Manuscript: Circulation timescales of Atlantic Water in the Arctic Ocean determined from anthropogenic radionuclides

Response to RC2
(comment posted 10 June 2025)

Dear RC2,

Thank you for your review and helpful suggestions.

This response letter includes responses to your comments, outlined below. The manuscript has been substantially restructured and large parts have been moved from the discussion to the introduction, methods, or results part. Furthermore, figures and corresponding text have been changed to refer to practical salinity instead of absolute salinity throughout the manuscript. We hope that the restructured and rewritten manuscript now transfers the main messages better.

On behalf of all co-authors,

Anne-Marie Wefing

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

The manuscript by Wefing et al. presents interesting results obtained from radionuclides that allow to further study changes in the Arctic Ocean circulation. I believe that the manuscript will be an important contribution to Arctic oceanography after major revisions. While I have few comments on the methods, results, and conclusion, I believe that the presentation of this study, i.e., the writing and organization of the manuscript has to be substantially improved. I am not referring to the English language but to the structure of the manuscript and the introduction of key concepts. In the following I will give examples of improvement. However, I will refrain from too many detailed word-by-word comments as I expect the text to be largely adapted after revisions. It is my strong believe that a large reconstruction of the manuscript will improve the flow of the text drastically and allow the great results to be better grasped by the reader.

Major points:

- Large parts of the discussion are actually results of methods. Here is a list that is likely not complete:

- Section 4.1.1: First paragraph belongs into methods; second paragraph is results
- Section 4.1.3: First paragraph is a mixture of methods, results, and figure legend, the beginning of the second paragraph is also rather results.
- Section 4.1.4: Second paragraph is methods; second paragraph is results; last paragraph is also full of results
- Section 4.2.1: First paragraph contains many results; second paragraph is a mixture of results and methods; third paragraph also contains many results
- Section 4.2.2: First paragraph is methods; second paragraph is partly results; third and fourth paragraphs are results.
- Section 4.2.3: Large parts of the first paragraph and the second paragraph should probably be introduced in the Introduction

As a consequence of having large parts of the results, methods, and introduction in the discussion section, parts of the conclusion repeat or summarize the results. After all sections are clearly separated, the Discussion will likely substantially decrease and now repetition will be needed in the Conclusion and also lead to a substantial reduction of its length.

The manuscript has been restructured and large parts of the discussion have been moved to the results section, some to the methods or introduction sections. The conclusions have been shortened. Figures, incl. those in the appendix, have been rearranged to fit to the new structure.

The Introduction does not seem to fit well enough to the rest of the paper. The scope of the study appears to me the placement or change in the shift of the Atlantic-Pacific waterfront in the Arctic Ocean. Reading the Introduction it remains unclear why this position actually matters. I also found that couple of concepts are not well enough introduced. The first paragraph is about atlantification, the second one about the flow of Atlantic and Pacific waters in the Arctic Ocean, the third one about the depth structure (difficult to follow, please see detailed comments in the minor comments part), the last paragraph is somehow about the connection to the global ocean and turns into a description of radionuclide studies in the Arctic (these two topics do not fit well into one paragraph). Afterwards there is a new section in the Introduction going into details of radionuclides, starting with a paragraph about the sources of two such radionuclides, the second one is about the flow of these radionuclides into the Arctic, the next paragraph is about classical tracers such as CFC-12 and SF6, the next one is about the difference between the classical to non-classical tracers, the last one is about the aims

of the study. While I think that the second subsection is well structured, I am left confused with the first one. After reading it, I am missing information about the importance of the study here. What is the problem that is going to be solved? What is the question? Afterwards, in the discussion, that is introduced when discussing literature about shifts in the frontal zone between Pacific and Atlantic water. I believe it would be crucial to bring all this up here. It would also help for the reader to explain why it matters if the boundary between Atlantic and Pacific waters moves a bit. At the moment, it is not even clear to me but I still find the application of the new tracers interesting. However, despite being an interesting application, the Introduction leaves me in the unknown why I should care about this application apart from a demonstration of the methods. It would therefore be of great importance to better explain the importance of this question. To do that, I would probably structure the first part as follows: 1) The Arctic is changing fast: changing sea ice, changing primary production, changing acidification, changing temperature, changing carbon sink, etc. 2) A large amount of these changes is driven by changes in the circulation (try to bring a few examples), Finish with a sentence stating that knowledge of the circulation and its changes is limited due to limited numbers of observations, 3) describe what we know about the flow paths, 4) describe what we know about the vertical column, 5) describe known changes over the last decade or two and known uncertainties. Say that it is a problem not to know because it makes it hard to assess changes and to make projections (if that is the main reason why we need these tracers). You can finish than with a brief sentence that tracers, such as radionuclides and CFCs can help. Then you can move to the second part of the Introduction. To me, that sounds more intuitive, but maybe you have a better idea or prefer your text.

