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Dear Dr Matsuoka,

Thank you so much for your further Editorial review of manuscript tc-2016-19 for *The Cryosphere*. Please find attached a revised resubmission of our manuscript entitled 'IMPACTS OF A DEVELOPING POLYNYA OFF COMMONWEALTH BAY, EAST ANTARCTICA, TRIGGERED BY GROUNDING OF ICEBERG B09B' which remains formatted as a Brief Communication for *The Cryosphere.* In light of your and both reviewers comments we have substantiality revised the results and discussion sections of the manuscript, to focus principally on the observational data as suggested, disentangling the observational data from the model projections. We firmly believe that the modelling outputs (based on multidecadal runs) add greatly to the single season observations, and are therefore critical to understand the mechanisms driving contemporary circulation changes in this important region; a region which is still undergoing substantial change.

Our previous submission did not clearly differentiate current observations of the region's transitional state from modelled projections of a future re-equilibriated steady-state, and this has obviously led to confusion. We hope that our updated manuscript clarifies the issues raised. In our resubmission we attempt to highlight that the aim of the modelling study was not simply to '*reproduce ocean properties*' (Reviewer Two), either before or after the Mertz Glacier calving event or the grounding of B09B in Commonwealth Bay, but rather to understand the mechanisms of change and potential future impacts across the region. Each of our model simulations represents the circulation after 30 years under the respective geometries, and therefore is unlikely to '*perfectly*' (Reviewer Two) simulate this complex system, which, importantly, remains in flux after the dramatic events of 2010.

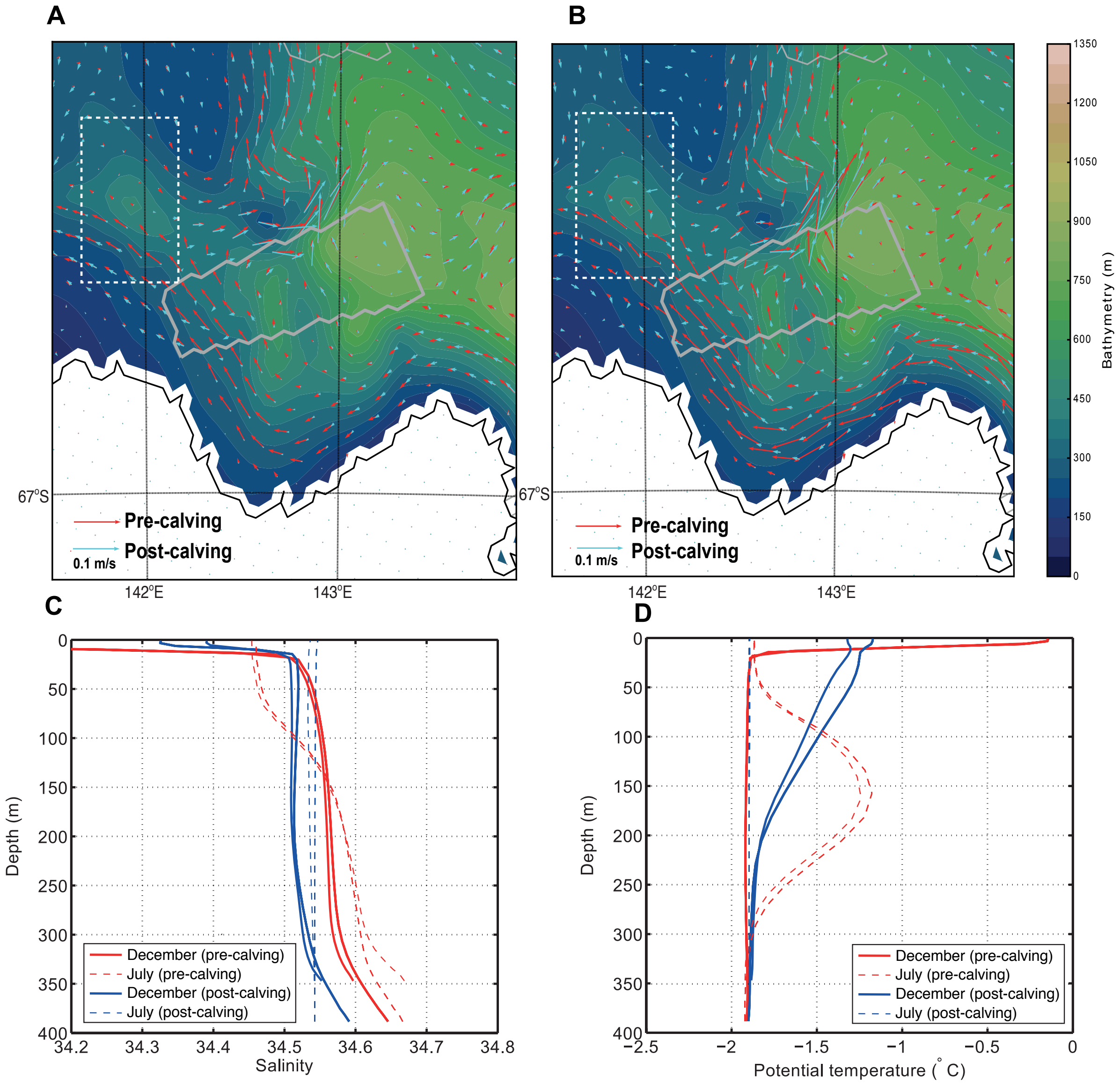
It is critical to clarify the complementary aims of the dual approach taken in this study: the observations provide evidence of a developing polynya whilst the multidecadal model runs provide mechanistic insights into the processes involved. To communicate this more clearly, we have substantially reformatted the manuscript to disentangle our observational data from the modelled scenarios. We have also added a further figure (Figure 2), which depicts the impacts on sea-ice production based upon the Tamaura et al., (2016) sea ice reconstructions for 2009 and 2012, which support our interpretation of a developing polynya in the lee of B09B. As asserted in our original resubmission, *'our model simulations do not show the current evolution of the impact of the calving, but rather simulate the ocean conditions for two stable ice geometries, before and after the Mertz calving'*; however, we argue that our modelling provides insights into the potential circulation changes (defined from simulated current velocity for the bottom 5 layers of the model), and that the simulated salinity and temperatures are useful measures with which to explore the potential future impacts of the event, as well as the mechanisms that continue to unfold.

Therefore, combined, the current observational data of a dynamic system together with modeled future projections enhance our understanding of the sensitivity of HSSW and AABW formation to changes in the local icescape. Our results show how movement of large icebergs such as B09B can alter regional ocean circulation and air-sea interaction patterns, producing new regions of dense water formation. Critically, we feel these observations are well suited to the format of a *Cryosphere* 'Brief Communication'.

In response to your review we respond to the following key points:

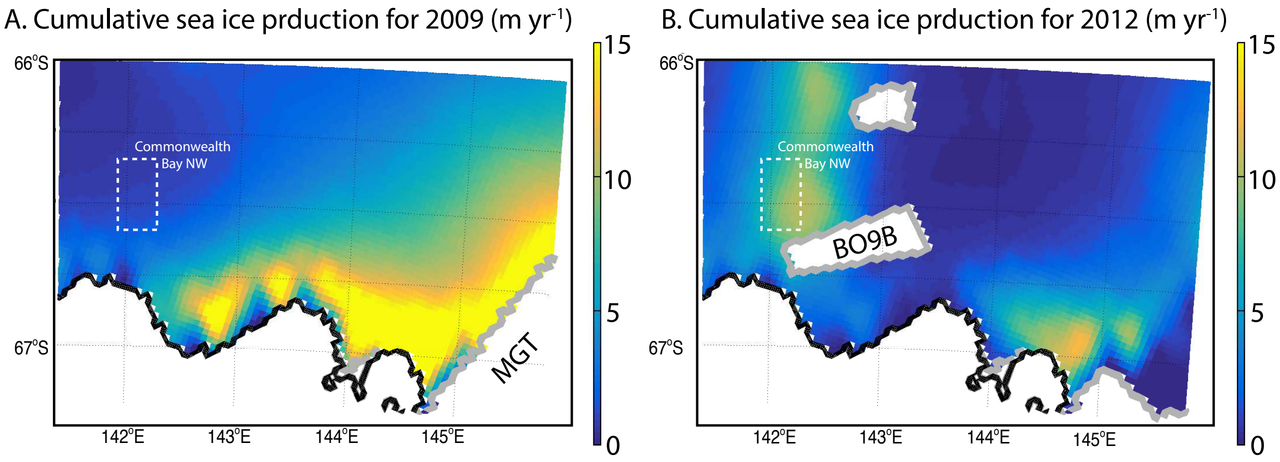
1. *If modelled velocity data is used to support the HSSW advection, the modelled velocity should be presented at the depths where HSSW is expected:*

We have updated the revised Figure 3 to demonstrate this, by presenting the velocity changes in the **lowest 5 layers** of the model, the result of which support our original interpretation. The blocking effects of B09B on water masses from the Mertz region can be clearly seen.



2. *'The author also claimed that there is an active polynya in Commonwealth Bay NW and generate HSSW that is convected to the sea floor (P7L11). However, it is unclear for me whether this water mass with the uniform salinity is locally made or advected from somewhere.'*

The velocity changes in the model domain suggest a local origin, although we cannot completely rule out advection from elsewhere. However, when combined with the variations in sea ice production interpolated from satellite observations between 2009 and 2012 (new Figure 2 below (Tamara et al., 2016), local production would appear likely. We have substantially rewritten the text to clarify this.



3. ‘*The results section includes discussion-type statements, beyond the results, which should appear in the discussion section. This confuses readers to judge what the data and model really show respectively, and what are author’s arguments based on the observation and modelling.’*

We have addressed this in our resubmission, disentangling our observations from the model projections. We hope our rewrite clarifies this.

