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Key Points:

- Simulations of basal melt and shelf circulation before and after the Mertz Glacier Tongue (MGT) calving are compared
- Changes in the regional icescape allow warmer water to enter the ice shelf cavity increasing the MGT basal mass loss by 57% at depth
- Changes in icescape influence shelf circulation and ocean-ice shelf interactions, but the response depends on the local factors

Supporting Information:

- Supporting Information S1

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Regional Changes in Icescape Impact Shelf Circulation and Basal Melting

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Abstract Ice shelf basal melt is the dominant contribution to mass loss from Antarctic ice shelves. However, the sensitivity of basal melt to changes in icescape (grounded icebergs, ice shelves, and sea ice) and related ocean circulation is poorly understood. Here we simulate the impact of the major 2010 calving event of the Mertz Glacier Tongue (MGT), East Antarctica, and related redistribution of sea ice and icebergs on the basal melt rate of the local ice shelves. We find that the position of the grounded tabular iceberg B9B controls the water masses that reach the nearby ice shelf cavities. After the calving of the MGT and the removal of B9B, warmer water is present both within the MGT cavity and on the continental shelf driving a 57% increase of the deep MGT basal melting. Major changes in icescape influence the oceanic heat flux responsible for basal ice shelf melting.

1. Introduction

The Antarctic Ice Sheet has a potential contribution to global sea level rise of 58 m (Fretwell et al., 2013) and is restrained by the floating ice shelves around the continent. Ice shelf mass loss, through calving and basal melting, can lead to decreased buttressing and dynamic changes to the upstream ice sheet at different rates for each Antarctic ice shelf (Fürst et al., 2016). Most of the Antarctic Ice Sheet grounded below sea level (marine-based ice) is in East Antarctica, and its melting would raise sea level by 19 m, five times larger than for West Antarctica (Fretwell et al., 2013). The Wilkes Basin near the Mertz Glacier Tongue (MGT) has a marine-based ice equivalent to a global sea level rise of 3–4 m (Mengel & Levermann, 2014). Variability of ice shelf basal melting and input of glacial meltwater into the ocean can also influence water mass properties on the Antarctic continental shelf.

The Adélie and George V Land coast (AGVL; 136–148°E) is one of the most monitored regions in East Antarctica with many studies covering the MGT (e.g., Giles, 2017; Legrésy et al., 2004; Lescarmontier et al., 2015; Massom et al., 2015; Mayet et al., 2013), the polynya distribution (e.g., Dragon et al., 2014; Fogwill et al., 2016; Massom et al., 2001; Tamura et al., 2012), the local bathymetry (e.g., Beaman et al., 2011), and the ocean circulation (e.g., Lacarra et al., 2014; Martin et al., 2017; Shadwick et al., 2013; Snow et al., 2016; Williams et al., 2008, 2010). Prior to the MGT calving, the AGVL region had the second highest sea ice production along the East Antarctic coast (Tamura et al., 2016), partly due to the presence of the MGT and other icebergs in the area (e.g., B9B iceberg) which formed barriers to westward moving sea ice within the Antarctic coastal current (Barber & Massom, 2007). This large polynya region is of global importance because brine rejection associated with enhanced sea ice growth produces Dense Shelf Water (DSW) that contributes to Antarctic Bottom Water (AABW) (e.g., Rintoul, 1998). Previous modeling studies have highlighted the impact of interannual variability in local sea ice production on DSW production and basal ice shelf melting before the calving event (Cougnon et al., 2013; Kusahara et al., 2017; Marsland et al., 2004).

