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FY 2016 Third Quarter Performance Metric: Identify Biases Relevant to Land Ice Evolution in Prototype Ice Sheet and ESM Coupled Simulations

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1.0 Product Definition

Potential future sea-level rise from the Antarctic ice sheet is expected to be a strong function of the integrity of Antarctica's fringing ice shelves, which limit the flux of ice from the continent to the surrounding oceans (Fürst et al. 2016). This hypothesis is supported by both observations (e.g., Scambos et al. 2014) and modeling (e.g., DeConto and Pollard 2016). To better simulate and anticipate such changes, climate-modeling centers need to couple dynamic ice sheet models with climate models and account for the relevant processes by which ice shelves melt, thin, and degrade to the point of collapse. For Antarctica, the potential for large increases in submarine melting of ice shelves due to changes in ocean circulation – and subsequent ocean heat delivery to ice-shelf cavities – is a key concern (e.g., Hellmer et al. 2012). Biases in coupled model simulations that impact the ocean state and circulation around Antarctica strongly impact modeled submarine melting, and in turn ice-sheet evolution in coupled climate-and-ice-sheet simulations. Identifying and understanding the causes for such biases is an important first step towards reducing them and improving projections of ice sheet evolution in coupled climate models.

2.0 Product Documentation

By comparing model output with observations, we have identified several important coupled model biases that lead to unrealistic sub-ice-shelf melt rates. From a partially coupled ice-sheet-and-ocean modeling framework, we have identified ocean mixed-layer biases that lead to either too little or too much vertical mixing at the ocean surface, with the result that either too much or too little warm, intermediate-depth water gains access to the Antarctic continental shelf. These biases, which cause modeled sub-ice-shelf melt rates to rapidly depart from the range expected from recent observations, leading to either far too much or far too little melting, are attributable to deficiencies in the partially coupled modeling framework. While both of these deficiencies can likely be remedied through full coupling of ocean, atmosphere, sea-ice, and land-ice model components, they point to a clear need for great care in addressing initially small biases in sea-ice formation, transport, and coupling to the ocean model, which can eventually have a strong impact on sea-surface salinity and mixed-layer depth.

From initial simulations using a fully coupled Earth System Modeling framework, we have examined modeled and observed sub-ice-shelf melt rates for Antarctica's two largest ice-shelf systems. For the Ross Ice Shelf, modeled submarine melt rates are slightly too large, but are generally within the range of observations and we find relatively small ocean temperature and salinity biases in the Ross Sea region. These are likely due to underestimates in sea-ice formation and/or export, which have a strong impact on ocean salinity. For the Filchner-Ronne Ice Shelf, modeled submarine melt rates are far too large, a bias that we attribute to too much warm, salty, intermediate-depth water making its way into the Filchner Trough, which is a key pathway connecting the open ocean and the sub-ice shelf cavity. This bias in the modeled ocean circulation is likely due to inadequate resolution of the Antarctic Slope Front, an ocean density structure responsible for blocking the flow of warm intermediate waters onto the Antarctic continental shelf. A poorly defined Antarctic Slope Front may be the result of a poorly defined Antarctica Coastal Current, the primary feature responsible for the ocean density structure that defines the front. In turn, inadequate model resolution may be responsible for the poorly defined coastal current. Thus, ocean model resolution around the Antarctic continent must be high enough to resolve fine-scale (tens of km or less) features (like the coastal current) in order to reduce the too warm ocean (and too large melt rates) biases currently found in the Filchner-Ronne Ice Shelf region.

We conclude that biases in modeled sub-ice-shelf melt rates, which will lead to biases in modeled discharge of ice to the oceans (and in turn, biases in modeled sea-level rise), can be minimized by correcting or minimizing Southern Ocean temperature, salinity, and mixed-layer biases and by ensuring that coupled model simulations are conducted with adequate spatial resolution.

3.0 Results

We have carried out two different types of simulations that allow us to explore and identify several critical biases that need to be recognized and addressed when coupling ice-sheet and ocean models. The first uses a regional, circumpolar, whole-Antarctic ,ice-sheet-and-ocean-model framework based on an offline but synchronous coupling of the BISICLES (Cornford et al. 2013, 2015) and POP2x ocean models (POPSICLES; Asay-Davis et al., in preparation). The second uses the Accelerated Climate Model for Energy (ACME), which allows for the coupling between ice sheets and oceans within global, fully coupled, Earth System Model (ESM) simulations.

