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Simulated South Atlantic transports and their variability during 1958–2007

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ABSTRACT

South Atlantic transports, as simulated by a global ocean-sea ice model forced with the Coordinated Ocean-ice Reference Experiments version 2 (CORE-II) interannually varying air-sea reanalysis data sets, are analyzed for the period 1958–2007. The ocean-sea ice model is configured at three different resolutions: from eddy-permitting to coarsened grid spacing. A particular focus is given to the effect of eddy fluxes and inter-ocean exchanges on the South Atlantic Meridional Overturning Circulation (SAMOC), as well as on the main factors contributing to the interannual variability during the integration period. Differences between refined and coarsened grid spacing models are more evident in coastal areas and in regions of high eddy activities. Major discrepancies are associated to both the parameterization of eddy fluxes and the coarse representation of the bathymetry. The refined grid spacing model produces higher values of both SAMOC index, defined as the maximum of the zonally-integrated northward cumulative volume transport (CVT) from surface to bottom across ∼34° S, and meridional heat transport (MHT). All models show high correlations between SAMOC index and MHT, as well as a strengthening of the transports in the 1980–2007 period. The strengthening of the SAMOC index is mainly dominated by surface and mode waters in all models. In surface and intermediate layers, the regions contributing to this trend are located east of 40° W. These changes are compensated by the strengthening of the poleward transport in deeper layers, mostly in the western part of the basin. The MHT trend is connected with the combined effect of a heat transport increase through the Drake Passage and a reduction of the heat loss through the eastern section between Africa and Antarctica, mainly associated with a strengthening in heat entering into the basin through the Agulhas system.

1. Introduction

The global Meridional Overturning Circulation (MOC), and in particular the Atlantic portion (AMOC), provides a key contribution toward the regulation of global climate. Variations in the strength of the MOC volume transport have been connected with extreme climate changes both in the past (Rahmstorf, 2002) as well as in future scenarios of global warming (Lenton et al., 2008). Over the past years, most efforts have been devoted to the monitoring, modelling and theoretical understanding of the North Atlantic MOC (e.g., Srokosz et al., 2012). The focus on the AMOC stability, variability and predictability is determined by its links to global climatic patterns, influence on poleward heat transport and overall effects on climate over the Northern Hemisphere continents (Hurrell et al., 2006; Marshall et al., 2001).

The South Atlantic Ocean is an area of convergence of different water masses originating in different basins and thus presents complex thermohaline properties. Besides, the South Atlantic Ocean serves as communicator between the North Atlantic and the Southern Ocean circulations (Garzoli and Matano, 2011). The Antarctic Circumpolar Current (ACC), flowing eastward from the Pacific Ocean through the Drake Passage and into the South Atlantic basin, favors the entrance of cold and relatively fresh waters that eventually flow to the north at intermediate depths (Cunningham et al., 2003; Orsi et al., 1995). On the opposite side of the basin, around the southern tip of Africa, the warm and salty waters of the Indian Ocean enter the Atlantic at upper and intermediate layers by means of the Agulhas circulation (Beal et al., 2011, and references therein). From the North Atlantic Ocean, cold and salty waters flow poleward in the deep layers. The densest waters of the bottom layers are originated at high latitudes in the Southern Hemisphere by surface cooling and sea-ice formation, and make their way equatorward spreading into the Atlantic basin (Talley, 2008). Far from being just a passive basin, the South Atlantic is a very active region where air–sea interactions

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and diapycnal fluxes induce water mass transformations, particularly in regions of intense mesoscale activities (Downes et al., 2011; Garzoli and Matano, 2011; Jullion and Heywood, 2010; Meijers et al., 2007; Rimaud et al., 2012; Sloyan and Rintoul, 2000; Stramma and England, 1999). The importance of the South Atlantic as a nexus between southern and northern oceans has been emphasized by several authors (Garzoli and Matano, 2011, and references therein), highlighting its role in global climate, being the only ocean basin that transports heat from the pole to the equator (Talley, 2008).

Enhancing our understanding of the South Atlantic MOC (hereafter SAMOC), its mechanisms, variability and consequences over climate is of paramount importance for improving interannual-to-decadal climate predictions and our knowledge on the stability of the global MOC to future forcings (Biastoch and Böning, 2013; Biastoch et al., 2008; 2009; Cimatoribus et al., 2012; Drijfhout et al., 2011). In particular, a deeper understanding of the following topics would be desirable: (i) How do ocean–atmosphere interactions modify South Atlantic properties and circulation? (ii) What is the role of mesoscale processes in South Atlantic fluxes? (iii) What is the role of inter-ocean exchanges in the structure of the SAMOC upper branch? (iv) What are its main sources of variability? Unfortunately, despite considerable recent efforts and the increasing monitoring of ocean properties in the area, lack of long term observations is presently hampering our understanding of the South Atlantic state and variability. Both observations and previous numerical studies have identified, since the mid-20th century, a sustained strengthening of meridional heat transport at mid-latitudes and an increase in the heat content over the Atlantic Ocean, with anomalies linked to changes in atmospheric fluxes (Lee et al., 2011). In addition, observations of the meridional heat transport in the South Atlantic show a strong correlation with the SAMOC index (defined as the maximum of the zonally-integrated northward cumulative volume transport from surface to bottom across ~34° S), suggesting that the SAMOC volume transport has also experienced a positive trend during the same period (Dong et al., 2014; 2011; 2009; Garzoli et al., 2013).

