

A Framework for Constraining Ocean Mixing Rates and Overturning Circulation from Age Tracers

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ABSTRACT: The age of seawater refers to the amount of time that has elapsed since that water encountered the surface. This age measures the ventilation rate of the ocean, and the spatial distribution of age can be influenced by multiple processes, such as overturning circulation, ocean mixing, and air–sea exchange. In this work, we aim to gain new quantitative insights about how the ocean’s age tracer distribution reflects the strength of the meridional overturning circulation and diapycnal diffusivity. We propose an integral constraint that relates the age tracer flow across an isopycnal surface to the geometry of the surface. With the integral constraint, a relationship between the globally averaged effective diapycnal diffusivity and the meridional overturning strength at an arbitrary density level can be inferred from the age tracer concentration near that level. The theory is tested in a set of idealized single-basin simulations. A key insight from this study is that the age difference between regions of upwelling and downwelling, rather than any single absolute age value, is the best indicator of overturning strength. The framework has also been adapted to estimate the strength of abyssal overturning circulation in the modern North Pacific, and we demonstrate that the age field provides an estimate of the circulation strength consistent with previous studies. This framework could potentially constrain ocean circulation and mixing rates from age-like realistic tracers (e.g., radiocarbon) in both past and present climates.

SIGNIFICANCE STATEMENT: The age of seawater—the local mean time since local water from different pathways was last at the surface—is a valuable indicator of ocean circulation and the transport time scale of heat and carbon. We introduce a novel constraint that relates total age flow across a density surface to its geometry, which provides new insights into constraining ocean circulation and mixing rates from age-like realistic tracers (e.g., radiocarbon).

KEYWORDS: Diapycnal mixing; Meridional overturning circulation; Ocean circulation; Tracers; Inverse methods

1. Introduction

The ocean circulation plays an important role in regulating the global climate, transporting heat and carbon on centennial-to-millennial time scales. It is well established that water masses in the deep ocean are mainly formed in the high-latitude North Atlantic and Southern Ocean (Lumpkin and Speer 2007; Talley 2013), but where and how the water comes back to the surface remains comparatively unsettled. It was recently argued that the abyssal circulation is shaped by mixing processes near the seafloor, especially over sloping boundaries (e.g., Ferrari et al. 2016; de Lavergne et al. 2017; Callies and Ferrari 2018). The divergence of buoyancy flux caused by turbulent mixing drives the diapycnal motion of water masses. Hence, the ocean circulation and diapycnal mixing processes

are closely related through the transformation of water masses (e.g., Stommel and Arons 1959; Munk 1966; Munk and Wunsch 1998; Groeskamp et al. 2016; Rogers et al. 2023; Wunsch 2023), and it is important to constrain the relationship between these two processes.

Ocean circulation and mixing processes also work together to influence ocean tracer distributions. The role of advection by the global overturning circulation in determining the distributions of long-lived tracers has long been recognized (Broecker 1991). The mixing both along and across isopycnals is also important in explaining tracer distributions, such as carbon, oxygen, and nutrients (Cimoli et al. 2023; Holzer et al. 2021a; Lund et al. 2011; Ellison et al. 2023; McPhee-Shaw et al. 2021; Chen et al. 2022). In this paper, we focus on the spatial distribution of the ideal age tracer and its connection to ocean circulation and mixing. While we utilize the ideal age tracer to demonstrate our method, it is also applicable to age derived from realistic tracers, such as radiocarbon.

Ideal age describes the mean time since the ocean water at an interior location was last in contact with the ocean surface (e.g., Sarmiento et al. 1990; England 1995). The magnitude of ideal age is equivalent to the equilibrium concentration of an “ideal age tracer,” which has zero concentration at the ocean surface and a uniform source of 1 yr yr^{-1} in the interior (Holzer and Hall 2000). Due to the existence of mixing, the

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ideal age value at a specific location below the ocean surface is determined by the integration of a set of different water transport pathways (e.g., Gebbie and Huybers 2012; Mouchet and Deleersnijder 2008; Mouchet et al. 2012). Thus, a transit time distribution (TTD) is needed to provide a full description of the transport history (see section 2 for more details). While the ocean TTD contains the full information about ocean transport, an observational description of the full TTD is difficult to achieve. In contrast, as the mean transit time of all the possible ventilation pathways, the ideal age provides a compact description of ocean transport and can be more easily constrained by observations. Thus, it is interesting and practical to investigate to what extent we can infer the circulation from the ideal age.

Ideal age has been used to assess and understand the change in circulation and ventilation under different climate states. For example, a recent study explores the change in ideal age due to climate change in the twenty-first century to understand the change in ocean ventilation (Chamberlain et al. 2019; Holzer et al. 2020). In paleoceanography, it is generally found that the age concentration during the Last Glacial Maximum (LGM), inferred from radiocarbon, could be systematically different from the current ocean (Skinner et al. 2017; Rafter et al. 2022). Several processes have been suggested to contribute to the change in the estimated age, including the strength and geometry of the overturning circulation (Muglia and Schmittner 2021; Zanolowski et al. 2022), isopycnal and diapycnal mixing (Jones and Abernathy 2021; Burke et al. 2015; Wilmes et al. 2021; Oka and Niwa 2013), and surface reservoir conditions (Gu et al. 2020; Zanolowski et al. 2022; Nadeau and Jansen 2020). The complexity of various processes affecting the age spatial distributions can pose challenges in deciphering information about ocean circulation from them. In this work, we focus on the following question: What can be quantitatively inferred about the diapycnal diffusivity and overturning circulation rate from the ideal age?

Here, we propose a quantitative framework that incorporates an integral constraint on the total age flow across the boundary of an arbitrary control volume. This framework draws inspiration from recent stratospheric studies (Linz et al. 2016, 2017, 2021). The framework enables us to utilize the spatial distribution of the ideal age tracer to constrain the relationship between the zonally integrated meridional overturning strength and the globally averaged effective diapycnal diffusivity across an arbitrary density level in an idealized single-basin simulation. Moreover, we have successfully adapted the framework to estimate the strength of the regional North Pacific abyssal circulation, utilizing a single vertical profile of zonal-mean ideal age simulated by a data-constrained inverse model. Our method holds particular promise in scenarios with limited data availability, which is common in paleoceanography studies. The construction of the integral constraint in this study bears resemblance to the approach taken in previous research by Lund et al. (2011). However, a notable distinction lies in the application scope; while Lund et al. (2011) focused on conservative tracers, our method is appropriate for age-like tracers, such as radiocarbon.

The paper is organized as follows. In section 2, the concept of ideal age and the integral constraint used in this research are discussed in detail, along with the configuration of the idealized ocean simulations. In section 3, the simulated age and meridional overturning streamfunctions are presented, and the integrated age flow budget expected by our age framework is tested with these simulations. In section 4, the age framework is used to constrain the diapycnal diffusivity and the strength of the meridional overturning circulation. Further discussion is provided in section 5, with a notable focus on the adaptation of the framework to estimate the North Pacific abyssal circulation. The conclusions can be found in section 6.

2. Methods

a. Definition of age and the ideal age tracer

The age of a fluid at a certain interior location $\mathbf{r}$ is the average time since the fluid particles at $\mathbf{r}$ last encountered the boundary. We take the ocean surface as the boundary and calculate the ideal age $\Gamma(\mathbf{r})$ as the average travel time from different pathways (e.g., Holzer and Hall 2000). In this paper, we assume the ocean is in a statistically steady state and focus on the climatological circulation and age. The ideal age $\Gamma(\mathbf{r})$ can be formally expressed as the first-order moment of the TTD, which describes the local proportion of water as a function of the travel time from the surface. The TTD can be thought of as a Green's function that propagates the tracer mixing ratio from the ocean surface into the ocean interior and is a complete description of advective and diffusive ocean transport (e.g., Hall and Plumb 1994; Waugh et al. 2003; Khatiwala et al. 2001; Siberlin and Wunsch 2011). The ideal age is often referred to as the “mean age” because it is the mean transit time from all different pathways.

Following Waugh and Hall (2002), the ideal age Γ can be interpreted as the equilibrium concentration of an ideal age tracer, which satisfies the transport equation:

$$\frac{\partial \Gamma}{\partial t} + \nabla \cdot \mathbf{F}^\Gamma = 1, \quad (1)$$

where $\mathbf{F}^\Gamma$ denotes the total advective–diffusive flux of the tracer, and the right-hand side is the source term of the ideal age tracer, which is equal to 1 (yr yr^{-1}). At the ocean surface, the boundary condition is $\Gamma = 0$. In a statistically steady state, the long-term mean of $\partial \Gamma / \partial t$ is approximately equal to 0. The left-hand side of Eq. (1) retains the same form for the evolution of any tracer, as it represents the material derivative of the tracer plus its diffusive flux. However, the 1 (yr yr^{-1}) source term on the right-hand side is specific to the ideal age tracer, which gets older at a spatially and temporally constant speed.

b. The age tracer framework

The age framework is built on the age evolution equation [Eq. (1)] and is adapted from Linz et al. (2016), a stratospheric study. We focus on the climatological ocean circulation and

mixing. However, it should be noted that the framework can be extended to time-dependent circulations (Linz et al. 2016).

Consider a control volume V in the ocean enclosed by its boundary S (e.g., Fig. 1), and integrate both sides of Eq. (1) over V . We have

$$\int_S \mathbf{n} \cdot \mathbf{F}^\Gamma dA = \int_V 1 dV = V, \quad (2)$$

noting that we assume $\partial\Gamma/\partial t = 0$. The equation states that the age flow across a closed surface is equal to the volume enclosed by that surface. In Eq. (2), $\mathbf{n}$ is the local normal vector of the boundary S . The validity of Eq. (2) is independent of the shape of V . In this paper, we focus on diapycnal diffusion and overturning circulation across isopycnals and choose our V accordingly. We let our boundary S of the control volume V (Fig. 1) be composed of an interior isopycnal S_σ , the ocean surface S_{surface} , and the ocean basin S_{basin} wherever it outcrops or incrops, respectively. The ocean surface S_{surface} is connected to S_{basin} wherever the two surfaces meet to form a closed boundary of V . The age flow budget in Eq. (2) can then be written as

$$\begin{aligned} \int_{S_{\text{basin}} + S_\sigma + S_{\text{surface}}} \mathbf{n} \cdot \mathbf{F}^\Gamma dA &= \underbrace{\int_{S_\sigma} \mathbf{n} \cdot \mathbf{F}_{\text{ADV}}^\Gamma dA}_{\mathcal{F}_{\text{ADV}}(\sigma)} + \underbrace{\int_{S_\sigma} \mathbf{n} \cdot \mathbf{F}_{\text{DIFF}}^\Gamma dA}_{\mathcal{F}_{\text{DIFF}}(\sigma)} \\ &+ \underbrace{\int_{S_{\text{surface}}} \mathbf{F}_{\text{SURF}}^\Gamma dA}_{\mathcal{F}_{\text{SURF}}(\sigma)} = V, \end{aligned} \quad (3)$$

which states that the sum of the diapycnal advective flow of age $\mathcal{F}_{\text{ADV}}(\sigma)$ and diffusive flow of age $\mathcal{F}_{\text{DIFF}}(\sigma)$ across the isopycnal surface, as well as the air–sea exchange of age at the outcrop region $\mathcal{F}_{\text{SURF}}(\sigma)$, is equal to the volume under that surface. By definition, there is no age flow across $S_{\text{basin}}(\sigma)$. A similar age budget has been applied in Gnanadesikan et al. (2007) to understand the change in age under global climate change. Our study can be considered as a new interpretation of this budget, with the focus on constraining ocean circulation.

With the constraint of Eq. (3), we can estimate the sum of total age advection $\mathcal{F}_{\text{ADV}}(\sigma)$ and diffusion $\mathcal{F}_{\text{DIFF}}(\sigma)$, given the knowledge of air–sea exchange $\mathcal{F}_{\text{SURF}}(\sigma)$. The air–sea exchange of ideal age $\mathcal{F}_{\text{SURF}}(\sigma)$ is due to the relaxation of the ideal age tracer toward zero concentration and can be diagnosed from the age concentration at the uppermost model layer. When applying our method to the real ocean, the air–sea exchange of age-like realistic tracers (e.g., radiocarbon and helium isotopes) can be parameterized, for example, as a function of the surface wind speed and mixed layer depth (e.g., DeVries 2014). Section S1 in the online supplemental material gives an example of how to convert the air–sea exchange flow of radiocarbon to the air–sea exchange of age. We also suggest readers consider directly applying our framework to realistic tracers, without the conversion to ideal age, when inferring the circulation of the real ocean (see section S1).

