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Is realistic Antarctic sea-ice extent in climate models the result of excessive ice drift?

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ABSTRACT

For the first time, we compute the sea-ice concentration budget of a fully coupled climate model, the Australian ACCESS model, in order to assess its realism in simulating the autumn–winter evolution of Antarctic sea ice. The sea-ice concentration budget consists of the local change, advection and divergence, and the residual component which represents the net effect of thermodynamics and ridging. Although the model simulates the evolution of sea-ice area reasonably well, its sea-ice concentration budget significantly deviates from the observed one. The modelled sea-ice budget components deviate from observed close to the Antarctic coast, where the modelled ice motion is more convergent, and near the ice edge, where the modelled ice is advected faster than observed due to inconsistencies between ice velocities. In the central ice pack the agreement between the model and observations is better. Based on this, we propose that efforts to simulate the observed Antarctic sea-ice trends should focus on improving the realism of modelled ice drift.

1. Introduction

The Antarctic sea ice is expanding and climate models have difficulties in simulating this trend (Turner et al., 2013a), for yet unknown reasons. A small number of climate model simulations, however, show a similar increase of Antarctic sea-ice extent to the observed one which may indicate that the internal variability of the climate system, rather than forcing due to greenhouse gas concentrations, plays a significant role (Zunz et al., 2013). This hypothesis is supported by Mahlstein et al. (2013), who studied Antarctic sea-ice area derived from a large ensemble of 23 climate models and found that the internal sea-ice variability is large in the Antarctic region indicating that both the observed and modelled trends can represent natural variations along with external forcings. Moreover, Polvani (2013) analysed forced and preindustrial control model simulations of four climate models to see whether their Antarctic sea-ice trends are due to the internal variability or not. They found that the observed Antarctic trend falls within the distribution of trends arising naturally from the coupled atmosphere–ocean–sea-ice system and concluded that it is difficult to attribute the observed trends to anthropogenic forcings. Consistent with Polvani (2013) and Swart and Fyfe (2013) show that when accounting for internal variability, an average multi-model sea-ice area trend is statistically compatible with the observed trend.

However, the validity of the hypothesis that the Antarctic sea-ice increase is due to the internal variability of the climate system remains uncertain because the models used to test the hypothesis show biases in the mean state and regional patterns, and overestimate the interannual variance of sea-ice extent, particularly in winter (Zunz et al., 2013). To confirm the argument of natural variability, a model would have to explain the observed sea-ice increase while simultaneously responding to anthropogenic forcings. Hence, it appears that the models can not be used to test precisely whether the observed sea ice expansion is due to the internal variability of the climate system or not.

In addition to the above mentioned model based studies, a recent observational study supports to some extent the argument of internal variability. Meier et. al (2013) analysed satellite data and showed that the Antarctic sea-ice extent in 1964 was larger than anytime during 1979–2012. This is a robust result, because within the wide range of uncertainty in the 1964 satellite estimate, the 1964 ice extent is higher than the monthly September average of any of the years of the satellite record from 1979–2012 and remains on the highest end of the estimates even when taking into

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consideration the variation within the month. According to Meier et. al (2013), the ice cover may currently be recovering from a relatively low level back to higher conditions seen in the 1960s. Hence, this result suggests that the current 33 year increase in the sea-ice extent is due to the long-term variability of the climate system. Whether this long-term variability is only due to the internal variability or due to the combined effects of forcings and the internal variability remains unclear.

Observations can also be used to show that the Antarctic sea-ice concentration trends are closely associated with trends in ice drift or with trends related to thermodynamics (Holland and Kwok, 2012). The observed Antarctic sea-ice drift trends can be explained by changes in local winds and the aspects of local winds can be attributed to large-scale atmospheric circulation modes (Uotila et al., 2013b), which have experienced significant changes in the last thirty years (Solomon et al., 2007, Turner et al., 2013b). Moreover, Holland and Kwok (2012) show where the evolution of Antarctic sea ice is controlled either by thermodynamic or dynamic processes during its autumnal expansion and in winter. This is particularly valuable because the relatively weak overall Antarctic sea-ice trend consists of strong regional but opposing trends (Turner et al., 2009). Holland and Kwok (2012) suggest that, by comparing their observational results with similarly processed climate model output, one can diagnose faults in a climate model due to thermodynamic or dynamic processes when simulating the Antarctic sea ice. This is the motivation of our study — to investigate whether a fully coupled climate model produces realistic contributions from thermodynamic and dynamic sea-ice evolution. In this way we should be able to address which processes in the model are too poorly represented to realistically simulate the currently observed sea-ice state, its variability and its trends. Results from such an analysis have not yet been published.

