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Key Points:
- Multiyear observations are used to assess the sensitivity of Adelie Land Bottom Water properties to changes in surface forcing
- Weaker buoyancy loss after calving of the Mertz Glacier Tongue reduced the density and volume of Dense Shelf Water available for export
- Corresponding reductions in density and volume of Adelie Land Bottom Water highlight the impact of local changes on the abyssal ocean

Supporting Information:
- Supporting Information S1

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Change in Dense Shelf Water and Adélie Land Bottom Water Precipitated by Iceberg Calving

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Abstract Antarctic Bottom Water supplies the deep limb of the global overturning circulation and ventilates the abyssal ocean. Antarctic Bottom Water has warmed, freshened, and contracted in recent decades, but the causes remain poorly understood. We use unique multiyear observations from the continental shelf and deep ocean near the Mertz Polynya to examine the sensitivity of this bottom water formation region to changes on the continental shelf, including the calving of a large iceberg. Postcalving, the seasonal cycle of Dense Shelf Water (DSW) density almost halved in amplitude and the volume of DSW available for export reduced. In the deep ocean, the density and volume of Adélie Land Bottom Water decreased sharply after calving, while oxygen concentrations remained high, indicating continued ventilation by DSW. This natural experiment illustrates how local changes in forcing over the Antarctic continental shelf can drive large and rapid changes in the abyssal ocean.

1. Introduction

The global overturning circulation regulates the transport and storage of heat, freshwater, carbon, and nutrients by the ocean. Antarctic Bottom Water (AABW) supplies the deep branch of this circulation and accounts for a larger volume of the global ocean than any other water mass (Johnson, 2008). AABW forms in a few key locations around the Antarctic margin, where strong cooling and sea ice formation in coastal polynyas forms Dense Shelf Water (DSW). DSW sinks from the continental shelf into the deep ocean, entraining surrounding Circumpolar Deep Water (CDW) to form AABW. Spreading through the deep ocean, AABW supplies oxygen and influences stratification and circulation on global scales.

AABW has undergone substantial change in recent decades. The warming, freshening, and decrease in volume of the AABW (Purkey & Johnson, 2010, 2012, 2013) are of sufficient magnitude to be of relevance to global climate. Warming of AABW accounts for 10–16% of the excess energy stored by the planet since 1970 and 9% of global thermosteric sea level rise (Purkey & Johnson, 2010, 2012). A number of regional studies have further documented trends in AABW (Azaneu et al., 2013; Rintoul, 2007; Sloyan et al., 2013; van Wijk & Rintoul, 2014). While the signal of change in AABW is clear from observations, the causes are not well understood, largely due to few observations being available on the Antarctic continental shelf, particularly in winter when DSW is formed. As a consequence, we do not yet have a mechanistic understanding of the sensitivity of AABW to changes in surface forcing near the Antarctic margin.

The Adélie Land continental shelf in East Antarctica (142–147°E; Figure 1a) contributes 5–25% of the global volume of AABW (Rintoul, 1998; Williams et al., 2008). DSW is formed in the Mertz Polynya, an area of low sea ice concentration and strong buoyancy forcing to the west of the Mertz Glacier Tongue (MGT), along the adjacent coastline (Figure 1b) and in Commonwealth Bay (Lacarra et al., 2014). Export of DSW through the Adélie Sill and subsequent entrainment as the DSW descends the continental slope forms the local variety of AABW, known as Adélie Land Bottom Water (ALBW). The ALBW can be traced to low latitudes of the Indian and Pacific Oceans (Mantyla & Reid, 1995; Nakano & Suginohara, 2002).

