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Darryn W. Waugh

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Darryn W. Waugh

Department of Earth and Planetary Sciences, Johns Hopkins University, 3400 N Charles Street, Baltimore, MD 21218, USA

Research

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Author for correspondence:
Darryn W. Waugh
e-mail: waugh@jhu.edu

Changes in the ventilation of the southern oceans over the past few decades are examined using ocean measurements of CFC-12 and model simulations. Analysis of CFC-12 measurements made between the late 1980s and late 2000s reveal large-scale coherent changes in the ventilation, with a decrease in the age of subtropical Subantarctic Mode Waters (SAMW) and an increase in the age of Circumpolar Deep Waters. The decrease in SAMW age is consistent with the observed increase in wind stress curl and strength of the subtropical gyres over the same period. A decrease in the age of SAMW is also found in Community Climate System Model version 4 perturbation experiments where the zonal wind stress is increased. This decrease is due to both more rapid transport along isopycnals and the movement of the isopycnals. These results indicate that the intensification of surface winds in the Southern Hemisphere has caused large-scale coherent changes in the ventilation of the southern oceans.

1. Introduction

The transport of surface waters into the interior (‘ventilation’) of the southern oceans is driven primarily by the stress due to the overlying westerly winds [1,2]. This wind stress has strengthened over recent decades, primarily as a consequence of Antarctic stratospheric ozone depletion [3], and studies suggest that this will have caused changes in the ocean’s overturning circulation [4–6] and the oceanic uptake of heat [7] and carbon [8,9]. There is, however, debate over the sensitivity of the southern ocean circulation to decadal changes in wind stresses [10–12]. Here, we examine changes in the ventilation of the southern oceans using ocean measurements of transient tracers, and perturbation experiments in a climate model where the zonal wind stress is increased.

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Oceanic measurements of chlorofluorocarbons (CFCs) can, as their atmospheric concentrations have increased rapidly from the 1930s to the mid-1990s and they are conserved within the oceans, be used to constrain the rates and pathways of ocean ventilation [13–15]. In the next section, we review several recent studies that have used CFC measurements made over the past three decades to examine changes in the ventilation of the southern oceans. These analyses show large-scale coherent changes in the ventilation, with a decrease in the water mass age of subtropical Subantarctic Mode Waters (SAMW) and an increase in the age of Circumpolar Deep Waters (CDW).

The cause of these observed changes in water mass ages is examined in §4 by comparisons with the observed changes in the wind stress and strength of the subtropical gyres, and analysis of the age in Community Climate System Model version 4 (CCSM4) perturbation experiments where the zonal wind stress is increased [16].

2. Tracer observations

Measurements of CFCs have been made in the southern oceans over the past three decades, primarily as part of the World Ocean Circulation Experiment (WOCE) in the 1990s and the CLImate VARiability and predictability (CLIVAR) and CO_2 Repeat Hydrography Program in the mid- and late 2000s. Several recent studies have used transit time distribution (TTD) theory [15,17] together with these repeat CFC measurements to estimate the change in the ‘mean age’ (the mean transit time since water has last contact with the surface) [18–20]. In this approach, the TTD is assumed to be an inverse Gaussian distribution with a specified width/mean ratio (Δ/Γ). Then the mean age Γ can be estimated independently from the CFC measurements for each cruise (WOCE and repeat), and the difference in these estimates is the change in mean age between cruises.

Waugh *et al.* [18] estimated the change in mean age between the late 1980s or early 1990s and the mid- or late 2000s for four meridional sections (in the southern Pacific, Indian and Atlantic oceans) and a zonal section across the subtropical South Pacific. As illustrated in figure 1, this analysis showed decreases in the mean age of subtropical thermocline and increases in subpolar waters (see figure 2*a* for a map showing the sections). The change in age averaged over the SAMW ($26.6 \leq \sigma_0 \leq 27.0\,\mathrm{kg\,m^{-3}}$) and subpolar CDW ($27.2 \leq \sigma_0 \leq 27.6\,\mathrm{kg\,m^{-3}}$) water masses (expressed as percentage change per decade) is shown in figure 2*b*. These water-mass averages reveal consistency among the sections, which were first sampled on different dates between 1989 and 1995 and re-sampled between 2005 and 2010, with a decrease in the SAMW age (of around 15–25% per decade) and an increase in CDW age (covering a larger range of 20–40% per decade).