In February 2010, the MGT calved and reduced in length by about half (Figure 1). The calving of the MGT led to a dramatic change in the local icescape (icebergs, ice shelves, and sea ice) (Lescarmontier et al., 2015; Massom et al., 2015; Mayet et al., 2013). The regional polynya area west of the MGT decreased by ~70% (Dragon et al., 2014) and the 2012 sea ice production for the AGVL region (east and west of the MGT) decreased by ~21% (Tamura et al., 2016), leading to an observed freshening and a decrease in density of DSW on the continental

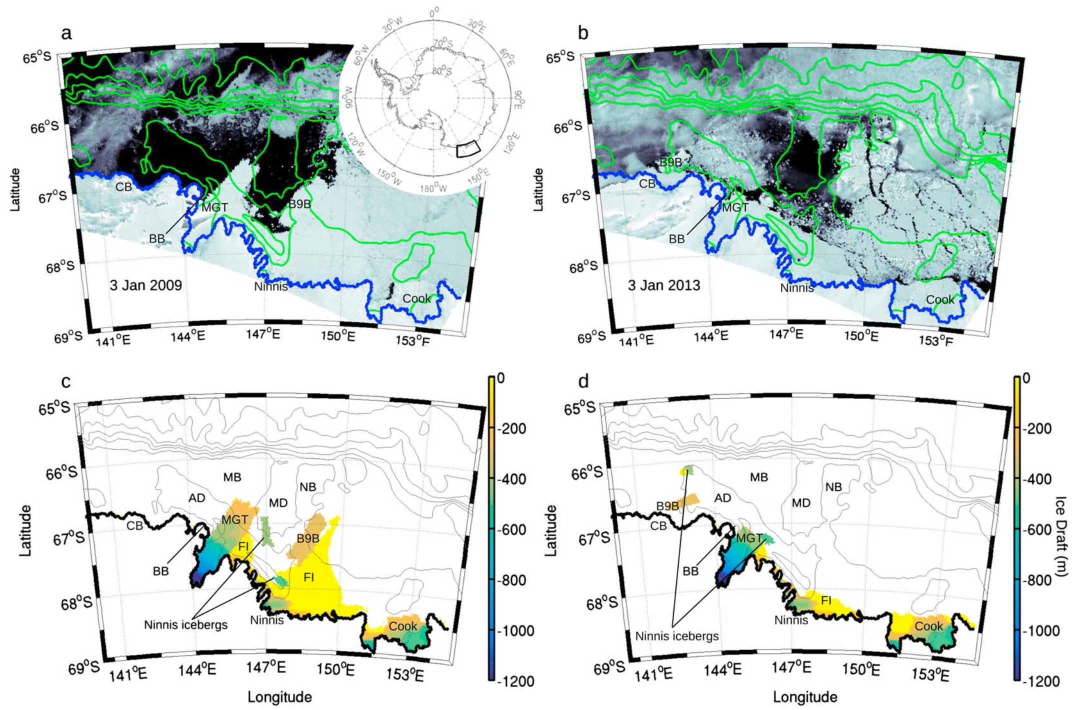

Figure 1. MODIS (Moderate Resolution Imaging Spectroradiometer) image of the MGT region (a) precalving (3 January 2009) and (b) postcalving (3 January 2013). The coastline from the model is highlighted in blue, and the bathymetry contours every 500 m in green. The ice draft (m) used in the model is shown for the (c)precalving and (d) postcalving simulation. The same coastline and bathymetry contours as in Figures 1a and 1b are shown in Figures 1c and 1d in black and grey, respectively. Key ocean, ice, and land features referred to in the text are labeled in Figures 1c and 1d. In the ocean: Adélie Depression (AD), Mertz Bank (MB), Mertz Depression (MD), and Ninnis Bank (NB); on the ice: Mertz Glacier Tongue (MGT), fast ice in yellow (FI), and B9B iceberg; along the continent: Commonwealth Bay (CB) and Buchanan Bay (BB).

shelf (Lacarra et al., 2014; Shadwick et al., 2013). The calving event makes this region an appropriate case study for modeling and understanding the implications of a regional change in icescape, in terms of its effect on both local ocean circulation and basal melt of the local ice shelves and icebergs.

