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Brief communication: A submarine wall protecting the Amundsen Sea intensifies melting of neighboring ice shelves

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Abstract

Disintegration of ice shelves in the Amundsen Sea has the potential to cause sea level rise by inducing an acceleration of grounded ice streams. Moore et al (2018) proposed that using a submarine wall to block the penetration of warm water into the ice shelf cavities could reduce this risk. We use a global sea ice-ocean model to show that a wall shielding the Amundsen Sea below 350 m depth successfully suppresses the inflow of warm water and reduces ice shelf melting. However, the warm water gets redirected towards neighboring ice shelves, which reduces the effectiveness of the wall.

1 Introduction

One of the consequences of the warming in the Earth's climate system is sea level rise. Sea level rise will impact coastal societies, and economic activities in these areas. Currently the main contributors to rising global mean sea level are a steric component driven by the thermal expansion of the warming ocean, the mass loss from the Greenland Ice Sheet, and the world-wide retreat of glaciers (Rietbroek et al., 2016). The remaining smaller sources are continental ground water depletion (Wada et al., 2012) and the Antarctic ice sheet (Rietbroek et al., 2016); though Antarctica's sea level contribution has accelerated in recent decades (Rietbroek et al., 2016).

Both modeling studies and paleoclimatological-proxy data indicate that the highest potential sea level contribution will come from the West Antarctic Ice Sheet (e.g., Joughin and Alley, 2011). One place that is vulnerable is the Amundsen Sea in front of Marie Byrd Land, where ice shelves currently prevent unrestricted flow of ice streams into the ocean. Warm water masses (a body of ocean water with a common formation history and a defined range of tracers, such as temperature and salinity, is called water mass), which flow onto the continental shelf and penetrate into the cavity under the ice shelves, drive high basal melting rates. Various processes control the flow of warm water masses into the ice shelf cavities. Wind-driven Ekman transport, which could be altered by sea ice conditions, lifts the warm and saline Circumpolar Deep Water (CDW) to shallower depths (Kim et al., 2017). During its transport onto the continental shelf the water mass is transformed into modified CDW (mCDW) by mixing with local water masses. In the Amundsen Sea the large-scale oceanic and atmospheric circulation controls the CDW uplift (Nakayama et al., 2018). It includes the tropic's influence via atmospheric wave trains

(Steig et al., 2012). These processes together drive the detected retreat of ice shelves in the Amundsen Sea through decadal oceanographic variability (Jenkins et al., 2018).

Since the West Antarctic Ice Sheet has a retrograde bedrock topography, it is susceptible to the Marine Ice Sheet Instability (Schoof, 2007),. In this situation, a retreat of the ice stream will lead to a larger ice thickness at the new grounding line position. This amplifies the ice flux across the new grounding line, which stretches and thins the ice further and ultimately triggers additional grounding line retreat. This sustained cascading grounding line retreat, accelerates the transport of grounded inland ice to the ocean. The disintegration of formerly grounded inland ice (by ice berg calving and ocean-driven melting) is ultimately what raises sea level.

Moore et al (2018) proposed a targeted geoengineering project that could reduce the risk of this ice sheet collapse mechanism by protecting the ice shelves from warm water with a submarine wall. Wolovik and Moore (2018) tested this idea with a simple flow line model (2-dimensional xz-plane model) of the Thwaites Glacier, which flows into the Amundsen Sea too. They imposed artificial pinning points to stabilize the ice shelves or to block the inflow of warm water masses by a submarine wall. Both measures successfully reduced ice mass loss (Wolovick and Moore, 2018).

2 Model setup

We use a global Finite Element Ocean Model (FESOM; Wang et al., 2014) to test the effects of erecting a wall in front of the Amundsen Sea ice shelves. The model has a variable horizontal resolution of (at least 5 km) around Antarctica and its adjacent ice shelf cavities and has 100 levels (z-coordinate). The interaction between the ocean and static ice shelves occurs via the three-equation system that describes the flux of heat and fresh water between the ocean and ice shelf base through an exchange controlling boundary layer (Holland and Jenkins, 1999). FESOM has proven its applicability for oceanographic studies of the Southern Ocean (Hellmer et al., 2012; Nakayama et al., 2014; Timmermann et al., 2012). Although ocean models with a too coarse resolution tends to underestimate basal melting of ice shelves (Naughten et al., 2018), our basal melting rates and mass losses are in reasonable agreement with recent observational estimates. The model utilizes the ocean bathymetry, ice shelf geometry and grounding line position data from RTOPO1 (Timmermann et al., 2010). We use the CORE2 forcing for atmospheric conditions (Large and Yeager, 2008) covering the years 1948—2007 to drive the ocean model. This period is run twice. The first full period is considered as spin-up and, hence, we restrict our analysis on the last complete forcing period.