Huhn *et al.* [20] performed a similar TTD analysis using measurements of CFC-12 and SF_6 made in the Weddell Sea 10 times between 1984 and 2011, and showed large increases in the age of both intermediate (Warm Deep Water and lower CDW) and deep (Weddell Sea Bottom Water and Weddell Sea Deep Water) waters. As shown in figure 2*b*, their change in lower CDW along the Prime Meridian is very similar to that for CDW in section A16. Álvarez *et al.* [19] also used TTD analysis together with repeat CFC measurements to examine changes in the mean age in the subtropical Indian Ocean (section I05; 32°S). Whereas the analysis in Waugh *et al.* [18] indicates a decrease in the age of SAMW along section I08 (90°E between 20 and 35°S), the Álvarez *et al.* [19] analysis indicates either constant ventilation or oscillations in the ventilation time, depending on depth. The reasons for these differences are unclear, and there is some uncertainty in the spatial extent of the Indian Ocean water mass with decreasing age.

In the above studies, an assumed functional form of the TTDs was used to infer changes in ventilation times from the tracer measurements. However, consistent results are obtained using methods not making this assumption. Waugh *et al.* [18] also used a data-constrained (‘assimilated’) ocean circulation model [21] in their analysis of the repeat CFC-12 measurements. This model differs in many aspects from the TTD model, including the data used to constrain the models, the functional form of the TTD, and how surface CFC-12 concentrations are set (see [18] for details), but produces results very similar to the TTD analysis. In addition, Tanhua *et al.* [22]

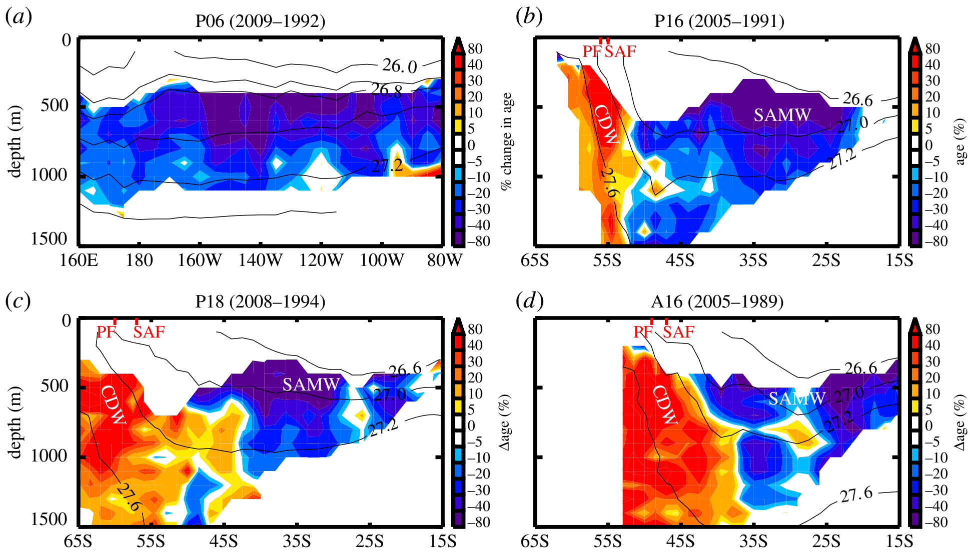

Figure 1. Vertical cross sections of the change in mean age between WOCE and repeat cruises for (*a*) P06 sampled in 1992 and 2009, (*b*) P16 sampled in 1991 and 2005, (*c*) P18 sampled in 1994 and 2008 and (*d*) A16 sampled in 1989 and 2005. The change in mean age is estimated from CFC-12 measurements using TTDs with $\Delta/\Gamma = 1.0$. Locations of the sections are shown in figure 2*a*. Contours show potential density referenced to the sea surface σ_0 (kg m^{-3}), acronyms correspond to water masses defined in the text, and the latitudes of the climatological polar front (PF) and subantarctic front (SAF) are marked on (*b–d*).