Here, we give an overview on South Atlantic volume and heat transports over the past 50 years as simulated by state-of-the-art global ocean models forced with atmospheric reanalysis data sets for the 1948–2007 period. We use numerical simulations performed with a global ocean-sea ice climate model configured at three different grid spacing—from eddy-permitting to very coarse—and forced by the Coordinated Ocean-ice Reference Experiments version 2 (CORE-II) interannually varying air-sea forcing data sets (Griffies et al., 2009; Large and Yeager, 2009). The aim of this study is to shed some light on the performance of forced ocean models in the representation of South Atlantic fluxes, the role of eddy fluxes in the area, and compare the numerical results with available observations when possible. Particular attention will be given to highlighting strengths and weaknesses of the models in the representation of South Atlantic fluxes. A few CORE-II papers have preceded this study, with a focus on the North Atlantic, Southern Ocean, global and regional sea level (Danabasoglu et al., 2014; Downes et al., 2015; Farneti et al., 2015; Griffies et al., 2014), and further studies are ongoing in the community detailing simulations of the Indian and Arctic oceans. The aim of CORE-II studies is to present a state-of-the-science overview of ocean climate models with respect to observations and literature for several regions and topics. The understanding of the evolution of the South Atlantic will involve forcing that might have remote origins. For example, variability from the Pacific and Indian Oceans (e.g., the cold and warm water routes contributing to the upper branch of the SAMOC) and remote surface fluxes (e.g., the strengthening of Southern Hemisphere winds) are requisite for a proper simulation of South Atlantic characteristics. Thus, when focusing on the mechanistic characterization of one ocean basin, it is necessary to use global ocean models forced with globally varying surface forcing.

The paper is organized as follow. In Section 2 we present the models and experiments. In Section 3 we describe the thermohaline structures in the models, comparing our results with observations, and give estimates of volume and heat transports in the South Atlantic area, together with their variability. We conclude with a summary of our results in Section 4.

2. The models and experiments

We use here the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (MOM), version 5 (Griffies, 2012). MOM uses $z*$ coordinates scaled with height in the vertical. MOM is run globally at three different horizontal and vertical grid spacings. The refined grid spacing version, MOM025, is the ocean-sea ice component from the CM2.5 coupled model that is documented in Delworth et al. (2012). The oceanic grid spacing is 1/4° (~28 km at the equator and progressively refines toward the poles), with 50 levels in the vertical. Although not eddy-resolving, MOM025 does not use a parameterization of mesoscale eddy-induced transport but only a parameterization for the effects of submesoscale, mixed layer eddies (Fox-Kemper et al., 2011). The second version, MOM1, is configured at 1° (or ~79 km at 45° S) grid spacing in the horizontal, with a meridional refinement to 1/3° near the equator (or ~38 km), and 50 vertical levels. The coarsened grid spacing version, MOM2, is run at 2° grid spacing in the horizontal (or ~157 km at 45° S), with a refinement up to 1° near the equator (or ~111 km), and 30 vertical levels.

In MOM1 and MOM2, mesoscale eddy-induced transports are parameterized using the approach of Ferrari et al. (2010). The time-dependent two-dimensional eddy-induced advection coefficient κ varies between 100 m^2/s and 600 m^2/s in MOM1 and between 800 m^2/s and 1400 m^2/s in MOM2. The along-isopycnal neutral diffusion coefficient is equal to 600 m^2/s in MOM1 and 800 m^2/s in MOM2. Further details on ocean physical parameterizations are provided in Griffies et al. (2005), Dunne et al. (2012), and Delworth et al. (2012).

The ocean models are forced with the CORE-II interannually varying air-sea forcing data sets (Griffies et al., 2009; Large and Yeager, 2009). CORE-II is an experimental protocol for ocean-ice coupled simulations forced with interannually varying atmospheric data sets for the period 1948–2007. This effort, involving several centers around the world, is coordinated by the CLIVAR Ocean Model Development Panel (OMDP). The hindcast simulations provide a framework for both model evaluation and studying variability and change at seasonal to decadal time scales.

Following the CORE protocol, the ocean models are run for five repeating cycles of the 60-year forcing. Only the last cycle is analyzed as a hindcast simulation, with the previous 4 cycles regarded as a spin-up period and a useful record for the characterization of biases, drifts, and stability of the oceanic properties and circulation. After five cycles, GFDL models have reached a suitable degree of equilibrium, as seen in Fig. 3 of Griffies et al. (2014) where global volume mean ocean temperature are shown. However, integrating the models for 300 years under CORE-II forcing is too short for achieving a fully equilibrated deep ocean, and more so in the Southern Ocean where low-frequency adjustment to local and remote forcing and deep bottom water formation processes imply the need for longer integrations. This important caveat will have to be taken into account when considering vertically integrated volume and heat budgets. It is also true that differences still exist between the fourth and fifth cycle, and models do not fully duplicate the variability and amplitude of their transports (see, for example, Fig. 2 of Danabasoglu et al. (2014), where the focus is on the AMOC time series at 26.5° N). However, by comparing South Atlantic volume transports from the fourth and fifth cycle in Fig. 13, we will see that our key results are robust.

As discussed in both Danabasoglu et al. (2014) and Griffies et al. (2014), the atmospheric forcing goes from year 2007 back to 1948 at the end of each cycle, generating an inconsistency between the