Prior to 2010, the Mertz Polynya was the third largest sea ice producer of all Antarctic polynyas (Tamura et al., 2008). However, calving of the MGT in February 2010 resulted in dramatic changes in the Adélie Land icescape (Figures 1c and 1d). A 97 km long iceberg, B9B, approached the eastern side of the MGT. The terminal end

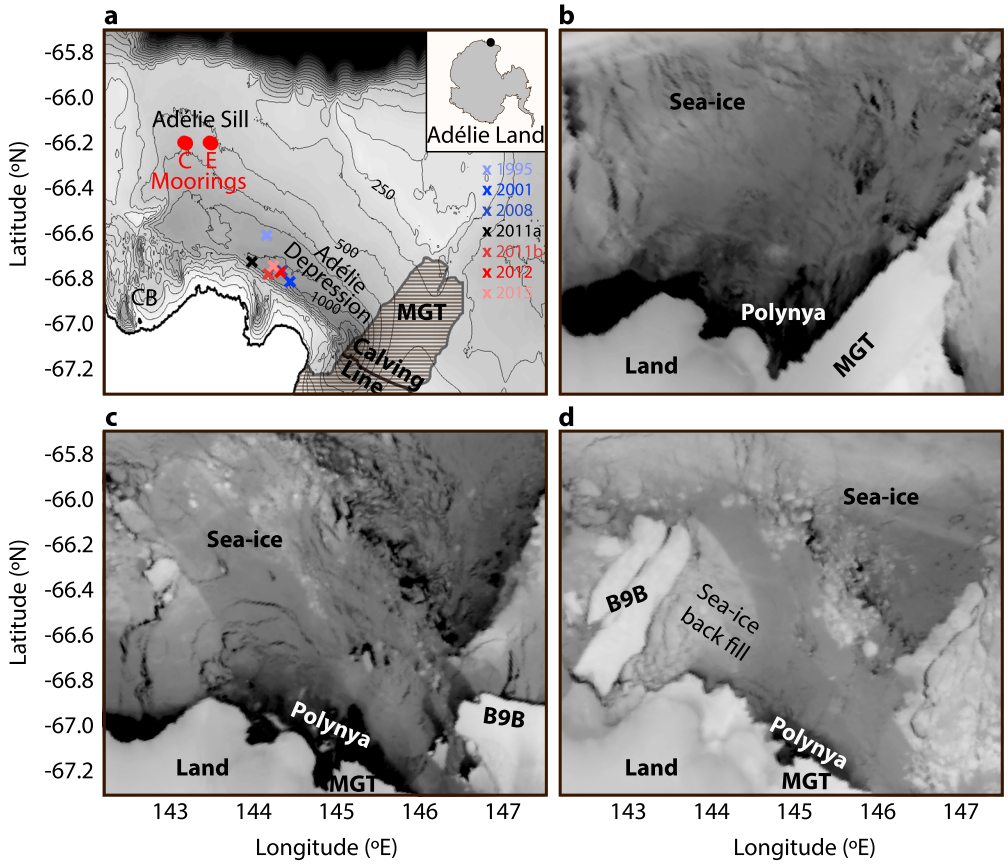

Figure 1. (a) Topographic map of the Adélie Land continental shelf (contour interval 250 m). East (E) and central (C) mooring locations are indicated in red circles. Conductivity, temperature, and depth measurement locations from 1995 to 2015 indicated by crosses. MODIS satellite images (Scambos et al., 2001) of the Adélie region on (b) 17 July 2006, (c) 18 July 2011, and (d) 14 July 2013. The Adélie Depression, Adélie Sill, iceberg B9B, and Commonwealth Bay locations are indicated. Hashed regions indicate the Mertz Glacier Tongue (MGT) and the thick solid line the position before and after the 2010 calving event.

of the MGT was broken off, reducing the length of the glacier tongue by about 80 km. The relocation of B9B and reduction in size of the MGT allowed sea ice to move in from the east, reducing the size and activity of the Mertz Polynya. Sea ice production decreased by 14–20% in the first winter after the calving event (Nihashi & Ohshima, 2015; Tamura et al., 2012). Regrounding of B9B off Commonwealth Bay led to formation of fast ice in areas formerly occupied by coastal polynyas, as well as backfilling of the Mertz Polynya by sea ice advected from the east, reducing sea ice production to 20–40% of its precalving mean value (Nihashi & Ohshima, 2015; Tamura et al., 2012, 2016).

