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BRIEF COMMUNICATION: 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, triggered by the impact of iceberg B09B, reshaped the oceanographic regime across the Mertz Polynya and Commonwealth Bay, regions where high salinity shelf water (HSSW) is formed, the precursor to Antarctic bottom water (AABW). 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 collision of the 97km long iceberg B09B with the Mertz Glacier Tongue in 2010 triggered 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 created by the local ice-sheet topography. Historically, newly-formed sea ice has been rapidly transported offshore by these winds; during the original AAE of 1911-1914, the sea ice 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 changed the local ice-scape considerably (Shadwick et al., 2013) (Lacarra et al., 2014) (Figure 1A). The presence of B09B 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). This last is particularly important given the region is critical to the 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, the Mertz and Commonwealth Bay polynyas were important sources of high salinity shelf water (HSSW) and dense shelf water (DSW) formation, which itself is a precursor to AABW. As AABW supplies the lower limb global thermohaline circulation system (Orsi et al., 1999), changes in the properties or rate of formation of AABW in response to changes in the local icescape could have widespread consequences on deep ocean circulation and ventilation.

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The loss of the 78 km-long Mertz Glacier Tongue, which had previously blocked the westward flow of ice into the Mertz Polynya and Commonwealth Bay, is estimated to have caused a marked reduction of sea-ice formation regionally (Shadwick et al., 2013; 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. Furthermore, it has been suggested that this regional ice and ocean reconfiguration could reduce the export of AABW from the Adélie region (Kusahara et al., 2011) with potentially global implications (Shadwick et al., 2013). Palaeoceanographic studies suggest this may be a cyclic process occurring on centennial (Campagne et al., 2015) and perhaps even millennial timescales (Harris et al., 2001). In contrast, other studies suggest the impacts on AABW formation may only persist for decades (Tamura et al., 2012), whilst the regional ice-scape remains affected by the loss of the Mertz Glacier tongue and the grounding of B09B has created an extensive area of fast-ice within Commonwealth Bay.

Given that the majority of AABW is formed in four principal sites around Antarctica (Orsi et al., 1999)– the Weddell Sea, the Ross Sea, Amery-Shackleton ice shelf and Adélie-George V Land off East Antarctica – 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 are not fully understood, and it is possible that the rates of AABW production from regional areas are temporally and spatially highly variable. 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 the 2013/2014 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 in

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velocity and advection of water masses between the Mertz Polynya and Commonwealth Bay for scenarios pre and post-grounding of B09B.

2. *In situ* observations and model simulations

2.1 *In situ* observations

We report observations of changes in ocean water properties recorded on the Australasian Antarctic Expedition (AAE) 2013/14 from the *RV 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 condtions (see Supplement 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 Modeled 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; Galton-Fenzi et al., 2012), with a model setup similar to that of Cougnon et al., 2013 (Cougnon et al., 2013). The model includes ocean/ice-shelf thermodynamics and frazil ice thermodynamics, but does not include sea-ice model/ocean coupling. To resolve the fine-scale regional polynya activity, the surface of the model is forced with monthly heat and salt fluxes based on sea ice concentration from a climatology-derived model using Special Sensor Microwave Imager (SSM/I) (Tamura et al., 2011). The model simulations are forced at the

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surface with data from the year 2009 (pre-calving) and 2012 (post-calving), providing general information on the ocean circulation for a stable ice geometry, that includes melt water from the B09B and other fast ice and icebergs/ice shelves present in the domain. 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 from Estimating the circulation and climate of the ocean, Phase II synthesis (ECCO2) for the period 1992-2013 (Wunsch, 2009).

3 Results

3.1 XCTD results

The casts are divided into three geographic areas to allow direct comparison with data from previous cruises from the same season (Figure 1).

3.2 Comparison with past data

Salinity and temperature data from the austral summer 2013/14 from Commonwealth Bay NW, Mertz NE and Mertz SW 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 that piled up to the east of the glacier tongue. 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 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 far colder, perhaps because the iceberg is blocking inflow of the warmer water from the east.