Shelf air-sea processes are important in driving variability of the ice shelf basal melt by regulating the ocean heat content within the ice shelf cavities (e.g., Cougnon et al., 2013; Gwyther et al., 2014; Khazendar et al., 2013; St-Laurent et al., 2015). However, the effect of tabular icebergs on ocean circulation and ice shelf basal melting has been poorly explored. Several studies have looked at the impact of icebergs on the broader scale and on freshwater input beyond the Antarctic continental shelf (e.g., Marsh et al., 2015; Stern et al., 2016). Regional studies have highlighted the role of grounded icebergs in enhancing sea ice production locally (e.g., Fogwill et al., 2016; Massom et al., 2001; Ohshima et al., 2013). Only a few regional studies on the continental shelf have shown the influence of changes in grounded iceberg locations on the ocean properties and ice shelf basal melting (e.g., Grosfeld et al., 2001; Nakayama et al., 2014; Robinson et al., 2010). Here we use a relatively high-resolution regional ocean model, with ocean-ice shelf thermodynamics, to investigate the impact of changes in local air-sea forcing and changes in icescape on both the basal melt rate of the local ice shelves and icebergs, and on the ocean properties on the continental shelf.

2. Model

We use a modified version of the Regional Ocean Modeling System (ROMS) (Shchepetkin & McWilliams, 2005) adapted for the MGT region, before and after the 2010 calving event (Figure 1; also see supporting information for the full domain and complementary details on the model setup — Figures S1 and Text S1). The model setup used here is similar to that described by Cougnon et al. (2013), using the same horizontal and vertical grid. The horizontal grid has a resolution of ~2.16 km near the southern boundary and ~2.88 km near the northern boundary. The vertical grid is arranged to give higher resolution at the top and bottom of the water column.

The model includes ocean-ice shelf thermodynamics described by three equations following Holland and Jenkins (1999), frazil ice thermodynamics following Galton-Fenzi et al. (2012), as used in previous studies (e.g., Cougnon et al., 2013; Gwyther et al., 2014), and a simplified analytic tidal forcing at the lateral boundaries.

The bathymetry in both simulations is based on RTopo-1 (Timmermann et al., 2010) and modified to include local high-resolution bathymetry (Beaman et al., 2011) as described in Mayet et al. (2013). The MGT and B9B iceberg ice draft, along with the underlying bathymetry, is based on an early version of the most up-to-date product by Mayet et al. (2013). Figures 1a and 1b show satellite images of the precalving and postcalving icescape configuration near the MGT. The ice draft used in the model is shown in Figures 1c and 1d. For the precalving configuration two Ninnis icebergs are defined in the model as in Cougnon et al. (2013), including one that differs from the 2009 satellite image (Figure 1a). The Ninnis iceberg directly east of the MGT in the precalving simulation left the region in the 2000s, although icebergs are regularly released from the Ninnis glacier and ground or remain alongside the MGT for several years (Massom et al., 2010). The bathymetry and ice draft used in the postcalving simulation are based on the ice shelf and iceberg configuration in 2012–2013. A climatology of "persistent" landfast sea ice (between 2010 and 2012 for the postcalving configuration) updated from Fraser et al. (2012) is also included.

The model is forced at the surface with monthly data from 2009 for the precalving simulation, and 2012 for the postcalving simulation. In the absence of a dynamic sea ice model, polynya activity is represented by forcing the surface of the ocean with heat and salt fluxes. These fluxes are calculated from sea ice production estimates from a climatology derived using Special Sensor Microwave Imager data (SSMI, Tamura et al., 2011, 2016). Surface wind stress in the model is calculated using the 10 m monthly wind record from ERA-Interim (Dee et al., 2011) from 2009 and 2012 to match the air-sea heat and salt fluxes. The same lateral boundary forcing is used in both simulations, based on the 22 year climatology (1992–2013) calculated from the ECCO2 monthly fields (Menemenlis et al., 2008; Wunsch et al., 2009). In this way, we ensure that any changes between the two simulations arise from changes in both icescape and associated change in surface forcing, rather than changes outside the AGVL region (see supporting information for details). The total run time of the model for each simulation is 33 years, using an annually repeating loop of the same lateral forcing for both simulations and an annually repeating loop of the surface forcing corresponding to each icescape. This 33 year run includes a spin-up phase of 30 years to reach equilibrium. The last 3 years of each run are averaged as a time step bin climatology (each time step of each year are averaged to get a one year climatology) for the analyses.

