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Ventilation of the Southern Ocean Pycnocline

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Southern Ocean, ventilation, overturning circulation, subduction, isopycnal mixing

Abstract

Ocean ventilation is the transfer of tracers and young water from the surface down into the ocean interior. The tracers that can be transported to depth include anthropogenic heat and carbon, both of which are critical to understanding future climate trajectories. Ventilation occurs in both high- and midlatitude regions, but it is the southern midlatitudes that are responsible for the largest fraction of anthropogenic heat and carbon uptake; such Southern Ocean ventilation is the focus of this review. Southern Ocean ventilation occurs through a chain of interconnected mechanisms, including the zonally averaged meridional overturning circulation, localized subduction, eddy-driven mixing along isopycnals, and lateral transport by subtropical gyres. To unravel the complex pathways of ventilation and reconcile conflicting results, here we assess the relative contribution of each of these

mechanisms, emphasizing the three-dimensional and temporally varying nature of the ventilation of the Southern Ocean pycnocline. We conclude that Southern Ocean ventilation depends on multiple processes and that simplified frameworks that explain ventilation changes through a single process are insufficient.

1. INTRODUCTION

Ventilation: the transfer of surface water and tracers (e.g., carbon) into the pycnocline and deep ocean

Pycnocline: the depth of the ocean above which 80–90% of the density range lies

Excess heat and carbon that are taken up by the surface ocean from the atmosphere are primarily transported into the subsurface ocean in just a few localized regions across the globe (Khatiwala et al. 2012). The three largest ventilation regions—defined as areas where young surface waters are injected into the interior ocean—are located in the midlatitude Southern Ocean (Sallée et al. 2010a) and in the convective areas of the North Atlantic (Bower et al. 2009) and Antarctic margins (Orsi et al. 1999). Each of these primary ventilation sites is characterized by sloping isopycnals that outcrop at the surface, providing a pathway between the surface and the deeper ocean along which water and tracers can move freely (**Figure 1**).

Atmosphere-sourced tracers, such as radiocarbon, oxygen, and chlorofluorocarbons (CFCs), highlight the ventilation pathways into the ocean interior (England & Maier-Reimer 2001, Willey et al. 2004, Khatiwala et al. 2012). As illustrated by the global oxygen distribution in **Figure 1**, the two high-latitude convection regions in the North Atlantic and Antarctic dominate the volume transport into the interior ocean and penetrate into the deep and abyssal waters of the global ocean (Khatiwala et al. 2012, Talley 2013). However, it is the shallower ventilation of the pycnocline from the surface of the midlatitude Southern Ocean that dominates global ocean anthropogenic heat uptake (~70%; Frölicher et al. 2015, Zanna et al. 2019) and provides the largest oceanic sink of anthropogenic carbon (~40%; Khatiwala et al. 2009) (**Figure 2**). The bulk of the global pycnocline volume outcrops in the Southern Ocean, on the northern edge of the Antarctic Circumpolar Current (ACC) (**Figure 1**). Understanding the mechanisms controlling

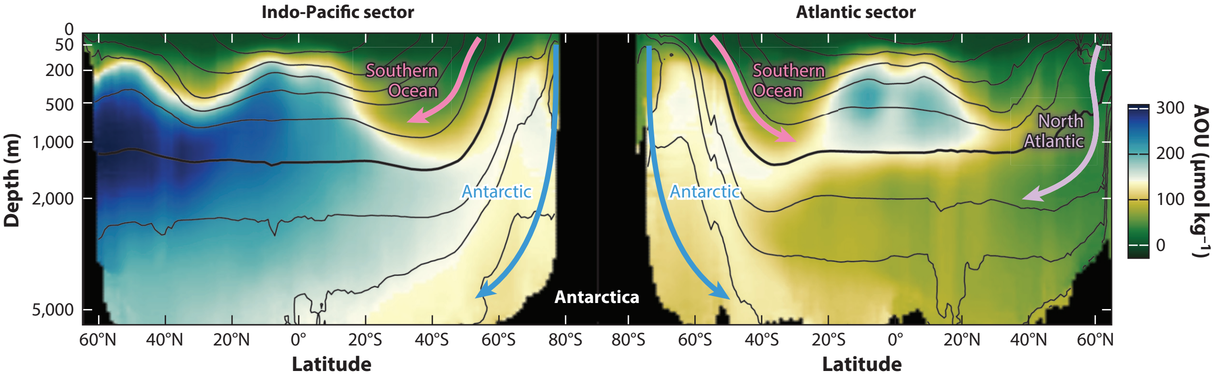

Figure 1

Observed distribution of apparent oxygen utilization (AOU), where lower AOU indicates younger water, showing the three primary global ventilation pathways (*green shading* and *arrows*). Note that this is an Antarctic-centric view, with a combined zonal average of the Indian and Pacific sectors shown on the left and a zonal average of the Atlantic shown on the right. Black lines show potential density (σ_2), with the heavy contour indicating $\sigma_2 = 1{,}036.5$ kg m^{-3}, which approximates the depth of the global pycnocline. Data are from Boyer et al. (2018).

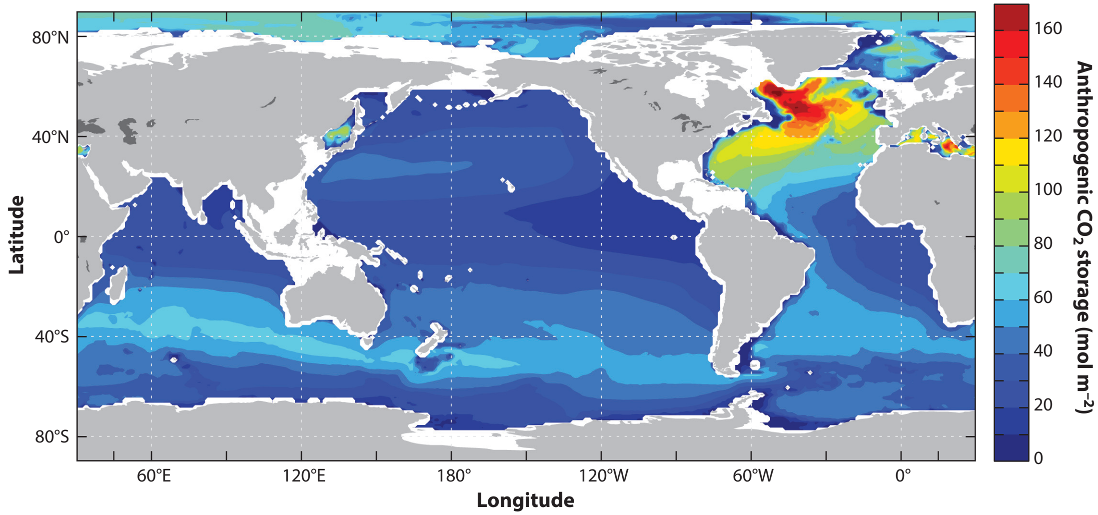

Figure 2

Depth-integrated anthropogenic CO_2 inventory. Figure adapted from Khatiwala et al. (2013) under a CC BY 3.0 license (**https://creativecommons.org/licenses/by/3.0**).

the ventilation of the pycnocline by Southern Ocean surface waters is therefore essential for interpreting recent variability in oceanic carbon uptake (Gruber et al. 2019b) and for predicting future rates of heat and carbon uptake (Kessler & Tjiputra 2016, Sallée 2018).

The ventilation site in the midlatitude Southern Ocean sits at the intersection of two distinct dynamical regimes. To the south is the ACC and the upwelling limb of the overturning circulation (Marshall & Speer 2012), while to the north the lateral subtropical gyre circulations dominate (McCartney 1982). At the boundary of these two regimes, the downwelling mode and intermediate waters are formed (Hanawa & Talley 2001), which are broadly aligned with the origin of the Southern Ocean ventilation pathway. Different studies have examined a range of ventilation mechanisms, with the dominant emphasis on the advection by the zonally integrated overturning circulation (e.g., Sabine et al. 2004, Sarmiento et al. 2004, Marinov et al. 2006, Frölicher et al. 2015, Liu et al. 2018, Shi et al. 2018). Over the past decade, it has emerged that several additional physical processes play a significant role in Southern Ocean ventilation, including localized subduction dynamics at mode water formation hot spots (e.g., Sallée et al. 2010a), eddy stirring along isopycnals (e.g., Abernathey & Ferreira 2015), and subtropical gyre circulations (e.g., Jones et al. 2016). In this review, we attempt to synthesize and compare what is known about the relative roles of these different dynamical processes in driving the ventilation of the mode and intermediate waters in the Southern Ocean.

