Review of Gerke et al.'s "The changing composition of the Gulf of St. Lawrence inflow waters observed from transient tracer measurements" (manuscript #: egusphere-2025-3999)

General comments:

The authors of this manuscript assess the mean ages of the waters in the Gulf of St Lawrence and suggest that there has been a gradual increase in the proportion of North Atlantic Central Waters from inshore areas to the entrance of the Gulf of St Lawrence is evidence of a shift towards deep waters dominated by North Atlantic Central Waters since 2022. They use transit-time distributions to derive the mean ages and then integrate them into a water mass analysis to analyze the water mass composition of the region. The authors use transient tracer measurements collected and described in Stevens et al. (2024) and use the same density surface to represent the core of the deep water inflow. CFC-12 has seen its maximum concentrations in the atmosphere, but SF6 continues to increase; CFC-12 is useful for water masses between 23-85 years in mean age whereas SF6 is useful for younger water masses and in helping to resolve the ambiguity in mean age estimates using the Inverse Gaussian transit-time distribution approach (e.g., Guo et al., 2025). Although, it seems like the authors here just relying on SF6 according to their Appendix B and back-calculate CFC-12, which makes me wonder what information the authors are getting from CFC-12. There may be data issues with regions lacking SF6 and in the regions where waters approach the time scale of CFC-12 beginning to be emitted, there are signal issues. I appreciate the trend analysis and other detailed efforts that went into this manuscript, especially to the end that the relative proportion of waters is changing, but the authors need to perform some additional analyses to convince me of their interpretation of the data beyond that. I suggest minor revisions. Specific comments are listed below:

Response:

We thank the reviewer for their constructive comments, which we believe will help improve the manuscript. While we will respond in detail to the specific points raised, we would first like to clarify a few possible misunderstandings.

We did analyze the gradual increase in the proportion of North Atlantic Central Waters (NACW) by assessing mean ages, and we interpret this as evidence of an ongoing shift in deep water composition as of 2022. However, previous studies (Gilbert et al., 2005; Jutras et al., 2020) also observed this shift but suggested that the transition to 100% NACW had occurred prior to 2022.

For our analysis, we relied on transient tracer data (CFC-12 and SF_6), as described in this study, not as in Stevens et al. (2024). Stevens et al. (2024) focused on the tracer (CF_3SF_5), which had been released in 2021 on the core deep water isopycnal of σ=27.26 kg/m^3. Because all three tracers were measured

simultaneously from the same water sample, and the main objective of the cruises was to track the released tracer (i.e. to analyze the deep water spread and dispersion over time in the Gulf of St. Lawrence), the sampling strategy was centered on this isopycnal, resulting in a high density of measurements at this depth.

This said, within the Gulf we have measurements of both SF_6 and CFC-12 at all locations. Only outside the Gulf, in the North Atlantic, is a lack of SF_6 measurements.

<u>Suggested changes in manuscript:</u>

In the revised manuscript, we will provide a more detailed description of these points to avoid any misunderstanding regarding what was measured and where. Also, we will revisit the methods sections to ensure that the methodology is clearly outlined.

Specific comments:

Line 36: You should add “abiotic” in front of “transient tracer concentrations” here; you could say “passive” but that would exclude radioactive transient tracers

<u>Response/Suggested changes in the manuscript:</u>

Thanks to the reviewer for pointing this out and we will add ‘abiotic’ in the revised manuscript.

Line 151: I’m not sure why a Delta/Gamma ratio of 1.2 was chosen; Ebser et al. (2018), which a co-author on your study was also a co-author on, found different ratios for different water masses (e.g., 0.5-0.6 where Labrador Sea Water dominates and 0.9 where North Atlantic Deep Water dominates). Please say more about Figure B1, which seems to be where 1.2 came from. Please also explain why you don’t consider using a different ratio of mean age to half-width for North Atlantic Central Waters as opposed to Labrador Current Waters.