Previous studies have shown that this model is reliable for different areas in East Antarctica, including the AGVL region, (e.g., Cottin et al., 2012; Cougnon et al., 2013; Fogwill et al., 2016; Galton-Fenzi et al., 2012; Gwyther et al., 2014). In addition, we performed an evaluation of the model with available observations, showing that the model reproduces many aspects of the water mass structure and ocean circulation both precalving and postcalving (see supporting information).

3. Changes in Basal Melting After the 2010 Calving Event

The precalving simulation indicates a basal mass loss from the entire MGT of 5.6 ± 0.5 Gt yr^{-1} (Table 1), corresponding to an area-averaged basal melt rate of 0.93 ± 0.08 m yr^{-1} (supporting information Table S1). The postcalving simulation produces comparable MGT basal mass loss of 6.0 ± 1.0 Gt yr^{-1}, corresponding to an area-averaged basal melting of 1.7 ± 0.3 m yr^{-1}. As such, the area-averaged melt rate of the MGT increased substantially (+89%) in the postcalving simulation, as the area available for melting decreased by 42% (Table 1).

The basal melting of the MGT is spatially heterogeneous (Figures 2a and 2b). In the precalving simulation, the highest rate of basal melting occurs near the narrowest point of the embayment (up to 7.5 m yr^{-1} locally). The rate of mass loss from ice drafts deeper than 900 m is 2.16 ± 0.05 Gt yr^{-1} in the precalving simulation, corresponding to 40% of the total basal mass loss of the MGT (Table 1). Another hot spot of melting is seen at the northeastern tip of the MGT, with melt rates up to 3.1 m yr^{-1} (Figure 2a), due to direct interactions with relatively warm water. The rate of mass loss from ice drafts shallower than 300 m is 1.4 ± 0.4 Gt yr^{-1} (Table 1). Finally, refreezing occurs along the western edge of the MGT cavity in the precalving simulation.

The postcalving simulation shows a similar distribution but increased magnitude of basal melting, with the maximum melt rate (up to 11.3 m yr^{-1} locally) again at the narrowest part of the MGT embayment, and a refreezing area along the western edge of the cavity. For ice drafts deeper than 900 m, giving the same area

Table 1
Basal Mass Loss for the Precalving and Postcalving Simulations With Their Standard Deviation

Ice Shelf	Mass loss precalving (Gt yr^{-1})	Mass loss postcalving (Gt yr^{-1})	% mass loss change	% basal ice shelf area change	% area-averaged melt change
Total[a]	23.8 ± 2	20.5 ± 3	−14	−19	+7
MGT	5.6 ± 0.5	6.0 ± 1.0	+7	−42	+89
B9B	5.3 ± 0.9	0.6 ± 0.1	−89	−69	−64
Ninnis	0.6 ± 0.4	1.3 ± 0.8	+117	0	+100
Cook	7.3 ± 1.4	4.5 ± 1.7	−38	0	−37
$M^b < -900$ m	2.16 ± 0.05	3.4 ± 0.5	+57	0	+57
$-900 < M^b < -600$ m	0.86 ± 0.04	1.7 ± 0.5	+98	0	+95
$-600 < M^b < -300$ m	1.2 ± 0.2	0.88 ± 0.3	−26	−50	+49
$M^b > -300$ m	1.4 ± 0.4	0.009 ± 0.005	−99	−99	−42

[a]All the ice in the model including all ice shelves, icebergs, and fast ice. [b]MGT ice draft.

precalving and postcalving, the rate of mass loss increases by 57% (Table 1). The calving of the MGT and associated change in sea ice distribution and ocean circulation also impacts ice shelves to the east. The basal mass loss from the Ninnis Ice Shelf (Figure 2) doubles after calving but remains relatively low (<1.5 Gt yr^{-1}; Table 1). In contrast, the mass loss from the Cook Ice Shelf, near the southeastern corner of the model domain, decreases by 38%, and there is no significant change in total averaged basal mass loss (Table 1).