4. *In Section 3.2 (P6L18-20), sea ice production is presented as “modeled” but it is basically taken from Tamura et al. (2016) (P4L23-24). So, cumulative sea ice production presented in Figure 2A and 2B are somewhat observations, not really modelling outputs. I see a similar problem at P8L5.*

We apologise for any confusion. This was not our intention but rereading the text we can see this was ambiguous. We have now rewritten the text to clarify this point. We hope this change is satisfactory.

Specific comments.

1. *P2L24: remove one “)” and double “the”*
   We have corrected this in our resubmission
2. *P4L12: Why is it necessary to show the Microcat CTD data? The main body of the manuscript does not use the Microcat data at all, and it appears only in Supplement Figure S1.*
   The CTD data is essential as the XCTD’s are working at their lower range (guaranteed to -2C), therefore direct comparison with a ‘cold water’ calibrated CTD provides confidence for us, and the reader, that the data is 100% reliable. We have stated this in the main text in our resubmission.
3. *P4L23: model/ocean coupling?*
   We have corrected this in our resubmission

4. *P5L24: Which depth range do you expect to see HSSW layer? It is said that the observed depth range is too shallow to observe it. The observed fact is the absence of HSSW, and inferring HSSW at greater depths is author's speculation in this case. Please more clearly distinguish observed facts and interpretations/discussion.*

   We apologise. There is clearly confusion here: we are referring only to our observations in the Mertz NE sector, where pre-2010 HSSW was generally recorded between 400 and 500m; only one of our observations exceeds this depth (~550m). Crucially, both of our XCTD casts suggest a return of HSSW below 380m, with similar profiles to pre-2008 casts. So whilst we cannot say decisively that production of HSSW has resumed, the evidence is consistent with this interpretation. We hope our rewritten manuscript is clear in regards to this important point. Critically, this point has no bearing on our discussion of the developing polynya in the Commonwealth Bay NW region.
5. *P6L10: add a reference to support a statement on the absence of HSSW prior to the B09B grounding.*
   We have added the relevant Laccrra et al. (2014) and Rintoul (1998) references here.
6. *P6L18: as the reviewer #2 pointed out, Tamura et al. (2016) is a boundary condition for the modelling, not a modelling output.*
   We appreciate this and acknowledge it throughout our resubmission.
7. *P6L24-P7L1: It is confusing. Fig. 2C/D show that shallow water is warmer and fresher (red solid curves) than deep water, which is said immediate above. So, these statements are not consistent.*
   We have addressed this in our resubmission.
8. *P8L8-10: Revise "The effect this change of..."*
   We are not quite sure what this issue is in regards to this statement in our original draft?
9. *Figure 1:*
   *- The caption can be clearer, starting for example "XCTD data. (a) locations of ....". It's better to say clearly what Figure 1 is about at the beginning, rather than what the panel a is about.*
   We have addressed this for Figure 1 and the other figures in our resubmission

   *- Blue labels on black parts of satellite imagery are very hard to read (especially on hard copy). Change the colour, or use a lighter colour to outline these letters.*
   We have corrected this in our resubmission.

   *- For panels (B)-(G), legends are common so it is adequate to show it in a single panel. In the text, the authors emphasized that salinity/temperature can be changed seasonally so data can be compared when they are collected in the same season. So, please indicate the month of these data together with the year; i.e. "December 201x" or such.*
   Due to the variable depths our casts achieved and the range in observational values, reporting these figures as a single panel would be extremely difficult to interpret, and would lose key details our discussion highlights. We have, however, updated the months in the panel legend as requested.

   *- It's hard to compare panels (B)-(G), because ordinate/abscissa of individual panels are not scaled. Are there any particular reasons not to scale these panels? Indeed, we need only one left axis for two panels next to each other. So, make only one left axis (not two left axes) and put one right axis to show approximate depths so that more readers can easily compare the observation and model results.*
   We have now scaled the depth axes and updated this in our resubmission.

*- Panels (B) and (E) do not show the post calving 2012 data (green curves), and post calving 2011 data (black curves).*
This reflects the fact that no data is available for these sectors in these years.

*- Show the seafloor in panels (B) to (E).*
The bathymetry of the sea floor in this region is highly complex and highly variable. It would not be possible to place the sea floor on the figure and present the data at a suitable scale to observe the changes apparent in our observations when compared to previous years.

*- Many CTD positions are shown but only for the 2013. Can you show 2013 XCTD positions only if the data are presented in panels B-G and add previous data points that are currently shown in Figure S2? In other words, please consider presenting information in Figure 1a and Figure S1 in a single panel more efficiently.*
We have attempted this in our resubmission, however adding the previous year CTD station makes the figure too complicated, therefore we have updated both Figures to complement each other. We trust this is satisfactory but would welcome any further suggested changes.

10. *Figure 2:*
    *- Depth should be all positive numbers.*
    We have updated these in our resubmitted manuscript.
    *- I see two curves for each legend in the each panel; e.g. there are two blue solid curves in panel C. Why?*
    It is normal to run more than one model run to demonstrate the robust nature of the outputs. We have clarified this in point in our resubmission.
    *- Please add a short sentence at the beginning of the caption to emphasize that you show model results in Figure 2.*
    We have done this in our resubmission.
    *- Show the seafloor in panels (B) and (E).*
    Following our earlier point from Figure 1, the bathymetry of the sea floor in this region is highly complex and highly variable. It would not be possible to place the sea floor on the figure and present the data at a suitable scale to observe the changes apparent in our observations when compared to previous years.
    *Supplement P2L13: "fluxes"*
    *Thank you. We have updated this in the resubmission.*
    *Supplement P2L15: Fig. S3 is cited before Figs. S1 and S2 are cited. Please make sections in the supplement that are associated with Figures S1 and S2 so that the points of these figures are clearer. Showing just figures in supplement does not really help.*
    *We have updated this in the resubmission.*

As you remark, Reviewer Two's comments are of a more general nature but we have attempted to address all of their concerns. Many of the points are addressed above but the following provide specific details to the issues raised.

1. *The direct ocean observation and surface boundary condition (sea ice production estimated from satellite) support the hypothesis of high coastal polynya activities (i.e., high sea ice production and remnant signal of dense water) on the lee side of B9B.*

Our resubmission highlights the Taumura et al., (2016) sea ice reconstruction specifically to build upon the reviewer's point.

2. *The numerical model forced by the observed sea ice production perfectly fails to reproduce ocean properties before and after the MGT calving (Fig. 2c). Although authors insisted that the model vertical constant profiles in winter support the findings in observation, I think that the explanation does not convince readers (at least me). In my reading, modeling result does not support active dense water formation in the lee side of B09B.*

Dense water (HSSW) is defined as being colder than -1.5C and sometimes saltier than 34.5 psu) (Cougnon et al., 2013). Both our observations and modelling studies achieve these characteristics. Our modelling also suggests that under the post calving configuration this water is being formed locally, as opposed to advecting in from the Mertz and Commonwealth Bay Polynyas as it did pre-calving (Lecarra et al., 2014). Additionally, the observations based on the Taumra et al (2016) paper supports this interpretation, and whilst we cannot completely rule out advection from elsewhere, local production of HSSW would appear likely from our results. We have substantially rewritten the text to clarify this point specifically to address Reviewer Two's point here.

*3. Discussing polynya activity with depth average ocean flow in summer does not make any sense (see also my previous comment [4]). Strong baroclinic structure is developed in summer (e.g., Lacarra JGR 2014) and thus ocean velocity would strongly depend on depth. Moreover, I could not see where modeled HSSW exists.*

As outlined, we have updated the key model outputs to reflect this, and in our resubmission only use the lowest five bottom layers. Critically, this does not change our interpretation.

We thank the reviewers for their constructive comments. As a result, we feel the manuscript has been considerably improved. We remain excited by our results which we consider are highly topical and timely, given the importance of AABW formation to the global thermohaline circulation system. Critically, our study demonstrates that cryospheric changes, such as the grounding of B09B, can exhibit a first order control on HSSW and AABW formation. This observation may perhaps explain in-part the long-term variability in AABW formation as highlighted by the marine geological reconstructions. Thus we believe our findings are important and timely and thus eminently suitable as a Brief Communication for the broad multidisciplinary readership of *The Cryosphere.* We do hope you agree!

Best regards,

Dr Chris Fogwill on behalf of the co-authors

# BRIEF COMMUNICATION: IMPACTS ~~EVIDENCE~~ OF A DEVELOPING POLYNYA OFF COMMONWEALTH BAY, EAST ANTARCTICA, TRIGGERED BY GROUNDING OF ICEBERG B09B

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**Abstract.** The dramatic calving of the Mertz Glacier Tongue in 2010, precipitated by the movement of iceberg B09B, reshaped the oceanographic regime across the Mertz Polynya and Commonwealth Bay, regions where high salinity shelf water (HSSW) – the precursor to Antarctic bottom water (AABW) – is formed. Here we ~~compare~~ present post-calving observations ~~with high resolution ocean modelling,~~ which suggest that ~~this~~ this reconfiguration has driven the development of a new polynya off Commonwealth Bay, where HSSW production continues due to the grounding of B09B. Supported by satellite observations and modelling o~~O~~ur findings demonstrate how local ~~changes in~~ icescape changes ~~can~~ may impact formation of ~~AABW~~HSSW, with potential implications for large-scale ocean circulation ~~and climate~~.