We begin by outlining the overturning-based conceptual model of Southern Ocean pycnocline ventilation to provide an overview of the relevant large-scale circulation of the region. The upper limb of the Southern Ocean overturning circulation is sketched on the right-hand face of the **Figure 3** schematic. The westerly winds in the Southern Hemisphere drive a divergent Ekman transport in the surface layer that results in widespread circumpolar upwelling south of the maximum wind stress at ~50°S (Marshall & Speer 2012). The upwelled waters that flow northward in the surface Ekman layer are in disequilibrium with the atmosphere, which leads to the strong air–sea exchange of heat and CO_2. The surface waters are colder than the atmosphere

Mode water: a relatively shallow water mass with weak stratification

Intermediate water: a low-salinity layer at intermediate depth, typically found below mode waters

Subduction: the transfer of water and tracers from the mixed layer into the stratified pycnocline

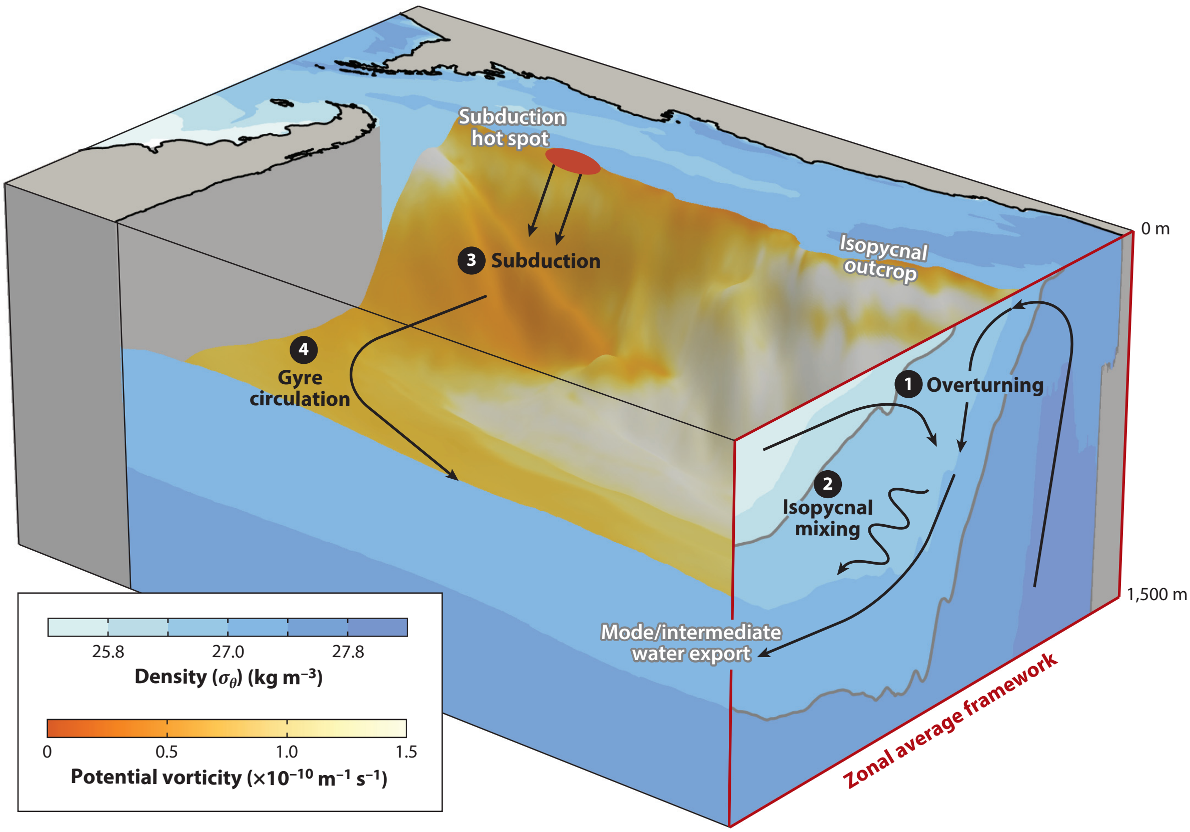

Figure 3

Schematic of Southern Ocean ventilation processes (enumerated). Blue colors show potential density on the outside faces and surface of the box; orange colors show potential vorticity on the isopycnal surface $\sigma_\theta = 27.0$ kg m^{-3} in the interior. Overturning circulation and isopycnal mixing processes are shown in the zonal average framework on the right-hand face. Localized subduction and gyre circulation processes are shown in the interior. Data are from an ACCESS-OM2-01 simulation (Kiss et al. 2020).

and in recent decades have taken up additional heat as they flow northward (Armour et al. 2016). The continual replenishment of surface waters from the Southern Ocean upwelling source drives large anthropogenic CO_2 uptake through the solubility pump (Morrison et al. 2015, Gruber et al. 2019b). At the northern edge of the ACC, Ekman pumping and convection in deep winter mixed layers inject young, weakly stratified waters deep into the interior. In this simplified conceptual model of ventilation, restratification of the mixed layer in spring subducts mode and intermediate waters into the permanent pycnocline, disconnecting these water masses from further interaction with the atmosphere (Stommel 1979), and the overturning circulation advects these waters northward toward the subtropics.

In addition to the advective transport into the pycnocline, the rich mesoscale eddy field in the Southern Ocean can directly drive ventilation of surface-sourced tracers into the interior, through stirring of tracers along isopycnals (e.g., Abernathey & Ferreira 2015), shown schematically on the right-hand face of the box in **Figure 3**. In a review of the processes ventilating the higher-latitude upwelling and subpolar regions of the Southern Ocean, Naveira Garabato et al. (2017)

suggested the adoption of a new paradigm for approaching high-latitude tracer ventilation studies, in which no prior assumptions are made about the relative dominance of overturning versus eddy-stirring mechanisms. We take a similar approach in this review for ventilation into the midlatitude Southern Ocean.

Isopycnal mixing: the combination of stirring along the isopycnals and small-scale tracer variance dissipation

Subduction rate: the rate at which water and tracers pass from the mixed layer into the stratified pycnocline

As a point of clarification, it is the total overturning circulation, also known as the residual overturning, that impacts ventilation. The residual overturning is sometimes decomposed into separate mean (also known as Eulerian) and eddy overturning components (e.g., Marshall & Speer 2012). Therefore, eddies play a major role in both the advective residual overturning ventilation process and the eddy-driven isopycnal mixing ventilation process.

Going beyond the zonally averaged, overturning-based framework of Southern Ocean ventilation, substantially more detail is revealed by moving to a three-dimensional view (inside the box shown in **Figure 3**). Northward subduction out of the deep winter mixed layers occurs in a handful of localized hot spots on the equatorward side of the Subantarctic Front, with locations constrained by interactions between the meandering ACC and underlying bathymetric features (Sallée et al. 2010a). Inflow from the large-scale horizontal circulations of both the ACC and subtropical gyres enters the subduction hot spots from the west, in addition to the surface overturning inflow from the south. Wind-driven mixing and buoyancy loss to the atmosphere drive deepening of the mixed layers in winter up to 500-m depth (Dong et al. 2008, Holte et al. 2012). Mode and intermediate waters form when waters cross the base of the deep mixed layers. The latter occurs through multiple processes, including seasonal restratification at the end of winter. The localization of subduction means that the ventilation associated with the advective transport into the Southern Ocean pycnocline may depend more strongly on regional or seasonal processes, rather than simply on the northward surface inflow of the overturning circulation. The subduction rate is often assumed to be the ultimate limit on the transport of water and tracers into the mode and intermediate waters and therefore a perfect measure of ventilation (e.g., Sallée et al. 2012). However, the amount of subsequent reventilation of subducted mode waters in the years following northward export from the mixed layer remains uncertain (Jones et al. 2016). It is also not clear whether subduction volume fluxes are directly relevant for interpreting changes in tracer uptake or storage, due to the additional impact of isopycnal mixing and other mechanisms of interior tracer redistribution (e.g., Waugh et al. 2019).

The three-dimensional view shown in **Figure 3** reveals that the export of mode and intermediate waters northward is strongly impacted by the horizontal circulation of the subtropical gyres. The rate that young waters and tracers spread around the gyres, and thereby northward into the permanent pycnocline, depends not only on the rate at which they are subducted from the deep Southern Ocean mixed layers but also on the speed at which the gyres circulate, which varies both among gyres and interannually (Jones et al. 2016, 2019, 2020; Waugh et al. 2019).

The relative contribution of each of the processes shown in **Figure 3** to ventilation of the Southern Ocean pycnocline remains an open question. Observational studies are hindered by a lack of data, particularly for isopycnal mixing. Modeling studies of ventilation processes are also challenging; in addition to the fact that eddy advection and diffusion are often parameterized in models, multiple ventilation processes respond in concert to changing forcing. For example, isopycnal mixing, overturning circulation, and gyre transport all increase with increasing westerly winds, making it difficult to isolate processes in perturbation simulations. However, an increased understanding of the sensitivity of ventilation to different circulation and mixing processes will lead to improved interpretation of observational trends and hence better future predictions.

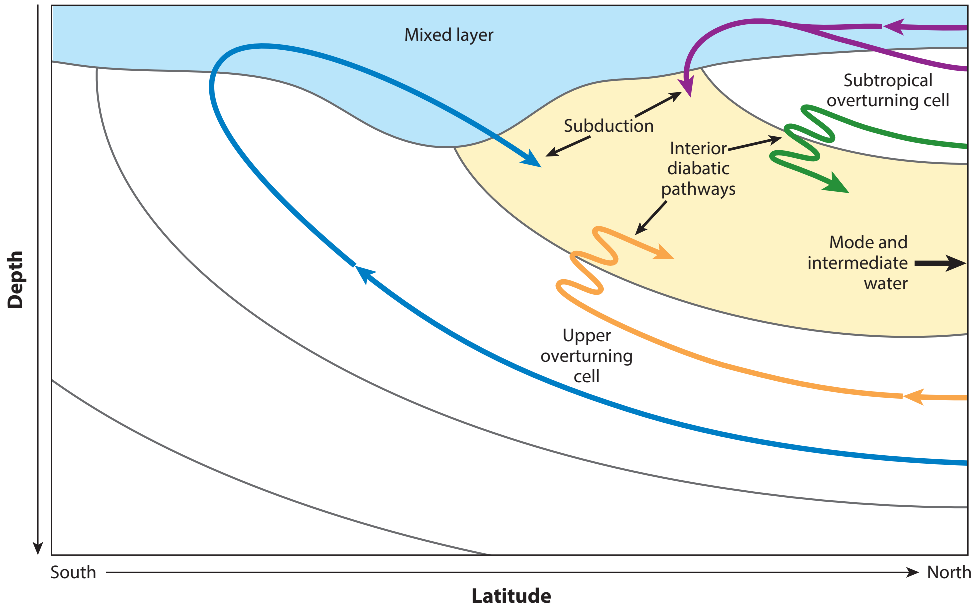

Figure 4

Idealized zonally averaged schematic of the overturning pathways into the mode and intermediate water layers (*shaded in yellow*). The blue and orange pathways make up the upper overturning cell, and the purple and green pathways make up the subtropical overturning cell. The blue and purple pathways pass through the mixed layer (*blue shading*) and subduct across the base of the mixed layer, whereas the orange and green pathways are transformed diabatically in the interior.

