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LETTER

Impact of ocean model resolution on understanding the delayed warming of the Southern Ocean

Simge I Bilgen and Ben P Kirtman

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL USA

E-mail: sbilgen@rsmas.miami.edu

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Abstract

Currently available historical climate change simulations indicate a relatively delayed Southern Ocean warming, particularly poleward of the Antarctic Circumpolar Current (ACC) compared much of the rest of the globe. However, even this simulated delayed warming is inconsistent with observational estimates which show a cooling trend poleward of the ACC for the period 1979–2014. A fully coupled model run at two resolutions, i.e. ocean eddy parameterized and ocean eddy resolving, driven by historical and fixed CO2 concentration is used to investigate forced trends south of the ACC. We analyze the 1961–2005 Southern Ocean surface and upper ocean temperatures trends simulated by the model and observational estimates to understand the observed trends in the SO. At both resolutions, the models successfully reproduce the observed warming response for the northern flank of the ACC. The eddy resolving simulations, however, are able to reproduce the observed near Antarctic cooling in contrast to the eddy parameterized simulation which shows a warming trend. The cause of this inconsistency between the observations and the ocean eddy parameterized climate models is still a matter of debate, and we show here results that suggest resolved ocean meso-scale processes may be an integral part of capturing the observed trends in the Southern Ocean.

1. Introduction

Over the last few decades, the Southern Ocean (SO) around Antarctica has been cooling, in striking contrast to the rapid warming observed in the Arctic, and even the relatively slow warming equatorward of the Antarctic Circumpolar Current (ACC). There has been a modest but statistically notable increase in sea ice cover concurrently with near surface cooling in the SO (poleward of the ACC) from the beginning of the satellite observations in 1979 through 2014 (Fan *et al* 2014, Armour and Bitz 2015, Armour *et al* 2016, Jones *et al* 2016). These negative sea surface temperature (SST) trends in the SO are, naively, at odds with greenhouse-gas induced warming over much of the World's Oceans in recent decades. Interestingly, these trends in the SO are not reproduced by the historical simulations with state-of-the-art coupled models participating in the Climate Modeling Intercomparison Project phase 5 (CMIP5) possibly because of the models' deficiencies introduced by, as hypothesized here, missing ocean dynamics associated with meso-scale processes. The cause of this inconsistency between the observations and the climate models is still a matter of debate, however, we show here results that suggest resolved ocean meso-scale processes may be an integral part of observed trends in the SO.

The SO is one of the most poorly sampled and highly variable regions of the global ocean (Gille 2008) emphasizing the complication of quantifying forced trends. Recent studies show that stratospheric ozone depletion (Sigmond *et al* 2011, Solomon *et al* 2015), greenhouse gas forcing (Fyfe 2015) unforced atmospheric variability (Kostov *et al* 2018), and natural variability (Polvani and Smith 2013; Zhang 2019) are the potential drivers responsible for the observed SO SST and sea-ice trends in recent decades. Strong internal variability is also linked to the SO SST (Swart *et al* 2018), which may explain a considerable portion of the observed change (Swart and Fyfe 2013, Polvani and Smith 2013, Lovenduski *et al* 2015). Indeed, Polvani and Smith (2013) and Zunz *et al* (2013) relate the discrepancy between observations and CMIP5 model simulations to the natural variability which may play a significant role in those historical observed trends of the SO. Zhang *et al* (2019) also concentrated on the potential physical drivers of historical SO trends, and show that these trends are consistent with a particular phase of the natural multidecadal variability of SO deep convection as derived from climate model simulations. In other words, they find natural multidecadal variability involving SO convection may have contributed vigorously to the observed trends. Moreover, in the SO, the background circulation upwells deep water masses unmodified by GHG forcing and reduce the rate of surface warming (Marshall *et al* 2015, Armour *et al* 2016). However, most of the CMIP5 experiments produce a gradual positive SO temperature response to GHG forcing, but they contradict on the magnitude of this regional response with some models warming much faster than others, and considerably faster than the observational estimates (Marshall *et al* 2014).

One of the most significant recent climate trends in the SO has been strengthening and poleward contraction of the circumpolar westerlies (Screen *et al* 2009). This trend corresponds to a shift of the Southern Annular Mode (SAM) index toward an progressively positive phase. Several studies suggest that this trend is largely human induced (Thompson and Solomon 2002, Gillett and Thompson 2003, Marshall *et al* 2004), and over the same time period these studies argue for relatively large warming north of the ACC and delayed warming or even cooling to the south.

