

## Reviewer 1

Dear Reviewer 1,

Thank you for your review and helpful suggestions.

Please find the responses to your comments below.

On behalf of all co-authors,

Anne-Marie Wefing

*Note: Reviewer comments in black (lines refer to the original manuscript), response in blue*

### General Assessment

This is a well-executed and ambitious study. The methodology is robust and clearly presented, and the figures—both in terms of quality and content—are excellent. However, the manuscript's organization and presentation could be improved. Given the amount of data and analysis presented, these adjustments are non-trivial but will significantly enhance readability. That said, some of these suggestions are inherently subjective.

**Title.** Recommendation: The current title focuses narrowly on Atlantic Waters, but the manuscript covers a broader range of water masses. Consider adjusting the title to reflect this broader scope, even in the abstract, where Atlantic water is only discussed in the final paragraph. Options might include:

Thank you for this comment. We agree that the title was not entirely representative of all the content in the manuscript and thus suggest the following revised title: "Changes in water mass composition and circulation in the central Arctic Ocean between 2011 and 2021 inferred from tracer observations"

### Section 3.

**Terminology:** Use terms consistently—e.g., choose either potential temperature or temperature, and salinity or practical salinity throughout.

Changed to "potential temperature" and "practical salinity" everywhere.

**Quantification:** Reduce the use of vague comparative language such as "around," "slightly more," or "much higher." Instead, refer directly to measured values, as these are available in the figures.

We reduced the use of vague language and refer the reviewer to the tracked-changes document.

Narrative Style: The figures are beautiful and highly informative—consider letting them speak more for themselves. The current text is thorough, but some passages feel overly explanatory, which detracts from readability.

Thank you for your positive feedback on the figures. We carefully considered your suggestion and tried to shorten the description where possible. However, we believe that a certain level of detail remains important to guide readers who may not be familiar with the field of tracer oceanography.

Section 3.3–3.6: These could potentially be moved to the Discussion, as they begin to interpret rather than purely describe.

In the first version of the submitted manuscript, these sections were part of the Discussion. Following the suggestions from reviewer 2 in the first round of reviews, we moved them to Results, so we would like to keep them this way. However, in order to avoid overinterpretation in the Results section, we have now removed some parts that were not purely descriptive .

Idea: It would be helpful to define Sections 1 and 2 by station numbers and geographic location early in the manuscript. This would eliminate the need to repeatedly remind the reader later. Maybe abbreviate to S1 and S2..

Sections 1 and 2 are now defined in Methods (section 2.1) and we shortened/adjusted the text referring to the sections in Results. We decided against an abbreviation, we think it is clearer referring to them as “Section 1” etc.

#### **Section 4.**

Some subsections (4.1, 4.5, 4.6) feel underdeveloped. Suggest adding a short note on uncertainty due to data resolution. Consider explicitly addressing the uncertainty introduced by the spatial and temporal resolution of the datasets. This would strengthen the interpretations, particularly those related to circulation patterns.

We added some notes on the limited temporal and spatial coverage to sections 4.1 and 4.5. Section 4.6 already includes a note on the better temporal resolution required for addressing long-term changes, which we feel captures the uncertainty due to data resolution (“Also, an extended temporal coverage with high spatial sampling resolution across multiple Arctic basins is probably required for the mid-depth layer, since changes occur more slowly than in the surface layer.”).

**Recommendation: Recommended for publication.**

## Specific Suggestions and Comments

**Lines 1–20:** The abstract would benefit from streamlining and reorganization. Consider introducing both new and historical datasets earlier, as both are essential for analyzing temporal changes — and should only be introduced once. For example, move the sentence starting with “Temporal changes in the circulation [...] between 2011 and 2021” (line 15) closer to the beginning to clarify the study’s focus.

The abstract has been changed according to the reviewer’s suggestions.

**Line 5:** Remove “mainly” — both datasets are necessary to characterize Atlantic Water (AW) changes.

removed

**Line 28:** Add original citations for the stated information.

We added references to Manabe & Stouffer, 1995, and Rahmstorf, 1996.

