The authors thank the reviewer for your very helpful comments and suggestions. We here provide a point-by-point response. The reviewer's comments are given in black, and our responses are given in blue color.

Reviewer #2 Comments to Author:

Review on 'Dual-tracer constraints on the Inverse-Gaussian Transit-time distribution improve the estimation of watermass ages and their temporal trends in the tropical thermocline' by Haichao Guo et al.

The aim of this study is to compare the 'real' mean (or ideal) ages with the mean ages inferred from Inverse Gaussian (IG) functions for the isopycnal sigma_theta=25.5 (including thermocline and intermediate waters) over the period 1981-2015. The ideal age cannot be observed, but the IG functions can be inferred form the observations of anthropogenic tracers like CFCs and SF6. Hence, it is of interest, in how far these observational inferred mean ages agree with the 'theoretical' ideal age. This can only be tested in a model study. The authors use the FOCI model to simulate mean age, CFC-12 and SF6. After a short model evaluation, the IG functions are inferred for different cases: from the modeled CFC-12 data alone, assuming fixed Delta/Gamma ratios, and by inferring both IG parameters Delta and Gamma from the modeled SF6 and CFC-12 fields. The IG parameter Gamma (mean age) and its temporal change between 1981 and 2015 is compared with the modeled ideal age.

This comparison of the mean age inferred from tracer data with the 'real' mean (ideal) age is important for the understanding and interpretation of tracer derived ages. A correct understanding of them helps to detect changes in ocean ventilation and, e.g. to infer anthropogenic carbon or ocean utilization rates from transient tracer data. This study provides a significant contribution to this topic, although the model analyses is restricted to the isopycnal sigma_theta=25.5.

The text is clear and well written, whereas the figures could need some improvement.

General comments:

For the case of constant Delta/Gamma ratios, the values 0f 0.8, 1.0, 1.2 and 1.4 are chosen. When inferring Delta/Gamma from CFC-12 and SF6, the color bar reaches from 0.2 to 1.8 (the same range has been used in He et al. 2018 to infer anthropogenic carbon from IG functions). Why is the range of the assumed Delta/Gamma ratios so much smaller (one could choose e.g. 0.2, 0.6, 1.0. 1.4 and 1.8)? (For the case Delta/Gamma=1.8 I would expect that the IG derived mean age is larger than the ideal age at least for the earlier years.)

A: We thank you for your thoughtful and constructive feedback on our work. We limited the Delta/Gamma for single-tracer constrained IG-TTD to 0.8 and 1.4 since the spatially constant ratio is considered as mean of a distribution varying in space and in time including the extremes (e.g., 0.2). Therefore, the ratio around 1 turns to be a good averaged approximation (He et al., 2018) and has been widely used in many other studies (e.g., Waugh et al., 2004, 2006; Tanhua et al., 2008; Jeansson et al., 2020, 2023). Instead of applying the extreme value of Delta/Gamma =0.2 globally, for the dual-tracer constrained IG-TTD we accepted that for some regions, the Delta/Gamma can be very low (e.g., 0.2).

In this study, only absolute values for the differences and temporal changes in age are presented. This implies, that difference between ideal and tracer derived age values and a temporal change in the ages is weighted equally, independent from the age value itself. I wonder whether this is appropriate. For young waters (Gamma~5 yr), an age change of +- 2 years over the considered time period or a difference between ideal and tracer derived age of ~2 yr is significant, whereas for old waters (Gamma~100 yr), such changes/differences would be negligible. I would thus suggest to also calculate relative age differences between ideal and tracer derived ages and also relative changes of age over time. If the results for the relative age changes/differences do not substantially differ from the absolute changes/differences presented here, this should be mentioned in the text. Otherwise, the relative age changes/differences need be discussed in addition to the absolute changes.

A: We thank the reviewer for this suggestion and have provided an additional figure showing the percent mismatch between mean age with different assumptions in the delta/gamma and ideal age (by using (mean age)/(ideal age) x 100-100, Fig S2). To be brief, besides the old waters in the northeast tropical Pacific and the Bay of Bengal with Delta/Gamma values higher than 1.0, the mean age of IG-TTD underestimates the ideal age. Moreover, the relative difference between ideal age and mean age is slightly higher in young waters.