<u>Response:</u>

We thank the reviewer for drawing our attention to Ebser et al. (2018). That study focuses on samples collected in the Eastern Tropical North Atlantic, off the coast of northwest Africa. It reports Δ/Γ values of 0.5-0.6 for the Labrador Sea Water

and Δ/Γ=0.9 for the North Atlantic Deep Water. However, these are different water masses than the North Atlantic Central Water (NACW) and the Labrador Current Water (LCW). The LCW represent near surface waters within the Labrador Sea and the Newfoundland shelf area, which subsequently mix with Labrador Sea Water found at depths of 1000-2000m. North Atlantic Deep Water (present around 3000m depth) is also distinct from NACW. Notably, Ebser et al. (2018) mention Atlantic Central Waters (depths above 800m) having a Δ/Γ=1.0, which likely better represents NACW conditions.

In our study we select Δ/Γ=1.2 for the Gulf of St. Lawrence deep water and adjacent regions near its entrance for several reasons. First, we used SF_6 and CFC-12 concentrations sampled and measured simultaneously at the same location, applying the assumptions outlined in the manuscript. Following a standard approach to gain information on the Δ/Γ ratio, we compared the mean ages derived from the individual tracers under varying Δ/Γ ratios. Agreement between the two tracer-derived mean ages (yellow lines in Figure B1a) indicates that the chosen Δ/Γ reflects local advective and diffusive transport characteristics. Since perfect agreement was not achieved across all ratios, and CFC-12-based ages were generally higher than those derived from SF_6, we examined whether this discrepancy could be related to the atmospheric decline of CFC-12 since 2002. To test this, we compared measured and calculated CFC-12 concentrations (again under varying Δ/Γ ratios) relative to observed SF_6 (e.g. Figure B1b). The calculated values were consistently slightly higher than the measured values across the full range of SF_6 concentrations (2-8ppt), with no systematic trend towards higher SF_6 values representing recently ventilated waters. We therefore concluded that the atmospheric decline of CFC-12 is not a relevant factor for our TTD analysis in this region.

As shown in Figure B1a, the tracer mean ages converge toward the 1:1 line as Δ/Γ was increases. However, Stöven et al. (2015) concluded that ratios approaching 1.8 make the age estimates highly sensitive to tracer saturation and age deviations. Consequently, we selected Δ/Γ=1.2 as an optimal balance: it reflects slightly diffusive dominated transport (Δ/Γ>1) while avoiding excessive age deviations (Δ/Γ>1.6).

We consider this choice consistent with conditions in LCW and NACW in the North Atlantic, where water residence times before entering the Gulf are relatively short. Unfortunately, only CFC-12 was measured in these regions, preventing us from computing local Δ/Γ ratios.

To include Δ/Γ values reported in Ebser et al. (2018), as suggested by the referee, we evaluated how the inferred LCW fraction would change when applying individual Δ/Γ-ratios for LCW (0.5) and NACW (0.9), when computing mean ages and mean age endmembers of the water masses. This analysis yielded even higher LCW contributions than those already inferred in our study.

In addition to further assess the plausibility of our chosen ratio, we examined Δ/Γ results derived from a one-dimensional Gaussian pipe model from the spreading of the CF_3SF_5 tracer analyzed in Stevens et al. (2024). In this model, Δ/Γ is calculated from the advective (Δ=ut) and diffusive ($\Gamma=(2kt)^{-1/2}$) terms. These resulted in values for the two surveys of 1.2 and 1.5, respectively, well within the same range as the ratio applied in our study, thus providing additional support for our choice.

<u>Suggested changes in manuscript:</u>

In the revised manuscript, we intent to provide a more detailed description of Figure B1 and explain more clearly how we justify the use of Δ/Γ=1.2 across all regions, both within the Gulf of St. Lawrence and for LCW and NACW. This description will follow the response outlined here. In addition, we will add a note on the uncertainty of mean ages outside the Gulf, where only CFC-12 measurements are available, as discussed by Guo et al. (2025) (see comment below).