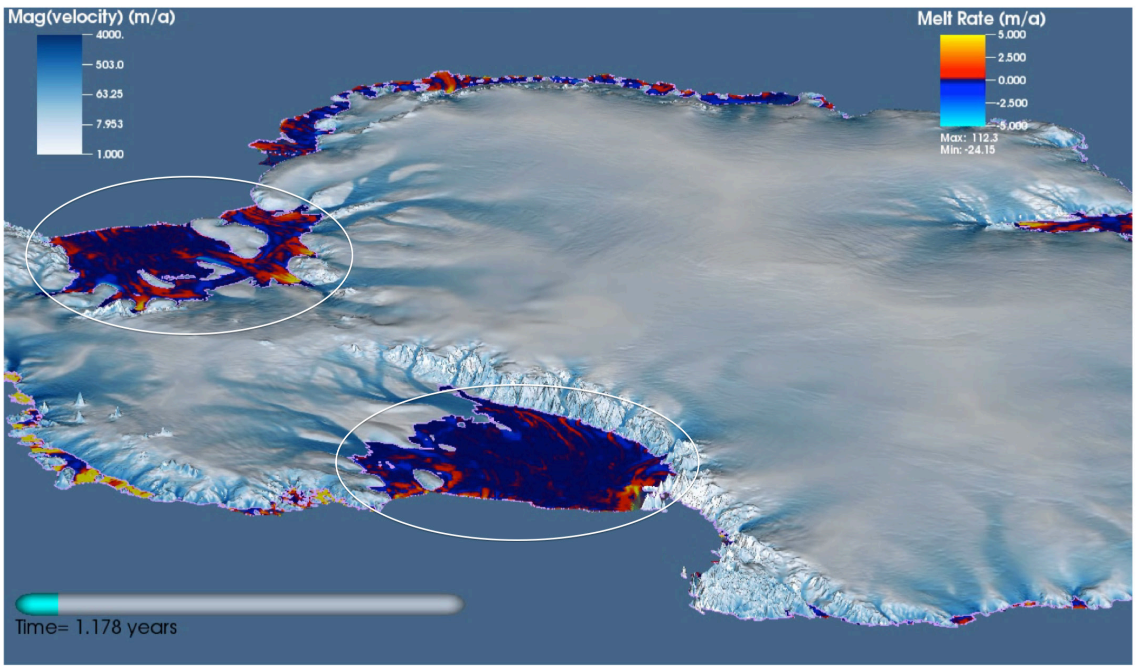

Figure 1. Time slice from a regional, circumpolar, POPSICLES simulation that includes ocean circulation beneath ice shelves. Shown are the ice surface speed (blue color bar) from the BISICLES ice sheet model and submarine melt rates (orange-red color bar) calculated from the POP2x ocean circulation model. Antarctica's two largest ice shelves, the Ross (foreground) and Filchner-Ronne (background), are circled.

Using the POPSICLES modeling framework (Figure 1), we highlight the importance of accurately modeling the ocean surface mixed layer. The mixed-layer depth is the thickness of the surface ocean where temperature and salinity properties are well mixed. Beneath the mixed layer, temperature and salinity, and thus ocean density, generally become more stratified (i.e., layered). Around coastal

Antarctica, the depth of the mixed layer serves as one of several strong controls on the access of dense, warm, well-stratified Circumpolar Deep Water (CDW, in the Ross, Amundsen, and Bellingshausen Seas) or Weddell Deep Water (WDW, in the Weddell Sea) to sub-ice-shelf cavities. If the mixed layer is too shallow, warm, stratified waters have easy access to sub-shelf cavities. Conversely, a mixed layer that is too deep blocks the access of warm, stratified waters to sub-shelf cavities. Figure 2 demonstrates the result of two POPSICLES simulations that use standard data sets for atmospheric forcing of coupled ocean-and-sea-ice models (Griffies et al. 2009, Large and Yeager 2009). Because our POPSICLES simulations do not include a dynamic sea-ice model, they require additional, explicit treatment of sea-surface temperatures and salinities (SST and SSS, respectively).

