Southern Hemisphere westerly wind control over the ocean’s thermohaline circulation

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Abstract

We examine the effect of the position of the southern hemisphere subpolar westerly winds (SWWs) on the thermohaline circulation (THC) of the World Ocean. The latitudes of zero wind stress curl position exerts a strong control on the distribution of overturning between basins in the Northern Hemisphere. A southward wind shift results in a stronger Atlantic THC and enhanced stratification in the North Pacific, whereas a northward wind shift leads to a significantly reduced Atlantic THC and the development of vigorous sinking (up to 1500m depth) in the North Pacific. In other words, the Atlantic dominance of the meridional overturning circulation depends on the position of the zero wind stress curl over the Southern Ocean in our experiments. This position has a direct influence on the surface salinity contrast between the Pacific and the Atlantic, which is then further amplified by changes in the distribution of Northern Hemisphere sinking between these basins. Our results show that the northward location of the SWW stress maximum inferred for the last glacial period may have contributed to significantly reduced NADW formation during this period, and perhaps an enhanced and deeper North Pacific THC. Also, a more poleward location of the SWW stress maximum in the current warming climate may entail stronger salinity stratification of the North Pacific.
1. Introduction

The geometry of the world ocean is characterised by zonal boundaries interrupted only at the latitudes of the Drake Passage (DP). This semi-compartmental distribution of water allows the development of distinct thermocline properties in each basin. In particular, thermocline water of the Atlantic Ocean is more saline than its Pacific counterpart (e.g. Levitus 1982). This remarkable feature is fundamental to the ocean’s thermohaline circulation (e.g. Gordon 1986; Seidov and Haupt 2002), and is thought to arise from net evaporation in the Atlantic (Warren 1983) and the thermohaline circulation (THC) itself (Manabe and Stouffer 1988). Exchange of thermocline water between basins is controlled by the Antarctic Circumpolar Current (ACC), a mighty current that is strongly linked with the Southern Hemisphere (SH) subpolar westerly winds (SWWs). The location of the fronts at its northern boundary controls the warm saline influence of Indian Ocean thermocline water due the Agulhas retroflection and the shedding of Agulhas Rings into the Atlantic (Sijp and England 2007; de Ruijter 1982). Also, the influence of cool fresh water (FW) originating from the Drake Passage (DP) depends on the latitudinal extent of the ACC. Indeed, de Ruijter (1982) show that the presence of the Agulhas Leakage, and therefore the Atlantic salinity budget (Gordon 1986; Weijer et al. 1999), depends critically on the latitude of the suptropical front and the ACC. Also, the penetration of cool fresh water originating from the DP into the Atlantic acts as a freshening influence (Rintoul 1991), and the relative importance of the so-called “warm water route” and “cold water route” into the Atlantic dominates the horizontal salinity exchange of the Atlantic thermocline at 30° S.
The dependence of the ACC core on the position of the SWW maximum, and the importance of this current for inter-basin watermass exchange led Sijp and England (2007) to use an intermediate complexity model to examine the effect of an equatorward shift of the SWWs on the subtropical thermocline. They find that the latitude of zero wind stress curl controls the relative influence of fresh water originating from the DP and saline water originating from the Indian Ocean on Atlantic thermocline water. A northward wind shift results in a reduction of the Agulhas Leakage into the Atlantic.