## 1. Introduction

The events triggered by the movement of the 97 km long iceberg B09B adjacent to the Mertz Glacier Tongue (MGT) in 2010 precipitated a significant iceberg calving event that was captured in real time from satellite data and shipboard observations (Shadwick et al., 2013). Prior to the calving event, Commonwealth Bay – the site of Sir Douglas Mawson’s Australasian Antarctic Expedition (AAE) of 1911–1914 – was usually free of sea ice, owing to the presence of an extensive coastal polynya maintained by strong off-shore katabatic winds sustained by the local ice-sheet topography and the presence of the Mertz Polynya to the east. Historically, newly-formed sea ice has been rapidly transported offshore by these winds; for example, during the original AAE of 1911-1914, the sea ice in Commonwealth Bay was stable enough to walk on for only two days each year (Mawson, 1940). In December 2010, however, the grounding of iceberg B09B in Commonwealth Bay in 2010 changed the local icescape considerably (Shadwick et al., 2013; Lacarra et al., 2014) (Figure 1A). The presence of the grounded iceberg B09B since 2010 has blocked the off-shore transport of sea ice, leading to the build-up of year-round fast-ice up to 3m thick landward of the iceberg (Clark et al., 2015). This transition from an area that was often ice-free to one of continuous fast-ice cover has created a natural experiment into the impacts of fast-ice change on both local biota (Clark et al., 2015) and ocean circulation (Shadwick et al., 2013; Lacarra et al., 2014). The latter is particularly important given the Adélie-George V Land region is a key region of formation of Antarctic bottom water (AABW; a generic term that encompasses the variable nature of such bottom waters (Orsi et al., 1999; van Wijk and Rintoul, 2014; Nihashi and Ohshima, 2015)). Prior to the calving of the Mertz Glacier, both the ~~the~~ Mertz and Commonwealth Bay polynyas were important sources of high salinity shelf water (HSSW) and dense shelf water (DSW) formation, which are precursors to AABW. As AABW supplies the lower limb of the global thermohaline circulation system (Orsi et al., 1999), changes in the properties or rate of formation of AABW in response to the local icescape can influence the continental shelf sea circulation (e.g. Cougnon, 2016), with widespread consequences ~~on~~ for deep ocean circulation and ventilation (Kusahara et al., 2011; Shadwick et al., 2013).

The loss of the 78 km-long Mertz Glacier Tongue in 2010, which had previously reduced westward flow of ice into the Mertz Polynya and Commonwealth Bay, is estimated to have caused a marked ~~reduction of~~impact on sea-ice formation regionally (Tamura et al., 2012; 2016). Furthermore, model studies suggest that this has led to a reduction in HSSW formation in the area (Kusahara et al., 2011), a hypothesis supported by *in situ* observations in 2011/2012 (Shadwick et al., 2013; Lacarra et al., 2014).

Together, these data indicate an abrupt reduction in the salinity and density of shelf water and an increase in carbon uptake in the region of the Mertz Polynya when compared to pre-calving levels. Palaeoceanographic studies suggest that the impacts of MGT calving on AABW formation may be a cyclical process, possibly occurring on centennial timescales (Campagne et al., 2015).

Given that the majority of AABW is formed at a number of ~~principal~~ key sites around Antarctica (Rintoul et al., 1998; Orsi et al., 1999~~; Cougnon, 2016~~) – including the Weddell Sea, the Ross Sea, Amery-Shackleton ice shelf, Cape Darnley, Vincennes Bay and Adélie-George V Land – any major long-term circulation change in these regions could have a significant impact on the global climate system. At present the long-term stability of AABW formation is not fully understood, and it is possible that the rates of AABW production from regional areas are highly variable both temporally and spatially (Broecker et al., 1998). Therefore, studying the impacts of natural perturbations such as the grounding of B09B can provide insights into the sensitivity of AABW formation to past and future changes in regional icescape.~~ (Broecker et al., 1998; Marsland et al., 2004; Cougnon et al., 2013).~~

Here we report new data that provides a snapshot of change in the region of the Mertz Polynya and Commonwealth Bay from *in situ* oceanographic observations from December 2013, the austral summer ~~(Figure 1)~~, which suggests the region is transitioning towards a new steady state (Figure 1). To explore the potential future impacts of these changes, ~~we~~ ~~We compare these results with~~ we use high-resolution ~~regional~~ ocean model simulations ~~that~~ to examine ~~pre- and post-calving~~regional ocean dynamics in two steady states (pre- and post-calving), focussing particularly on changes in velocity and advection of water masses between the Mertz Polynya and Commonwealth Bay for scenarios pre- and post-grounding of B09B.~~ in 2010.~~

## 2. ~~*In situ* observations and model simulations~~

### ~~2.1~~ *In situ* observations and comparison with past data

We report observations of changes in ocean water properties recorded during December 2013 on the Australasian Antarctic Expedition 2013-2014 (AAE 2013-2014) from the *MV Akademik Shokalskiy*. A research programme was designed to examine the changes in the region since the Mertz Glacier calving event in 2010, building upon observations from previous research expeditions in the region (Shadwick et al., 2013; Lacarra et al., 2014). To compare the current oceanographic conditions in the region with previous measurements, expendable conductivity temperature and depth probes (XCTDs; model XCTD-1, Tsurumi-Seiki Co.) were deployed.~~, which~~ To demonstrate the reliability of the XCTD data, test casts were assessed against ~~a~~ repeat casts using Seabird-SBE37SM microcat CTD calibrated for cold water conditions (see SOM Figure S1). A TSK TS-MK-21 expendable XCTD system was used to gather oceanographic data, which was recorded on a laptop computer. Given the marked expansion of fast-ice in Commonwealth Bay, in some locations XCTDs and ~~the~~ microcat were deployed through the fast-ice as well as in open water from the vessel. Although some deployments were opportunistic, many were repeat casts of previous stations in Commonwealth Bay and in the Mertz Polynya to allow direct comparison with studies taken during past austral summers (Figure 1).

### ~~2.2 Modelled simulations~~

~~To gain an increased understanding of the regional oceanographic changes triggered by the events that began in 2010, high-resolution regional ocean model simulations were undertaken using a modified Rutgers version of the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005), with a model setup following Cougnon (2016; see SOM for full model description and set up). The model includes ocean/ice-shelf thermodynamics and frazil ice thermodynamics, but does not include sea-ice model/ocean coupling. Without a dynamic sea-ice model, the fine-scale polynya activity is resolved by forcing the surface of the model with monthly heat and salt fluxes from Tamura *et al*. (2016) data set that is based on sea-ice concentration estimated with the Tamura *et al*. (2007) algorithm. This algorithm estimates thin ice thickness using Special Sensor Microwave Imager (SSM/I) observations and the European Centre for Medium-Range Weather Forecast Re-Analysis data (ERA-Interim). In summer the data set is supplemented with heat and salt fluxes using monthly climatology from ERA-interim. The model simulations are forced at the surface with data from the year 2009 (pre-calving) and 2012 (post-calving), providing general information on the ocean circulation for stable ice geometries that includes melt water from the B09B and other fast-ice and icebergs/ice shelves present in the domain. The results from these simulations are not restricted to the year chosen for the forcing, and can be compared with other years of similar salt and heat flux intensity both pre- and post-calving (see SOM for discussion). The same lateral boundary forcing is used in both pre- and post-calving simulations. Lateral boundary fields, including salinity, horizontal velocities and potential temperature, were relaxed to a climatology calculated from monthly fields estimated from the circulation and climate of the ocean, Phase II synthesis (ECCO2) for the period 1992-2013 (Wunsch, 2009).~~

## ~~3 Results~~

### ~~3.1 Comparison with past data~~

The XCTD results from December 2013 are divided into three geographic areas to allow ~~direct~~ comparison with data from previous cruises from the same season (Figure 1 and SOM Figure S2). Salinity and temperature data from the austral summer 2013/14 from northwest of Commonwealth Bay ('Commonwealth Bay NW'), northeast ('Mertz NE') and southwest ('Mertz SW') of the MGT are compared to previous years in Figure 1B, C and D respectively. As salinities and water density vary both spatially and seasonally across the region (Lacarra et al., 2014), ~~we can only~~here we compare our data to that collected in similar seasons (December / January) and locations (Figure 1, SOM Figure S2).

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In Commonwealth Bay NW (Figure 1B) our results show an increased salinity at ~350 m (34.62‰) since the pre-calving values of 2008 (34.55‰). We also find a temperature decrease of ~0.2˚C from -1.7˚C in 2008 to -1.9˚C in 2013. In the Mertz NE region (Figure 1C), we measure the salinity at ~550 m to be 34.7‰, ~~markedly~~ higher than the post-calving salinity low in 2012 of ~34.58‰, and similar to those immediately post-calving (2011) ~~the~~and pre-calving (2008)~~ measurements~~. The water is also colder, and importantly, shows minimal ~~stratification~~ stratification~~of~~ ~~temperature~~ through~~out~~ the water column in comparison to previous ~~casts~~Austral summer CTD casts. Finally, in December 2013 i~~I~~n the Mertz SW (Figure 1D), we record an increase in salinity and decrease in temperature in the upper water column (~200-400 m): ~~where~~ the salinity is 34.56~~8~~‰ compared to 34.52‰ in 2008, whilst the temperature is -2˚C, somewhat ~~higher~~colder than previous ~~seasons~~years, which ~~are~~ clustere~~d~~ around -1.8˚C. Unfortunately, in th~~is region~~e Mertz SW ~~we~~the XCTD casts did not reach a sufficient depth to

~~compare~~analyse the structure of deeper circulation within the former Mertz Polynya~~ the lower water column with previous data~~.

