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

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Response to reviewers

We thank each of the reviewers for their detailed reviews, and in light of their comments and suggestions have updated our manuscript as outlined in the following paragraphs.

The reviewers raise two key issues. Firstly, they request more details of the model, and question suitability of 2009 climatology in driving the pre-calving simulation. Secondly, they raise questions over the apparent contradiction between our observations and model simulations. In our resubmission we address these points directly, with an expanded model description and climatological analysis (within the main text, and the supplementary information), and perform further analysis of the trends in circulation and sea ice production off Commonwealth Bay in the model simulations that support our assertion that a polynya has developed in the lee of iceberg B09B. In addition, we have reformatted the figures within the main body of the text in line with the reviewer's comments, and include additional figures in the supplementary files to address the reviewer's specific comments as outlined in the paragraphs below. Again, we wish to thanks the reviewers for their detailed comments that have substantially strengthened this Brief Communication in the *Cryosphere*.

Reviewer One

1 The title is somewhat misleading. A polynya is defined as a region of lower sea ice concentration than what would otherwise be expected given the climate of that region. We can easily see that this is a new polynya from satellite imagery/other data. What this paper presents is the oceanographic consequences of this new polynya. As such, I suggest changing the title to reflect this focus.

1. We understand the reviewers point here, and as such have reworded the title to, "IMPACTS OF A DEVELOPING POLYNYA OFF COMMONWEALTH BAY, EAST ANTARCTICA, TRIGGERED BY GROUNDING OF ICEBERG B09B"

2 I have an issue with the recurring reference to the "grounding of B09B". B09B has significantly grounded twice (at least!) since its calving from the Ross Ice Shelf in 1987. As such, reference to the "grounding B09B" is ambiguous. Perhaps change to "recent re-grounding" or similar.

2. We recognise the reviewer's point regarding the long-history and multiple groundings of B090B since its calving in 1987, but here we are discussing the instance of grounding in Commonwealth Bay post Mertz Glacier Tongue calving in 2010, as outlined in the title, abstract and Page 2, Line 15 of the manuscript. There are many other manuscripts (many of which we include within the 20 references available) that detail the history and events prior to and during the Mertz Glacier calving in 2010, but this is not the purpose of this Brief Communication for the *Cryosphere*, which aims to understand the observations from 2013 from Commonwealth Bay through our model analysis.

> 3 Line 1: "triggered by the impact" – this hasn't been proven. There is an argumen that the calving of the MGT was precipitated by the movement of B09B which alterec the current configuration, thus calving without an impact. This was outlined in detail by Mayet et al., 2013 (JGR Oceans). This important work on the MGT calving is not citec

3. We acknowledge this point, and have changed the wording in Line 1 to, '…precipitated by the movement…". We agree that Mayet et al., 2013 provides an important discussion of the hydrological events during the MGT calving event, but are unfortunately limited as to the number of references we can include.

> 4 P2, L5, other places: The point is made that local changes in the icescape can influence AABW formation, but this ignores the fact that B09B was produced thousands of km away (i.e., not only local, but remote icescape changes can have large impacts).

4. We remove the word 'local' from line 6, page 2, and 'regional' from line 8, page 3, to acknowledge that changes in the icescape away from Adelie Land may also have an affect in this region.

> 5 P2, L11-13: There is more to the existence of the CB polynya than just these factors, i.e., the presence of the MGT, B09B, many smaller grounded icebergs around which fast ice forms, all located upstream of the CB polynya.

5. We thank the reviewer for this comment – we are here talking about the historically present Mertz polynya as opposed to the newly created one in the lee of B09B off Commonwealth Bay, and have changed the wording of Page 2, Lines 13 and 14 to clarify this.

> 6 P2, L13-15: The text before and after the semicolon is a non sequitur. Also "the sea ice" is ambiguous.

6. We have changed the wording of this sentence to make its meaning more obvious.

7 P3, L1-2: As with P2, L5: There is more to the westward flow blocking than just the MGT. See the description provided by Massom et al., 2003 (JGR).

7. We have changed 'blocked' to 'reduced' to reflect this point.

8 P3, L11-13: This sentence could do with a re-write. Also, mention that while the MGT calving cycle may be cyclic, the re-grounding of B09B in CB is likely to be a "spanner in the works".

8. We thank the reviewer for this comment, and have restructured the sentence accordingly, and highlighted that we are talking about the impacts of MGT calving on AABW formation being cyclical, as opposed to the appearance of 'megabergs' such as B09B.

9 P3, L16: For completeness, you need to mention the contribution of Cape Darnley polynya to AABW – see paper by Ohshima et al., 2013 (Nature Geo).

9. We thank the reviewer for suggesting this and in our updated manuscript we add the AABW sites at Cape Darnley and off Vincennes Bay.

10 P4, section 2.1: There is absolutely no mention of which month observations were conducted. This seriously adds to confusion in the interpretation of figures.

10. We thank the reviewer for spotting this omission, and have added the month (December 2013) accordingly.

11 P4, L24: Tamura et al.'s heat and salt flux data are based on thin ice thickness data, not sea ice concentration data.

11. We acknowledge this, and have updated this section of the manuscript and include further details both in the text and in the supplement.

12 P5, L1: I see a major issue with forcing the model using 2009's heat and salt flux data. As shown in Tamura and Williams et al. (2012), 2009 was a strongly anomalous year for sea ice production in the Mertz Glacier polynya. In fact, assuming you didn't use the MODIS fast ice mask (which there is no mention of in this manuscript), 2009 had the highest sea ice production of all years observed. The use of 2009 may

have been able to be justified if the pre-calving observations were also conducted in 2009, but they weren't (they were conducted in 2008). While not explicitly stated, it appears that the authors have simply chosen 2009 because it was the year before calving occurred. This appears to be a very poor choice, and has probably influenced the conclusions drawn from the modeling component here. Unless I'm missing something here, I think it would have been much more sensible to force the pre-calving model run using either a more normal year for sea ice production, or a sea ice production climatology based on all of Tamura's years of observation. The choice of 2012 for post-calving seems fine, however. Perhaps the choice of 2009 could be justified by performing a sensitivity analysis? I'm not sure how a sensitivity analysis could be done without rerunning the whole model though.

12. 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 from Tamura et al., (2016; Figure 1). 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}. 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 0.82 kg m^{-2}. As a result, 2007 to 2009 is considered as being a representative period for the pre-calving MGP region. Ultimately 2009, the year closest to the calving, was chosen as the main purpose of the simulations in this study is to illustrate the general ocean conditions related to a stable ice geometry pre- and post-calving. Also, a single year forcing was preferable to a pre-calving climatology, when compared to a single year forcing for the post-calving simulation, that is restricted to one year due to data availability. 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 as seen from Figure S3. We have added this detail in full to the supplementary information, due to length

restrictions of the main body.

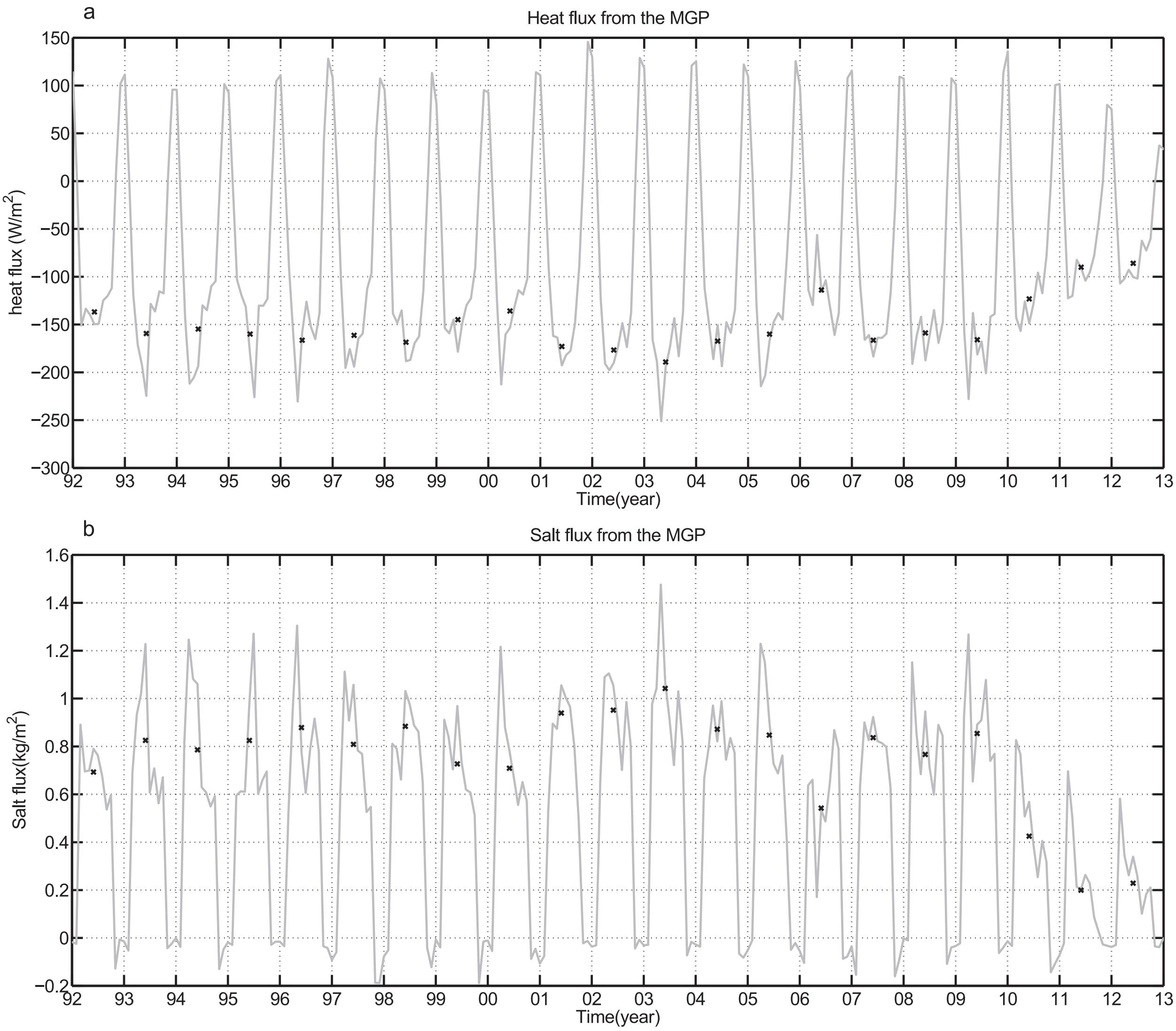


Figure 1. Monthly surface heat (a) and salt (b) fluxes averaged over the Mertz Glacier Polynya (MGP) from Tamura et al., (2016) data set, with winter time averages (May to September inclusive) shown with crosses (Cougnon 2016).

13 Section 2.2: The description of the model setup/domain is completely inadequate. What is the resolution? Latitudinal and longitudinal extents? Grid setup? Bathymetry used? What hope does someone have of reproducing your results without this fundamental information? Or are you tasking the text "similar to Cougnon et al., 2013" with providing this information? How similar, exactly? In this case, you need to be more explicit here. And how was the fast ice treated in the model? What was its horizontal extent? Tamura and Williams et al. (2012) highlighted the importance of using accurate fast ice in polynya studies, but the fast ice implementation in the model is not even mentioned here. Was the "dagger" fast ice forming around grounded icebergs to the north of the pre-calving MGT included? This acts to extend the MG polynya (both pre- and post-calving). So many unanswered questions related to the model domain.

13. We have now fully outlined the model description in the supplementary material to cover all these points as outlined below:

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 (2016). 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 fuxes 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.*

14 P5, L18: "piled up" is a very vague statement, it's possible to be much more exacting. As showed by Massom et al. (2010, JGR Oceans), the very thick fast ice immediately east of the MGT was thermodynamically thickened, and not "piled up" at all. Or are you referring to the largely dynamically-thickened fast ice (which probably was "piled up") east of the pre-2010 grounded position of B09B (see Fraser et al., 2012, Journal of Climate)? I'm not sure which you're referring to, because you state "piled up

14. We understand the point the reviewer makes here, and have changed the wording accordingly. We are discussing the geographical source of the sea ice, as opposed to the mechanism by which it built up.