Proxy records infer a more northward location of the SWWs (e.g. Ledru et al. 2005; Kaiser et al. 2005; Lamy et al. 2003) and the ACC (Hebbeln et al. 2002; Mohtadi and Hebbeln 2004; Lamy et al. 2003; Kaiser et al. 2005), by up to 5°-6° latitude, during glacial periods. In contrast, the warming climate of today exhibits a poleward contraction of the SWWs (Das 1956; Thresher 2002; Thompson and Solomon 2000). Toggweiler et al. (2006) conjecture a feedback between the carbon cycle, global temperature and the position of the SWWs whereby cooler climates correspond to a more northward location of the SWWs. Williams and Bryan (2006) use an idealized model to show that a 3° C global cooling can cause an equatorward shift in the peak westerly wind stress position of 7° in latitude without substantial changes in amplitude. Based on the re-appearance of a certain foraminifera species in the Atlantic, Berger and Wefer (1996) speculate that the Agulhas Leakage was absent during glacial times due to a more northward location of the subtropical front (Howard and Prell 1992), leading to fresher Atlantic surface salinity and reduced NADW formation. Weijer et al. (2002) find that a reduction in Agulhas Leakage into the Atlantic in a coarse resolution model leads to a modest reduction in NADW formation.
Toggweiler and Samuels (1993) and Toggweiler and Samuels (1995) were the first to examine the effect of the strength of the Southern Hemisphere westerlies on Northern Hemisphere overturning. They proposed that the rate of NADW formation is largely dictated by the winds at the latitudes of Drake Passage through the so-called 'Drake Passage effect’. At this latitude, the westerlies produce a northward Ekman transport of around 17 Sv that may only be replenished by geostrophic flow at depths below the Drake Passage sill, where NADW resides. Rahmstorf and England (1997) later pointed out that heat loss over the North Atlantic remains an important driver for deepwater formation, modulating the influence of the winds. Note that while Toggweiler and Samuels (1993) and Toggweiler and Samuels (1995) examine the effect of the magnitude of the winds, we explore changes in the latitude of the maximum wind belt.

Sijp and England (2007) show that a 6° latitude northward shift in the latitude of zero wind stress curl over the Southern Ocean (SO) entails a 3 Sv reduction in NADW formation due changes in inter-basin salinity exchange through the SO. However, the main focus of this study was on the thermocline changes, and only one latitude shift was considered. The present study extends on this by considering a suite of latitude shifts at 2° increments ranging from a 6° poleward, through to an 8° equatorward shift. We thus focus our attention on the dependence of the THC on the position of the SWWs in general.

Apart from a response in NADW due to wind shifts over the Southern Ocean, we might expect additional changes in the North Pacific. This is because the more saline conditions in the Indian and Pacific Oceans arising from a more northward location of the SWWs could
lead to the initiation of a vigorous North Pacific THC, and therefore further decrease the rate
of production of NADW. The general sensitivity of NADW and the North Pacific THC over
a wide range of positive and negative displacements of the SWWs has not been examined.
This is one of the goals of the present study.

Here, we systematically examine NADW formation and the North Pacific THC as a function
of the latitude of zero wind stress curl over the SO in an intermediate complexity model. We
find that the rate of NADW formation depends on the position of the SWWs, whereby an
increasingly northward location corresponds with increasingly reduced NADW formation.
This effect is reinforced by a strong response in the North Pacific, whereby a more northward
location of the SWWs causes significantly enhanced and deeper North Pacific THC.

2. The Model and Experimental Design

This study employs the University of Victoria Intermediate Complexity Coupled Model de-
scribed in detail in Weaver et al. (2001), which comprises a global ocean general circulation
model (GFDL MOM Version 2.2, Pacanowski 1995) coupled to a simplified atmospheric
model and a dynamic-thermodynamic sea-ice model. A global domain is used with hori-
zontal resolution of 3.6° longitude by 1.8° latitude in each model component. While air-sea
heat and freshwater fluxes evolve freely in the model, a non-interactive wind field is em-
ployed. The wind forcing is taken from the NCEP/NCAR reanalysis fields (Kalnay et al.
1996), averaged over the period 1958-1997 to form a seasonal cycle from the monthly fields.
Fresh water fluxes between the ocean and the atmosphere are determined by evaporation and precipitation, while river run-off and changes in sea-ice volume also affect oceanic salinity. Moisture transport in the atmosphere occurs by way of advection and diffusion. The atmosphere employs a spatially varying moisture diffusion coefficient that attains maximum values in the mid latitudes of the southern hemisphere. Precipitation occurs when relative humidity exceeds a threshold value. The atmospheric model also diffuses heat. There are 19 vertical levels in the ocean model. To model vertical mixing, a horizontally uniform diffusivity that increases with depth is employed, taking a value of $0.3 \text{ cm}^2/\text{s}$ at the surface and increasing to $1.3 \text{ cm}^2/\text{s}$ at the bottom. In the ocean, isopycnal mixing is implemented after Redi (1982), and eddy-induced advection after Gent and McWilliams (1990). We set the atmospheric $CO_2$ concentration to the pre-industrial level of 280ppm.