## 3. Discussion

Data from the region west of B09B (Commonwealth Bay NW) shows evidence of a shift in water properties following the grounding of B09B in its position during December 2013 (Figure 1B). Prior to the grounding, the water column was stratified, with relatively warm and fresh water overlying a colder, saltier layer. Following the grounding of B09B, the entire water column below 100 dbar has changed, transitioning to become slightly saltier, colder and evidently more well-mixed by 2013 (Figure 1B). Whilst salinity values are not yet as high as those in regions of HSSW production pre-calving, our observations suggest that the Commonwealth Bay NW area maybe becoming an area of deep convection and HSSW formation, in a region where historically no HSSW was formed (Lacarra et al., 2014). Although we cannot discount that this water mass may have been advected from other regions, this interpretation is supported by interpolation of satellite derived sea-ice concentrations, which suggest that sea~~-~~-ice production in the Commonwealth Bay NW region has been significantly enhanced post-calving of the MGT and grounding of B09B (Figure 2; Tamura et al 2016). These estimates suggest that sea-ice production within the former Mertz Glacier polynya has decreased markedly compared to 2009 levels (Figure 2A; Tamura et al 2016), and has become restricted to an area closer to the coast (Figure 2B; Tamura et al 2016). Contrastingly, sea-ice production in the area of Commonwealth Bay NW, in the lee of the B09B iceberg, is shown to have increased markedly by 2012 (Figures 2B), compared to pre-

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calving estimates (Figure 2A). Combined, the evidence of enhanced sea~~-~~ice production, deep ~~convention~~convection and HSSW production in the Commonwealth Bay NW region suggest that an emerging polynya may be developing in the lee of B09B.

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Calving of the MGT ~~Mertz Glacier~~ released a large volume of sea ice from the immediate east of the Mertz Glacier ~~MGT~~and s~~. S~~ubsequent melting of the sea ice produced a significant input of fresh water and rapid freshening of the upper ocean post-calving (Shadwick et al., 2013), as seen in Figures~~s~~ 1C and 1D (Green)~~, D~~. Our observations ~~suggest~~ hint at a partial recovery of upper ocean salinity by 2013 in the Mertz NE (Figure 1C) and Mertz SW (Figure 1D) regions as of December 2013. Unfortunately, as mentioned, our ~~The~~ 2013 XCTD measurements do not extend to sufficient depths to sample the ~~HSSW~~ layers below 550m, critical to HSSW production. However, the apparent reduction in the amount of buoyant fresh water in the upper water column may pre-condition these regions for a resumption or strengthening of HSSW formation in future years, if sufficient formation of sea ice and subsequent brine rejection occurs. Prior to the grounding of B09B in its present position, intrusions of relatively warm modified Circumpolar Deep Water were observed in the Mertz NE region (Figure 1C~~F~~). Our observations suggest this was not occurring in December 2013, when the ~~The~~ upper water column in 2013 ~~is also~~was found to be colder (~0.8°C) and unstratified with respect to temperature.~~,~~ ~~perhaps because the iceberg is blocking inflow of the warmer water from the east.~~

~~Data from the polynya region west of B09B (Commonwealth Bay NW) shows evidence of a shift in water properties following the grounding of B09B in its position during December 2013 (Figure 1B,~~

~~E). Prior to the grounding, the water column was stratified, with relatively warm and fresh water overlying a colder, saltier layer. Following the grounding of B09B, the entire water column below 100dbar underwent major change, transitioning to becoame saltier, colder and evidently more well-mixed by 2013. The salinity values are not yet as high as those in regions of HSSW production pre-calving, our observations suggest that the Commonwealth Bay NW area maybe in the process of forming a new polynya, becoming an area of deep convection and HSSW formation, in a region where historically no HSSW was formed, although we cannot discount that this watermass may have been advected from other regions. However, interpolation of satellite sea-ice concentrations suggest that sea ice production in the Commonwealth Bay NW region is significantly enhanced post-calving and grounding of B09B (Tamura et al 2016), supporting our interpretation of an emerging polynya. These observations suggest deep convection and HSSW formation now occurs in the polynya west of B09B, in a region where historically no HSSW was formed. The deep salinity values observed in the polynya west of B09B in 2013 (34.60‰ to 34.61‰) were higher than the salinities of 34.50‰ to 34.55‰ observed prior to calving, although still substantially less than the HSSW formed in the Mertz and Commonwealth Bay polynyas pre-calving.~~

### ~~3.2 Model simulation results~~

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~~The numerical simulations pre- and post-calving indicate a change in oceanographic conditions in the area of the B09B iceberg, demonstrating the development of a polynya area in the lee of B09B post-calving. The modelled sea-ice production (Tamura et al 2016) within the Mertz Glacier polynya~~

~~decreases and is restricted to an area closer to the coast. On the other hand, sea-ice production in the lee of the B09B iceberg post-calving is shown to increase markedly (Figures 2A and B).~~

~~The modelled ocean circulation for December shows that pre-calving, a westward coastal current carried water masses from the Mertz polynya and Commonwealth Bay areas towards the Commonwealth Bay NW XCTD positions (red squares on Figures 2A and B), forming a stratified water column with warm and fresh surface water (Figure 2C). The cold and salty water mass simulated pre-calving at the NW Commonwealth Bay XCTD positions is advected from the Mertz polynya and Commonwealth Bay post-calving. Modelled water column stratification is stronger in winter when there is sea-ice production. The model simulates a relatively warm layer at around 150 m depth (-1.18 ˚C) in July pre calving (Figure 2D). From 250 m to the ocean floor there is a cold (-1.92 ˚C) and salty (34.67) water mass that originates from the advection of HSSW from the Mertz polynya and Commonwealth Bay.~~

~~Post calving, the coastal current is blocked by the B09B iceberg, associated with a decrease in sea ice production within the Mertz polynya; little HSSW is advected into the area of the Commonwealth Bay NW XCTDs. The model average for December shows a stratified water column in summer, due to the advection from the north of a relatively warm water mass in summer. However, in winter the water column post calving at the Commonwealth Bay NW XCTDs is entirely homogeneous in potential temperature (-1.90 ˚C) and salinity (34.54), illustrating an active polynya that locally produces HSSW capable of being convected to the sea floor. The model does not simulate an increase in salinity post-~~

~~calving, but the seasonality illustrates the potential of a polynya developing in the lee of the B09B iceberg to locally form HSSW dense enough to sink to the sea floor, as inferred from the trends in the summer observations. It should be noted that our model simulations do not show the current evolution of the impact of the calving, but rather simulate the ocean conditions for two stable ice geometries, before and after the Mertz calving, thus can not be directly inter-compared to our XCTD data. However, the trends indicated from our regional model simulations provide valuable insights into mechanisms driving the circulation changes triggered as a response to the grounding of B09B off Commonwealth Bay.~~

## ~~34 Discussion~~

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~~In combination~~ Our~~the~~ *in situ* ~~XCTD measurements~~observations, in combination with satellite observations, ~~and high-resolution regional ocean modelling across the Mertz Polynya and Commonwealth Bay~~ provide valuable insights into ocean dynamics post-~~Mertz~~ MGT calving and grounding of B09B in this region that is critical to HSSW production. Whilst the implications for shifting focus of HSSW on regional AABW formation are ~~currently~~ unquantified, the changes recorded locally~~, particularly the blocking effect that B09B has on the coastal current since 2010,~~ demonstrate that this region is still undergoing marked and dramatic oceanographic changes ~~that have important implications~~ (Shadwick *et al.*, 2013; Clark et al., 2015). To further explore ~~the~~potential future impacts of these changes once the region has re-equilibrated, we use high-resolution ocean modelling to

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construct pre- and post-calving steady states independently, allowing us to look at the possible implications on regional HSSW production.

### 3.1 Exploring the processes driving the new Commonwealth Bay p~~Pp~~olynya

To gain an increased understanding of how these regional oceanographic changes triggered by the events that began in 2010 could develop over future ~~seasons~~years, high-resolution regional ocean model simulations were undertaken to compare two ~~hypothetical~~ steady states in Commonwealth Bay, both pre- and post-~~sot0~~calving of B09B. These were run using a modified Rutgers version of the Regional Ocean Modelling System (ROMS) (Shchepetkin and McWilliams, 2005), with a model setup following Cougnon (2016; see SOM for full model description and set up). The model includes ocean/ice-shelf thermodynamics and frazil ice thermodynamics (Galton-Fenzi et al., 2012), but does not include sea-ice model/ocean coupling . Without a dynamic sea-ice model, the fine-scale polynya activity is resolved by forcing the surface of the model with monthly heat and salt fluxes from the Tamura *et al*. (2016) data set, ~~that~~which is based on sea-ice concentration estimated with the Tamura *et al*. (2007) algorithm. This algorithm estimates thin ice thickness using Special Sensor Microwave Imager (SSM/I) observations and the European Centre for Medium-Range Weather Forecast Re-Analysis data (ERA-Interim) (Tamura et al., 2016). In summer the data-set is supplemented with heat and salt fluxes using monthly climatology from ERA-interim. The model simulations are forced at the surface with data from the year 2009 (pre-calving; SOM Figure S3) and 2012 (post-calving), providing general information on the ocean circulation for stable ice geometries that includes melt water from the B09B and other fast-ice and icebergs/ice shelves present in the domain. The results from these simulations are not restricted to the year chosen for the forcing, and can be compared with other years of similar salt and heat flux intensity both pre- and post-calving (see SOM for discussion). The same lateral boundary forcing is used in both pre- and post-calving simulations. Lateral boundary fields, including salinity, horizontal velocities and potential temperature, were relaxed to a climatology calculated from monthly fields estimated from the circulation and climate of the ocean, Phase II synthesis (ECCO2) for the period 1992-2013 (Wunsch, 2009). Each 33 year run includes a spinup phase of 30 years to reach equilibrium using a repeating loop of the climatology forcing. A climatology of the last 3 years of the run is used for the analysis presented here.

The numerical simulations pre- and post-calving indicate a change in oceanographic conditions in the area of the B09B iceberg, ~~demonstrating the~~supporting our interpretation of the development of a polynya area in the lee of B09B post-calving (Figure 3).