15 P5, L20-21: Figure 1D shows very similar salinities in 2008 vs 2011 though.

15. We thank the reviewer for this comment, but respond that the profiles of the salinities in 2008 and 2011 differ markedly. For example, at 200 m, in 2008 the salinity was 35.48, whilst in 2011 it was 34.43, a significant difference.

16 P6, L7 vs L21. The comment is made in L7 that the post-grounding water column is saltier than pre-calving, based on observations. However, in L21 you say that the post-grounding water column is fresher, based on model results. This is also manifested in Fig 1A vs Fig 2C. No mention of this discrepancy is made in the text of this paper. It seems like a major failure of the model to reproduce the observations. Could you make a comment about this?

16. We acknowledge that this difference has not been fully explored in our original manuscript therefore in our updated manuscript we add the following text to section 3.2:

    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, 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 in winter. 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.

17 P7, L22: The blocking of the coastal current is a major result of the model, yet its importance is not emphasized anywhere in the discussion. Here might be a good place to include it.

17. We thank the reviewer for highlighting this important model result, and on Page 6, Line 18, comment upon this and also in the discussion, Page 7, Line 11.

18 P8, L2: How does the sea ice production compare between your pre and post-calving years?

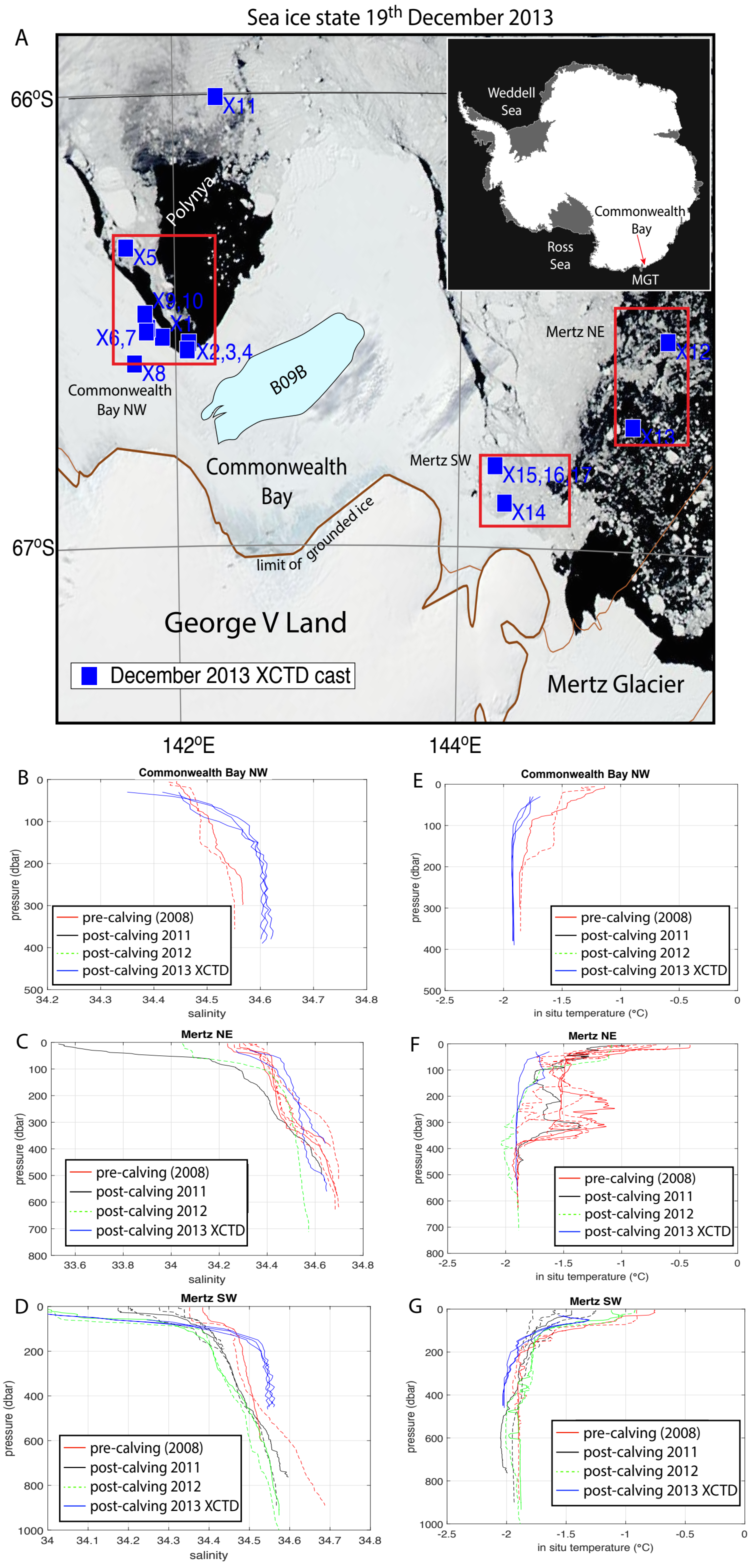
18. We add further information of this to Page 8, Lines 14-16, supported by new panels on Figure 2 to show sea-ice production pre and post calving.

19 P8, L10: Is HSSW formed in this region able to go on to form AABW? A comment on the bathymetry in the region of the new polynya would be appropriate here.

19. We have added discussion on the contribution of HSSW form this region to AABW formation to Page7, Lines 10 to 11, and also in the Supplementary Information.

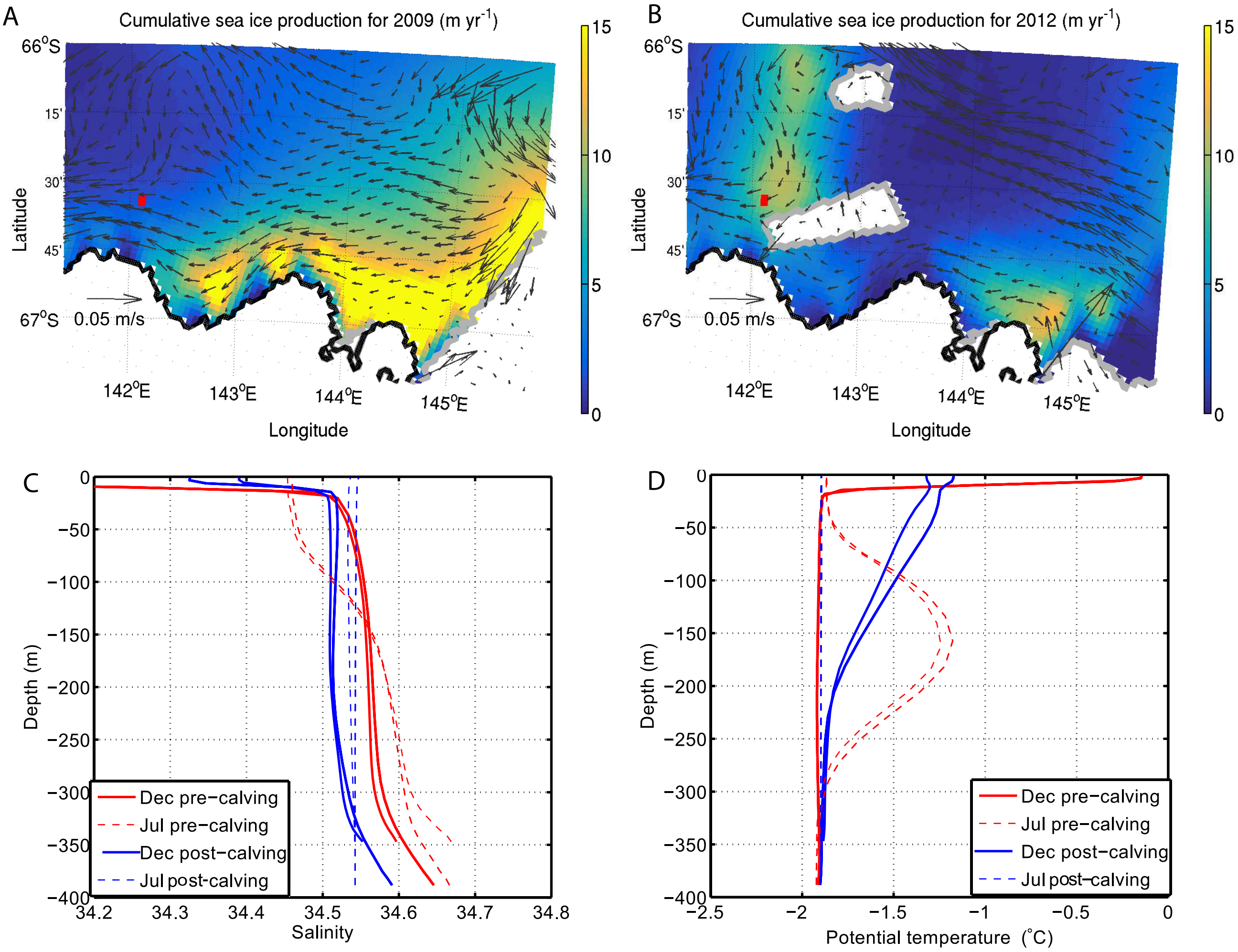
20 Figure 1 is very poorly presented. There are numerous typos (Decmebr and Tounge). The font size varies wildly across the figure, much of the text is illegible. Both inset maps for Fig 1A are almost useless. The lower left one really suffers from not having a coastline drawn. Fig 1A needs much more annotation. What is continent? What is fast ice" What is pack ice? How does the date of acquisition of this image relate to the time of field observations? Fig 1A should be zoomed out a little to provide more context – we can't even see the "original" B09B grounding location or the full extent of the tongue. There is absolutely no representation of the icescape pre-calving! The caption is confusing in the way that it references the sub-figures (and doesn't even mention sub-figures E, F or G). The figure refers to both B9B and B09B. The color "blue" is given a capital letter in the caption for some reason (and "red" doesn't even

20. Figure 1 has been updated and reformatted in line with the reviewer's suggestions.


Sea ice state 19th December 2013
A
66°S
67°S
142°E
144°E
Polynya
Weddell Sea
Ross Sea
Commonwealth Bay
MGT
Mertz NE
Mertz SW
Commonwealth Bay NW
B09B
Commonwealth Bay
limit of grounded ice
George V Land
Mertz Glacier
December 2013 XCTD cast
Commonwealth Bay NW
Mertz NE
Mertz SW
pre-calving (2008)
post-calving 2011
post-calving 2012
post-calving 2013 XCTD
pressure (dbar)
salinity
in situ temperature (°C)

21 Figure 2 is very poorly presented. Summer and winter figures seem randomly placed. Wouldn't it be a good idea to arrange all "winter" figures on the left, and all "summer" figures on the right? And why does "Nov-Dec" appear before "Aug-Sep"? It's chronologically backward. Fig 2B has no label on the legend. This figure is completely illegible in print, and only slightly better online. There's a fundamental problem with the presentation of Figures 2A and 2B: since the pre-calving vectors are directly over-plotted on the post-calving vectors, and there's no translucency, then it's impossible to assess if the underlying vector if the overlying vector completely obscures it. It's a terribly unreadable way to present two vector fields. At the very least, one series of vectors should be offset slightly. Possibly most importantly, the outline of B09B appears to bear little resemblance to the shape of that in Fig 1. Why is the eastern end of B09B not tapered in the model domain? B09B is referred to as both "B09B" and "B09b" in the caption. Finally, the caption could use some revisions, English-wise – some strange sentences as well as some parenthesis nastiness.

21. Figure 2 has been updated in our resubmission, with the panels now showing the simulated changes in vertically integrated velocity and cumulative sea ice production, together with the changes in salinity and temperatures in the model domain. The 'shape' of B09B is realistic in the scale of the model domain, but we acknowledge does not perfectly capture the shape of B09B in the Landsat image.