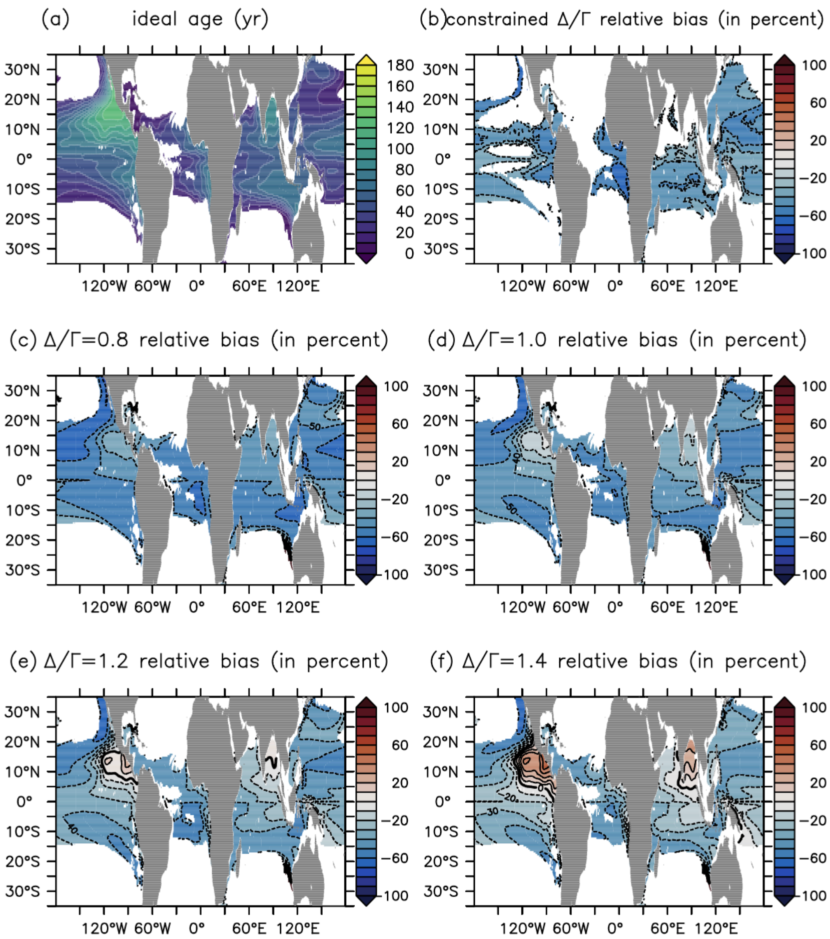

Fig. S2: Panel (a) shows the distribution of ideal age (yr) averaged from 1981 to 2015 on isopycnal layer σ_0= 25.5 kg/m3 in the esm-piControl simulation. Panels (b-f) show the percent mismatch between mean age with different assumptions about the value of delta/gamma and the simulated ideal age (by using (mean age)/(ideal age) × 100-100).

The analyses focuses on the globally integrated/averaged mean age of the tracer inferred IG functions, i.e. the global distribution is 'condensed' to one number. This implies that regional differences might cancel out (e.g. the trend in age and the difference between tracer derived mean age and ideal age could differ between regions and even have opposite signs). In reality, also age changes for specific regions (e. g. upwelling, or water mass formation regions) are of interest, not only globally averaged values. Therefor, I would suggest to show at least one map with the differences between tracer derived and ideal age (for the 'best' tracer derived mean age), and also one map with the differences in the temporal trend between tracer derived ('best' result) and ideal age.

A: We thank you for your suggestion and totally understand your concern. We have added a map showing the temporal trend of ideal age and tracer-derived age (Fig 9) and discussed it in the revised manuscript:

“Noteworthy, the dual-tracer constrained IG-TTD demonstrates superior performance in discerning spatial patterns and magnitude of temporal changes in ideal age compared to the single-tracer constrained IG-TTD (Fig.9). The single-tracer constrained IG-TTD is very sensitive to the chosen value of Delta/Gamma, commonly showing a spurious age increase with low values of Delta/Gamma and an age decrease with high values of Delta/Gamma across all ocean basins (Fig.9c-f). While the dual-tracer method exhibits some spurious trends in the eastern tropical Atlantic and western tropical Indian Ocean, it generally provides a more accurate representation of the spatial patterns and magnitudes of true ideal age trends. Notably, it correctly identifies regions with no significant trends in ideal age (Fig.9a,b).”