The modelled ocean circulation for December shows that in the pre-calving simulation, a westward coastal current carries~~d~~ water masses from the Mertz polynya and Commonwealth Bay ~~areas~~regions towards ~~the~~ Commonwealth Bay NW ~~XCTD positions (red squares on~~ Figures 3~~2~~A and B), forming a stratified water column with warm and fresh surface water (Figure 3~~2~~C). The dramatic change in flow from the Mertz polynya region is shown in more detail in Figure S4. The cold and salty water mass simulated pre-calving at the NW Commonwealth Bay ~~XCTD positions~~ is advected from the Mertz polynya and Commonwealth Bay~~ post-calving~~. Modelled water column stratification is stronger in winter when there is sea-ice production. The model simulates a relatively warm layer at around 150 m depth (-1.18 ˚C) in July pre calving (Figure 3~~2~~D). From 250 m to the ocean floor there is a cold (-1.92 ˚C) and salty (34.67‰) water mass that originates from the advection of HSSW from the Mertz polynya and Commonwealth Bay.

Post calving, the coastal current is blocked by the B09B iceberg, associated with a decrease in sea~~-~~ice production within the Mertz polynya (Figure 2~~1~~); little HSSW is advected into the area of the Commonwealth Bay NW (F~~f~~igure 3~~2~~)~~ XCTDs~~. The model average for December shows a stratified water column in summer, due to the advection from the north of a relatively warm water mass in summer. However, in winter the water column post~~-~~-calving ~~at~~in ~~the ~~Commonwealth Bay NW ~~XCTDs~~ is entirely homogeneous in potential temperature (-1.90 ˚C) and salinity (34.54‰), illustrating that under a stable post-calving geometry an active polynya is present~~ under a stable post-calving geometry,~~ ~~that~~which locally produces HSSW capable of being convected to the sea floor. ~~The model does not simulate anthe increase in salinity post-calving as recorded by the 2013 XCTD data, but ~~T~~t~~he seasonality illustrates the potential of a polynya developing in the lee of the B09B iceberg to locally form HSSW dense enough to sink to the sea floor, as inferred from the trends in the summer observations. It should be noted that our model simulations do not show the current evolution of the impact of the calving, but rather simulate the ocean conditions for two stable ice geometries, before and after the Mertz calving. ~~Each 33 year run includes a spinup phase of 30 years to reach equilibrium using a repeating loop of the climatology forcing., A climatology of the last 3 years of the run is used for the analysis presented here. ~~T~~t~~hus, whilst our simulations cannot be directly inter-compared to our XCTD data~~. However~~, the trends ~~indicated from our regional model simulations~~in both regional circulation and

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local salinity and temperature provide valuable insights into mechanisms driving ~~the~~ circulation changes potentially triggered as a response to the loss of the MGT and the grounding of B09B off Commonwealth Bay.

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## 34.2~~1~~ ~~A developing polynya~~Implications of data and modelling

~~Combined,~~ O~~o~~ur XCTD data, in combination with satellite-~~-~~derived estimates of sea-ice production, ~~and the high-resolution model simulations suggest~~indicate that the regional reconfiguration of the Mertz Polynya and Commonwealth Bay ~~due~~ and the grounding of~~to~~ ~~B09B~~ iceberg B09B has had a continuing~~,~~ ~~and continues to have a~~ marked oceanographic impact, suggesting a shift from a equilibrated regime to a ~~more~~ transitional one. High-resolution model simulations suggest that, once re-equilibrated to a new steady state, this may result in ~~led to~~ a shift in the focus of HSSW production (Figure 1)~~, and importantly, enhanced sea-ice production in the lee of B09B since its grounding in Commonwealth Bay in 2010 (Figure 2)~~. Data from Commonwealth Bay NW ~~in particular suggests that a new~~hints at the development of a polynya ~~has developed~~ west of B09B, where today HSSW formation ~~is~~ may be ~~formed~~ taking place outside the previously ~~well established~~well-established foci of regional HSSW production in the former Mertz or Commonwealth Bay polynyas (Lacarra et al., 2014). The effect this change of location will have on regional ocean circulation is currently ~~unknown~~unquantified, and much of the impact depends on the changes occurring deep in Commonwealth Bay itself under the perennial fast-ice that has formed across the bay ~~due to~~triggered by the grounding of B09B (~~Clark et al., 2015;~~

Lacarra et al., 2014; Clark et al., 2015; Cougnon, 2016).

Whilst the observations we present cannot account for seasonal variability (Lacarra et al., 2014), which can only be fully reconciled by the recovery and analysis of the *in situ* CTD arrays deployed in the region, our data and model analysis suggest that water mass characteristics have been affected markedly in the area off Commonwealth Bay and across the former Mertz Polynya. Regardless, our analysis suggest ~~shows~~ that the grounding of B09B off Commonwealth Bay in 2010 has ~~apparently~~ led to the development of a new polynya to its leeward side that is capable of producing HSSW outside the Mertz Polynya or the former Commonwealth Bay Polynya (Lacarra et al., 2014), as supported by satellite interpolations of sea ice production (Tamura et al., 2016).

## 4~~5~~. Conclusions

Before the Mertz Glacier calving event, dense shelf water production from the Adélie shelf supplied 15-25% of the global volume of AABW (Rintoul, 1998). Several studies have documented the decrease in activity of the Mertz and Commonwealth Bay polynyas ~~–~~, and reduction in salinity and density of HSSW ~~–~~, following the calving event (Tamura et al., 2012; Shadwick et al., 2013; Lacarra et al., 2014)~~,~~ and subsequent grounding of B09B. This study captures a unique snap-shot of change in key areas of the Adélie Land continental shelf, and further enhances our understanding of the sensitivity of HSSW formation to changes in the local icescape. Critically, it illustrates how movement of large icebergs can alter regional ocean circulation and air-sea interaction patterns, producing new polynyas and hence new regions of dense water formation. ~~Observations and model simulations provide evidence that changes~~

~~in the regional icescape have led to a shift in the location of polynyas and HSSW formation on the Adélie Land continental shelf.~~ While the salinity of HSSW produced in the ~~B09B~~ polynya found in the lee of B09B does not ~~reach~~ achieve the high values observed in the Mertz and Commonwealth Bay polynyas pre-calving of the MGT, HSSW formed in ~~the~~ this new polynya may, in part, compensate~~s~~ ~~in part~~ for the reduction in dense water production by these now much weaker polynyas.

~~Before the Mertz Glacier calving event, dense shelf water production from the Adélie shelf supplied 15-25% of the global volume of AABW (Rintoul, 1998). Several studies have documented the decrease in activity of the Mertz and Commonwealth Bay polynyas, and reduction in salinity and density of HSSW, following the calving event (Shadwick et al., 2013; Tamura et al., 2012). Our modelling shows marked changes in sea ice production post-MGT calving, with reductions in both the Mertz Polynya and in Commonwealth Bay. Importantly, our model simulations suggests production of HSSW, dense enough to sink to the sea floor and eventually contribute to DSW formation in the lee of B09B (Figure 2). This study further enhances our understanding of the sensitivity of HSSW and AABW formation to changes in the local icescape, and illustrates how movement of large icebergs can alter regional ocean circulation and air-sea interaction patterns, producing new polynyas and hence new regions of dense water formation.~~

~~AABW formation is highly sensitive to changes in the ocean-ice domain and forms a critical component of global thermohaline circulation. Studies of the response of the ocean and cryosphere to events like the calving of the Mertz Glacier and grounding of B09B in Commonwealth Bay provide insight into the~~

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~~consequences of natural and anthropogenic-driven changes. The observed formation of AABW is limited to a few locations around Antarctica, where conditions transform buoyant surface waters to water of sufficient density to sink to the sea floor, maintaining the deep ocean stratification, contributing to large-scale heat and salt budgets, and ventilating the abyss (Orsi et al., 1999). Our work~~ This remarkable ‘natural experiment’ underscores the ~~remarkable~~ sensitivity of ~~this global phenomenon~~HSSW to local changes in the cryosphere and provides insight into the consequences of regional change on ocean circulation.~~.~~

## 5~~6~~. Acknowledgements

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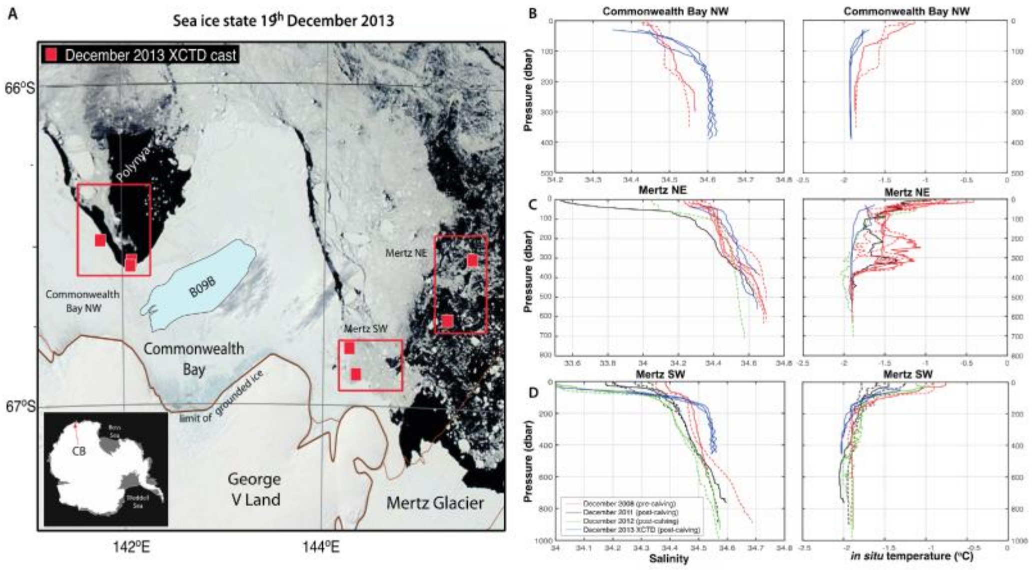