22 Figure S1 adds very little to this manuscript. It would be sufficient to say that the xctd matches the microcat values very closely (possibly give an RMS difference, or similar measure of agreement).

22. The supplementary figures now include Figure S1, S2 and S3, which add important information. Figure S1 is kept in the supplement for completeness.

Furthermore, we have addressed each of the technical corrections highlighted by Reviewer One.

Reviewer Two

[1] Although this paper speculated the local DSW formation in the lee side of B9B from the T-S profiles (Fig.1 B and E), T-S profiles in the Mertz SW region (Fig.1 D and G) have also a similar structure. There is a possibility that DSW is advected from the east.

1. We appreciate the reviewer's point in regards to advection of water masses from the East, but our modelling argues against this hypothesis. This can be seen in Figure 2 and is discussed in the text with our vertically integrated velocity profile suggesting little advection from the East due to the blocking effect of B09B.

[2] Showing a summer image in Fig. 1A is misleading. Polynyas in winter and spring have different roles. While winter polynya plays a role in high sea ice and DSW productions, spring polynya is a sea ice melting area. It seems to me that showing winter sea ice concentration or sea ice production is a direct way to indicate an active formation region of sea ice and DSW.

2. Figure 1 is provided for context, not necessarily to show the polynya activity per se.

[3] The ocean model failed to reproduce the ocean properties. The observation (Fig. 1 B) shows an increase in summer salinity, but model does not. The temperature profiles are also different between the two.

3. We thank the reviewer for this comment, and have addressed this point as per point 16 of Reviewer One's comments.

[4] There are no pronounced differences in ocean velocity. In first place, how can you speculate the polynya activity from ocean velocity? I expect that a (bottom) salinity field is more suitable to show the activity before and after the relocation of B9b.

4. We now present the vertically integrated horizontal velocity together with the changes predicted in sea ice production which demonstrate the changes in ocean circulation together with the changes in sea ice production post grounding of B09B.

[5] Figure 1 should be revised. It is too small to see. Larger area which covers the Adelie Depression and the MGT is preferable. Please add bottom contour, grounding line, and ice front line to easily understand the regional configuration. I expect that active sea ice production near the B9B is on the Adelie Bank, not the Adelie Depression. If so, it seems to be difficult for the local water to be dense enough and to be exported from the Adelie Sill (where is the main pathway of DSW formed in the Adelie Depression).

5. We address this in point 16 in our response to Reviewer One

[6] More detail of the model configuration is required in section 2.2. Model description in

6. We have added further detail of the model setup to the text supported in detail in the supplementary information, as outlined in point 13 to Reviewer One.

[7] There are several sentences throughout the manuscript to speculate the impact on AABW. I don't think that emphasizing the connection to AABW at many place is important because this paper examined only the polynya near one large iceberg without showing the relative importance in the total DSW and AABW production. Some of them should be removed.

7. We recognise the reviewers point here and have addressed this throughout our revised manuscript.

We have addressed each of the minor comments highlighted by Reviewer One in the text of our updated manuscript.

We thank the reviewers for their input and detailed comments.
Dr Chris Fogwill on behalf of the co-authors.

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

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Christopher J. Fogwill[1*], Erik van Sebille[2], Eva A. Cougnon[3,4,5], Chris S.M. Turney[1], Steve R. Rintoul[3,4,5], Benjamin K. Galton-Fenzi[4,6], Graeme F. Clark[1], E.M. Marzinelli[1], Eleanor B. Rainsley[7], Lionel Carter[8]

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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 post-calving observations with high-resolution ocean modelling, which suggest that this reconfiguration has driven the development of a new polynya off Commonwealth Bay, where HSSW production continues due to the grounding of B09B. Our findings demonstrate how local changes in icescape can impact formation of AABW, with implications for large-scale ocean circulation and climate.

1. Introduction

The events triggered by the movement of the 97km 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

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rate of formation of AABW in response to the local icescape can influence the continental shelf sea circulation (Cougnon, 2016), with widespread consequences on 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 sea-ice formation regionally (Tamura et al., 2012). 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, occurring on centennial timescales (Campagne et al., 2015).

Given that the majority of AABW is formed at a number of principal sites around Antarctica (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. 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). We compare these results with high-resolution regional ocean model simulations that examine pre- and post-calving ocean dynamics, particularly changes

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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

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 were assessed against a 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

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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). 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 we can only compare our data to that collected in similar seasons and locations (Figure 1).

Calving of the Mertz Glacier released a large volume of sea ice from the immediate east of the MGT. Subsequent 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 1C, D. Our observations suggest a partial recovery of upper ocean salinity by 2013 in the Mertz NE and Mertz SW regions. The 2013 measurements do not extend to sufficient depth to sample the HSSW layer. However, the reduction in the amount of buoyant fresh water in the upper water column may pre-condition these regions for a

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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 1F). The water column in 2013 is also colder (~0.8˚C) perhaps because the iceberg is blocking inflow of the warmer water from the east.

Data from the polynya 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 became saltier, colder and evidently more well-mixed. 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

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

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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.

4 Discussion

In combination the *in situ* XCTD measurements, satellite observations and high-resolution regional ocean modelling across the Mertz Polynya and Commonwealth Bay provide valuable insights into ocean dynamics post-Mertz calving in this region 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).

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4.1 A developing polynya

Combined, our XCTD data and the high-resolution model simulations suggest that the regional reconfiguration of the Mertz Polynya and Commonwealth Bay due to B09B has 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 polynya has developed west of B09B, where today HSSW is formed outside the previously 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, 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 the grounding of B09B (Clark et al., 2015; Lacarra et al., 2014; 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. Regardless, our analysis shows 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.

5. Conclusions

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 does not reach the high values observed in the Mertz and Commonwealth Bay polynyas pre-calving of the MGT, HSSW formed in the new polynya compensates in part for the reduction in dense water production by these now much weaker polynyas.

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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 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 underscores the remarkable sensitivity of this global phenomenon to local changes in the cryosphere.

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6. Acknowledgements

This work was supported by the Australasian Antarctic Expedition 2013-2014, the Australian Research Council (FL100100195, FT120100004 and DP130104156) and the University of New South Wales. EC is supported by CSIRO and Institute for Marine and Antarctic Studies (University of Tasmania) through the Quantitative Marine Science PhD Program. We would also like to thank Dr Jan Lieser (University of Tasmania) for the sea ice imagery used in Figure 1. Computing resources were provided by both the Tasmanian Partnership for Advanced Computing and the Australian National

Computing Infrastructure under grants m68 and gh8. We thank members of the AAE 2013-2014 Captain and crew of the *MV* *Akademik Shokalskiy* and of the *Aurora Australis,* as well as Australian Antarctic Division Expeditioners.

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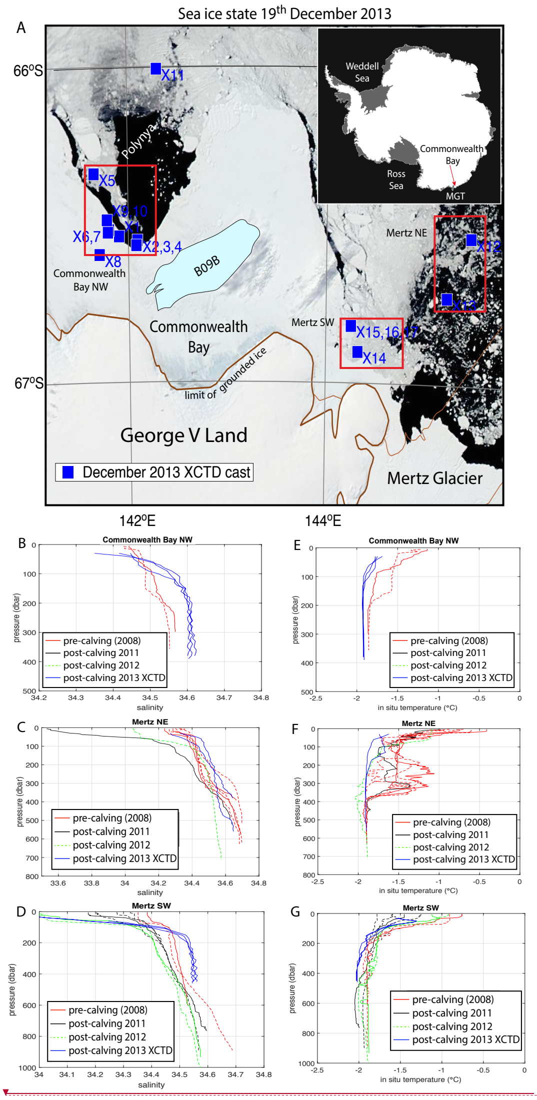
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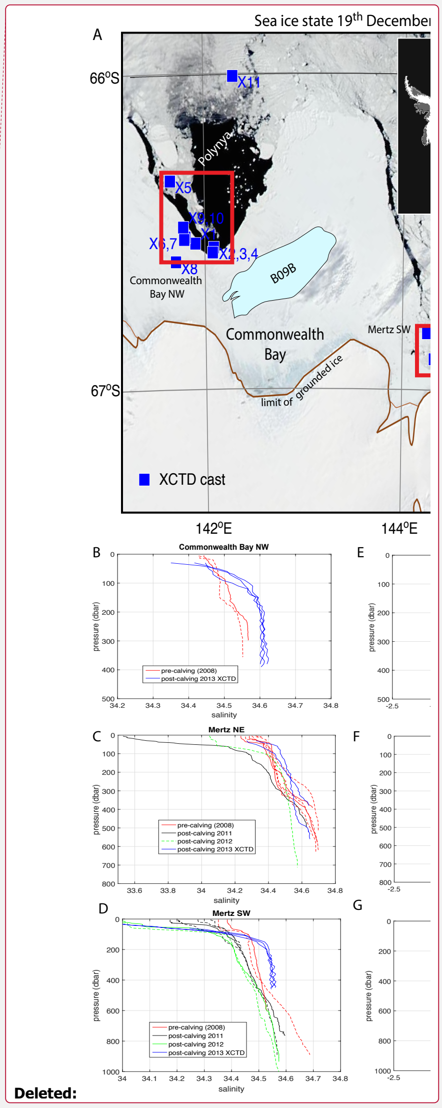
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Figure 1. A. Visible MODIS image of the Commonwealth Bay and Mertz Glacier region of Adélie Land, Antarctica on the 19th of December 2013 (credit Dr Jan Lieser; source NASA WORLDVIEW), with the sites of the December 2013 XCTD casts. The outline of the grounded B09B iceberg is indicated, with a map of the Antarctic Continent inset. Comparison between salinity from XCTD casts in 2013 (blue) and CTD profiles from previous years from 2012 (green), 2011 (black) and 2008 (pre-calving; red) B. Commonwealth Bay NW, C. NE Mertz and D. SW Mertz. 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).

