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CORE-II

An assessment of Southern Ocean water masses and sea ice during 1988–2007 in a suite of interannual CORE-II simulations

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ABSTRACT

We characterise the representation of the Southern Ocean water mass structure and sea ice within a suite of 15 global ocean-ice models run with the Coordinated Ocean-ice Reference Experiment Phase II (CORE-II) protocol. The main focus is the representation of the present (1988–2007) mode and intermediate waters, thus framing an analysis of winter and summer mixed layer depths; temperature, salinity, and potential vorticity structure; and temporal variability of sea ice distributions. We also consider the interannual variability over the same 20 year period. Comparisons are made between models as well as to observation-based analyses where available.

The CORE-II models exhibit several biases relative to Southern Ocean observations, including an underestimation of the model mean mixed layer depths of mode and intermediate water masses in March (associated with greater ocean surface heat gain), and an overestimation in September (associated with greater high

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latitude ocean heat loss and a more northward winter sea-ice extent). In addition, the models have cold and fresh/warm and salty water column biases centred near 50°S. Over the 1988–2007 period, the CORE-II models consistently simulate spatially variable trends in sea-ice concentration, surface freshwater fluxes, mixed layer depths, and 200–700 m ocean heat content. In particular, sea-ice coverage around most of the Antarctic continental shelf is reduced, leading to a cooling and freshening of the near surface waters. The shoaling of the mixed layer is associated with increased surface buoyancy gain, except in the Pacific where sea ice is also influential. The models are in disagreement, despite the common CORE-II atmospheric state, in their spatial pattern of the 20-year trends in the mixed layer depth and sea-ice.

1. Introduction

The Southern Ocean remains poorly sampled by observational programs, compromising a complete understanding of circulation and water mass formation. Thus we rely on climate models to complement observations. Modelling strategies include, but are not limited to, assimilated solutions tightly constrained to observations, varying parameters in individual models, and international multi-model efforts. The Coordinated Ocean-ice Reference Experiments (CORE; Danabasoglu et al. (2014); Griffies et al. (2009)) fall under the latter category. The goal of the second phase of this modelling effort (CORE-II) is to contribute to future model development by investigating the hypothesis that multiple models computing fluxes based on identical bulk formulae and the same prescribed atmospheric state (Large and Yeager, 2009) produce similar ocean and ice representations of the past and present climate. Griffies et al. (2009) evaluated seven ocean-ice models forced with CORE-I Normal Year Forcing (Large and Yeager, 2004), and results were presented from primarily global and/or zonally averaged viewpoints. Here we expand upon the CORE-I effort by evaluating the representation of present and multi-year to decadal observed trends in 15 CORE-II interannually forced models. To capitalise on the CORE-II effort, several regional studies are presently being undertaken, and are contributing to a special issue of Ocean Modelling. For example, Danabasoglu et al. (2014) evaluated the North Atlantic region, Griffies et al. (2014) focussed on sea-level processes, and studies pertaining to the Indian, Pacific and Arctic basins are underway. These publications will provide a detailed model assessment of key circulation, water mass, and sea-ice processes important to global climate modelling.

Given the complex and vast research areas pertaining to Southern Ocean circulation (see Rintoul and Naveira Garabato, 2013, for a review), the CORE-II analysis for this region has been divided into two papers. The first Southern Ocean paper presented here has two foci: i) properties of upper ocean water masses that are key players in the storage and uptake of anthropogenic carbon (cf., Sabine et al., 2004); and ii) sea-ice concentration and extent, which has a first-order role in ocean surface heat and freshwater fluxes. The companion Southern Ocean paper (Farneti et al., 2015) assesses the Antarctic Circumpolar Current (ACC) transport and meridional overturning circulation of the Southern Ocean, with an emphasis on mesoscale processes.

