Future decline of Antarctic Circumpolar Current due to polar ocean freshening

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The Antarctic Circumpolar Current is the world’s strongest ocean current and plays a disproportionate role in the climate system due to its role as a conduit for major ocean basins. This vast current system is linked to the ocean’s vertical overturning circulation, and is thus pivotal to the uptake of heat and CO₂ in the ocean. The strength of the Antarctic Circumpolar Current has varied substantially across warm and cold climates in Earth’s past, but the exact dynamical drivers of this change remain elusive. This is in part because ocean models were not able to adequately resolve the eddies and dense shelf water formation that control current strength. Here, we use a global ocean model which resolves such processes to diagnose the impact of future thermal, haline and wind conditions on the strength of the Antarctic Circumpolar Current. By 2050, our model suggests the strength of the Antarctic Circumpolar Current will decline by ∼20% in an extreme scenario. This decline is further supported by simple scaling theory, and is driven by ice shelf melting around Antarctica, which weakens the zonal density stratification historically influenced by surface temperature gradients. Such a strong decline in transport would have critical implications for the entire global ocean circulation, and hence the Earth’s climate system.

The ACC has an observed transport of about 173 Sverdrups (1 Sverdrup = 10⁶ m³/s) (10), making it the world’s strongest ocean current. The ACC is the only current which encircles the planet without encountering continental boundaries, and also supports the global-scale overturning circulation among the three major ocean basins (11). ACC transport is constrained by geostrophic balance due to the thermal wind relationship, which is a function of the meridional and vertical density distribution throughout the Southern Ocean (12, 13). The configuration of these density layers is subject to alterations by surface winds as well as by salinity and temperature exchanges at the surface (14, 15), all of which are subject to rapid changes due to ongoing climate change (16–20).

Dominant westerly winds, a characteristic feature of the Southern Ocean, induce a northward Ekman transport that tends to intensify the inclination of density layers, steepening the depth-variable meridional density gradient. However, this process is counteracted by enhanced baroclinic eddies and convective mixing, together moderating the meridional density gradient and compensating transport (14, 21–23). On the other hand, the response of the ACC to variations in the surface buoyancy distribution (i.e., heat or freshwater fluxes) is also critical and has been influenced by past climatic changes (24, 25).

The ACC is also intimately linked to Antarctic Bottom Water formation along the Antarctic margins. Turbulence-resolving direct numerical simulations (13, 26, 27) and idealised simulations with an eddying primitive equation model (28) have shown that convection around the Antarctic continent, which feeds the AABW without the requirement of wind forcing, could...
lead to a circumpolar current similar to the ACC. This is consistent with idealised case study from a reduced gravity model where the initiation of AABW formation leads to a large increase in zonal transport (29). These results suggest that a change in convection around the Antarctic, which is closely tied to meltwater and sea-ice production around the Antarctic continent (30), could directly change the ACC. In recent decades, AABW formation has been observed to decline significantly (31), and freshening by glacial meltwater has played a crucial role in reducing the convection that feeds AABW formation (30). Recent high-resolution modelling by (32), found that the AABW may decline by 42% by 2050 in response to a constant meltwater perturbation from the Shared Socioeconomic Pathway 5-8.5 future projection in CMIP6. If the link between AABW formation and thermal wind transport is apparent in the real ocean, this would suggest that the ACC is set for a long-term decline in strength.

A comprehensive assessment of historical observations and climate models by (33) recently found that zonal transport in the Southern Ocean has accelerated in past decades. This acceleration has so far been attributed to enhanced meridional temperature gradients in the region, and is isolated to a relatively narrow band centered at 52°S. ACC transport through the Drake Passage, on the other hand, has remained unchanged between 2005 and 2019, suggesting that the zonal transport acceleration seen by (33) has not influenced the ACC in the Drake Passage (34). It is still unknown how enhanced ice shelf melting, which will flux enormous volumes of freshwater into the Southern Ocean, will disrupt the recent acceleration of zonal transport or the relatively stable ACC in the future. In order to explore this question, we use an eddy-resolving global ice-ocean model to explore the impact of projected surface freshwater and temperature fluxes on the zonal transport in the Southern Ocean. Our results show that the impact of surface warming will be quickly overwhelmed by the polar freshening due to ice melt in the Southern Ocean. Thus, the ACC, and zonal transport more generally, is projected to slow down by around 20% by 2050.