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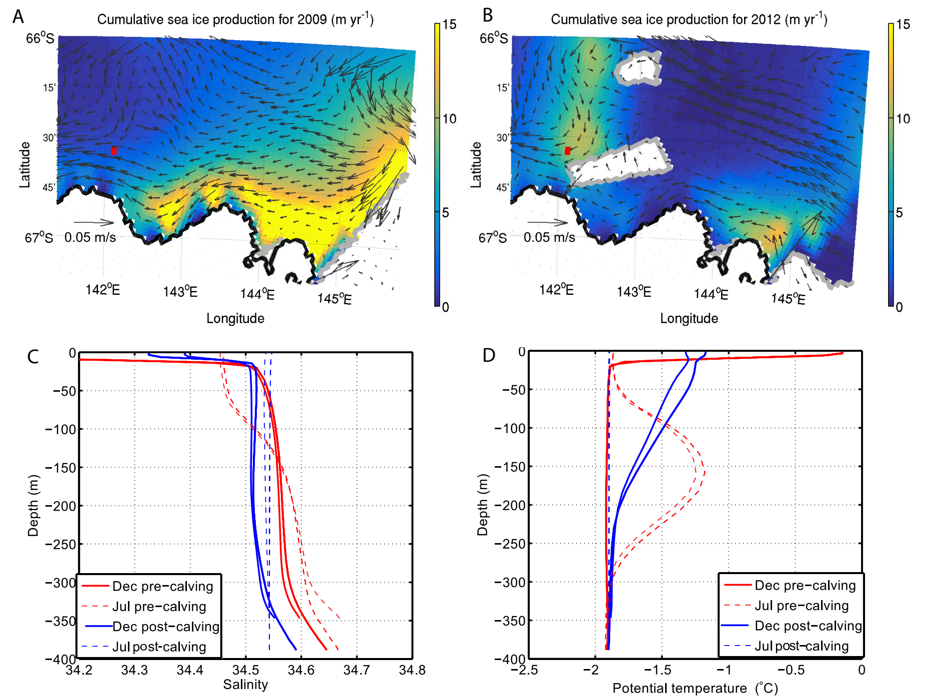
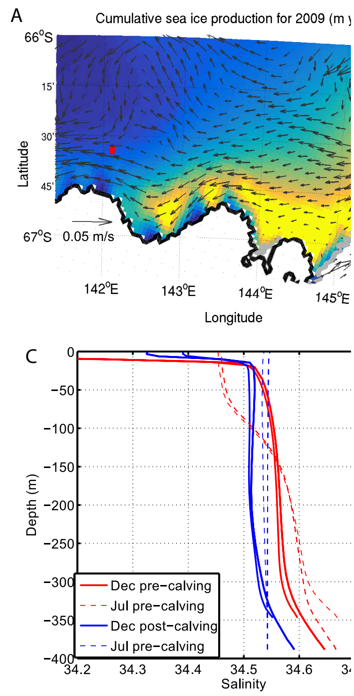


Figure 2. Upper panels: Cumulative sea ice production (m/yr) for the two years of forcing for A. pre- (2009) and B. post- (2012) calving simulations, overlaid with the vertically integrated horizontal velocity (m/s) in December, from the model climatology (black vectors). Red squares mark the Commonwealth 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: salinity (C) and potential temperature (D) for the the XCTD stations in Commonwealth Bay NW pre (red) and post calving (blue) simulations, averaged for December (solid line) and July (dashed line).



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3.2 Comparison with past data

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Galton-Fenzi, B. K., Hunter, J. R., Coleman, R., Marsland, S. J., and Warner, R. C.: Modeling the basal melting and marine ice accretion of the Amery Ice Shelf, Journal of Geophysical Research: Oceans, 117, C09031, 10.1029/2012JC008214, 2012.

Harris, P. T., Brancolini, G., Armand, L., Busetti, M., Beaman, R. J., Giorgetti, G., Presti, M., and Trincardi, F.: Continental shelf drift deposit indicates non-steady state Antarctic bottom water production in the Holocene, Marine Geology, 179, 1-8, http://dx.doi.org/10.1016/S0025-3227(01)00183-9, 2001.

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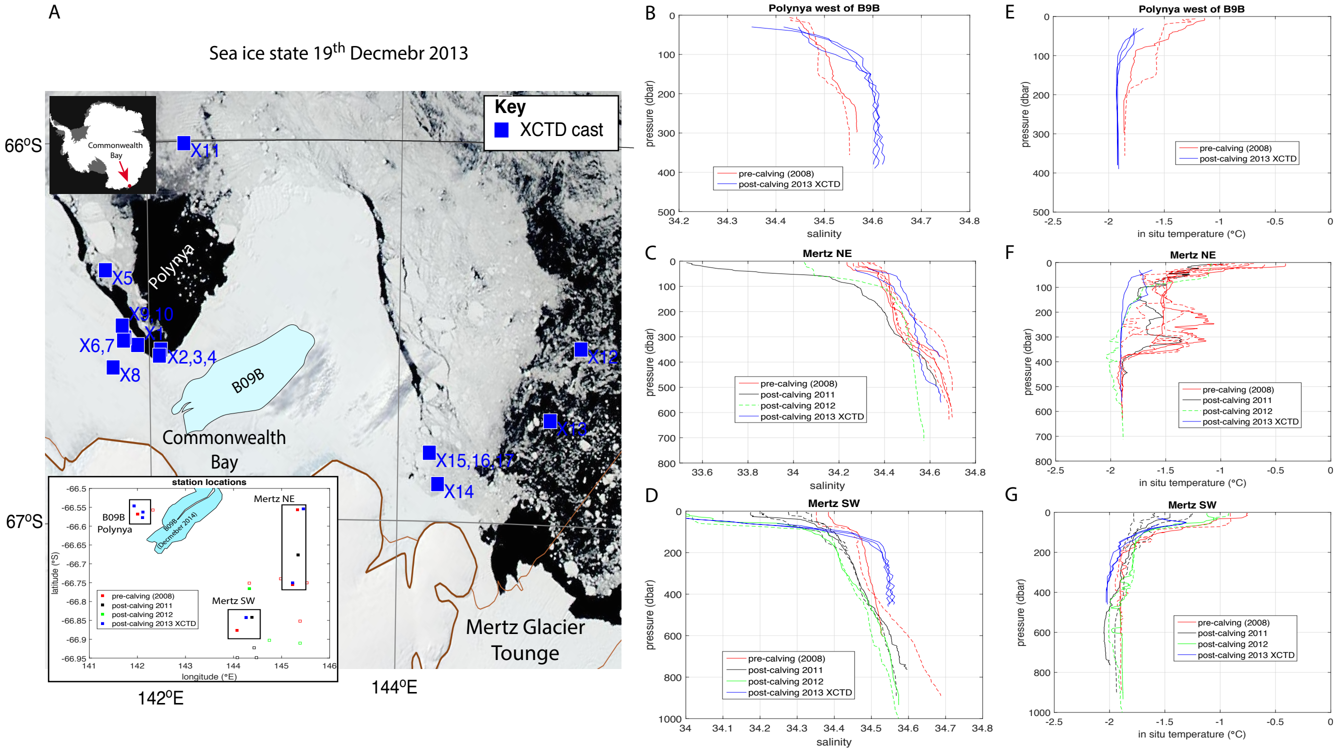
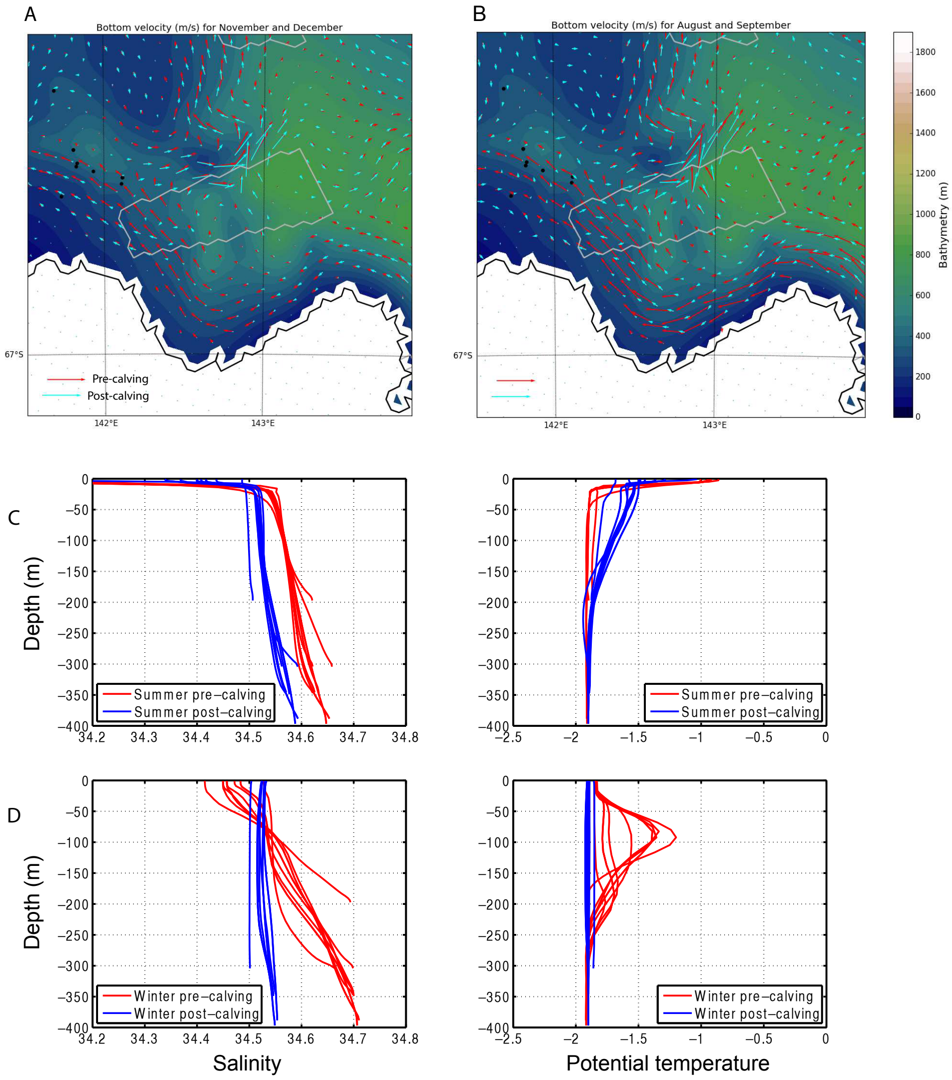

A
Sea ice state 19th Decmebr 2013
Key
XCTD cast
66°S
67°S
142°E
144°E
X11
X5
Polynya
X9,10
X1
X6,7
X2,3,4
X8
B09B
Commonwealth Bay
X12
X13
X15,16,17
X14
Mertz Glacier Tounge
Commonwealth Bay
station locations
B09B Polynya
Mertz NE
Mertz SW
pre-calving (2008)
post-calving 2011
post-calving 2012
post-calving 2013 XCTD
latitude (°S)
longitude (°E)
B
Polynya west of B9B
pressure (dbar)
salinity
pre-calving (2008)
post-calving 2013 XCTD
E
Polynya west of B9B
in situ temperature (°C)
C
Mertz NE
F
Mertz NE
D
Mertz SW
G
Mertz SW



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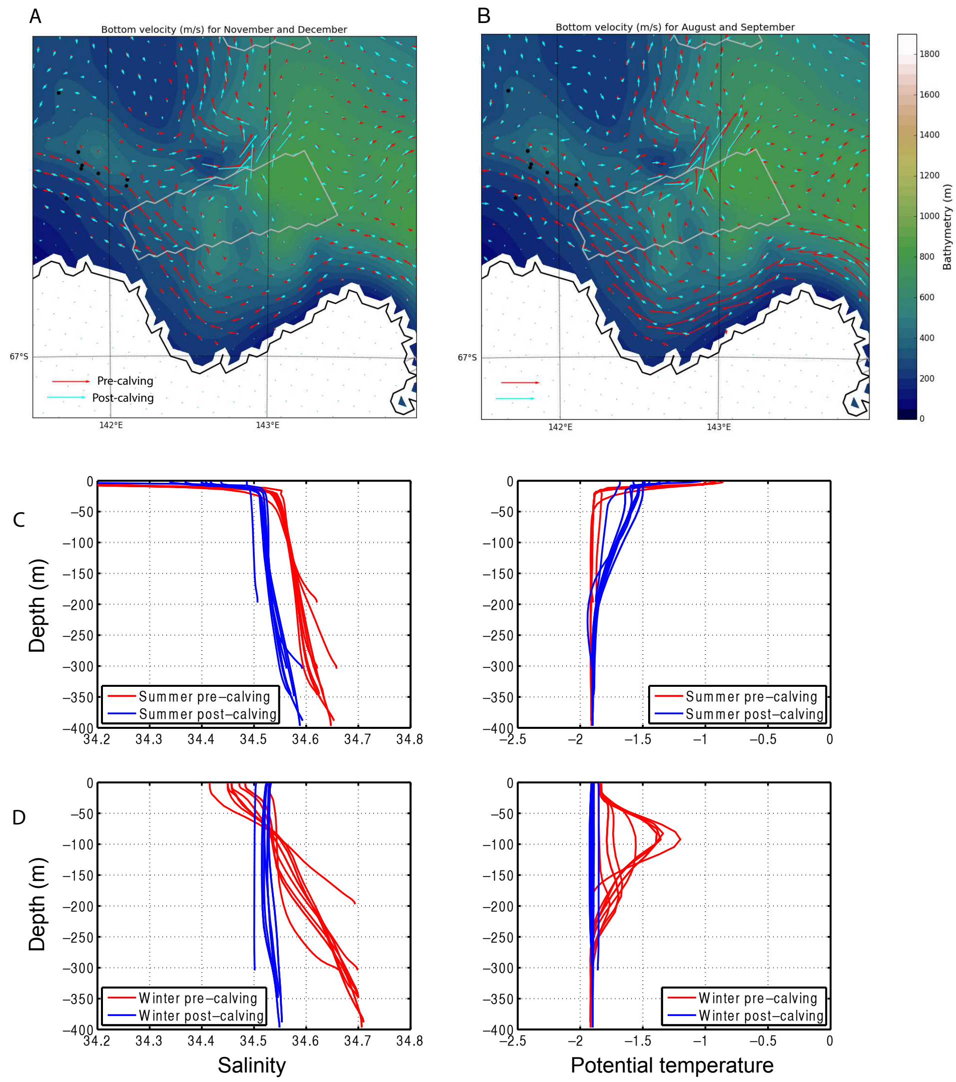