Lines 167-168: According to Guo et al. (2025), your estimates of the mean age are likely biases wherever you only use CFC-12 and no SF6 so did you see any spatial discontinuities or other signs that your estimates were different where you have SF6 vs where you do not? You can evaluate the bias you would have in regions where you have SF6 measurements by doing the mean age estimation with both CFC-12 and SF6 and again with only CFC-12 to assess the bias. Analysis was done to corroborate the CFC-12 measurements with the back-calculated CFC-12 concentrations in Appendix B where there are SF6 data but it's unclear to me what information CFC-12 is then providing.

<u>Response:</u>

We thank the reviewer for raising this point. As explained in our response to the previous comment, the simultaneous sampling of CFC-12 and SF_6 throughout the Gulf ensures that Δ/Γ can be chosen consistently, and that we have both tracers sampled at all locations. Thus, there are no discontinuities in mean age estimates between sites with and without SF_6 measurements in this region.

In the adjacent Atlantic, SF_6 measurements are indeed lacking, and as Guo et al. (2025) have shown, mean ages based solely on CFC-12 can be biased when applying a fixed Δ/Γ without local determination. In our analysis, however, we use the Atlantic data only to calculate multi-year average mean ages, where the associated uncertainty in the averages is weighted more heavily than the exact choice of Δ/Γ.

<u>Suggested changes in manuscript:</u>

In the revised manuscript we intent to describe the potential bias in the mean age estimates for the Atlantic Ocean, as they are only based on CFC-12 measurements, and we will refer to Guo et al. (2025).

Lines 174-177/Equations 1-4: Is the water in the Gulf of St Lawrence exclusively composed of LCW and NACW? There's also the cold intermediate layer and surface/ warm slope water, I thought. Also, while the mean ages of two IG TTD for LCW and NACW would linearly sum to a new mean age, the resulting TTD will not be IG. So are you assuming that the TTDs for LCW and NACW are not IG but their sum is IG (in which case the TTDs for LCW and NACW will still need to have their means linearly combine)? Or are you going to use a sum of two IGs as your TTD?

<u>Response:</u>

We thank the reviewer for this comment. The deep water we focus on in this study does consists solely of LCW and NACW. While intermediate and surface waters are present in the Gulf, they do not occur at the σ=27.26 kg/m³ isopycnal. At this depth mixing with surface and intermediate waters is highly unlikely, as also present in Jutras et al. (2020) 'While the contribution of the CIL is important for the intermediate waters of the Laurentian Channel (100–150 m depth), the deep waters (below 150 m) are composed almost exclusively of a mixture of LCW and NACW (see Section 3.1).'.

We appreciate the reviewer raised the point about the combination of two IG-TTDs. As shown by Stöven and Tanhua (2014), a 2-IG-TTD approach can be applied, in which mean ages from two different water masses are linearly combined using a mixing factor α (see the following equation).

$$\boldsymbol{\Gamma = \alpha * \Gamma_1 + (1-\alpha) * \Gamma_2}$$

For our case, assuming Δ/Γ=1.2 for both NACW and LCW, the average mean ages are Γ1=86.5 years and Γ2=12.5 years, respectively. The mixing factor α can then be determined for each computed mean age value within the Gulf. The analysis

yields results, that are consistent with those obtained from our water mass analysis based on temperature, salinity and mean age (see Figure below).