Figure 1. ~~A.~~ Comparison of new XCTD observations with previous data from the Commonwealth Bay and Mertz Glacier region of Adélie Land, Antarctica. A. Locations of XCTD casts taken in December 2013 on the AAE 2013-2014. The outline of the grounded B09B iceberg is indicated. Base map is vi~~Vi~~sible MODIS image ~~image of the Commonwealth Bay and Mertz Glacier region of Adélie Land, Antarctica on~~from the 19th of December 2013 (credit Dr Jan Lieser: source NASA WORLDVIEW). ~~;~~ ~~with the sites of the December 2013 XCTD casts. The outline of the grounded B09B iceberg is indicated, with~~ ~~.~~Inset bottom left: ~~a map of the Antarctic Continent~~location map (CB Commonwealth Bay)~~ inset~~. Charts show c~~C~~omparison between salinity and temperature from XCTD casts in 2013 (blue) and CTD profiles from the same month in previous years where data is available for that region (~~from~~ 2012: ~~(~~green~~)~~; ~~;~~ 2011: ~~(~~black~~;~~) ~~and~~ 2008, ~~(~~pre-calving~~;~~ red) from ~~B.~~ Commonwealth Bay NW (B), ~~C.~~ NE Mertz (C) and ~~D.~~ SW Mertz (D). ~~. Comparison between temperature from XCTD (Blue)~~

~~casts in 2013 and CTD profiles from previous years 2012 (green), 2011 (black) and 2008 (pre-calving; red) in E. Commonwealth Bay NW, F. NE Mertz and G. SW Mertz~~ (See SOM Figure S2 for details of specific sites of historic data).

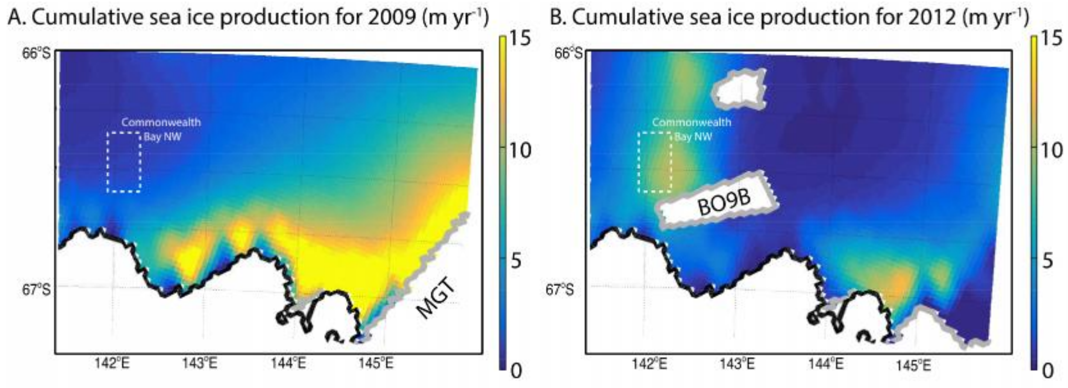
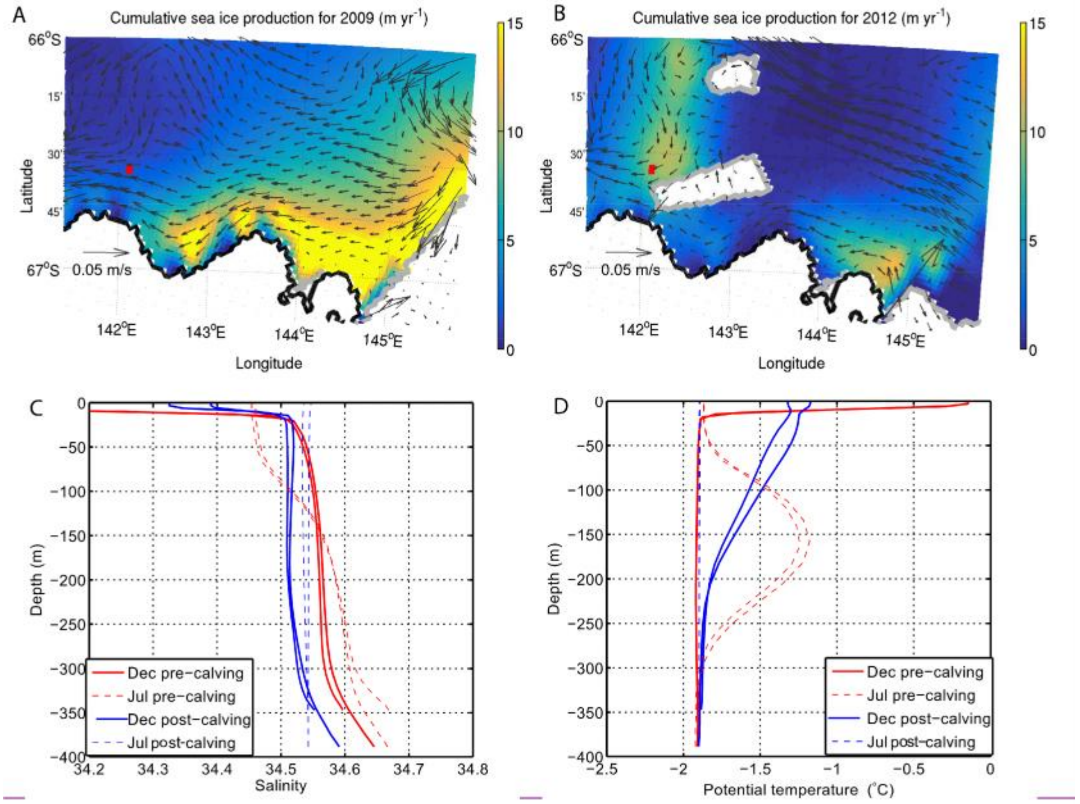


Figure 2. Cumulative s~~S~~ea-ice production estimated from the Special Sensor Microwave Imager (SSM/I) observations for the Mertz and Commonwealth Bay region for pre-2009 (A) and post~~-~~-2012 (B)

MGT calving (~~from~~after Tamura et al., 2016).



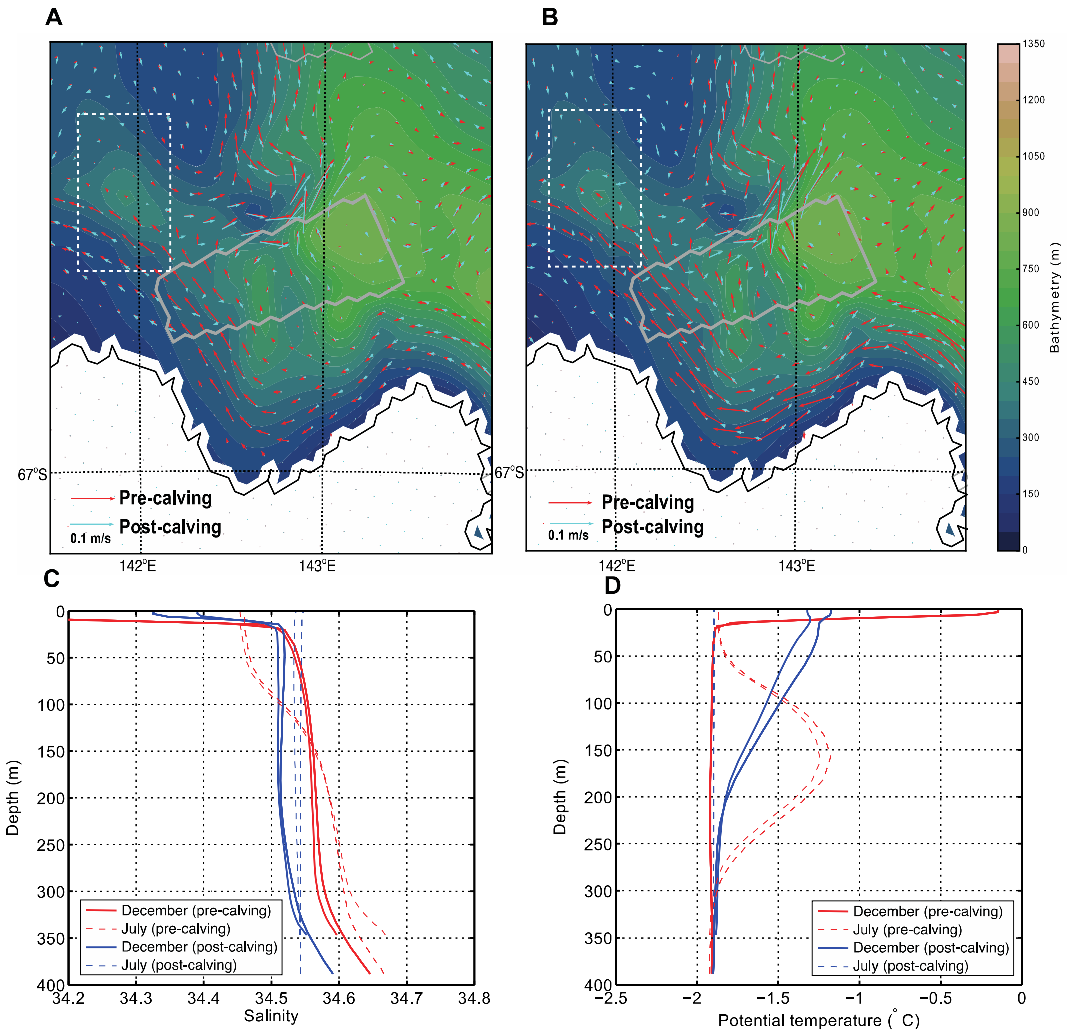


Figure 3~~2~~. Results of high-resolution model ~~similations~~simulations. Upper panel~~s~~: Simulated bottom current velocity (m/s) from ROMS~~s~~, averaged on the 5 lowest layers of the model for both pre-calving (red vectors) and post-calving (cyan vectors) geometries near Commonwealth Bay for summer (A.