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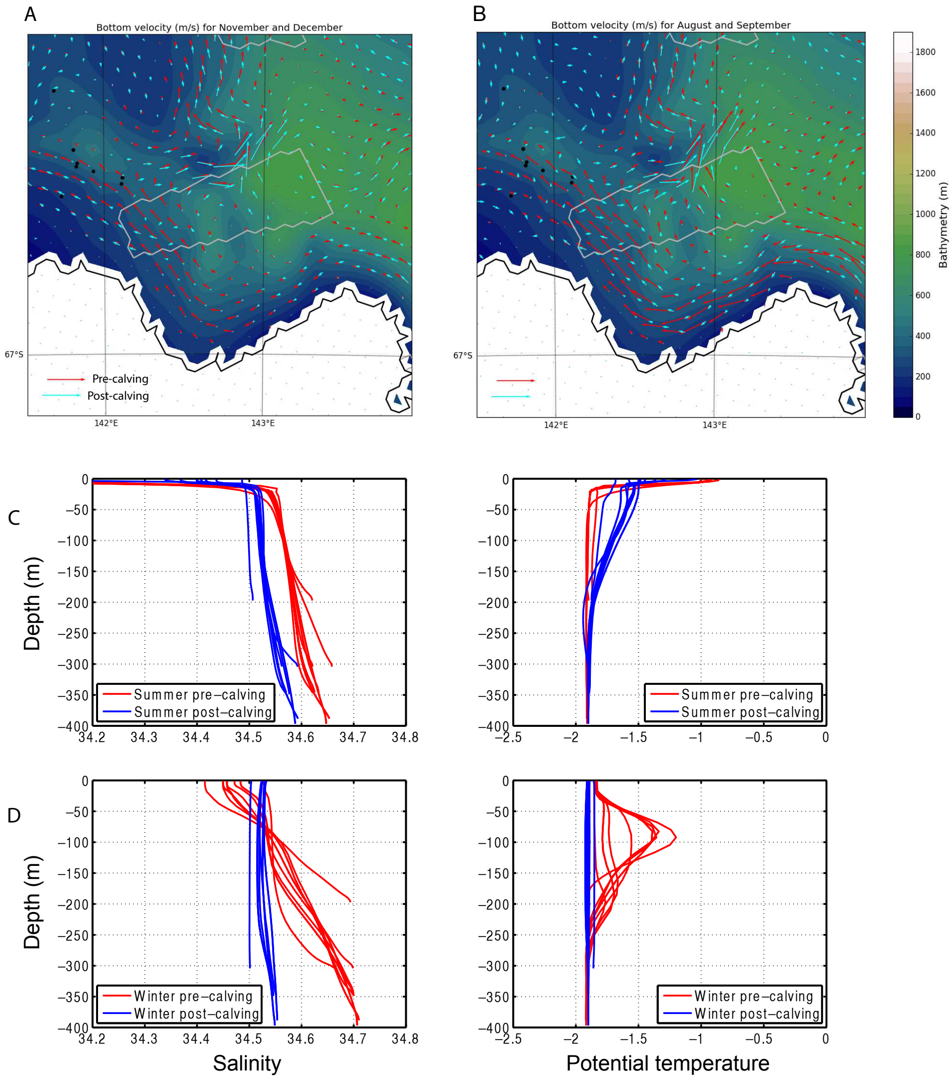

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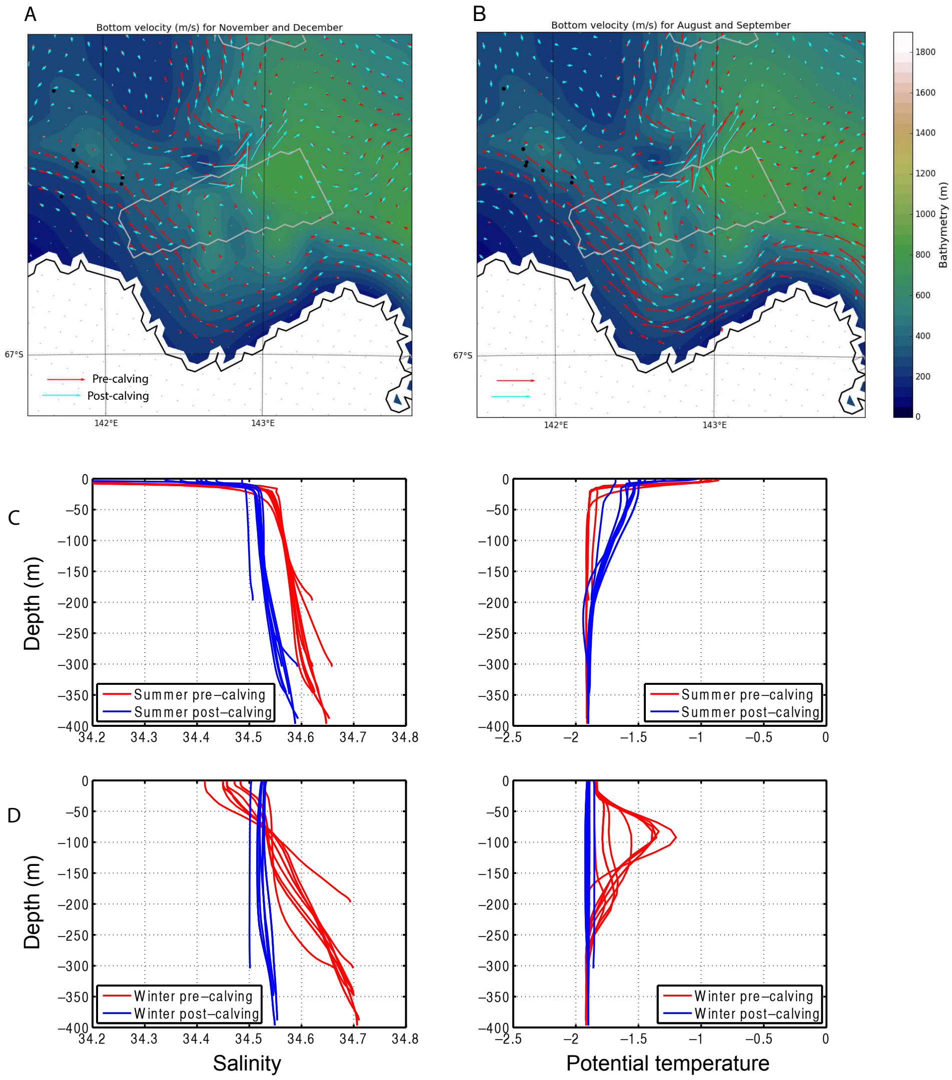

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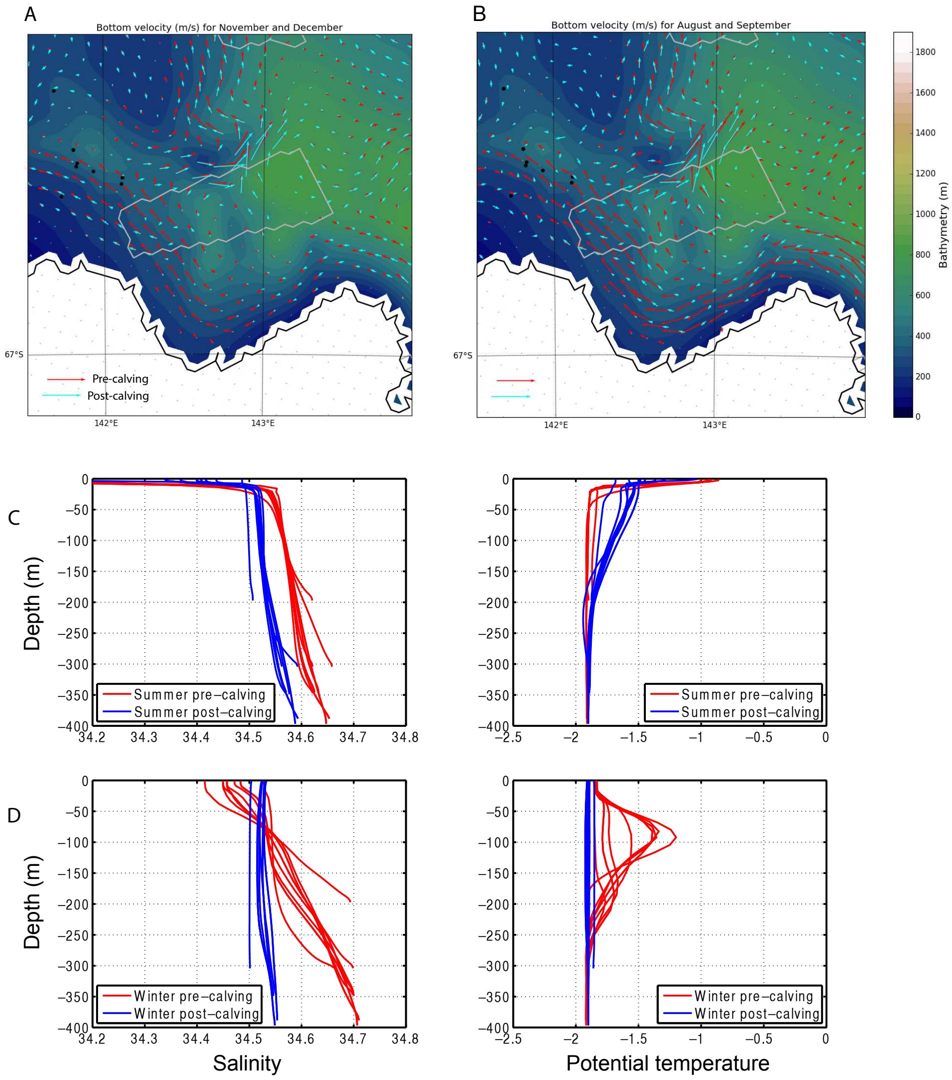

