# Mesoscale ocean eddies and climate change over the Southern Ocean


**Sergey Kravtsov[1], Andy Hogg[2], Igor Kamenkovich[3], and John M. Peters[1]**

[1] Department of Mathematics, Atmospheric Sciences Group, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53201

[2] Research School of Earth Sciences, Australian National University [3] RSMAS/MPO, University of Miami


## Introduction

The Southern Ocean is one of the most critical parts of the climate system, but lack of observational constraints and complexity of ocean currents in this region result in its being poorly understood and not well represented in climate models. **We use intermediate-complexity ocean models to interpret recent climate change over the Southern Ocean detected in observations and output of Coupled Model Intercomparison Project phase 3 (CMIP3; Meehl et al. 2007) simulations.**

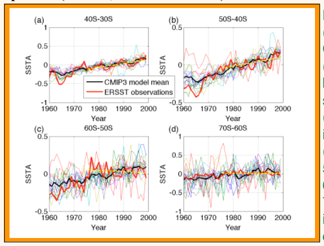


**Fig. 1.** The observed (heavy red line) and CMIP3 simulated (model-mean: heavy black line) sea-surface temperature (SST) (ºC) averaged in four latitude bands: (a) 40º–30ºS; (b) 50º–40ºS; (c) 60º–50ºS; and (d) 70º–60ºS. The individual-model outputs are plotted by light lines. Yellow dashed lines show observed 1975–99 SST trend. Model ensemble mean follows the observed SST changes fairly well.

## Observed and CMIP3 simulated trends

We compute, following Kravtsov and Spannagle (2008), multi-model means of various climatic characteristics across the ensemble of CMIP3's 20-th century simulations and compare them with the corresponding observed time series. **Figure 1** shows such a comparison for the sea-surface temperature (SST) anomalies (relative to 1970–99 climatology) averaged over various latitudinal bands within the Southern Ocean; the observational analysis used ERSST data (Smith et al. 2008). The CMIP-model ensemble-mean SST closely follows the observed time series, with interannual-to-decadal deviations that can easily be interpreted to be due to intrinsic variability present in the observed SST record. On the other hand, there are systematic differences in the observed (ERA-40; Uppala et al. 2005) and simulated sea-level pressure (SLP) trends (**Fig. 2**), presumably due to lack of stratospheric ozone forcing in many of the CMIP3 models considered (Arblaster and Meehl 2006). As a result, the models underestimate, by a factor of 2–5, the observed increase of about 5–10% per decade of the wind stress over the Southern Ocean. **If the simulated wind stress forcing of the ocean is so different from observations, then why is the SST response so similar?**

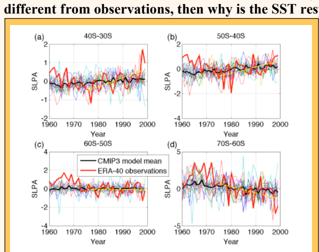


**Fig. 2.** Same as in Fig. 1, but for the sea-level pressure (SLP) (mb) changes over the Southern Ocean. The models much underestimate the amplification of north–south SLP difference and, hence, the resulting increase of winds over the Southern Ocean.

## Effects of increasing winds in an eddy-resolving Southern Ocean model

In recent years, the research into the role of small-scale (~10-km) processes associated with oceanic *mesoscale eddies* in setting up the Southern Ocean's dynamical regime has intensified (Hallberg and Gnanadesikan 2006; Radko and Marshall 2006; Hogg et al. 2008). In particular, modeling evidence suggests that eddies substantially affect the response of the surface and mid-depth oceanic temperatures to changes in the wind forcing associated with human-induced global change (Fyfe et al. 2007).

We studied these effects using the eddy-resolving quasigeostrophic general circulation model (Q-GCM, version 1.3.1) in ocean-interior–mixed-layer configuration used by Hogg et al. (2008); in particular, this configuration included the Southern Ocean's topography. While this model is dynamically idealized in the sense that it does not resolve explicitly the thermodynamics of the Southern Ocean, it is ideally suited for simulation of the ocean circulation's perturbations about the mean state, including those due to nonlinear processes and eddies (see **Fig. 3**, top).