In our model, the basal melting is parameterised via the three-equation method (Holland & Jenkins, 1999), using a velocity-dependent formulation for the estimation of heat and salt fluxes at the ocean-ice shelf interface (Gwyther et al., 2015). As a result, the basal melt rate in our model is a function of both the friction velocity (u_*) and the thermal forcing (T_*). Estimation of u_* and T_* for the ice deeper than 600 m for the MGT (same area precalving and postcalving within the embayment) shows that T_* increases by 39% between the precalving and the postcalving simulations, while u_* increases by 26%, illustrating that the increase in ocean temperature is the main driver of the 69% increase in area-averaged basal melt rate of the MGT for ice deeper than 600 m (supporting information Text S2 and Table S2).

The effect of the large tabular iceberg B9B on the area has been poorly studied. B9B rested for ~20 years on the Ninnis Bank (Mayet et al., 2013), forming a barrier against westward moving sea ice (Massom et al., 2001) and allowing a small polynya area in its lee (western side) (Massom, 2003). In our simulations, B9B iceberg precalving shows significant basal mass loss (5.3 ± 0.9 Gt yr^{-1}), which is of the same order as the MGT (Table 1). After calving, B9B shows a substantial decrease in basal mass loss, partly due to its ~70% decrease in area following partial breakup of the iceberg during the initial phase of the calving. In its precalving location,

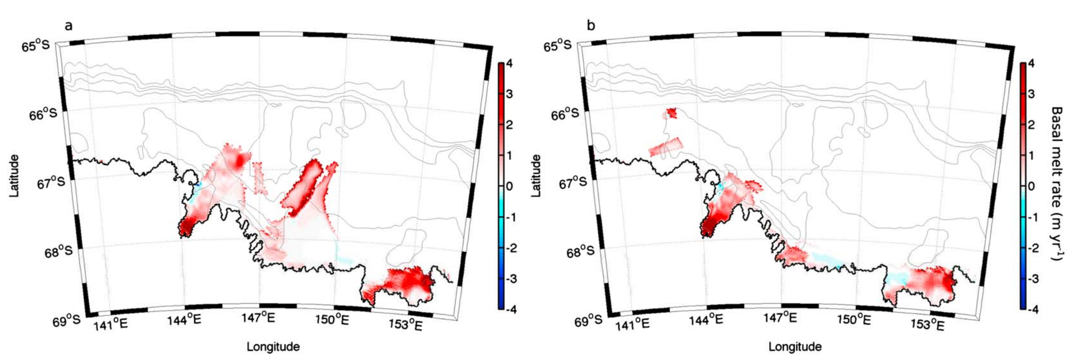

Figure 2. Time-averaged basal melting (m yr^{-1}) for the (a) precalving and (b) postcalving simulations. Positive values of basal melting correspond to melting and negative to refreezing beneath the ice shelf. Bathymetry contours every 500 m are also shown on each panel.