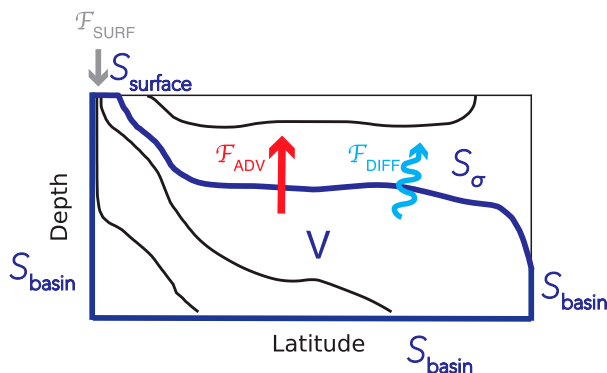


FIG. 1. Schematic diagram on the age framework. Black contours show isopycnal surfaces. The dark blue contour is the boundary S of the control volume V . The schematic diagram is drawn in the latitude–depth space, but the integration is actually in the three-dimensional space. Arrows indicate age flows: diapycnal age advection $\mathcal{F}_{\text{ADV}}(\sigma)$ (red arrow), diapycnal age diffusion $\mathcal{F}_{\text{DIFF}}(\sigma)$ (blue arrow), and air–sea age flow at the ocean surface $\mathcal{F}_{\text{SURF}}(\sigma)$ (gray arrow).

In the following discussions, we will continue to focus on ideal age and take $\mathcal{F}_{\text{SURF}}(\sigma)$ as known.

We consider two scenarios for the application of this constraint on the sum of $\mathcal{F}_{\text{ADV}}(\sigma)$ and $\mathcal{F}_{\text{DIFF}}(\sigma)$. The first scenario assumes we have some prior knowledge of the ocean velocity field; thus, we know the age advection $\mathcal{F}_{\text{ADV}}(\sigma)$ across isopycnal surface S_σ . In this scenario, the total diffusive flow $\mathcal{F}_{\text{DIFF}}(\sigma)$ and the globally averaged effective diapycnal diffusivity $\kappa_{\text{eff}}(\sigma)$ can be inferred from the age framework. The second scenario prescribes the effective diffusivity $\kappa_{\text{eff}}(\sigma)$, and we focus on how the meridional overturning strength across an arbitrary density surface S_σ can be inferred from the spatial distribution of age on S_σ .

c. MITgcm model configuration

To test the age framework, we perform a set of four single-basin ocean circulation simulations with different mixing parameters using the Massachusetts Institute of Technology General Circulation Model (MITgcm; Marshall et al. 1997). The horizontal resolution of the model is 1° , and there are 30 vertical levels with uneven spacing from 10 m at the surface to 250 m at the bottom. We do not expect the results to be substantially sensitive to this specific configuration of the model. The model domain spans a zonal range of 60° to mimic the Atlantic basin (Fig. 2a). There is a closed basin north of 45°S and a zonally reentrant channel in the south. A zonally smoothed ridge with the maximum height of 2 km provides the form stress that balances the momentum input into the Antarctic Circumpolar Current from surface wind forcing (Munk and Palmén 1951).

The model is forced with a zonally uniform wind stress (Fig. 2d). Surface temperature θ is restored to a prescribed temperature profile θ_s (Fig. 2c) with a relaxation time scale of 20 days. For salinity, a zonally uniform freshwater flux is prescribed (Fig. 2b). A weak relaxation (time scale of 2 years) of surface salinity toward 35 psu is also used to prevent a drift in salinity and

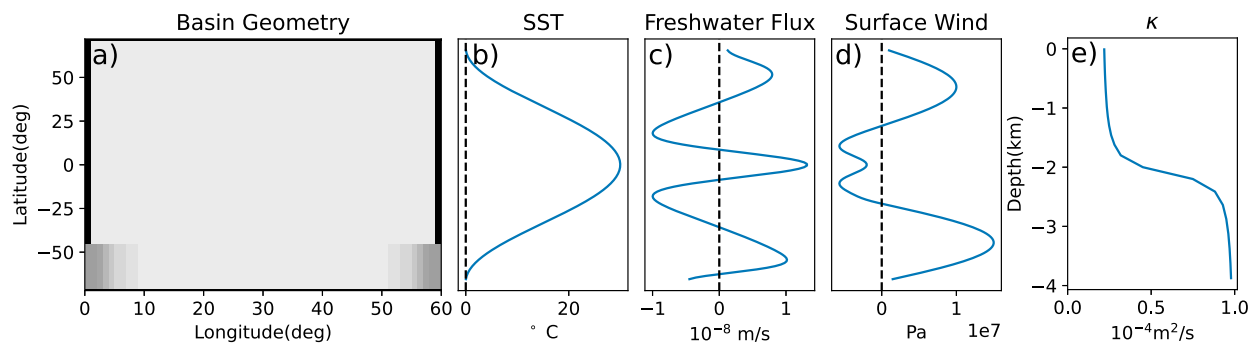


FIG. 2. Model configuration for the MITgcm simulations. (a) The basin configuration. The depth is 4000 m everywhere except a 2000-m-deep submarine sill, indicated by gray shading with the contour interval of 250 m. (b) Prescribed sea surface temperature profile. (c) Surface freshwater flux input, which is the difference between precipitation and evaporation. (d) Surface wind stress. The vertical dashed black lines in (b)–(d) indicate zero values of the abscissa. The sea surface temperature, freshwater flux, and surface winds are all zonally symmetric. See section 2c for further details about the surface forcing. (e) The diapycnal diffusivity $\kappa_{\text{dia}}(z)$ profile for the Control simulation.

bistability of the ocean circulation (Stommel 1961). A nonlinear equation of state (Jackett and McDougall 1995) is applied.

For the Control run, vertical mixing is implemented with a bottom enhanced diapycnal diffusivity (Fig. 2e), which increases from $2 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ at the surface to $1.3 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ at the bottom with a transition depth of 2000 m (Bryan and Lewis 1979). Unresolved eddies are represented using the skew-flux form of the Gent–McWilliams (GM) parameterization with $K_{\text{GM}} = 500 \text{ m}^2 \text{ s}^{-1}$ and a constant isopycnal diffusivity $K_{\text{Redi}} = 500 \text{ m}^2 \text{ s}^{-1}$. The momentum is dissipated via Laplacian viscosity, biharmonic viscosity, and vertical viscosity with coefficients $A_h = 1.0 \times 10^4 \text{ m}^2 \text{ s}^{-1}$, $A_4 = 1.0 \times 10^{12} \text{ m}^4 \text{ s}^{-1}$, and $A_v = 1.0 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$, respectively. Vertical convection is represented by an implicit vertical diffusion with a diffusivity of $100 \text{ m}^2 \text{ s}^{-1}$ whenever the stratification is unstable, following the configuration in Sun et al. (2020). The age tracer evolves with time with a source term of 1 yr yr^{-1} in the interior of the ocean below the top grid layer of the model. At the sea surface (i.e., top grid layer), the age tracer is restored to zero with a relaxation time scale of 1 day. We find the equilibrium spatial distribution of ideal age is not sensitive to this relaxation time scale, as long as it is sufficiently short. (Results are similar for 0.5, 1, and 2 days, which are not shown.) The simulation is carried out for 7000 years to ensure an equilibrium state for both the circulation and the ideal age tracer.

In addition to this Control run, we have three additional runs where we modify mixing parameters to test our framework: 1) We double the diapycnal diffusivity parameter κ in the kappa2x simulation; 2) we double the Gent–McWilliams eddy thickness parameter in the KGM2x simulation (Gent and McWilliams 1990; Gent et al. 1995); and 3) we double the Redi isopycnal mixing parameter in the KRedi2x simulation (Redi 1982). All other settings are kept the same as in the Control run.

3. Simulation results

a. Meridional overturning circulation and age spatial distribution

The residual overturning streamfunctions for the four simulations, defined as a function of latitude and density, are calculated as (e.g., Nurser and Lee 2004)

$$\Psi(y, \sigma) = -\frac{1}{T} \int_0^T \int_{x_e}^{x_w} \int_{z_{\text{bot}}}^0 v_r(x, y, z, t) \mathcal{H}[\sigma'(x, y, z, t) - \sigma] dz dx dt, \quad (4)$$

and are shown in Fig. 3. Here, σ denotes the potential density σ_2 referenced to 2000 dbar. The term T denotes the averaging period, x_w and x_e represent the western and eastern boundaries of the basin, respectively (for the Southern Ocean, we integrate zonally around the globe along each latitude circle), and z_{bot} represents the ocean bottom. The term v_r is the residual meridional velocity that includes both the Eulerian-mean meridional velocity $\bar{v}$ and the meridional component of eddy bolus velocity due to the parameterized eddies v_{GM} . The term $\mathcal{H}$ is the Heaviside function. Physically, the streamfunction represents the northward transport above the density layer σ . The streamfunction shown in Fig. 3 in density space is mapped back to depth space, with the zonal-mean depth $\hat{z}(y, \sigma)$ of isopycnal σ defined implicitly by

$$\int_{x_e}^{x_w} \int_{z_{\text{bot}}}^{\hat{z}(y, \sigma)} dx dz = \frac{1}{T} \int_0^T \int_{x_e}^{x_w} \int_{z_{\text{bot}}}^0 \mathcal{H}[\sigma'(x, y, z, t) - \sigma] dz dx dt, \quad (5)$$

that is, the total cross-sectional area below $\hat{z}$ at latitude y is equal to the cross-sectional area of fluid denser than σ_2 .

In all four simulations, the overturning streamfunction is characterized by a pole-to-pole clockwise upper cell and an anticlockwise lower cell, which is qualitatively similar to previous single-basin simulations (e.g., Wolfe and Cessi 2011; Nikurashin and Vallis 2012; Burke et al. 2015) and captures the leading-order structure of the global two-cell circulation (e.g., Lumpkin and Speer 2007; Talley 2013; Cessi 2019; Youngs et al. 2020). Doubling the magnitude of diapycnal diffusivity $\kappa_{\text{dia}}(z)$ (Fig. 3, kappa2x) leads to a stronger overturning streamfunction, which is consistent with the prediction in Wolfe and Cessi (2011) and Nikurashin and Vallis (2012). The stratification also weakens due to the enhanced diapycnal mixing. Doubling the isopycnal diffusivity Redi parameter

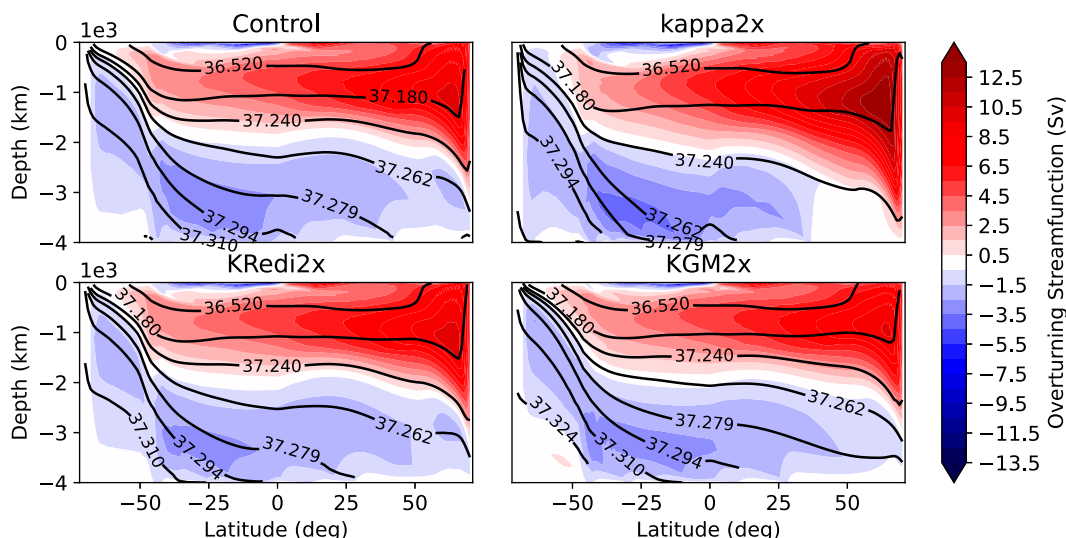


FIG. 3. Residual overturning streamfunctions (contour interval 1 Sv; color) and zonally averaged depth of σ_2 isopycnal surfaces (numbers indicate the corresponding σ_2 values; black) of the four simulations. Maximum streamfunction values for the upper (lower) cell for the four simulations in Sv are 9.5 (3.7) for Control; 10.1 (4.0) for kappa2x; 9.6 (3.4) for KRedi2x; and 9.4 (4.0) for KGM2x.