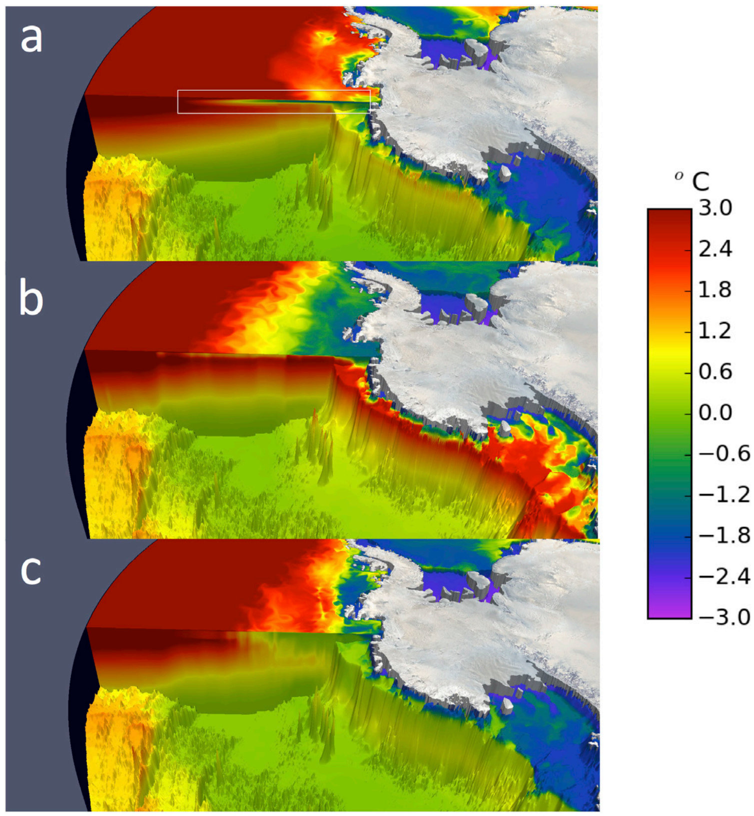

Figure 2. Cross-sections through the Amundsen Sea Embayment of West Antarctica (105 deg. W) showing ocean potential temperature and mixed-layer biases when using two different forcing data sets. (a) The model initial condition with a reasonable mixed-layer depth (mixed layer is highlighted by white box). After ~33 years of Forcing 1 (panel b), the model mixed layer shoals and allows warm Circumpolar Deep Water (CDW; water mass colored red at depth in figures) to flood the sub-ice-shelf cavity, causing too much ice-shelf melting. Conversely, after ~33 years of Forcing 2 (panel c), the mixed layer deepens and allows too little CDW into the ice-shelf cavity, causing too little ice-shelf melting (see also Figure 3).

This was done by restoring SST and SSS values to those taken from two different CESM simulations – both forced by the same atmospheric forcing used for the POPSICLES simulations – that include coupled ocean-and-sea-ice models. We refer to these here as “Forcing 1” and “Forcing 2”, depending on from which CESM simulation the restoring values were derived. While both simulations start off with a physically realistic mixed layer (Figure 2a), they both diverge dramatically within about a decade. In one case, the mixed layer shoals, allowing too much CDW into the sub-ice shelf cavity, with the result that submarine melting rates dramatically increase and depart from observations Figure 2b and Figure 3, green line). In another case, the mixed-layer depth grows, with the result that too little warm, deep water has access to the sub-ice-shelf cavity. The result is that submarine melt rates dramatically decrease, also departing from observations (Figure 2c and Figure 3, blue line).

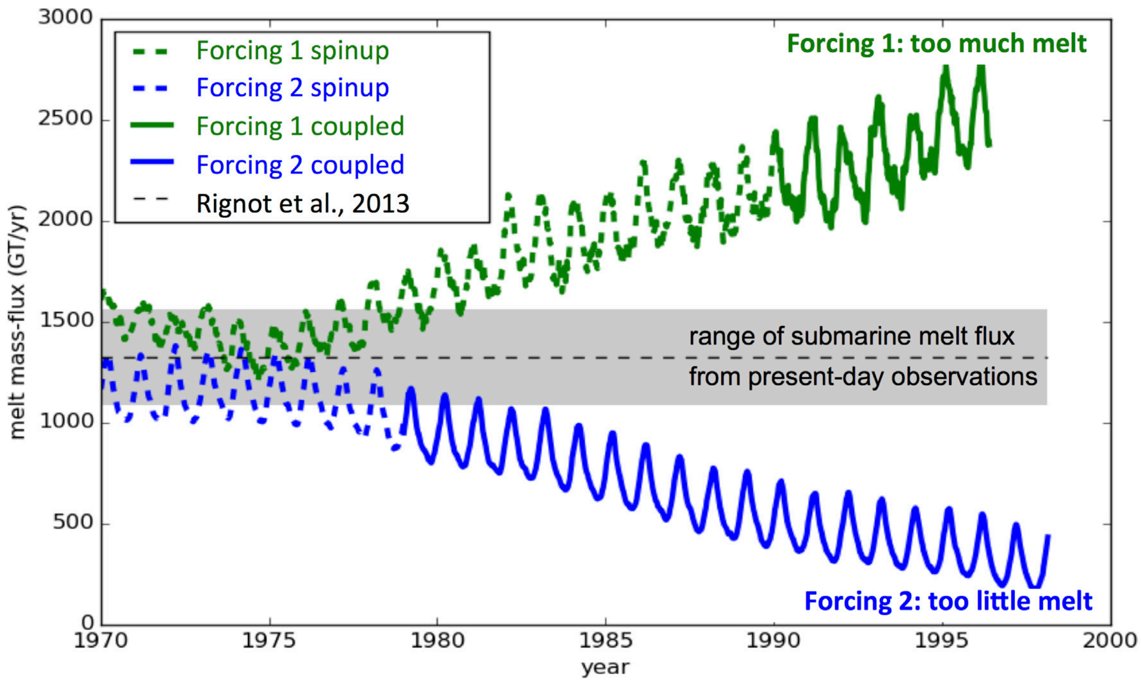

Figure 3. Consequence of mixed-layer biases shown in Figure 2 with respect to net melt rates modeled for all Antarctic ice shelves. For the mixed layer that shoals unrealistically under Forcing 1, allowing too much CDW into the ice-shelf cavity (a, b in Figure 2), modeled melt rates quickly grow much larger than the range of observations (From Rignot et al. [2013]). The impact on a dynamic ice-sheet model would be too much ice-shelf thinning and rapid grounding-line retreat. For the mixed layer that deepens unrealistically under Forcing 2, allowing too little CDW into the ice-shelf cavity (a, c in Figure 2), modeled melt rates quickly decrease to values much smaller than the range of observations. The impact on a dynamic ice-sheet model would be too little ice-shelf thinning and grounding-line advance. Neither case would allow a dynamic ice-sheet model to maintain a quasi-equilibrium within the range of observations over the past few decades.