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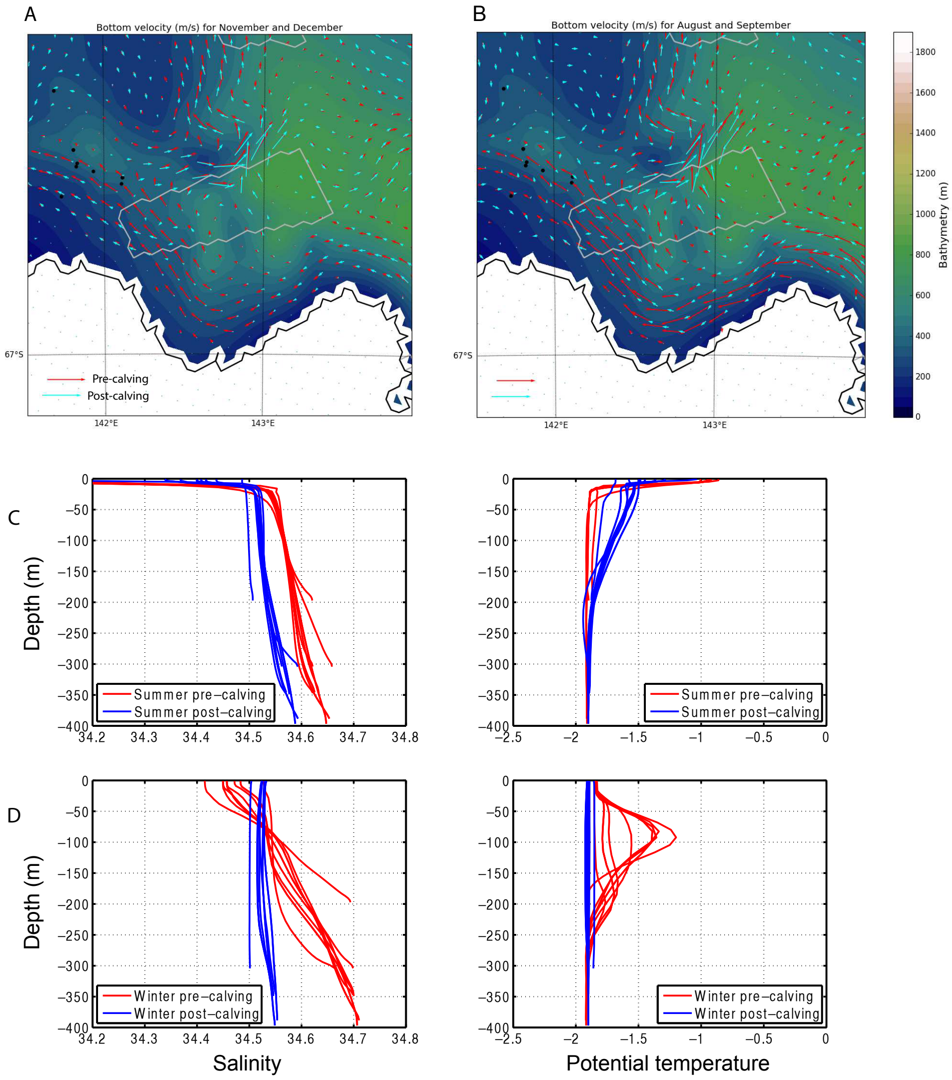

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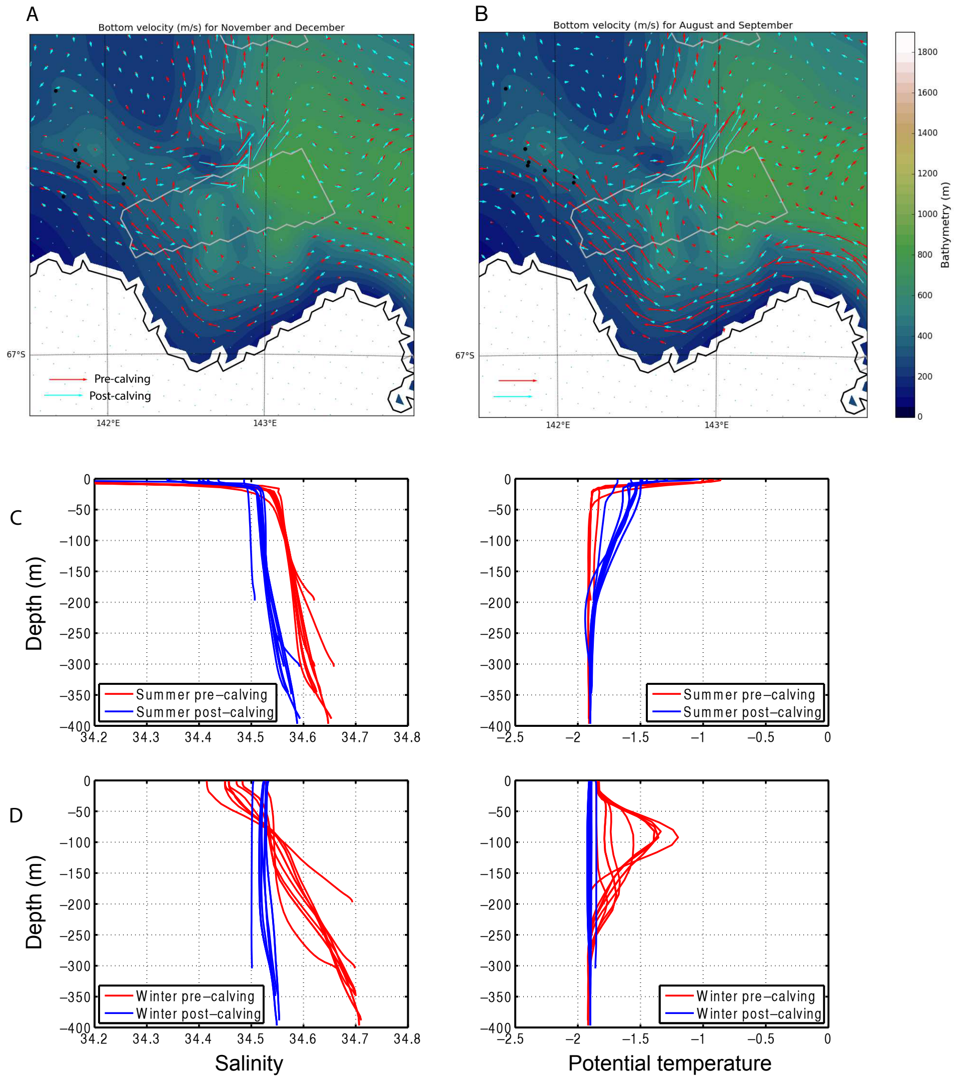

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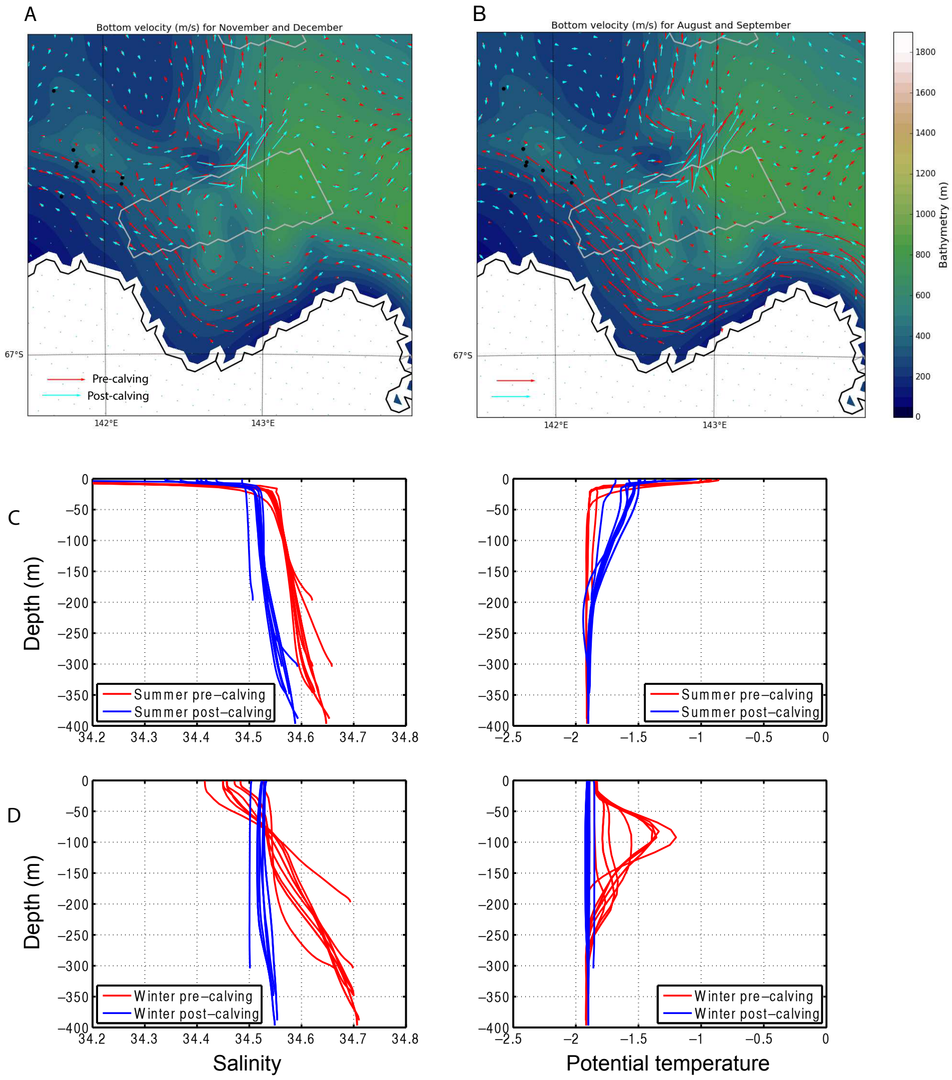

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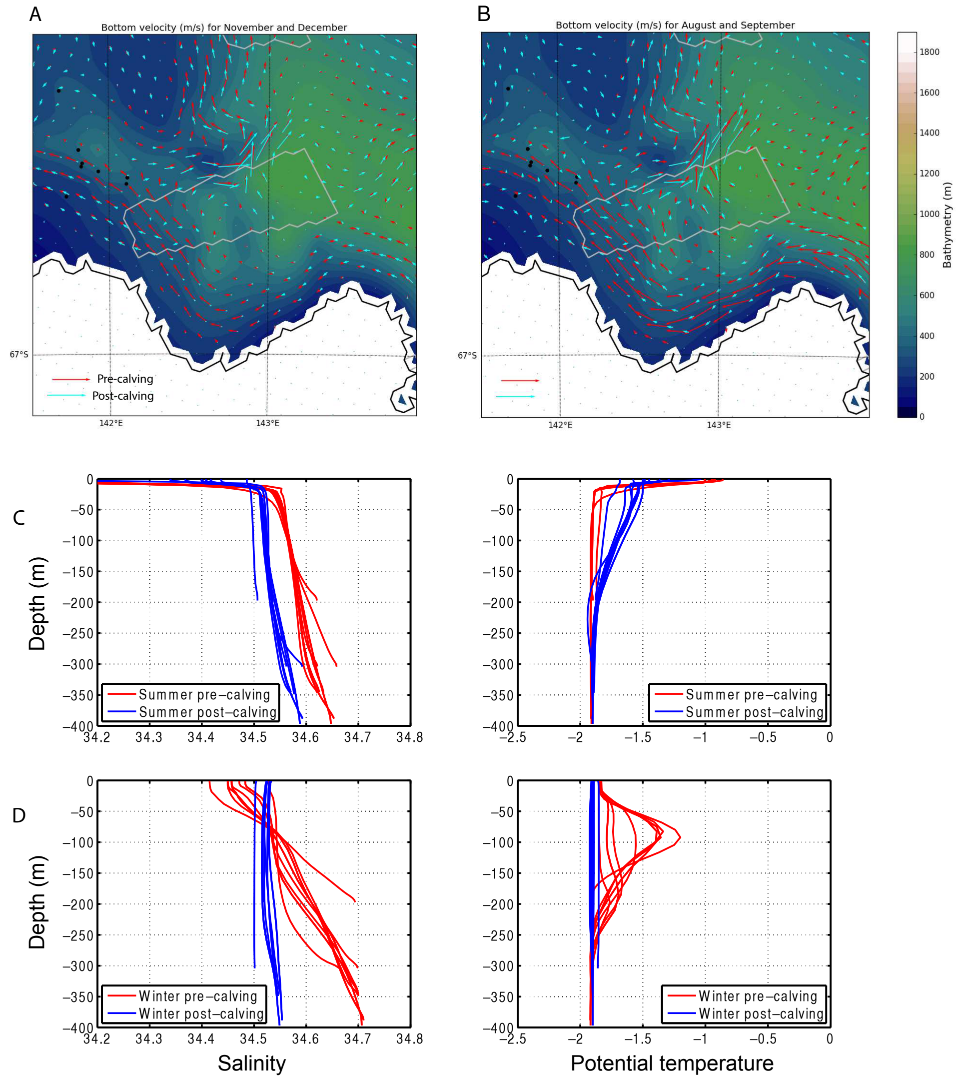