Previous studies have shown that the density of DSW on the continental shelf decreased after the calving event, in response to the reduction in sea ice formation. These studies relied on summer hydrographic measurements on the continental shelf and a shelf mooring located a hundred kilometers from the DSW export pathway (Lacarra et al., 2014). The mooring revealed links between changes in surface forcing and DSW properties in Commonwealth Bay (Lacarra et al., 2014). While the highest salinities (and largest interannual variability) precalving were observed in Commonwealth Bay, these high salinities were not observed outside of the isolated deep basin in Commonwealth Bay (Lacarra et al., 2011). To assess the impact of changes in DSW on ALBW, time series of water mass properties at the Adélie Sill and in deep water downstream are needed.

Numerical simulations show a decrease in density and export of DSW and consequent changes in AABW in response to the calving event (Kusahara et al., 2011b, 2017). In recent years, an accelerated freshening has been observed in the AABW layer within the Australian-Antarctic Basin with possible links to the MGT calving (Menezes et al., 2017). However, no observational study has yet directly linked changes in the density of DSW exported from the shelf to changes in ALBW in the deep ocean.

We exploit the natural experiment provided by the MGT calving event to explore the sensitivity of DSW and AABW formation to regional change. Seven years of moored records from the sill through which DSW is exported to the deep ocean (Figure 1a) provide measurements of the seasonal cycle of density and thickness of the DSW layer available for export, both before and after calving. We link changes in DSW export to changes in ALBW downstream of the sill, using repeat hydrographic sections spanning a 21 year period. Contemporaneous measurements of the properties of DSW leaving the shelf and of the ALBW in the deep ocean provide a unique opportunity to investigate the sensitivity of AABW to changes in DSW hydrographic properties.

2. Method

Moorings deployed at the Adélie Sill are used to document water mass properties before and after calving of the MGT. Three years of observations are available prior to calving (1998, 1999, and 2008) and four years after calving (2011–2014) (supporting information Table S1; Williams et al., 2008). Each array includes a set of moorings deployed across the Adélie Sill with one in the centre (water depth of 593 m, latitude 66.198°S, and longitude 143.173°E) and one on the eastern (548 m, latitude 66.199°S, and longitude 143.479°E) flank of the sill (Figure 1a). Instruments on the moorings record temperature, salinity, and pressure at depths from 406 to 592 m. Salinity measurements at the 592 m instrument on the central mooring in 2011–2012 showed evidence of drift through time and is linearly adjusted to the average annual trend of all other 2011 instruments. All temperature and salinity measurements are quality controlled and filtered to remove data spikes. A moving average filter of width 10 days is applied to remove the high-frequency variability and to improve clarity of the monthly and interannual features. For further details see supporting information section S2.

Conductivity, temperature, and depth (CTD) data taken during the austral summer months between 1993 and 2015 (Figure 1a and Table S2; Lacarra et al., 2011; Sambrottoa et al., 2003; Shadwick et al., 2013; Snow et al., 2016) are analyzed to provide time series of shelf and abyssal ocean temperature, salinity, and dissolved oxygen. Measurements were taken on the continental shelf at the Adélie Depression and Adélie Sill, and in the abyssal ocean along the repeat occupations of the World Ocean Circulation Experiment (1990–2000) and GO-SHIP SR3 line (140°E).

Conservative temperature and absolute salinity are used throughout. Calculations of conservative temperature (Θ, °C), absolute salinity (S_A, g kg^{-1}), and surface freezing temperature (Θ_f, °C) were performed using the Gibbs Sea Water package (McDougall & Barker, 2011). Potential density referenced to the surface (σ_0, kg m^{-3}) and 3,500 m ($\sigma_{3,500}$, kg m^{-3}) are calculated from Θ and S_A using the Thermodynamic Equation Of Seawater-2010 (McDougall & Barker, 2011).