A possible explanation for the cooling trend south of the ACC comes from modeling and observation studies which demonstrate that a strengthening and poleward shift of the westerlies induce, within weeks, a negative SST response around Antarctica (Hall and Visbeck 2002, Russell *et al* 2006, Fyfe *et al* 2007, Ciasto and Thompson 2008, Marshall *et al* 2014, Purich *et al* 2016, Kostov *et al* 2018). This rapid response is evidence that anomalous equatorward transport of colder water contributes to the cooling response south of ACC (Ferreira *et al* 2015, Kostov *et al* 2017), and GCM's consistently show this negative SST response on time scales shorter than 2 years (Kostov *et al* 2018).

Can the above fast response explaining the observed cooling trend south of the ACC? Ferreira *et al* (2015) show that the SO response to poleward intensification of winds is timescale-dependent. An atmospheric pattern analogous to a positive SAM pattern triggers fast cooling followed by slow warming around Antarctica. On the longer time scales, the circumpolar upwelling and equatorward transport of surface waters by the SO's residual mean meridional overturning circulation (MOC; Armour *et al* 2016), and the increase in mesoscale eddy activity causes enhanced poleward heat transport which drives the warming south of the ACC (Screen *et al* 2009). While these previous studies provide the potential drivers or mechanisms of the SO SST trends, they do not explain the historical observed cooling of the SO over the most recent few decades (figure 1(a)).

A key question is, why recent studies with the eddy-parameterized simulations show that the SO poleward of the ACC has been warming, albeit delayed with respect other parts of the globe, whereas observational estimates indicate a relative cooling trend. Within eddy-parameterized simulations, delayed warming of the SO surface is seen to be fundamental response of the ocean to greenhouse gas induce forcing (Armour and Bitz 2015). We argue that while climate models seem to be adequately representing the delayed SO warming equatorward of the ACC, the eddy parametrized (CMIP5) models are not able to reproduce the recent period of surface cooling near Antarctic. The causes of the eddy parameterized models' inability to reproduce the observed 1979–2014 SO cooling south of the ACC is still a matter of debate. Here we hypothesize that ocean eddy processes are critical in terms of capturing the correct response to trends in the atmospheric forcing, and that to reproduce the cooling trend, we need ocean eddy resolving models.

The current literature provides compelling evidence suggesting that meso-scale processes will considerably impact the simulation of the climate, although multi-decade to century length experiments in eddy-resolving regime are, by now, very limited in number and has not been fully tested to date (Kirtman *et al* 2012). For example, Delworth *et al* (2012) find improvements in many aspects of the climate with increasing resolution, though subsurface ocean temperature drift may be intensified in the eddy-permitting regime when eddy heat transports are neither properly resolved nor parameterized. Kirtman *et al* (2012) found evidence of stronger forcing of the atmosphere by SST variability arising from ocean dynamics eddy-resolving simulations in the extra-tropics, and in the SO in particular. (Putrasahan *et al* 2016) established a connection between interannual variability of Agulhas region SST that is associated with ENSO via a tropical-subtropical oceanic teleconnection that was only present in the ocean eddy resolving simulations. Cheng *et al* (2016), develop a strategy, using a Lagrangian particle-tracking model, to quantify Agulhas leakage in an ocean-eddy-resolving climate model showing that resolving mesoscale features in the Agulhas Current System is necessary to form retroflection and constrain leakage realistically.

Previous modeling studies have been limited in terms of accounting for the multiple diverse processes that take place in the SO. For example, (Böning *et al* 2008) show observational evidence indicating that isopycnal slopes in the SO have not changed over the last few decades despite the positive trends in