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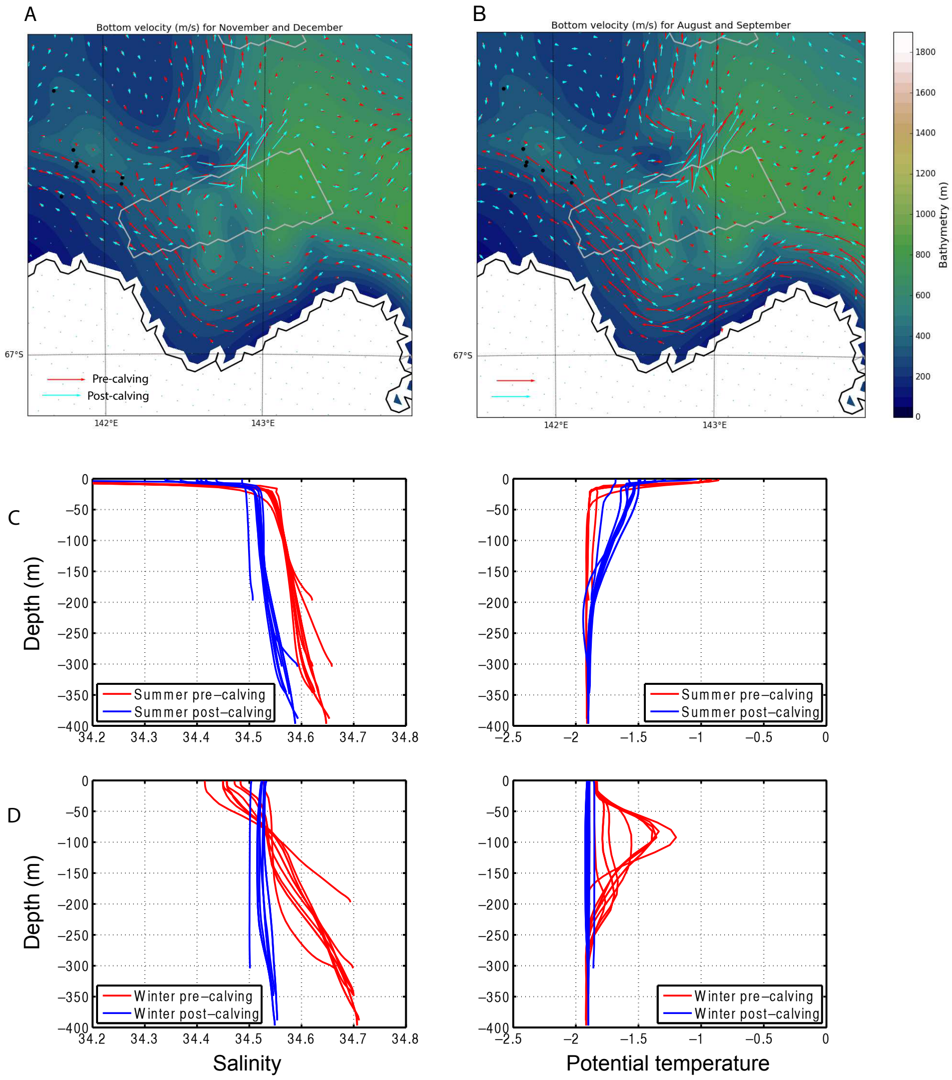

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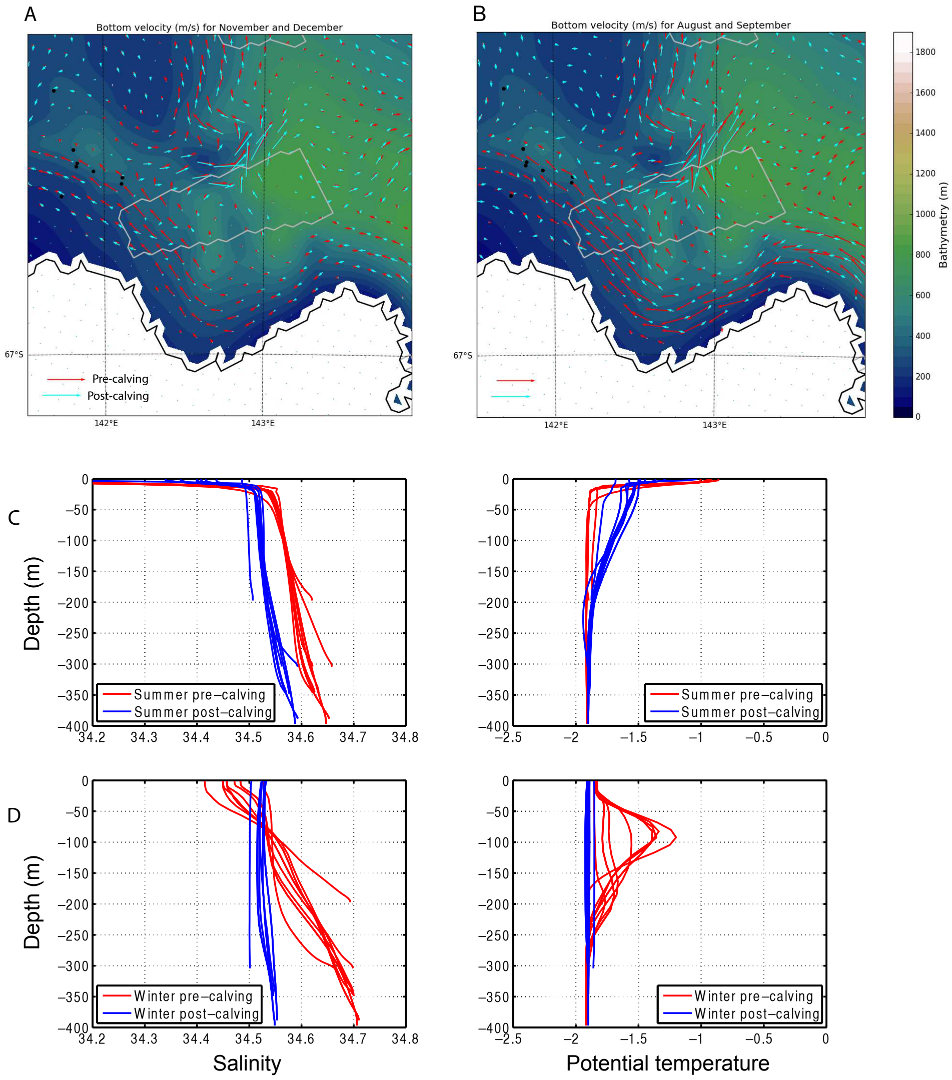

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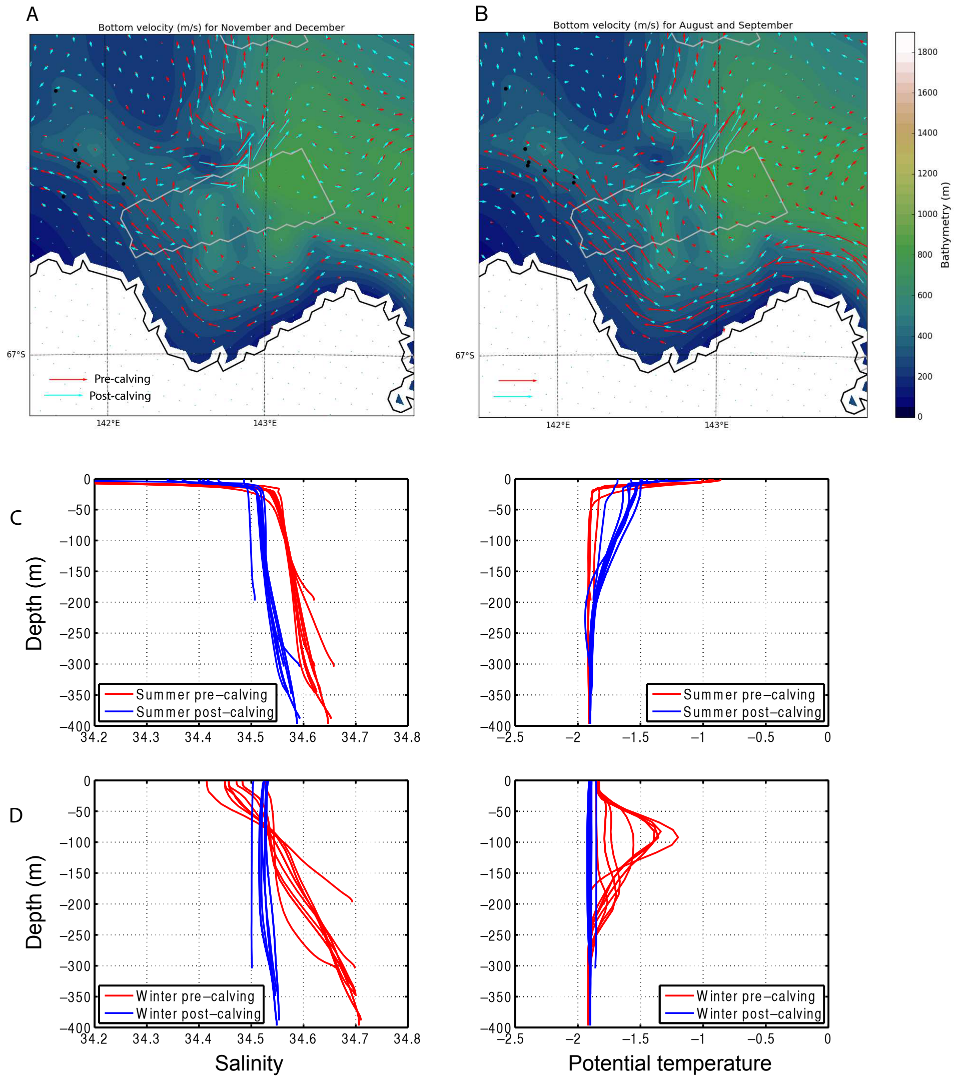