(Fig. 3, KRedi2x) slightly reduces the stratification in the deep Southern Ocean. The abyssal cell also becomes slightly weaker due to the reduced stratification. Increasing the GM parameter (Fig. 3, KGM2x) slightly increases the stratification in the deep ocean. The maximum magnitudes of both the upper cell and the lower cell are similar to the Control run.

The zonally averaged mean age concentrations are shown in Fig. 4. The age concentrations in all four simulations are qualitatively consistent with the meridional overturning circulation, with the youngest water at the northern edge and the

southern edge of the simulated domain. As the mixing parameters and the underlying advective fields are different in the four simulations, the spatial distributions of ages are quantitatively different. In the kappa2x run, the age becomes much younger than in the Control run, with the age maximum decreasing from 1048 to 549 years. This is likely due to a combination of both the change in meridional overturning and the increased diapycnal diffusivity. The relative roles of advection and diffusion on diapycnal age transport will be discussed in more detail in the next section. In the KRedi2x run, the

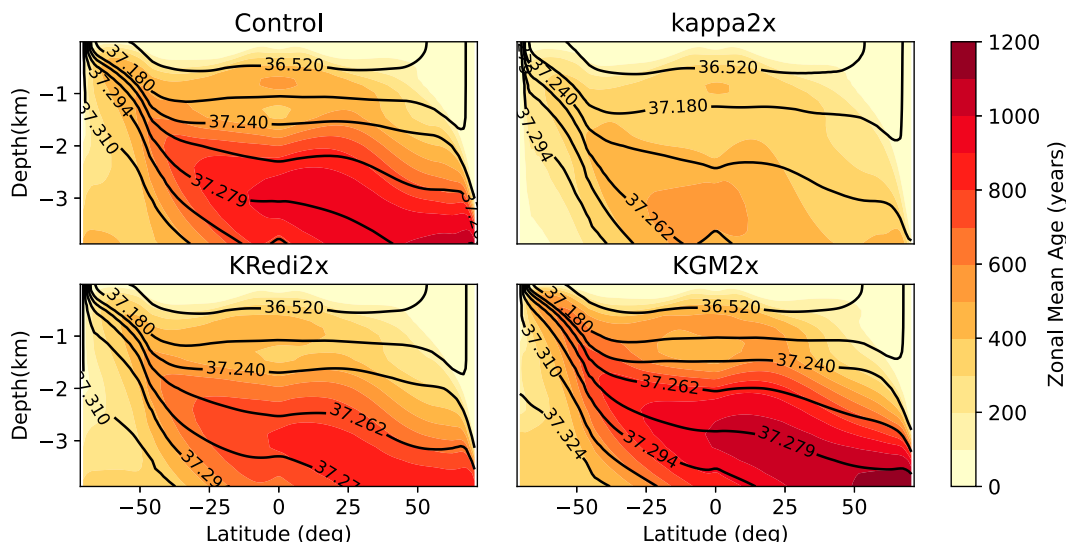


FIG. 4. Zonal-mean age concentration (contour interval 100 years; color) of the four simulations and zonally averaged depth of σ_2 isopycnal surfaces (numbers indicate the corresponding σ_2 values; black). Maximum age for the four simulations (years) is 1048 for Control, 549 for kappa2x, 863 for KRedi2x, and 1159 for KGM2x. See Fig. S10 for the difference in zonal-mean age between the perturbation runs and the Control run.

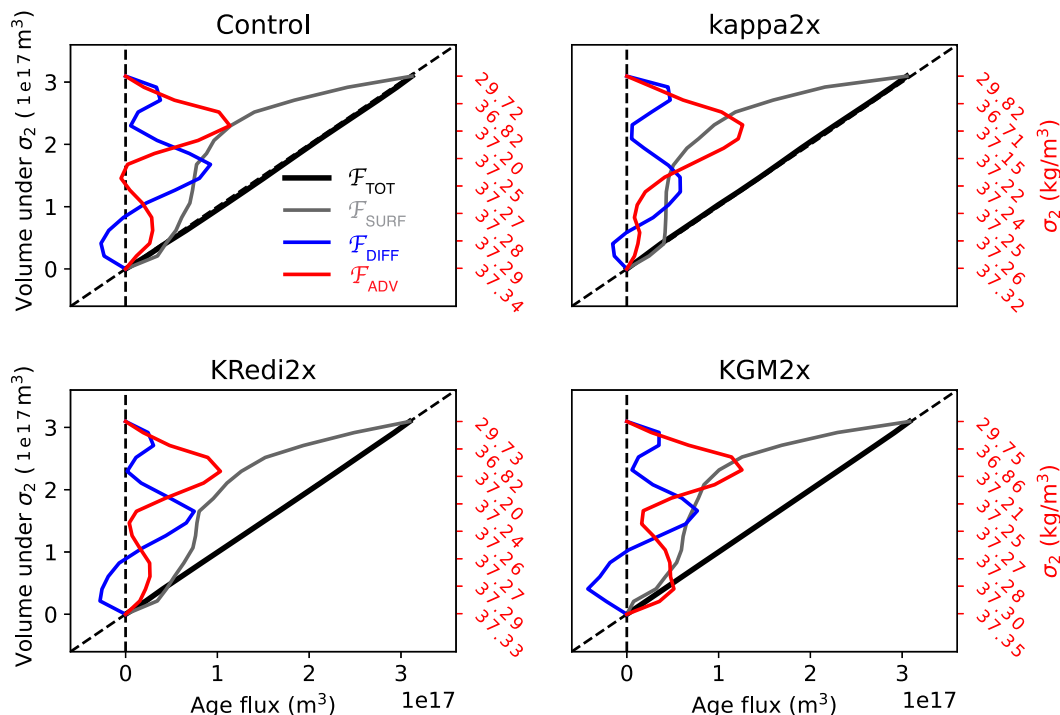


FIG. 5. Age flow budget of the four simulations. The vertical axis indicates the total volume below certain potential density σ_2 levels (left y axis; black) and the corresponding σ_2 (right y axis; red). See Fig. 1 for a schematic diagram of the vertical coordinate system; see Fig. S9 for the zonal-mean depth of the vertical axis tick in each panel. The horizontal axis shows the age flows across the corresponding isopycnal σ_2 surfaces. Positive indicates the upward flow out of the volume below σ_2 , and negative indicates the downward flow into the volume. Four flows are presented: the surface age flow $\mathcal{F}_{\text{SURF}}(\sigma)$ (gray line), which is the surface relaxation of age toward zero, representing the air–sea exchange of age tracer; the total diapycnal diffusive age flow $\mathcal{F}_{\text{DIFF}}(\sigma)$ (blue line), which includes parameterized turbulent diapycnal mixing of age (Bryan and Lewis 1979), a small contribution of convective flow, and a small diapycnal contribution of Redi flow (see text); the total diapycnal advective flow $\mathcal{F}_{\text{ADV}}(\sigma)$ (red line), which includes both the resolved Eulerian flow and the parameterized GM eddy bolus advection; and the total age flow (black line), which is the sum of the three previous terms. The tilted dashed line shows the one-to-one relationship of total age flow and volume under isopycnal σ_2 predicted by the theory, and the vertical dashed line shows the zero age flow line.

spatial pattern is quite similar to the Control run, but the overall age becomes younger, which can be explained by the increased ventilation due to the stronger isopycnal mixing (Jones and Abernathy 2019, 2021). In the KGM2x simulation, we also see a similar age pattern to the Control run, but with slightly older maximum age (from 1048 to 1159 years), which is consistent with the slightly weaker overturning strength. The spatial pattern of age will be expanded upon with the quantitative analysis that follows.

b. Age flow budget

The age flow across the integration surfaces for the four simulations is shown in Fig. 5, based on Eq. (2). The surface flow $\mathcal{F}_{\text{SURF}}(\sigma)$ plays a dominant role in the age flow budget of all four simulations, even though the outcropping area $S_{\text{SURF}}(\sigma)$ is typically much smaller than the area of the isopycnal surface S_σ (Fig. 3). This surface flux $\mathcal{F}_{\text{SURF}}(\sigma)$ describes the ventilation at the ocean surface where the isopycnal outcrops. The advective age flow $\mathcal{F}_{\text{ADV}}(\sigma)$ (red line in Fig. 5) is characterized by a two-peak structure, which corresponds to the upper cell and the lower cell of the overturning

circulation. For the diffusive age flow $\mathcal{F}_{\text{DIFF}}(\sigma)$ of the four simulations (blue line in Fig. 5), a small peak near the surface can be observed, corresponding to the large vertical gradient across the thermocline. Below that depth, the diffusive flow $\mathcal{F}_{\text{DIFF}}(\sigma)$ changes with depth in opposition to the advective flow $\mathcal{F}_{\text{ADV}}(\sigma)$. At the densest layers, the diapycnal transport becomes negative, with positive air–sea exchange $\mathcal{F}_{\text{SURF}}(\sigma)$ and advection $\mathcal{F}_{\text{ADV}}(\sigma)$ dominating the ventilation of the densest water mass. The sum of these age flows, the total age flow, in all four simulations falls closely onto the theoretical one-to-one line, consistent with Eq. (3). This good agreement is not trivial; it indicates that numerical diffusion and transient effects are both negligible in our configuration.

The total advective flow $\mathcal{F}_{\text{ADV}}(\sigma)$ includes contributions from both the resolved Eulerian velocity and the eddy-bolus GM velocity and the total diffusive flow $\mathcal{F}_{\text{DIFF}}(\sigma)$ includes the parameterized diapycnal diffusivity, convective adjustment, and a small contribution from the Redi term, as shown in Fig. S6. The diapycnal contribution from the Redi term could be due to the tapering process of large isopycnal slopes [the tapering scheme of Danabasoglu and McWilliams (1995) is

used in our simulations], as well as the difference between the in situ density surface used in the MITgcm and the potential density σ_2 used in the analysis. For the latter case, it is worth noting that for the real ocean, different choices of the global density variable (e.g., σ_2 , σ_4 , and neutral density) all lead to different diapycnal contributions of the isoneutral mixing (Hochet et al. 2019). Therefore, this effect should not be considered to be a numerical artifact. In practice, when applying our framework, there could be uncertainty in the estimate of density. We quantify the influence of potential uncertainty in the density surface in the Control simulation by replacing its density with the density in the kappa2x run, and the result is shown in Fig. S5. We find that the relative contribution of advection and diffusion can change, so the result should be interpreted carefully. However, Eq. (3) still holds true even if the integration surface is not identical to the true isopycnal.

Despite the common features shared by the age budget in all four simulations, the individual age flows $\mathcal{F}_{\text{ADV}}(\sigma)$, $\mathcal{F}_{\text{DIFF}}(\sigma)$, and $\mathcal{F}_{\text{SURF}}(\sigma)$ are sensitive to the mixing parameters. A larger diapycnal diffusivity (Fig. 5, kappa2x) enhances age diffusion $\mathcal{F}_{\text{DIFF}}(\sigma)$ near the surface. However, $\mathcal{F}_{\text{DIFF}}(\sigma)$ become weaker in the middepth. In the middepth, the larger diffusivity leads to increased advective age flow $\mathcal{F}_{\text{ADV}}(\sigma)$, due to the stronger overturning circulation. At the densest level, both $\mathcal{F}_{\text{ADV}}(\sigma)$ and $\mathcal{F}_{\text{DIFF}}(\sigma)$ become weaker than the Control run. The surface flux $\mathcal{F}_{\text{SURF}}(\sigma)$ in the kappa2x run is generally smaller than the Control simulation, due to the much younger equilibrium age near the ocean surface. Doubling the Redi parameter (Fig. 5, KRedi2x) slightly reduces both the advective and diffusive transport in the middepth but increases the surface flux. The overall influence of doubling the Redi parameter on the age flows across isopycnal surfaces seems small in our simulation, but varying the Redi parameter over a larger range could significantly change the ventilation (Gnanadesikan et al. 2015; Jones and Abernathy 2019, 2021). Thus, our result should not be interpreted to mean that the isopycnal mixing parameter is not important in the age flow budget, considering the larger uncertainty in the estimation of the Redi parameter. For the KGM2x run, the advective transport $\mathcal{F}_{\text{ADV}}(\sigma)$ becomes stronger due to the increased GM eddy bolus velocity. (The Eulerian age advection has also changed; see Fig. S6.) The term $\mathcal{F}_{\text{DIFF}}(\sigma)$ for the densest layers also becomes larger due to the increased age gradient. In summary, the relationship in Eq. (3) holds true in all simulations with different parameters, even though the contributions of age advection, age diffusion, and air–sea age flow can be different.

