Technical corrections

Lines 36-37: Please rephrase and further explain this sentence. How can variations in Earth's precession simultaneously cause both cooling and warming at lower latitudes?

We have revised the text accordingly and included a new citation to guide readers to the relevant discussion.

A recent study, for example, suggests that equatorial upwelling is dynamically coupled to the large-scale overturning circulation (Toggweiler et al., 2019) and is sensitive to precessional forcing. This linkage allows precession to directly influence tropical warming and cooling by modulating oceanic heat uptake and transport at low latitudes, potentially contributing to global Holocene temperature trends (Toggweiler and Si, 2025).

First paragraph of the Materials and Methods section: Please provide more information about the two cores (e.g. water depth, core length, and geographical location). In addition, please indicate here that core ODP U1304 was also used for planktonic foraminiferal analyses.

Revised

Line 217: Please add references.

Revised. (Thornalley et al., 2009)

Line 218: What do you mean by “Starting ~11 ka”?

Revised as: Beginning around 11 ka, paired Mg/Ca- $\delta^{18}\text{O}$ measurements of the thermocline

Line 225: Please rephrase this sentences for more clarity.

We replace this sentence as: Primary productivity proxy, derived from total alkenone concentration ($\text{C}_{37\text{total}}$), also supports enhanced ventilation in the subpolar region between approximately 11 and 6 ka (Figure 2c).

Lines 233-234: Please add the core names used by Colin et al., 2010 or add "Rockall Trough" on Figure 1.

Revised in both text and figure.

Lines 236 and 238: Please be consistent when you write "subpolar mode water".

Revised

Line 245: Please explain how “the termination of deglaciation after ~8 ka” has strengthened the subpolar gyre.

Revised as: In case of the mid-Holocene, reduced freshwater input likely improved Labrador Sea ventilation as deglaciation concluded after ~8 ka, contributing to a strengthening of the subpolar gyre.

Line 247: “Nevertheless, the effects of stronger subpolar convection appear to have been limited to subsurface layers or winter conditions.” Please further clarify the underlying assumption and support it with appropriate references from the existing literature.

We revised as below: Nevertheless, the effects of stronger subpolar convection appear to have been limited to subsurface layers or winter conditions. This is evident from sea surface temperature reconstructions at ODP Site U1304, where SST-alk records indicate persistently warm conditions between ~11 and 6 ka. Likewise, diatom and foraminifera assemblages from the Nordic Sea indicate optimal conditions persisting until ~ 7ka (Andersson et al., 2010; Koç et al., 1993), further suggesting that enhanced convection did not significantly alter surface conditions during this period.

Line 262: “a weaker subpolar gyre over the last 6 kyr” are you sure? According to Törnålle et al., 2009, the subpolar gyre oscillated between weak and strong phases during the last 6 ka.

We agree with the reviewer’s comment. Törnålle et al. (2009) showed that the subpolar gyre has oscillated between weak and strong phases over the past 6 ka. A strong subpolar gyre enhances the Atlantic subsurface inflow, resulting in fresher conditions. However, our discussion focuses on long-term changes, as inferred from the co-variability of alkenone C37 data, ϵNd isotope records, and subsurface salinity (Section 6.2.3, Figure 2 b and c). In light of this, we have revised the relevant sentence to clarify our interpretation: Unlike during the mid-Holocene, an overall weaker subpolar gyre over the last 6 kyr, as inferred from the multi-proxy evidence

above, does not appear to have been compensated by a recovery in subtropical circulation at mid-latitudes.

Line 267: please change “millennials” to “millennia”.

Revised

Line 279: Maybe I am missing something here, but I can't see any Red arrow in Figure 1a.

We removed the red arrows during figure preparation, as they were not essential for conveying the general point. We apologize for not updating the manuscript accordingly.

Lines 280-283: We can't see this information from Figure 2e!

Apologize for not being clear. The sentence is revised.

This relatively cold SST associated with tropical upwelling is well documented in temperature reconstructions from planktonic foraminiferal assemblages at ODP 658 (Figure 2e, deMenocal et al., 2000), which are dominated by *G. bulloides*—a species indicative of nutrient-rich upwelling waters at low latitudes (fauna data in Figure 2 of deMenocal et al., 2000).

Line 284: “Enhanced summer heating” when and where?

Revised. Enhanced summer heating over the northern continents during the mid-Holocene ...

Line 287: “during this period” please indicate the time-interval here.

Revised. “during the mid-Holocene”

Line 290: Please change “In the late Holocene” to “During the late Holocene”.

Revised

Line 294: "Consequently, the east-west SST gradient reversed" from what to what? Please explain further.

Revised. This weakening also explains the observed reduction in upwelling intensity and surface warming at Site 658. Together with the cooling to the east, the cross-basin SST gradient reversed, transitioning from a positive west-to-east gradient to a negative one.

Line 395: Please change “The late-Holocene summertime cooling” to “The mid- to late Holocene ...”

Revised

First all apologies to submit my recommendation so late.