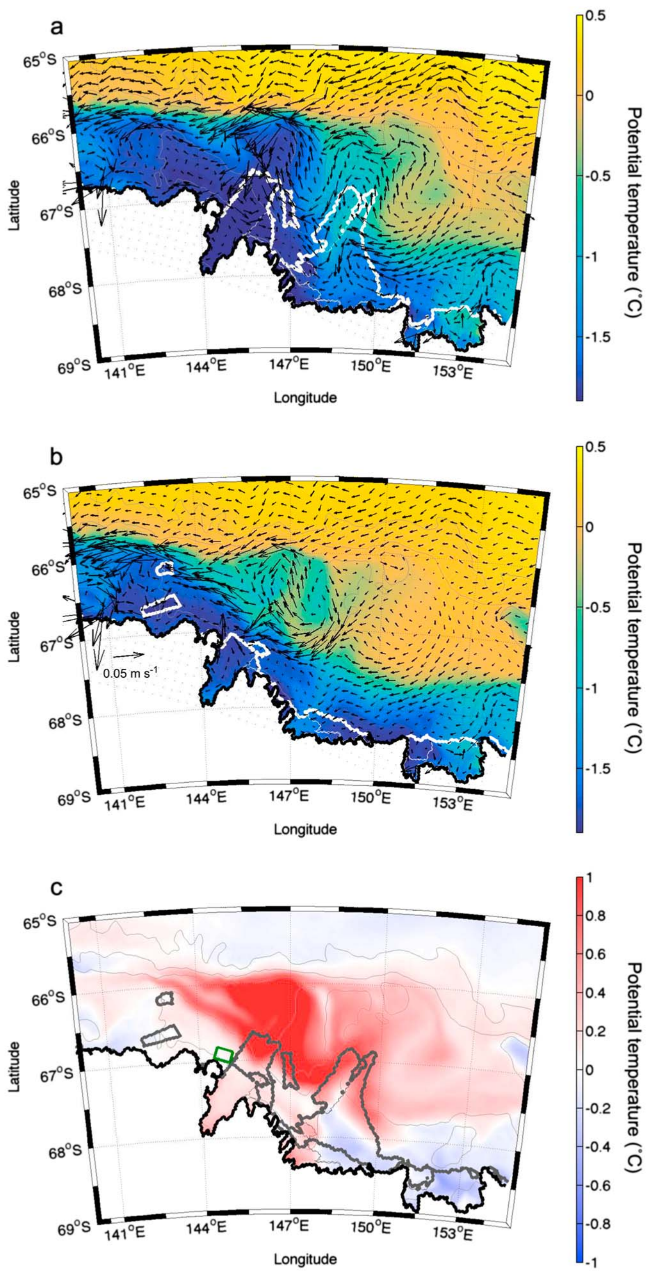

Figure 3. Time and depth-averaged potential temperature (°C) overlaid with the depth-averaged velocity field for the (a) precalving and (b) postcalving simulations. (c) The depth-averaged potential temperature difference, postcalving minus precalving. Positive values indicate warming and negative values cooling of the postcalving simulation compared to the precalving. The black contours for the three panels illustrate the coast line, and the white (grey) contours in Figures 3a and 3b (Figure 3c) illustrate the ice mask in the model and stationary ice features (icebergs, fast ice, and ice shelves).

B9B is more exposed to warmer far-field water masses than it is during postcalving, when it is grounded near the coast north of Commonwealth Bay.

4. Warmer Water on the Continental Shelf After the 2010 Calving Event

Both the ocean circulation and distribution of heat on the continental shelf change in response to the different icescape and associated surface forcing (Figure 3). In the precalving simulation, the vertically integrated ocean velocity along the shelf break and the depth-averaged potential temperature (Figure 3a) illustrate three main pathways for the modified Circumpolar Deep Water (mCDW) to flow onto the continental shelf in the MGT vicinity. One pathway is onto the Mertz Bank, allowing mCDW to interact with the northern tip of the MGT and drive high basal melt rate (Figure 2a). A second mCDW pathway is onto the Ninnis Bank. Finally, a westward flow of relatively warm mCDW ($\Theta > -1$°C), from the east of the model domain (~67.5°S, 152°E), less modified compared to the inflow via the Mertz Bank ($-1.3 < \Theta < -1$°C), is deflected by B9B (~ 67–67.5°S, 148–149°E).

In the postcalving simulation, pathways for mCDW onto the continental shelf are similar, including via the Mertz and Ninnis Banks, although the flow is generally weaker (Figures 3a and 3b). However, east of the Ninnis Bank and where the B9B iceberg was located (~67°S, 149°E), the postcalving simulation shows an intensification of the westward current. This path allows warmer mCDW ($\Theta > -0.3$°C) to flow nearer to the postcalving MGT ice front and along the southwestern flank of the Mertz Bank.