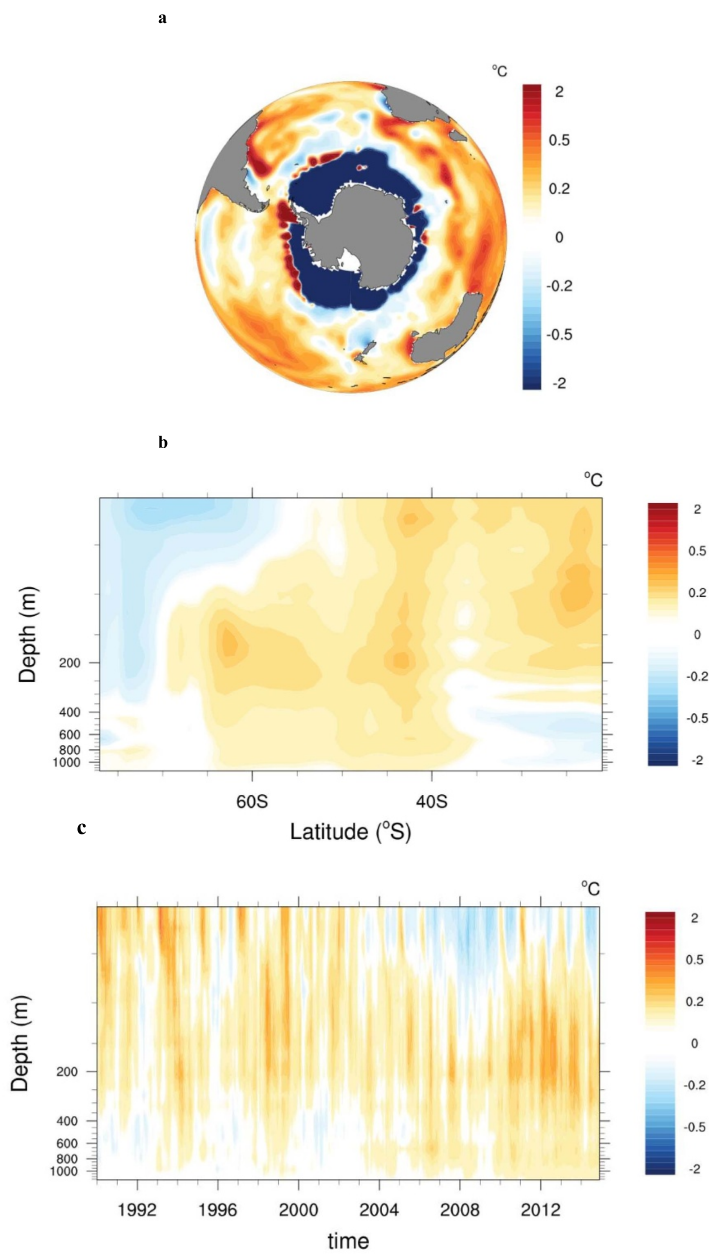

Figure 1. Temperature dataset over 1979–2014 (a) SST anomaly based on HadISST data set; **(b)** Zonal-mean vertical structure of ocean potential temperature anomaly from EN4 data set. **(c)** Time evolution of ocean potential temperature anomaly from EN4 data set (20°S–90°S).

the SAM. Their results are consistent with the eddy compensation phenomenon and support the possibility that unresolved eddy processes that are missing in typical ocean eddy parameterized climate simulations can significantly modulate anomalies in the wind-driven circulation. In other words, these ocean eddy parameterized models that lack the ability to simulate realistic eddy compensation overestimate the magnitude of the anomalous residual upwelling under a poleward intensification of the westerlies. This may be a source of SO warming bias in the response of low-resolution GCMs to SAM. Resolved ocean meso-scale processes may be an integral part of capturing the correct response to trends in the atmospheric forcing, and that to reduce the SO warming bias between observations and the model studies an eddy-resolving ocean component is needed.

The ability of eddy-resolving fully coupled climate models to simulate changes accurately in the SO, a region where the dynamics are substantially modulated by ocean meso-scale eddies, has received limited attention. Eddy parameterized models (order 1 degree), however, have been used to understand the response to greenhouse gases in the SO. For example, Armour *et al* (2016) considered the ensemble of CMIP5 models driven by historical radiative forcing and global ocean with the ocean-only simulations with constant radiative forcing. Remarkably, both the ocean-only GCM and ensembles of CMIP5 models capture the principal features of enhanced warming within the zonal bands along ACC's northern flank but the SST cooling to the south is not reproduced. The results presented here provide support for the hypothesis that the cooling around the Antarctic is intimately connected with ocean mesoscale processes that cannot be captured by ocean eddy parameterized models typically used for IPCC simulations. We note that the approach outlined here is far short of providing a complete explanation of delayed warming. Our goal is to suggest ocean mesoscale features are likely to be important. How this mechanism works is left for a further more detailed study.