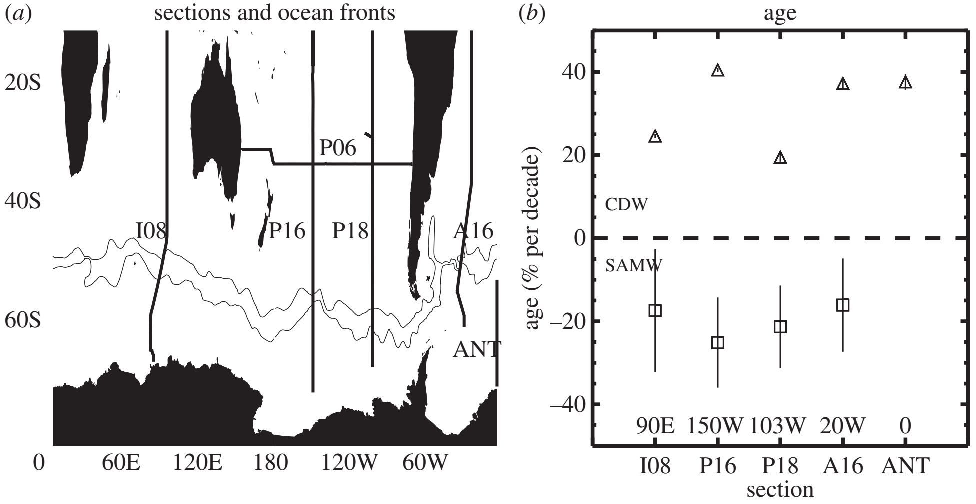

Figure 2. (*a*) Map showing sections (thick lines) and the climatological PF and SAF (thin curves). (*b*) Difference in mean age for CDW and SAMW water masses for the repeat sampling of the meridional sections shown in (*a*). Change in age is expressed as percentage change per decade, relative to age from the original cruise.

presented a new observational method that makes no assumptions about the transport and mixing and uses historical (e.g. 1990s) CFC-12 and modern (e.g. the late 2000s) SF$_6$ measurements to detect changes in ventilation. Applying this method to P18 measurements of CFC-12 in 1994 and SF$_6$ in 2007, Tanhua *et al.* [22] inferred an increase in the ventilation rate in the subtropical thermocline, consistent with results described earlier.

The differences in the subtropical Indian Ocean aside, the above analyses of transient tracer measurements using three different methods indicate that coherent, large-scale changes in water mass ages between the early 1990s and the late 2000s occur in the southern oceans, with decreases in the age of subtropical SAMW and increases in the age of polar CDW.

3. Connections to surface winds

The above analysis of transient tracers shows that there have been changes in water mass ages in the southern oceans, but does not identify the cause of these changes. One possible cause is the observed strengthening of the wind stresses over the southern oceans over the past few decades (figure 3*a*). We examine this possible connection, first by comparing with other observations, and then analysing climate model simulations.