Measured bottom temperatures, predominantly taken in austral summer by the marine cruises *ANT XI/3 (Miller and Grobe, 1996)* and *ANT XXVI/3 (Gohl, 2010)*, provide confirmation that the simulated bottom temperature distribution is reasonable (Figure 1). In the control simulations (CTRL) undisturbed bathymetry is used. In the simulation called WALL, we have erected a submarine wall between Thurston Island and Siple Island (Figure 2). It follows approximately the continental shelf break and blocks the ocean circulation below 350 m depth.

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3 Results

The CTRL experiment agrees with observations. Simulated warm water masses flow through submarine troughs towards the ice shelves in the Amundsen Sea Embayment. Measured bottom temperatures, taken in austral summer, confirm in general to the simulated bottom temperature distribution (Figure 1).

The erected wall blocks the ocean below 350 m depth in the WALL and suppresses the direct inflow of warm and also salty mCDW into the interior of the Amundsen Sea Embayment in front of the western Marie Byrd Land. Consequently, the simulated ocean is generally cooler (Figure 2) and fresher within the walled region. Enhanced sea ice formation, enabled by an overall colder water column, releases salty brine into the underlying ocean within the walled region. This does not compensate for the reduced mCDW saline inflow.

We also detect a slight cooling of the bottom temperatures east of the walled region, which is upstream of the coastal current flowing (westward) along the continental shelf break. The outflow of cooler water masses from the walled region through the Abbot Ice Shelf (south of Thurston Island) contributes to this cooling. The deflected warm water mass flows westward and rises the temperature on the west side of the walled region. This causes the temperature to rise in the westernmost corner of the walled region around Siple Island. The warm water mass penetrates through the Getz Ice Shelf (between the groundling line of Antarctica and Siple Island) into the walled region.

In the walled region, the lower ocean temperature reduces melting of ice shelves. However the restrained warm water mass advances into the neighboring region, where ice shelves experience intensified melting and amplified ice mass loss (Figure 2). Therefore the warm water mass, that would have otherwise impacted the Amundsen Sea Embayment, shifts to fringing ice shelves.

Figure 3 depicts the longitudinal dependence of the simulated basal melting rates around Antarctica. In the Amundsen Sea Embayment the ice mass loss around Pine Island drops significantly by 6/7 (85 %). The reduction in ice mass loss in the walled Amundsen Sea Embayment sector goes along with a rising mass losses further in the west. The ice mass loss increases up to 50 % for parts the Getz Ice Shelf (~130° W, eastern Marie Byrd Land). In the western Bellingshausen Sea, east of the Amundsen Sea Embayment, the basal mass loss is reduced, because cooler water masses flowing out of the walled region through the Abbot Ice Shelf. West of the Antarctic Peninsula, in the George VI Ice Shelf, the ice mass loss increases by up to 10 %. The wall has little impact on basal melting of ice shelves fed by ice streams from the East Antarctic Ice Sheet with the exception of Amery Ice Shelf, where the rate increases by approximately 5 %. The wall in the Amundsen Sea triggers most probably a perturbation that propagates via the Antarctic Coastal Current towards the Prydz Bay in front of the Amery Ice Shelf. All above reported intensified melting rates are larger than the standard deviation (1-sigma) of the 20 years melting rate. Overall the integrated basal melting mass loss around Antarctica is about 10 % lower for the WALL experiment. So the enhanced ice mass losses of adjacent ice shelves do not compensate completely the reduction in the walled region.

4 Conclusions

An enormous submarine wall of sufficient height along the continental shelf shields the Amundsen Sea Embayment and suppresses the inflow of warm circumpolar water mass onto the continental shelf. This cools bottom water masses in the shielded ice shelf cavities, which reduces basal shelf melt rates. However, the warm water mass is redirected towards ice shelves surrounding the Amundsen Sea enhancing basal melting rates of up to 50 %. In particular, the ice shelves to the west (central and west Getz Ice Shelf) show steeply increased melting rates. Overall, the wall reduces the integrated basal melting mass loss by 10 % across all coastal ice shelves of Antarctica. Our results indicate that suppressing the flow of warm water masses into a restricted group of ice shelves results in redirecting it towards a different location. There it enhances basal melting and, ultimately, amplifies ice mass loss. However, it is an open question if this triggers Marine Ice Sheet Instability in the other shelves, because the stability depends on the distribution of pinning points, sloping of the bed, the depth and width of submarine troughs, and the softness of the bed, for instance. The onshore bed properties of the western Marie Byrd Land, where Pine Island and Thwaites Glaciers are located, are probably more favorable for a stable situation than in the eastern Marie Byrd Land sector. Though, the bed properties under the ice are still known insufficiently.

