Answer to Referee comment 2 on "Circulation timescales of Atlantic Waters in the Arctic Ocean determined from anthropogenic radionuclides" (from 23 Sep 2020)

Dear Reviewer 2,

Thank you for your detailed review of the paper. We will gladly incorporate your suggestions into the revised version of the manuscript.

Please find preliminary answers regarding some of your specific comments below. We will provide final point-by-point answers to all comments together with the revised version of the manuscript after the open discussion is closed (20th October 2020).

On behalf of all co-authors,
Anne-Marie Wefing

Wefing et al. present a compilation of I-129 and U-236 measurements collected in the Arctic Ocean over the last 10 years and use this data to determine water circulation timescales using two different models (a binary mixing approach, and the transit time distribution model). The geographic distribution of their data is impressive and allows for a nice comparison of circulation times between the different Arctic basins. I have only minor suggestions, which aim to improve the clarity of the paper and to provide further explanation for some of the statements that have been made in the results & discussion. Comments are listed below, divided by section.

Introduction:

Page 2, Line 28: Pacific waters are not considered part of the Polar Mixed Layer, they reside below this fresher, colder, surface layer. See for example, Figure 15 in Steele et al. 2004, JGR (doi: 10.1029/2003JC002009)

Reply: Thanks for pointing that out. Throughout the paper, we now use the term "surface layer" or "Polar Surface Water" (which comprises the Polar Mixed Layer and the halocline, Rudels et al., 2005) instead of Polar Mixed Layer.

Page 2, line 28 was changed to:

> *"Both Pacific Waters and freshwater largely reside in the upper water column of the Arctic Ocean, including the Polar Mixed Layer and the upper halocline."*

Page 5, line 108: You say here that there is only one study using the TTD model in the Arctic, but later you compare your results to Tanhua et al. (2009) and Stoeven et al. (2016). Why are those other two studies not mentioned here?

Reply: On page 5, line 108, we specifically refer to the use of the TTD model to determine lateral transit times of Atlantic Waters rather than ventilation times, by using anthropogenic radionuclides released by nuclear reprocessing plants. In this regard, (to our knowledge) only the study by Smith et al. (2011) was conducted. This is now clarified in the paper. The studies by Tanhua et al. (2009) and Stöven et al. (2016) are mentioned some paragraphs above, in the context of other ventilation studies, when introducing the TTD model in general (page 4, lines 85-88).

Materials & Methods: Table 1: How did you choose these depth ranges? Why the gap between surface and Atlantic layer? The Rudels definitions based on density and temperature suggest that the two water masses would be adjacent (i.e. one ends at potential density 27.7, the other begins there).

Reply: We defined only two input functions for radionuclides entering the Arctic Ocean, one in the Norwegian Coastal Current and one for the FSBW and BSBW. Therefore, we chose to limit the application of the binary mixing model to the surface mixed layer and the TTD model to the mid-depth Atlantic layer. Table 1 was slightly changed, now including an extra column for the depth ranges.

Page 7, lines 169-172: This explanation of the global fallout signal is repetitive with the previous section. Remove or combine with the previous section rather than repeating here.

Reply: The first paragraph of section 2.3.1 has been changed and now reads

> *"In our application of the binary mixing model for the surface layer of the Arctic Ocean, we assumed that water labeled with the time-dependent tracer signal entering the Arctic Ocean in the surface AW input function only mixes with water carrying the global fallout signal of 1x10^7 at l^(-1) for I-129 and U-236 (i.e., Pacific and Atlantic water not labeled with reprocessing plant releases)."*

Page 9, lines 221-223: The explanation of how this parameter relates to lateral mixing should be moved up by lines 200-205, where you first introduce this concept.

Reply: The explanation of Delta has been moved up to the description of Gamma and Delta, which now reads

> *"Delta is related to the second moment of the PDF and is a measure of its width, i.e., it describes how much a tracer signal disperses during the flow as a result of lateral mixing. The larger this mixing, the more incorporation of waters with different ages occurs within a water parcel sampled downstream from the initialization point of the input function. For Delta = 0, …"*

Results:

Page 13, line 288: Please explain further what you mean by a change in the circulation pattern (change from what pattern to what pattern?) Could this result also be due to a speeding up of the circulation rather than a shift in geographic location?

Reply: See answer to the comment below. This sentence was moved to the paragraph below, discussing the changes between sampling years. In principle this change could be due to a speeding up of the circulation but this is highly speculative based only on data from two years.

Page 13, line 300: Data on the Arctic Oscillation is available- I am familiar with the NOAA data portal (https://psl.noaa.gov/data/climateindices/) but perhaps there are other international portals as well. Based on the observed trends in the AO index, can you confirm that the AO position could produce the observed trends in your data (i.e. was it in a different state in 2012 compared to 2016)? I'm also not sure I fully understand why a shift in the AO position would result in younger ages over the Lomonosov Ridge.

Reply: Between 2011/12 and 2015, no clear trend in the AO index could be observed. However, a shift in the AO index could result, in general, in a change of the spreading of Atlantic waters across the Arctic Ocean, especially in the Makarov Basin. A change in the fraction of Atlantic-derived waters at a certain sampling location mainly influences the dilution factors obtained from the binary mixing model. For instance, more Pacific Waters present at the stations in the Makarov Basin would lead to higher dilution factors, as observed for 2015.

