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.

Major comments:
The "Introduction" section should be reorganized. The topic of the article is the underlying mechanisms for the younger ventilation during the LGM relative to the PD, in tandem with the oldest ventilation age during the last deglacial according to the IAGE. However, the present Introduction introduces too much about the $\Delta^{14}C$ age, and the definition and application of the IAGE are lacking. Moreover, the significance of understanding the ventilation age during the LGM and last deglacial should be highlighted more clearly.
Thanks for the comments. This manuscript is actually motivated by the different temporal evolution of $\Delta^{14}C$ age and ideal age. Therefore, it is our opinion that a brief introduction about the $\Delta^{14}C$ age is necessary, and a more detailed definition of IAGE is elaborated in section 2. The introduction is revised in the manuscript to highlight the importance of ventilation age: "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, and details of IAGE set up is now clarified in the revised manuscript: "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. Line 168: How is the threshold of 70% defined? It is not clarified in the manuscript. Whether the evolution results would be different if using different values (such as 60%, 80%)?
The other reviewer brought up a similar concern which is now addressed. We have performed additional analysis showing that the conclusion is actually somewhat insensitive to the choice of this value, which is now clarified in the revised manuscript: "The IAGE value is calculated

where the percentages of AABW% and NADW% exceed 70% below 1 km in the global ocean (Fig. 3a). The conclusion is somewhat insensitive to the choice of dye concentration value for NADW and AABW. A higher (lower) value of 80% (60%) indicates less (more) mixing with other water masses and thus does not affect the main results" in line 185-188. Figure R1 below shows the results using 60%, and the results are similar to that using the fraction value of 70% in figure 3 in the manuscript.

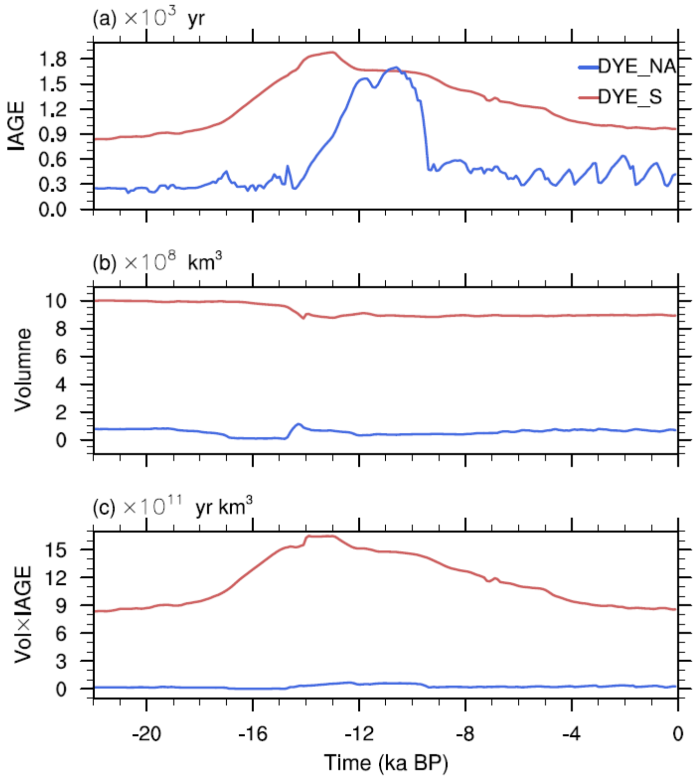

Figure R1 Time evolutions for water masses sourced from the North Atlantic (Dye_NA) and Southern Ocean (Dye_S). (a) The global volume-weighted average of ideal age (IAGE) where fractions of water are greater than 60%. (b) The total water volume where fractions of water are greater than 60%. (c) The age of total volume of water from the Southern Ocean and North Atlantic.

3. Line 190-195: Authors indicated that the evolution of IAGE is more similar to the strength of AABW than GMOC. However, changes in the AABW transport may be a part of GMOC. In other words, the AABW transport and GMOC are interactive, and in the modelling who is the reason and who is the result? It makes me confused about the appearance of the GMOC across the manuscript. More discussions or clarifications about this point should be added.