**Line 32:** Replace “driven” with “linked to” or “associated with” — warming is likely the true driver.

replaced

**Line 41:** Replace “was” with “is,” or clarify the time frame. Consider citing Smith et al. (2021) here, as it discusses AO-related boundary current changes.

replaced

**Line 47:** Use “the two *primary* large-scale circulation patterns.”

changed

**Line 49:** Add original references.

We added references to Aagaard & Carmack, 1989, and Carmack, 2000.

**Lines 70–73:** Remove “extensive.” Add original sources: e.g., Polyakov et al. (2005) use T anomaly propagation, Dmitrenko et al. (2008), Woodgate et al. (2001), Li et al. (2021). For tracers, include Frank et al. (1998); Broecker & Peng (1982) may not be the best reference for CFCs/SF<sub>6</sub>.

Removed “extensive”. We added references to Woodgate et al. (2001), Polyakov et al. (2005), Dmitrenko et al. (2008), Li et al. (2021) for hydrographic measurements, and to Frank et al. (1998) for gas tracers.

**Figure 1:** Consider color-coding historical data by cruise or sampling year for clarity.

Thank for pointing this out. Figure 1 has been updated, now also including the stations shown in the isosurface map in Figure 6, which were missing before. Different symbols now denote different sampling years.

**Line 89:** Also cite Smith et al. (2011).

Smith et al 2011 did not combine I129 and U236, so we added the reference at the beginning of this paragraph instead, about the general use of anthropogenic radionuclides as Atlantic Water tracers in the Arctic.

**Line 95:** Add a supporting citation.

We added references to Smith et al. (2011) and Wefing et al. (2021).

**Line 98:** Add a reference for the statement about timescales “on the order of decades or below.”

We added references to Solomon et al. (2021) and Polyakov et al. (2025).

**Line 103:** Cite a source for the convergence of waters before exiting via Nares or Fram Strait.

We added references to Newton & Sotirin (1997) and de Steur et al. (2013).

**Line 107:** Replace “Arctic system” with a more specific term (e.g., Arctic Ocean circulation or stratification).

Replaced by “circulation in the Arctic”

**Line 139:** “Data from *six* expeditions.”

changed

**Lines 142–145:** Use original references.

We added references to Smith et al. (1998, 1999, 2005), Steier et al. (2008), Sakaguchi et al. (2012).

**Lines 158–159:** Remove the phrase referencing Raimondi et al. (2024) and Payne et al. (2024).

removed

**Line 180:** Rephrase to “This model calculates mixing lines...” for clarity.

rephrased

**Line 195:** Clarify whether “mid-depth” here matches the typical depth range used for AW elsewhere in the manuscript.

Yes, this has been clarified.

**Lines 245–249:** Consider revising to: “Station 5 shows a sharp decrease between 700 and 1000 m.

We are not sure to what the reviewer is referring here, since a sharp decrease between 700 and 1000m was not observed for station 5.

**Line 280:** “Color-coded” may be redundant — consider removing.

removed

**Line 306:** “Close to the temperature maximum” — is this referring to the AW core? Clarify.

Yes, this has been clarified.

**Line 319:** Sentence beginning with “The compilation of available 129I data...” may not be necessary — consider cutting.

removed

**Line 330:** Rephrase: “To account for differences in sampling depths and water mass composition...”

rephrased

**Line 333:** “Very low” may be unnecessary — consider deleting.

deleted

**Lines 343–345:** Replace “shallow” with “surface waters” for consistency.

replaced

**Line 365:** [Appears incomplete — please confirm if something’s missing.]

We have modified the sentence to “The TTD parameters  $\Gamma$  and  $\Delta$ , and the derived  $\Delta/\Gamma$  ratio and  $t_{mode}$  for SAS2021 and JOIS 2020 (Canada Basin) are presented in Fig. 8.” and hope this improves readability.