Results

We assess changes in zonal transport in a set of three simulations from the high-resolution, 1/10th-degree ocean-sea ice ACCESS-OM2-01 model - a ‘neutral’ climate simulation, and two future perturbation runs. The Repeat-Year Forced simulation represents a neutral climate state, and is spun up with forcings consistent with 1 May 1990 to 30 April 1991 cycling over 180 years. This simulation provides a foundational perspective of the oceanic system’s behaviour without considering the effect of rapid polar melting and resulting freshening. Two future perturbation experiments are then produced by branching off the RYF run, one which is forced with projected global temperature, meltwater and wind perturbations (hereby, the Future Perturbation experiment), and another that is forced with projected global temperature and wind perturbations only (hereby, the Future Perturbation without meltwater experiment), from 1991 to 2050. The future perturbation experiments are identical to those used in (32), and the RYF simulation is explored extensively in (35). Further information on the model setup and simulations is also provided in the materials and methods section.

Broadly, the suite of ACCESS-OM2-01 simulations reveal a long-term decline in zonal transport in the Southern Ocean (as shown in figure 1). Understanding this declining trend is crucial for predicting broader climatic and oceanic changes in the coming decades. The time-mean zonal transport pattern in the Repeat-Year Forced (RYF) simulation shows a strong circumpolar series of jets comprising the ACC (figure 1a). Over the final ten years of the RYF simulation, the Drake Passage transport and zonally-averaged zonal transport between 70-50°S is strong, at 140 Sv and 103 Sv respectively (dashed black lines in figure 1d and e).

Contrasting with the RYF simulation, the future perturbation simulation (averaged over the decade from 2040 to 2050) shows major shifts in zonal transport over different parts of the Southern Ocean. An increase in westward zonal transport (blue colour) is visible over the Antarctic continental slope, consistent with the location of the Antarctic Slope Current in this model. This strengthening ASC has been previously reported in a more idealised meltwater perturbation setup with the same model (36). In the rest of the Southern Ocean, there is an overall drop in eastward transport, signalling a decrease in Antarctic Circumpolar Current (ACC) and zonal transport. This decline is visible in both the zonal and vertically integrated transport in figure 1d and e, with an approximate decrease of about 20% over four decades in both the Drake Passage transport and the zonally-averaged transport, calculated between 70°S and 50°S.

The future perturbation without meltwater simulation shows that this drop in ACC and zonal transport is entirely due to meltwater production around Antarctica (compare red and blue lines in figure 1d and e). When the model is forced solely by projected changes to winds and temperature, the zonal transport and ACC transport remains broadly unchanged. Indeed, there is a slight acceleration of zonal transport between 2000 and 2040 when only thermal and wind changes are used to force the model. This acceleration of zonal transport may be due to the same mechanisms highlighted by (33) - enhanced meridional thermal gradients accelerating the thermal wind transport in the Southern Ocean. However, in our model, future projections of Antarctic meltwater rapidly offset this slight temperature-driven acceleration, signalling a profound shift in the dynamics controlling Southern Ocean transport.

Zonal transport in the Southern Ocean is supported by the density and stratification profiles in the water column. In order to understand the sharp drop in zonal transport over future decades, it is thus essential to understand the changes to the meridional and vertical profiles of temperature, salinity and density this part of the world. There is a fresh-to-salty, cold-to-warm, and dense-to-light zonally-averaged meridional gradient at the surface of the Southern Ocean (red lines in figure 2a to c). In a depth-averaged sense, however, the salinity gradient is flipped (black lines in figure 2a), because of the inclusion of the saltier, sub-surface Circumpolar Deep Water along the Antarctic margins, and the subducted freshwater in the Antarctic mode water further north. Nevertheless, the mean meridional gradient in density in the Southern Ocean has dense water in the south, and lighter water in the north.

The change in this mean gradient reveals the root cause of the decline in zonal transport in the future (figure 2d
The sea surface salinity drops along the Antarctic margins (latitudes southwards of 65°S), and there is enhanced freshening in the subpolar latitudes (latitudes northwards of 65°S) consistent with the subduction of the Antarctic mode water. In deep subpolar latitudes, there is a slight trend towards increased salinity. The temperature field, on the other hand, generally warms across most regions of the ocean, with substantial increases noted in particular around the Antarctic margins. The increase in temperature around the Antarctic margins is not seen in the future perturbation without meltwater simulation (not shown), implying that the warming of the Antarctic margins here is a meltwater-driven phenomenon. The net impact of this spatially heterogeneous freshening and warming is a net lightening of the entire water column, as shown in figure 2f and i. The subsurface salification of the Antarctic margins is offset effectively by the warming signal there, leading to a loss in density in the margins. Further north, warming in the mixed layer and freshening of the Antarctic mode waters combines to lighten the subsurface ocean (figure 2i). These shifts in temperature and salinity have significant repercussions on the overall stratification, which can influence ACC and zonal transport. This increase in top-to-bottom stratification is primarily attributed to the accumulation of freshwater near the Antarctic margin and subsurface warming in the subpolar latitudes. Similar stratification changes were showcased for the same simulations by (32).