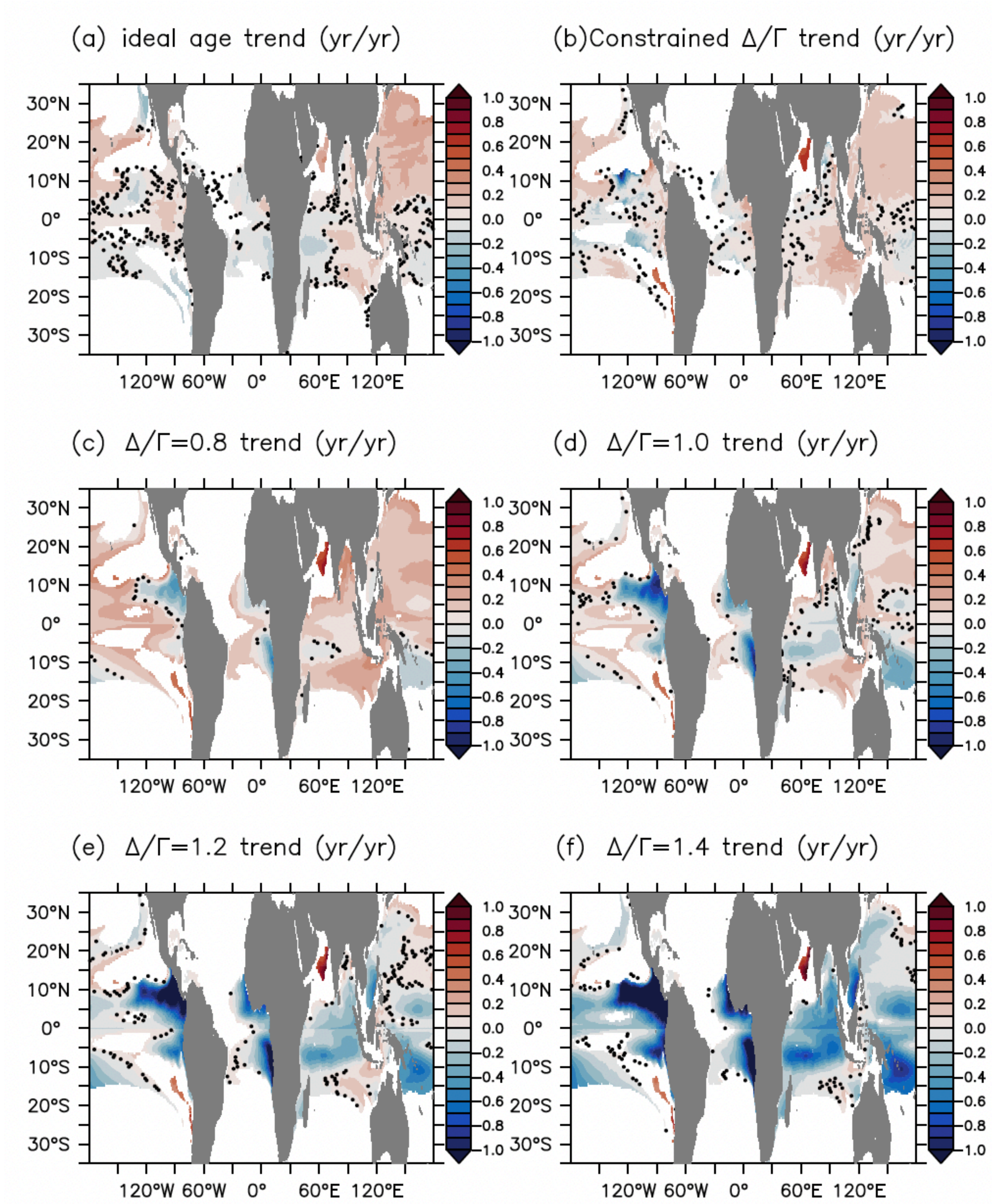

Fig.9: Temporal trend of ideal age (a) and mean age of IG-TTD with different assumptions on the value of delta/gamma (b-f) on isopycnal layer σ_0= 25.5 kg/m3 in the *esm-hist* simulation. Stippling designates areas where the ratio of standard deviation and mean of the regression slope of ideal age (or mean age) against time exceeds 1 (i.e., no significant trends).