We discuss here the properties of the three primary water masses forming in the Southern Ocean, namely Sub-Antarctic Mode Water (SAMW), Antarctic Intermediate Water (AAIW), and Antarctic Bottom Water (AABW), as well as the deep seasonal mixed layer depths associated with their formation. The subduction of mode and intermediate waters is strongly influenced by the flux of water across the mixed layer base (e.g. Sallée et al., 2010a). The depth of the seasonal mixed layers is governed by overlying wind and buoyancy forcing at the ocean surface, as well as sea ice via both freshwater from melting ice transported equatorward and isolation of the ocean from atmospheric buoyancy fluxes. Strong winter surface buoyancy loss excites vigorous mixing across the mode and intermediate water mass formation regions in the southeast Indian and Pacific basins, resulting in deep mixed layers exceeding 500 m (de Boyer Montégut et al., 2004; Holte and Talley, 2009). In summer, these mixed layer depths reduce to approximately 100 m (Sallée et al., 2010b). AABW forms primarily in the Weddell Sea, Ross Sea and along the Adelie coast through the combined diapycnal mixing of southward flowing Circumpolar Deep Waters and the high salinity shelf waters made dense due to brine rejection (cf., Orsi et al., 1999; Speer et al., 2000; Rintoul and Naveira Garabato, 2013). The companion Southern Ocean CORE-II manuscript by Farneti et al. (2015) addresses the formation, circulation, and associated buoyancy fluxes of AABW.

Observations and models have indicated that most of the ocean surface has warmed and freshened over the past half century (Durack and Wijffels, 2010; Helm et al., 2011), shifting the surface density outcrops poleward. Reduced surface density (increased buoyancy) enhances stratification in the upper ocean and leads to shoaling of the deep winter mixed layers associated with the subduction of mode and intermediate waters (e.g., Downes et al., 2010; Sallée et al., 2010b). In addition, less entrainment of cold deeper water into the mixed layer (due to enhanced upper ocean stratification) can compensate for the negative surface heat flux feedback response to increasing sea surface temperature (Large and Yeager, 2012). Despite a coherent shoaling response to increased greenhouse gases, numerous coarse resolution coupled climate models represent mixed layer depths shallower than observed due to excessive overlying freshwater input (Sallée et al., 2013a). Here we investigate the role of both heat and freshwater fluxes in dictating the mixed layer depth and isopycnal outcropping in models compared to observations.

Two other factors contribute to the surface buoyancy fluxes that influence the mixed layer depths associated with mode and intermediate waters: the surface wind stress; and the salinification and freshening associated with the freezing of sea ice and *in-situ* thermodynamic melting. The strong westerly winds overlying the ACC induce a northward Ekman transport, driving cooler high latitude waters into the upper ocean water mass mixed layer regions (e.g., Naveira Garabato et al., 2009). Also, between the latitude of the maximum westerlies (~47°S) and the peak of the easterlies (~73°S), the winds act to upwell warm, salty and carbon-rich waters from the deep ocean. These winds have strengthened and shifted poleward over the past few decades (e.g., Thompson and Solomon, 2002; Chen and Held, 2007; Thompson et al., 2011), enhancing upwelling and northward surface Ekman transport.

Trends in sea ice are not uniform around the Antarctic continent. Sea-ice concentration has decreased in the Amundsen–Bellingshausen Sea in recent decades (Abram et al., 2013; Comiso and Nishio, 2008; Simpkins et al., 2013; Zwally et al., 2002), associated with increased polar freshening and atmospheric influences (Holland and Kwok, 2012; Turner et al., 2009). Conversely, sea-ice concentration has *increased* in the Ross Sea and climate models fail to represent these observed trends (Abram et al., 2013; Comiso and Nishio, 2008; Zwally et al., 2002). We investigate the ability of the CORE-II models to represent these distinct regional sea-ice trends, and the resultant influence on upper Southern Ocean water mass properties.

This study assesses whether the CORE-II ocean-ice models are a viable tool for process-based research, by evaluating their