**Line 411:** Clarify which layer is being referred to — “surface” vs. AW could be confusing. Add original Rudels reference.

Sentence changed to: “The circulation times obtained for Atlantic Water in the surface layer in 2021...”

Reference changed to Rudels 2009.

**Line 431:** Rephrase and support with citations: e.g., “Because 129I is introduced via Atlantic waters and diluted by Pacific inflow, its distribution across the SAS2021 section reflects the Atlantic–Pacific water mass composition in PSW.”

Changed accordingly and references added.

**Line 531:** Sentence on TTD-derived mode ages not needed in the Discussion — already addressed in Results.

removed

**Lines 564–571:** Quantify terms like “slowdown” and “increasing ages” for accessibility to broader readership.

We added that the slowdown is between 3-8 years, depending on the location and depth.

**Lines 598–600:** Consider omitting this restatement if already covered earlier.

We believe it is still important to repeat this statement here in the Conclusions, even though it was covered in the Results already, since it is an important finding of this study. We shortened the sentence to “Along the transect of the SAS2021 expedition, we observed a sharp drop in radionuclide concentrations in the surface layer between the Amundsen and the Makarov Basins, directly at the Lomonosov Ridge.”

**Line 615:** This is the first  $^{129}\text{I}$  and  $^{236}\text{U}$  dataset north of Greenland — highlight this earlier, perhaps in the abstract.

This has been added to the abstract.

**Line 651:** Add a sentence defining equation terms: e.g., “...where  $f_A$ ,  $f_{\text{Pac}}$ ,  $f_{\text{SIM}}$ , and  $f_{\text{Met}}$  represent the fractions of Atlantic Water, Pacific Water, sea-ice melt, and meteoric water, respectively.”

added

## Reviewer 2

Dear Reviewer 2,

Thank you for your review and helpful suggestions.

This response letter includes responses to your comments, outlined below.

On behalf of all co-authors,

Anne-Marie Wefing

*Note: Reviewer comments in black (lines refer to the original manuscript), response in blue*

First, I want to apologize for the time I have taken to re-review the manuscript. I should have been faster but my agenda has filled up faster than I could keep up.

Second, I want to thank the authors for the large efforts to restructure the manuscript. I am very honestly impressed and have really not much more to say than that this is excellent work. The little more I would like to be addressed is here:

### Major

While I get why it is important how the circulation works, wouldn't it be possible to show some implications of changes between Atlantic and Pacific waters? I understand that this shift is not the main part of this paper but it is what you can analyze, in addition to the slowing of the Atlantic water circulation. It would really be helpful to better explain why it is important to know if there is a difference. Does it effect carbon or nutrients, does it affect sea ice, or ocean heat uptake or ecosystems? Basically, if I am not an oceanographer with an interest in the Arctic, it becomes hard to understand why this importance is important beyond the fact that the Arctic is important in general. There might not be space in the abstracts but at the end of the first paragraph of the Introduction, you could explain how changes inside the Arctic Ocean specifically impact the north Atlantic. Which change of which current would cause bad results for Atlantic Overturning, for example. Also, it could be interesting to say what a larger extend of Pacific waters at the surface in the Arctic might mean or what a slowdown of the Atlantic waters at depth could mean.

Thank you for your comment, we have expanded the introduction to include the impacts of changes in the Atlantic-Pacific Water distribution in the surface layer and of changes in circulation in the Atlantic layer. We hope the motivation for this study is now clearer and refer to the tracked-changes version of the manuscript.

## Minor

Lines 3 and 4: I would suggest reordering the sentence to follow the principle “old before new” by moving the circulation that you study to the beginning of the sentence and the radionuclides to the end of the sentence. That would then directly link to the next sentence that starts with the radionuclides.

Changed to: “Here, we investigate Atlantic Water circulation in the central Arctic Ocean in 2021 and to assess temporal changes thereof between 2011 and 2021 by using the long-lived anthropogenic radionuclides  $^{129}\text{I}$  and  $^{236}\text{U}$ .”

