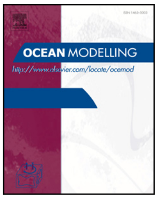
Ocean Modelling 93 (2015) 84–120

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod



Virtual Special Issue
CORE-II

# An assessment of Antarctic Circumpolar Current and Southern Ocean meridional overturning circulation during 1958–2007 in a suite of interannual CORE-II simulations

Riccardo Farneti[a,*], Stephanie M. Downes[b], Stephen M. Griffies[c], Simon J. Marsland[d], Erik Behrens[e], Mats Bentsen[f], Daohua Bi[d], Arne Biastoch[e], Claus Böning[e], Alexandra Bozec[g], Vittorio M. Canuto[h], Eric Chassignet[g], Gokhan Danabasoglu[i], Sergey Danilov[j], Nikolay Diansky[k], Helge Drange[l], Pier Giuseppe Fogli[m], Anatoly Gusev[k], Robert W. Hallberg[c], Armando Howard[h,s], Mehmet Ilicak[f], Thomas Jung[j], Maxwell Kelley[h], William G. Large[i], Anthony Leboissetier[h,n], Matthew Long[i], Jianhua Lu[g], Simona Masina[m,o], Akhilesh Mishra[g], Antonio Navarra[m,o], A.J. George Nurser[p], Lavinia Patara[e], Bonita L. Samuels[c], Dmitry Sidorenko[j], Hiroyuki Tsujino[q], Petteri Uotila[d,r], Qiang Wang[j], Steve G. Yeager[i]

[a] *International Centre for Theoretical Physics (ICTP), Trieste, Italy*
[b] *Research School of Earth Sciences and ARC Centre of Excellence for Climate System Science, Australian National University (ANU), ACT, Australia*
[c] *NOAA Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, NJ, USA*
[d] *Centre for Australian Weather and Climate Research, a partnership between CSIRO and the Bureau of Meteorology, Aspendale, Australia*
[e] *GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany*
[f] *Uni Research Ltd. Bergen, Norway*
[g] *Center for Ocean-Atmospheric Prediction Studies (COAPS), Florida State University, Tallahassee, USA*
[h] *NASA Goddard Institute for Space Studies (GISS), New York, NY, USA*
[i] *National Center for Atmospheric Research (NCAR), Boulder, CO, USA*
[j] *Alfred Wegener Institute (AWI), Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany*
[k] *Institute of Numerical Mathematics, Russian Academy of Sciences, Moscow, Russia*
[l] *University of Bergen, Bergen, Norway*
[m] *Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Bologna, Italy*
[n] *Trinnovim LLC, New York, New York, USA*
[o] *Istituto Nazionale di Geofisica e Vulcanologia (INGV), Bologna, Italy*
[p] *National Oceanography Centre Southampton (NOCS), Southampton, UK*
[q] *Meteorological Research Institute (MRI), Japan Meteorological Agency, Tsukuba, Japan*
[r] *Finnish Meteorological Institute, Helsinki, Finland*
[s] *Medgar Evers College of CUNY, New York, NY, USA*

## ARTICLE INFO

*Article history:*
Received 1 March 2015
Revised 15 June 2015
Accepted 21 July 2015
Available online 30 July 2015

*Keywords:*
Global ocean–sea ice modeling
Model comparisons
Southern Ocean meridional overturning circulation
Antarctic Circumpolar Current
Southern Ocean dynamics

## ABSTRACT

In the framework of the second phase of the Coordinated Ocean-ice Reference Experiments (CORE-II), we present an analysis of the representation of the Antarctic Circumpolar Current (ACC) and Southern Ocean meridional overturning circulation (MOC) in a suite of seventeen global ocean–sea ice models. We focus on the mean, variability and trends of both the ACC and MOC over the 1958–2007 period, and discuss their relationship with the surface forcing. We aim to quantify the degree of eddy saturation and eddy compensation in the models participating in CORE-II, and compare our results with available observations, previous fine-resolution numerical studies and theoretical constraints. Most models show weak ACC transport sensitivity to changes in forcing during the past five decades, and they can be considered to be in an eddy saturated regime. Larger contrasts arise when considering MOC trends, with a majority of models exhibiting significant strengthening of the MOC during the late 20th and early 21st century. Only a few models show a relatively small sensitivity to forcing changes, responding with an intensified eddy-induced circulation that provides

---

* Corresponding author. Tel.: +390402240307.
*E-mail address:* rfarneti@ictp.it (R. Farneti).

http://dx.doi.org/10.1016/j.ocemod.2015.07.009

some degree of eddy compensation, while still showing considerable decadal trends. Both ACC and MOC interannual variabilities are largely controlled by the Southern Annular Mode (SAM). Based on these results, models are clustered into two groups. Models with constant or two-dimensional (horizontal) specification of the eddy-induced advection coefficient $\kappa$ show larger ocean interior decadal trends, larger ACC transport decadal trends and no eddy compensation in the MOC. Eddy-permitting models or models with a three-dimensional time varying $\kappa$ show smaller changes in isopycnal slopes and associated ACC trends, and partial eddy compensation. As previously argued, a constant in time or space $\kappa$ is responsible for a poor representation of mesoscale eddy effects and cannot properly simulate the sensitivity of the ACC and MOC to changing surface forcing. Evidence is given for a larger sensitivity of the MOC as compared to the ACC transport, even when approaching eddy saturation. Future process studies designed for disentangling the role of momentum and buoyancy forcing in driving the ACC and MOC are proposed.