November - December) and winter (B. August – September). The outline of B09B can be seen in light grey, and the location of Commonwealth Bay NW area (white box).~~Cumulative sea ice production (m/yr) for the two years of forcing for A pre- (2009) and B. post- (2012) calving simulations, overlaid with the vertically integrated horizontal velocity (m/s) in December, from the model climatology (black vectors). Red squares mark the Commonwealth Bay NW XCTD sites used in Figure 1B and E, and the simplified outline of B09B in the model domain can be seen in B.~~ Lower panels: modelled salinity (C) and potential temperature (D) from independent simulations with ROMS (n=2), for the ~~the XCTD stations in~~ Commonwealth Bay NW ~~after a 30 year model simulation~~ for ‘stable’~~,~~ pre (red) and post calving (blue) geometries ~~simulations~~, averaged for December (solid lines) and July (dashed lines).

# BRIEF COMMUNICATION: IMPACTS OF A DEVELOPING POLYNYA OFF COMMONWEALTH BAY, EAST ANTARCTICA, TRIGGERED BY GROUNDING OF ICEBERG B09B

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**Contains:**
**Section 1: Model description**
**Section 2: Selection of model climatology**
**Figure S1: Comparison between XCTD and microcat salinities**
**Figure S2: CTD and XCTD station locations used in inter-comparison**
**Figure S3: Monthly surface heat (a) and salt (b) fluxes averaged over the Mertz Glacier Polynya (MGP) from Tamura et al., (2016) data set, with winter time averages (May to September inclusive) shown with crosses.**

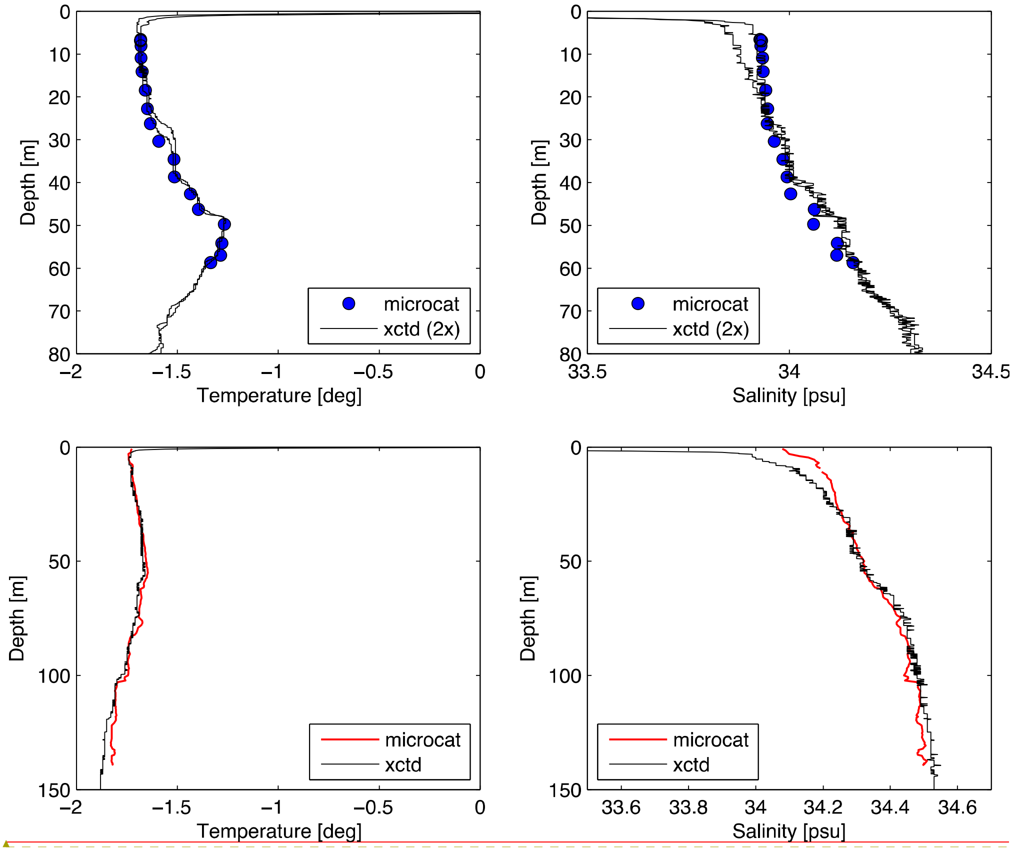
## Section 1. Model description

The model used here is based on the Rutgers version of the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005) that includes ocean/ice shelf and frazil ice thermo-dynamics (Galton-Fenzi et al., 2012; Dinniman et al., 2003). The horizontal and vertical grid is the same than presented in Cougnon et al. (2013~~6~~). Without a dynamic sea ice model, the fine-scale polynya activity is resolved by forcing the surface of the model with monthly heat and salt from Tamura et al. (2016) data set that is based on sea ice concentration estimated with the Tamura et al. (2007) algorithm. This algorithm estimates thin ice thickness using Special Sensor Microwave Imager (SSM/I) observations and the European Centre for Medium-Range Weather Forecast Re-Analysis data (ERA-Interim). Water masses formed on the continental shelf in the model are controlled by the variability of the air/sea forcing as well as by the glacial melt water released from the local ice shelves. The model has been set up to compare the ocean and basal ice shelf melting changes post-calving compared with other years of similar heat and salt fluxes intensity within the MGP region. The year 2009 and 2012 are chosen for the pre- and the post-calving air/sea forcing simulations respectively, after analysing the monthly heat and salt fluxes averaged over the Mertz polynyna area for the period 1992 to 2013 (Figure S3). The year 2009 is representative to an average to strong sea ice production year in terms of heat and salt fluxes and 2012 was chosen in consideration of the fast ice and its representation of permanent features between 2010 and 2012 (A. Fraser personal communication). Fast ice is parameterised as in Cougnon et al. (2013) and Cougnon (2016), using an updated version of Fraser et al. (2012). Lateral boundary fields, including salinity, potential temperature and horizontal velocity, were relaxed to a climatology calculated from the monthly fields from the Estimating Circulation and Climate of the Ocean, Phase II synthesis (ECCO2) for the period 1992-2013 (Wunsch et al., 2009). It is important to note that salinity values used in the model are on the Practical Salinity Scale (PSS78) and are dimensionless. The total run time of the model simulation was 33 years for each simulation. This 33 year run includes a spinup phase of 30 years to reach equilibrium using a repeating loop of the climatology forcing. A climatology of the last 3 years of the run are used for the analyses.

## Section 2. Selection of 2009 climatology

The choice of the year 2009 for the PRE simulation forcing was made after analysing the monthly heat and salt fluxes averaged over the Mertz Glacier Polynya (MGP) area for the period 1992 to 2013. The period from 2007 to 2009 was identified as a constant sustained period with a winter average (May to September inclusive) of about -164 W m$^{-2}$, while the average over the pre-calving period (1992-2009) is of -159±17 W m$^{-2}$ (See Figure S3). Similarly, the salt fluxes averaged for 2007-2009 is of about 0.82 kg m$^{-2}$, while the averaged for 1992 to 2009 is of 0.82±0.1 kg m$^{-2}$. 2007 to 2009 can therefore be considered as being a representative period for the pre-calving MGP region. As a result, 2009 (the year closest to the calving) was chosen as the focus of the pre-calving simulation in this study to explore the general ocean conditions related to a stable ice geometry pre- and post-calving. Furthermore, given that only a single-year forcing is available for the post-calving simulation, a comparable single-year climatology is preferable for the pre-calving simulation. In the post-calving scenario, 2012 was chosen in consideration of the fast ice and its representation of permanent features between 2010 and

2012 (A. Fraser personal communication). In summary, the results from these simulations are not restricted to the year chosen for the forcing, they can be compared with other years of similar salt and heat flux intensity between 1992-2009.



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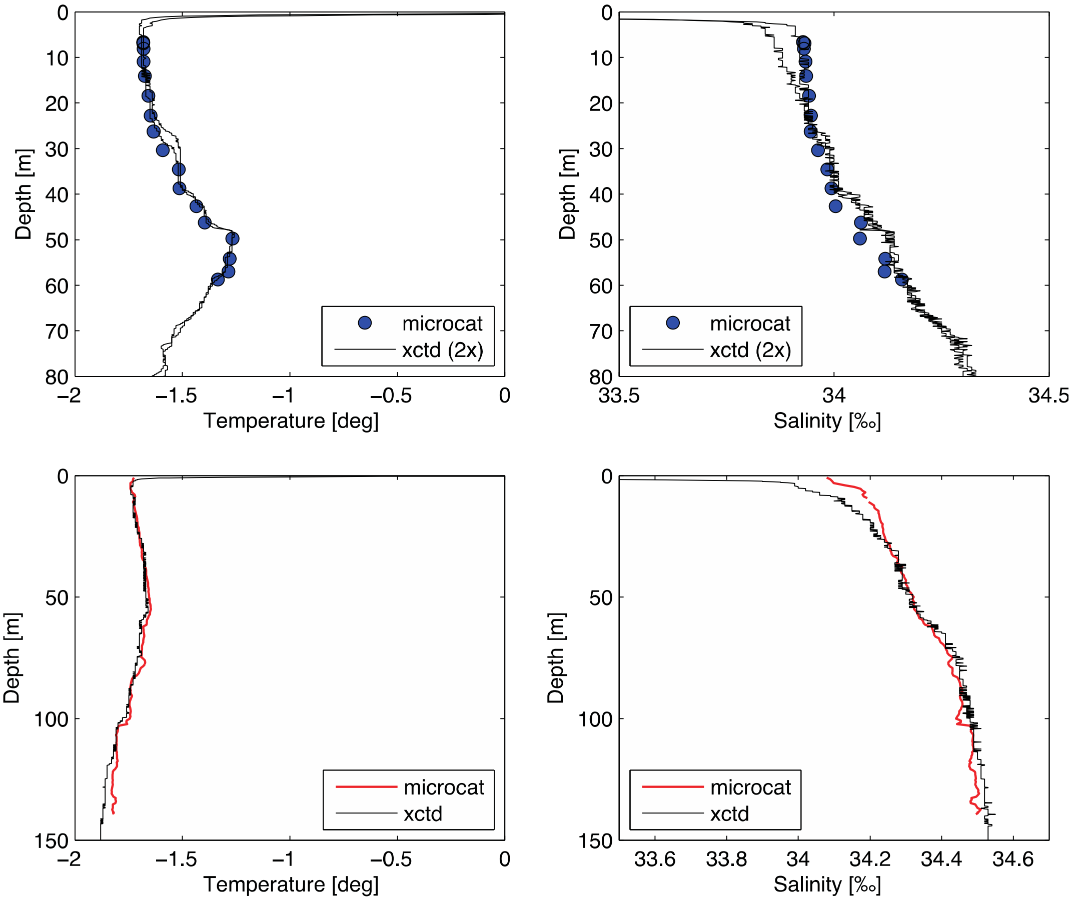