2. ZONALLY AVERAGED RESIDUAL OVERTURNING CIRCULATION

2.1. Multiple Southern Ocean Overturning Pathways

The overturning circulation in the Southern Ocean is often conceptualized into a zonal mean framework with distinct overturning cells (Speer et al. 2000, Marshall & Speer 2012). The two shallowest Southern Ocean overturning cells feed into the midlatitude subduction zone: The light subtropical cell to the north has southward-flowing surface waters, and the upper overturning cell to the south, which is dominated by wind-driven upwelling of deep waters, has northward-flowing surface waters (**Figure 4**). Observational estimates show that both northern- and southern-sourced waters contribute to the subduction of mode and intermediate waters (Sallée et al. 2010a, Cerovečki et al. 2013, Katsumata et al. 2013).

The subtropical and upper overturning cells provide the source water for subduction and therefore may be expected to act as a strong control on the rate of ventilation. However, several factors complicate the relationship between ventilation and overturning transport. One issue is that the net overturning transport in each cell includes a component that is diabatically transformed beneath the mixed layer and therefore does not experience air–sea interaction or contribute directly to ventilation (green and orange pathways in **Figure 4**). Thus, it is possible for the upper overturning circulation to increase via an enhancement of the interior diabatic exchange with no impact on the ventilation. Observational inverse estimates suggest that the diabatic routes into the mode and intermediate water layers may be of comparable magnitude to the adiabatic routes (Katsumata et al. 2013, Naveira Garabato et al. 2013). Another complexity highlighted in **Figure 4** is that it is theoretically possible for the subduction volume flux across the base of the mixed layer (and therefore the ventilation) to increase via an enhancement of the subtropical cell with no change in the upper overturning circulation, and vice versa. However, often the upper overturning circulation is assumed to be the only component of the overturning that impacts Southern Ocean ventilation. While **Figure 4** is highly idealized and excludes details such as diabatic transformations after subduction and interbasin differences in transports and water mass properties, it is a useful starting point to highlight the complex relationship between ventilation and the transport in the two upper overturning cells.

A third complicating factor in determining the relationship between overturning transport and tracer ventilation is that differences in surface tracer concentration between the two overturning cells will determine the relative importance of the subtropical and upper overturning cell transports for different tracers. For example, a change in the circulation of the subtropical overturning cell may have more impact on anthropogenic carbon subduction (Iudicone et al. 2016) than on anthropogenic heat subduction, as heat uptake occurs nearly exclusively in the upwelling regions south of the ACC (Armour et al. 2016), whereas CO_2 is absorbed in both subtropical southward-flowing western boundary currents and the ACC (Gruber et al. 2009).

2.2. A Complex Relationship Between Ventilation and Overturning

Given these complications, it is unsurprising that there is mixed evidence for how Southern Ocean ventilation varies with the overturning circulation. Observational evidence for recent changes in subduction and overturning transports is scarce; we discuss these recent observed changes in Section 6 and focus here solely on modeling assessments.

One of the best methods of quantifying ventilation in models is to use spatially uniform, surface-sourced passive tracers, such as CFCs. Patara et al. (2021) employed this method in an eddy-permitting ocean model with a range of surface forcing perturbations. They found that a >30% increase in the upper overturning cell resulted in a 5–10% increase in Southern Ocean ventilation. However, a similar-magnitude change in ventilation also occurred due to changes in the winter mixed-layer depth with no change in the overturning. This implies that the upper overturning cell does influence ventilation but is not the only process to do so. Furthermore, a change in ventilation does not imply a change in overturning circulation.

Another method of quantifying ventilation, more commonly used in model studies, is the subduction volume flux across the base of the mixed layer. In Section 4, we discuss the complexities associated with the calculation of subduction and to what extent it is a good measure of ventilation. There are a small number of modeling studies that have quantified how the subduction volume flux varies in future climate simulations and for which simultaneous changes in the overturning circulation are available. In the Coupled Model Intercomparison Project Phase 3 (CMIP3) suite of models, the Southern Ocean subduction volume flux consistently decreases in future climate change simulations (∼15–20% decrease by 2100; Downes et al. 2010, Liu & Wang 2014), despite a consistent increase in the strength of the upper overturning circulation (∼15% increase in the mean overturning by 2100; Sen Gupta et al. 2009). The subtropical overturning circulation in the CMIP3 models increases in the Pacific (Wang & Cane 2011) but has not been analyzed in other basins. The CMIP5 model suite responds to future climate forcing in a qualitatively similar way to the CMIP3 models, with indications of declining Southern Ocean subduction (Sallée et al. 2013a) and strengthening of the upper overturning cell transport (Downes & Hogg 2013, Sallée et al. 2013b). The subtropical overturning cell transport decreases in the multimodel mean in the CMIP5 models (Sallée et al. 2013b). A single climate model study by Saenko et al. (2011) is also consistent with the CMIP3 and CMIP5 multimodel comparison analyses, finding that subduction decreases and upper overturning transport increases in response to a climate change

Ideal age: the mean time since water was in the surface layer, as determined by a passive tracer

scenario. Saenko et al. (2011) found no change in the subtropical cell overturning transport. In summary, climate models run with future climate scenario forcing simulate a decrease in the subduction volume flux in the Southern Ocean, despite simulating an increase in the upper overturning circulation. The response of the subtropical overturning cell to climate change forcing is inconsistent across these model studies and has been less extensively analyzed.

In addition to these climate change scenario simulations, several modeling studies have also analyzed subduction and overturning responses to more idealized Southern Ocean wind stress perturbations. Studies using eddy-permitting ocean and climate models found that both the net subduction volume flux and the upper overturning circulation increased in response to an isolated strengthening of the Southern Hemisphere westerly winds, but both the subduction and upper overturning decreased for southward-shifted or poleward-intensified winds (Farneti et al. 2010; Downes et al. 2011, 2017; Hogg et al. 2017). Surprisingly, the ideal age of the mode and intermediate water masses in these simulations decreased for all wind perturbations, despite varying sign changes in the overturning and subduction metrics (Downes et al. 2017, Hogg et al. 2017, Waugh et al. 2019).

2.3. Overturning Control on Ventilation Is Tracer Dependent

Moving beyond the ventilation of volume transport to consider the ventilation of different tracers introduces further complexity due to variations in air–sea tracer equilibration timescales (e.g., Jones et al. 2014), spatially varying source concentrations, and the effect of redistribution changes in the original tracer distributions (e.g., Bronselaer & Zanna 2020). Here, we focus on the ventilation of anthropogenic heat and carbon to highlight how the ventilation dependence on the overturning circulation is different for different tracers.

Model studies indicate that Southern Ocean heat uptake depends strongly on the upper overturning strength, despite the potentially complex relationship between ventilation and overturning described above (e.g., Marshall & Zanna 2014, Armour et al. 2016, Morrison et al. 2016, Liu et al. 2018, Newsom et al. 2020). We attribute this strong dependence to the fast air–sea equilibration timescale and the high-latitude location of the heat uptake from the atmosphere. The surface absorption of anthropogenic heat in the Southern Ocean occurs predominantly to the south of the main subduction zone (Frölicher et al. 2015, Zanna et al. 2019). The upper overturning circulation, and in particular the surface Ekman transport, is the dominant process controlling the transport of anthropogenic heat from the southern uptake region to the midlatitude subduction zone (Armour et al. 2016). The uptake rate is also controlled by the upper overturning circulation, because upwelling waters replenish the cold surface waters, allowing for continued uptake. Therefore, the ventilation of anthropogenic heat depends strongly on the upper overturning strength, because both the uptake rate and the transport toward the subduction zone are controlled primarily by the upper overturning circulation. However, as outlined in the following sections, other processes (such as gyre circulation and isopycnal mixing) may also be important for controlling the variability in northward transport of anthropogenic heat away from the subduction zone.

In contrast to heat uptake, past studies indicate that anthropogenic carbon ventilation only weakly depends on the upper overturning circulation (e.g., Mignone et al. 2006, Lovenduski et al. 2008, Lovenduski & Ito 2009, Ito et al. 2015, DeVries et al. 2017, Bronselaer et al. 2018). The majority of these studies consider the net impact of changing atmospheric forcing on anthropogenic carbon uptake and therefore cannot isolate the impact of changes in overturning from changes in other drivers of ventilation, such as isopycnal mixing, gyre circulation, or wind-driven changes in gas exchange rates. One exception is the matrix transport model approach of DeVries et al. (2017), which directly isolates the impact of recent decadal changes in the overturning circulation. They found that the 20–30% decrease in the upper overturning circulation from the 1990s to the 2000s resulted in only an ∼2% decrease in anthropogenic carbon uptake over the Southern Ocean. It seems probable that the weaker impact of the upper overturning circulation on the ventilation of anthropogenic carbon compared with anthropogenic heat is due to the difference in surface uptake patterns. While anthropogenic heat uptake occurs nearly exclusively over the high-latitude upwelling region of the Southern Ocean (Zanna et al. 2019), anthropogenic carbon uptake is more widespread, with substantial uptake also occurring in the subtropical southward-flowing western boundary currents (Gruber et al. 2009). It has been hypothesized that an increase in the upper overturning circulation could even result in a decrease in the uptake of anthropogenic carbon, due to the reduction in surface residence time and the relatively long equilibration timescale of CO_2 (e.g., Lovenduski et al. 2008; Gruber et al. 2019a,b). However, modeling studies appear to contradict this hypothesis, and simulations show a weak direct relationship between the upper overturning strength and anthropogenic carbon uptake (e.g., Lachkar et al. 2007, DeVries et al. 2017). For tracers with longer equilibration timescales, such as bomb $\Delta^{14}C$, there may be an inverse relationship between the upper overturning strength and tracer ventilation (Ito et al. 2004, Lachkar et al. 2007), because a more rapid overturning circulation reduces the residence time in the surface layers, which limits the uptake of tracer from the atmosphere.