(a) Observations

An intensification of surface westerly winds is expected to lead to changes in the horizontal wind-driven circulation. The horizontal circulation north of the Antarctic Circumpolar Current is to a good approximation in Sverdrup balance and is dependent on the wind stress curl (which is dominated by the meridional gradient of the zonal wind stress in the southern mid-latitudes). Meteorological reanalyses show an increase in the magnitude of the wind stress curl in southern mid-latitudes (with the largest increase around 40°S; figure 3*a*), and consistent with this an increase in the intensity of the southern subtropical gyres [23,24]. This increase in gyre strength will be expected to lead to more rapid transport of (young) surface waters into the subtropical thermocline and a decrease in the age of SAMW. Thus, the observed decrease in SAMW age is consistent with the observed increase in wind stress curl and strength of the subtropical gyres. Furthermore, there is quantitative agreement as the wind stress curl, gyre strength [23,24] and SAMW age (figure 2*b*) all changed by around 20–30% between the early 1990s and the late 2000s.

An intensification of surface winds is also expected to lead to changes in vertical transport, through changes in Ekman pumping. An increase in wind stress curl will lead to increased northward Ekman transport and formation rates of subtropical mode waters, and to a strengthened and poleward-shifted Ekman divergence and enhanced subpolar upwelling [4,5]. These changes will lead to a spatial pattern for changes in age similar to that inferred from the above tracer observations, i.e. increased transport into subtropical mode waters will lead to a decrease in the age of these waters, while increased subpolar upwelling will bring up more deep, old waters that mix with younger surrounding waters and increase the age of subpolar waters.

(b) Climate models

To further explore the connection between ventilation and surface wind stress, we examine the simulated age in coupled atmosphere–ocean climate models. Analysis of the age in simulations with increasing greenhouse gases shows a strengthening of the southern westerlies, a decrease in the age of mode waters, and an increase in polar waters [25,26]. This is qualitatively consistent with the above observed change, but there are many other changes in these simulations (e.g. global warming), and it is not possible to make a clear link between changes in surface winds and ventilation in these simulations.

A cleaner analysis is possible using perturbation experiments where there is a specified change in the wind stress. Gent & Danabasoglu [16] performed a pair of such experiments using CCSM4. In the first experiment (‘PERT1’), the wind stress is increased by 50% south of 35°S from a pre-industrial control experiment, whereas in the second experiment (‘PERT2’) there is a larger increase and a southward shift in the location of the peak wind stress; figure 3*b*. The CCSM4 simulations include an ideal age tracer, which quantifies the mean time since water had contact with the ocean surface. (The ideal age tracer equals the mean age Γ, after an initial spin-up

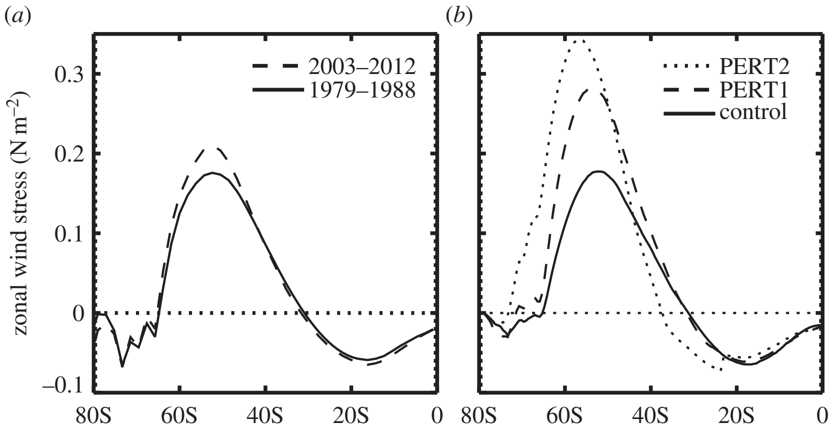

Figure 3. Zonal-mean zonal wind stress in the Southern Hemisphere, from (*a*) National Centers for Environmental Prediction reanalyses (1979–1988 and 2003–2012 averages) and (*b*) CCSM4 experiments (control, PERT1 and PERT2).

phase [27].) Figure 4*a* shows the zonal-mean ideal age from year 863 of the control experiment, which is the initial date for the PERT experiments. In upper waters the ideal age in the control run is in steady state, but for deeper waters the age is still slowly increasing, e.g. there is an increase in the ideal age of 10–20 years between year 863 and year 963 for waters with ideal age older than 500 years (figure 4*b*). To account for this, we examine the difference in ideal age between the PERT experiments at year 100 and the control experiment at year 963.