To examine the effect of a series of displacements of the SWWs, we have taken the standard NCEP wind field of the model and applied a wind shift to the entire field, tapering it back to the original field outside the latitudes of the southern hemisphere westerlies, as shown in Figure 1 for +/- 6° latitude shifts. This amounts to adding a quasi-sinusoidal anomaly to the original wind field to create a local shift in the winds; similar to Oke and England (2004). For simplicity, we only consider the effect of a change in direct momentum transfer to the ocean associated with a wind shift. Thus, the wind shift is not applied to the model sea-ice, evaporation, or moisture advection. We ran the model to equilibrium without a wind shift for 4000 years from idealized initial conditions to obtain a control experiment, denoted $S_0$. Similarly, we obtained steady states where an equatorward wind displacement $\delta_w$ of -6°,-4°,-2°,0°, 2°, 4°,6° and 8° is applied. The average latitude of zero wind stress curl in the SO
is 53.1°S in \( S_0 \). We denote the experiments according to the latitudinal wind displacement applied, whereby \( S_{-2} \) denotes a 2° poleward shift, and \( S_2 \) a 2° shift to the north. We conduct one additional experiment, denoted NAFW, wherein the wind stress is held fixed, as in \( S_0 \), but fresh water fluxes are altered in the North Atlantic. This additional experiment is described in context below.

3. Results

All results shown in this paper are derived from the final steady-state at 4000 years for all experiments. Figure 2 shows the Atlantic meridional overturning streamfunction (annual mean) for the control experiment \( S_0 \) and the experiments where the SWWs are shifted equatorward and poleward by 6° of latitude. The equatorward wind shift in \( S_6 \) causes significantly enhanced North Pacific overturning (compare Fig. 2a with c), whereby the negligible shallow overturning cell of 3.7 Sv is increased to a 10.5 Sv cell extending to around 1500m depth. Also, there is a 5.1 Sv reduction in NADW formation (compare Fig. 2b with d), from 20.1 Sv in \( S_0 \) to 15.0 Sv in \( S_6 \). Thus, a northward shift of the SWWs causes a seesaw-like behaviour of NH sinking whereby sinking in the NA is reduced and sinking in the North Pacific is enhanced. This is due to a decrease in the salinity contrast (see Fig. 6a) between the Indo/Pacific and the Atlantic, caused directly by the northward wind shift in \( S_6 \), and amplified by THC changes. This result is also described briefly by Sijp and England (2007), who found that a northward migration of the ACC associated with the wind shift results mainly from a decrease in the Agulhas Leakage of saline thermocline water from the Indian Ocean into
the Atlantic. This change also leads to a cooling of the Atlantic and the Indian Ocean sector of the Southern Ocean (Fig. 6c), and a warming of the North Pacific associated with invigorated deep overturning there. An opposite response occurs in experiment $S_{-6}$, where the SWWs are shifted poleward by 6° latitude (Fig. 2 e,f). In this poleward wind shift case, freshening and a modest cooling of the Indian and Pacific Oceans coincides with warmer and more saline conditions in the Atlantic (Fig. 6). The higher salinity contrast between the Pacific and the Atlantic drives only a 1 Sv increase in NADW in this experiment, and a slight reduction in the already small overturning in the North Pacific (Fig. 2 e). The freshening in the North Pacific under the poleward wind shift in $S_{-6}$ is shallow (Figure not shown), and therefore represents an increased salinity stratification there, reinforcing the fresh water cap that inhibits deep water formation in the North Pacific.