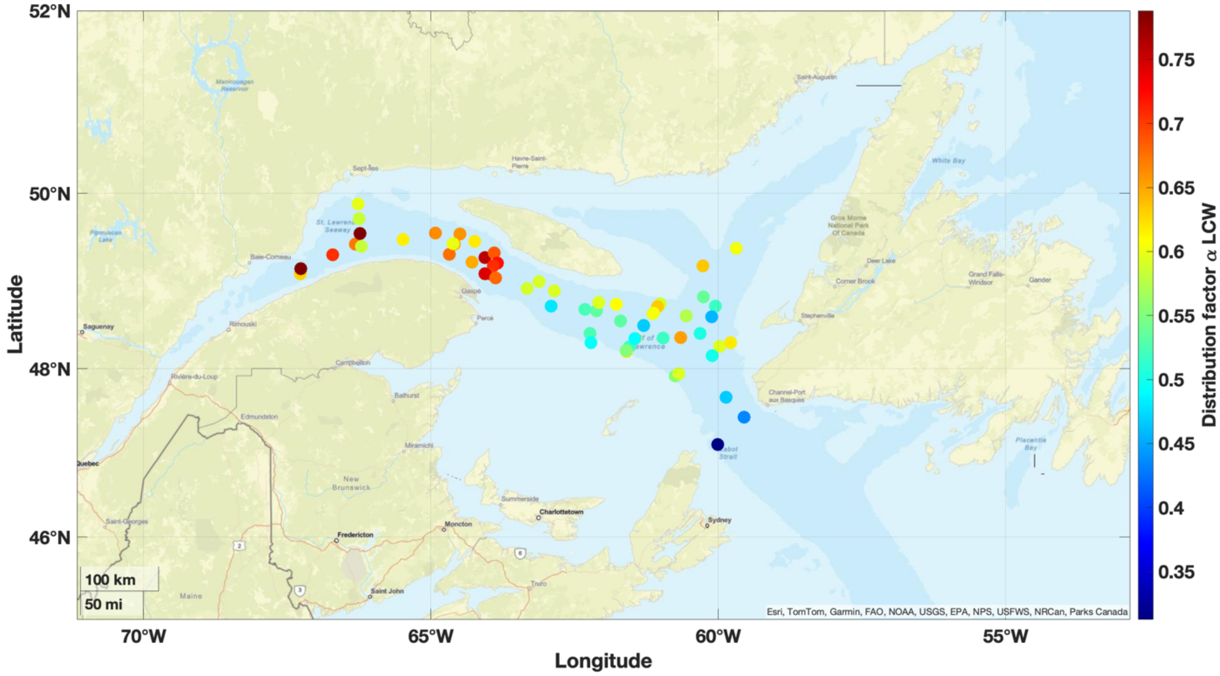

Figure: Distribution factor α on the $\sigma_{\Theta} = 27.26$ kg/m^3 isopycnal deep water in the Laurentian Channel from the 2-IG-TTD analysis using observed mean age (Γ) plotted on a map of the Gulf of St. Lawrence.

<u>Suggested changes in manuscript:</u>

In the revised manuscript, we will briefly include the results of the 2-IG-TTD analysis. We do not intent to go into detail on the method itself, as this would considerably extend the method section, but instead refer to Stöven and Tanhua (2014). We will also highlight that the results are consistent with the water mass fraction analysis based on three parameters.

Lines 246-247: Is the sudden discontinuity in temperature and salinity at the eastern tip of Anticosti Island physical or actually due to the availability of SF6 on one side and lack of SF6 measurements on the other?

<u>Response:</u>

SF_6 and CFC-12 were measured simultaneously at all locations within the Gulf of St. Lawrence. Therefore, the observed discontinuity in temperature and salinity

near the eastern tip of Anticosti Island is not related to tracer availability and is most likely of physical origin.

Suggested changes in manuscript:

We do not plan to add specific information on this point in the revised manuscript. However, by improving the overall description of tracer usage and sampling in the method section, we aim to avoid such misunderstanding.

Figures 4-5: When I see waters with mean ages of 60+ years using the tracer-based constraints you have, there becomes a signal detection issue because of the very low concentrations of CFC-12 in its first couple of decades of being emitted and the fact that you used a backwards calculation to infer the CFC-12 concentrations from the mean ages that you got from SF6 measurements (lines 450-452). Your Figure 4d makes it look like this generally is reflected in your uncertainties, but your Figure 4b has mean ages of up to 100 years, which shouldn't be detectable using CFC-12 and/or SF6. Also, your Figures 4a-b makes it look like waters are being ventilated after mixing with waters coming from the St Lawrence River in the western part of the Gulf of St Lawrence and there is a barrier for younger waters southeast of the Gulf of St Lawrence to get into the Gulf there through the Laurentian Channel, which leads to an increase in age as the waters reside for longer within the southeastern portion of the Gulf. Your interpretation is that the younger waters in the western portion of the Gulf are due to a higher portion of LCW mixing with the other waters there but is the mix of high and intermediate proportions of LCW shown in Figure 5 in the western portion of the Gulf with large variability over a small spatial distance due to potential data issues such as the ones I've pointed out in this comment and others? For example, you tend to have higher proportions of LCW where you don't look like you have SF6 measurements in the western part of the Gulf.