4. Application of the ideal age framework: Constraints on diapycnal diffusivity and overturning circulation

After validating the age flow budget in our simulations, we next show that the ideal age framework developed in section 2 constrains the magnitude of the (global) diapycnal diffusivity and overturning circulation. Assuming the surface age flow is known a priori (section 2b), the age framework constrains the sum of the age advection $\mathcal{F}_{\text{ADV}}(\sigma)$ and diffusion $\mathcal{F}_{\text{DIFF}}(\sigma)$ across a certain isopycnal surface [see Eq. (3)]. In this section, we separately explore two scenarios: 1) inference of the global

area-averaged effective diapycnal diffusivity from a known velocity field and 2) inference of the global overturning strength from a known diffusivity field. The first scenario focuses on how diffusivity can be linked to the diffusive flow $\mathcal{F}_{\text{DIFF}}(\sigma)$ from the age distribution, and the second scenario focuses on how the strength of overturning circulation can be linked to the age advection $\mathcal{F}_{\text{ADV}}(\sigma)$. A more detailed discussion on how these two application scenarios can be combined to constrain the relationship between effective diffusivity and overturning circulation can be found at the end of this section.

a. Inferring effective diapycnal diffusivity with prior knowledge of the velocity field

In this subsection, we infer the globally averaged effective diffusivity profile from ideal age. We assume the velocity field is known for simplicity, which is obviously a strong assumption. Under this scenario, the global age diffusion $\mathcal{F}_{\text{DIFF}}(\sigma)$ can be acquired from the age framework in Eq. (3). The effective diffusivity $\kappa_{\text{eff}}(\sigma)$ experienced by the age tracer can be expressed as

$$\kappa_{\text{eff}}(\sigma) = \frac{\mathcal{F}_{\text{DIFF}}(\sigma)}{\int_{S_\sigma} \Gamma_z dA}. \quad (6)$$

Here, the vertical gradient of ideal age Γ_z approximates the diapycnal age gradient Γ_{dia} , and S_σ is the isopycnal surface as in Eq. (3). We expect the inferred effective diffusivity to be consistent with the prescribed diapycnal diffusivity (Fig. 2e); however, the age tracer can also be influenced by convection, diapycnal contribution of Redi diffusion, numerical diffusion, and covariance between the diapycnal age gradient and the diapycnal diffusivity $\kappa_{\text{dia}}(z)$. Thus, it is worth comparing the estimated effective diapycnal diffusivity $\kappa_{\text{eff}}(\sigma)$ and the prescribed diapycnal diffusivity $\kappa_{\text{dia}}(z)$.

As a baseline for our comparison, the prescribed diapycnal diffusivity $\kappa_{\text{dia}}(z)$ is mapped from depth to density coordinate (Fig. 6), which is denoted as $\kappa_{\text{ref}}(\sigma)$, i.e.,

$$\kappa_{\text{ref}}(\sigma) = \frac{\int_{S_\sigma} \kappa_{\text{dia}}(z) dA}{\int_{S_\sigma} dA}. \quad (7)$$

Two versions of the globally averaged effective diapycnal diffusivity are calculated: 1) the effective diapycnal diffusivity felt by the age tracer diagnosed by the model $\kappa_{\text{eff,model}}(\sigma)$ (red dots); and 2) the inversely estimated diapycnal effective diffusivity $\kappa_{\text{eff,inv}}(\sigma)$ (blue dots). Formally,

$$\kappa_{\text{eff,model}}(\sigma) = \frac{\mathcal{F}_{\text{DIFF,diagnosed}}(\sigma)}{\int_{S_\sigma} \Gamma_z dA} = \frac{\int_{S_\sigma} \kappa_{\text{dia}}(z) \Gamma_z dA}{\int_{S_\sigma} \Gamma_z dA}, \quad \text{and} \quad (8)$$

$$\kappa_{\text{eff,inv}}(\sigma) = \frac{\mathcal{F}_{\text{DIFF,inv}}(\sigma)}{\int_{S_\sigma} \Gamma_z dA}. \quad (9)$$

Here, $\mathcal{F}_{\text{DIFF,diagnosed}}(\sigma)$ is the age diffusion diagnosed by the model and $\mathcal{F}_{\text{DIFF,inv}}(\sigma)$ is inferred using our framework [Eq. (3)].

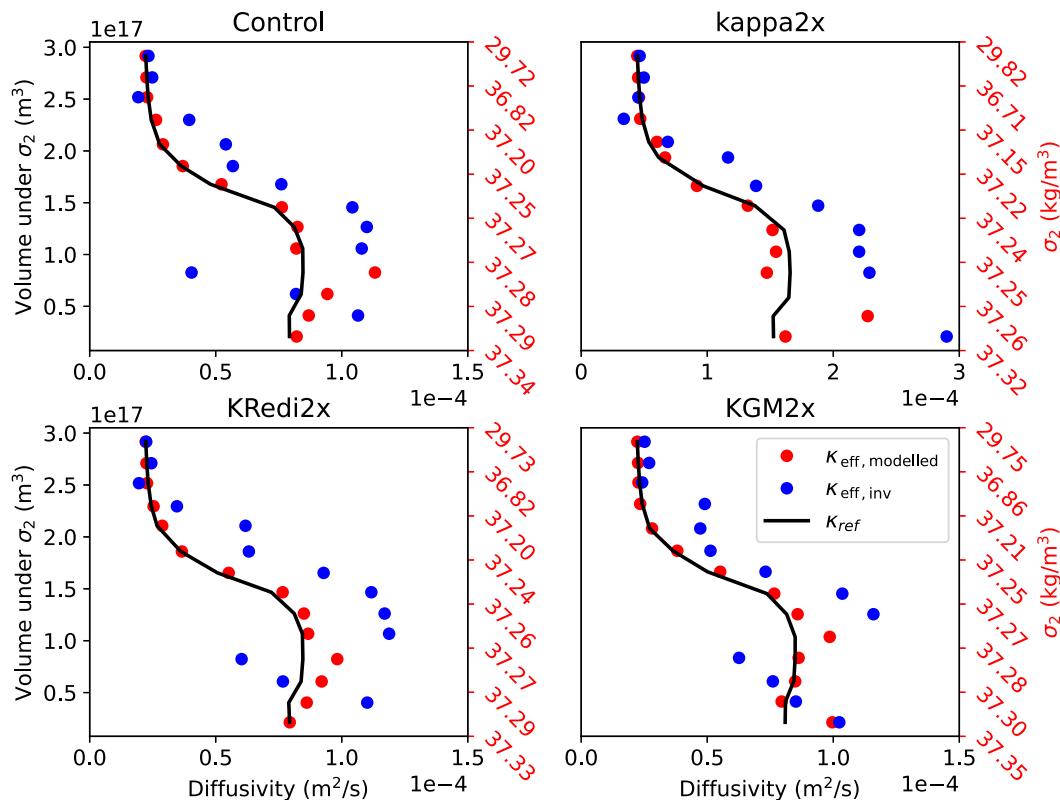


FIG. 6. Inferring globally averaged effective diapycnal diffusivity $k_{\text{dia}}(\sigma)$ of four simulations with age tracer. The result is shown in density coordinate, where the vertical axes show the isopycnal values and the corresponding volume below the corresponding isopycnal surfaces (see Fig. S9 for the zonal-mean depth of the vertical axes ticks). The prescribed isopycnal diffusivity is averaged on isopycnal surfaces for reference $\kappa_{\text{ref}}(\sigma)$ (black line). Both the diffusivity calculated from model-diagnosed diapycnal age diffusion $k_{\text{eff,modelled}}(\sigma)$ and the diffusivity inverted from the total age flow budget $k_{\text{eff,inv}}(\sigma)$ (blue dots, which include the contribution of model-diagnosed diapycnal diffusive age flow, the diapycnal contribution of convective age flow, and the diapycnal contribution of Redi flow) are shown.

The difference between $\kappa_{\text{eff,modelled}}$ and $\kappa_{\text{dia}}(z)$ indicates the covariance between the diapycnal age gradient and the diapycnal diffusivity $\kappa_{\text{dia}}(z)$. The influence of convection, the diapycnal contribution of Redi diffusion, and numerical diffusion are included in $\kappa_{\text{eff,inv}}(\sigma)$.

In all four simulations (Fig. 6), $\kappa_{\text{eff,modelled}}(\sigma)$ (red dots) is similar to $\kappa_{\text{ref}}(\sigma)$ (black lines), which suggests that the globally averaged effective diffusivity felt by the age tracer is consistent with the isopycnal average of the prescribed diapycnal diffusivity $\kappa_{\text{dia}}(z)$ in the model. In other words, the spatial covariance between κ_{dia} and Γ_z on isopycnal surfaces makes a negligible contribution to $\kappa_{\text{eff,modelled}}$. In contrast to $\kappa_{\text{eff,modelled}}(\sigma)$, the inversely estimated $\kappa_{\text{eff,inv}}(\sigma)$ (blue dots) has a larger difference from $\kappa_{\text{ref}}(\sigma)$. This discrepancy can be explained by scrutinizing the diapycnal contribution of Redi flows, diapycnal contribution of convective flows, and modeled diapycnal diffusive flows in Fig. S6. We find that numerical diffusion makes a negligible contribution to $\kappa_{\text{eff,inv}}(\sigma)$ in all four simulations, and both the diapycnal component of Redi flux and the convection flux contribute to $\kappa_{\text{eff,inv}}(\sigma)$, with the relative importance of these two flows varying in the four different simulations.

There are a few outliers of large $\kappa_{\text{eff,modelled}}(\sigma)$ and $\kappa_{\text{eff,inv}}(\sigma)$ values that are outside the range of the panels in Fig. 6, which are included in Fig. S7. Those large values happen at isopycnal levels where the total age diffusion $\mathcal{F}_{\text{DIFF}}(\sigma)$ and integrated age gradient $\int_{S_\sigma} \Gamma_z dA$ change sign or are close to zero in Fig. 5. The existence of those outliers suggests that in practice, the inverse estimation should be interpreted carefully where the integrated diapycnal age gradient $\int_{S_\sigma} \Gamma_z dA$ is small.

Qualitatively, the inverse estimation $\kappa_{\text{eff,inv}}(\sigma)$ from the ideal age can be used to reconstruct the diapycnal diffusivity profile $\kappa_{\text{ref}}(\sigma)$. The analysis in this section can be considered as a global integral version of “Munk balance” of the ideal age tracer or a water mass transformation (WMT) analysis (e.g., Walin 1982; Groeskamp et al. 2019) on it. Estimating diffusivity using the age could be particularly valuable in paleo-oceanographic studies, as age-like radiocarbon data are more abundant than historical temperature and salinity data.

b. Inferring meridional overturning circulation strength with prescribed diapycnal diffusivity

Now, we discuss how the globally integrated meridional overturning circulation rate through an isopycnal level can be

inferred from the ideal age with prescribed diapycnal diffusivity at that level. It is a strong assumption that the spatial distribution of diapycnal diffusivity $\kappa_{\text{dia}}(z)$ at an isopycnal σ is known a priori. A sufficient condition is to prescribe the effective diapycnal diffusivity $\kappa_{\text{eff,inv}}(\sigma)$ or the total age diffusion $\mathcal{F}_{\text{DIFF}}(\sigma) = \int_{S_\sigma} \kappa_{\text{dia}}(z) \Gamma_z dA = \kappa_{\text{eff,inv}}(\sigma) \int_{S_\sigma} \Gamma_z dA$. The total age advection $\mathcal{F}_{\text{ADV}}(\sigma)$ can then be inferred from the age framework [Eq. (3)]. The zonal-mean global overturning streamfunction of the modern ocean has a two-cell structure (Lumpkin and Speer 2007), and this geometry of the overturning streamfunction will be used in subsequent analysis.