2. Data and model experiments

To quantify historical changes in the SO SST, we use *in situ* and adjusted satellite-derived SSTs dataset based on the Met Office Hadley Centre's Global Sea Ice and Sea Surface Temperature (HadISST), and ocean state estimate based on the Met Office Hadley Center's quality controlled subsurface ocean temperature dataset EN4 version 1.1 for the period 1961–2005.

Four numerical experiments are reported here. The first experiment (i.e. eddy parameterized control, referred to as fixed CO_2) is a 500 year simulation with atmospheric composition corresponding to 2000 levels using a 1° atmosphere and land components coupled to ocean and sea-ice components with zonal resolution of 1°. The second experiment is based on the six ensemble members of comprehensive GCM (CCSM4) participating in CMIP5 driven by historical radiative forcing for the period of 1940 to 2005 using the same ocean, ice, atmosphere and land models resolution with the first experiment (i.e. eddy parameterized control, referred to as climate of 20th century). The third experiment (i.e. eddy-resolving transient, referred to as climate of 20th century) is a 75 year (after spin up) 20th century transient simulations with observational estimates of atmospheric composition and employing the 0.1° ocean and sea-ice components models. The atmosphere and land model resolutions are also increased to 0.5°. To be clear, we are not arguing that nothing is to be gained by increasing the atmospheric resolution, however the focus of the results presented here is on role of resolved ocean eddies in SO climate trends. The model configuration in the fourth experiment is identical to that used in a third experiment but forced by atmospheric composition corresponding to 2000 level (CO_2 forcing is fixed at 368.9 ppm) i.e. that is an eddy resolving 70 year control simulation (referred to as fixed CO_2). The system is initialized from a high-resolution simulation with a fixed year 2000 CO_2 forcing (368.9 ppm). It is integrated for 10 years with a fixed year 1940 CO_2 level to reduce the initialization shock before observed twentieth-century CO_2 forcing is applied. Further details about spin-up process, model configurations and validation can be found in Kirtman *et al* (2012) and Cheng *et al* (2016).

The experiments discussed above are summarized in table 1. For all experiments, from coarse to high resolution simulations, the difference between the transient response and the constant composition control runs, computed as the 1961–2005 mean, is examined to show the mean change over the SO for the south of 20°S.

3. Results

3.1. SO trends in observational estimates

For comparison with the model simulations, our analysis of the observational estimates covers the period 1961–2005, which both *in situ* and adjusted satellite-derived SSTs are available, and ocean temperature measurements have reasonable coverage within the SO, based on the HadISST (Rayner *et al* 2003) and EN4 quality controlled ocean data version 1.1 (Good *et al* 2013), respectively. The observed zonal-mean temperature and SST change over the SO, computed as 1990–2014 minus 1961–1985 mean, is dominated by a region of warming centered near 45°S that extends from the surface to over 1000 m (figure 1). Rapid surface warming occurs in zonal bands along the northern flank of the ACC, with notable cooling to the south (figure 1(a)). The observed SST patterns are mirrored by the response in zonal-mean ocean temperature (figure 1(b)); the maximum warming occurs in the vicinity of the ACC (40°–50°S)—consistent with the observed trends since the 1950s as Gille (2008) and Rhein (2013). Figure 1(c) shows the time evolution of the zonal and meridional (0–80°S) mean of temperature with a maximum depth of 1000 m. The structure of ocean cooling is robust across surface and near-surface especially for last two decades but there is a notable warming trend for the subsurface temperature from 200 m to 1000 m for the same period. The ocean state estimate suggest that (figure 1(b)) anomalous transport of heat by the MOC has enhanced the warming north of the ACC and reduced warming to the south as it was shown by Armour *et al* (2016). However, subsurface temperature observations are limited in accuracy and spatial coverage (with no observations available under sea ice) over the SO, especially south of the ACC (Gille 2008, Durack *et al* 2014). To further understand the SO trends, we turn our focus to numerical climate models.

3.2. SO response in ocean eddy parameterized models

We first consider the difference between the eddy parameterized CCSM4 simulations participating in phase 5 of the Coupled Model Intercomparison Project (CMIP5) driven by historical radiative forcing and the equilibrium simulations with atmospheric composition corresponding to 2000 level.