The too shallow and too deep mixed layers shown in Figure 2 can both be traced back to the lack of a dynamic sea-ice model and the requirement that, in the POPSICLES simulations, sea-ice impacts on SST and SSS are treated using restoring to values from previous simulations (which were not focused on Southern Ocean or coastal Antarctic processes). For Forcing 1, the effect of sea-ice formation on ocean-surface salinity and density and vertical mixing is underestimated by the use of SSS restoring. This is because in reality (or, equivalently, in a coupled ocean-and-sea-ice model) dense, salty water at the surface tends to sink rapidly (promoting vertical mixing), leaving SSS values relatively constant. Thus, SSS restoring is a poor proxy for the actual salinity changes that occur and strongly affect density and vertical mixing. For Forcing 2, we find unrealistically high SSS values that clearly result in too dense surface waters, which then lead to unrealistic deep convection and surface mixing (this is a common problem also found in coarse resolution climate models, e.g., Petty et al. [2014] and Holland [2014]). Moving to a coupled ACME framework, which includes a fully dynamic sea-ice model and accounts for sea-ice impacts on surface-water density, should improve or remove both of these biases. This clearly points to the importance of a dynamic sea-ice model in ACME simulations. It also points out deficiencies in current metrics used for identifying sea-ice biases, which focus mostly on sea-ice area, extent, and thickness. Future metrics should also address coupled ocean-and-sea-ice processes that can lead to important biases in the ocean mixed-layer depth.

Using the ACME modeling framework (Figure 4), we highlight regional biases in submarine melting rates that follow from large regional biases in ocean temperature and salinity. In Table 1, we compare the spatially integrated, net melt flux from three observationally based studies to those diagnosed from our ACME simulation. For the Ross Ice Shelf, the modeled melt flux is slightly too large, but is clearly within the range of observational studies (and likely within a range that could be "tuned" using free parameters in the equations that couple the ice-shelf and ocean thermodynamics). For the Filchner-Ronne Ice Shelf, the modeled melt flux is too large by a factor of ~4 early in the simulation. Near the end of the simulation, melt rates begin to increase steadily and become 10 to 20 times larger than observations. Spatial maps of melt rates also confirm that, in general, modeled melt rates for the Ross Ice Shelf are reasonable, and that while modeled melt rates for the Filchner-Ronne Ice Shelf start off as reasonable, they become much too large by the end of the simulation (Figure 5).

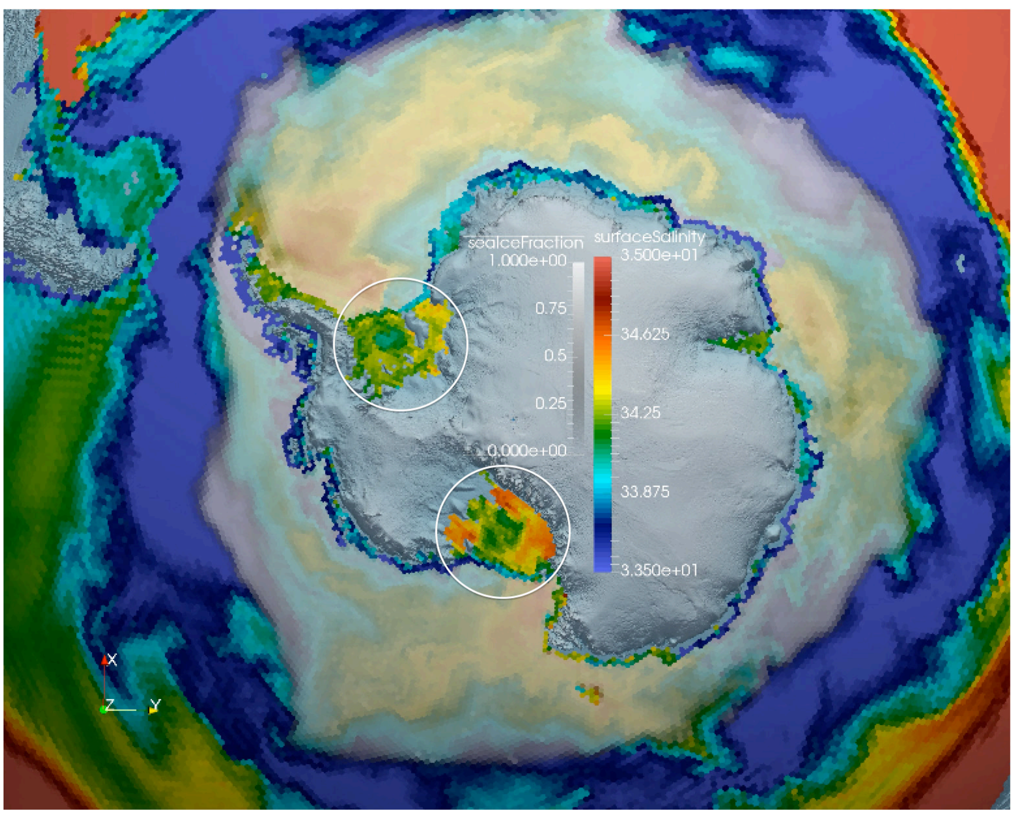

Figure 4. Time slice from a global, coupled, ACME simulation that includes ocean circulation beneath ice shelves. Gray-scale represents sea-ice concentration and colors represent sea-surface salinity. The Ross (bottom) and the Filchner-Ronne (top) ice shelves are circled (also shown in Figure 1).