Figure 4*c*,*d* shows the PERT-control difference in the zonal-mean ideal age. In both experiments, there are substantial decreases (greater than 50 years) in the ideal age within the subtropical ventilated thermocline (30–55°S, $\sigma_0 = 26.0$–$27.75\,\mathrm{kg\,m^{-3}}$). These changes in ideal age are much larger than the interannual variability in the control experiment (interannual standard deviation is less than 5 years in the subtropical thermocline). Thus, consistent with the observations, an increase in the wind stresses in CCSM4 leads to younger ages in subtropical mode and intermediate waters.

The decrease in the ideal age in the subtropics could be due to several processes. One potential process is changes in the along-isopycnal transport (due to a stronger subtropical gyre). To isolate the impact of along-isopycnal transport, we calculate the change in ideal age at fixed density. This ‘isopycnal change’ is shown in figure 4*e*,*f*, where we have calculated the change for a given latitude and density, and then used the initial density distribution to map the change at fixed density back to depth space. As expected from the imposed increase in wind stress, there is a decrease in subtropical ideal age in the ventilated thermocline at fixed latitude and density. Comparison with figure 4*c*,*d* shows that this isopycnal change in ideal age explains a lot, but not all, of the change at fixed depth. Furthermore, the relative contribution of along-isopycnal changes varies between locations and experiments. Around 30–40°S the along-isopycnal change is 60–80% of the total change in both PERT experiments, whereas around 50°S the along-isopycnal change is 20–40% of the total change in PERT2 but is around twice the total change in PERT1.

The above differences mean that processes other than along-isopycnal transport are contributing to the decrease in age at fixed depth. This additional process is the movement of isopycnals. A deepening (downward movement) of isopyncals leads to a decrease in ideal age at fixed depth as the ideal age increases with depth, and the reverse occurs when isopyncals move up. The isopyncals move down between 20 and 45°S for PERT1 and between 30 and 60°S for PERT2, and, as discussed above, in these regions the decrease in age at fixed depth is larger than the along-isopycnal decrease in age (i.e. age at fixed depth decreases because of both deepening of isopycnals and increased along-isopycnal transport). By contrast, between 45 and 55°S in PERT1