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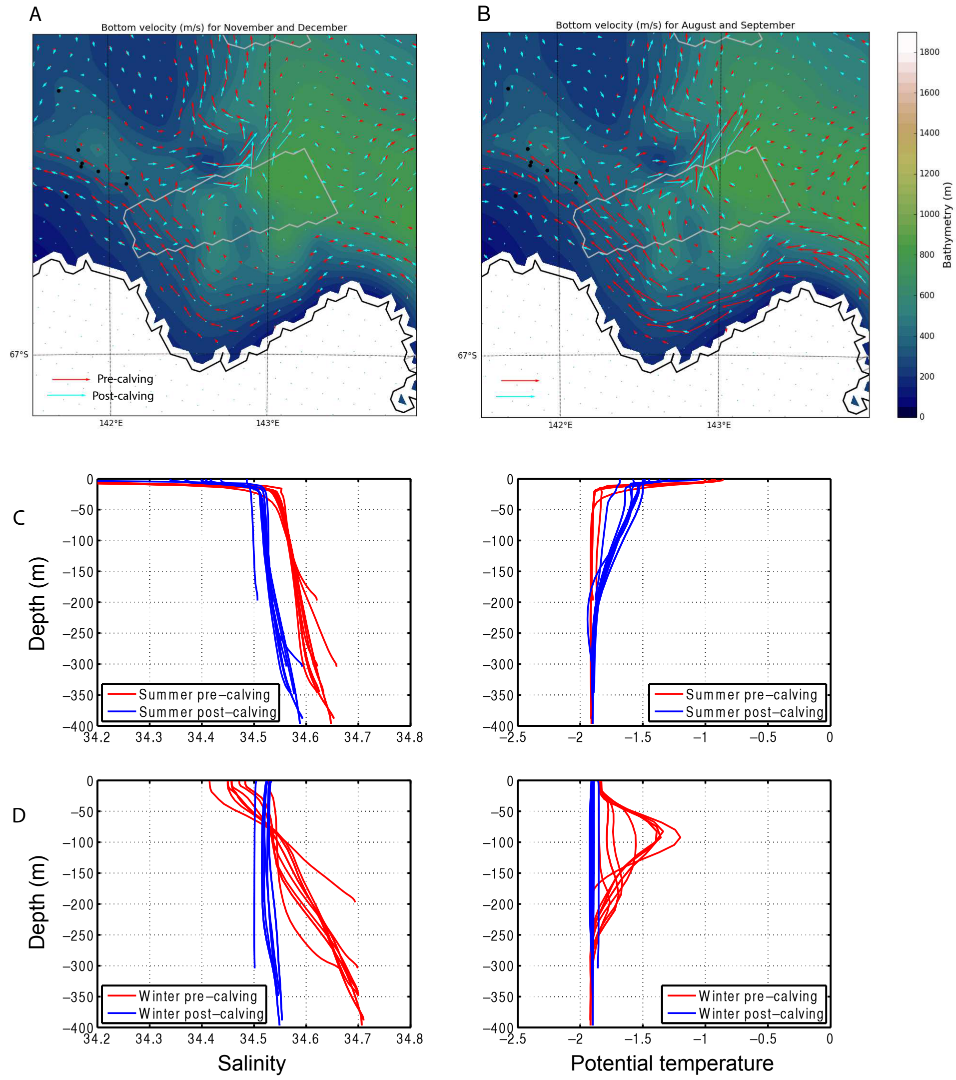

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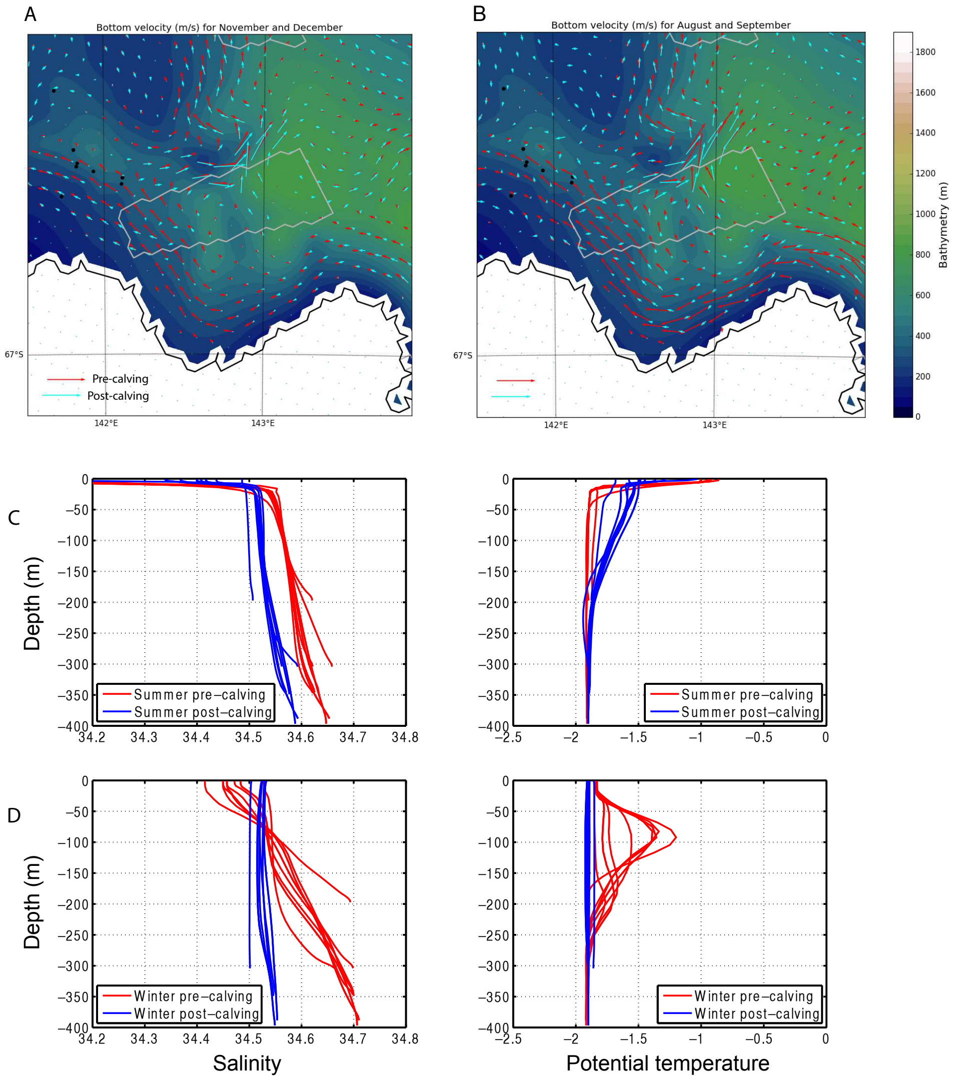

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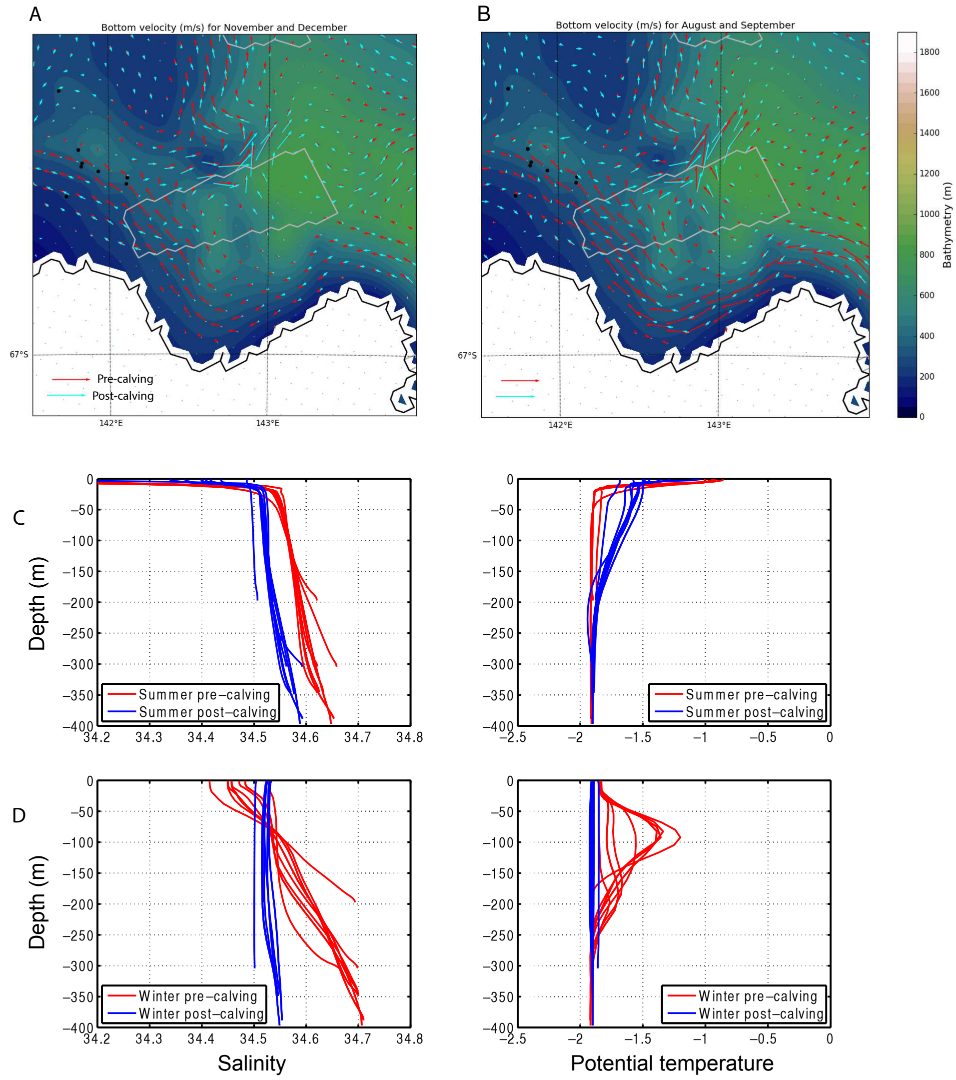

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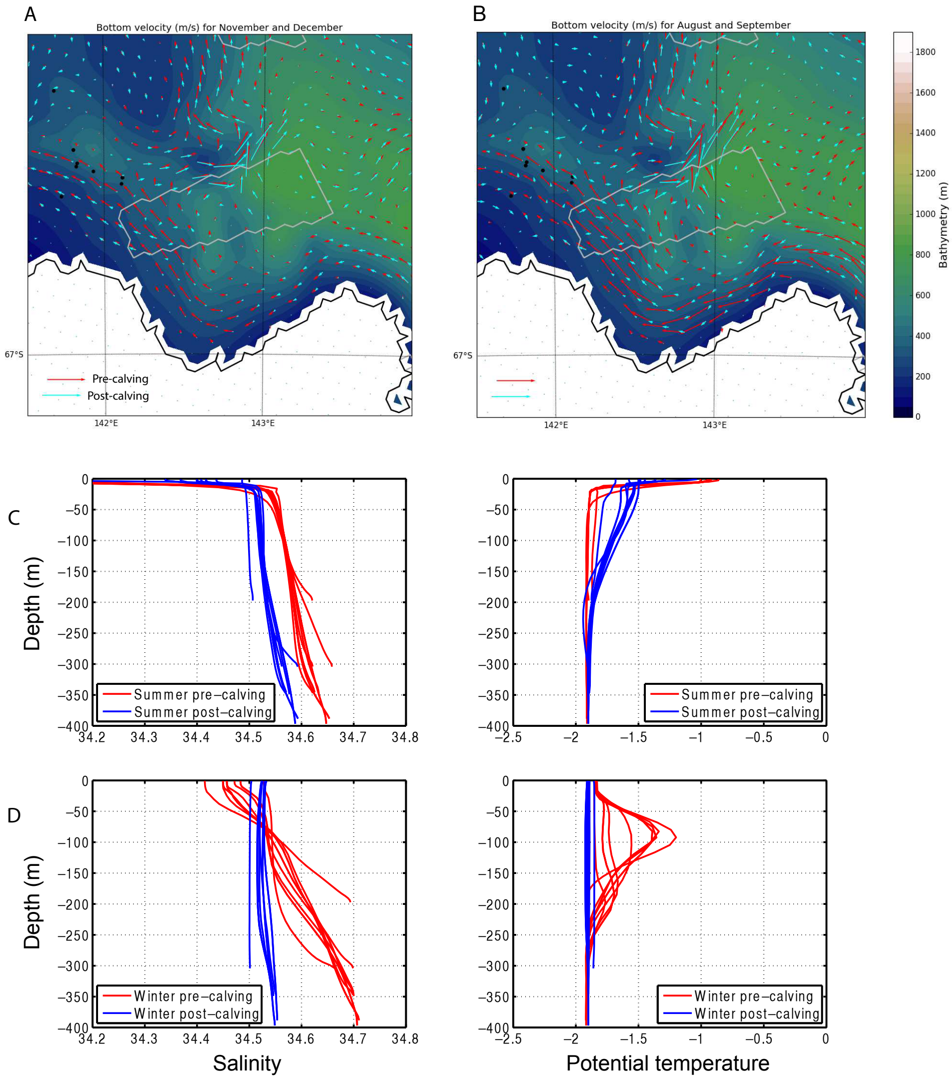
A
Bottom velocity (m/s) for November and December
Pre-calving
Post-calving
67°S
142°E
143°E
B
Bottom velocity (m/s) for August and September
Bathymetry (m)
C
D
Depth (m)
Summer pre−calving
Summer post−calving
Winter pre−calving
Winter post−calving
Salinity
Potential temperature