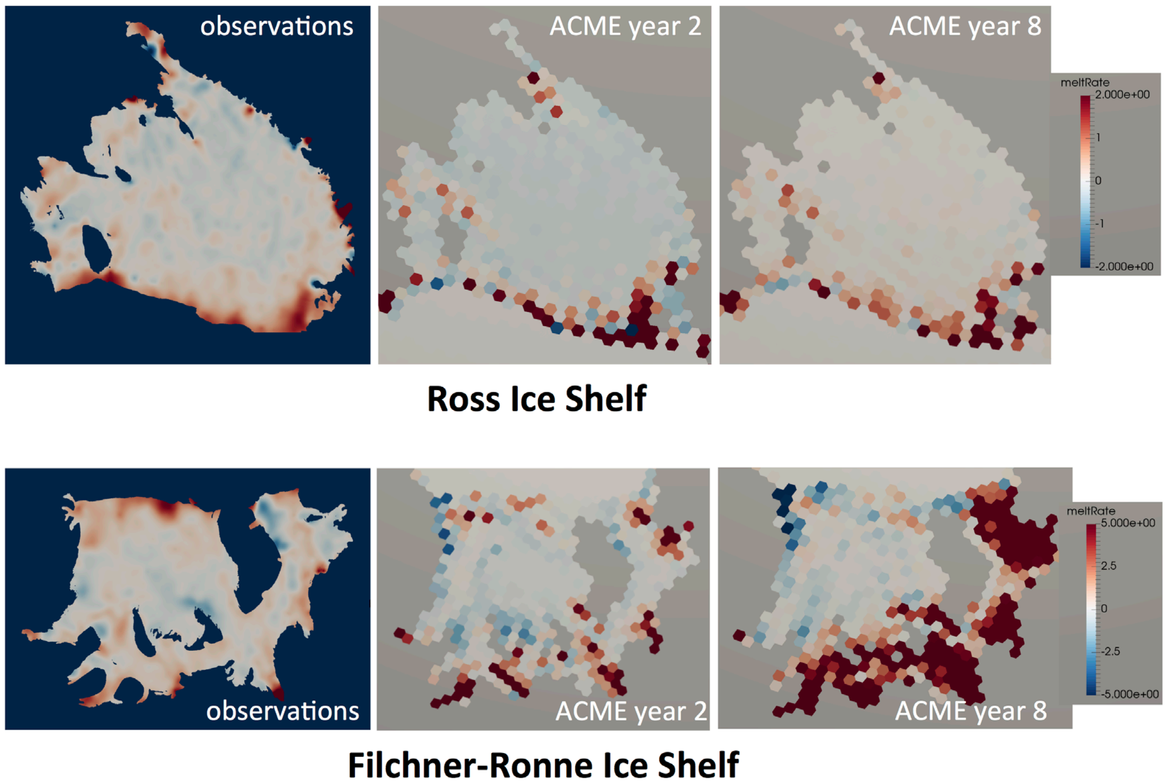

Figure 5. Observed (left column) and modeled (middle and right columns) sub-ice-shelf melt rates for the Ross (top row) and Filchner-Ronne (bottom row) ice shelves. Observations are from Moholdt et al. (2014) and modeled values are from a fully coupled ACME simulation.

Table 1. Estimated basal mass balance (in Gt a-1) for Ross and Filchner-Ronne ice shelves from three observationally based studies versus initial estimates from a coupled ACME simulation. For observations, approximate uncertainties are included in parentheses. For the Filchner-Ronne Ice Shelf, the ACME model value in brackets is taken from near the end of a 9-year simulation, when melt rates are strongly increasing. Note that the values for study 3 are slightly lower because they are based on steady-state assumptions (study 1: Moholdt et al. [2014]; study 2: Rignot et al. [2013]; study 3: Depoorter et al. [2013]).

	ACME	**Study 1**	**Study 2**	**Study 3**
Ross	-94	-50(64)	-48(15)	-34(25)
Filchner-Ronne	-435 [-2375]	-124(66)	-155(22)	-50(30)

A comparison of temperature and salinity across observed and modeled profiles just outside of the Ross Ice Shelf cavity is shown in Figure 6, and at the 300 m depth contour in Figure 7. Modeled temperatures and salinities are reasonably close to observations; in particular, the east-west trend in sloping salinity contours is well captured in the ACME simulation (Figure 6, panels b and d). Modeled salinity is clearly still too low at depth (more clearly seen in Figure 7, panels c and d), however, and temperatures appear slightly too low near the surface (Figure 5, panels a and c), although this may also represent a summertime bias in the observations. If real, this model salinity bias is likely related to too little sea-ice formation and/or export in the coupled model simulation, resulting in too little dense and saline brine formation. Hence, improvement of sea-ice model biases may be expected to improve on these minor biases in the Ross Sea and ice-shelf regions.