In summary, there is not a simple relationship between ventilation and the overturning circulation. This result indicates that other physical processes also contribute to the magnitude of Southern Ocean ventilation. These additional processes are discussed in detail in the following sections.

3. ISOPYCNAL MIXING

In the ocean interior, water parcels can move along the neutral tangent plane (also known as the isopycnal plane) without a change in potential energy. The vigorous mesoscale eddies of the Southern Ocean drive stirring along such isopycnal surfaces. This stirring generates fine-scale structure (fronts and filaments) in tracers, which is then dissipated through small-scale processes, and ultimately by molecular diffusion. In coarse-resolution ocean models, these processes are parameterized as isopycnal diffusion. High-resolution models instead may resolve the stirring process directly, with numerical diffusion taking the place of molecular diffusion. Because of the steep slope of Southern Ocean isopycnals, isopycnal mixing can drive strong exchange of tracers between surface and deep waters, contributing to the subduction of heat, carbon, and other tracers of surface ventilation. A visualization of the isopycnal mixing process is shown in **Figure 5**.

A conceptually difficult point is that the same eddies that do isopycnal stirring also contribute to the residual overturning circulation, via eddy-induced advection. Eddy-induced advection occurs due to the cumulative effect of correlations between eddy velocity and eddy thickness anomalies, which can induce a net volume flux along an isopycnal layer (in much the same way as the Stokes drift induced by surface waves). This eddy transport emerges in frameworks such as the transformed Eulerian mean (Marshall & Radko 2003), the temporal residual mean (McDougall & McIntosh 2001), and thickness-weighted averaging (Young 2012) and plays a central role in the theory of the zonally averaged residual overturning circulation (Marshall & Radko 2003). In contrast to eddy-induced advection, isopycnal mixing does not result in net mass or volume flux; its effects can be modeled as a purely diffusive process. In coarse-resolution climate models, isopycnal mixing is associated with the Redi coefficient (Redi 1982), while eddy-induced advection is represented by the Gent–McWilliams parameterization (Gent & McWilliams 1990). Thus, despite being caused by the same eddies, isopycnal mixing is distinct from the residual

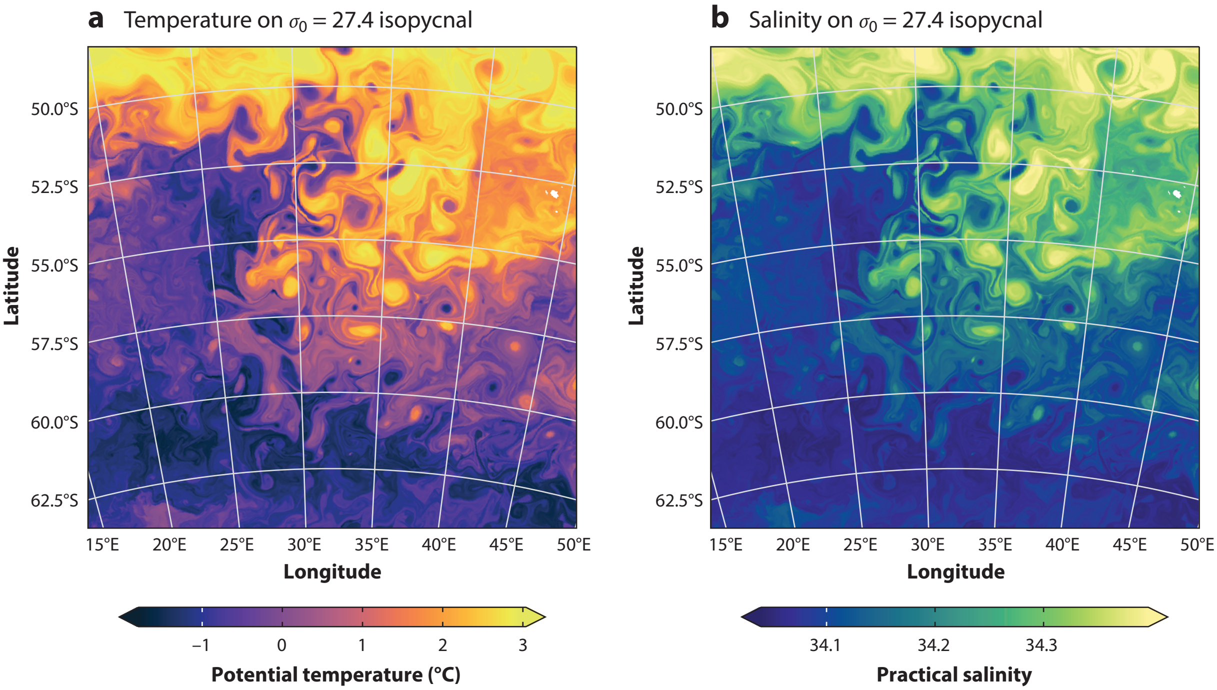

Figure 5

Visualization of the isopycnal mixing process as revealed in the (*a*) potential temperature and (*b*) salinity fields of a high-resolution numerical simulation. Data are from the MIT General Circulation Model (MITgcm) LLC2160 simulation (Rocha et al. 2016). The concentrations of the two tracers, plotted on the $\sigma_0 = 27.4$ kg m^{-3} potential density surface, reveal an intricate pattern of eddies and filaments that reflect the underlying stirring patterns of the velocity field. The temperature and salinity variations compensate exactly to maintain a constant potential density. Isopycnal mixing thus drives transport of heat and salt southward and upward, along the sloping isopycnal surface.

overturning circulation. In particular, isopycnal mixing can drive ventilation even in locations of weak or net-zero residual overturning.

The recent Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) organized a large international collaboration around quantifying Southern Ocean mixing rates. For isopycnal mixing, these efforts produced new observational constraints on the isopycnal diffusivity, K, in the Drake Passage region. Diffusivities were measured with subsurface isopycnal floats (LaCasce et al. 2014; Balwada et al. 2016, 2021) and a tracer release experiment (Tulloch et al. 2014); in all cases, the relatively sparse observations were compared with eddy-resolving numerical simulations. These studies found observational evidence of middepth (~1,500 m) mixing rates of $O(1{,}000)$ m^2 s^{-1} upstream of Drake Passage, while comparison with the numerical simulations suggested suppressed diffusivities of $O(500)$ m^2 s^{-1} higher in the water column. The results also hinted at strong zonal variability in mixing rates along the path of the ACC (Balwada et al. 2016).

The relative importance of advection versus isopycnal mixing for meridional tracer transport can be characterized via a Péclet number:

$$P_e = \frac{V_{res} L}{K}, \quad 1.$$

where V_{res} is a representative magnitude of the residual velocity, L is a meridional length scale, and K is a representative isopycnal diffusivity. We can make a rough estimate for P_e as follows. We assume that a 10-Sv northward transport of mode and intermediate waters (Sallée et al. 2013b) occurs over a layer 500 m thick across 50°S (Cerovečki et al. 2013); this yields an average V_{res} of 0.0005 m s^{-1}. For L, we choose 1,000 km as approximately representative of the scale over which isopycnals slope down from the surface to their interior depth (Cerovečki et al. 2013). Together with $K = 500$ m^2 s^{-1} in the depth range of mode and intermediate waters (Tulloch et al. 2014, Naveira Garabato et al. 2016), this yields $P_e \sim 1$. Analyses of transient tracer measurements also suggest $P_e \sim 1$ in mode and intermediate waters (Waugh et al. 2003, Hall et al. 2004). These estimates thus indicate that residual advection and isopycnal diffusion may play comparable roles in Southern Ocean ventilation. However, strong zonal variations in both mixing and advection along the path of the ACC (Sallée et al. 2010b, Thompson & Naveira Garabato 2014) are likely to tip the balance at a local level in favor of one process or another. It is notable that, while subduction hot spots and pathways of mode and intermediate waters are localized (Sallée et al. 2010a, Cerovečki et al. 2013; see also Section 4), this localization is not found in the distribution of tracers such as oxygen or CFCs, implying that alongstream advection and mixing play a role in homogenizing variations in subduction.

Antarctic Intermediate Water (AAIW): a low-salinity water mass found at intermediate depths in the Southern Ocean

Subantarctic Mode Water (SAMW): a water mass that typically forms in the midlatitude Southern Ocean

Direct observational evidence for the relative importance of advection versus isopycnal mixing is rare. However, a crucial insight was provided by Naveira Garabato et al. (2016), who analyzed the microstructure dissipation of temperature variance and kinetic energy in the ACC; this technique permitted an estimate of the amount of temperature variance produced by isopycnal versus diapycnal mixing. They concluded that, for both upwelling Upper Circumpolar Deep Water and downwelling Antarctic Intermediate Water (AAIW), the dominant heat balance was between isopycnal advection and isopycnal mixing. In the Upper Circumpolar Deep Water, isopycnal mixing of temperature worked in opposition to the residual circulation, ventilating the ocean interior even in regions of net advective upwelling. This insight inspired a broader reassessment of the potential importance of isopycnal mixing processes in high-latitude ventilation (Naveira Garabato et al. 2017). However, for Subantarctic Mode Water (SAMW), the water mass most involved in the uptake of anthropogenic heat and carbon, isopycnal mixing played a minor role in the heat budget in comparison with diabatic processes.