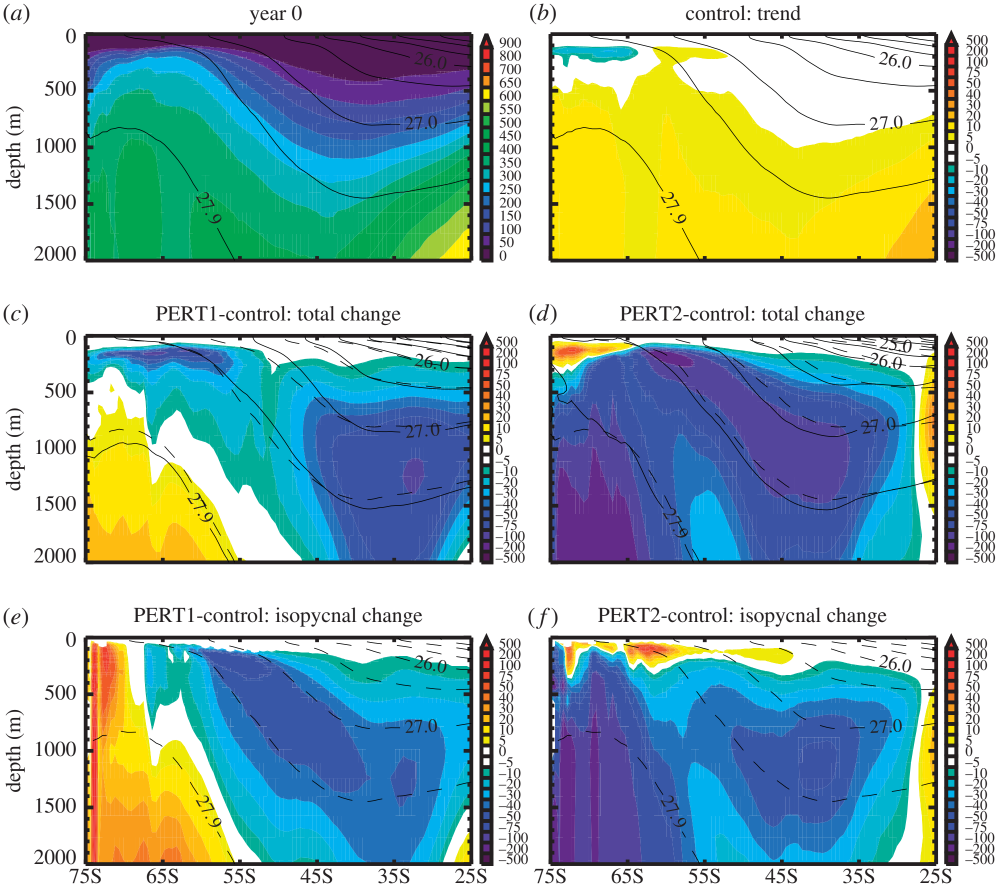

Figure 4. Distributions of zonal-mean ideal age (in years) from CCSM4 experiments: (*a*) distribution for year 863 of the control experiment (and year 0 of PERT experiments), (*b*) trend between year 863 and year 963 of the control experiment, (*c*,*d*) PERT1–control difference and (*e*,*f*) PERT2–control difference. The differences in (*c*–*f*) are between year 100 in PERT experiments and year 963 in the control experiment. (*c*,*e*) Changes at fixed latitude-depth, whereas (*d*,*f*) show changes calculated at fixed density-latitude that are mapped in depth-latitude space. Contours show zonal-mean potential density (dashed contours are for the control run, and solid contours are for PERT1 and PERT2, respectively).

there is a shallowing of isopycnals which increases the age at fixed depth, and opposes the along-isopycnal decrease. In this region, the decrease in age at fixed depth is then less than the decrease at fixed density.

The decrease in the subtropical age is larger in the PERT2 than in the PERT1 experiment. This is consistent with the above discussion relating the observed decrease in age within the subtropical SAMW to the observed increase in wind stress curl and subtropical gyre strength. In particular, the percentage decrease in subtropical age in the CCSM4 experiments is similar to the increase in barotropic stream function, e.g. the peak stream function in the subtropical South Pacific is around 30, 40 and 60 Sv for the control, PERT1 and PERT2 experiments, while the age at 700 m (after 100 years) in the same region is 100, 75 and 50 years (not shown).

There are also large changes in the ideal age in subpolar intermediate waters of the PERT experiments (figure 4*c*,*d*). However, the sign of the change below 1000 m varies between the two experiments: in PERT1, the ideal age is slightly older, whereas in PERT2 the ideal age is much younger than in the control. The large decrease in subpolar age in PERT2 occurs within 5 years of the wind stress perturbation and is due to enhanced convection that brings younger near-surface waters to depth. In PERT2, there is a large increase in the wind stress in subpolar regions (figure 3*b*), and this results in increased surface heat loss, reduced buoyancy, and enhanced vertical mixing and convection that leads to a dramatic increase in mixed layer depths and decrease in subsurface ages (not shown). In PERT1, there are only very small changes in the subpolar wind stresses (figure 3*b*), and changes in the subpolar surface heat fluxes and vertical mixing do not appear to be the cause of the ageing of subpolar waters in PERT1. An alternative process that could be causing this ageing is a strengthening of the overturning circulation which would (as discussed earlier with regard to the observed changes) increase the upwelling of old, deep CDW.