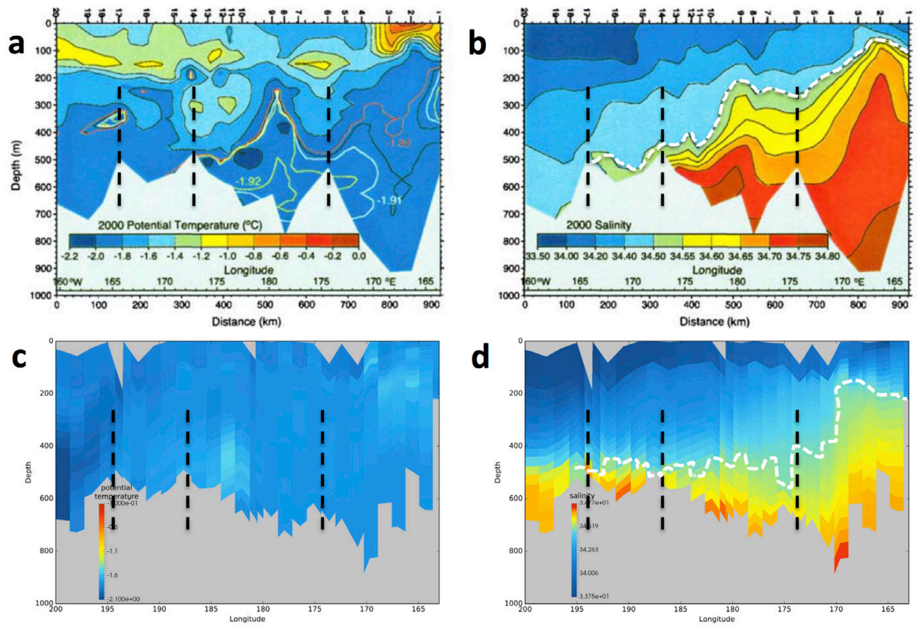

Figure 6. Temperature (a,c) and salinity (b,d) versus depth and longitude in front of the Ross Ice Shelf. The top row (a,b) shows observations in year 2000 from Smethie and Jacobs (2005) and the bottom row (c,d) shows fields taken from year 8 of a fully coupled ACME simulation that includes ocean circulation in ice-shelf cavities. The white dashed contour in panels b and d follows an approximate salinity value of 34.5. Vertical black dashed lines mark common topographic features between the top and bottom rows.

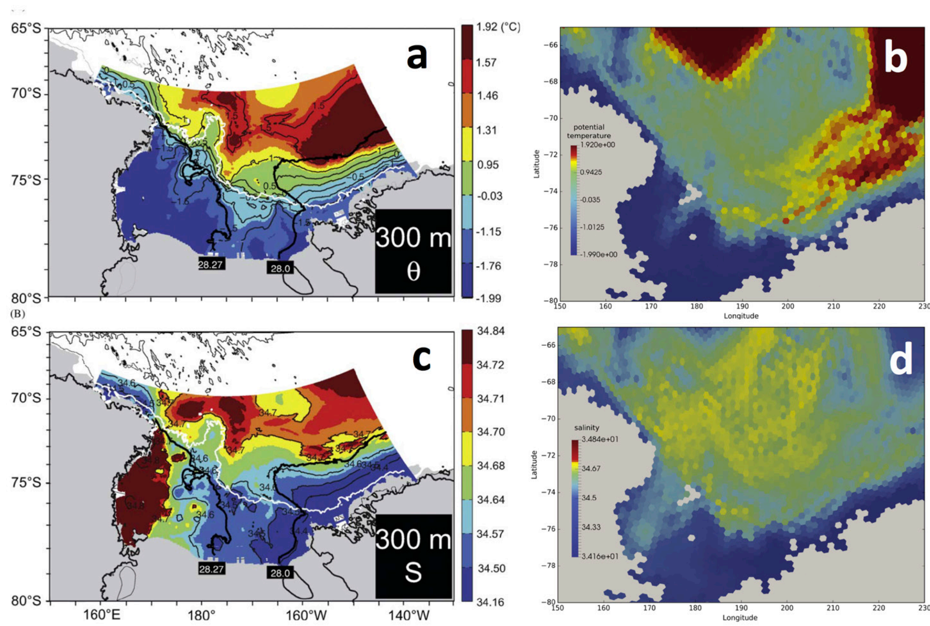

Figure 7. Temperature (a,b) and salinity (c,d) at 300 m depth in front of the Ross Ice Shelf, from observations of Orsi et al. (2009) (a,c) and averaged over the last 4 years of a fully coupled ACME simulation that includes ocean circulation in ice-shelf cavities (b,d).