We performed Q-GCM ensemble runs forced by linearly increasing wind-stress forcing and examined the SST trends simulated in these runs. Bottom panel of Fig. 3 shows the dependence of the south–north temperature difference trend on the rate of change of wind-stress forcing. The temperature difference was computed for SSTs zonally averaged between 55º–50ºS and 50º–45ºS (blue line), as well as for the 60º–50º/50º–40ºS SSTs (green line). In all cases, the eddy-induced south–north SST mixing overwhelms other effects (e.g., basin-wide Ekman-advection cooling). For the wind-stress increase of about 7% per decade (in the middle of the observed wind-stress change range), the simulated 60º–50ºS SST rate of change is of about 0.1ºC per decade, **which is alone sufficient to rationalize the observed 0.3ºC difference between the Southern Ocean's SSTs in 60s and 90s** (Fig. 1c).

The nature of the increasing wind-stress effect onto the Southern Ocean's temperature distribution is linked to the Southern Ocean's being in the so-called eddy saturated state (e.g., Hogg et al. 2008), so that increased momentum input transmits directly to the eddy field (i.e., makes currents more variable) rather than increasing long-term time-mean currents. Increased mesoscale turbulence mixes warmer water in the northern part of the Southern Ocean with colder water in the south, thus resulting in the southern warming and northern cooling trends.

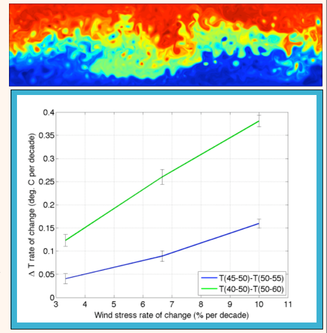


**Fig. 3.** Q-GCM results. Top: Snapshot of the mid-depth potential vorticity from a Q-GCM simulation. Note the presence of realistic frontal features and well developed eddy field. Bottom: Trend in the south–north temperature difference as a function of the magnitude of wind-stress trend. Wind-induced eddy trends alone have magnitude comparable to the observed trends (see Fig. 1).

## Southern Ocean climate change in a coarse-resolution general circulation model

The ocean components of CMIP3 models have coarse resolutions which are insufficient to explicitly simulate the oceanic eddy field; the effects of the latter are parameterized in these models by eddy-diffusion closure schemes of Gent–McWilliams type. Otherwise, however, these models are dynamically much more complete than our idealized eddy-resolving Q-GCM, and are able, among other things, to provide comprehensive description of the Southern Ocean's three-dimensional structure and its response to climate change. What would be the oceanic response of these models to the *observed* intensification of wind over the Southern Ocean (in contrast to a much weaker wind change simulated by these models in coupled settings; see Fig. 2)?

To address this question, we examine a simulation of a global ocean general circulation model (OGCM) forced by the observed 1979–2001 history of daily winds, atmospheric surface temperature and humidity, constant cloud cover, and linearly increasing solar constant to mimic "global warming" radiative effects. The model has a 2º horizontal resolution and parameterizes eddy effects in the ocean interior using Gent-McWilliams scheme. **Figure 4** provides the comparison of the simulated and observed SST trends in the Southern Ocean. The model's entire Southern Ocean is cooling, with cooling rates that exceed or even oppose the observed trends. This cooling can be explained by a combination of increasing northward advective Ekman transport and trends in ocean–atmosphere heat exchange, both tied to increasing winds.

We attempted to better parameterize eddy effects in our OGCM by repeating the above simulation, but adding a 10% per decade linear increase of Gent-McWilliams (GM) eddy diffusivity to model the eddy saturated Southern Ocean. The results shown in Fig. 4 do indicate some slight improvement in the 60º-50ºS band; overall, however, the variable GM coefficient in the ocean interior fails to reproduce the mixing rates simulated by the eddy-resolving model. This is most probably due to lack of explicitly parameterized horizontal eddy-mixing amplification in the OGCM's surface mixed layer.