The tracer ages obtained from the binary mixing model should not directly be affected by a higher Pacific Water fraction bringing the global fallout signal, as this should only move the samples towards to global fallout endmember along the binary mixing line. However, the mixing lines converge towards the global fallout endmember and hence the tracer age determination becomes less precise. In addition, the change in tracer ages could reflect changing AW pathways resulting from a shift in the location of the Atlantic-Pacific Water front.

The paragraph about changes observed between sampling years for tracer ages and dilution factors has been changed and now reads:

> *"Regarding differences between sampling years (2011/12 vs. 2015), a slight decrease of tracer ages over time could be observed for the central Arctic Ocean (Fig. 4b). In the Makarov Basin, dilution factors significantly increased from about 2 in2011/12 to 10-20 in 2015. This implies that the Pacific Water fraction increased over time and can be explained by a shift of the Atlantic-Pacific water front that generally determines the water mass provenance in the Makarov Basin.*
>
> *The alignment of the Atlantic-Pacific front across the Arctic Ocean is influenced by the prevailing atmospheric circulation (indicated by, e.g., the Arctic Oscillation index; Morison et al. (2012); Alkire et al. (2019) and ref. therein). However, no clear trend in the AO index was observed between 2011/12 and 2015 and hence the reason behind changes in the Pacific Water fraction in the Makarov Basin remains unclear. Tracer ages should not be affected by the water mass provenance but could change as a result of potentially changing AW pathways in the central Arctic Ocean."*

Page 14, line 314: Why is the Atlantic layer considered to be between 250-500 m here compared to the 250-300 m range that is used in other figures/discussion sections? In general it is not clear why each depth range is chosen (aside from the entire Atlantic layer definition given for the 250-800 m range).

Reply: We agree, the choice of depth layers is not entirely consistent. Figure 5a has been changed such that all samples between 250 and 800m depth are averaged and plotted here.

Page 15: There is no discussion of the one yellow point near the Laptev Shelf in figure 6a. Why does this data point give such an old age?

Reply: A possible explanation for the high mean age and Delta/Gamma ratio of this sample could be the choice of the input function. The following sentences have been included in the discussion of the mean ages (page 15):

“A high mean age and the highest Delta/Gamma ratio were found for one station close to the Laptev Sea shelf. This result was rather unexpected given the proximity of this station to the initialization point of the input functions and was due to the comparably low I129 and U236 concentrations measured at 300m depth. A possible explanation could be a higher influence of the FSBW input function at that depth, rather than the mixture of FSBW and BSBW that is used for our Atlantic layer input function. Using the FSBW input function instead, the mean age for this station would be on the order of 10 years and the Delta/Gamma ratio would be about 0.5, which is much more reasonable. In the context of this study, the Laptev Sea shelf data point will therefore not be discussed further.”

Discussion:

Page 16, line 388: Pacific water is not part of the polar mixed layer. The point of this paragraph is a good one (that we need more conservative tracers to use in Arctic surface waters), but this should be re-worded to remove the “Polar Mixed Layer” terminology in reference to the Alkire study. They consider Pacific water to be part of the upper halocline in Alkire et al. 2019.

Reply: see reply to comment above (Page 2, line 28). “Polar Mixed Layer” has been changed to surface layer or Polar Surface Water.

Page 18, lines 403-410: You provide possible explanations for the high mean ages and significant mixing observed in the Nansen Basin and Fram Strait, but I am curious why this signal also appears near the Laptev Shelf. The mean age estimates for this sample are very different than other estimates in the literature. This large mean age also stands out on Figure 7. Since you do not discuss the Laptev Sea as much as the other basins, I suggest either removing the Laptev Sea box from this figure or expanding on the discussion of this region.

Reply: See answer to the comment above (referring to page 16, line 388). The Laptev Sea box was removed from Figure 7.

Page 19, line 446-447: It is stated that the difference between the mode ages in this study and the Mauldin study may be due to the positive AO phase in the 1990s. Please explain how that would affect the mode ages in the Canada Basin in particular. It is not currently clear how this explains the difference between the two estimates.

Reply: Mauldin et al. (2010) report advective times for transport within the Arctic Ocean Boundary Current (AOBC). The positive AO phase during the 1990s can be associated to accelerated boundary current flow (as described in Karcher et al. 2012) and therefore low advective ages in the Canada Basin. The mode age obtained from I-129 and U-236 for 2015 cannot clearly be attributed to the boundary current and the pathways of Atlantic waters to the Canada Basin probably differ as consequence of a weakening of the AOBC due to the transition of the AO to a more negative phase (Karcher et al. 2012). Since we have only one station covering the Atlantic layer in the Canada Basin we cannot state how the circulation modes affect the mode ages. However, there is currently a new paper under review in Journal of Geophysical Research: Oceans which examines the dispersion of I-129 in more detail, under different AO phases (pers. comm. J.N. Smith).

This explanation has been included in the corresponding paragraph which now reads:

> *"Here it should be noted that the latter employed data from the 1990s when the Arctic Oscillation was in a positive phase and exceptionally strong cyclonic boundary current conditions prevailed in the Arctic Ocean, associated with accelerated boundary current flow (Karcher et al., 2012). This implies low advective ages. The Canada Basin mode age obtained from I-129 and U-236 for 2015 cannot unambiguously be attributed to the boundary current. Additionally, AW pathways to the Canada Basin probably changed as a consequence of a weakening of the boundary current due to the transition of the AO to a more negative phase (Karcher et al., 2012). "*