A comparison of observed and modeled temperature and salinity across the Filchner Trough, a primary pathway connecting the Filchner-Ronne Ice Shelf cavity to the open ocean, is shown in Figure 8. At the start of the simulation, temperatures are slightly too warm and salinities are reasonable, which agrees with the generally reasonable melt rates modeled early in the simulation Figure 5, lower-middle panel). Near the end of the simulation, however, warm and salty WDW can be clearly seen in the Filchner Trough, which serves as a direct conduit to the cavity beneath the Filchner Ice Shelf. There, prevailing circulation patterns provide this warm water access to the entirety of the Filchner-Ronne Ice Shelf, resulting in the excessive modeled melt rates (Figure 5, lower-right panel). Thus, the large bias in modeled melt rates for the Filchner-Ronne Ice Shelf is explained by excess WDW making its way into the ice-shelf cavity.

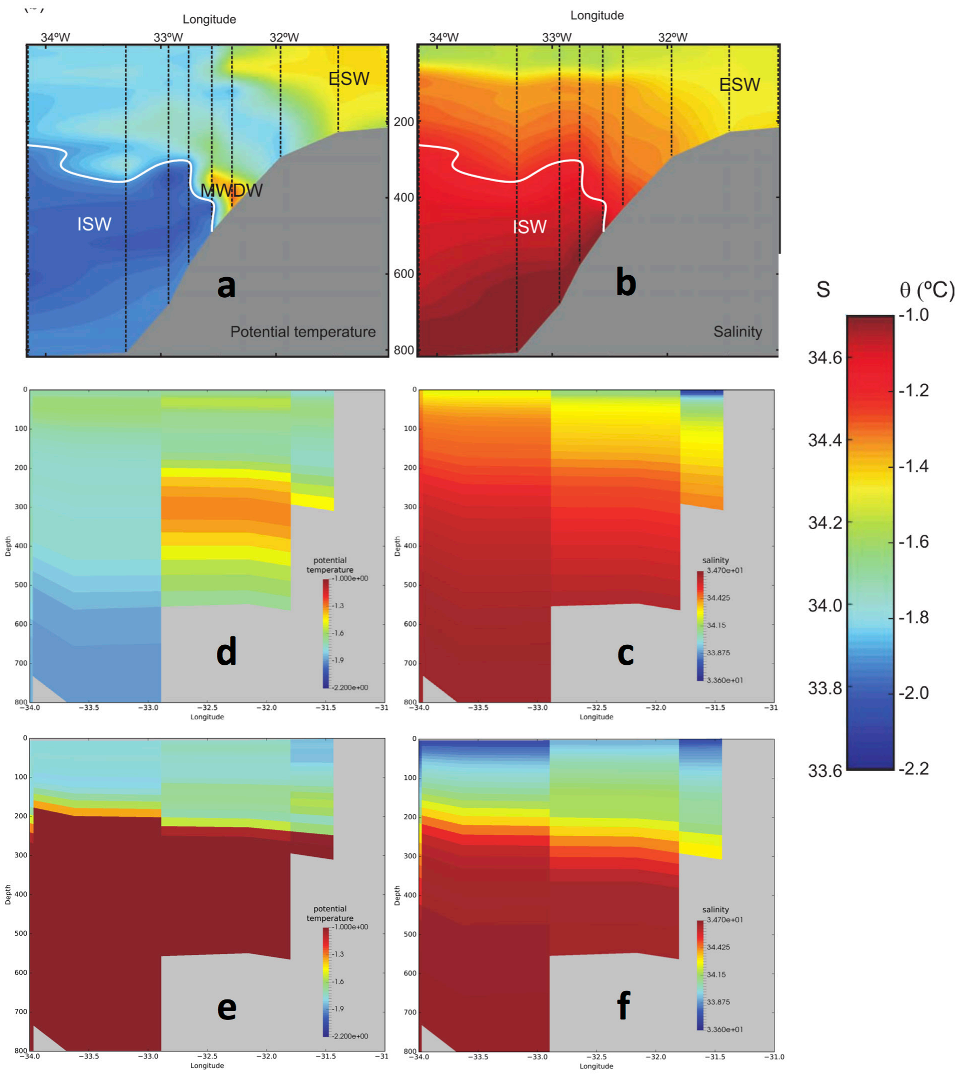

Figure 8. Temperature (left column) and salinity (right column) versus depth along a transect across the Filchner Trough, a primary conduit on the continental shelf connecting the open ocean to the Filchner-Ronne Ice Shelf cavity. The top row shows observations in year 2005 from Nicholls et al. (2009). The middle and bottom rows show fields taken from a fully coupled ACME simulation that includes ocean circulation in ice-shelf cavities. The middle row represents the ocean state at year 1 of the simulation and the bottom row represents the ocean state at year 8.