**Figure S1. Comparison between XCTD and microcat temperatures (°C) salinities (‰~~psu~~)**

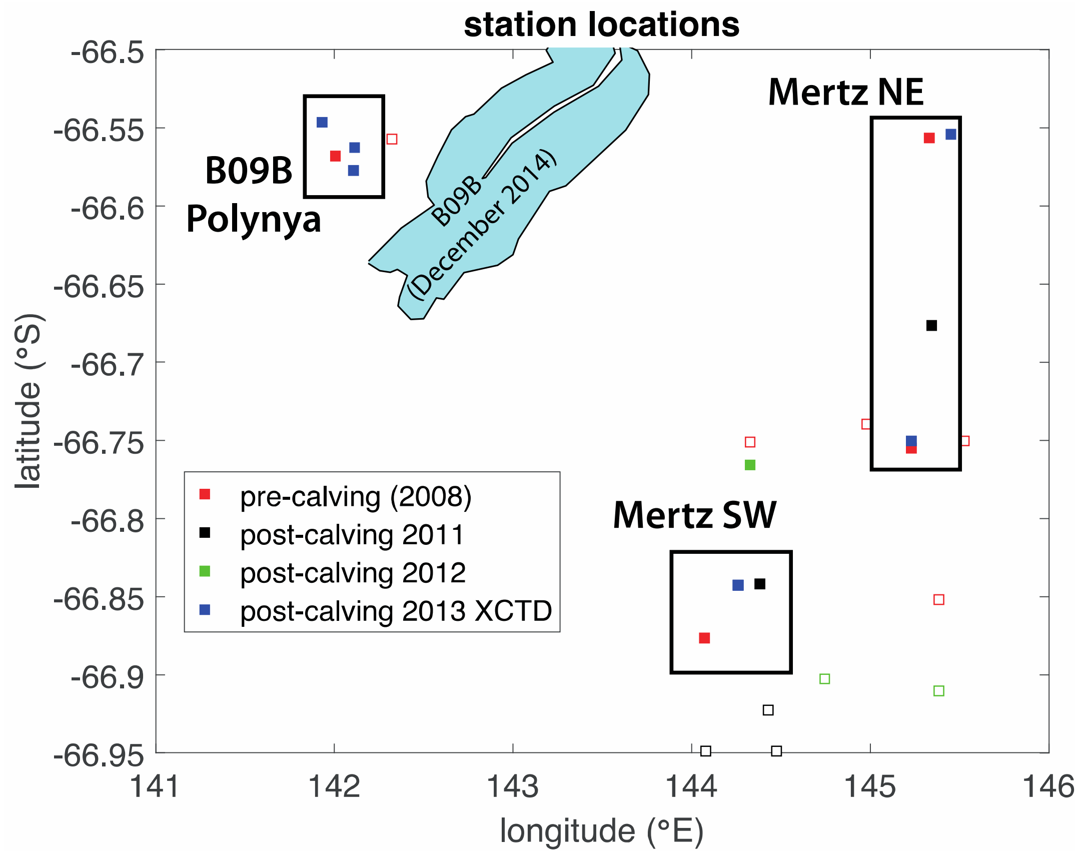

**Figure S2.~~:~~ CTD and XCTD station locations used in inter-comparison**

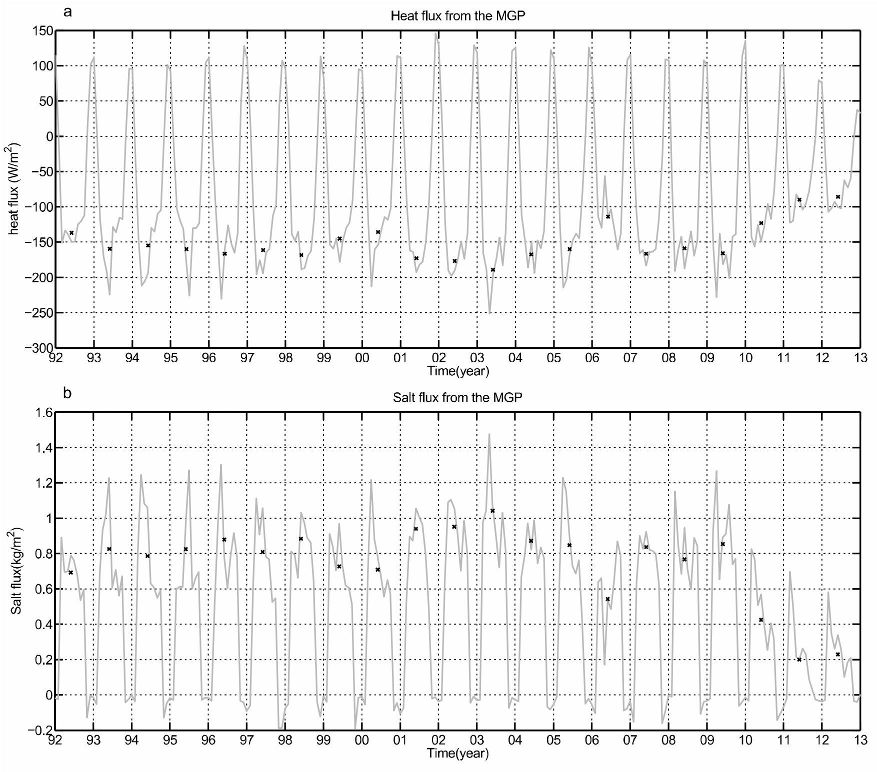

**Figure S3. Monthly surface heat (a) and salt (b) fluxes averaged over the Mertz Glacier Polynya (MGP) from Tamura et al., (2016) data set, with winter time averages (May to September inclusive) shown with crosses (Cougnon 2016).**

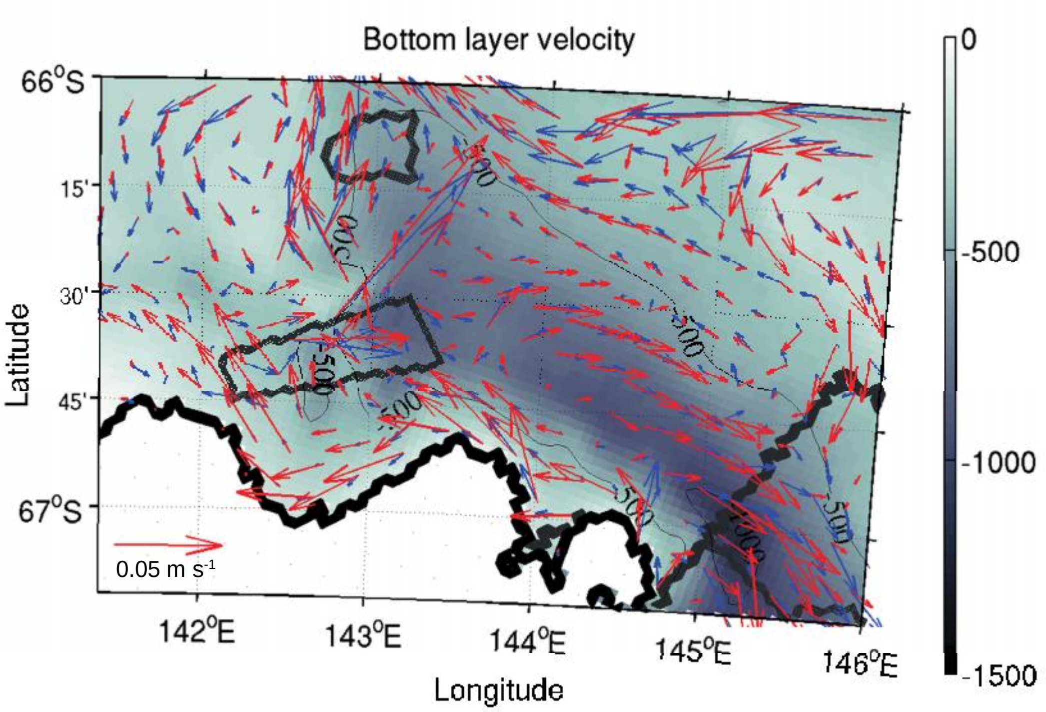

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**Figure S4.**

**Time averaged horizontal velocity at the bottom layer of the model (m s-1) for the pre-calving (red) and post-calving (blue) simulations, for extended Commonwealth bay/Mertz Polynya area. Note vastly decreased post-calving westwards flow from Mertz Polynya. The grey contours outline the ice mask used in the model for both simulations and the black contour outlines the coastline. The bathymetry of the model (m) is shown at the background.**

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