The upwelling and downwelling limbs of the overturning circulation make opposite contributions to total age advection flow $\mathcal{F}_{\text{ADV}}(\sigma)$. Thus, we separate an isopycnal surface into an upwelling zone and a downwelling zone of the overturning circulation [similar to Linz et al. (2016) approach for the stratosphere] at a certain latitude $y_b(\sigma)$. This separation by a single latitude $y_b(\sigma)$ should not be considered as a precise description of the true direction of seawater velocity. Instead, it should be interpreted as a simplification of the geometry of the overturning circulation. Different definitions of the boundary $y_b(\sigma)$ will be introduced and explored in the next paragraph. The total diapycnal transport in the upwelling zone $\psi_{\text{up}}(\sigma)$ and downwelling zone $\psi_{\text{down}}(\sigma)$ can then be defined as

$$\psi_{\text{up}}(\sigma) = \int_{S_{\sigma_{\text{up}}}} \omega dA, \quad \psi_{\text{down}}(\sigma) = - \int_{S_{\sigma_{\text{down}}}} \omega dA, \quad (10)$$

where ω is the diapycnal velocity. By water volume conservation, $\psi_{\text{up}}(\sigma) = \psi_{\text{down}}(\sigma)$, so we denote this value as the total meridional overturning strength $\psi_{\text{tot}}(\sigma)$. The term $\psi_{\text{tot}}(\sigma)$ is dependent on our definition of the upwelling and downwelling zones, and it is equal to the true maximum meridional overturning $\Psi_{\text{max}}(\sigma)$ only if the boundary $y_b(\sigma)$ corresponds to the latitude where the true meridional overturning streamfunction $\Psi(y, \sigma)$ reaches its maximum at each isopycnal level σ . The total diapycnal age advection $\mathcal{F}_{\text{ADV}}(\sigma)$ can be expressed as the contribution of the upwelling and downwelling zones, i.e.,

$$\mathcal{F}_{\text{ADV}}(\sigma) = \int_{S_\sigma} \mathbf{n} \cdot \mathbf{F}_{\text{ADV}}^\Gamma dA = \int_{S_{\sigma_{\text{up}}}} \Gamma \omega dA + \int_{S_{\sigma_{\text{down}}}} \Gamma \omega dA. \quad (11)$$

If we denote the volume-flux-weighted average upwelling and downwelling ages as $\Gamma_{\text{up}}^{\text{flux}}$ and $\Gamma_{\text{down}}^{\text{flux}}$, where

$$\Gamma_{\text{up}}^{\text{flux}}(\sigma) = \frac{\int_{S_{\sigma_{\text{up}}}} \Gamma \omega dA}{\int_{S_{\sigma_{\text{up}}}} \omega dA}, \quad \Gamma_{\text{down}}^{\text{flux}}(\sigma) = \frac{\int_{S_{\sigma_{\text{down}}}} \Gamma \omega dA}{\int_{S_{\sigma_{\text{down}}}} \omega dA}, \quad (12)$$

then Eq. (11) can be expressed as

$$\begin{aligned} \mathcal{F}_{\text{ADV}}(\sigma) &= \Gamma_{\text{up}}^{\text{flux}}(\sigma) \psi_{\text{up}}(\sigma) - \Gamma_{\text{down}}^{\text{flux}}(\sigma) \psi_{\text{down}}(\sigma) \\ &= \psi_{\text{tot}}(\sigma) [\Gamma_{\text{up}}^{\text{flux}}(\sigma) - \Gamma_{\text{down}}^{\text{flux}}(\sigma)]. \end{aligned} \quad (13)$$

Thus, the meridional overturning rate $\psi_{\text{tot}}(\sigma)$ can be related to $\mathcal{F}_{\text{ADV}}(\sigma)$, i.e.,

$$\psi_{\text{tot}}(\sigma) = \frac{\mathcal{F}_{\text{ADV}}(\sigma)}{[\Gamma_{\text{up}}^{\text{flux}}(\sigma) - \Gamma_{\text{down}}^{\text{flux}}(\sigma)]} = \frac{\mathcal{F}_{\text{ADV}}(\sigma)}{\Delta \Gamma^{\text{flux}}(\sigma)}. \quad (14)$$

Because it is impossible to calculate the flux-weighted average age difference $\Delta \Gamma^{\text{flux}}(\sigma) = \Gamma_{\text{up}}^{\text{flux}}(\sigma) - \Gamma_{\text{down}}^{\text{flux}}(\sigma)$ without the information of the velocity fields, we choose to approximate $\Delta \Gamma^{\text{flux}}$ with the area-weighted average age difference $\Delta \Gamma^{\text{area}}(\sigma) = \Gamma_{\text{up}}^{\text{area}}(\sigma) - \Gamma_{\text{down}}^{\text{area}}(\sigma)$ to estimate $\psi_{\text{tot}}(\sigma)$ (cf. Linz et al. 2016). The consequence of this approximation under different definitions of the boundary $y_b(\sigma)$ is discussed below. When considering the climatological advection in a statistically steady state, there is actually an extratemporal correlation term between age and circulation. However, in our simulations, we find this correlation term is generally small, so we ignore this term in the following discussion.

The choice of the boundary $y_b(\sigma)$ impacts the average age difference $\Delta \Gamma^{\text{area}}(\sigma)$ and also impacts how well the reference circulation strength $\psi_{\text{tot}}(\sigma)$ reflects the true maximum meridional overturning strength $\Psi_{\text{max}}(\sigma)$. We examine two different definitions of the boundary $y_b(\sigma)$ (Figs. 7 and 8). Since the upper and lower overturning cells are in opposite directions, we define the upwelling and downwelling zones separately for the two cells. The boundary $y_b(\sigma)$ of the upwelling and downwelling regions can be defined in two ways: First, with knowledge of the true overturning circulation, the latitude of the maximum of the overturning streamfunction at each isopycnal level is defined as the boundary as shown by the black line in Fig. 7 (“MaxStream” case). Second, a fixed latitude is used as the boundary of the two regions, as shown by the gray lines, where we test 40°N(S) as the boundary for the upper (lower) cell (“40°” case). (40° is chosen subjectively, any latitude could be used, with the resulting streamfunction representing the total overturning between the upwelling and downwelling regions.)

The true maximum overturning strength $\Psi_{\text{max}}(\sigma)$ in Fig. 7 can be well approximated by $\psi_{\text{tot,ref}}(\sigma)$ under both definitions of $y_b(\sigma)$. The reference strength of meridional overturning $\psi_{\text{tot,ref}}(\sigma)$ is calculated using the definition in Eq. (10). The inversely estimated strength $\psi_{\text{tot,inv}}(\sigma)$ is calculated using Eq. (14), with $\mathcal{F}_{\text{ADV}}(\sigma)$ inferred from the age framework [Eq. (3)], while $\mathcal{F}_{\text{DIFF}}(\sigma)$ is prescribed. For all four simulations, the inversely estimated total overturning strength $\psi_{\text{tot,inv}}(\sigma)$ can be relatively well estimated for the MaxStream case (Fig. 9), where the boundary $y_b(\sigma)$ is chosen as the latitude of the maximum streamfunction $\Psi_{\text{max}}(\sigma)$. The deviation between the inversely estimated value $\psi_{\text{tot,inv}}(\sigma)$ and the reference value $\psi_{\text{tot,ref}}(\sigma)$ becomes larger when using the fixed latitude 40°N(S), especially for the upper cell of the “Control” and “kappa2x” simulations. As indicated by Eq. (14), the discrepancy between the reference meridional overturning strength $\psi_{\text{tot,ref}}$ and the inversely estimated strength $\psi_{\text{tot,inv}}$ can be explained by the discrepancy between the flux-weighted average age $\Gamma_{\text{up(down)}}^{\text{flux}}(\sigma)$ and area-weighted average age $\Gamma_{\text{up(down)}}^{\text{area}}(\sigma)$. A detailed comparison of the differences between $\Gamma_{\text{up(down)}}^{\text{flux}}(\sigma)$ and $\Gamma_{\text{up(down)}}^{\text{area}}(\sigma)$ can be found in appendix A.

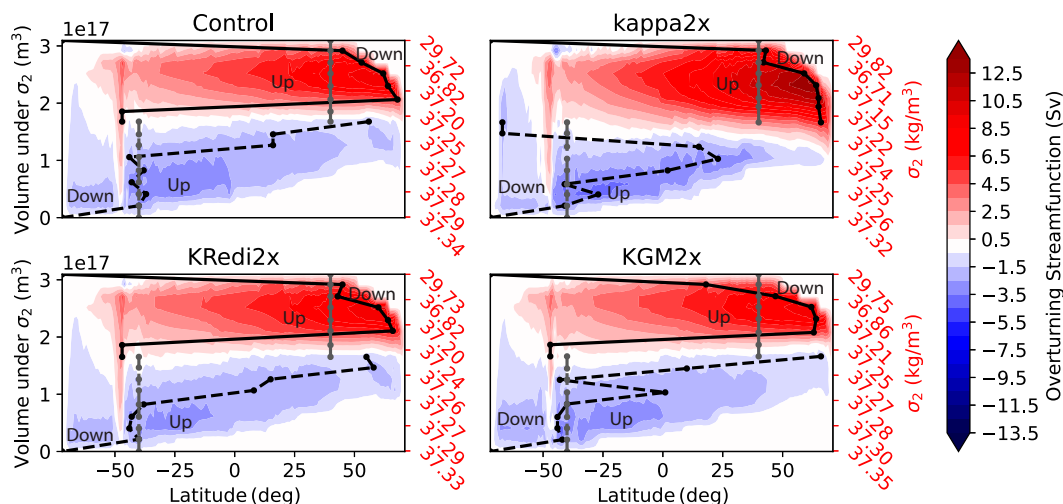


FIG. 7. The residual overturning streamfunctions shown in isopycnal coordinates (see Fig. S9 for the zonal-mean depth of the vertical axis ticks). The boundaries between the upwelling and downwelling zones are plotted, with two different definitions: 1) the boundary defined by the latitudinal position of the maximum absolute value of the overturning streamfunction (MaxStream case; black lines), which can be considered as the ideal boundary; and 2) the boundary defined by 40°N/S for the upper (lower) cell (40° case; gray lines), which is a more realistic boundary when the geometry of circulation is unknown. The boundaries for the upper cells are shown as solid lines, and the boundaries for the lower cells are shown as dashed lines. The bottom of the upper cells and the top of the lower cells are the same for all four simulations and are subjectively defined based on the geometry of the circulation in the Control simulation. Note that there could be multiple local maxima with similar peak values near the boundary of the upper and lower cells, so the dynamically defined boundary (MaxStream) can have large shifts between adjacent isopycnal levels.

Despite the discrepancy between $\psi_{\text{tot,ref}}(\sigma)$ and $\psi_{\text{tot,inv}}(\sigma)$ that exists when $y_b(\sigma)$ is fixed as 40°N/S , the relative magnitude of $\psi_{\text{tot,ref}}(\sigma)$ between different layers is still correctly captured by $\psi_{\text{tot,inv}}(\sigma)$. Hence, the method can at least be employed to provide a rough estimate of the change in the maximum global overturning strength $\Psi_{\text{max}}(\sigma)$ with depth, even in cases where the separation of upwelling and downwelling zones is not precise. When the separation is precise, $\psi_{\text{tot,inv}}(\sigma)$ can be considered

as a good approximation of the true maximum overturning strength $\Psi_{\text{max}}(\sigma)$.

Although the total age diffusion $\mathcal{F}_{\text{DIFF}}(\sigma)$ is prescribed when implementing the calculation, the scenario provides a relationship between the effective diapycnal diffusivity $\kappa_{\text{eff}}(\sigma)$ and the overturning strength $\Psi_{\text{max}}(\sigma)$. Given an estimate of the plausible range of $\kappa_{\text{eff}}(\sigma)$, the range of $\Psi_{\text{max}}(\sigma)$ can be constrained and vice versa. In a paleoceanographic study,

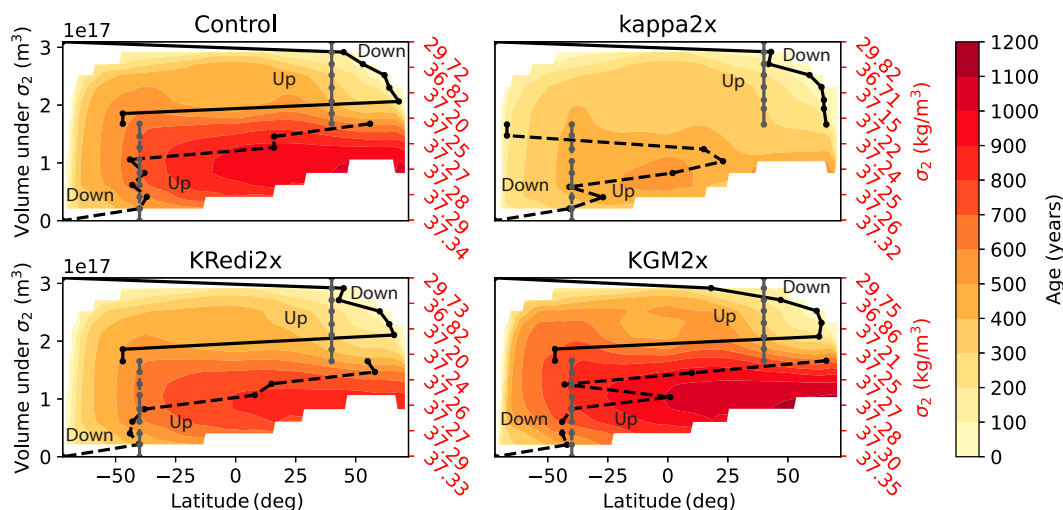


FIG. 8. The zonal-mean age in isopycnal coordinates (contour interval: 100 years). The boundaries between the upwelling and downwelling zones are as shown in Fig. 7.