Several factors could be important for the biased temperature and salinity in the region of the Filchner-Ronne Ice Shelf. In coastal Antarctica, ocean isopycnals (constant density surfaces) are steeply tilted, forming the Antarctic Slope Front, which inhibits the access of warm, deep water to the Antarctica continent. The Antarctic coastal easterly winds, which drive the Antarctic Coastal Current (flowing from east to west), help to maintain these tilted and depressed isopycnals through onshore Ekman pumping of cold, fresh, surface waters. Biases in, or inadequate resolution of, the coastal easterlies and/or the westward flowing Antarctic Coastal Current could result in reduced coastal Ekman pumping and thus the shoaling of warm, deep waters (as demonstrated in model experiments by Spence et al. [2014]). Other factors could include inaccurate mid-depth ocean properties in this region due to either bad initial conditions or inadequate ocean model spin-up time, or biases in the sea-ice model that lead to an inaccurate location for, or inadequate strength of, the Antarctica Slope Front. The latter feature is generally considered to be responsible for “blocking” the flow of WDW into the Filchner Trough. Interestingly, this coupled model bias – very warm WDW making its way into the Filchner Trough and from there into the sub-ice-shelf cavity – is similar to what was seen in regional simulations of the Filchner-Ronne Ice Shelf/ocean system under an A1B climate change scenario (Hellmer et al. 2012). This suggests that breakdown of the Antarctic Slope Front and the resulting ocean circulation pattern seen in the ACME simulation, while not observed under present-day climate conditions, may be a realistic and robust state under a changing climate.

4.0 References

Asay-Davis, XS, DF Martin, WD Collins, SL Cornford, DM Holland, WH Lipscomb, MW Maltrud, EG Ng, and SF Price. The POPSICLES v. 0.5 coupled ocean-ice sheet model, *Geosci. Model Dev.,* (in prep.).

Cornford, SL et al., 2013: Adaptive mesh, finite volume modeling of marine ice sheets. *Journal of Computational Physics*, **232**, 529–549, doi:10.1016/j.jcp.2012.08.037.

Cornford, SL, et. al., 2015: Century-scale simulations of the response of the West Antarctic Ice Sheet to a warming climate. *The Cryosphere*, **9**, 1579–1600, doi:10.5194/tc-9-1579-2015-supplement.

Deconto, RM and D Pollard, 2016: Contribution of Antarctica to past and future sea-level rise. *Nature*, **531**, 591–597, doi:10.1038/nature17145.

Depoorter, MA, JL Bamber, JA Griggs, JTM Lenaerts, SRM Ligtenberg, MR Van Den Broeke, and G Moholdt, 2013: Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature*, **502**, 89–92, doi:10.1038/nature12567.

Fürst, JJ, G Durand, F Gillet-Chaulet, L Tavard, M Rankl, M Braun, and O Gagliardini, 2016: The safety band of Antarctic ice shelves. *Nature Climate Change*, **6**, 479–482, doi:10.1038/nclimate2912.

Griffies, SM, et al., 2009: Coordinated Ocean-ice Reference Experiments (COREs), *Ocean Modell.*, **26**, 1–46.

Hellmer, HH, F Kauker, R Timmermann, J Determann, and J Rae, 2012: Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current. *Nature*, **485**, 225–228, doi:10.1038/nature11064.

Holland, PR, 2014: The seasonality of Antarctic sea ice trends. *Geophys. Res. Lett*, **41**, 4230–4237, doi:10.1002/2014GL060172.

Large, WG, and S Yeager, 2009: The global climatology of an interannually varying air-sea flux data set. *Clim. Dyn.*, **33**, 341–364.

Moholdt, G, L Padman, and HA Fricker, 2014: Basal mass budget of Ross and Filchner-Ronne ice shelves, Antarctica, derived from Lagrangian analysis of ICESat altimetry. *J Geophys Res-Earth*, **119**, 2361–2380, doi:10.1002/2014JF003171.

Nicholls, KW, S Østerhus, K Makinson, T Gammelsrød, and E Fahrbach, 2009: Ice-ocean processes over the continental shelf of the southern Weddell Sea, Antarctica: A review. *Rev. Geophys*, **47**, RG3003, doi:10.1029/2007RG000250.

Orsi, AH, and CL Wiederwohl, 2009: A recount of Ross Sea waters. *Deep-Sea Research Part II*, **56**, 778–795, doi:10.1016/j.dsr2.2008.10.033.

Petty, AA, PR Holland, and DL Feltham, 2014: Sea ice and the ocean mixed layer over the Antarctic shelf seas. *The Cryosphere*, **8**, 761–783, doi:10.5194/tc-8-761-2014-supplement.

Rignot, E, S Jacobs, J Mouginot, and B Scheuchl, 2013: Ice-Shelf Melting Around Antarctica. *Science*, **341**, 266–270, doi:10.1126/science.1235798.

Scambos, T, J Bohlander, C Shuman, and P Skvarca, 2004: Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophys. Res. Lett*, **31**, 18.

Smethie, WM, Jr., and SS Jacobs, 2005: Circulation and melting under the Ross Ice Shelf: estimates from evolving CFC, salinity and temperature fields in the Ross Sea. *Deep Sea Research Part I: Oceanographic Research Papers*, **52**, 959–978, doi:10.1016/j.dsr.2004.11.016.

Spence, P, SM Griffies, and MH England, 2014: Rapid subsurface warming and circulation changes of Antarctic coastal waters by poleward shifting winds. *Geophys. Res. Lett.*, **41**, 4601-4610, doi:10.1002/(ISSN)1944-8007.

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