What is driving the fast warming rate of the Southern Hemisphere midlatitude ocean?

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Abstract— **Significant warming has occurred across many ocean basins over the past 50-years. This has been observed through an increase in the oceanic heat content (OHC) which describes the depth integrated temperature change. The OHC trend displays a maximum value (ie. warming) in the midlatitude band stretching from 35°-50°S. However, this warming pattern is unable to be accounted for by changes in local heat fluxes. It is associated with a Sverdrup-like response to poleward strengthening winds and a poleward shift of the Southern Hemisphere supergyre and Antarctic Circumpolar Current of almost 1°. The heat required for this midlatitude warming is mostly derived from surface heat fluxes from south of 50°S, which is advected northward by enhanced Ekman transport induced by the poleward-strengthening winds. These results highlight the relationship between winds and surface heat fluxes in Southern Hemisphere midlatitude oceans.**

I. Introduction

A significant warming has occurred across the world's oceans, particularly across the Southern Ocean [1] throughout the latter part of the 20th century and into the 21st century. The increase in the oceanic heat content (OHC), a good measure of the warming, displays considerable spatial differences, with maximum values in the midlatitude band around 35°-50°S as shown in Fig. 1 of [2]. The consensus is that the warming is likely due to anthropogenic forcing, however volcanic and anthropogenic aerosols may have masked an even stronger warming signal, as shown in climate modelling studies [3], [4].

The relative importance of wind and surface heat flux changes in driving the warming pattern are the subject of much research. For example, a poleward shift in the midlatitude gyre circulation is associated with an upward trend of the southern annular mode, which has been driven by an increase in greenhouse gases and stratospheric ozone depletion [5]. However, recent Argo float measurements infer a downward and southward displacement of isopycnals, which suggests that wind forcing alone may not be the only driver of the warming [6].

A number of studies have relied upon ocean-only and fully coupled climate models to evaluate the role of wind [7], [8]. Imposing a wind in a coupled model framework generates changes in surface heat fluxes because these fluxes respond to both the wind and the wind-forced changes in sea surface temperature (SST). However, as isolating the impacts of wind and surface flux components can be quite difficult using surface heat flux outputs from climate model experiments as part of the Third Coupled Model Intercomparison Project (CMIP3) allows a simple heat budget to be undertaken in the Southern Hemisphere (SH) midlatitude oceans.

II. Model experiments

Outputs from one simulation of the late 20th century climate from 17 CMIP3 models are utilized (see Table I). All 17 models incorporate forcing from anthropogenic aerosols (direct) and increasing CO_2, however only 7 models include volcanic aerosols (Table I, right column). As an aside models with volcanic aerosols have been shown to lead to smaller trends in global OHC [9], [10], however this is not the focus on this study. As many climate models suffer from spurious drift in their subsurface variables the corresponding pre-industrial control runs are required to correct these deviations. The 17 models were selected for this study due to their availability of a control run to remove drift. Monthly anomalies and trends of full-depth temperature, wind, and surface heat fluxes are constructed for the late 20th century (1951-1999). The net surface heat fluxes are constructed from latent and sensible heat fluxes, and from the longwave and shortwave radiation fluxes. The observed oceanic temperature trends, of which the OHC is calculated from (defined as the integrated temperature over the upper 2000m) is taken from [11].

III. Poleward shift in SH oceanic circulation

A popular hypothesis for the fast oceanic warming of the SH midlatitude band is the poleward shift in the SH circulation, which include the supergyre and Antarctic Circumpolar Current (ACC) as proposed in [1] and [12]. To test this climatological zonally-averaged temperatures from the observed and the 17-model ensemble are shifted poleward by 0.5° and 0.75°, respectively and are then compared to observed (1960-2007) and modelled (1951-1999) trends in zonally-averaged temperature. It is this difference between the shifted and the original field which reflects the impact of such a shift on ocean temperatures.