3. Results

3.1. Change in DSW Properties and Seasonal Cycle After Calving

For each of the three years of mooring measurements prior to the calving, a similar seasonal cycle in the DSW layer is found (Figure 2) (references to seasons indicate austral seasons). Brine released during sea ice formation in winter increases the absolute salinity and density of DSW, with maximum values reached in early spring (approximately 27.98 kg m^{-3}). The salinity of DSW at the sill declines rapidly through the summer, reaching a minimum in autumn. DSW denser than 27.88 kg m^{-3} (the threshold sometimes used to define DSW of sufficient density to form AABW; Bindoff et al., 2001) is present at the sill for about 6 months of the year at depths exceeding 450 m and forms a layer exceeding 200 m thickness for 3 months of the year. Conservative temperature is relatively constant near the surface freezing point during winter and spring, with winter waters averaging −1.912°C. Warmer temperatures occur at shallower depths in summer. Variability in the precalving summer temperature occurs both spatially and temporally (maximum summer temperatures range from −1.57°C to −1.82°C).

Postcalving, the seasonal cycle of DSW salinity and density has the same phase but about half (57%) the amplitude. Winter sea ice formation increases the salinity and density of DSW in spring, but the maximum salinity/density reached is much lower after calving (maximum salinity (density) reduced by 0.093 g kg^{-1} (0.07 kg m^{-3})). Postcalving, water denser than 27.88 kg m^{-3} is only found at the deepest instrument on the central mooring for about 3 months of the year, forming a layer less than 46 m thick (the vertical separation between the two deepest instruments); in 2011 no DSW exists at depths shallower than the sill depth (≈430 m). A reduced summer warming signal occurs after the calving, with the maximum observed temperature −1.82°C. Postcalving temperatures reach −1.96°C, and this cooling may be a result of a number of

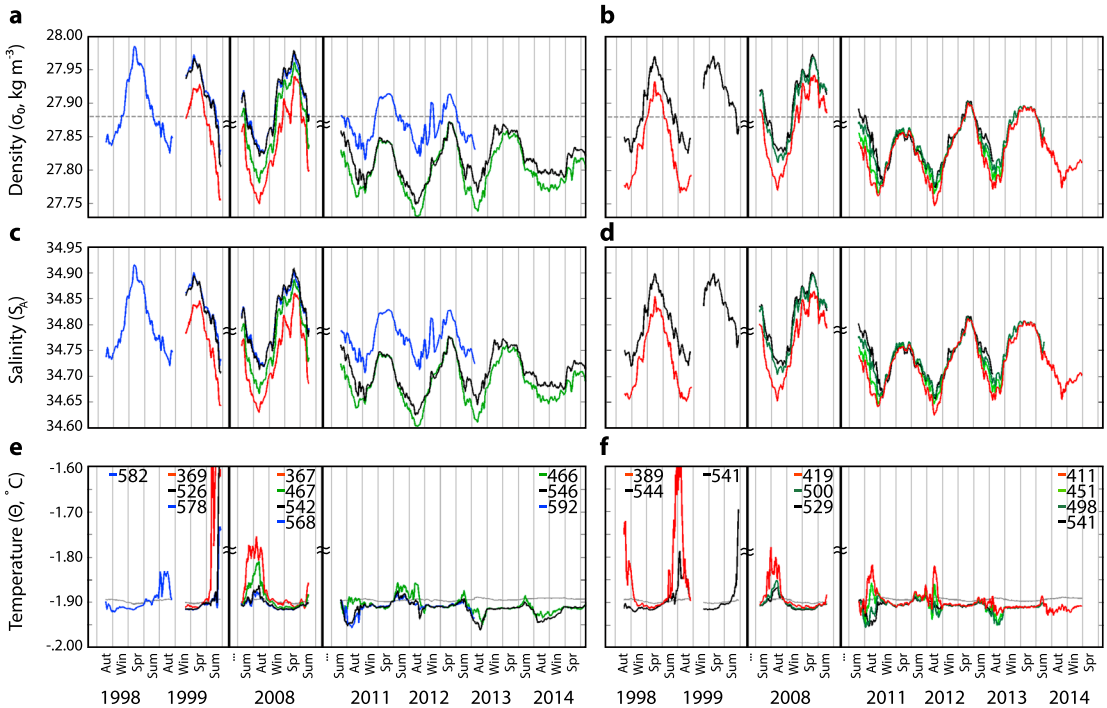

Figure 2. Time series of (a and b) potential density referenced to the surface (σ_0, kg m^{-3}), (c and d) absolute salinity (g kg^{-1}), and (e and f) conservative temperature (°C) at the central (a, c, and e) and eastern (b, d, and f) moorings. The horizontal dashed grey line in (a) and (b) shows the 27.88 kg m^{-3} density level, and the horizontal grey line in (e) and (f) is the surface freezing temperature. Instrument depths for each year are in (e) and (f) and given in meters. Seasons are December, January, and February (summer), March, April, and May (autumn), June, July, and August (winter), and September, October, and November (spring).