The introduction has been restructured. The focus of this study is not particularly the AW-PW front, but the overall changes in the distribution and circulation times of Atlantic Water over time, and how anthropogenic radionuclides can be used to this purpose. This hopefully became more clear also through the restructured discussion. The detailed description on the use of I129 and U236 as tracers in the Arctic has been moved to the methods part.

Usually, I would not add this to the major comments but the word ‘note’ is used far too many times in my opinion. I am not sure if it is correct, but I had learned a while ago during my studies that ‘note that’ or ‘it should be noted that’ should not be used in scientific writing. If something is noteworthy, I was told, it should be written in a way that the reader knows it is noteworthy. Given the numerous times this word is used, I believe removing it can substantially reduce the text and improve readability.

Sentences containing the word ‘note’ have been rewritten, please refer to the track changes manuscript for details.

Minor comments:

- The first sentence of the abstract is hard to understand as it remains very unclear what and how circulation changes contribute to Atlantification and what processes of Atlantification are meant. It is also unclear what role the Arctic circulation plays in these processes.
- The second sentence of the abstract talks about recent variability and trends. It is unclear what variability and trends the authors are referring to. It is also unclear why the circulation needs to be better understood
- Sentence three in the abstract could be improved by relying on the 'old-before-new' principle. If the sentence was started with: "Here, we investigate the Atlantic water ciruculation times and mixing in the Arctic Ocean to better understand the mixing between Atlantic and Pacific Waters using…", the reader would first be referred to what they know from the previous sentence before going to the new subject, i.e., radionuclides and TTD.
- The sentence from line 8 to 9 does not fit here. First you write about the data from 2021, then you talk about changes in this sentence, then you go back to 2021 and finally you go back in line 15 to temporal changes. I'd suggest moving the sentence in line 8 to 9 to line 15. That would also allow you to safe some words in line 15.
- Line 11: I am not sure what below refers to? Below the surface? Please precise.
- Line 11: I am also not sure what similar refers to, similar to what? And comparably high compared to what?
- Line 14: Similar: higher circulation times than what?
- Line 15 to 16: Please indicate what kind of shift you find, a shift towards the Eurasian basins or another direction. Just a shift, is not informative enough. Also please indicate the distance of the shift.
- Last sentence of the abstract: I would re-order it and say that the increase in mode ages suggests a slowdown of the AOBC, which is in line with recent studies basied on gas tracers.

The abstract has been rewritten, taking the comments above into account. Details have been clarified. Since we do not calculate absolute water mass fractions from I129, but only use the concentrations to derive qualitative changes, we refrain from giving a quantitative estimate of the shift of the AW-PW front.

- Section 1.1: First paragraph: There are often missing links between the sentences. The first one is about Arctic amplification. The second one is direction about a special reason and a new concept, Atlantification. It remains unclear how the third sentence connects to the second one. The fourth sentence then connects to the second one although the connection only becomes clear at the end of the sentence. The last one then connects to the one above. Please try to restructure the paragraph to better connect the sentences and think what the topic of this paragraph really is, Arctic amplification as mentioned in the first sentence or Atlantification as this is the topic of most sentences in the paragraph.

  As mentioned above (under major comments), the introduction has been restructured and rewritten.

- Line 37: How is the upper layer defined? The surface layer? But Pacific winter waters also sink below? Please be precise:

  This has been rewritten as follows: "The PSW layer is highly stratified and generally entails Pacific Water, river runoff, sea-ice meltwater, as well as transformed Atlantic Water. Pacific Water enters the Arctic Ocean through Bering Strait, mainly resides in the Canada and Makarov basins, and is restricted to the PSW layer due to its low density…"

- Paragraph 3 of the Introduction: It is hard to follow this paragraph, although I am familiar with the physical oceanography in the Arctic. I have no precise advise how to restructure it at hand right now, but I'd strongly suggest to give it another try. In line 43, it is for example not clear what 'it' refers to, in line 44 it would be helpful to be more quantitative and not just write 'deeper' (is it deeper than something else?). I am really puzzled after this paragraph.