Numerous recent model studies have attempted to probe this question from different perspectives. Using an idealized high-resolution channel simulation that directly resolved isopycnal stirring, Abernathey & Ferreira (2015) explored the uptake of an idealized surface-forced tracer under different values of westerly wind stress. Although upwelling increased in response to winds, stronger mesoscale eddy stirring overwhelmed the advective effects, leading to greater tracer uptake. This finding is in agreement with the suggestion of Naveira Garabato et al. (2017) that isopycnal mixing can effectively decouple ventilation from overturning in the Southern Ocean. However, the idealized nature of the simulations limits the interpretation in terms of real-world impacts. Using similar models, Balwada et al. (2018) probed the submesoscale regime by varying the resolution from 20 km to 1 km; they found increased ventilation as a function of resolution, suggesting that submesoscale isopycnal stirring plays an important role in transferring tracers across the mixed-layer base.

Other studies using coarse-resolution models have examined the impact of parameterized isopycnal mixing on tracer uptake. A set of climate model experiments varied the Redi coefficient independently from the Gent–McWilliams coefficient, enabling explorations of the impacts of isopycnal mixing on stratification (Pradal & Gnanadesikan 2014), radioisotopes (Gnanadesikan et al. 2015a), carbon uptake (Gnanadesikan et al. 2015b), and oxygen distribution (Bahl et al. 2019). Focusing on carbon uptake as a proxy for ventilation, Gnanadesikan et al. (2015b) found that stronger isopycnal mixing could enhance ocean carbon uptake by 20%, which they attributed to strong ventilation by isopycnal diffusion along the sloping isopycnals of the Southern Ocean.

Several modeling studies have examined the role of isopycnal mixing in anthropogenic heat uptake in both coarse-resolution (Armour et al. 2016, Liu et al. 2018) and eddy-rich configurations (Morrison et al. 2016). Ocean heat uptake provides a somewhat less direct view on ventilation than passive tracers, since changes in temperature can cause dynamical feedbacks that drive circulation changes, but there is still much that can be learned from such model experiments. These studies separated the simulated northward anthropogenic heat transport into components associated with the residual overturning and isopycnal mixing and found that isopycnal mixing played a major role in a narrow-latitude window between approximately 37°S and 45°S. The percentage that isopycnal mixing contributed to the total northward heat transport anomaly, averaged over this midlatitude region, varied from ∼25% (Armour et al. 2016) to ∼40% (Morrison et al. 2016) to ∼65% (Liu et al. 2018). The overall conclusion from these studies was that the residual overturning dominates the anthropogenic heat transport from a whole Southern Ocean perspective, which is compatible with the observational finding of Naveira Garabato et al. (2016) that isopycnal mixing is less important for the heat budget in SAMW density classes. However, isopycnal mixing was shown to be a significant, or even the dominant, process in a narrow latitudinal band roughly aligned with the Southern Ocean subduction zone.

4. SUBDUCTION

The zonal mean framework that is often used to describe Southern Ocean overturning and the associated tracer transport is a valuable conceptual model that has been used for many years, but it has limitations. One of these limitations is that the zonal mean framework obscures the regional and localized nature of subduction. The process of transferring water and tracers from the mixed layer into the stratified pycnocline occurs in hot spots with relatively small surface areas (**Figure 6*d***), where young mode and intermediate waters are created (Sallée et al. 2010a, 2012). The presence or absence of these hot spots is determined by the specific local interplay among bathymetry, stratification, and the air–sea exchange of heat and momentum (e.g., Iudicone et al. 2007, Jones et al. 2019). In zonal mean frameworks, these local subduction regions are averaged out and thereby hidden, even in more sophisticated treatments where the mean is carried out along circulation streamlines (e.g., Abernathey et al. 2010).

The zonal asymmetry of Southern Ocean subduction has important consequences for the global ocean circulation, the uptake of heat and carbon, and the sensitivity of these processes to future emissions scenarios. Therefore, it is important to include this asymmetry in conceptual and numerical models of ocean circulation (Rintoul 2018). Furthermore, subduction can vary substantially in time; it is a process that is localized temporally as well as spatially (Cerovečki et al. 2013, Cerovečki & Mazloff 2015).

Subduction occurs in regions of open ocean convection, on horizontal scales from tens of kilometers up to the scale of ocean gyres—several thousand kilometers across (Williams & Follows 2011, Williams & Meijers 2019). Subduction can be diagnosed on different timescales; instantaneous subduction offers a different view from annual or decadal averages of subduction. The basic process of annual subduction involves both (*a*) year-to-year variations in the depth of the seasonal mixed layer and (*b*) the wind-induced downwelling of fluid and tracers through the base of the seasonal mixed layer. Throughout the autumn and winter, the surface ocean loses buoyancy, encouraging convective overturning and turbulent mixing; these processes cause the mixed layer to become thicker. Throughout the spring, the surface ocean gains buoyancy, which causes the mixed layer to become thinner. During this period of mixed-layer thinning, there is a subduction period over which fluid transfers from the mixed layer into the permanent thermocline (Stommel 1979). It is worth noting that the distinction between the seasonal thermocline and the main/permanent

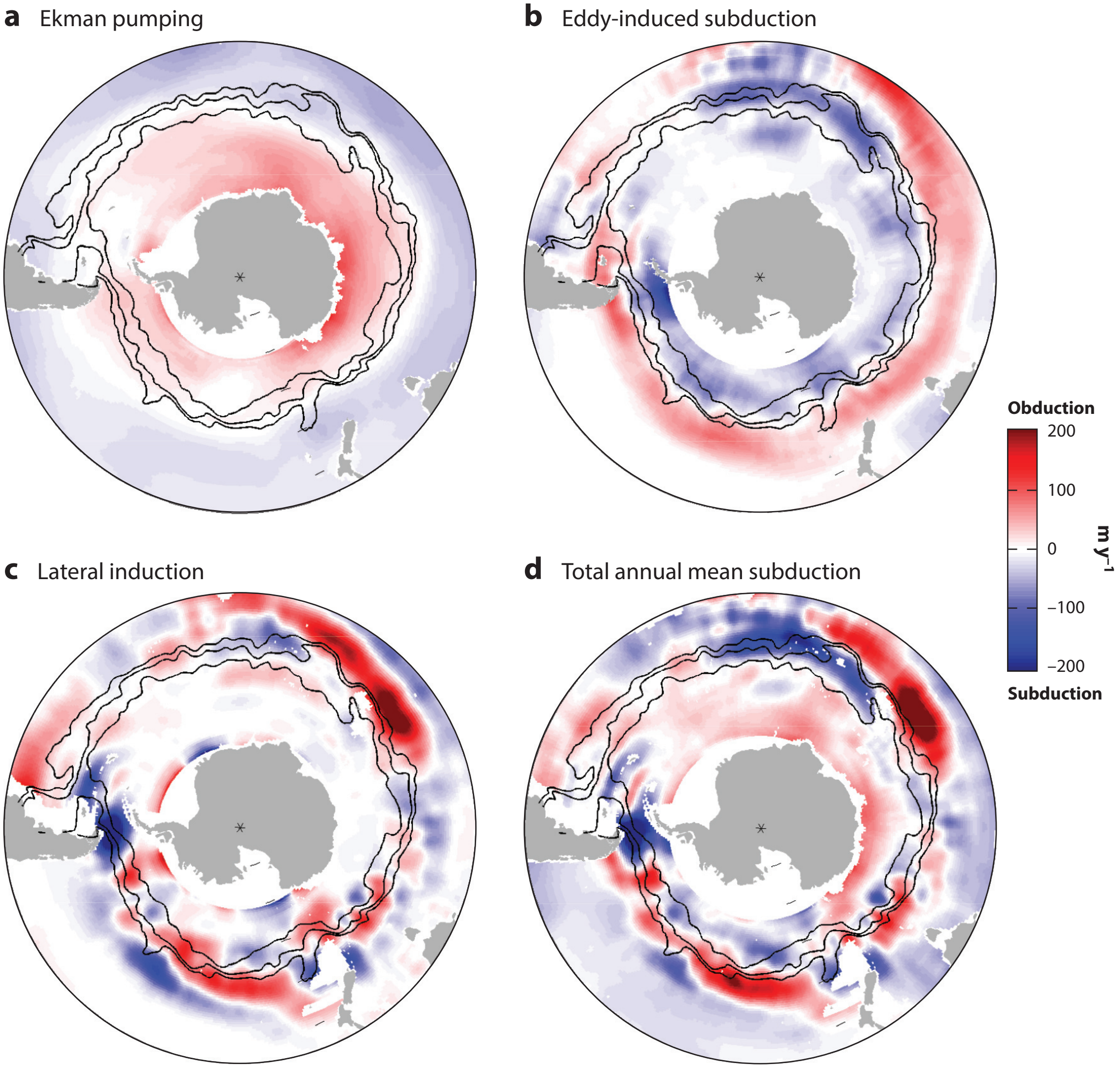

Figure 6

The different components of annual mean subduction, with negative values indicating downward subduction into the pycnocline: (*a*) Ekman pumping, (*b*) eddy-induced subduction, (*c*) lateral induction by the mean geostrophic flow, and (*d*) total annual mean subduction. Figure adapted with permission from Sallée et al. (2010a); copyright 2010 American Meteorological Society.

thermocline depends on the year-to-year variations in the maximum depth of the mixed layer. This distinction raises the possibility that variations in the maximum mixed-layer depth over multiyear or decadal timescales may need to be considered; it is possible for fluid and tracer that has been subducted to once again come into contact with the mixed layer after several years (Jones et al. 2016). This could be thought of as the reventilation of previously subducted mode waters.