The change in subpolar age in neither PERT experiment matches the changes inferred from the CFC observations. The sign of the change is different in PERT2, whereas the magnitude of the increase in PERT1 is limited to depths below 1000 m and is much weaker than observed (e.g. at 1500 m the increase in PERT1 is only around 4%). The cause of these differences is unclear. It could be that the change in subpolar winds is unrealistic in both experiments (e.g. there is a large increase in PERT2 but observations show little change between the late 1970s and the early 2010s (figure 3*a*)).

4. Concluding remarks

Analysis of CFC-12 and SF_6 measurements made in the southern oceans over the past three decades reveals large-scale coherent changes in the ventilation, with a decrease in the age of subtropical SAMW and an increase in the age of CDW and polar deep waters. The decrease in subtropical age is consistent with the observed intensification of the zonal wind stresses and subtropical gyre strength over the same period and is also consistent with the response in CCSM4 to a strengthening of the zonal wind stress.

There are several outstanding issues that require further investigation. One issue is the cause of the observed changes in subpolar waters. This could be due to changes in the overturning circulation and increased upwelling of CDW. However, the CCSM4 experiments show that changes in buoyancy forcing can play a major role in changes in the age of subpolar waters.

Another issue is the role of eddies and mixing in the observed and modelled changes in age. In the above comparisons of changes in the subtropical gyre circulation and SAMW ages, the focus is on changes in the advective circulation (stream function), but it is known that mixing processes play an important role in the determining tracer (and mean age) distributions [15]. Further research is needed to determine how this mixing changes as the zonal wind stress increases, and what role this plays in changes in ventilation. The role that mixing plays in ventilation also needs to be explored further in the model simulations. The CCSM4 simulations examined here do not resolve eddies, and use a Gent and McWilliams eddy parameterization [28] with spatially varying diffusivity. The changes in isopycnal slopes in the CCSM4 PERT2 simulation are similar to those in a CM2.4 eddy-permitting simulation [16], suggesting that CCSM4 may be simulating the appropriate response to changes in the wind stress. However, as the balance between advective and mixing processes that determines ventilation is not necessarily the same as that which controls isopycnal slopes, there remains some uncertainty in how well CCSM4 simulates the response of ventilation times and mean age to changes in the wind stress.

The inferred changes in ventilation will be expected to impact the ocean uptake and distribution of heat, carbon and other biogeochemical tracers. There is some consistency with observed changes in these fields, with warmer/saltier waters south of the polar front and cooler/fresher waters north of the polar front [2,29], increases in dissolved oxygen in the subtropical Indian Ocean and decreases in polar Southern Ocean [30,31], and a slow-down of carbon uptake in Antarctic waters in recent decades [32] due to enhanced upwelling of polar CDW, which brings carbon-rich deep waters to the surface. However, more work is needed to identify the role of changes in ventilation in the changes in these tracers.

As Antarctic stratospheric ozone depletion is the primary cause of the strengthening of the surface westerly winds over the past few decades [6], the above analysis suggests that Antarctic ozone depletion caused the changes in ventilation of the southern oceans. However, natural decadal variability and increased greenhouse gases could also be contributing, and quantifying the relative contribution of natural variability, increased greenhouse gases and ozone depletion to past changes in ocean ventilation is an open question. As is the question of future changes in the ventilation. This is likely to depend on the recovery of stratospheric ozone and the magnitude of greenhouse gas increases. The recent trend of intensifying summer westerly winds may slow or reverse as ozone recovers [3,33,34], but it is expected that the continued increases in greenhouse gases will lead to strengthened westerlies during other seasons. The integrated impact of these seasonally varying trends in westerlies on the ocean's ventilation, uptake of heat and anthropogenic carbon is unknown.

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