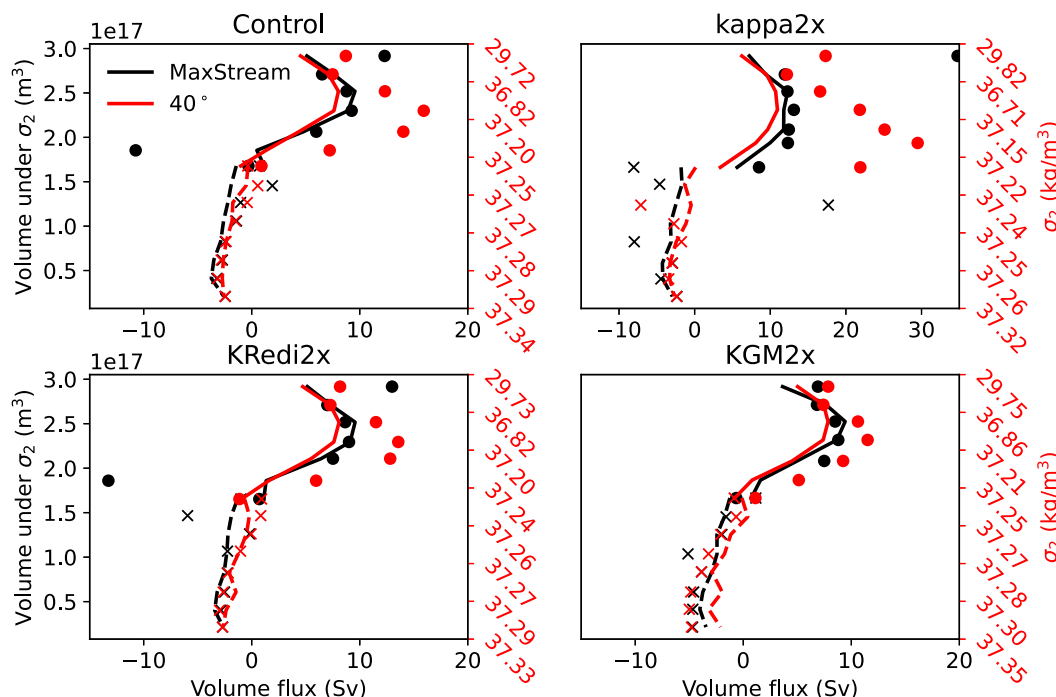


FIG. 9. The reference meridional overturning strength $\psi_{\text{tot,ref}}(\sigma)$ (lines) and the inferred overturning strength $\psi_{\text{tot,inv}}(\sigma)$ (dots and crosses) of four simulations. The values for the upper cells are shown as solid lines and dots, and the values for the lower cells are shown as dashed lines and crosses. Black lines and markers show the result for the MaxStream case, and red ones are for the 40° case. (Note that there are a few outliers; see supplemental Fig. S8, near the boundary between the upper cell and the lower cell, where both the total age flow and the age difference are small.)

Lund et al. (2011) used conservative $\delta^{18}\text{O}$ tracer to constrain the ratio between the abyssal Atlantic overturning strength $\Psi_{\text{max,Atl}}$ and the regional-averaged effective diapycnal diffusivity $\kappa_{\text{eff,Atl}}$ during the LGM. They demonstrated that reasonable inferences about $\kappa_{\text{eff,Atl}}$ can be made from the deviation of the ratio $\Psi_{\text{max,Atl}}/\kappa_{\text{eff,Atl}}$ compared to the present-day value. Our integral constraint can help to offer similar inferences about the magnitude of global overturning circulation strength $\Psi_{\text{max}}(\sigma)$ and effective diapycnal diffusivity $\kappa_{\text{eff}}(\sigma)$ in the past, by utilizing nonconservative age-like tracers (e.g., radiocarbon). An example of adapting our method to estimate modern North Pacific abyssal circulation from the ideal age is shown in section 5.

5. Discussion

a. Applying age framework to infer regional overturning circulation

The effectiveness of the age framework is demonstrated in section 4 using a highly idealized basin configuration. In the real ocean, the geometry and strength of overturning circulation across different basins can vary significantly. Our ultimate objective is to adapt the framework to infer regional overturning circulation rates. Although direct generalization of the framework to any arbitrary region may be challenging, it is feasible to apply it to specific regions by incorporating

additional assumptions. In this subsection, we utilize the age framework in Eq. (2) to infer the strength of the modern North Pacific abyssal meridional overturning circulation.

The ideal age inferred from an Ocean Circulation Inverse Model (OCIM) is used for our analysis (Fig. 10a). The OCIM is a three-dimensional dynamical ocean model that assimilates ocean tracer data to estimate the climatological mean state of the ocean circulation (DeVries and Primeau 2011; DeVries 2014; DeVries and Holzer 2019). Specifically, we use the Control run output of the OCIM2-48L variant (Holzer et al. 2021a), where the horizontal resolution is 2° , and there are 48 uneven vertical layers. The diapycnal diffusivity is parameterized using a recently developed global model of tidal energy dissipation (Lavergne et al. 2020), and the isopycnal mixing is represented by Gent–McWilliams and Redi parameterizations, with $K_{\text{GM}} = K_{\text{Redi}}$ inversely estimated by the model. We refer interested readers to appendix B for a more detailed introduction to the OCIM output used in this study. The ideal age concentration in Fig. 10a is calculated from OCIM-assimilated circulation and mixing and is constrained by the spatial distribution of realistic tracers [temperature, salinity, chlorofluorocarbons (CFCs), natural $\delta^3\text{He}$, and natural radiocarbon]. That allows us to assess our age framework with a realistic age spatial distribution, while having a data-constrained reference circulation strength. The reference OCIM-assimilated Pacific meridional overturning streamfunction is shown in Fig. 10b. It is not utilized in the subsequent inverse estimate from ideal age, to avoid circular reasoning.

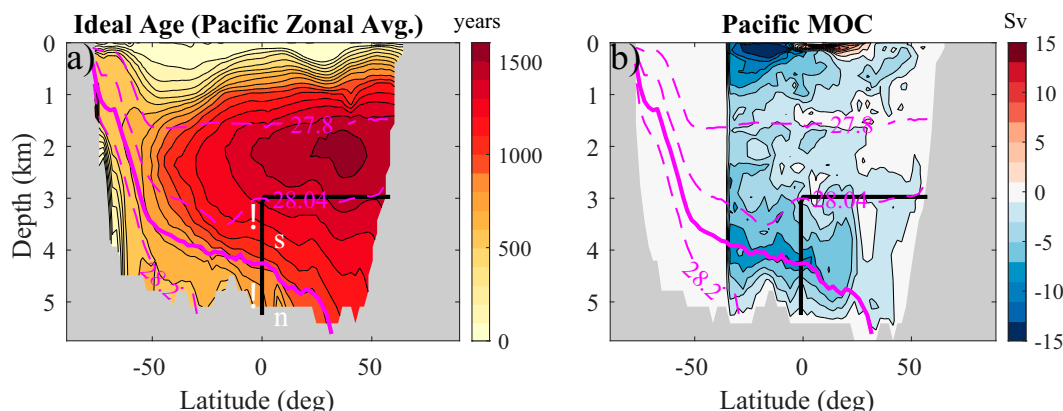


FIG. 10. The data-constrained ideal age and meridional overturning circulation streamfunction from the OCIM. (a) The ideal age (interval: 100 years) zonally averaged in neutral density γ coordinate and mapped back to depth coordinate. The terms Γ_n (865 years) and Γ_s (1228 years) represent the area-weighted average age of the northward water and southward water, respectively, above and below 28.125 kg m^{-3} at the southern boundary of the PAZ. (b) Streamfunction of the Pacific meridional overturning circulation (interval: 2 Sv), which is also remapped from γ to depth coordinate. The heavy black line delineates the PAZ. Our streamfunction is slightly different from Fig. 2a in Holzer et al. (2021b), likely due to the usage of different density coordinate definitions in the numerical calculation. The magenta lines indicate zonal-mean neutral density γ surfaces (contour labels in kg m^{-3}), with the thick solid one highlighting the 28.125 kg m^{-3} level. This level corresponds to the depth of the maximum vertical age gradient at the southern boundary of the PAZ, which is also the boundary between the younger southward flow and the northward flow above it (see text). The volume of the PAZ is $11.2 \times 10^{16} \text{ m}^3$, and the advective age flow at the southern boundary of the PAZ $\mathcal{F}_{\text{ADV}}^{\text{PAZ},S}$ is $9.1 \times 10^{16} \text{ m}^3$.

de Lavergne et al. (2017) inferred from seafloor geometry that the upwelling in the abyssal Pacific becomes weak above 3000-m depth, which corresponds to the bottom of an age maximum zone in the middepth North Pacific. Hence, we focus on the so-called Pacific abyssal zone (PAZ; following Holzer et al. 2021a) below 3000-m depth and north of the equator (indicated by the thick black contour in Fig. 10). Here, we choose to define the control volume with a constant depth, rather than a constant isopycnal, for simplicity although isopycnals here are close to horizontal. We note again that the framework does not rely on a particular geometry. According to our age framework in Eq. (2), the total age flow exiting through the top and southern boundaries of the PAZ is equivalent to the volume of water V_{PAZ} within it. We assume that the age flow at the upper boundary of the PAZ at 3000 m is negligible due to the presence of the middepth age maximum zone, which indicates limited ventilation from lower depths. We further assume that the age flow at the southern boundary of the PAZ is dominated by the advection flow $\mathcal{F}_{\text{ADV}}^{\text{PAZ},S}$ and ignore the isopycnal age diffusion. Then, $\mathcal{F}_{\text{ADV}}^{\text{PAZ},S} \approx V_{\text{PAZ}}$. A comparison between the OCIM-diagnosed age advection $\mathcal{F}_{\text{ADV,OCIM}}^{\text{PAZ},S}$ ($9.1 \times 10^{16} \text{ m}^3$) and V_{PAZ} ($11.2 \times 10^{16} \text{ m}^3$) confirms that they are of similar magnitude, although numerous assumptions have been made. We also find the difference between V_{PAZ} and $\mathcal{F}_{\text{ADV,OCIM}}^{\text{PAZ},S}$ mainly comes from the contribution of mesoscale eddy transport (both GM and Redi) of age on the southern boundary of the PAZ (which is $2.0 \times 10^{16} \text{ m}^3$). The advection ($1.0 \times 10^{16} \text{ m}^3$) and diapycnal diffusion ($-0.7 \times 10^{16} \text{ m}^3$) of age on the top boundary of PAZ are somehow smaller, and they partially oppose each other.

The Pacific abyssal overturning strength Ψ_{PAZ} can then be linked to the vertical profile of the zonal-mean age at the southern boundary of the PAZ, i.e.,

$$\Psi_{\text{PAZ}} = \frac{\mathcal{F}_{\text{ADV}}^{\text{PAZ},S}}{\Gamma_s - \Gamma_n} \approx \frac{V_{\text{PAZ}}}{\Gamma_s - \Gamma_n}. \quad (15)$$

Here, Γ_s and Γ_n are the area-weighted age of the southward and northward limbs of the PAZ circulation, respectively (see Fig. 10a). de Lavergne et al. (2017) pointed out that the depth of the boundary between the younger, deeper northward limb of the PAZ circulation and the older, shallower southward return flow corresponds to the depth where the vertical age gradient reaches its maximum. In our case, that depth at the southern boundary of the PAZ corresponds to the isopycnal level $\gamma = 28.125 \text{ kg m}^{-3}$ [We use neutral density γ in this analysis, following Holzer et al. (2021a)]. This boundary inferred from age spatial distribution is confirmed by the OCIM-assimilated circulation in Fig. 10b.

