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On the difficulty of modeling Circumpolar Deep Water intrusions onto the Amundsen Sea continental shelf

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ABSTRACT

In the Amundsen Sea, warm Circumpolar Deep Water (CDW) intrudes onto the continental shelf and flows into the ice shelf cavities of the West Antarctic Ice Sheet, resulting in high basal melt rates. However, none of the high resolution global models resolving all the small ice shelves around Antarctica can reproduce a realistic CDW flow onto the Amundsen Sea continental shelf, and previous studies show simulated bottom potential temperature at the Pine Island Ice Shelf front of about −1.8 °C. In this study, using the Finite-Element Sea ice–ice shelf-Ocean Model (FESOM), we reproduce warm CDW intrusions onto the Amundsen Sea continental shelf and realistic melt rates of the ice shelves in West Antarctica. To investigate the importance of horizontal resolution, forcing, horizontal diffusivity, and the effect of grounded icebergs, eight sensitivity experiments are conducted. To simulate the CDW intrusion realistically, a horizontal resolution of about 5 km or smaller is required. The choice of forcing is also important and the cold bias in the NCEP/NCAR reanalysis over the eastern Amundsen Sea prevents warm CDW from intruding onto the continental shelf. On the other hand, the CDW intrusion is not highly sensitive to the strength of horizontal diffusion. The effect of grounded icebergs located off Bear Peninsula is minor, but may act as a buffer to an anomalously cold year.

1. Introduction

Surrounding Antarctica, cold and dense water is formed due to intense sea-ice formation in coastal polynyas (e.g. Haid and Timmermann, 2013). This water spreads over the bottom of the continental shelf, in some cases interacts with ice shelves, descends the continental slope, and contributes to the Antarctic Bottom Water (AABW). The AABW is mainly formed in the Weddell and Ross Seas and off Adélie land (Orsi et al., 1999). Since the AABW formation is one of the drivers of the global thermohaline circulation, transporting heat from the tropics to higher latitudes (Schmitz, 1995), the understanding of AABW formation is important for assessing the global climate.

In contrast to other continental shelf regions surrounding Antarctica, warm Circumpolar Deep Water (CDW) can be found over the continental shelves of the Amundsen and Bellingshausen Seas (e.g. Jacobs et al., 1996, 2011, 2013; Moffat et al., 2009; Jenkins et al., 2010; Martinson and McKee, 2012; Wåhlin et al., 2013; Walker et al., 2013). This warm water intrudes onto the continental shelf through submarine glacial troughs and flows into the ice shelf cavities of the West Antarctic Ice sheet (WAIS) resulting in high basal melt rates (e.g. Jacobs et al., 1996, 2011, 2013; Jenkins and Jacobs, 2008; Jenkins et al., 2010). For instance, Pine Island Ice Shelf (PIIS) and Thwaites Glacier (TG) together are melting rapidly, draining ~4% of the entire Antarctic ice sheet (e.g. Wingham et al., 2009; Joughin and Alley, 2011; Shepherd et al., 2012; Rignot et al., 2013).

Melting of ice shelves attached to the WAIS can have large impacts on the global ocean. First, a collapse of the WAIS has the potential to raise global sea level by 3.3 m (Bamber et al., 2009), and 10% of the observed sea level rise has been attributed to the thinning of the WAIS (Rignot et al., 2008). Second, it may cause the freshening of the shelf water locally in the Amundsen Sea as well as remotely in the Ross Sea (Jacobs et al., 2002; Jacobs and Giulivi, 2010). This may lead to a change in the characteristics of the Antarctic Bottom Water (AABW) formed in the Ross Sea (Jacobs et al., 2002; Rintoul, 2007) and thus may influence the global thermohaline circulation. Therefore, investigations on possible interactions between the melting of small ice shelves in West Antarctica and the large-scale ocean circulation are crucial for understanding climate change in the Southern Ocean.

Several regional models successfully simulate the CDW intrusion onto the Amundsen Sea continental shelf (Thoma et al.,

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2008; Schodlok et al., 2012; Assmann et al., 2013). Schodlok et al. (2012) show that CDW intrudes mainly through the submarine glacial trough on the eastern Amundsen Sea continental shelf (trough E in Fig. 1) all the way into the PIIS cavity. Thoma et al. (2008) and Assmann et al. (2013), on the other hand, show the importance of both trough C (Fig. 1) as well as trough E. Assmann et al. (2013) and Walker et al. (2013) demonstrate that the interaction between an eastward undercurrent and the trough bathymetry steadily provides warm CDW for the continental on-shelf flow.

To study the possible interaction between ice shelf melting in the Amundsen Sea and freshening of the Ross Sea, however, a high resolution circumpolar or global model resolving all the small ice shelves of the WAIS is required. Based on the published model studies investigating ice shelf-ocean interaction, only Timmermann et al. (2012) and Kusahara and Hasumi (2013) resolve all the ice shelves around Antarctica, but both models do not show realistic basal melt rates in the Amundsen Sea especially for PIIS; simulated melt rates for PIIS are 8–13 Gt yr^{-1} for Timmermann et al. (2012) and Kusahara and Hasumi (2013), while observation-based estimates range from 28 to 101 Gt yr^{-1} (Jacobs et al., 1996; Rignot, 1998; Jacobs et al., 2011; Depoorter et al., 2013; Nakayama et al., 2013; Rignot et al., 2013; Dutrieux et al., 2014). Timmermann et al. (2012) attributed the deficiency mainly to a cold bias in the NCEP/NCAR Reanalysis (NCEP-REAN) winter temperature (Assmann et al., 2005). However, a suite of sensitivity studies revealed that even with a warmer forcing, the model still shows an Amundsen Sea much colder than in reality (Nakayama et al., 2013). Using a circumpolar model, Holland et al. (2014) reproduce CDW intrusion onto the Amundsen and Bellingshausen Seas for modeling trends in Antarctic sea ice thickness, but an analysis of the sensitivities of CDW intrusion is not conducted.