Why is the mean age not inferred by calculating the Delta/Gamma ratio from SF6 and CFC-12 at every grid point for every year?

The results presented here are based on spatially variable Delta/Gamma ratios, but without temporal change (the Delta/Gamma ratios from the years 2000, 2005, 2010 and 2015 are applied to the whole time series). Maybe the age calculation with the actual, time varying Delta/Gamma ratios could even replace the four diffent age calculations presented here.

A: We appreciate the reviewer's idea of using a time-varying constrained Delta/Gamma ratio. However, we here also focus on how to reconstruct the past ventilation change as long as possible based on the available measurements. If we constrain the Delta/Gamma ratio according to where and also when we have observations of both CFC-12 and SF6, we would have to limit our temporal analysis mostly to the period after 2000 rather than starting in 1981 since between 1981 and 2000 only CFC-12 measurements are available. We have clarified this in the revised manuscript. Our results suggest that it is reasonable to apply the Delta/Gamma ratio constrained in specific years to all previous or afterward measurements (at least within a few decades investigated here). We also re-evaluated and used this technique in a follow-on manuscript on “Variation of ventilation in the North Atlantic over the past three decades - a climate change signal” (https://www.researchsquare.com/article/rs-5595029/v1)

Specific comments:

l. 119-120 and Fig. 1

Why has the isopycnal 26.0+-0.5 been chosen? The whole analyses is restricted to the isopycnal 25.5,

wouldn't it be more reasonable to show the data for this isopycnal (25.5 +-0.5) here?

A: We thank the reviewer for pointing this out, and we have modified the figure showing the data for isopycnal 25.5 +- 0.5 kg/m3 and modified the paragraphs describing it.

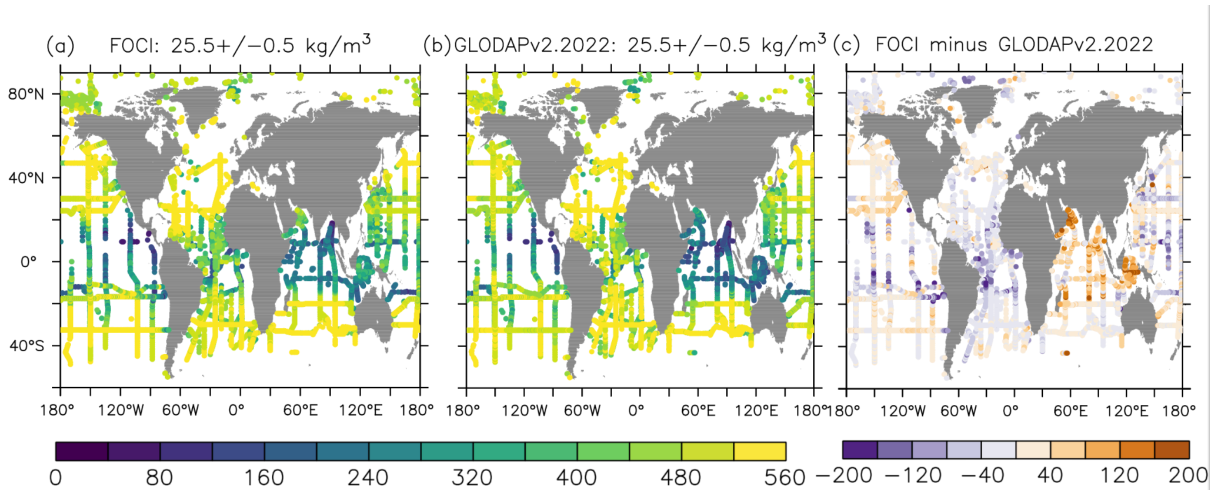

Fig. 1: Distribution of (a) subsampled simulated CFC-12, (b) observed CFC-12 mixing ratio, and (c) their difference on the isopycnal layer $\sigma 0 = 25.5 \pm 0.5$ kg · m^{-3} , with the unit of parts per trillion (ppt).

l.323-327

The results from the study in Peacock and Maltrud (2006) are interpretated wrongly.