Response:

We thank the reviewer for pointing this out, and we agree that more explanation is necessary. Again, SF_6 and CFC-12 were measured simultaneously at all locations within the Gulf of St. Lawrence, and the backward-calculated CFC-12 concentrations were only used for the TTD analysis, not for any direct data evaluation.

The fact that mean ages exceed the atmospheric age of a tracer (e.g., 85 years for CFC-12) arises from the interpretation through the transit time distribution (TTD). Mean ages do not simply reflect the time since a water parcel last contacted the atmosphere (tracer age), when analyzing the tracer concentration. Instead, it accounts for the distribution and mixing of water masses. The tail of the TTD

represents older water, so the mean age can exceed the tracer's atmospheric lifetime, especially when tracer concentrations are low. As noted by Guo et al. (2025) as well, 'for water with an ideal age under 200 years, the CFC-12-based IG-TTD can provide meaningful mean ages up to this limit, despite the tracer's shorter ~80-year atmospheric history.'

The deep waters at σ=27.26 kg/m^3 are separated from surface waters by the cold intermediate layer, so young waters from the St. Lawrence River are unlikely to influence them. The increase in mean age towards the St. Lawrence Estuary is instead due to a higher fraction of LCW. As our analysis focuses on data east of the Lower St. Lawrence Estuary, before any upwelling of deep water towards the surface occurs, influence of surface St. Lawrence River seems unlikely at these depths (As also stated by Jutras et al. (2020), as shown in the previous comment). Given the general circulation pattern of deep water into the Gulf and surface water out, the observed mean age variability primarily reflects processes within the deep water of the Laurentian Channel.

Following a comment from M. Jutras, we also examined other isopycnals along the Laurentian Channel in the deep water and observed some mixing with younger LCW from shallower deep water regions. However, data coverage is limited, as our sampling targeted σ_Θ = 27.26 kg/m^3.

<u>Suggested changes in manuscript:</u>

In the revised manuscript, we intent to add a figure of mean ages and water mass fractions throughout the deep water layer, plotted against distance to Cabot Strait. This analysis will illustrate the internal mixing during the transit through the Laurentian Channel. We will also clarify that the influence of the St. Lawrence River on these deep waters is unlikely.

Figure 6: I'm not sure what the purpose of showing the relative stability of the oxygen concentrations is here because oxygen concentrations can change due to respiration changes, which isn't part of your analysis here. If you use your TTDs to calculate the preformed oxygen, on the other hand, then that may be worth showing. This figure, on the other hand, does show a trend in the variables that support your interpretation of the relative proportion of NACW vs LCW changing.

<u>Response:</u>

We thank the reviewer for this comment. The respiration rate was analyzed in detail in Nesbitt et al. (2025) and has been considered in our analysis. We

included the oxygen measurements primarily to illustrate that using oxygen to calculate water mass fractions is challenging, and to highlight in the discussion that oxygen concentrations still show a slight decrease, consistent with Blais et al. (2024).

Suggested changes in manuscript:

In the revised manuscript we plan to move the oxygen plot to the Supporting Information, leaving only the mean age and LCW fraction time series figure. This will still allow us to refer to the plot to make the two relevant points mentioned in the response. Additionally, we will add that the number of data points does not allow to refer this to a statistically significant trend, following an analysis pointed to by a comment from M. Jutras.

Lines 327-330: Where was this shift previously reported to be occurring, specifically?

Response:

We thank the reviewer for this comment. Previous studies report this shift for the deep water of the Gulf of St. Lawrence, specifically at the Cabot Strait and throughout the Laurentian Channel.

Suggested changes in manuscript:

In the revised manuscript, we intent to add this information on specific locations to each referenced historic fraction analysis.