Our results show that the integrated zonal and ACC transport declines in response to polar freshening. By visualising the zonally- and depth-integrated transport (figure 3, we explore the regions where the transport change is greatest, and the stratification changes which bring about this transport decline. In the future perturbation without meltwater simulations, there is a negligible change in depth-integrated transport south of 55°S, and an increase in zonal velocity north of 55°S (i.e., north of the Drake Passage latitudes). There is also minimal change in density, as indicated by the isopycnal lines in figure 3a and c.

On the other hand, the future perturbation run has substantial changes in density both in the Antarctic margins and in the subpolar latitudes (including the latitudes of the Drake Passage). The general decrease in density (compared red and black lines in figure 3d) is consistent with the lightening water column shown in 2i. There is a steepening of isopycnals in the Antarctic margins (i.e., increasingly negative slope), compared with a flattening of isopycnals further north. This suggests that there is an increase in geostrophic shear near the Antarctic margins, potentially enhancing the westward component of transport. Concurrently, a reduction in the eastward component of transport is inferred due to the decrease in geostrophic shear, as evidenced by the flattening of isopycnals there.

**Discussion**

The observed weakening of the ACC in our future perturbation simulation is a critical finding that has profound implications for understanding future oceanic and climatic changes. The reduction in ACC and zonal transport, of
Fig. 2. Summary of the temperature, salinity and density properties of the Southern Ocean in the suite of simulations conducted. Time-mean surface (red lines) and depth-averaged (black lines) a) salinity, b) temperature and c) density in the RYF (dashed lines) and future perturbation (solid lines) simulations. Change in surface (red lines) and depth-averaged (black lines) d) salinity, e) temperature and f) density between the RYF (time-mean over the final ten years of simulation) and future perturbation simulation (time-mean between 2040 and 2050). Zonally-averaged change in g) salinity, h) temperature and i) density between the RYF and future perturbation simulation.

Fig. 3. Zonal transport change between the RYF and future perturbation simulations. a) Depth-integrated zonal transport change in the future perturbation (without meltwater) simulation, b) Depth-integrated zonal transport change in the future perturbation simulation, c) zonally-integrated zonal transport change in the future perturbation (without meltwater) simulation and d) zonally-integrated zonal transport change in the future perturbation simulation. Red and black contour lines in panels c and d show selected time-mean densities in the RYF (black) and future (red) simulations.
approximately 20% over four decades, suggests a substantial reconfiguration of Southern Ocean dynamics. This change in the ACC, one of the planet’s major current systems, could have far-reaching impacts on global climate patterns, oceanic heat distribution, and marine ecosystems. The freshening of surface and subsurface waters, particularly around the Antarctic margins, and the salinification of deeper ocean layers, highlights the major alterations to the ocean’s thermohaline structure that are underway. The reduced formation of Antarctic Bottom Water causes a decrease in water column density, especially in the upper layers, and plays a crucial role in global heat and nutrient distribution (32).

Additionally, the warming signal observed in most locations, especially around the Antarctic margins, aligns with broad expectations of future ocean warming.

The rapid change in the thermohaline characteristics of the Southern Ocean in our simulations directly leads to a drop in zonal and ACC transport in the model via thermal wind balance. In fact, using a fundamental thermal wind balance-derived scaling for zonal transport for ACC-like system (13), we can reproduce the drop in zonal transport seen in the model. Taking the thermal wind relationship between geostrophic velocity gradient and meridional density gradient \( f \partial u / \partial z \approx (\rho_0 \partial \rho / \partial y) \), estimate geostrophic zonal velocity and integrated transport as \( u \sim (\rho \Delta \rho H) / (\rho_0 W) \) and \( T \sim (\rho \Delta \rho H^2) / (\rho_0 f W) \), respectively, where \( f \) is the Coriolis frequency, \( z \) is the vertical dimension with height \( H \), \( g \) is the gravitational acceleration, \( \rho_0 \) is the reference density and \( y \) is the meridional dimension with width \( W \). Now, the net change in the transport (due to the change in density gradient in the meridional direction) is estimated as:

\[
\delta T \sim \frac{g \Delta \rho H^2}{\rho_0 f} \sim \frac{g H^2}{f} (-\alpha \delta \Delta \Theta + \beta \delta \Delta S),
\]