The localized, regionally varying nature of subduction is a consequence of the localized, regionally varying properties of eddies, waves, and other nonlinear processes. The divergence of mesoscale and submesoscale eddy mass fluxes in the surface layer (**Figure 6*b***) makes an important contribution to localized subduction (Bachman et al. 2017). Mesoscale eddies, which have a rich spatial structure related to the location of jets and fronts, transport convective products away from their formation sites and thereby either enhance the subduction rate (Visbeck et al. 1996, Marshall 1997) or minimize the prospect of reventilation. Submesoscale instabilities can enhance the net subduction of water via dense filaments (Taylor et al. 2018). Standing meanders in the ACC (sometimes described as stationary eddies) also contribute to localized subduction; in particular, these standing Rossby waves dominate the subduction of anthropogenic carbon in the Southern Ocean (Langlais et al. 2017). Interactions among Southern Ocean jets, topographic features, and stratification can lead to abrupt changes in subduction affecting intermediate water, further reinforcing the notion that subduction is set by the regional nature of such processes (Klocker 2018). Other regionally varying processes contribute to the subduction rate of SAMW and AAIW, such as the nonlinear process of cabbeling (Nycander et al. 2015, Groeskamp et al. 2016) and the formation, advection, and melting of sea ice (Cerovečki et al. 2019).

Many quantitative estimates suggest that subduction is determined largely by the process of lateral induction, defined as the transfer of fluid and tracer across a horizontally sloping mixed-layer base by the mean flow (**Figure 6*c***). However, there are reasons to treat the concept of lateral induction with care. In mixed-layer volume and heat budgets, the term referred to as lateral induction is typically a mathematical construct that uses time-averaged mixed-layer structure and time-averaged circulation fields (Sallée et al. 2010a). This averaging obscures the way in which the time-evolving mixed layer interacts with the time-evolving circulation, potentially overinflating the importance of lateral induction. Very few published studies have discussed this limitation, but it is an area of active research. For example, Close & Goosse (2013) found that in coupled climate models, the process of lateral induction makes only a small contribution to the heat budget of the mixed layer. The relative importance of lateral induction in time-varying budgets promises to be a rich area of future study.

Numerical studies show that in a high-emissions scenario, there is a reduction in SAMW and AAIW subduction rates, potentially decreasing the absorption and storage of CO_2 in the Southern Ocean (Downes et al. 2009). CMIP3 models responded with a reduction in the Southern Ocean subduction rate of ~15–20% (Downes et al. 2010, Liu & Wang 2014). In CMIP5 models, the Southern Ocean mixed layers become shallower, warmer, and fresher (Sallée et al. 2013a). The response of subduction to climate forcing is also highly regional and localized (Downes et al. 2017). Changes in the wind stress restructure the Southern Ocean large-scale circulation, including the flow of the ACC in its primary jets, and this affects the formation rates of SAMW and AAIW in this complex region (Downes et al. 2011). These estimates might change in future CMIP iterations, as developments such as increased vertical resolution are expected to be important for estimating eddy-induced subduction (Hiraike et al. 2016).

While subduction is often assumed to be a rate-limiting step for Southern Ocean ventilation (e.g., Sallée et al. 2012), SAMW age and volume do not appear to vary consistently with the subduction rate (Downes et al. 2017, Waugh et al. 2019, Portela et al. 2020). Water mass properties in the interior are also rapidly homogenized across the subtropical gyres after subduction (**Figure 7**). This suggests that the distribution of ventilated tracer concentration in the interior may be less dependent on the subduction rate and more dependent on the transport and mixing processes between the base of the mixed layer and the interior location.

5. SUBTROPICAL GYRE TRANSPORT

Recent studies have suggested an additional link between transport in the subtropical gyre and the rate of thermocline ventilation. The effect of gyre transport on ventilation was first highlighted

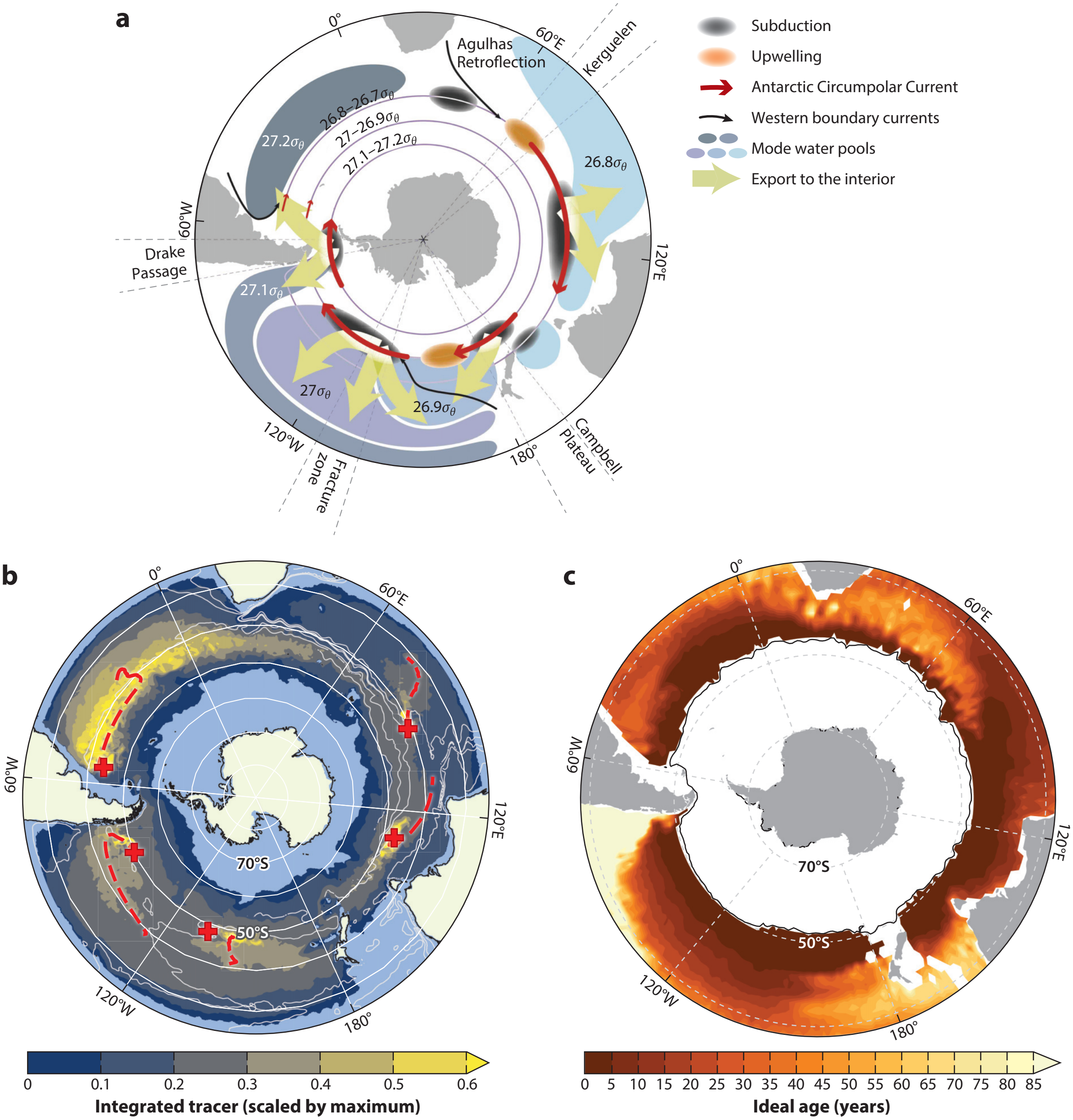

Figure 7

The contrast between the localized hot spots of subduction at the base of the mixed layer (panel *a*) and the subsequent interior ventilation pathways shown by passive tracers (panel *b*) and ideal age (panel *c*). (*a*) Intense subduction hot spots (*black*), export pathways (*green*), and mode and intermediate water pools (*blues*). (*b*) Lateral ventilation pathways for passive tracers released by Jones et al. (2016) in different subduction hot spots. Red crosses show release locations, dashed red lines show mean pathways for the first 10 years, and colors show the depth-integrated tracer distribution. Gray lines are Montgomery potential contours. (*c*) Ideal age on isopycnal layer $\sigma_2 = 35.5$ kg m^{-3} from the model simulation described by Waugh et al. (2019). Panel *a* adapted with permission from Sallée et al. (2010a); copyright 2010 American Meteorological Society.

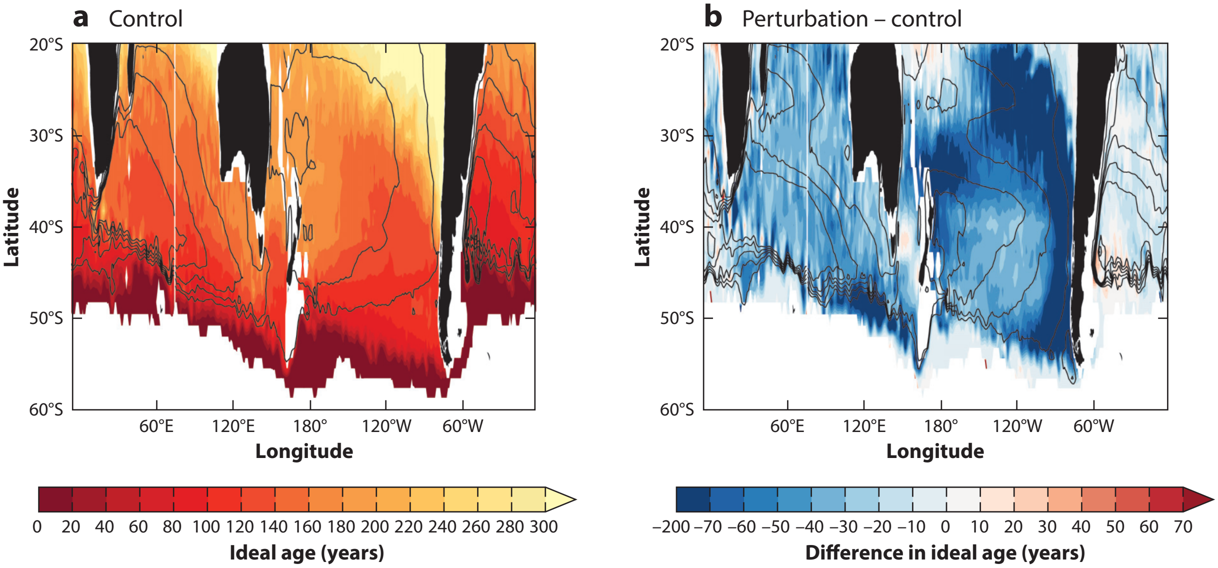

Figure 8

Maps of (*a*) age in a control simulation and (*b*) differences between age in a perturbation simulation with increased and poleward-shifted winds and age in the control simulation, on the $\sigma_2 = 36$ kg m^{-3} surface. Black lines show the barotropic streamfunction with the contour levels 0, 210, 220, 230, and 240 Sv for the control simulation (panel *a*) and the perturbation simulation (panel *b*). Figure adapted with permission from Waugh et al. (2019); copyright 2019 American Meteorological Society.