First, the IG derived CFC values are smaller (half of) than the CFC values derived from the 'real'

TTD (actual value). This would imply that the IG derived TTD is too old compared to the real TTD, in l. 326-327 the opposite is stated.

Second, the mean age of the 'real' and of the IG TTD are identical, because the parameters Delta and Gamma for the IG function are derived by calculating mean age and width of the 'real' TTD. Hence, it is wrong to say the mean age of the IG TTD differs from the 'real' water age. The difference is that the IG function contains a smaller fraction of young water, thus the inferred CFC values are smaller and the water 'appears' older compared to the 'real' TTD. One could also conclude that the shape of the 'real' TTD in this case differs significantly from the shape of an IG function.

A: We agree that TTD can have different shapes (e.g., contain multimodal), and the IG shape might lose some information. We thank the reviewer for this comment and would like to explain why we still think Peacock and Maltrud (2006) implicitly suggested that IG-TTD tends to underestimate the real mean age of TTD (or ideal age) with modified sentences below.

For example, Peacock and Maltrud (2006) compared the concentration of CFC-like tracer derived by convolution of ocean surface CFC boundary condition with the model-simulated TTD ("actual" CFC) and the one derived by the same boundary condition with the IG-TTD ("predicted" CFC). Both TTD and IG-TTD share the same Gamma and Delta. They found that "predicted" CFC-like concentrations are only half of "actual" values at a depth of 245 meters in the tropical regions (see their Fig.~13). In other words, to achieve the same abiotic transient tracer concentration inferred from model-simulated TTD, the IG-TTD mean age would need to be reduced, i.e., the mean age of IG-TTD is smaller than the mean age of “real” TTD with the same partial pressure of CFC.

l.326

'directly simulated CFC-like tracer'

This is misleading, as the CFC-like tracer in Peacock and Maltrud (2006) is inferred from the modeled TTD (convolution integral of TTD and assumed tracer surface concentration). This is not what I understand as 'directly simulated'.

Regarding the difference between tracer derived and 'real' TTDs also the study from Chouksey et al. (2022) could be mentioned. There, tracer inferred IG-TTDs are compared with TTDs inferred from modeled (numerical) floats for the AAIW range. In some cases, the tracer derived TTDs are younger, in some cases older than the float based TTDs. Also, the shape of the float derived TTDs sometimes differs from the shape of an IG function.

A: We really appreciate this correction and are sorry that we misunderstood this part from Peacock and Maltrud (2006). We have corrected this in the revised manuscript. We clarified this: “Peacock and Maltrud (2006) compared the concentration of CFC-like tracer derived by convolution of ocean surface CFC boundary condition with the model-simulated TTD ("actual" CFC) and the one derived by the same boundary condition with the IG-TTD ("predicted" CFC). Both TTD and IG-TTD share the same Gamma and Delta.”

We also enjoyed the reading of Chouksey et al. (2022), who compared the simulated float-derived TTD shape and the one applying the IG function. We thank the reviewer for this very appropriate reference and have added it to our revised manuscript.

l.327-328

Here, the study from Steinfeldt et al. (2024) could be cited. These authors found an increase of age (and hence a negative anomaly of anthropogenic carbon) with time for the old deep waters of the Atlantic when parameterizing the TTD as a single IG function. Assuming a contribution of an additional 'old' TTD leads to smaller age changes over time.

A: We thank the reviewer for this relevant reference and have added it to our revised manuscript.

l.351-352

'...and also from the cut-off of the long-tail of old ages in the spectrum due to the limited

atmospheric history length of CFC-12 and SF6'

This is not true, as the IG-functions always include a long tail towards high ages. This tail is more pronounced for higher Delta/Gamma ratios, leading to the increase of the mean age with the Delta/Gamma ratio. What is true is that this tail cannot be constrained from CFC-12 and SF6, as is correctly stated in l. 335. Please rephrase.