The article 'Late Holocene cooling and increased zonal asymmetry in the mid-latitude North Atlantic' by Si, Herbert and Toggweiler present new alkenone-derived SST and concentrations from the North Atlantic and collate them with other records for the region to decipher how the present-day sub polar frontal zone has evolved during the Holocene. The aim is to help understanding better the global Holocene conundrum with a focus on the mid-latitudes North Atlantic, with a special emphasis on a recent hypothesis that states that precession could directly trigger warming and coolings in the tropics (Toggweiler and Si, 2025).

The article reads well and, in my opinion, could be published after minor to moderate revisions. I am listing these suggestions in the order of appearance along the article.

Line 61: should read 'SW-NE' tilt I guess?

Corrected.

Chapter 3: The productivity-weighted SST calibration is a very interesting approach. There are already efforts to accommodate regional calibrations in the North Atlantic (Filippova et al., 2016) and productivity-weighted (Schneider et al., 2010) that perhaps should be discussed, along with the limitation that any past changes in regional paleoceanography would inevitably alter the SST estimation based on the UK'37 but, at least for the North Atlantic, I find it quite convincing. Since you suggest a similar approach that in Schneider et al., 2010 for their productivity-weighted seasonal signal, but have different results in the southern ocean (opposite signs), please explain a little more with appropriate equations (line 95) how was computed your map in the supplementary information.

We thank the reviewer for bringing up the studies by Filippova et al. (2016) and Schneider et al. (2010), which escaped our attention at the time of writing. We have now incorporated a discussion of these works in the revised manuscript.

Our approach to calculating the productivity-weighted sea surface temperature (SST) in Figure S1 is simpler compared to that of Schneider et al. (2010). At each grid cell, we compute the weighted SST as: $(NPP_i * SST_i) / \sum NPP_i$, where the index i represents individual months, and NPP_i and SST_i denote the monthly net primary productivity and sea surface temperature at that grid, respectively.

We appreciate the reviewer's observation regarding the differing results in the Southern Ocean compared to Schneider et al. (2010). We currently do not have a definitive explanation for this

discrepancy. But we note that existing core-top data from the Southern Ocean also exhibit mixed signals, suggesting regional complexities and highlighting the need for further investigation.

Results: You should show the U1308 data at least once, even if not all the Holocene has been measured, as it is, as I understand, a new set of unpublished data. Only a gradient testifies that those data actually exist in Figure 4, but the full U1308 Holocene SST record should at least be shown also in Figure 2, aside that of the one derived from site U1304. Also, I would recommend plotting the age control points directly on the two new sediment records you publish at the bottom of the timescale (e.g. triangles), so the reader could easily evaluate the quality of the age model. Finally, sometime around 6 ka you have a step-like decrease in SST that is poorly commented. Is this change seen in the other record? It probably means something interesting, such as a SST front movement around core location(s). Please be less eager to dismiss the structure of your SST timeseries and invest more in commenting your results before rushing on a broader interpretation.

Revised. We labeled age control points and also include SST of U1308 in main figure.

The reviewer is correct that the rapid surface cooling at ~6 ka appears to be approximately synchronous with the abrupt termination of the African Humid Period. We have highlighted this connection at the beginning of Section 6.2.3, and further elaborated on it toward the end of the section, where we discuss how wind-driven inter-gyre circulation may be linked to summer heating over northern continents. That said, we fully acknowledge the ongoing debate regarding the nature of the African Humid Period's termination, whether it was abrupt or more gradual.

In Figure 5 you show the early/mid-Holocene result extracted from the TRACE transient run. It would be useful to compare it with the PMIP ensemble-mean multi-model output for the mid-Holocene since all models could capture those frontal zones quite differently. A nice example that you did not discuss, too, is the model output from the MITgcm model that was used by Sachs, 2007, Geophysical Research Letters. In fact, the striking difference in the magnitude of the Holocene cooling btw the East and Western part of the Atlantic are all driven by an extreme cooling recorded in the 3 cores published in Sachs, 2007. These cores are apparently strongly influenced by the slope waters of the Northwest Atlantic region, that are rightfully captured by the MITgcm model seen in the publication by Sachs. 20 years later, models have evolved so much that they could help documenting what is happening in this NW corner of Nova Scotia

probably much better than the MITgcm seen in the Sachs publication. This is another point that should be scrutinized in more details, too, in my opinion

We selected TRACE-21k because it is one of the few transient climate simulations capable of capturing the dynamic evolution of climate from the LGM through to the Holocene, a key advantage over earlier PMIP simulations, which are typically designed to approximate equilibrium climate at discrete time slices. Moreover, the ability of models to realistically simulate critical oceanic features, such as western boundary currents, ocean fronts (e.g., the NAC), and the East Greenland Current, which supplies cold, fresh water to the subpolar gyre, depends strongly on spatial resolution. Given their coarser resolution, many earlier generations of fully-coupled models are likely insufficient for accurately representing the complex ocean–atmosphere dynamics in this region. This is why we included a newer version of the model with higher resolution (TraCE-21K-II, Figure S3). Notice that the newer model begins to capture a localized cooling along the East Greenland coast, although greenhouse gas–driven warming still dominates across much of the North Atlantic.