We thanks for the comments, and this is now clarified in the revised manuscript: "This bell shaped deglacial evolution of global IAGE aligns with similar transport evolutions of the residual GMOC and global AABW (Fig. 1d, Fig. 2d-f) as well as the AABW% in dye tracer from the Southern Ocean (Fig. 3, Fig. 2g-i). Here, the GMOC is diagnosed as the maximum in the GMOC streamfunction below 600 m from 33° S-60° N and, therefore, the main feature of the GMOC follows the upper clockwise cell mostly confined to the Atlantic sector. Since the abyssal ocean is predominately filled by AABW, the evolution of IAGE corresponds more closely to the

AABW intensity than GMOC as shown in figure 1 that the decrease in global AABW transport aligns with the increase in global mean IAGE during the same period (14–13 ka)" in line 203-210.

4. Authors highlighted the importance of the AABW transport changes in regulating the ventilation age during the LGM and the last deglacial and indicated that the AABW transport changes are associated with sea ice and buoyancy flux over the Southern Ocean. However, this conclusion only appears simply in the Abstract and Summary, and analysis is lacking in the manuscript. More discussions about the mechanisms driving AABW transports should be added. At least, the evolution of sea ice during the LGM and last deglacial should be provided and the relationship between sea ice and AABW transport needs to be analyzed briefly. Moreover, the ultimate driving factors are also necessary to be discussed (i.e. the external forcings), maybe the role of freshwater injection or continental ice sheet during the LGM and last deglacial on the sea ice, on the AABW transport, and on the ventilation age should be discussed.
The evolution of sea ice, as suggested, is added in figure 6, 7, 11, and 12. And the role of freshwater injection and continental ice sheet in AABW and ventilation age is also discussed. The revised manuscript now reads: "Model simulations further suggest that the strong glacial AABW transport is dominated by changes in surface buoyancy forcing over the Southern Ocean (Ferrari et al., 2014; Jansen, 2017; Jansen and Nadeau, 2016; Liu, 2023; Shin et al., 2003; Sun et al., 2018). The sea ice expansion at the LGM enhanced the brine rejection during winter, leading to extremely saline and dense AABW. Thus, the glacial deep ocean is filled with greatly expanded cold-salty AABW water mass with higher densities, contributing to a stronger AABW transport. The stronger glacial AABW transport, in turn, reflects a shorter residence time in the ocean interior, as indicated by the overall younger LGM IAGE compared to the water age at the PD" in line 161-167, and "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.

5. The simulated ventilation age during the LGM and last deglacial need to be compared with the various proxy reconstructions comprehensively in the manuscript. Please add some discussions on this point.
We acknowledge the importance of model validation using proxy observations. However, the transient ocean simulation of the last deglaciation (C-iTRACE) has been examined in greater detail in Gu et al. (2020, 2021), Zanowski et al. (2022). The scope of this modeling study is to better understand the deglacial evolution of deep ocean ventilation age.

Minor comments:

1. Fig. 1 only provides the global mean IAGE and Pacific mean IAGE. What is about the Atlantic mean? Any opinion?

Overall, the water age in the Atlantic is considerably younger than that in the Pacific. As a result, Atlantic was not included in Figure 1 in the original manuscript. But it is now included in figure 1 in revised manuscript.

2. Line 124: suggest replacing "in contrast to" with "younger than"

Revised as suggested.

3. Lines 126-127: This sentence is confusing. Pleas rewrite.

Revised as suggested.

4. Lines 152-154: The description here is unexpected, and I suggest removing it or making it clear.

Revised as suggested.

5. Line 170: The multiple sign is missing.

Corrected.

6. The order of subpanels in Fig. 6 and Fig. 7 should be rearranged, as Fig.6g-h and Fig. 7g-h appear earlier than Fig. 6a and 7a. (Line 244-245).

Corrected.

7\. Fig. 6 and Fig. 7. The left string of figures may be "C-iTRACE".

Corrected.

7. More quantified information should be added in the Abstract and Summary section (for example, the exact value of the ventilation age during the LMG and the last deglacial).

Revised as suggested.