A: We thank the reviewer for pointing out this, and we have modified the sentence as “Such a difference might arise from the assumption that the transit-time distribution of water parcels follows the unimodal Inverse Gaussian distribution and from the limited atmospheric history length of CFC-12 and SF_6 which cannot constrain well the long tail towards high ages in the spectrum. “

Figures:

In general, the maps showing global distributions are too small. This could be changed easily, e.g.:

Fig.1: placing the color bar below the figures and showing latitude labels only on the left figure

would allow to increase the maps itself significantly

A: We have modified Fig. 1 as suggested.

Fig. 2 and 5:

These figures stretch over one whole page, but there is a lot of free space between the single maps, which could be enlarged

A: We have modified our figures according to suggestions as shown below. For Fig. 2, we combined panels (d) and (e) into one panel and removed the ample free space. For Fig. 5, we combined mean and specific years constrained Delta/Gamma in *esm-piControl* simulation and *esm-Hist* simulation.

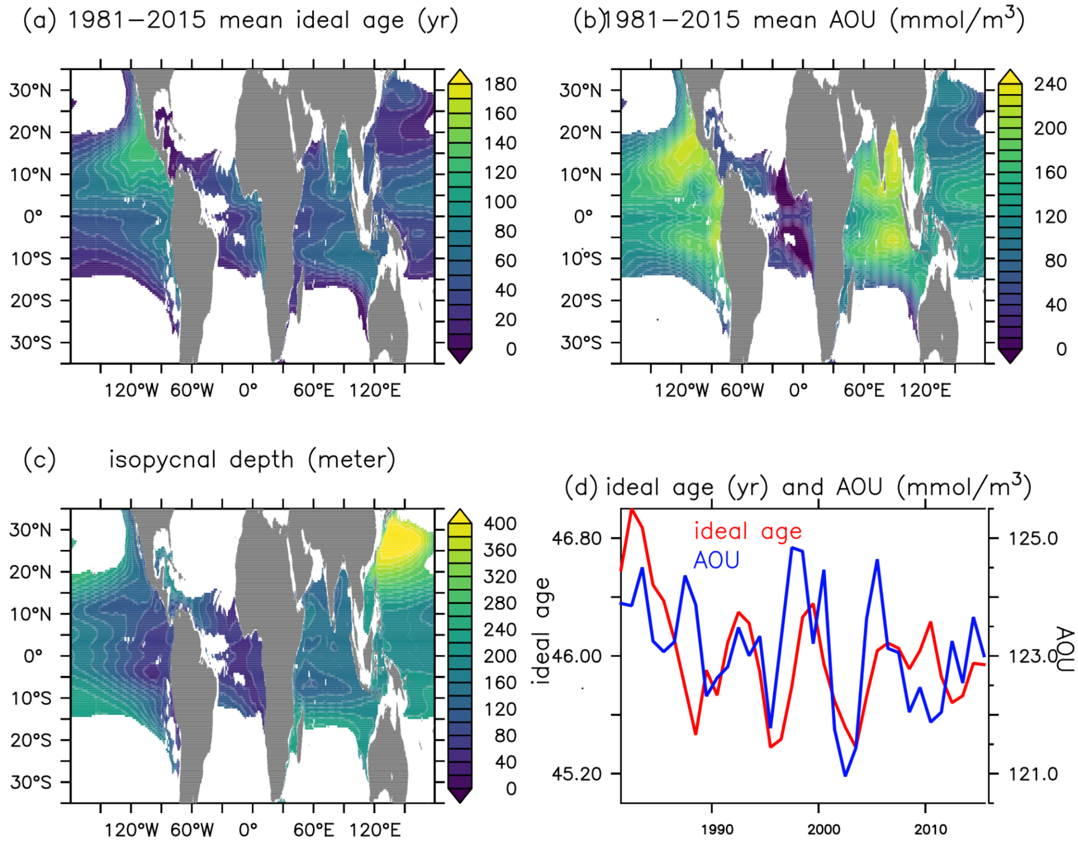

Fig.2: Distribution of (a) ideal age (yr), (b) apparent oxygen utilization (AOU, mmol·m^{-3}), and (c) depth (meter) averaged from 1981 to 2015 at isopycnal layer σ_0=25.5 kg·m^{-3} in *esm-piControl* simulations. Waters shallower than the local winter mixing depth have been excluded. Panel (d) presents the temporal evolution of ideal age (red line, with left y-axis) and AOU (blue line, with right y-axis) averaged at the isopycnal layer σ_0=25.5 kg·m^{-3} in *esm-piControl* simulation.