Data from the polynya west of B09B, northwest of Commonwealth Bay, shows evidence of a shift in water properties following the grounding of B09B in its present position (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 is saltier, colder and evidently more well-mixed. These observations suggest deep convection and HSSW formation occurred 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 substantially 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.

3.3 Model simulation results

Our high-resolution model simulations indicate a change in bottom ocean circulation in summer (Figure 2A) and in winter (Figure 2B) post-calving, suggesting the presence of a polynya in the lee of the B09B iceberg, as indicated by the changes in water properties recorded by the XCTD profiles. The model results show a marked change in bottom current velocity post-calving, in both summer and winter (Figure 2A and B). Pre-calving, a westward coastal current carried water masses from the Adélie Depression and Commonwealth Bay into the area where iceberg B09B is presently grounded (Figure 2), resulting in a stratified water column with HSSW present at depth (Figure 2C and D), as seen in the observations from 2008 (Figure 1B). In the model, the water column is stratified even in winter, indicating that the high salinities at depth are advected into the region from the Mertz and Commonwealth Bay polynyas (Figure 2D). After the grounding of B09B, the modelled salinities are lower and the water column is well-mixed in winter. The coastal current is largely blocked by the iceberg and little HSSW is advected into the region from the east (McCartney and Donohue, 2007), potentially explaining the reduction in salinity at depth. The homogenous water column suggests local deep convection in the polynya west of B09B, as inferred from the observations.

4 Discussion

The combination of *in situ* salinity measurements and high-resolution regional ocean modelling across the Mertz Polynya and Commonwealth Bay provides unique insights into ocean dynamics post-Mertz calving in this region critical to HSSW production and AABW formation. The changes recorded demonstrate that this region is still undergoing marked and dramatic oceanographic change that has important implications (Shadwick et al., 2013; Clark et al., 2015).

4.1 A developing polynya?

Both the 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. Data from the north-west of Commonwealth Bay 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 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).

Whilst the data 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. Critically the grounding of B09B 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 polynyas.

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, HSSW formed in the new polynya compensates 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). This study further enhances our understanding of the sensitivity of HSSW and AABW formation to changes in the local icescape, by showing how movement of large icebergs can also alter regional ocean circulation and air-sea interaction patterns, producing new regions of dense water formation.

Regional icescapes are likely to change in the future as a result of both natural and anthropogenic drivers. Studies of the response of the ocean and cryosphere to events like the calving of the Mertz Glacier and grounding of B09B provide insight into the consequences of such 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 (Orsi et al., 1999). AABW and its modified counter parts spread from these highly localised source regions throughout the global ocean, 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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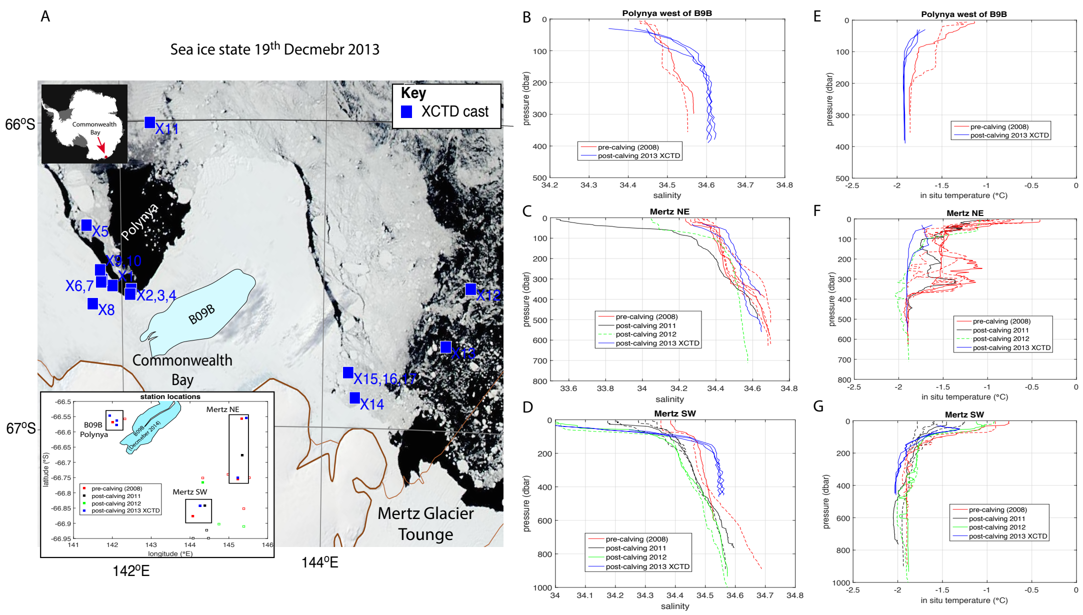