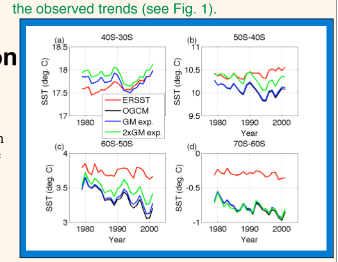


**Fig. 4.** SST trends: observed (red lines) and OGCM simulated subject to the observed wind changes (Fig. 2): (i) control (black lines), (ii) linearly increasing (1% per decade) GM mixing (blue lines), and (iii) linearly increasing (1% per decade) GM mixing, but with the double base GM mixing coefficient (green lines). OGCM's entire Southern Ocean cools with rates exceeding the observed rates. The inclusion of wind-stress dependent eddy diffusion parameterization corrects, to a certain extent, some of the model biases [e.g., green line in (c) is closer to the observed trend (red line)], but still fails to achieve the SST trend magnitudes modeled in an eddy-resolving idealized simulation (Fig. 3).

## Discussion

The results presented here allow us to argue that the similarity of the CMIP3-simulated SST response to the observed one (Fig. 1), despite very different wind forcing (Fig. 2), is due to the models' making two large opposing errors which balance each other. One of the errors associated with model-underestimated wind intensification is caused by the absence of the related surface cooling in the models (Fig. 4). The other, compensating, error, has to do with nonlinear dynamics of ocean-eddy response to the changing wind input (Fig. 3), since these ocean eddies are grossly under-resolved in the current generation of climate general circulation models (GCMs).

We took initial steps in parameterizing the latter effect in a GCM by tying the model's eddy diffusion parameters to wind forcing (Fig. 4). Such parameterizations may lead to better estimates of climate sensitivity to changes in the external forcing. We intend to pursue this line of study in future work.

## References


Arblaster, J. M., and G. A. Meehl, 2006: Contributions of external forcings to Southern Annular Mode trends. *J. Climate*, **19**, 2896–2905.

Fyfe, J. C., et al., 2007: The role of poleward-intensifying winds on Southern Ocean warming. *J. Climate*, **20**, 5391–5400.

Hallberg, R., and A. Gnanadesikan, 2006: The role of eddies in determining the structure and responseof the wnd-driven Southern Hemisphere overturning. *J. Phys. Oceanogr.*, **36**, 2232–2252.

Hogg, A. McC., M. P. Meredith, J. R. Blundell, and C. Wilson, 2008: Eddy heat flux in the Southern Ocean: Response to variable wind forcing. *J. Climate*, **21**, 608–620.

Kravtsov, S., and C. Spannagle, 2008: Multidecadal climate variability in observed and modeled surface temperatures. *J. Climate*, **21**, 1104–1121.

Meehl, G. A., et al., 2007: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Amer. Meteor. Soc.*, **88**, 1383–1394.

Radko, T., and J. Marshall, 2006: The Antarctic Circumpolar Current in three dimensions. *J. Phys. Oceanogr.*, **36**, 651–669.

Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore, 2008: Improvements to NOAA's historical merged land–ocean surface temperature analysis. *J. Climate*, **21**, 2283–2296.

Uppala, S. M., et al., 2005: The ERA-40 re-analysis. *Quart. J. Royal Meteor. Soc.*, **131**, 2961–3012.


## Acknowledgements


This research was supported by the Office of Science (BER), U. S. Department of Energy (DOE) grant DE-FG02-07ER64428, as well as by 2009 UWM RGI grant (SK) and NSF grant OCE-0749723 (IK). We acknowledge modeling groups, PCMDI, and WCRP's WGCM for their roles in making CMIP3 set available, and DOE for this dataset's support.


## For further information

Please contact *kravtsov@uwm.edu*. A PDF-version of this poster can be downloaded from *www.uwm.edu/~kravtsov/downloads/SO_poster.pdf*.

UNIVERSITY of WISCONSIN
UWMILWAUKEE
College of Letters and Science
ATMOSPHERIC SCIENCE
DEPARTMENT OF MATHEMATICAL SCIENCES