  This paragraph about the Arctic Ocean water column has been rewritten and slightly extended to include the mid-depth Atlantic layer as well as intermediate and deep waters.

- Paragraph 4: The topic sentence is about connections to the global circulation and the paragraph about radionuclides. It remains unclear how the connection works, and how changes impact regions beyond the Arctic Ocean. Please expand this explanation substantially and then cut the paragraph once you go to the past tracer studies.

  The description about the connection of the Arctic Ocean to the global circulation has been moved to the first paragraph of the introduction and extended.

- Section 1.2, first paragraph: I am confused that U236 is mainly introduced via global fallout but still the liquid release is dominant in the Arctic. Could you clarify this please?

  This has been clarified in the text (line 141-144 of the revised manuscript).

- Line 79 and 80: You say that the concentration and distribution was assessed in the Canada Basin but you do not say what was found and why this matters. Without that information, this sentence is not really helpful to the reader.

  This sentence has been removed.

- In the major point I have not really said anything about paragraph 3 of section 1.2, but I would likely introduce these tracers first in the section as they are older and then you can introduce your new tracers with their distinct advantages. This would likely even increase the importance of the new tracers.

  This section (now section 1.3) has been restructured.

- I'd suggest cutting the sentence from line 85 to 87 in two sentences for improved readability.

  The sentence has been split in two.

- Line 116: Do you really need the second reference? If it is also described in the first one, I am not sure what the second reference adds. If it adds something, please describe its additional value. Same goes for line 124.

  The second reference has been removed in both places.

- Lines 134 and 135: The part of the sentence that starts with ", which are listed … " can just be replaced by "(Table 1)" to safe words.

  This has been shortened.

- Lines 194 to 196 can easily be added to the figure legend and to not need to be part of the main text.

  This part has been moved to the figure legend of Figure 3.

- Figure 4: I found it very hard to distinguish the colors of this colormap. It might be an issue with my eyesight but I'd like to encourage the authors to adjust or change the colormap.

  All colormaps were chosen according to recent scientific studies (Thyng et al., 2016, https://doi.org/10.5670/oceanog.2016.66; Crameri et al., 2020, https://doi.org/10.1038/s41467-020-19160-7). We are not sure which panel/colormap of Fid. 4 the reviewer is referring to. We have increased the size of the datapoints in panel c and d.

- Line 198: It might be more easily to read if ‘Section 1’ would be replaced by a more descriptive name like ‘Eurasian section’ or ‘Section through the Eurasian basins’.

  This has been rewritten to “For all profiles from the Eurasian Basin section (Section 1), …” (line 235).

- Line 211: In the Introduction, these fallout levels were never quantified.

  The global fallout levels for both radionuclides have been added to section 2.2 (line 146).

- Line 214: Similar to above, I’d suggest replacing ‘Section 2’ by a more descriptive name.

  This has been rewritten to “For the section through the Makarov Basin and north of Greenland (Section 2), …” (line 251).

- Line 221: Is the word significant used here to describe statistically significant values? If not, I’d suggest replacing it by substantial or a similar word to avoid misunderstandings.

  Has been replaced by “substantially”.

- Lines 225 to 226: Please try to be more quantitative, maybe in %?

  Decrease of I129 concentrations in % has been added.

- Line 229: Is this also related to a change in the MLD?

  The change in salinity is related to a change in water mass composition, i.e., more Pacific Water in the Makarov Basin. The same holds for the change in I129 and U236, which are diluted by Pacific Water and freshwater in the MB. The MLD decreases from EB to MB, the water column is more stratified in the western Arctic (MB). We do not assume that the change in MLD generally leads to a change in tracer concentrations.

- Line 236: especially above 32 or only at salinities above 32?

  This applied only to salinities above 32, so “especially” has been removed.

- Line 241: This is not really a topic sentence. It would be easier to read to state here the main message of the paragraph and not just the figure legend of the figure that is going to be described.

  The first sentence has been rewritten to “Different sampling regions showed different relations between I129 and salinity (Fig. 5c).” (line 280).

- Lines 264 and 265: Instead of writing that differences were observed, you could just directly say what differences where observed to safe space and to safe time of the reader.

  The decrease of I129 concentrations has been stated in the first sentence (line 303-304).

- Line 315: It might be helpful to explain what meteoric means. Please do not mind that comment if I am just not well educated and should understand it.

  This has been further clarified: "… meteoric water (net precipitation and river runoff)…" (line 397).