Table 1. Experiment design.

Model/Obs.	Atm	Ocn	Experiment	Period	Name
CCSM4 (CMIP5)	1°	1°	Climate of the 20th century	1941–2005	LRC
CCSM4	1°	1°	Atmospheric composition corresponding to 2000	500 yrs	LRC (CTRL)
CCSM4	0.5°	0.1°	Climate of the 20th century	1941–2014	HRC07
CCSM4	0.5°	0.1°	Atmospheric composition corresponding to 2000	1948–2018	HRC08 & HRC09
Hadley Center			HadISST (for SST) EN4 (for temperature with depth)	1871–2018	Observational Estimates

The eddy parameterized simulations broadly capture the observed changes over 1961–2005 with the bands of rapid warming along the ACC's northern flank; nevertheless the model simulates considerably more SO SST warming than is observed (figure 2(a)). The spatial pattern of SHF trends broadly opposes the pattern of SST trends (figures 2(a) and (b)), the regions that have warmed strongly have increasingly taken up heat to the ocean, which as showed by Armour *et al* (2016, their figure 2(b)). The SST and SHF patterns from the eddy parameterized model are consistent with their multi model ensemble of CMIP5 models, and both broadly capture the same signals. Armour *et al* (2016) also show that the poleward of 50 ° S, accounts for 60% of surface heat uptake, whereas only 23% is heat storage. This indicates, less than one third of the anomalous heat taken up at the surface is stored locally; the majority is transported northwards, as seen by figure 2(c) with a robust increase in northward meridional heat transport (MHT) across the ACC (especially between 55° S to 20° S). These eddy parameterized simulations robustly capture the substantial warming in the vicinity of the ACC; however, to the south there is notable inconsistent temperature response in the first 1 km compared to the observational estimates (compare figures 2(d) with 1(b)). These eddy parameterized simulations produce excessive warming throughout the depth of SO for the whole time period (compare figures 2(e) with 1(c)).

3.3. SO response in ocean eddy resolving model

In this section, the ocean eddy resolving simulations are examined in much the same way as the ocean eddy parameterized simulations. In particular, we examine the same region for the same time period with the ocean eddy resolving simulations. To obtain an estimate of the forced response, the ensembles of perturbed control time series are subtracted from the 20th century transient simulations with observational estimates of atmospheric compositions (figure 3) using the same averaging periods as in the ocean eddy permitting simulations (figure 2). The ocean eddy resolving coupled model captures the principal features of the observational estimates; enhanced warming within the zonal bands along ACC's northern flank similar to the ocean eddy parameterized model (figure 3(a)). The warming north of the ACC in the eddy resolving simulation is notably weaker than the eddy parameterized model (figures 2(a) vs. 3(a)) and in better agreement with the observational estimates (figure 1(a)).

Overall, regions that have warmed strongly have increasingly lost heat to the atmosphere, whereas regions that have warmed less (or cooled) have increased heat up-take (figures 3(a) and (b)). These SHF patterns have been driven by air-sea temperature gradients: anomalous surface heat loss has mainly occurred in the vicinity of ACC and to the north, where the ocean surface has warmed more rapidly than the atmosphere (see also Armour *et al* 2016). Conversely, anomalous surface heat uptake has occurred south of the ACC, where the atmosphere has warmed more rapidly than the ocean surface. Notably, the spatial patterns of SHF in the eddy resolving simulation and in the eddy parameterized simulation are largely opposed over the SO. However, even the eddy resolving simulation has some inconsistencies for some regions: for instance, the south of South Africa where Agulhas retroflection region warms strongly, anomalous surface heat uptake from the atmosphere occurs. On the other side, to the west where strong warming continues, that region increasingly lost heat to the atmosphere as expected. Generally, the eddy resolving model agrees more favorably with current SHF observational estimates based on turbulent fluxes of sensible heat and latent heat estimated from bulk formula by Armour *et al* (2016; see their figure 1(b)).