Figure 1. A. Visible MODIS image of the Commonwealth Bay and Mertz Glacier region of Adélie Land, Antarctica on the 19th of December 2013 (credit Dr Jan Lieser), with the sites of XCTD casts, the outline of B09B is indicated, with a map of the Antarctic Continent and the locations of XCTD casts from this study and CTD cast from previous years used in comparison inset. Comparison between salinity from XCTD casts in 2013 (Blue) and CTD profiles from previous years from B. NW Commonwealth Bay, C. NE Mertz and D. SW Mertz. Comparison between temperature from XCTD (Blue) casts in 2013 and CTD profiles from previous years from B. NW Commonwealth Bay, C. NE Mertz and D. SW Mertz.

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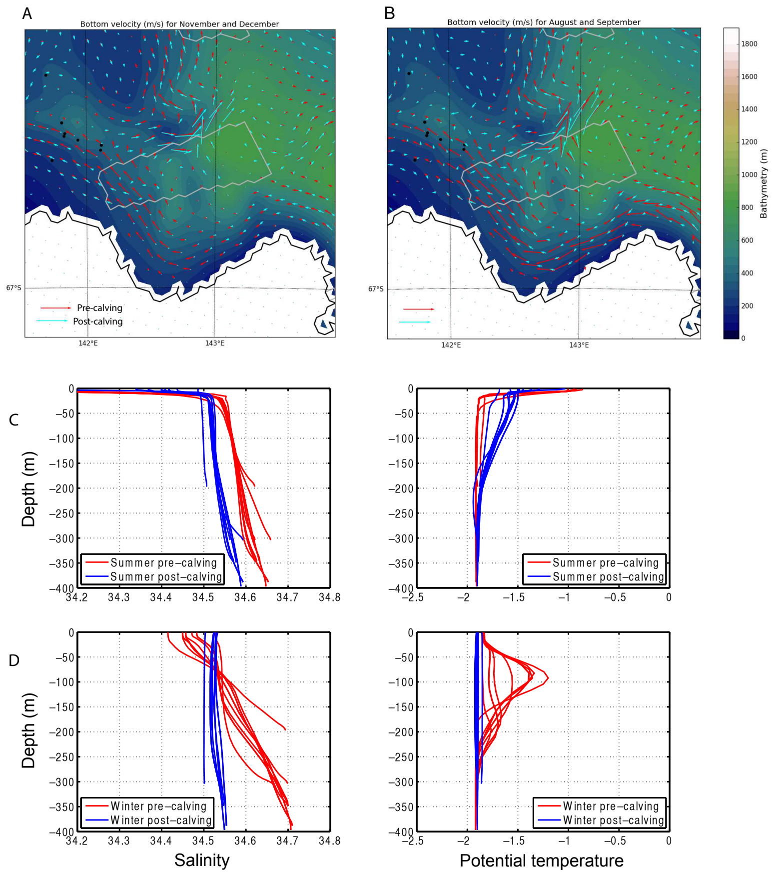

Figure 2. Simulated bottom current velocity averaged on the five bottom layers of the model (m/s) for both pre-calving (red vectors) and post-calving (cyan vectors) simulations near Commonwealth Bay for A summer (November - December) and B winter (August – September). The outline of B09B can be seen and the location of our XCTD casts in the B09B polynya. C. Simulated mean salinity (psu) (left) and potential temperature (ºC) (right) for summer (November-December) and D. simulated mean salinity (psu) (left) and potential temperature (ºC) (right) for winter (August and September) at the XCTD sites 1 to 10 (polynya west of B09b), for both pre-calving (red) and post-calving (blue) simulations.