in a high-resolution numerical study that used passive tracers to identify the pathways of SAMW export into the subtropical ocean (Jones et al. 2016) (**Figure 7*b***). These pathways were dominated by the lateral, geostrophic circulation; in short, SAMW is advected more rapidly along the ACC (in the case of Australian and Atlantic mode water pools) or via the subtropical gyres (in the case of Indian and Pacific mode water pools). These results suggested that indicators of ventilation may be sensitive to changes in the subtropical gyre circulation.

Several recent modeling studies have tested the sensitivity of ventilation to variations in wind stress. Waugh et al. (2019) analyzed the evolution of ideal age in a series of idealized wind stress perturbation experiments using an eddy-permitting global ocean model. The ideal age responded linearly to changes in Southern Ocean wind stress, with the change in age on isopycnal surfaces in the subtropics best explained through a simple Sverdrup balance—implying that geostrophic gyre transport (rather than subduction rate or meridional overturning circulation) governed the ventilation rate (**Figure 8**). This result is consistent with recent studies by Jones et al. (2019, 2020), who estimated the influence of wind stress variations on recently ventilated heat content in the South Pacific; they found that wind stress curl over the subtropical gyre exerts greater control on heat content than higher-latitude forcing. Furthermore, Waugh et al. (2021) found that the effect of gyre forcing on the ventilation age is localized within each ocean basin.

The discovery that gyre and other lateral circulation can alter the pathways and the ages of ventilated Southern Ocean waters suggests a revision of the conceptual model of ventilation. A salient point here is that the interaction of the localized nature of subduction with the geostrophic flow implies that recently subducted water may avoid being reventilated into the mixed layer if it can be moved laterally away from the subduction region (**Figure 7**). Thus, the mismatch between subduction rates and overturning estimates (see Section 2.2) may be reconciled by taking into account the effect of lateral mean flow. On the other hand, it should be emphasized that the

VENTILATION TIME VERSUS VENTILATION RATE

The ventilation time is the mean time since water at a given location was last in contact with the mixed layer, which is equivalent to the ideal age. Mixing creates a distribution of times since last contact, which is known as the transit time distribution (Haine & Hall 2002) and corresponds to the Green's function used to estimate the ocean storage of anthropogenic carbon (Hall et al. 2004, Waugh et al. 2006) or a change in passive ocean heat content (Zanna et al. 2019). The ideal age can, therefore, be used as a proxy for anthropogenic carbon and passive heat storage, with a decrease in age corresponding to more anthropogenic carbon or heat storage.

The ventilation rate is the flux of water across the bottom of the mixed layer into the ocean interior and is equivalent to the net subduction rate. Subduction can be highly localized and intermittent.

There is an expectation that an increase in subduction will lead to a decrease in the ideal age. However, the relationship between these two measures of ventilation is unclear, for three reasons:

1. Ideal age varies spatially throughout the ocean interior, but subduction is calculated at the base of the mixed layer.
2. Subduction estimates the transport of water into the interior, while ideal age integrates that transport over recent history.
3. Ideal age is sensitive to mixing along the export pathway.

Therefore, the relative sensitivity of these metrics may differ in response to the variety of physical processes governing ventilation.

metrics used to evaluate ventilation in the above studies (recently ventilated heat content and ideal age) do not specifically measure the rate of ventilation (see the sidebar titled Ventilation Time Versus Ventilation Rate). For example, the decrease in ideal age found by Waugh et al. (2019) (**Figure 8**) may be explained by a decrease in the time taken for water to advect along the gyre pathway, rather than by an increase in the net rate of ventilation.

6. RECENT CHANGES IN SOUTHERN OCEAN VENTILATION

A wide range of changes have been observed in the Southern Hemisphere atmosphere and oceans over the last four decades. These include a shift of the summertime Southern Annular Mode (SAM) to a more positive phase and an accompanying strengthening and poleward shift of the westerly winds (Fogt & Marshall 2020). These changes in winds are expected to cause changes in the ventilation of the Southern Ocean pycnocline; however, our ability to detect changes in ventilation is very limited, as there are no direct measurements of ventilation and only sparse long-term measurements of properties that can be used to infer aspects of the ventilation in the Southern Ocean.

While long-term measurements are limited, the deployment of a large number of Argo floats providing vertical profiles of temperature and salinity in recent years has enabled examination of changes in ocean properties in Southern Ocean mode waters, and possible changes in ventilation, since 2005. For example, Sallée et al. (2010b) examined how Argo-derived mixed-layer depths changed with the phase of the SAM and showed that, although the SAM is often viewed as a zonally symmetric variation, there are large zonal variations in the Southern Ocean mixed-layer depth. They showed that a positive SAM is associated with deeper mixed layers over the eastern Indian and central Pacific Oceans but with shallower mixed layers over the western Pacific and Indian Oceans. These variations were related to changes in the meridional wind in different phases of the SAM. Given the recent trends in the SAM, this analysis suggests that there may have been trends in the mixed-layer depth, and Sallée et al. (2010b) estimate mixed-layer depth changes as large as 100 m in areas with the deepest mixed layers.

Analyses of the interannual variability and trends in the formation rate and volume of SAMW and AAIW differ between the two density classes. For example, Kwon (2013) found no significant correlation between the SAM and the SAMW subduction rate but did show that more pycnocline waters were entrained into AAIW density classes during positive phases of the SAM, while Portela et al. (2020) showed an increase in the volume of SAMW between 2006 and 2015 but a decrease in the AAIW volume. The increase in SAMW volume was also reported by Gao et al. (2018), who showed that the SAMW layer thickened, deepened, and warmed, with the pattern of changes similar to that of the wind stress curl, suggesting that wind forcing, and resulting changes in Ekman pumping, can explain the observed SAMW changes. The regional nature of the variability in SAMW formation is also evident in the thickness of the SAMW pools in the Pacific and Indian sectors, which vary out of phase with each other, driven by the relative phases of the SAM and the El Niño/Southern Oscillation (Meijers et al. 2019).

More direct estimates of ventilation are possible from measurements of CFCs, sulfur hexafluoride (SF_6), and other transient tracers. The atmospheric concentrations of these gases have increased over time, and ocean measurements show the pathways of recently ventilated water with high concentrations of these tracers. It is therefore possible to estimate the (mean) ventilation age from these tracers (Talley et al. 2016).

Quantification of long-term changes in these age estimates is again limited by available measurements. However, several studies have used repeat measurements of transient tracers to estimate changes in ideal age in the Southern Ocean pycnocline and have generally shown a decrease in SAMW age (implying an increase in the ventilation rate). For example, Waugh et al. (2013) and Ting & Holzer (2017) showed a decrease in SAMW age between the early 1990s and mid-2000s for meridional sections in all three Southern Ocean basins (**Figure 9**), while Fine et al. (2017) showed a similar decrease for three zonal sections sampled over a similar time period. However, not all repeat observations show a clear decrease in SAMW age; analyses of data from the southern Indian Ocean by Álvarez et al. (2011) and Tanhua et al. (2013), using different approaches, indicate no long-term change in the age between the early 1990s and mid-2000s, while Fine et al. (2017) showed insignificant or inconsistent trends between the 1990s and 2010s. It is unclear whether these differences are due to spatial variations in decadal trends, natural year-to-year variability, or uncertainties in estimates of the age change.

The general decrease in SAMW age has been linked to the intensification and poleward shift of the peak wind stress. However, the connection has only been made qualitatively, and the mechanisms involved have not been isolated. Waugh et al. (2013) and Ting & Holzer (2017) showed an increase in age in subpolar, upwelling Circumpolar Deep Water at the same time as the decrease in SAMW age. These changes are consistent with more rapid transport of young surface water into SAMW and more rapid upwelling of old, deep water into subpolar Circumpolar Deep Water and suggest that an increase in the strength of the upper overturning circulation (in response to wind stress changes) is the cause of the ventilation changes.