The large heat taken up poleward of 50°S in the eddy parameterized simulations is transported northward (figure 2(c)) by residual-mean meridional current and there is net heat transport convergence

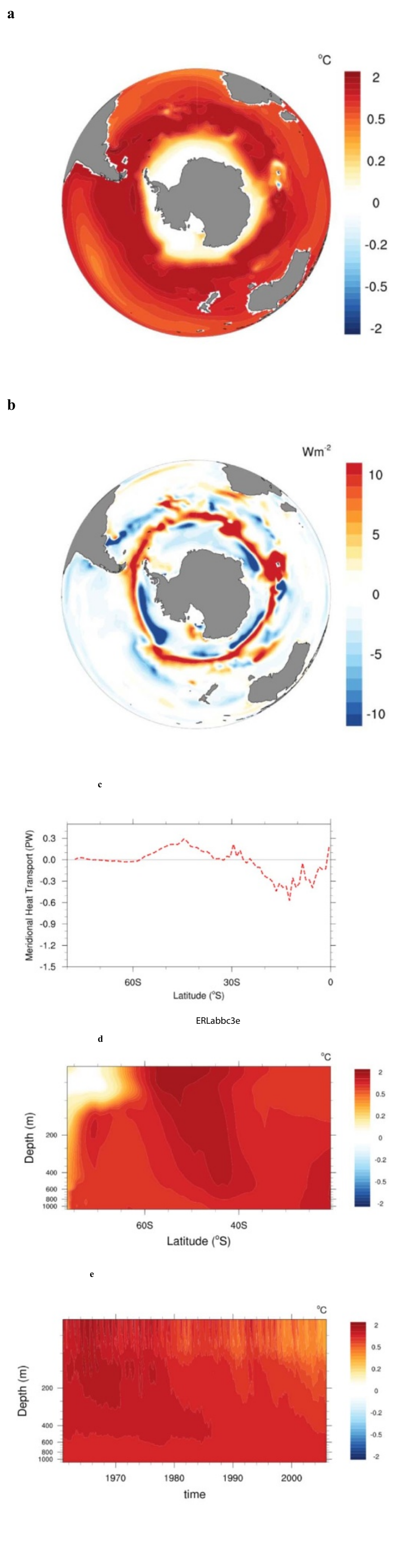

Figure 2. Eddy parametrized model response to CO_2 forcing over 1961–2005 (**a**) Annual mean SST anomalies (**b**) Total SHF, including SW (positive into ocean) (**c**) Anomalous MHT (**d**) Zonal-mean vertical structure of ocean potential temperature anomaly (**e**) Time evolution of ocean potential temperature anomaly (20° S–90° S).

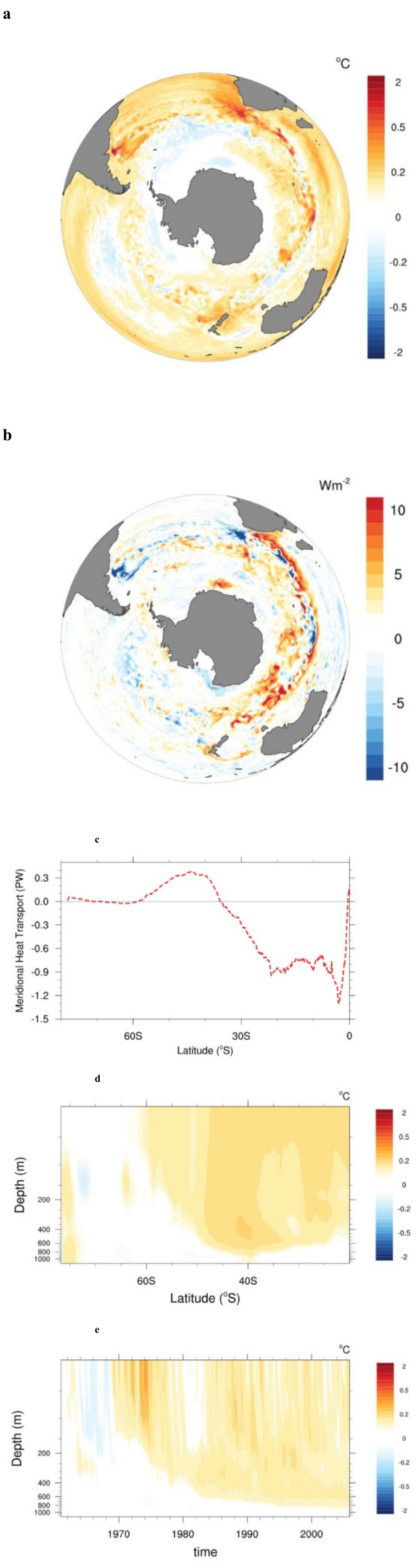

Figure 3. Eddy resolving model response to CO_2 forcing over 1961–2005 (**a**) Annual mean SST anomalies (**b**) Total SHF, including SW (positive into ocean) (**c**) Anomalous MHT (d) Zonal-mean vertical structure of ocean potential temperature anomaly (**e**) Time evolution of ocean potential temperature anomaly (20° S–90° S).