where \( \alpha \) is the thermal expansion coefficient; \( \beta \) is the haline contraction coefficient, \( \Theta \) is the temperature, \( S \) is the salinity, \( \delta \) represents the change in a property over time, and \( \Delta \) represents the change in a property from south to north. We take \( \delta \Delta \Theta \) and \( \delta \Delta S \) from the model output (figure 2a and b), and assume \( H = 4500 \) m, \( g = 9.81 \) m s\(^{-2}\), \( f = -1.25 \times 10^{-4} \) s\(^{-1}\), \( \rho_0 = 1035 \) kg m\(^{-3}\), \( \alpha = 10^{-4} \) K\(^{-1}\), and \( \beta = 7.5 \times 10^{-4} \) kg m\(^{-2}\) s\(^{-1}\). This thermal wind-derived scaling predicts that, given a temperature and salinity change consistent with the model output, we would expect a transport change, \( \delta T \), of -32 Sv. This prediction is remarkably close to the integrated zonal transport change in figure 1e, indicating that the zonal transport in the Southern Ocean is primarily thermally wind-driven. Our scaling results solidify the conclusion that stratification changes, specifically polar freshening around Antarctica, will drive a dramatic slowdown of the ACC and zonal transport in future decades.

**Materials and Methods**

Here, we summarise the diagnostics used to analyse the zonal transport and property changes in the Southern Ocean, and provide further details on the ocean model simulations assessed. In this analysis, we assess changes to the zonal- and depth-integrated transport, and zonal- and depth-averaged temperature, salinity and density in the ocean model.

The globally-averaged (zonally-averaged) transport [in Sv], for instance, is given by

\[
T = \frac{1}{\Sigma \lambda} \int \int \int ud\phi d\lambda dz
\]

where \( u \) is the zonal velocity, \( \phi \) is the latitudinal dimension, \( z \) is the depth dimension, and the integral is calculated over the longitudinal (\( \lambda \)) dimension. The depth-integrated (zonally-averaged) transport [in Sv/degree] is then \( T^\lambda (\phi) = \frac{1}{\Sigma \lambda} \int ud\lambda dz \), and the zonally-averaged transport [in Sv/degree/m] is given by \( T^\lambda (\phi, z) = \frac{1}{\Sigma \lambda} \int ud\lambda dz \).

The zonally-averaged thermohaline properties in the model are given by

\[
\overline{T}^\lambda (\phi, z) = \frac{1}{\Sigma \lambda} \int C d\lambda
\]

and depth-averaged properties may be calculated as

\[
\overline{T}^\lambda z (\phi) = \frac{1}{\Sigma \lambda \Sigma z} \int \int C d\lambda dz
\]

where \( C \) is any conservative scalar property (in this case, temperature, salinity, or density). These relatively simple diagnostics reveal a fundamental shift in the Southern Ocean driven by polar freshening.

**Data.** The primary tool used in this analysis is the ACCESS-OM2-01 ocean-sea ice model (see (35) for details). ACCESS-OM2-01 has a 0.1-degree horizontal resolution and has 75 vertical z\(^{-1}\) levels. The model is composed of the MOM5.1 ocean model (37) coupled with the CICE5.1.2 sea ice model (38), and forced with the JRA55-do v1.3 atmospheric forcing product (39). The ACCESS-OM2-01 model significantly improves representation of dense shelf water formation and Antarctic margins processes, which directly impacts the accuracy of representation of the Antarctic Circumpolar Current (40, 41). The ACCESS-OM2-01 model has been analysed extensively in a variety of studies, and an exhaustive summary of the model specifics are provided in (35).

Three simulations are conducted using this ocean model - a Repeat-Year Forcing case (RFY), a future perturbation case without meltwater, which forces the ocean with projected changes to wind and temperature (only) and a future perturbation case which forces the ocean with projected changes to wind, temperature and meltwater. In the RFY case, the ocean model is forced by 55 km and a 3-hourly temporal resolution JRA55-do v1.3 forcing cycling over the 1 May 1990 to 30 April 1991 time period. This year was found to be adequately ‘neutral’, in that no major modes of climate variability were active during this time, by (42). The RFY simulation is spun up for 180 years to produce a neutral control simulation, against which the future perturbation simulations may be compared. In this work, we analyse the monthly temperature, salinity, density and zonal transport in the RFY case, time-averaged over the final 10 years (i.e. years 170 - 179) of the RFY simulation.

The two future perturbation simulations analysed in this work are identical to the simulations assessed in (32). In these simulations, an RFY simulation is first spun up for 200 years, as detailed above. Then, two different simulations are branched off from the RFY simulation - one with perturbed anomalous winds and thermal forcing, and one with perturbed anomalous wind, temperature and meltwater forcing fields. For the years 1991-2019, the historical JRA55-do v1.3 forcing field is used to force the future simulations, and beyond 2020, the CMIP6 high-emissions scenario, Shared Socioeconomic Pathway 5-8.5 (SSP5-8.5) is used as the model forcing field (43). In this analysis, we assess the monthly temperature, salinity, density and zonal transport in the future perturbation simulations, averaged over the final 10 years of the simulation (i.e., 2040 - 2050).

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