- Line 330: Some N:P ratio is introduced and difficulties are mentioned. However, this method is never mentioned or explained before. Please explain it in the Introduction or the Methods. Otherwise, it is very hard to understand.

  The N:P ratio as a method to determine water mass fractions is mentioned in line 413 (this part has been rewritten following suggestions of RC1). This is an established method which has been used in numerous studies, several of which are listed as references. Here, it is only used as a comparison to provide context for the I129 concentrations. Since our study does not focus on the use of new tracers to quantify water mass fractions, we decided not to introduce this method in the introduction or methods and suggest not to put too much focus on it. We now use the term "N:P method" consistently when referring to this method.

- Line 337: Please excuse me if I misunderstood the method, but could the difference in the I129 concentrations not simply indicate a difference in the age of the waters but the waters could still have the same mix of Pacific and Atlantic waters, just older Atlantic waters?

  Older Atlantic Waters indeed have lower I129 concentrations. However, it is very unlikely that this explains the difference in I129 concentrations observed between the Amundsen and Makarov Basin due to the following:

  - Older waters would have higher U236 concentrations, which are not observed.
  - Surface waters in the Makarov Basin would have to be about 15-20 years older than in the Amundsen Basin to explain the observed decrease of about 50% in concentrations (assuming an age of about 15 years in the Amundsen Basin: 50% of the I129 concentrations found in the surface layer input function 15 years prior to sampling in 2021, i.e., 2006, would correspond to input function concentrations found around 1990). This is not observed in other studies.

- Waters in the halocline layer have similar I129 concentrations in both basins. Hence, waters in the upper 50m would have to be substantially older than at around 100m in the Makarov Basin to explain the lower I129 concentrations, while this would not be the case in the Amundsen Basin. Furthermore, there is no evidence for a substantially faster circulation of halocline waters compared to the waters at the surface.

We added a sentence to point this out (line 423-425).

- It would also not harm to have a bit of caveats on the number of sampled stations, i.e., how robust is the determination of the shift in the position of the fronts.

  This has been added to the end of section 4.2.

- Line 371: Think about properly introducing the NO parameter in the Methods

  As for the N:P ratios, we consider the NO parameter more as an auxiliary tracer to the radionuclide dataset and therefore decided not to introduce it in the introduction or methods. However, the comparison to the NO parameter has been slightly extended (last paragraph in subsection 4.4).

- In some places you use absolute salinities and in other places practical salinity units. Please try to use one of them consistently everywhere, preferably practical salinity units (personal taste).

  We now use practical salinity consistently throughout the paper. Figures and text have been changed accordingly.

- Lines 396 and 398: It would be helpful to introduce the concept of mode and mean ages and the associated differences earlier.

  We are not sure what the reviewer is referring to. Maybe this is referring to lines 403-404 in the submitted manuscript ("Previous studies suggested the mode age as a more suitable age measure for the lateral transport of Atlantic Water in the Arctic Ocean compared to the mean age (Smith et al., 2011; Wefing et al., 2021)."). This sentence has been moved to the methods (subsection 2.5).

- Lines 418 and 419: The last sentence in this paragraph does not help a lot. What does this refer to? And please mention the implications as it is not informative without that information.

  This sentence has been removed and the reference has been included in the sentence before.

- Lines 455 and 456: Higher than what? Lower than what?

  This sentence has been rewritten (lines 457-459).

- Lines 487 to 489: I think this discussion merits a bit more detail. I do not understand immediately how these different atmospheric patterns affect the Arctic Ocean circulation.

  This has been moved to the introduction (section 1.1) and expanded.

- Line 546: This is where the discussion of your results really starts while the text before is mainly an Introduction.

  Section 4 (Discussion) has been rearranged and large parts have been moved to methods/results as suggested.

- Line 558: Maybe add also higher spatial coverage here.

  Has been added.

- Line 559: Do you mean data here (including also models) or do you explicitly refer to observations. If it is the second, please use observations.

  Has been changed to “observations”.

- Line 568: I think it would be better using the active voice here.

  Has been changed to “We attributed this to …”.

- Line 573: At the end of this line, it looks as if a new paragraph is starting.

  Has been split in two paragraphs.

Again, I want to re-iterate that I find this paper very valuable for the understanding of the Arctic Ocean circulation. It is especially because of this value that I believe that a large investment in the writing and structuring could be very valuable and really help to transfer the main messages of this paper.

We agree with the reviewer and hope that new structure of the paper improved its readability and conveys the main messages more clearly.