equatorward of the ACC (see also Armour *et al* 2016; see their figure 2(d)). However, both in the eddy parameterized and eddy resolving simulations, there is also southward heat transport starting from 25°S to the equator which a significant difference between the previous eddy parameterized modelling studies including the Armour *et al* (2016), and our study. Also, in the eddy resolving simulation, the southward transport starting from 30°S to the equator (figure 3(c)) is substantially stronger compared to eddy parameterized case.

In terms of comparing the forced temperature response as a function of depth (figures 2(d) vs. 3(d)), to the south of the ACC the similarity between the ocean eddy resolving and eddy parameterized simulations breaks down. There is surface and subsurface cooling poleward of the ACC and warming within the northern flank in the eddy resolving simulations that is qualitatively similar to the observational estimates, whereas in the eddy parameterized simulations the warming is strikingly stronger. While the ocean cooling is somewhat weaker near Antarctica when the eddies are resolved, the patterns of the observed temperature change are robustly captured by the finer resolution simulations (figure 3(d)).

Comparing the time evolution of the subsurface temperature response in the eddy resolving simulations and the observations (figures 3(e) vs. 1(c)) show clear differences, yet the qualitative character is consistent, and it is considerably different compared to the eddy parameterized simulation (figure 2(e)). This is readily apparent in terms of the magnitude of the temperature response over time, and also how this response in distributed in the vertical. This is, perhaps, most notable near the surface (0–200 m) from 1970 to 2000 and in the subsurface (400–1000 m) response from 1961–1995.

Overall, the differences in the structure and character of the temperature changes near Antarctic are considerably different between the ocean eddy parameterized simulation and the ocean eddy resolving simulation. Indeed, the ocean eddy resolving results are in better qualitative agreement with observational estimates and are distinct from previously identified modelling studies in the SO. The near Antarctic cooling is, thus a general feature of how the real ocean responds to GHG forcing—independent of variations in radiative forcing and feedbacks, or trends in atmospheric circulation, and we are only able to capture this response when we resolve ocean mesoscale features (i.e. eddies, boundary currents, fronts).

4. Summary and concluding remarks

Currently available historical climate change simulations indicate a relatively delayed SO warming, particularly poleward of the ACC compared much of the rest of the globe. However, this delayed warming is inconsistent with the satellite record which shows a significant cooling trend especially for the poleward of the ACC from 1979 through 2014 (Fan *et al* 2014, Armour and Bitz 2015, Armour *et al* 2016, Jones *et al* 2016). We assume that the eddies are important for the recent SO trend (until 2014). Therefore, we show here results that suggest resolved ocean meso-scale processes may be an integral part of capturing the observed cooling trends in the SO. We note, however, after 2014 there appears to be a well-defined warming trend suggesting that the SO is beginning to respond the increased radiative forcing associated with increases in CO_2. Hopefully, the results presented here will help understand why the SO response is delayed with respect to much of the rest of the globe.

The objective of the numerical experiments presented here was to show the potential importance of resolved ocean meso-scale processes in capturing the observed negative SST trend (1961–2005) poleward of the ACC. To demonstrate the importance of resolved ocean eddies, coupled model simulations at two resolutions, i.e. ocean eddy parameterized and ocean eddy resolving, driven by historical and fixed CO_2 concentration were diagnosed in the SO and compared to observational estimates. In our study, we emphasize the GHG forcing response in terms the observed SO SST trends instead of other possible potential drivers of the historical SO temperature trends. The other forcing (e.g. ozone) which contribute to the historical trends of the SO is left for a subsequent study.