The wall proposed by Moore et al (2018), which would block only the channelized flow of warm water in troughs leading directly to Pine Island and Thwaites Glaciers in the Amundsen Sea Embayment, would need 10—50 km^3 of material. By comparison, the construction of the Suez Channel required the excavation of about 1 km^2 of material (Moore et al., 2018). The simulated wall in our experiment, with a length of about 800 km, is substantially larger than the originally proposed wall in size. Our results suggest that a too small wall blocking only the water flow in the troughs leading to Pine Island, for instance, may redirect the warm water to neighboring ice shelves with a retrograde bed. There it increases basal melting and may trigger Marine Ice Sheet Instability. For dynamical reasons the (geostrophic) flow of water masses turns to the left (on the Southern hemisphere), if it is not hindered by a topographic obstacle. Therefore warm water masses might even recirculate into the ostensibly protected area if the wall is too small, as the inflow of warm water masses through the Getz Ice Shelf into the walled region suggests.

Geoengineering aims to attenuate the impact of the ongoing anthropogenic climate change, such as sea level rise, but the proposals could have adverse side effects. To evaluate these effects of using walls to protect Antarctica's ice shelves, fully coupled simulations between a dynamic ice sheet/shelf model and a global climate model will be required. These experiments should include ice shelf-ocean interaction and a sufficiently high spatial resolution in both ice sheet and ocean models around Antarctica to be able to accurately track grounding line movement and the flow of warm water masses entering ice shelves, respectively. This would give higher confidence that blocking warm water flow in the walled regions does not result in enhanced melting in the surrounding regions, triggering cascading retreat.

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Author contributions

CR designed the study and wrote the manuscript. ÖG and QW developed and configured the model. ÖG ran the simulations. ÖG and VK performed the analysis. VK and CR prepared the figures. All authors contributed in interpreting the results and improving the text.

Competing interests

The authors declare that they have no conflict of interest.

Data availability

The data is available from the first author ÖG upon reasonable request.

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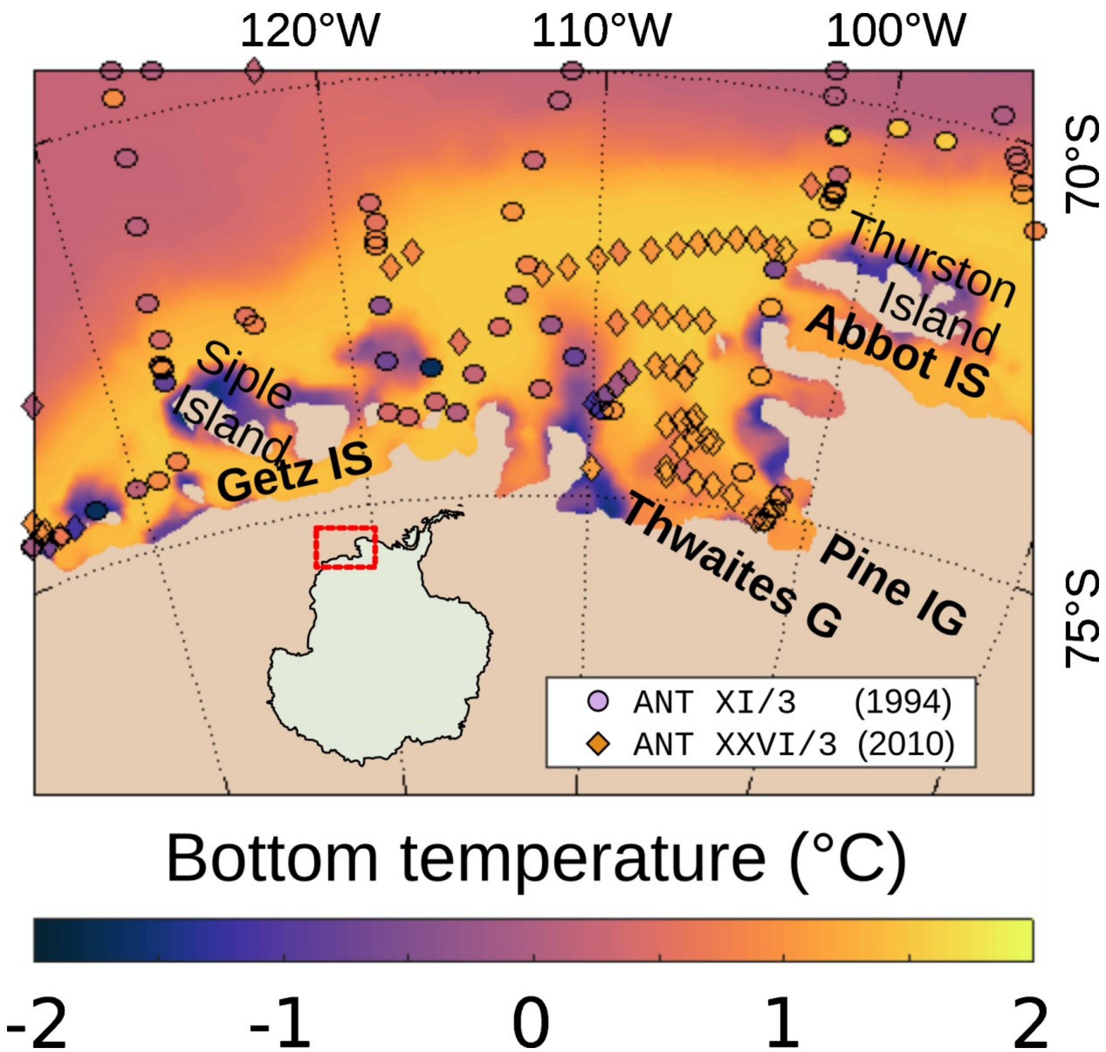