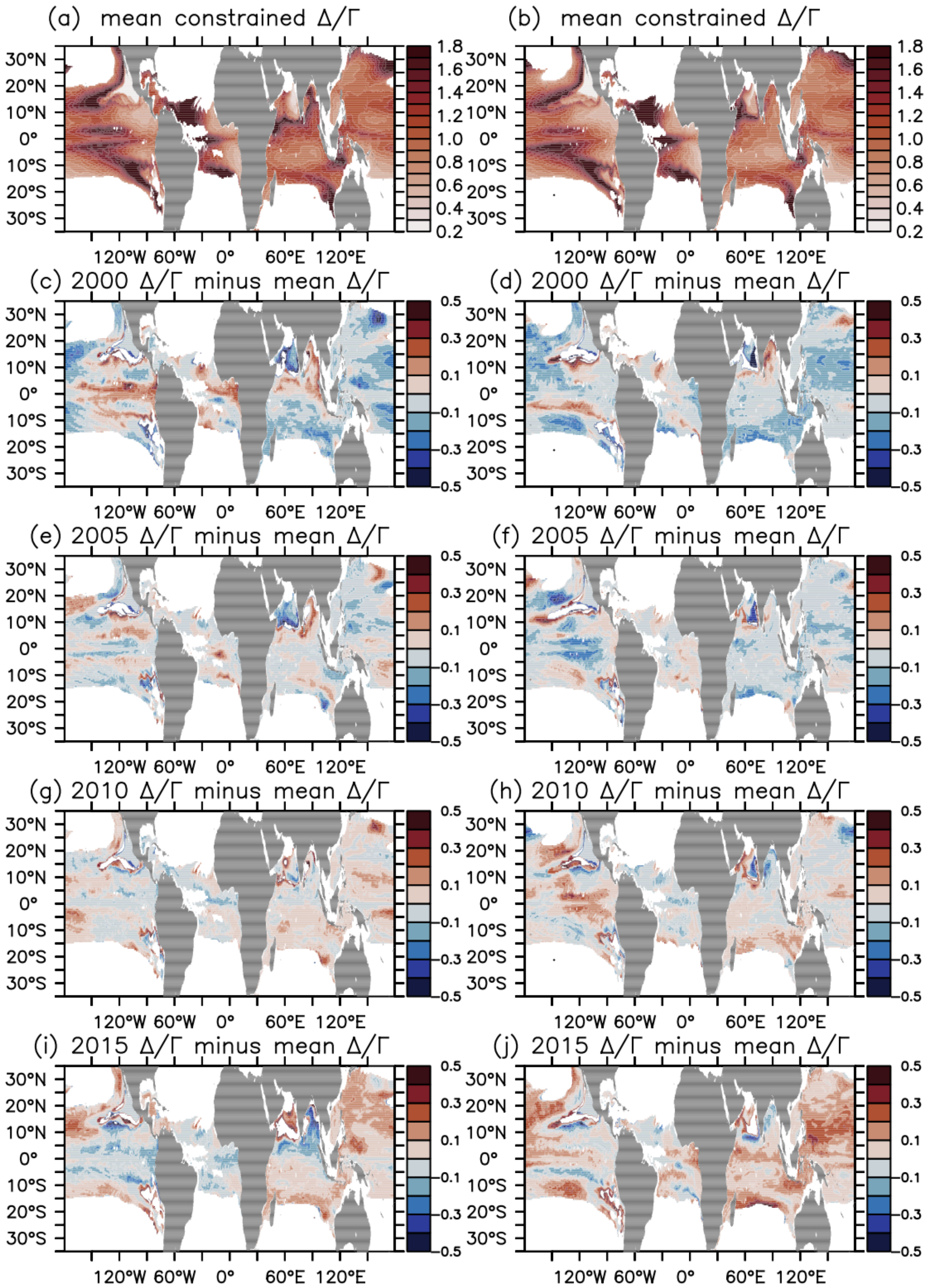

Fig. 5: Delta/Gamma constrained by the simulated concentration of CFC-12 and SF_6 on isopycnal layer σ_0=25.5 kg·m^{-3} under pre-industrial and historical forcing conditions. Panels (c,e,g,i) show Delta/Gamma constrained in 2000, 2005, 2010, and 2015, minus the temporal mean Delta/Gamma (panel a) in the *esm-piControl* experiment. Panels (d,f,h,j) show Delta/Gamma$ constrained in 2000, 2005, 2010, and 2015, minus the temporal mean Delta/Gamma (panel b) in the *esm-Hist* experiment. During the calculation, we assume 100% surface saturation of both tracers.