The area over the Mertz Depression and Bank (67–66°S, 144–150°E) postcalving is warmer by more than 1°C (Figure 3c), highlighting that B9B precalving redirects and modifies water masses in its lee. B9B blocks the passage of mCDW on its eastern side and leads to cooling of the water masses in its lee, both through glacial meltwater release and sea ice formation within the small polynya forming in its lee. The high melt rate of B9B precalving is a consequence of mCDW interacting mainly along its eastern and northwestern flanks (Figure 2a).

Postcalving, B9B no longer provides a barrier to restrict the inflow of warm waters from the east across the Ninnis Bank, Mertz Depression, and along the southern flank of the Mertz Bank. The remnant B9B is currently located north of Commonwealth Bay, directly west of the coastal Mertz Glacier Polynya (MGP) and away from relatively warm water circulation.

Within the deepest part of the Adélie Depression west of the MGT, the ocean circulation and potential temperature are essentially unchanged postcalving (Figures 3a and 3b). The depth-averaged potential temperature is close to the surface freezing temperature, suggesting that the wintertime convection due to polynya activity is still strong enough after calving to mix the whole water column. However, the bottom layer of the model (not shown) has freshened by 0.101 ± 0.003 within the deepest part of Adélie Depression north of Buchanan Bay (green box in Figure 3c), likely in response to the decreased sea ice formation and associated brine rejection.

The decrease in sea ice production is given in the model by a 52% decrease in salt flux input into the ocean for the green square area in Figure 3c. This decrease in salt input reduces the strength of winter convection. The related freshening signal north of Buchanan Bay is in good agreement with observations taken in 2010 and 2012, which show a decrease in bottom salinity of 0.12 (Lacarra et al., 2014). Shadwick et al. (2013)

use three years precalving (1978, 2001, and 2008) and 2012 postcalving for a similar area, finding a decrease in bottom salinity ranging from 0.08 to 0.15.

5. Discussion

The increase in area-averaged basal melt rate of the MGT after calving should imply a drop in surface elevation of the glacier after several years, assuming a constant ice velocity toward the ocean. The increase in area-averaged basal melt of ice deeper than 900 m of ~1.8 m yr^{-1}, suggests a drop in surface elevation of ~18 cm yr^{-1} after calving. Unfortunately, the currently available satellite data do not allow changes to be estimated with sufficient accuracy. The two main satellites present before calving, ICESat and ENVISAT, ended their exact repeat operations in 2009 and 2010, respectively. There is no digital elevation model (either stereo-optical or INSAR based) with the required and repeated accuracy over the period. Cryosat-2 detects a slight but not significant elevation decrease in the area (Helm et al., 2014). In the coming years a significant thinning signal may be revealed with the continuation of Cryosat-2 and the introduction of Sentinel-3 data.

A recent modeling study of the region (Kusahara et al., 2017) find that basal melting of the MGT reduces, and bottom salinity in the MGP increases associated with a decrease in bottom potential temperature, after calving, in contrast with our results and with observations of freshening and no change in potential temperature of bottom waters (Lacarra et al., 2014; Shadwick et al., 2013). Both models find an increased signal of mCDW on the shelf east of the MGT after calving, however, in Kusahara et al. (2017) this signal also explains the increase in bottom salinity in the MGP. The two models differ in several important respects. The global coupled ocean-sea ice model of Kusahara et al. (2017) has coarser horizontal resolution (5–6 km in the AGVL region); their simulated sea ice production rates are higher than the Tamura et al. (2008) estimates; they use different bathymetry and ice draft; and their ocean-ice shelf parameterization is independent of velocity and depends only on temperature. All of these factors may influence the modeled response to calving of the MGT. Few studies have shown the importance of friction velocity in the spatial distribution of the ice shelf basal melt when using a velocity-dependent formulation (e.g., Dansereau et al., 2014; Gwyther et al., 2015, 2016). Dinniman et al. (2016) highlighted the need for high horizontal resolution and a realistic shape of the ice shelf cavity. The topography of the ice shelf cavity influences the magnitude of the melt rate (Holland et al., 2008; Little et al., 2009), in particular near the grounding line as shown by plume model studies (e.g., Jenkins, 2011). The difference in ice draft may be of particular importance. In their model, ice drafts are limited to depths of 550 m, while we show that mass loss at depths (>600 m) is significant (Table 1).

