Dear Editor and reviewers,
We appreciate the expert comments provided by reviewers. Below we provide a detailed point-by-point response to all these comments. The reviewers' comments are shown in black, and our responses follow in red font. The quoted texts in the revised manuscript are in blue. Line numbers in this response reflect those in the revised manuscript unless otherwise noted. We thank the reviewers for the detailed comments and suggestions, also the time and effort that they invested into the review. We believe the revisions have strengthened the manuscript.

General Comments
1. The manuscript lacks a detailed description of ideal age tracer in these models, as readers in the community may not be familiar with C-iTRACE and iTRACE modeling. Therefore, it is necessary to provide a clearer context on model set up for idea age tracer (e.g. England, 1995).
Thanks for the suggestions. This is now clarified in revised manuscript as "First, the ideal age (IAGE) is included, which is set to 0 at the ocean surface and ages at a rate of 1 year/year thereafter passively advected and diffused into the ocean interior. Thus, IAGE is a passive circulation tracer measuring the time elapsed since the last contact with the atmosphere and working like a clock counting time after being restored to zero (England, 1995; Koeve et al., 2015). In turn, the IAGE represents the "true" model ventilation age, although it does not account for the insulation effect of sea ice" in line 109-113.

2. It would be worthwhile to discuss the importance of understanding the age of water and ventilation in the introduction.
The introduction in the revised manuscript now reads: "Discussion about past and future climate change is often difficult without reference to the global ocean circulation, because of its critical role in storing and transporting heat, carbon, and nutrients. Ice core records demonstrate significant variability in atmospheric carbon dioxide (CO_2) concentrations on the glacial-interglacial timescale (Sigman and Boyle, 2000; Monnin et al., 2001; Schmitt et al., 2012). During the last glacial period, atmospheric CO_2 levels were approximately 90 parts per million by volume (ppmv) lower than the Holocene value of 280 ppmv (11.7-0 ka where ka indicates "thousand years ago). This variation in CO_2 is closely coupled with long-term climate changes and the carbon cycle in the Earth system. Various oceanic processes thus have been suggested to regulate atmospheric CO_2, such as air-sea gas exchange (Long et al., 2021), biological production (Broecker, 1982; Sigman et al., 2021; Sigman and Boyle, 2000), and ocean circulation (Ai et al., 2020; Marcott et al., 2014; Tschumi et al., 2011; Skinner et al., 2015, 2010). Consequently, understanding past changes in global ocean circulation provides a good opportunity, not only for a more accurate constraint on the past climate change and carbon cycle, but also for insight into future climate change with rising atmospheric CO_2 level" in line 21-31.

3. It would be worthwhile to describe how the strength of the AABW physically affects the ventilation processes in two basins and, as AABW is part of the AMOC, why the AABW transport reduces during the deglaciation from a coupled view.
This is clarified in the revised manuscript as "Physically, the water in the deep overturning regions gradually recirculates into the other ocean basins so that age generally increases with distance from the formation regions. The reduced AABW transport amounts to longer transit time from the formation site at the surface to the abyssal ocean, leading to the increased IAGE. The weakening of AABW is further suggested to be attributed to the surface buoyancy forcing

over the Southern Ocean mainly in response to the deglacial atmospheric CO_2 increase and retreating ice sheets on land (Ferrari et al., 2014; Jansen, 2017; Jansen et al., 2018; Jansen and Nadeau, 2016; Liu, 2023; Pedro et al., 2018). During the HS1, the freshwater input in the northern North Atlantic reduces NADW formation, leading to the slowdown in the Atlantic Meridional Overturning Circulation (AMOC) and reduced heat transfer into the North Atlantic. Consequently, heat accumulates in the Southern Hemisphere resulting in a warming in the Southern Ocean. Collectively, with the deglacial increase of atmospheric CO_2, sea ice around Antarctica is retreated with less brine rejection, ultimately contributing to the weakening of AABW transport towards north (Fig. 6i-j, Fig. 7i-j, Fig. 11g, and Fig. 12g)" in line 350-360.

4. Figure 4: What is driving the IAGE from the North Atlantic to get much older from 12 to 10 ka?
This is clarified in revised manuscript as "The mean IAGE for AABW water mass increases from 836 years at the LGM to 1813 years at 14 ka due to the weakening of AABW transport, while the age of NADW increases by up to 1500 years during the period of 12–11 ka due to more NADW sinking into deeper depths in the Arctic (Fig. 2j-l), resulting in a relatively older water age for NADW and the lag of 2000 years between the maxima of Dye_NA and Dye_S (Fig. 3a-b)" in line 272-275.

5. No units in figures 6, 7, 8, 11, 12, and 13
Corrected.

6. Line 76 and 39: Check grammar
Corrected.

7. Line 8: Remove "postal code"
Corrected.

8. Line 11: "CO2" to "CO_2"
Corrected.

9. Line 95 and Line 368: "Gu, Liu, Jahn, et al., 2019", Remove "Liu, Jahn"
Corrected.

10. What's the meaning in Line 170: "8 10^8 km^3" and "7 10^{11} yr km^3".
The is corrected in the revised manuscript: "Furthermore, the volume of AABW is about 9×10^8 km^3 at the LGM and PD, such that the volume integrated IAGE for AABW is about 7×10^{11} yr km^3 at both LGM and PD (Fig. 3b and 3c)" in line 189-191.

11. Line 45: Remove the comma symbol in "Zanowski et al., (2022)"
Corrected.