Fig.4:

latitude labels could be omitted at the right figure

The labels at the color bar are 'cut off' at the right side (the same holds for figure 2b)

A: We have modified our figures according to suggestions.

Fig. 3a, 6a and 7a: quantity and unit for the color bar are missing

the correlation values 0.95 and 0.9? at the Taylor Diagram overlap with the color bar

A: We have added the unit for the color bar and overcome the overlap between the Taylor Diagram and the color bar. We show Fig. 3 as an example here.

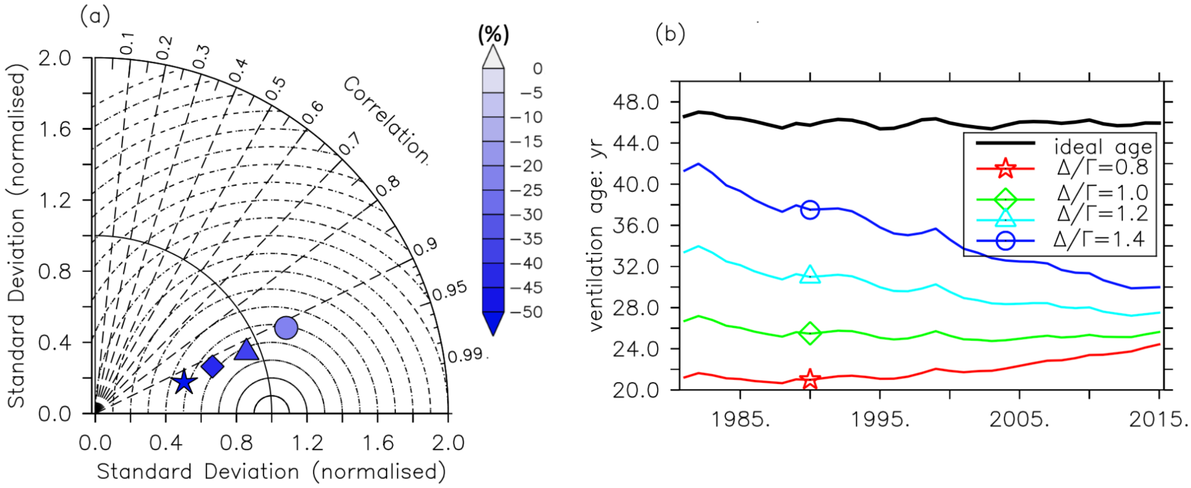

Fig. 3: In the pre-industrial control run, panel (a) presents the Taylor Diagram between 1981 to 2015 averaged mean age of IG-TTD and the ideal age (as reference) at isopycnal layer σ_0=25.5 kg·m^{-3} and the color pattern provides the bias in %. The symbols of star, diamond, triangle and circle indicate Delta/Gamma as 0.8, 1.0, 1.2 and 1.4 respectively are applied in IG-TTD calculation. Panel (b) shows the global-averaged ideal age (black), and mean age with Delta/Gamma of 0.8 (red), 1.0 (green), 1.2 (cyan), and 1.4 (blue) from 1981 to 2015.

Minor comments:

Title: 'water mass' in two words

A: We have modified the word according to suggestions.

Additional literature:

Chouksey, M., Griesel, A., Eden, C. and Steinfeldt, R. (2022), Transit Time Distributions and ventilation pathways using CFCs and Lagrangian backtracking in the South Atlantic of an eddying ocean model. J. Phys. Oceanogr., 52(7), 1531-1548, 2022, doi:10.1175/JPO-D-21-0070.1.

Steinfeldt, R., Rhein, M., and Kieke, D. (2024), Anthropogenic carbon storage and its decadal changes in the Atlantic between 1990–2020, Biogeosciences, 21, 3839–3867, doi:10.5194/bg-21-3839-2024.