The PAZ abyssal circulation $\Psi_{\text{PAZ,inv}}$ inferred from Eq. (15) is 9.8 Sv ($1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$) (with $\Gamma_n = 865$ years and $\Gamma_s = 1228$ years), which is quite close to the reference strength of 9.9 Sv. To get a sense of the uncertainty of our analysis, we take the difference between $\mathcal{F}_{\text{ADV}}^{\text{PAZ},S}$ and V_{PAZ} as the potential error in the estimate of the advective age flow. This difference can lead to a 1.9 Sv (20%) uncertainty in the estimation of circulation strength. This analysis proves that the age framework can be used to infer PAZ abyssal circulation strength. Since the geometry of the abyssal Pacific circulation is shaped by seafloor distribution, we expect that this method can be applied to constrain the magnitude of the

circulation in the past, as long as the bottom topography remains the same. We leave the estimation of past circulation for future exploration. Interestingly, a recent study found that the vertical exchange at the top of the PAZ during the LGM is even weaker than in the present day (Millet et al. 2024), which makes our assumption of small vertical exchange plausible for the LGM.

b. Application to observational data

The ideal age tracer cannot be directly observed, but it can be inferred from real tracers such as radiocarbon, CFCs, tritium and helium isotopes, and argon. Obtaining an estimate of ideal age from these real tracers is nontrivial, however. To do so, some characteristics of the mixing history (i.e., the TTD) must be assumed or constrained, due to the nonlinear relationship between the concentration of real tracers and the ideal age during mixing. For example, the radiocarbon concentration at a given location will be predominantly influenced by younger water parcels with shorter transit time (e.g., Khatiwala et al. 2009; DeVries and Primeau 2011; Gebbie and Huybers 2012; Koeve et al. 2015). Without knowledge of the full mixing history, it is still possible to make approximate estimations of the ideal age using limited tracer observations, but these come with extra uncertainties (Gebbie and Huybers 2012). To explore the uncertainty caused by the conversion from realistic tracers to ideal age, we perform an extra analysis in section S1. We add a radiocarbon tracer to our Control simulation and estimate ventilation age from it. If we directly use standard radiocarbon age (e.g., Gebbie and Huybers 2012) and assume all local water comes from a single pathway in the estimate of the ventilation age, the error in the estimate of diffusivity and circulation could be nonnegligible, especially near the ocean surface. In practice, the framework should be directly applied to age-like realistic tracers. We find the diffusivity and overturning strength estimated using radiocarbon will be as good as using ideal age, so it is not necessary to convert radiocarbon to ideal age in terms of applying our framework. The idea of directly using age-like realistic tracers to constrain ocean circulation has been shown to be promising (Orsi et al. 1999, 2002), and our framework presents a new way to extract the information in the spatial distribution of these tracers. However, the ideal age provides unique constraints (i.e., the 1 s^{-1} source term is independent of the local age concentration, so the total age flow going out of a control volume does not depend on the age inside the volume) as well as a conceptually useful way to understand ocean transport. (See section S1 for a more thorough discussion.)

6. Conclusions

a. Key conclusions

We implement an integral constraint for the ideal age tracer, inspired by recent progress in stratospheric studies (Linz et al. 2016, 2017, 2021). Age is a unique tracer, as it contains the historical information accumulated in the transport of water parcels. Due to the spatially constant source term of 1 s^{-1} , the total advective and diffusive age flow across an

isopycnal surface can be linked to the volume below it, accounting for the air–sea age exchange at the ocean surface between the boundary of the basin and where the isopycnal outcrops. This allows us to constrain the sum of advective and diffusive transport from the spatial distribution of the age tracer. A relationship between globally averaged effective diapycnal diffusivity and meridional overturning circulation can then be constrained by the spatial distribution of ideal age. The integral constraint has been further adapted to infer regional overturning circulation strength for the modern North Pacific abyssal circulation. If applying the constraint to observations, radiocarbon can be used directly. Ideal age is more directly related to ventilation time and more appropriate for models.

Age-like tracers have been used in previous studies to infer past and present ocean circulation rates (e.g., Chen et al. 2020, 2023; Zhao et al. 2018; Rafter et al. 2022; Li et al. 2023), but this study provides new insights. First, although the age itself is a direct measurement of the ventilation time scale, the absolute value of the age at a given location does not necessarily reflect the rate of the overturning circulation. Second, the overturning circulation rate can be indicated by the difference in spatially averaged age across distinct zones where the diapycnal flow has opposing directions.

b. Implications and future research

Our integral constraint links the size of a control volume and the age flow across its boundary, which is independent of the age distribution in its interior. Even if circulations under different climate states form distinct spatial distributions of age inside a control volume, the total age flow across its boundary must remain the same. This unique conservation law can provide additional quantitative information in interpreting the spatial distribution of age tracers under climate change or during the past.

For example, our framework is also applicable to the ideal ventilation age (IVA; Zhang 2016). The change in Southern Ocean sea ice extent during the LGM could influence the distributions of age-like realistic tracers by modifying the air–sea exchange (e.g., Zanowski et al. 2022; Nadeau and Jansen 2020). An IVA tracer is thus defined to mimic the transport of realistic tracers (Zhang 2016; Gu et al. 2020; Zanowski et al. 2022), which shares a similar definition to the ideal age tracer, except that its surface concentration is determined based on the surface sea ice fraction instead of being prescribed as zero. Since the evolution of realistic tracers will be influenced by the sea ice distribution, the IVA tracer better mimics the distribution of age-like realistic tracers like radiocarbon. Although the spatial distributions of ideal age and IVA tracers can be quite different, our study indicates that for both tracers, the spatially averaged age difference between two zones of opposite water flow can be linked to the same overturning circulation. Thus, the framework developed for the ideal age tracer in this study can also be applied to understand the spatial distribution of the IVA tracer.

A similar idea of utilizing the age difference has recently been implemented in Rafter et al. (2022) to infer past ocean

circulation. This study inferred that a slowdown of the Pacific deep circulation occurred during the LGM based on the increase in spatially averaged age difference between the older Pacific Ocean and the younger Southern Ocean. Our study supports Rafter et al.'s (2022) analysis that the difference in spatially averaged age between two regions can reflect the strength of overturning circulation, but there are also some confounding factors to keep in mind: 1) The spatial correlation between the diapycnal velocity and the age distribution could lead to a discrepancy between spatially averaged age and flux-weighted average age—the latter is directly related to the overturning strength; 2) the change in diapycnal diffusivity could lead to a change in the diapycnal advective flow $\mathcal{F}_{\text{ADV}}(\sigma)$ in Eq. (14), which should also be taken into account in the inverse estimation of the overturning rate; and 3) for the real ocean, the interbasin age flow from other basins could also play a role, which should be taken into account when studying the change in the age difference between the Southern Ocean and the Pacific Ocean (Jones and Cessi 2016; Thompson et al. 2016; Sun and Thompson 2020). Our discussion of the vertical profile of age tracers in section 5 provides an alternative method that can avoid the influence of interbasin transport.

A limitation of our current analysis is that the application to the globally integrated circulation is only tested in an idealized single-basin configuration. Future work is needed to fully explore to what extent the conclusions still hold for a more realistic ocean circulation with the existence of multiple basins and more complex overturning pathways. Future work will also explore how this framework can be extended to estimate regional circulation and mixing rates in other oceanic zones. Ultimately, the theory developed in Eq. (2), in which the total age flow across the boundary of a control volume is equal to its size, does not depend on the shape of the control volume. This flexibility suggests the ability to define control volumes that separate different basins to handle more complex and realistic circulation configurations.

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Data availability statement. The output from the MITgcm, along with all Python and MATLAB code required for generating the figures, is publicly accessible at https://github.com/boerz-coding/test_age_framework.git.

APPENDIX A

Discussion on the Discrepancy between the Flux-Weighted and Area-Weighted Average Age

The difference observed between the reference meridional overturning strength $\psi_{\text{tot,ref}}$ and the inversely estimated strength $\psi_{\text{tot,inv}}$ can be attributed to the discrepancies between the flux-weighted average age $\Gamma_{\text{up(down)}}^{\text{flux}}(\sigma)$ and the area-weighted average age $\Gamma_{\text{up(down)}}^{\text{area}}(\sigma)$ (Fig. A1). $\Delta\Gamma^{\text{flux}}$ is calculated as the advective age flow $\mathcal{F}_{\text{ADV}}(\sigma)$ divided by the reference meridional overturning flow $\psi_{\text{tot,ref}}$, which can be considered as a reference value of the “true” age difference related to the meridional overturning, and $\Delta\Gamma^{\text{area}}$ is the age difference which can actually be calculated without the velocity field. It can be seen that the magnitude of flux-weighted age difference $\Delta\Gamma^{\text{flux}}$ becomes unrealistically large near the boundary between the upper and lower cells at the middle depth, which is due to the small meridional overturning $\psi_{\text{tot}}(\sigma)$. Our result suggests that discrepancies do exist between the flux-weighted age $\Gamma_{\text{up(down)}}^{\text{flux}}$ and the area-weighted age $\Gamma_{\text{up(down)}}^{\text{area}}$, especially for the 40° case.

The discrepancy between flux-weighted age difference and area-weighted age difference $\delta\Delta\Gamma(\sigma) = \Delta\Gamma^{\text{flux}}(\sigma) - \Delta\Gamma^{\text{area}}(\sigma)$ can be formally expressed as a function of the spatial covariance between the diapycnal velocity $\omega(\sigma)$ and age $\Gamma(\sigma)$:

$$\delta\Delta\Gamma(\sigma) = \frac{\int_{S_{\sigma_{\text{up}}}} (\omega - \omega_{\text{up}}^{\text{area}})(\Gamma - \Gamma_{\text{up}}^{\text{area}})dA}{\underbrace{\psi_{\text{tot}}(\sigma)}_{\delta\Delta\Gamma_{\text{up}}(\sigma)}} - \left[\frac{\int_{S_{\sigma_{\text{down}}}} (\omega - \omega_{\text{down}}^{\text{area}})(\Gamma - \Gamma_{\text{down}}^{\text{area}})dA}{\underbrace{\psi_{\text{tot}}(\sigma)}_{\delta\Delta\Gamma_{\text{down}}(\sigma)}} \right], \quad (\text{A1})$$

where $\omega_{\text{up(down)}}(\sigma)$ and $\Gamma_{\text{up(down)}}^{\text{area}}(\sigma)$ are area-weighted average diapycnal velocity and average age, which are separately calculated for the upwelling and downwelling zones. Thus, the discrepancies $\delta\Delta\Gamma_{\text{up}}(\sigma)$ and $\delta\Delta\Gamma_{\text{down}}(\sigma)$ can be formally interpreted as the spatial covariance between age and velocity, normalized by the meridional overturning $\psi_{\text{tot}}(\sigma)$.

The flux-weighted and area-weighted ages for the upwelling and downwelling zones [$\Gamma_{\text{up}}^{\text{flux}}(\sigma)$, $\Gamma_{\text{down}}^{\text{flux}}(\sigma)$, $\Gamma_{\text{up}}^{\text{area}}(\sigma)$, $\Gamma_{\text{down}}^{\text{area}}(\sigma)$] are separately explored in Figs. A2 and A3. The upper cell and the lower cell are discussed separately below.

For the upper cell (Fig. A2), when the boundary $y_b(\sigma)$ is defined as MaxStream, $\Delta\Gamma^{\text{flux}}(\sigma)$ and $\Delta\Gamma^{\text{area}}(\sigma)$ are close to each other for both the upwelling and downwelling regions in all four simulations, except the few points near the

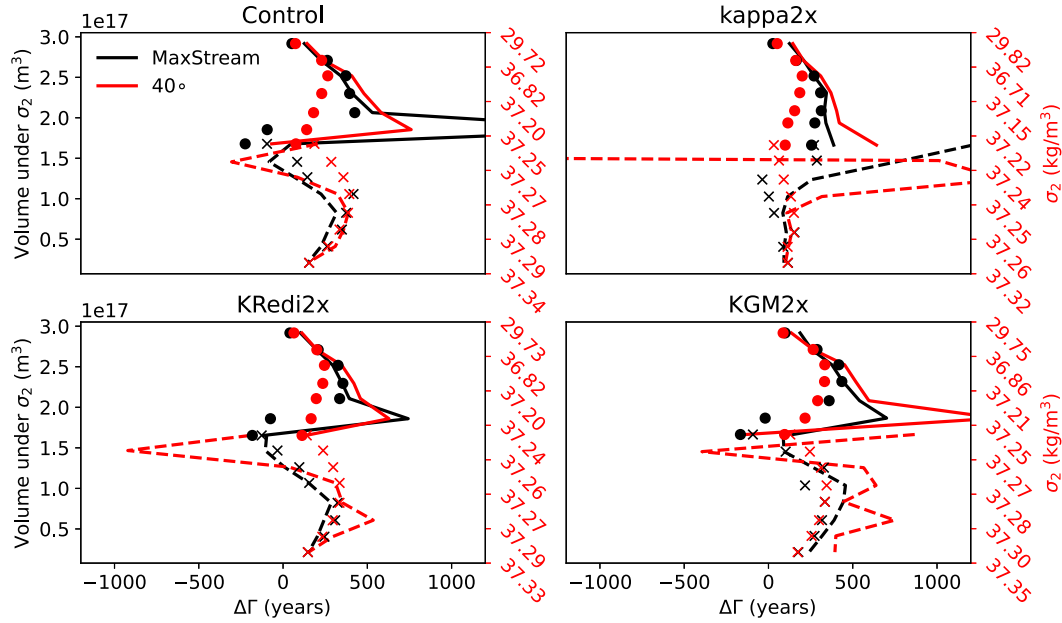


FIG. A1. The volume-flux-weighted age difference (lines) and the area mean age difference (dots and crosses) of four simulations. The values for the upper cells are shown as solid lines and dots, and the values for the lower cells are shown as dashed lines and crosses. The black lines and markers show the results of the MaxStream case, and the red ones show the 40° case.