The observed trend in SH oceanic temperatures is shown in Fig. 1a, which describes a general surface warming of over 0.3°C (for 48 years), and a large warming in the 35°-50°S band extending down to 1500m. A subsurface cooling

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of -0.3°C in the subtropics is also evident at around 500m. The impact of a poleward shift in climatological observed temperatures by 0.5° and 0.75° is shown in Figs. 1b and c, respectively. While the 0.75° shift produces too strong a warming, both shift magnitudes feature a warming centred around 43°S, consistent with the observed trend, and a subtropical subsurface cooling that increases with the extent of the shift. The model-ensemble trends show a somewhat weaker response in the subtropics with very little cooling and a general warming extending to the equator (Fig. 1d). This may be due to the fact that many models do not include volcanic aerosols (Table I, right column). The shifts in climatological temperature in the models (Figs. 1e and f) mimic the observed pattern from the shifts with a greater magnitude of warming and cooling for a 0.75° shift as opposed for a 0.5° shift.

Do models with volcanic forcing produce a more realistic temperature trend structure? Fig. 2a and b highlight the difference in temperature trend patterns between two CMIP3 model ensembles, one which has a volcanic aerosol forcing and one that does not. The volcanic aerosol ensemble (Fig. 2a) shows a better matching structure to the observed pattern (Fig. 1a) with cooling in the subtropics between depths of 500-1000m. The non-volcanic ensemble (Fig. 2b) shows virtually no cooling, but a strong surface-to-subsurface warming, consistent with the observed and modeled shifts in climatological temperature. However, this does not exclude the possibility of anthropogenic aerosols as a potential forcing factor, although targeted modeling experiments that include the indirect aerosol effect overestimate the cooling effect, resulting in weaker globally-averaged OHC trends than what has been observed [10].

The shift patterns are indicative of wind-induced changes in the SH circulation. Previously it has been shown using a CMIP3 model ensemble that a reduction in the zonal wind stress in the SH midlatitudes with an increase in the higher latitudes have pushed the zero wind stress curl line (edge of the gyre circulation) poleward by about 0.7° [13], [2]. The trend in wind-stress curl from the model-ensemble is shown in Fig. 4, along with the zonally-averaged OHC trend for the SH. The positive curl changes at around 42-43°S signifies the point where Ekman convergence, generated from the decreases (increases) in westerlies from the north (south). It is here that the zonally-averaged OHC trends are the largest in the SH (right panel, Fig. 4) implying that large-scale wind changes have altered the location of Ekman convergence and thus the overall warming of the SH oceans.

Wind changes impact the subsurface ocean via Rossby wave propagation, where heat is distributed slowly (rapidly) to a shallower (deeper) depth off the western (eastern) side of the South American continent. This eventually leads to a steady-state Sverdrup balance, which is confirmed using a wind-driven oceanic model [14], which produces a steric height change along the SH midlatitude band consistent with the OHC trends, as in Fig. 3 of [2]. Thus, due to the poleward shift in the gyre circulation as a result of wind changes the SH midlatitude band has become effective in storing heat.

IV. Surface heat fluxes in the SH

Is the heat gain to the SH midlatitude band a consequence of local surface heat flux changes, or due to a cross-hemispheric heat transfer from the Northern Hemisphere (NH)? Modelling studies such as [15] propose the opposite; that is, a heat exchange from the SH to the NH is possible as a response to the greater aerosol-induced cooling in NH. In fact, an all-model average heat flux change over the NH is smaller than that needed for an increase in the NH ocean heat content [2], excluding the possibility of a southward cross-hemispheric heat transport. In the last section a poleward shift of between 0.5 and 0.7° was proposed as the most likely scenario to account for the ocean temperature trend pattern in the SH. As this process is not adiabatic and requires a heat source to the ocean, this source must come from the surface heat fluxes in the SH.

The change in surface heat fluxes from the model-ensemble is presented in Fig. 4, which shows a mismatch between the latitude of the maximum flux change and location of the greatest top-to-bottom warming trend (Fig. 4, right panel). Also shown in Fig. 4 are the implied OHC changes, calculated from the surface heat fluxes (see equation 1 in [2]), over the 35°-50°S and 50°S southward latitude bands. The northward heat transport, which is calculated as the difference between the actual OHC changes (see equation 2 in [2]) and the heat gain from the atmosphere, is also indicated (vertical arrows in Fig. 4). The results show that about 50% of heat accumulated south of 50°S is advected northwards; very little heat transfer occurs north of the fast warming band (35°S).