## 1. Introduction

The Southern Ocean's grip on past, present and future global climate has been long recognized (Toggweiler and Samuels, 1995; Russell et al., 2006; Watson and Naveira-Garabato, 2006; Toggweiler et al., 2006; Kuhlbrodt et al., 2007; Toggweiler and Russell, 2008; Marshall and Speer, 2012, to cite a few). The Southern Ocean has a primary influence on the evolution of the Earth's climate and ecosystems. In this region of strongly tilted isopycnals, intermediate, deep, and bottom waters upwell and interact with the atmosphere, exchanging physical and chemical properties (Rintoul and Naveira-Garabato, 2013). Thanks to the large regions of upper ocean water mass formation in the Southern Ocean, this region is responsible for about 40% of the oceanic uptake of anthropogenic carbon dioxide from the atmosphere, and accounts for about 70% of the excess heat that is transferred from the atmosphere into the ocean (Frölicher et al., 2015). The unblocked region circling Antarctica permits the development of the Antarctic Circumpolar Current (ACC), responsible for inter-basin exchanges and the development of a global meridional overturning circulation (MOC). The ACC and its zonal channel, blocking the transport of warm salty water of northern origins, isolate Antarctica and the ocean around it.

The meridional density gradient and associated tilted isopycnals that largely control the strength of the ACC also play an important role in the Southern Ocean branch of the global MOC, as southward flowing deep water upwells along the steeply sloped isopycnals associated with the ACC. In a simplified zonally-averaged framework, water sinking in the North Atlantic flows southward as North Atlantic deep water (NADW). Reaching Southern Ocean latitudes, some of the NADW transforms into upper circumpolar deep water (UCDW), which upwells nearly adiabatically along the slanted density surfaces within the ACC belt. Upon outcropping, air–sea buoyancy exchanges and diapycnal mixing converts UCDW into Antarctic Intermediate Water (AAIW) and SubAntarctic Mode Water (SAMW) that flows equatorward and closes the Upper Cell of the Southern Ocean overturning as its surface branch. Another portion of the poleward-flowing NADW is transformed into lower circumpolar deep water (LCDW) that, denser than UCDW, upwells further south close to the Antarctic coast. Here, cooling from air–sea fluxes and salinification from brine rejection transforms LCDW into AABW. AABW sinks and is exported equatorwards as the deep branch of the Lower Cell of the Southern Ocean overturning (Marshall and Speer, 2012; Rintoul and Naveira-Garabato, 2013; Sloyan and Rintoul, 2001; Speer et al., 2000). A schematic representing the Southern Ocean MOC in both depth- and density-space is given in Fig. 16 (to be discussed further in Section 4), where the main water masses are also shown.

Southern Ocean dynamics – and the focus here will be on the ACC transport and the upper branch of the MOC – is believed to be controlled to different extents by both momentum and buoyancy forcing (e.g. Gnanadesikan and Hallberg, 2000; Bryden and Cunningham, 2003; Marshall and Radko, 2003; Olbers et al., 2004; Marshall and Radko, 2006; Hogg, 2010; Morrison et al., 2011; Rintoul and Naveira-Garabato, 2013). However, most of the attention so far, both from the theoretical and modeling community, has been devoted to the role of the wind stress, and especially on the effects of past and future changes (Abernathey et al., 2011; Allison et al., 2010; 2011; Farneti et al., 2010; Gent and Danabasoglu, 2011; Jones et al., 2011; Meredith and Hogg, 2006; Munday et al., 2013; Sijp and England, 2004; Toggweiler et al., 2006). The strong westerly winds that overlie the Southern Ocean play a major role in driving both the overturning circulation and the large horizontal transport of the ACC. These winds have strengthened in recent decades, at least partly due to anthropogenic processes (Marshall, 2003b; Thompson et al., 2011; Thompson and Solomon, 2002). Not only have the westerly winds increased their magnitude but they have also shifted polewards, inducing a significant reorganization of the large-scale circulation, modifying the position of the main fronts and subduction rates (Downes et al., 2011a).

Recently, the observationally based study of Böning et al. (2008) concluded that the ACC transport and associated isopycnal tilt have been largely unaffected by the poleward shift and intensification of the westerlies over the past few decades. The results from Böning et al. (2008), and previous modeling studies (Hallberg and Gnanadesikan, 2006; Meredith and Hogg, 2006), ignited a new line of research with fine and coarse resolution ocean models, emphasizing the primary role of mesoscale eddies in setting the Southern Ocean response to the changes in forcing (Farneti et al., 2010; Gent and Danabasoglu, 2011; Morrison and Hogg, 2013; Munday et al., 2013). In fact, the limited sensitivity of the ACC transport to wind perturbations is achieved through the response of the mesoscale eddy field. Strengthening winds increase the tilt of the isopycnals and the baroclinicity of the ACC, generating a store of available potential energy. The potential energy is then removed by baroclinic instability, spawning mesoscale eddies and increasing the eddy kinetic energy (EKE), resulting in a flattening of the isopycnals. The ACC transport is thus insensitive to decadal changes in winds (Meredith et al., 2012), which do not influence the mean transport but rather feed directly into the mesoscale circulation, and is said to be in the *eddy saturation* regime, as first discussed by Straub (1993).

An eddy saturated state, or equivalently a relatively small change in isopycnal tilt within the ACC, was originally also associated with an insensitivity of the MOC to forcing changes (Böning et al., 2008; Farneti et al., 2010). The Southern Ocean MOC is in fact a balance between a wind-driven circulation and an opposing eddy-induced transport. In the Southern Ocean, winds drive a northward Ekman flow generating an Eulerian-mean circulation and steepening of the isopycnals. Baroclinic instability is again responsible for generating eddies that push the isopycnals down, reducing their slope, and feeding an eddy-induced overturning that is thus opposing the wind-driven cell. This is the basis for the residual-mean theory applied to the Southern Ocean MOC (Andrews and McIntyre, 1976; Marshall and Radko, 2003; McIntosh and McDougall, 1996; Olbers et al., 2004).