Observational study by Aoki et al. (2017) shows changes in oceanic conditions after the MGT calving, with a decrease in mCDW west of the MGT but an increase east of the MGT. They also observe an increase in continental meltwater signal within the Adélie depression but they cannot clearly identify the source. They use Kusahara et al. (2017) to justify that continental meltwater may come from further east (West Antarctic Ice Sheet). However, other possible sources might be more local, such as from the Ninnis Ice Shelf just east of the MGT (further discussion in supporting information).

Here we show that B9B, in its precalving position, blocks warm waters from reaching the MGT and releases relatively high amounts of glacial meltwater (Table 1). Grosfeld et al. (2001) show that icebergs grounded in front of the Filchner Ice Shelf can decrease the thermohaline ventilation within the ice shelf cavity and subsequently decrease the ice shelf basal melting. Robinson et al. (2010) show that water masses within McMurdo Sound can be influenced by the proximity of giant icebergs allowing heavy sea ice cover and preventing warm water from accessing the ice shelf cavity. A modeling study by Nakayama et al. (2014) show that grounded icebergs west of the Pine Island (PI) Glacier act as a barrier against westward moving sea ice formed within the PI polynya, which can decrease the sea ice formation within the polynya and the associated Winter Water layer thickness, allowing mCDW to flow closer to the PI ice front. We conclude that changes in icescape can impact the basal melt of local ice shelves; however, the response varies regionally.

6. Summary

Our study highlights some consequences of regional changes in icescape (ice shelves, tabular icebergs, and sea ice) and associated changes in surface forcing on basal melting and ocean circulation. Specifically, we demonstrate that changes in location of the tabular iceberg B9B, and the calving of about half the length of the MGT, alter regional ocean currents and temperatures. This in turn leads to an increase in basal melt of the MGT and Ninnis Ice Shelf (Table 1). Before the MGT calving, B9B redirects (by its location and thickness, Figure 3) and modifies (by releasing large amount of glacial meltwater, Table 1) the relatively warm mCDW entering the continental shelf along the AGVL region, altering the water masses reaching the ice shelf cavities.

Associated with the MGT breakup and relocation of B9B to the west, the sea ice conditions change, and the brine rejection significantly decreases leading to the presence of a fresher bottom water mass within the Adélie depression, in agreement with hydrographic measurements. In parallel, the column-averaged ocean warms to the north and northeast of the MGT by more than 1°C (Figure 3), providing a source of warmer water into the MGT cavity and driving a 57% increase in the basal mass loss for ice deeper than 900 m.

Iceberg calving events may increase in frequency with enhanced ocean-driven basal melt of Antarctic Ice Shelves (Liu et al., 2015). Our results suggest that increased numbers of large tabular icebergs, with sufficient thickness to ground on the continental shelf, will influence ocean circulation and heat transport, and hence the rate of basal melt of local ice shelves. In the Mertz region, the combined effects of drifting and regrounding of iceberg B9B and the calving of the MGT increase the rate of basal melt. Studies in other regions have found that grounding of icebergs can reduce the rate of basal melt of nearby ice shelves (e.g., Grosfeld et al., 2001; Robinson et al., 2010). We conclude that ocean-ice shelf interaction is sensitive to changes in the regional icescape, including changes precipitated by calving, drift, and grounding of large icebergs, but that the nature of the response will depend on local factors including bathymetry and the location of icebergs relative to ice shelves and ocean currents, and associated changes in air-sea fluxes.

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