The 5.1 Sv NADW reduction in the equatorward shift experiment $S_6$ has a direct effect on the North Pacific THC by way of the inter-basin see-saw effect proposed by Saenko et al. (2004), whereby a reduction in NADW formation leads to an enhanced North Pacific THC. To get a sense of the direct contribution of this 5.1 Sv decrease in NADW on the increase in the North Pacific THC seen in $S_6$, we conduct an additional experiment denoted NAFW where FW is added to the North Atlantic so as to achieve a 5 Sv reduction in NADW formation upon equilibration. This FW flux is compensated everywhere else in the world ocean, while the wind stress is held fixed as in $S_0$. NADW formation in NAFW slows to 15.2 Sv, and the North Pacific THC increases to only 6.1 Sv. This indicates that a significant enhancement in the North Pacific THC is derived directly from the equatorward wind shift in $S_6$, independent of NADW changes, as North Pacific sinking occurs at a rate of 10.5 Sv.
in that experiment. This increase and deepening in the North Pacific THC likely contributes further to the reduction in NADW formation in $S_6$. Against this, Sijp and England (2007) find a 3 Sv decrease in NADW formation in their equatorward wind shift experiment, whereby a response in the North Pacific is suppressed. This indicates that the direct effect of the wind-shift on NADW formation (by altering the Atlantic salinity budget) and the indirect effect (via the North Pacific THC) each contribute to NADW reduction by a comparable degree.

The direct influence of the wind shift on North Pacific overturning can be understood when considering the effect of the position of the SH westerlies on the depth of the mode water isopycnals. Sijp and England (2007) suppress NP sinking, yet they find that changes in Ekman pumping arising from an equatorward shift of the SH westerlies leads to deeper intermediate water isopycnals throughout the entire Pacific (see their Fig. 12). This teleconnection increases the available potential energy for overturning in the Pacific, but not the Atlantic. Similarly, the effect of deepening isopycnals that outcrop in the subpolar regions of the Northern Hemisphere is described by Toggweiler and Samuels (1998) for the North Atlantic, who find that an enhanced ACC causes a deepening of the isopycnals that outcrop there, allowing sinking to occur in the presence of warmer ambient water. This sharpened contrast facilitates deep sinking.

Figure 4 shows the vertical profile of globally averaged temperature (T) and salinity (S) difference from control $S_0$ for $S_{-4}$, NAFW and $S_6$. An equatorward wind shift leads to a vertical redistribution of salt from the deep ocean to the ventilated thermocline, including intermediate waters. The remarkable agreement between the salinity profiles of NAFW and
shows that it is the freshening of the NADW formation sites and NADW reduction that is responsible for the vertical redistribution of salt in S$_6$ (Fig. 4a). Conversely, a poleward wind shift leads to an increased global salinity stratification in experiment S$_{-4}$. This is due to more saline conditions at the NADW formation sites and a 1.0 Sv increase in NADW production in S$_{-4}$. The equatorward wind shift in S$_6$ leads to a warming of the ocean interior (Fig. 4b), whereas the $4^\circ$ poleward shift in S$_{-4}$ leads to a global-mean cooling of the ocean at depths below the surface mixed layer. Temperature at the depths ventilated by mode and intermediate water (500-1000m depth) and the bottom ocean (below 3500m depth) are most sensitive to the wind shift. The vertical temperature change profile of NAFW differs markedly from S$_6$, indicating that different processes are responsible for changes in temperature and salinity in S$_6$.