Figure 1 Observed potential ocean temperature at the bottom in the Amundsen Sea Embayment – the displayed region is highlighted red square on the Antarctica map. The plot shows the simulated mean ocean temperatures for the control run (CTRL, years 1948—2007), while individual observed bottom temperatures are represented by circles (ANT XI/3; Miller and Grobe, 1996) or diamond (ANTXXVI/3; Gohl, 2010) taken in 1994 and 2010, respectively.

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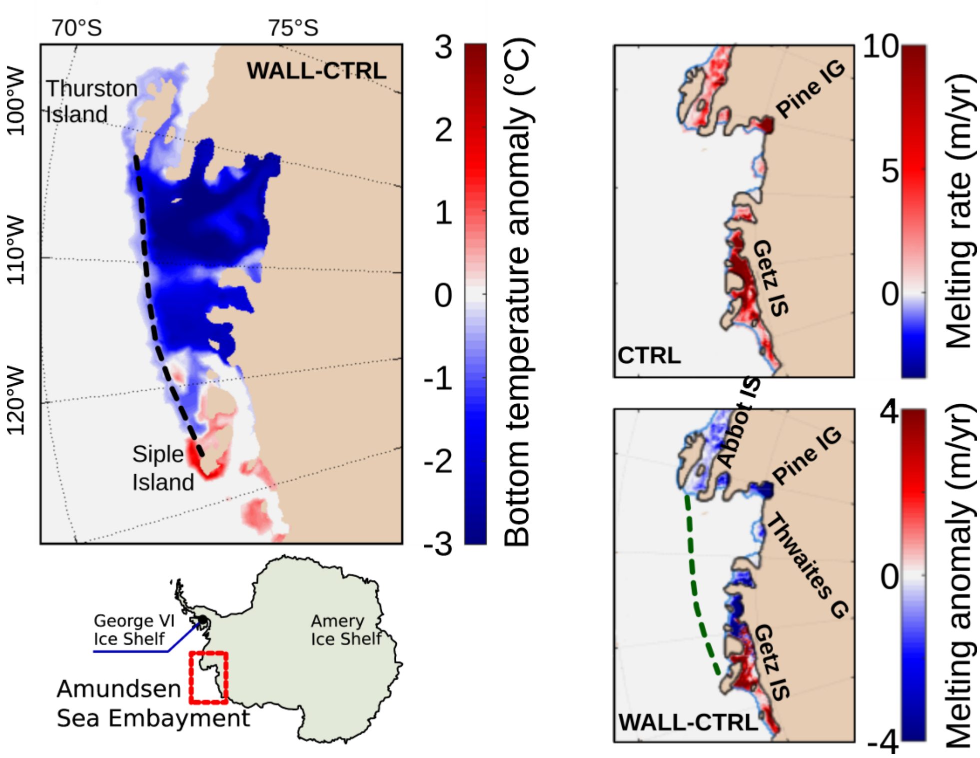

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Figure 2 The left subplot show the potential ocean temperature anomaly (WALL – CTRL) at the bottom of the Amundsen Sea Embayment and adjacent ice shelf cavities. The location of the wall is marked as a dashed line. The right subplots display simulated basal melting rates of ice shelves. The upper right plot show the melting rates for the control run (CTRL) and the lower right plot shows basal melting anomaly (WALL - CTRL). The ice shelf edges are highlighted by solid blue lines. The following abbreviations are used Abbot IS (Abbot Ice Shelf), Pine IG (Pine Island Glacier), Thwaites G (Thwaites Glacier) and Getz IS (Getz Ice Shelf). On the Antarctica map (lower left), the red square marks the depicted Amundsen Sea Embayment region and other locations discussed in the text.