Related to this, recent studies have shown that coupled ocean–ice models, where atmospheric states are prescribed, can reproduce observed Antarctic sea-ice trends under realistic atmospheric forcing and/or when they are constrained with observations. Massonnet et al. (2013) assimilated sea-ice concentration into an ocean–ice model to generate Antarctic sea-ice volume time series from 1980–2008. Additionally, Zhang (2013) shows by an ocean–ice model that intensifying winds result in increase in sea-ice speed, convergence and sea-ice deformation. The sea-ice deformation increases the volume of thick ice in the ocean–ice model along with a significant sea-ice concentration increase in the Southern Weddell Sea. Importantly, Holland et al. (2014) show that a free-running ocean–ice model forced by atmospheric re-analyses can reproduce Antarctic sea-ice concentration and drift trends as observed. Hence, atmospheric states of a fully coupled climate model seem crucial for the modelled sea-ice trends. Accordingly, an assessment of the thermodynamic and dynamic processes related to the evolution of sea-ice concentration in a fully coupled climate model is an important next step to understand why climate models have not been able to simulate Antarctic sea ice realistically.

We hypothesise that climate models simulate the seasonal evolution of integrated Antarctic sea-ice area, and integrated extent, reasonably well, even with relatively unrealistic dynamic and thermodynamic components of the sea-ice concentration budget, partly due to the balancing of biases of these components. For example, during its autumnal expansion sea ice is advected over a larger area when its speed is higher, but at the same time it melts more at the northernmost ice edge where the ocean and atmosphere are warm and the thermodynamics limits the dynamical expansion of sea ice. In order to produce observed regional sea-ice concentration trends in decadal time scales, and the overall sea-ice area or extent trends for the right reasons, and therefore with the correct mass, energy and momentum fluxes, climate models need to simulate regional dynamical and thermodynamical processes correctly.

To test the success of our hypothesis, we compare modelled dynamic and thermodynamic components of the Antarctic April–October sea-ice concentration budget as derived from the output of a well performing state-of-the-science climate model with the observed budget of Holland and Kwok (2012). The observed sea-ice concentration budget data of Holland and Kwok (2012) is only available from April to October which limits our analysis to these months. We present the models, methods and data used for this analysis in the next section. In the results and discussion section, we compare modelled sea-ice concentration budgets with observed ones and discuss how their differences affect the sea-ice evolution. Finally, in the last section we present the main conclusions of this study along with their implications.

2. Methods and data

We analyse data from four *historical* and one *rcp85* realisation simulated by the Australian Community Climate and Earth-System Simulator coupled model version 1.0 (ACCESS1.0) and 1.3 (ACCESS1.3) as submitted to the phase five of the Coupled Model Inter-comparison project (CMIP5) database Table 1, Fig. 1 and Dix et al. (2013). ACCESS1.0 and ACCESS1.3 differ in two important aspects: their sea-ice albedos are different and their atmospheric cloud microphysics schemes are different. Both these differences can be expected to affect the sea-ice performance. Therefore we wanted to see how much their sea-ice concentration budgets differ. The ACCESS configurations are one of the better performing CMIP5 models in terms of global sea-ice extent with a climatology relatively close to the observed one (Uotila et al., 2013a; Liu et al., 2013), thus justifying its selection for this study.

Moreover, similar analysis as for the ACCESS coupled model (Bi et al., 2013a, ACCESS-CM;) output, are carried out for the output from an ACCESS ocean–sea-ice model (ACCESS-OM; Bi et al., 2013b) simulation forced with prescribed atmospheric conditions and bulk formulae of Large and Yeager (2009) following the Coordinated Ocean-ice Reference Experiment phase 2 Inter-annual Forcing (CORE-II IAF) protocols as described in Griffies et al. (2012) (Table 1). Following Danabasoglu et al. (2014), we use the fifth cycle of a CORE-II IAF simulation for the analysis of ACCESS-OM presented here. Note that the ACCESS-OM simulation ends in 2007 which is the last year of CORE-II IAF.

The ACCESS-CM and ACCESS-OM configurations share the ocean and sea-ice models and by analysing their differences we can assess the role of the prescribed atmospheric forcing in driving changes in the Antarctic sea-ice concentration. The sea-ice model of ACCESS is the LANL Community Ice CodE version 4.1 (Hunke and Lipscomb, 2010), which uses the elastic-viscous-plastic rheology, and the ocean model is an implementation of the 2009 public release of the NOAA/GFDL MOM4p1 community code (Griffies et al., 2009). Both ACCESS-CM and ACCESS-OM use an identical horizontal discretisation on an orthogonal curvilinear tripolar grid with a nominal one degree resolution having additional refinements in the Arctic, in the Southern Ocean, and near the Equator. The ACCESS-CM atmospheric model has a horizontal resolution of 1.25° latitude by 1.875° longitude. ACCESS-OM is forced by CORE forcing with spherical T62 resolution (approximately 1.9°), although many meteorological variables, such as winds, are based on the NCEP/NCAR reanalysis with a coarser horizontal resolution of 2.5° latitude × 2.5° longitude.

There is a significant difference in the computation of sea-ice surface energy balance between ACCESS-CM and ACCESS-OM. As described in Bi et al. (2013a) ACCESS-CM has a semi-implicit atmospheric boundary layer that requires determination of the surface