These results suggest that NADW formation, the North Pacific THC, the Agulhas Leakage, the salinity contrast between the Pacific and the Atlantic and the global vertical salinity contrast are functions of the position of the zero wind stress curl over the Southern Ocean. To show this, Figure 5 shows these variables as a function of the applied displacement ($\delta_w$) of the SWWs. The formation of NADW decreases with increasing wind stress displacement $\delta_w$, and vice versa. NADW sinking rates range from 21.2 Sv (a 1.0 Sv increase) in S$_{-6}$ to 13.5 Sv (a 6.6 Sv decrease) in S$_8$ (Fig. 5a). In contrast, the North Pacific THC increases markedly in S$_8$, to reach 13.5 Sv, coincidentally matching the rate of NADW production in S$_8$. THC changes are strongest for positive (northward) $\delta_w$, and weaker for negative values of $\delta_w$. This is indicated by the steeper slope of the NADW and NPDW curves to the north of the present day position. In other words, if the winds are displaced to the south from their northernmost
position in our experiments (8 °), the associated THC changes become small, or “saturated”, once the present day SWW position is reached. The inter-basin salinity contrast decreases with increasing wind displacement $\delta_w$. Both NADW formation rates and the interbasin salinity contrast are closely linked, whereby a reduced contrast corresponds to reduced NADW formation (Fig. 5a, also see Seidov and Haupt 2002). The Agulhas Leakage (Fig. 5b) decreases with increasing $\delta_w$, due to an encroachment of the ACC on the Cape of Good Hope. Unlike previous studies, this result is derived from a parameter sensitivity analysis in relation to a range of wind shift magnitudes. A stronger Agulhas Leakage corresponds to a stronger inflow of warm saline Indian Ocean water into the Atlantic, causing this basin to become more saline. This corresponds to an enhanced salinity contrast between the Pacific and Atlantic, and more vigorous NADW formation. In contrast, the North Pacific THC increases with increasing $\delta_w$ (Fig. 5c). This is due to more saline conditions in the North Pacific, directly forced by the wind shift, and the THC see-saw effect derived from reduced NADW formation. The vertical salinity contrast also increases with increasing equatorward wind shift, due to decreasing NADW production as winds move to the north. The redistribution of salt from the deep ocean to the thermocline of the Indian and Pacific Oceans stimulates and deepens the North Pacific THC. Passive tracer experiments reveal that AABW is reduced by approximately 50 percent in $S_6$, and increased by approximately 24 percent in $S_{-4}$ (Figure not shown).

By Agulhas Leakage we refer to the water transported from the Indian Ocean to the Atlantic by the mean flow in the model, as eddies are not resolved. We derive this value from the barotropic streamlines connecting the subtropical gyres of the South Atlantic and the In-
dian Ocean. Although eddies constitute an important component of the observed Agulhas Leakage, this transport may also include a mean flow component (de Ruijter et al. 1999). In addition, the eddy-induced tracer transports are parameterized by the isopycnal diffusion and isopycnal thickness diffusion in the model.

To examine the influence of the Agulhas leakage more closely, we now examine the relative contributions of changes in Agulhas leakage and the Falkland/ Malvinas current to the total horizontal transport across 30°S in the upper 300m of the Atlantic. Figure 6 shows the time evolution of the change in total salt budget terms of the upper 300m in the Atlantic and the change in the meridional salt flux in the western half and the eastern half of the Atlantic across 30°S in response to an equatorward wind shift. By approximation, we assume that the salt flux across 30°S in the western half of the Atlantic is influenced by the Brazil-Malvinas confluence, and the flux in the eastern half is influenced by Agulhas leakage. After one hundred years, most of the surface freshening in the Atlantic results from a reduction in net horizontal salt transport across 30°S in the east Atlantic (Fig. 6a). The reduction in net horizontal salt transport across 30°S is mainly driven by a reduction in the eastern Atlantic (Fig. 6b), suggesting that the Atlantic freshening is initiated by a reduction in Agulhas leakage.
4. Summary and Conclusions