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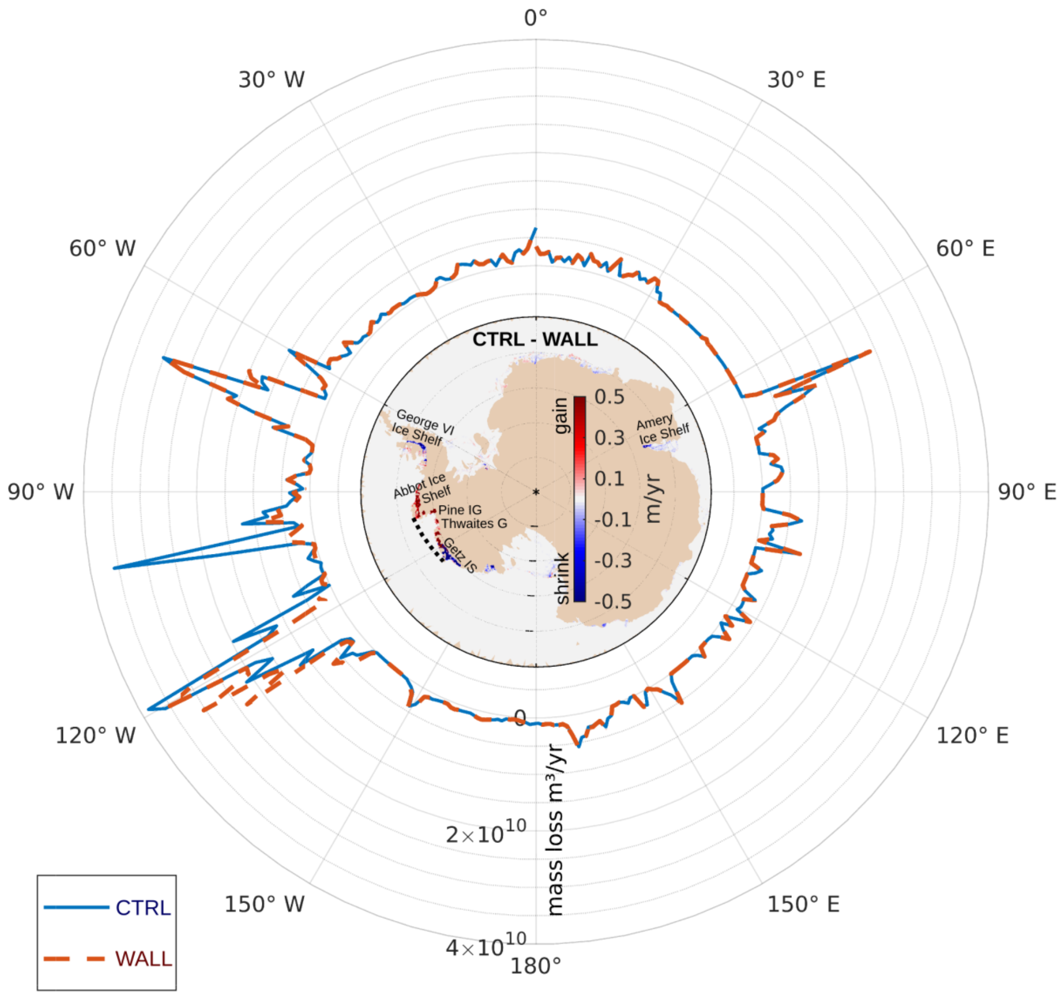

255 **Figure 3 Mean basal melting rates around Antarctica. In the outer ring the longitudinal-dependent distributions are shown as lines for both simulations: standard simulation without wall (CTRL, blue solid line) and simulation with wall (WALL, red dashed line). The wall's location in the Amundsen Sea is marked by the black dashed line in the center map. The map of Antarctica shows the spatial distribution of the melting rate anomaly, where positive numbers (red color) represents reduced melting rates if wall is present (see colorbar). The following abbreviations are used: Pine IG (Pine Island Glacier), Thwaites G (Thwaites Glacier) and Getz IS (Getz Ice Shelf).**