With this study, we aim to clarify the main factors controlling warm water intrusions onto the Amundsen Sea continental shelf. We have conducted several sensitivity studies with regard to horizontal resolution, forcing, and horizontal diffusivity (Table 1). We also briefly discuss the importance of grounded icebergs in this region.

2. Model Description

We use the global Finite-Element Sea ice–ice shelf-Ocean Model (FESOM), the details of which are described in Timmermann et al. (2009, 2012) and Timmermann and Hellmer (2013). For the CTRL case, we use a tetrahedral mesh with a horizontal spacing of 100 km along non-Antarctic coasts, which is refined to ~20 km along the Antarctic coast, 10–20 km under the large ice shelves in the Ross and Weddell Seas, ~5 km in the central Amundsen and Bellingshausen Seas, and ~2.5 km in the eastern Amundsen Sea (e.g. Fig. 1). Although St-Laurent et al. (2013) argue that a model resolution of ~1 km is needed to fully resolve mesoscale processes, the maximum resolution is set to ~2.5 km due to computational constraints. While the mesh size varies between 30 and 40 km in the offshore Southern Ocean, it increases to about 400–450 km in the vast basins of the Atlantic and Pacific Oceans. In total, the grid comprises about 3 million grid nodes.

To allow for an adequate representation of ice shelf cavities, we apply a hybrid vertical coordinate system with 46 layers and a z-level discretization in the mid- and low-latitude ocean basins. The top 21 layers along the Antarctic coast are terrain-following (sigma coordinate) for depths shallower than 650 m (Fig. 2). As pointed out by some studies (e.g. Mellor et al., 1994; Griffies et al., 2000; Lemarié et al., 2012), sigma-coordinates have difficulties in accurately computing the horizontal pressure gradient, advection and diffusion, and they induce artificial advection and diffusion along the sigma layers. At the shelf break of the Amundsen Sea, the surface-referenced isopycnals are nearly horizontal (e.g. Fig. 4 of Nakayama et al., 2013), and thus the main diffusion and advection take place horizontally. Therefore, to avoid unrealistic mixing along sigma layers, we restrict sigma levels to the upper 650 m of the water column. In the z-coordinate region, bottom nodes are allowed to deviate from their nominal layer depth in order to allow for a correct representation of bottom topography, similar to the shaved-cells approach in finite-difference z-coordinate models. We note that steep slopes of sigma layers at the entrance to the cavities might influence sub-ice circulation

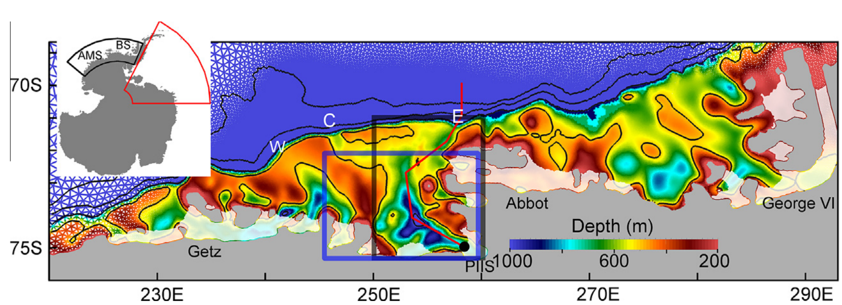

Fig. 1. Horizontal grid of the Amundsen and Bellingshausen region of the global model domain for the CTRL case (HG1), where the color indicates the depth of the model bathymetry. The bathymetry contours of 500, 1000, 2000, and 3000 m are also shown (black lines). Letters E, C, and W denote the submarine glacial troughs located on the eastern, central, and western Amundsen Sea continental shelf, respectively. The location of Getz, Pine Island, Abbot and George VI Ice Shelves are shown. The red line represents the section shown in Fig. 2. The time series of ice front bottom potential temperature (black dot) are shown in Fig. 3. In the area enclosed by the gray rectangle, air temperature and mixed layer depth are averaged, which is shown in Fig. 8. Satellite pictures of the area enclosed by the blue rectangle are shown in Fig. 10. The inset shows Antarctica with regions surrounded by black and red lines denoting the location of the enlarged portion and the location where temperature and salinity are restored, respectively. AMS and BS stand for Amundsen and Bellingshausen Seas. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

Table 1
Description of all the sensitivity cases. The case name, horizontal grid, diffusivity, forcing, and switch for grounded iceberg setting are shown.

Case	CTRL	HG2	HG3	HG4	kh1	kh2	NCEP-REAN	Grounded icebergs	Grounded icebergs with NCEP-REAN
Horizontal grid	HG1	HG2	HG3	HG4	HG1	HG1	HG1	HG1	HG1
k_h	0.9	0.9	0.9	0.9	0.45	0.05	0.9	0.9	0.9
Forcing	NCEP-CFSR	NCEP-CFSR	NCEP-CFSR	NCEP-CFSR	NCEP-CFSR	NCEP-CFSR	NCEP-REAN	NCEP-CFSR	NCEP-REAN
Grounded icebergs	Off	Off	Off	Off	Off	Off	Off	On	On