bottom of the upper cell (typically with “volume under σ_2 ” $< 2.0 \times 10^{17} \text{ m}^3$). At the bottom of the upper cell, the overturning is weak and there are no clear separations between upwelling and downwelling zones. When the boundary $y_b(\sigma)$ is defined as 40° , the discrepancies in all simulations between

$\Delta\Gamma^{\text{flux}}(\sigma)$ and $\Delta\Gamma^{\text{area}}(\sigma)$ become larger for the downwelling part, while for the upwelling part, the discrepancies are still small. This suggests that due to the narrowness of the downwelling zone caused by the formation of North Atlantic Deep Water (NADW), $\Gamma_{\text{down}}^{\text{flux(area)}}(\sigma)$ is more sensitive to the

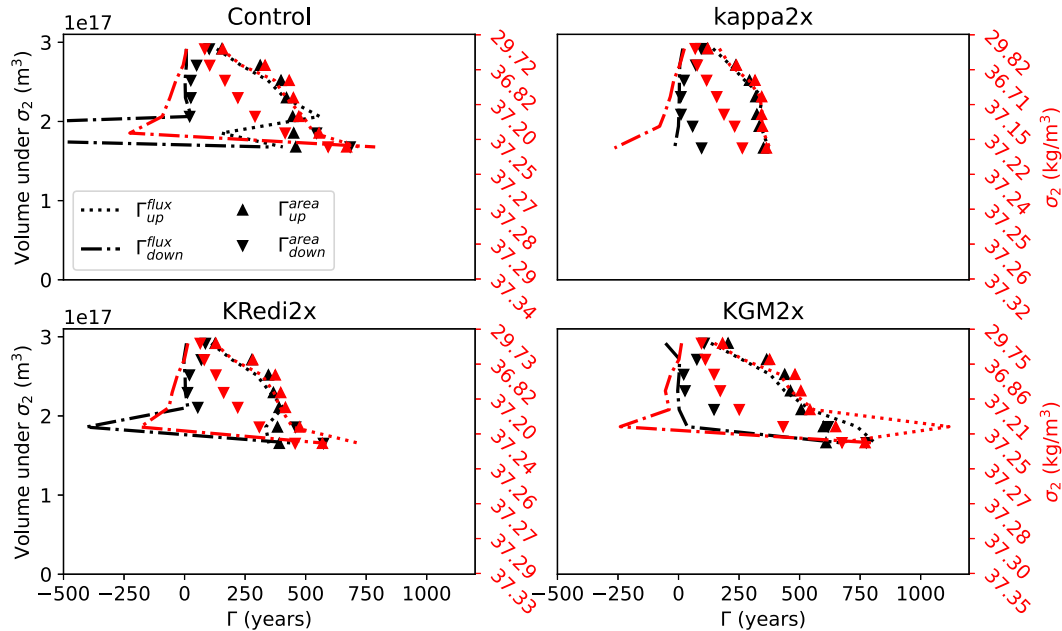


FIG. A2. As in Fig. A1, but $\Gamma_{\text{up}}^{\text{area(flux)}}$ and $\Gamma_{\text{down}}^{\text{area(flux)}}$ are shown separately. Only the results for the upper cell are shown in this figure. The black lines and markers show the results of the MaxStream case, and the red ones show the 40° case.

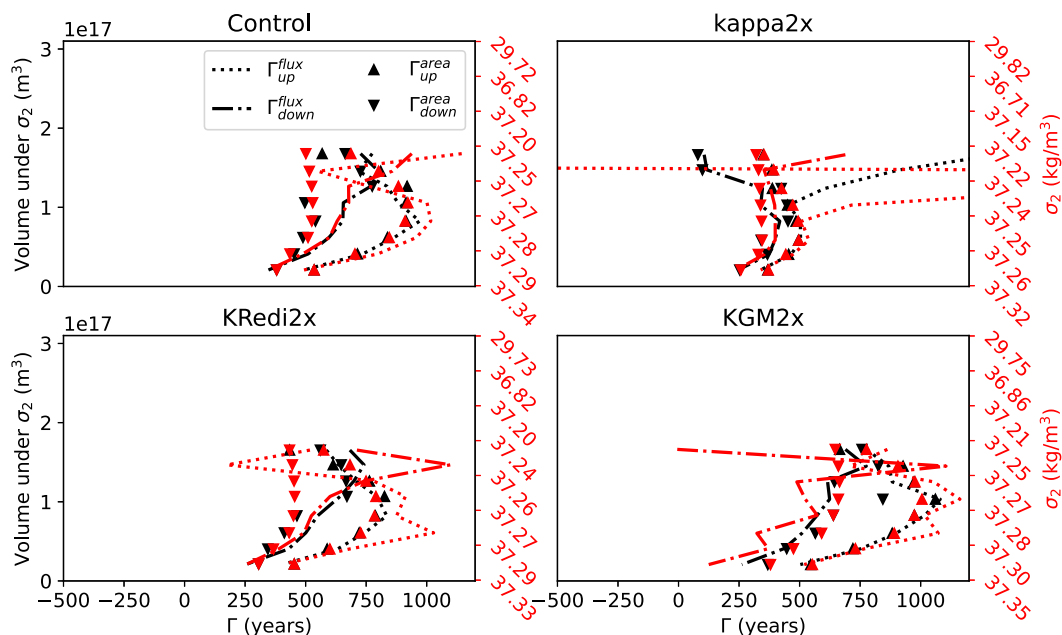


FIG. A3. As in Fig. A2, but for the lower cell.

definition of the boundary compared to $\Gamma_{up}^{flux(area)}(\sigma)$. Compared to MaxStream case, the $\Gamma_{down}^{flux}(\sigma)$ in the 40° case generally becomes smaller (again, except the few points near the bottom of the upper cell). That is consistent with our expectations, as the actual upwelling water between the boundary of the MaxStream case and the 40° case (see Figs. 7 and 8) causes a significant upwelling age flow contribution to the so-called downwelling zone of the 40° case [see Eq. (A1)]. That upwelling age flow contributes negatively to $\Delta\Gamma_{down}^{flux}(\sigma)$. The term $\Delta\Gamma_{down}^{area}(\sigma)$ becomes larger, as the older water between the two boundaries is defined as part of the downwelling zone in the 40° case.

For the lower cell (Fig. A3), $\Delta\Gamma_{up}^{flux}(\sigma)$ and $\Delta\Gamma_{up}^{area}(\sigma)$ in the upwelling zone are close to each other for the MaxStream case in all simulations (except for the few points near the top of the lower cell). For the 40° case, although $\Delta\Gamma_{up}^{flux}(\sigma)$ becomes larger than the MaxStream case in the Control and KRedi2x simulations, the $\Delta\Gamma_{up}^{area}(\sigma)$ does not change significantly in all simulations. This suggests that when inferring the overturning rate using $\Delta\Gamma_{up}^{flux}(\sigma)$, the fixed latitude in the 40° case can well approximate the $\Delta\Gamma_{up}^{flux}(\sigma)$ related to the maximum meridional overturning circulation $\Psi(y, \sigma)$. As for the downwelling zones, there are significant discrepancies between $\Delta\Gamma_{down}^{flux}(\sigma)$ and $\Delta\Gamma_{down}^{area}(\sigma)$ for both the MaxStream and the 40° case in all simulations except the KGM2x one. This suggests that the spatial covariance between age $\Gamma(\sigma)$ and diapycnal velocity $\omega(\sigma)$ is not negligible for the downwelling zone of the lower cell, at least in our simulations. This result is not surprising, given the strong upwelling and downwelling patterns, as well as sharp meridional age gradients, near 50°S (see Figs. 7 and 8). This issue warrants attention in future research to better understand and address the spatial correlation between $\Gamma(\sigma)$

and $\omega(\sigma)$ when inferring the overturning rate using area-weighted $\Delta\Gamma_{down}^{area}(\sigma)$.

APPENDIX B

An Introduction to the OCIM Output

This appendix provides an introduction to the OCIM2-48L output used in this research. OCIM2-48L solves linearized steady-state momentum equations with any discretization errors assigned to an adjustable forcing field (Holzer et al. 2021a). The density used for the calculation of dynamical balance and isopycnal mixing is prescribed as the climatological density field. Six different circulation tracers are assimilated: potential temperature (Θ), salinity (S), CFC-11, CFC-12, natural radiocarbon ($\Delta^{14}\text{C}$), and natural $\delta^3\text{He}$. It also assimilates the climatological average air-sea heat and freshwater fluxes, as well as mean dynamical sea surface topography. These observations are assimilated into OCIM2-48L by adjusting model parameters to minimize a quadratic cost function that measures the misfit between model and observations. These parameters include (i) a set of parameters to adjust the local geostrophic momentum balance to account for the unresolved physics and model discretization errors, (ii) a set of parameters to adjust the restoring temperature and salinity used for simulating air-sea heat and freshwater fluxes at the sea surface, (iii) a set of parameters to adjust the local mantle $\delta^3\text{He}$ injection rate along midocean ridges, and (iv) a single parameter to control the global relationship between gas-transfer velocity and wind speed, using a quadratic wind speed dependence, and ν is the isopycnal mixing parameters K_{GM} and K_{Redi} at each grid point, with the condition $K_{GM} = K_{Redi}$ forced by the model (Holzer et al. 2021a).

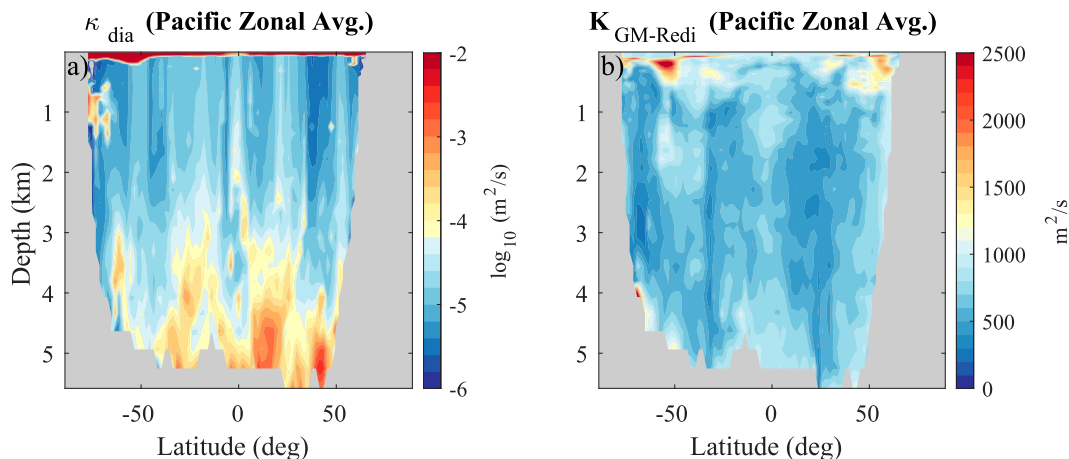


FIG. B1. Pacific zonal-mean mixing parameters of the OCIM. (a) Diapycnal mixing parameter prescribed in the model. (b) Isopycnal mixing parameter estimated by the model.

The diapycnal diffusion κ_{dia} is implemented as vertical mixing, similar to MITgcm. The term κ_{dia} is parameterized using a recently developed global model of tidal energy dissipation due to breaking internal waves generated by tides flowing over uneven topography (Fig. B1a; Lavergne et al. 2020). Here, we only use the output from the Control run of OCIM2-48L. The model-assimilated isopycnal diffusion is shown in Fig. B1b.

Various versions of the OCIM have been employed to explore a wide range of oceanic phenomena. These include examining water mass composition and ideal age of the global ocean (DeVries and Primeau 2011), studying the oceanic anthropogenic carbon dioxide (CO_2) transport (DeVries 2014; Holzer and DeVries 2022), understanding the distribution of mantle $\delta^3\text{He}$ sources (DeVries and Holzer 2019), investigating the global ^{39}Ar distribution (Holzer et al. 2019), examining the ventilation of the mid-depth North Pacific (Holzer et al. 2021a), exploring the biological carbon pump (Holzer et al. 2021b), estimating ocean silicic and phosphate cycles (Primeau et al. 2013; Holzer and Primeau 2013; Holzer et al. 2014), and modeling ocean element cycling (John et al. 2020).

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