The process responsible for this northward heat transfer is the wind-induced Ekman transport, allowing upwelled water at the surface to gain heat before sinking (and moving equatorward) along the steep isopycnal surfaces to form Antarctic Intermediate Mode Water. The models can actually simulate this process quite well [2], however the model-ensemble OHC change is weaker north of 35°S, possibly indicating that the models underestimate how much heat is derived from north of 35°S. Thus, for a poleward shift to occur in this midlatitude band a heat source, in the form of surface heat fluxes, is required from the high latitudes. As a consequence of the heat flux changes, a wind-driven poleward shift allows for Ekman transport to drive this heat northwards where it sinks along the steep isopycnal surfaces. These processes, driven by increases in greenhouse gases [13] and through the impact of stratospheric ozone depletion [12] have all contributed to the fast warming of the SH midlatitude band.

V. Conclusion

The heat required for the fast, deep warming in the 35°-50°S midlatitude band is largely derived from the surface heat fluxes south of 50°S, where the surface flux into the ocean is far larger than that of the midlatitude band. The heat south of 50°S is advected northward by an enhanced northward Ekman transport induced by the poleward-strengthening winds and penetrates northward and downward along the outcropping isopycnals to a depth of over 1000 m. These results highlight

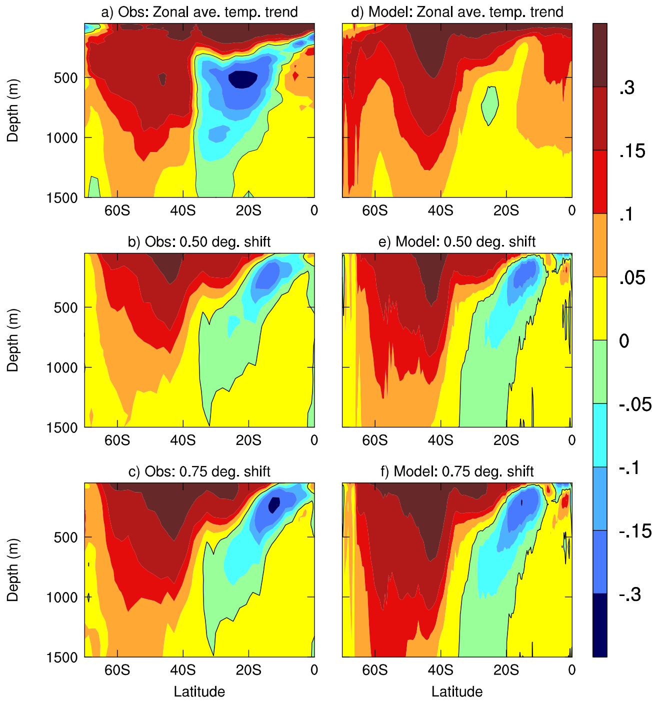

Fig. 1. (a) Total trends in the observed zonally-averaged temperature (°C per 48 years) over the 1960-2007 period, and zonal-mean temperature changes (°C) resulting from (b) 0.5° and (c) 0.75° poleward shifts in the observed climatology. (d)-(f) Same as the observed, but for the 17-model ensemble over the 1951-1999 period (trend units are °C per 49 years).

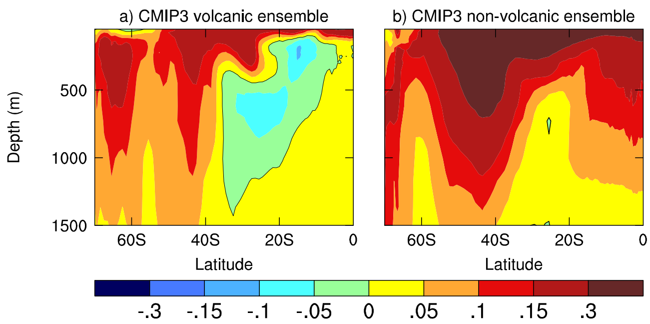

Fig. 2. (a) Total trends in modelled zonally-averaged temperature for 1951-1999 (°C per 49 years) from CMIP3 model ensembles that include (a) volcanic aerosol forcings and (b) no volcanic aerosol forcings.