We find that the stratification of the North Pacific depends on the location of the SWWs in a coupled climate model. A northward shift of the SWWs causes the onset of a vigorous and deeper North Pacific THC extending to 1500m depth and reduced NADW formation. Despite this challenge to Atlantic dominance over the meridional overturning circulation, the deepest watermass derived from the Northern Hemisphere still arises from North Atlantic sinking. In contrast, a poleward wind shift causes enhanced salinity stratification in the North Pacific, an increase in salinity contrast between the Atlantic and the Pacific and moderately enhanced NADW formation. We also show a dependence of Agulhas Leakage strength on the position of the SWWs. A northward displacement of the SWWs acts to reduce the leakage, whereas a southward wind shift increases the leakage. In effect, the position of the SWWs regulates the degree of connectedness of the joint subtropical “supergyre” of the Indian and Atlantic Ocean (de Ruijter 1982). The surface salinity contrast between the Pacific and the Atlantic depends on the latitude of zero wind stress curl over the Southern Ocean, whereby a southward location corresponds to an increased contrast and vice versa. The change in THC in response to a wind shift is reinforced by a local salinity feedback operating inside each basin, whereby enhanced sinking corresponds to more saline conditions at the sinking regions, due to increased poleward salt transport from the subtropics (see also Bryan 1986).

Further enhancement of THC changes occurs due to the Pacific-Atlantic see-saw (Saenko et al. 2004), with an opposite effect of the wind shift on NADW and the North Pacific THC. In particular, a northward shift enhances and deepens the North Pacific THC, and inhibits
NADW. Subsequent to this, the North Pacific THC enhancement and deepening further decreases NADW and the salinity contrast between the Pacific and the Atlantic, and vice versa. This results in a 5.1 Sv NADW reduction under an equatorward wind shift of 6° in latitude. NADW reduction is only 3 Sv under a 6° shift in Sijp and England (2007). This difference with the present study arises in the absence of a response in the North Pacific THC. This lack of response in the North Pacific is due to their model configuration, wherein an artificial fixed FW flux is applied to the North Pacific to suppress deep sinking there. This shows that in the presence of a response in the North Pacific, the inter-basin see-saw, and the direct effect of the wind shift inside the Atlantic, contribute in similar degrees to the NADW reduction.

Similarly, we find that local effects inside the Indian/Pacific, and the see-saw effect contribute to changes in the North Pacific THC at comparable magnitudes. The strongest impact occurs under an 8° wind shift -the maximum value examined in our experiments-, wherein overturning rates are equally distributed among the Pacific and the Atlantic (although the Atlantic THC extends to greater depth), taking sinking rates of 13.5 Sv for both NADW and the North Pacific THC. The control of the SWW position on the stability of the North Pacific stratification allows a breakdown of the stable stratification there for a sufficiently northward location of the Southern Ocean winds in the model we use. The threshold for this event is expected to vary among models, as it is determined by local factors such as runoff in the North Pacific and global factors such as large-scale atmospheric moisture transport. Notably, the THC response is not linear: changes are strongest for a displacement of the winds to the north of their present day position, and weaker for a poleward shift.