The differences between the eddy parameterized and eddy resolving response to changing GHG forcing can be summarized as follows:

- The eddy parameterized simulations (coarse resolution) are ubiquitously warmer than the eddy resolving (high-resolution) simulations. The larger differences are poleward of the ACC with notable decreases of sea SSTs.
- The SST front associated with ACC is better resolved in the eddy resolving simulations compared to the eddy parameterized simulations.
- The ocean eddy parameterized simulations broadly capture the observed changes over 1961–2005 with the bands of rapid warming along the ACC's northern flank; nevertheless the response is considerably stronger than the observational estimates indicate.
- In the high resolution experiments, rapid surface warming occurs in zonal bands along the northern flank of the ACC, with notable cooling to the south similar to the observations.
- The spatial pattern of SHF trends in the eddy-parameterized model broadly opposes the pattern of SST trends (figures 2(a) and (b)). However, in the eddy resolving model, we see that regions that have warmed strongly have increasingly lost heat to

the atmosphere, whereas regions that have warmed less (or cooled) have increasing taken up heat (figures 3(a) and (b)).

- The eddy parameterized model and eddy resolving model show similar MHT patterns across the ACC region; however there is a considerable reduction in southward transport in eddy parameterized model.

While we attribute most of the differences between the eddy parameterized and eddy permitting model to resolved and un-resolved relatively ocean mesoscale processes, we acknowledge that the test in not completely clean in the sense that there are changes in changes in the coupled models that are required when increasing the resolution. For instance, the eddy parameterized model has parameterized boundary processes (Fox-Kemper *et al* 2011) that are not included in the eddy permitting model, and the ocean bottom topography and the atmosphere topography are different just to name a few. We also note key difference in the mesoscale coupling and their impact on the air-sea fluxes (e.g. Frenger *et al* 2013, Bishop *et al* 2017) and eddy-damping effects (Renault *et al* 2016), which affects the eddy kinetic energy. All of these processes may play important roles in the differences noted here. Essentially, we view all these processes, among others, as part of resolving eddy mesoscale processes, and we have not determined which process is dominant in adequately capturing ocean heat uptake and surface trends. We seek to document that ocean mesoscales processes are important factors that are not captured in the bulk of IPCC class simulations.

Within the ocean modeling community, it is mostly assumed that high resolution simulations should mainly produce finer results than the low resolution simulations (Fox-Kemper 2019), and in general increasing resolution show systematic improvements in many aspects of the climate (Delworth *et al* 2012, Kirtman *et al* 2012). While this is clearly the case for surface currents and internal variability, (Chassignet 2020) state that greatly enhanced horizontal resolution does not necessarily deliver unambiguous bias improvement in in all regions for all models. They show the biases in the low-resolution simulations are familiar and their gross features—position, strength, and variability of western boundary currents, equatorial currents, ACC—are significantly improved in the high-resolution models. However, despite the fact that the high-resolution models 'resolve" most of these features, the improvements in temperature or salinity are inconsistent among the different model families and some regions show increased bias over their low-resolution counterparts. On the other hand, (Chassignet 2020) use not fully coupled models thus, many important feedbacks could be overlooked. Overall we note that we focused on how the resolved eddies impact simulation without any changes to the parametrizations with one modeling family—we take it for granted that significant effort is still required to ensure that inter comparison among different low resolution and high resolution models with fully coupled regime can be further refined to produce improved simulations.'

Finally we note that we focused on how resolved ocean eddies impact the simulation of SO climatic response to increases GHGs. In particular, we noted how the eddy parameterized simulations failed to capture the qualitative nature of the observed response. Based on these results we assert that the delayed SO warming and near Antarctic cooling are thus a general feature of the increased ocean's dynamical response (due to ocean eddies) to GHG forcing—independent of variations in radiative forcing and feedbacks, or trends in atmospheric circulation. The eddy parameterized simulations do not resolve eddies and rely on parameterizations to represent them. Therefore, the ocean eddy parameterized model is missing an important element of the ocean's response to GHG forcing and cannot reproduce the historical observed changes. While the eddy resolved produces a more realistic response, it is by no means perfect and significant effort is still required to ensure that the model with increased resolutions can be further refined to produce improve simulations. We also note that the approach outlined here falls short of providing a complete explanation of the observed cooling of the SO over the most recent few decades. Our findings is to suggest ocean meso-scale features are likely to be important to reproduce the trends. How this mechanism works and how this timescale dependent notable disagreement about the sign of the SST anomaly in the eddy-parameterized and eddy-resolving models resolves are left for a further more detailed study.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iD

Simge I Bilgen https://orcid.org/0000-0002-3534-9793

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