physical processes such as increased iceberg melt or changes in external meltwater sources (Aoki et al., 2017). The decrease in density postcalving exceeds the range of interannual and spatial variability: a statistically significant (95% confidence) reduction in density occurred at all locations and years from 2011 to 2013 at depths between 451 and 546 m (Figures S2 and S3), the depth range likely to contribute to DSW export given a sill depth of 430 m.

3.2. Impacts of DSW Change on ALBW

DSW exported from the Adélie Sill is a source water for ALBW. The large changes in DSW properties (section 3.1) would be expected to influence the properties of ALBW. However, the properties of the ALBW depend on a number of factors, including the properties and transport of DSW leaving the shelf and the rate of entrainment of ambient waters as the DSW descends the continental slope. Direct observations are needed to assess the sensitivity of ALBW to changes in DSW.

To explore the connection between the shelf and deep ocean, we compare observations in the Adélie Depression (66.7°S, 144.2°E; Figure 1a and Table S2), at the sill moorings where the dense water is available for export, and in the ALBW core between 1994 and 2015 (see section 2). (The ALBW core is defined as the densest bottom water present on the SR3/140°E section between 63.2°S and 64.4°S. The bottom water present at these stations is separated from Ross Sea Bottom Water further offshore (supporting information section S2) and is too cold, fresh, and dense to have originated in the Ross Sea (Rintoul, 1998; Rintoul & Bullister, 1999)).

There is substantial variability of both sea ice production (Tamura et al., 2016) and ALBW properties (Figure 3) prior to calving. However, for both variables, the decrease in density postcalving falls outside the range of precalving variability and is statistically significant at 95% confidence. Similarly, the postcalving decrease in density of DSW in the polynya and at the sill is statistically significant at 95% confidence. The difference between the precalving and postcalving mean density measured at the sill exceeds the range of values observed in the three years sampled prior to calving by factors of 3.6, 6.7, and 14.5 at the central 568–592 m, central 526–546 m, and eastern 529–541 m instruments, respectively (Figure 3a).

Density in the core of the ALBW at 140°E (63.2–64.4°S), downstream of the sill, shows a similar steep decline after the calving event (Figure 3b). The density is 0.01 kg m^{-3} lower than any density measurements prior to