Our results show that there may be a connection between the lower values of NADW forma-
tion inferred for glacial periods (e.g. Boyle and Keigwin 1987; Boyle 1995; Rutberg et al. 2000), and the more northward location of the SWWs cited in paleoclimatic reconstructions. We find a stronger response of NADW than previous studies that only focus on a reduction of the Agulhas Leakage (Weijer et al. 2002), as inferred for glacial periods (Peeters et al. 2004). Previous studies do not take into account the effect of a concurrent onset of the North Pacific THC in response to a more northward location of the SWWs. This mechanism may have been responsible for significantly reduced NADW formation during glacial periods. At the higher end of the estimates, Moreno et al. (1999) suggest a northward SWW displacement of 9° of latitude. To compare, our experiment with an 8° shift in latitude results in a 33 percent reduction in NADW formation, if a North Pacific THC response is present. Interestingly, the enhanced North Pacific overturning in our poleward wind shift experiments is consistent with the relatively vigorously circulating vertically expanded equivalent of present day North Pacific Intermediate Water inferred by Galbraith et al. (2007), Keigwin (1998) and Kennett and Ingram (1995) for the LGM. Our results suggest the inferred northerly location of the SWWs as a contributing factor to inferred coeval Pacific overturning during the LGM. Finally, all our results are obtained for changes in winds only applied to the oceanic surface flux of momentum. The direct effect of winds on buoyancy forcing (e.g. the effect on evaporation) remains unchanged in all experiments. This allows us to isolate the direct effect of the position of zero wind stress curl on the ocean circulation, and on ocean properties. Notably, as ocean properties respond, particularly SST, this will alter the surface buoyancy fluxes. In this regard, our experiments include important oceanic feedbacks, as argued for in Rahmstorf and England (1997).
Delworth et al. (2006) analyze two recent versions, CM2.1 and CM2.0, of the global coupled climate model developed at the Geophysical Fluid Dynamics Laboratory (GFDL). In these state-of-the-art climate models, the mean position of maximum zonal wind stress around 50°S is simulated to be more equatorward in CM2.0 than in CM2.1 (see their Fig. 1). No deep water formation occurs in CM2.0, despite the equatorward shifted SH westerlies. This is likely because in their model the North Pacific is too fresh compared to observations. There is also an equatorward displacement of the CM2.0 winds in the NH, leading to a reduction in the latitudinal extent of the subtropical gyre in the North Pacific. The associated reduced transport of salt and heat to the sub-polar North Pacific leaves this region too cold and fresh, suppressing overturning there.

We also re-ran our experiments in a cooler model climate obtained by reducing the atmospheric concentration of CO₂ to 200 ppm, and obtain similar results. In contrast to the above, the projected poleward wind shift in the warming climate of today is expected to lead to an enhanced salinity contrast between the Atlantic and the Pacific, contribute to NADW stability and enhance salinity stratification in the North Pacific. Also, the greater sensitivity of NH overturning to an equatorward wind shift compared to a poleward wind shift could suggest that if the glacial SH westerlies were indeed situated further towards the equator, these cooler climates may have been more sensitive to variations in the SH westerlies than the present-day climate.

In conclusion, the out of phase response in the Pacific and Atlantic to shifts in the SWWs shows a strong control of the latitude of zero wind stress curl over the distribution of thermo-
haline sinking in the Northern Hemisphere. In particular, a northward shift tilts the Pacific-Atlantic see-saw in favour of the North Pacific THC. The opposite occurs under a poleward wind shift. This amplified response to a change in salinity contrast between the Atlantic and the Pacific arising from the wind shift is a result of mutual reinforcement by the anomalies in NADW and the North Pacific THC. Our results show a hitherto unexplored control of the SWWs over the global thermohaline circulation that may have been active during glacial periods, and that may have implications for our knowledge of past and future warm climate states.

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References


List of Figures

1  Zonal mean showing the zonal component of the wind stress ($\tau_x$) for $S_0$ (solid), $S_6$ (dashed) and $S_{-6}$ (dotted). No wind shift is applied north of 20 °S. 26

2  Steady state annual-mean meridional overturning streamfunction (annual mean), with Indian and Pacific overturning in the left column (a,c), and Atlantic overturning in the right column (b,d). The first row (a,b) shows $S_0$, the second row (c,d) shows $S_6$ and the bottom row (e,f) shows $S_{-6}$. Values are given in Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ sec}^{-1}$). ................................................................. 27