Line 7 and 8: Similar suggestion, it might be easier to read when you first say what you are looking at and then say with what you are going to look at it.

Changed to: “We obtain tracer ages as well as the mixing of different endmembers in the surface layer from a mixing model.”

Line 10: Is significant used in a statistical sense? Otherwise, I’d suggest to replace it by substantial or a similar word.

Changed to “substantial”

Lines 14 to 15: Are we still in waters north of Greenland or is this sentence about halocline waters? I am a bit confused if it means that Pacific waters take more time than Atlantic waters or that Atlantic waters take more time on one side of the ridge than on the other. Please clarify. I think that it would be highly important to say that you speak of Atlantic waters in both cases, and that they take different routes with different transport times.

Changed to: “Circulation times of Atlantic Water in the mid-depth layer point to a longer transport route on the Makarov Basin side of the Lomonosov Ridge compared to the Amundsen Basin.”

Lines 16 to 18: Please clarify that you talk about surface waters to avoid confusion.

Changed to: “In the surface layer, we find a shift of the Atlantic-Pacific Water front from the Makarov Basin towards the Lomonosov Ridge from 2011/12 to 2015 and 2021.”

Lines 24 to 26: Between physics and ecosystems, there is also the biogeochemistry with changes in acidification and primary production. Maybe worthwhile to add this here.

Added, including a reference to Juranek (2022).

Paragraph 2 of Introduction: Maybe also add a sentence or two on the consequences for the Arctic of this Atlantification in terms of sea ice and biogeochemistry.



We added the following at the end of paragraph 2: With respect to biogeochemistry, the shift to more Atlantic-like conditions might increase nutrient availability and potentially also support projected increases in primary production (Henley et al. 2020).

Paragraphs 2 and 3 of the Intro: Maybe also add something of enhanced freshening and potential consequences.

We added the following at the end of paragraph 2: Further, enhanced freshening of the Arctic and resulting changes in stratification also affect sea-ice growth and primary production (Ardyna and Arrigo, 2020).

Lines 94 and 95: Please indicate a bit more precisely why the surface can be used for radionuclides. I know it is almost obvious but it would not hurt to say that the radionuclides are not mainly entering the ocean from the surface.

Changed to: “In contrast to CFCs and SF<sub>6</sub>, <sup>129</sup>I and <sup>236</sup>U can also be used to assess circulation times in the surface layer, which is in contact with the atmosphere, as they are introduced mainly via liquid discharges and not through air-sea gas exchange.”

Figure 8: It looks strange to see 3 times AB in the figures on the x-Axis. Maybe add a subscript or something to clarify that each point is another station.

Changed

Line 414: Transport of what? Please try to be more precise to allow for a good understanding

Sentence changed to: Young waters with high tracer concentrations found in the central Amundsen Basin suggest a more direct transport of waters containing the tracer signal compared to the southern Eurasian Basin, potentially as part of the Transpolar Drift

Lines 414-419: If I understand it right, the high age comes from the transport times and the low concentration from both, the transport time and the dilution. However, the dilution does not affect the age as that comes from the mixing line? Wouldn't it be better to separate the sentence to make that clear. I am not even sure if my understanding is correct.

The sentence has been separated into: “The much higher tracer ages (30-50~years) in PSW samples from the Canada Basin (JOIS2020, grey squares in Fig. 7) compared to the SAS2021 samples from the central Arctic are due to the longer travel time of Atlantic Water to the Canada Basin. The higher dilution of the tracer signal in the surface Canada Basin is explained by the fact that mainly Pacific Water is present at the surface.”

Further clarification: The ages are obtained from the mixing lines, i.e., the concentration of <sup>129</sup>I relative to <sup>236</sup>U (changing over time due to different shapes of input functions of both). The dilution is obtained from the absolute concentration of both tracers.

Line 535: You can remove the last sentence and add the references to the sentence before, I think.

removed