However, there have also been significant changes in the subtropical gyres over recent decades, which could have also caused changes in ventilation. For example, Roemmich et al. (2007) compared data from Argo floats in the early 2000s with data from the World Ocean Circulation Experiment hydrographic survey in 1991–1996 and showed that a spin-up occurred in the South Pacific gyre circulation, which continued through 2014 (Roemmich et al. 2016). Consistent changes are also observed in the other southern gyres (Cai 2006), and these studies have linked the increase in the gyre circulations to the changes in wind stress curl. As discussed in Section 5, an increase in

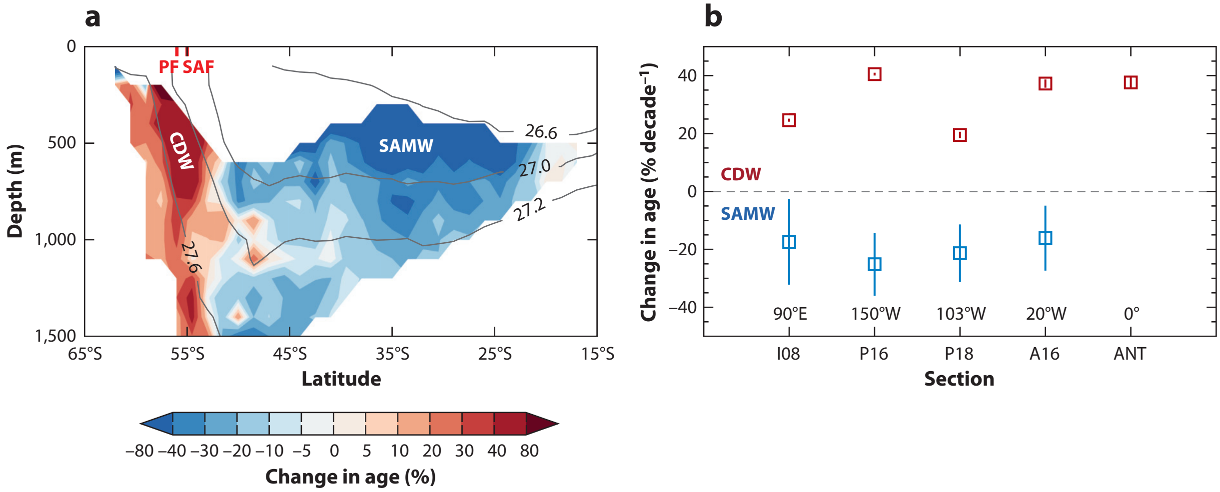

Figure 9

(*a*) Vertical cross section of the change in age estimated from observed dichlorodifluoromethane (CFC-12) in the Pacific between 1991 and 2005 (along section P16, 150°W). Contour lines show potential density referenced to the sea surface, σ_0 (kg m^{-3}); the latitudes of the climatological Polar Front (PF) and Subantarctic Front (SAF) are marked in red. (*b*) Differences in the mean ages of Circumpolar Deep Water (CDW) and Subantarctic Mode Water (SAMW) for repeat sampling of observed CFC-12 along five meridional sections. The change in age is expressed as percentage change per decade, relative to age from the original cruise. Figure adapted from Waugh (2014).

the subtropical gyre circulation will lead to younger ages in mode waters, and thus the observed decrease in SAMW age could equally be due to strengthening subtropical gyres in response to increased wind stress. Thus, the identification of age trends in observations is not amenable to attribution from causal mechanisms.

Although not a direct measure of ventilation, observations of the Southern Ocean carbon cycle have been used to suggest changes in the ocean circulation and ventilation (e.g., Gruber et al. 2019b). However, there is large uncertainty in the estimates of the carbon cycle changes and the processes involved. Initial observational studies showed a weakening of the Southern Ocean carbon sink up to the early 2000s (e.g., Le Quéré et al. 2009), but later observations showed a reinvigoration until the early 2010s (Landschützer et al. 2015). These changes have been linked to a 1990s strengthening and then a weakening of the upper overturning circulation through the 2000s (e.g., Gruber et al. 2019b). In particular, DeVries et al. (2017) connected a more vigorous upper overturning circulation in the 1990s to an increase in the upwelling of carbon-rich deep waters in subpolar water, increased outgassing of natural carbon, and a reduced ocean carbon sink (with the reverse for the weakening of overturning in the 2000s). They also showed an opposing change in anthropogenic carbon, with increased (decreased) uptake of anthropogenic carbon associated with the stronger (weaker) upper overturning circulation, but these changes are smaller than those in natural carbon (which dominates the overall carbon sink). An increased anthropogenic carbon uptake during the 1990s is consistent with the decreased age in mode and intermediate waters discussed above (e.g., Waugh et al. 2013, Ting & Holzer 2017) but is inconsistent with Gruber et al.'s (2019a) observational estimate of anthropogenic carbon, which shows a reduction of storage in intermediate waters between the 1990s and the 2000s. These inconsistencies still need to be resolved.

7. DISCUSSION

It would be nice to be able to conclude here that a single process provides the dominant control on Southern Ocean ventilation; however, the evidence presented above indicates otherwise. Multiple processes are involved in the ventilation of the Southern Ocean pycnocline, and none is sufficient, on its own, to explain variations in ventilation. The rate at which the pycnocline is ventilated depends on the rate of subduction in localized hot spots, lateral transport is needed to avoid reventilation of subducted water, and meridional volume/tracer transport is required to spread this ventilated water northward into the subtropics. This meridional transport may occur via the overturning circulation, the subtropical gyres, or eddy mixing along isopycnals—and it is likely that all three of these transport mechanisms operate together. Thus, while individual ventilation processes are relatively well understood, the dependence of ventilation on this chain of processes means that a more holistic approach may be needed to fully understand the ventilation problem.

Many modeling studies have examined how Southern Ocean ventilation responds to atmospheric forcing changes. However, in the majority of these studies, it is unclear which dynamical processes contributed to the ventilation change, because multiple processes would have responded to the forcing perturbation, but often only a single process was analyzed. Using observations or realistic ocean models, it is difficult to isolate the impact of only one ventilation process (e.g., localized subduction) while holding other factors constant (e.g., overturning and gyre circulations, isopycnal mixing, and wind impact on gas exchange rates).

Common approaches to understanding ventilation sensitivity include offline transport modeling, which has been used to isolate the impact of the overturning circulation (e.g., DeVries et al. 2017). Idealized, eddy-resolving numerical simulations could be another approach to independently evaluate different ventilation mechanisms. However, considerable insight could also be gained from analyzing the responses of multiple ventilation processes to forcing change within the same model simulation. One example of this approach is the combined analyses of Downes et al. (2017), Hogg et al. (2017), and Waugh et al. (2019), who unexpectedly found that decreasing age in mode waters (i.e., increased ventilation) was correlated with gyre circulation changes but not with changes in the subduction rate or upper overturning transport. This approach could be taken further in future modeling experiments, in particular aiming to disentangle the roles of individual mechanisms in governing the system response, or determining the extent to which these individual mechanisms may compensate for each other.

Observational studies of ventilation have been used to reveal the contributions of individual processes but are difficult to place in context with competing mechanisms. Nonetheless, we argue that such process-based observational work is of inestimable value to progress in this area. In this respect, we highlight the contributions of the recent DIMES program (e.g., Balwada et al. 2021) in providing new insights into the rate of isopycnal mixing. Of the processes listed above, isopycnal mixing is the one that is least well constrained by direct observations, and better estimation of isopycnal mixing from observations will help to constrain and interpret research into Southern Ocean ventilation.

The recent emergence of ultra-high-resolution global-scale models (e.g., Rocha et al. 2016, Ajayi et al. 2021) holds major potential for advancing understanding of Southern Ocean ventilation, since many of the important processes—topographic eddy hot spots, eddy bolus transport, mesoscale isopycnal mixing, and near-surface submesoscale fronts—can be fully resolved. However, to date, ultra-high-resolution models have not been configured with tracers such as CFCs or anthropogenic carbon that can be used to assess ventilation. Moreover, the computational cost of such models limits their run time to several years—insufficient time for tracers to penetrate deep into the pycnocline. Despite these challenges, we are optimistic that ultra-high-resolution simulations will soon be used to gain a much more detailed and realistic picture of the physics of Southern Ocean ventilation.

Recent studies highlighted in this review suggest that the subduction diagnostic is not a suitable metric to explain volume and age changes on interior isopycnals (Waugh et al. 2019, Portela et al. 2020). It follows that studies of ventilation would be easier to evaluate or compare if a single representative metric (or a small selection of metrics) could be developed. Our primary suggestion is that idealized or CFC-like passive tracers may provide a more reliable measure of ventilation for future studies.

SUMMARY POINTS

1. Multiple metrics have been used to quantify ventilation, including the subduction rate, ideal age, and overturning circulation; these metrics respond differently to simulated changes in forcing, which complicates the attribution of ventilation changes to individual processes.
2. Differences in spatial patterns of tracers at the ocean surface, as well as variations in air–sea equilibration timescales, influence the extent to which the overturning circulation controls tracer ventilation. In particular, anthropogenic heat uptake is strongly dependent on the strength of the upper overturning circulation, while carbon uptake is only weakly dependent.
3. Sparse observations suggest that isopycnal mixing may be less important than other mechanisms for ventilation of mode waters but may be an important factor in intermediate water ventilation. While modeling analyses have not directly quantified how important isopycnal mixing is for ventilation of different water masses, simulations of heat uptake suggest that it may be the primary northward heat transport mechanism in a narrow window between approximately 37°S and 45°S.
4. The zonally averaged framework, in which the overturning circulation and isopycnal mixing are viewed, is not a good predictor of changes in ventilation, because (*a*) the ventilation of tracers across the base of the mixed layer is highly localized (both spatially and temporally) in subduction hot spots and (*b*) tracer transport away from the hot spots into the interior is dependent on zonal, in addition to meridional, transport processes.
5. Mode and intermediate waters are advected along subtropical gyre or Antarctic Circumpolar Current pathways after subduction. Simulated pycnocline age and heat content are best explained by transport of the subtropical gyres rather than by the overturning circulation or the subduction rate.
6. Tracer observations indicate that Southern Ocean ventilation increased from the early 1990s to the mid-2000s. This ventilation increase is consistent with both an observationally inferred strengthening of the upper overturning circulation and an intensified subtropical gyre circulation over the same period.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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