3  Steady state difference in sea surface salinity (SSS) for (a) $S_6-S_0$ and (b) $S_{-6}-S_0$ and difference in sea surface temperature (SST) for (c) $S_6-S_0$ and (d) $S_{-6}-S_0$. ................................................................. 28

4  Steady state vertical profile of globally-averaged difference in (a) temperature (°C) and (b) salinity (psu) from control $S_0$ for $S_{-6}$ (blue), experiment NAFW (black) and $S_6$ (red). ................................................................. 29
Overturning and salinity diagnostics as a function of the applied displacement of the SWWs: (a) NADW formation (Sv, solid) and surface salinity contrast between the Pacific and the Atlantic Ocean (psu, dashed) between latitudes 30°S and 30°N, (b) Agulhas Leakage (Sv) and (c) NPIW formation (Sv, solid) and global vertical salinity contrast (psu, dashed) between the surface and the bottom. All transport values are given in Sv (1 Sv = 10^6 m^3 sec^{-1}).

Time evolution of the change in total salt budget of the upper 300m ocean in the Atlantic (a) and (b) the change in the meridional salt flux in the western half (blue) and the eastern half (black) of the Atlantic across 30 °S in the upper 300m in response to an equatorward wind shift. Here, the Atlantic has been divided in two equal halves, and the total flux is shown in red. Budget fluxes (a) are decomposed according to transport process: isopycnal diffusion (iso), convection and diapycnal diffusion (conv, Kv), vertical advection (w), meridional advection (adv y) and surface fluxes (stf). Changes in Atlantic salt flux are calculated with respect to time 0 and in response to an equatorward wind shift of 6°latitude initiated at time 0.
Figure 1: Zonal mean showing the zonal component of the wind stress ($\tau_x$) for $S_0$ (solid), $S_6$ (dashed) and $S_{-6}$ (dotted). No wind shift is applied north of 20°S.
Figure 2: Steady state annual-mean meridional overturning streamfunction (annual mean), with Indian and Pacific overturning in the left column (a,c), and Atlantic overturning in the right column (b,d). The first row (a,b) shows $S_0$, the second row (c,d) shows $S_6$ and the bottom row (e,f) shows $S_{-6}$. Values are given in Sv ($1\text{ Sv} = 10^6 \text{ m}^3 \text{ sec}^{-1}$).
Figure 3: Steady state difference in sea surface salinity (SSS) for (a) $S_6 - S_0$ and (b) $S_{-6} - S_0$ and difference in sea surface temperature (SST) for (c) $S_6 - S_0$ and (d) $S_{-6} - S_0$. 
Figure 4: Steady state vertical profile of globally-averaged difference in (a) temperature (°C) and (b) salinity (psu) from control $S_0$ for $S_{-6}$ (blue), experiment NAFW (black) and $S_6$ (red).
Figure 5: Overturning and salinity diagnostics as a function of the applied displacement of the SWWs: (a) NADW formation (Sv, solid) and surface salinity contrast between the Pacific and the Atlantic Ocean (psu, dashed) between latitudes 30°S and 30°N, (b) Agulhas Leakage (Sv) and (c) NPIW formation (Sv, solid) and global vertical salinity contrast (psu, dashed) between the surface and the bottom. All transport values are given in Sv (1 Sv = 10^6 m^3 sec^-1).
Figure 6: Time evolution of (a) the change in total salt budget of the upper 300m in the Atlantic and (b) the change in the meridional salt flux in the western half (blue) and the eastern half (black) of the Atlantic across 30°S in the upper 300m in response to an equatorward wind shift. In (b), the Atlantic has been divided in two equal halves, and the total flux is shown in red. Budget fluxes in (a) are decomposed according to transport process: isopycncal diffusion (iso), convection and diapycnal diffusion (conv, Kv), vertical advection (w), meridional advection (adv y) and surface fluxes (stf). Changes in Atlantic salt flux are calculated with respect to time t=0 and in response to an equatorward wind shift of 6°latitude initiated at time t=0.