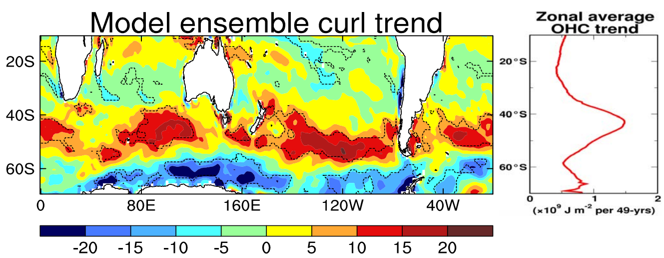

Fig. 3. All-model ensemble-mean total trend over 1951-1999 for (left) wind stress curl ($\times\ 10^{-3}$ N m^{-3} per 49-years) and (right) zonally-averaged OHC ($\times\ 10^{9}$ J m^{-2} per 49-years). Significant trends at the 95% confidence level for the wind stress curl are shown within the dashed lines.

TABLE I

COUPLED CLIMATE MODELS USED IN THIS STUDY

Model	**Institution (country)**	**Volcanic aerosols?**
BCCR-BCM2.0	Bjerknes Centre for Climate Research (Norway)	-
CCCMA CGCM3.1(T47)	Centre for Climate Modeling and Analysis (Canada)	-
CCCMA CGCM3.1(T63)	Centre for Climate Modeling and Analysis (Canada)	-
CNRM-CM3	Centre National de Recherches Météorologiques (France)	-
CSIRO Mk3.0	CSIRO Marine and Atmospheric Research (Australia)	-
CSIRO Mk3.5	CSIRO Marine and Atmospheric Research (Australia)	-
GFDL CM2.0	Geophysical Fluid Dynamics Laboratory (United States)	Y
GFDL CM2.1	Geophysical Fluid Dynamics Laboratory (United States)	Y
GISS-AOM	Goddard Institute for Space Studies (United States)	-
FGOALS-g1.0	Institute of Atmospheric Physics (China)	-
IPSL CM4	Institute Pierre Simon Laplace (France)	-
MIROC3.2(medres)	Center for Climate System Research (Japan)	Y
MIROC3.2(hires)	Center for Climate System Research (Japan)	Y
ECHO-G	Meteorological Institute of the University of Bonn (Germany/Korea)	Y
MRI CGCM2.3.2	Meteorological Research Institute (Japan)	Y
CCSM3	National Center for Atmospheric Research (United States)	Y
UKMO HadCM3	Hadley Centre for Climate Prediction and Research (United Kingdom)	-

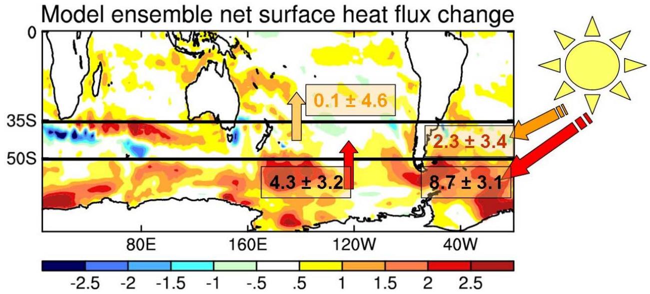

Fig. 4. All-model ensemble-mean net heat flux changes for 1951-1999 (Wm^{-2} per 49-years). Also shown are the implied OHC changes ($\times$ 10^{22} J) from the surface heat fluxes (values next to striped arrows), and the northward heat transfer changes (values next to vertical arrows), based on the difference between the model simulated OHC trends and the implied OHC trends from the surface heat fluxes. The standard deviation of intermodel spread is indicated as the uncertainty value.

the relationship between the wind and surface heat flux response in this region. However, as none of the 'current-crop' of CMIP3 models resolve eddies and given that eddy fluxes could offset the increase in the northward Ekman transport, the heat source for the fast, deep warming in the SH midlatitude band remains a contentious point of research.

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