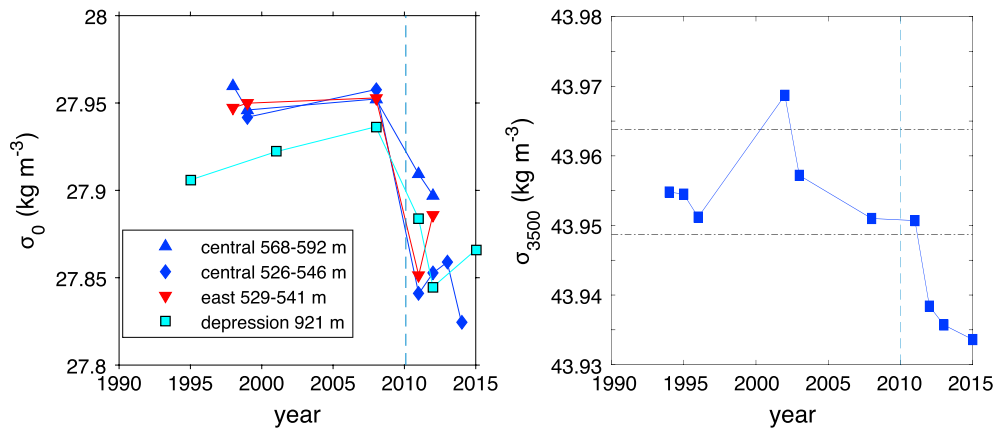

Figure 3. (a) Adélie shelf potential density referenced to the surface (σ_0, kg m^{-3}) from (cyan squares) January conductivity, temperature, and depth measurements within the Adélie Depression (Figure 1a and Table S2) and central spring mean mooring measurements from 526 to 546 m (blue diamonds (black lines in Figure 2a)) and 568–592 m (blue triangles (blue lines in Figure 2a)) and eastern mooring depths 529–541 m (red triangles (blue lines in Figure 2b)). (b) Potential density referenced to 3,500 m ($\sigma_{3,500}$, kg m^{-3}) averaged over the deepest 100 m of the water column in the core of the Adélie Land Bottom Water layer along repeat hydrographic line SR3, between 63.2°S and 64.4°S. Dashed blue line denotes calving event. Dashed black lines in (b) is the *t* test 95% confidence interval about the mean of the data from 1994 to 2008.

2010 and outside the bounds of the 95% confidence interval on the precalving mean, despite the variability observed prior to calving. There is a short lag in the ALBW response, with the sharp decline occurring 1 year later than observed on the shelf, reflecting the 1 year flushing time of the Adélie Depression (Lacarra et al., 2014) and spreading of the signal to 140°E. The mean density for the years 2012 to 2015 is 0.02 kg m^{-3} lower than the mean density between the years 1994 and 2011. The near synchronous, statistically significant step change in properties of DSW (section 3.1) and ALBW (Figure 3b) provides direct observational evidence that DSW changes propagate to the deep ocean and affect bottom water properties.

The conservative temperature-absolute salinity (Θ-S_A) and oxygen-absolute salinity relationships provide further insight into the impact of the calving event on bottom water properties (Figure 4). Between 1994 and 2008 (i.e., prior to calving), the Θ-S_A curves shift toward fresher values. Over this period, the densest ALBW (i.e., mean properties near the seafloor) freshened by 0.020 g kg^{-1} and cooled by 0.115°C, with little change in density ($\Delta\sigma_{3,500} = -0.003$ kg m^{-3}) (Figure 4a). The densest ALBW freshened further by 0.008 g kg^{-1} in 2011, the first year after the calving of the MGT. Between 2011 and 2013 the temperature of the densest ALBW increased abruptly by 0.146°C (Aoki et al., 2013, show evidence of a similar warming in 2012) and density decreased by 0.015 kg m^{-3}, while salinity increased slightly (by 0.009 g kg^{-1}). The temperature and density of the densest bottom water in 2015 were similar to 2013, with a small decrease in salinity (0.008 g kg^{-1}).

The calving event led to reduced polynya activity (Tamura et al., 2016) and freshening of the DSW exported from the shelf. However, the primary impact of exporting fresher and lighter DSW was to make the ALBW core warmer and lighter, with little change in salinity. This counterintuitive result can be understood using the evolution of Θ-S_A profiles over the last two decades (Figure 4a). Between 1994 and 2011, the Θ-S_A profiles shift to fresher values and change shape, but the density of the densest ALBW changes little. Changes in the shape of the Θ-S_A curve require a change in properties of the end-members (DSW and CDW) that mix to form bottom water. Export of fresher and lighter DSW is thus consistent with the evolution of the Θ-S_A curve with time. After calving, the density of the densest ALBW is reduced and the slope of the Θ-S_A curves is lower and more nearly follows isopycnals (dotted lines in Figure 4a). The alignment of Θ-S_A profiles with isopycnals implies that mixing between new DSW and the ambient bottom water over the continental slope occurs largely along isopycnals. The positive slope of isopycnals in the Θ-S_A plot, in turn, means that fresher and lighter DSW mixes with warmer ambient water, producing warmer ALBW (see supporting information section S3).

The oxygen-absolute salinity relationship (Figure 4b) provides further insight into the evolution of ALBW. Oxygen concentration in the densest bottom water does not change between 1994 and 2011, despite the gradual freshening over this period. Deep convection continues in the polynya, producing oxygen-rich DSW that descends the continental slope mixing with ambient fluid of similar density (and oxygen concentration).

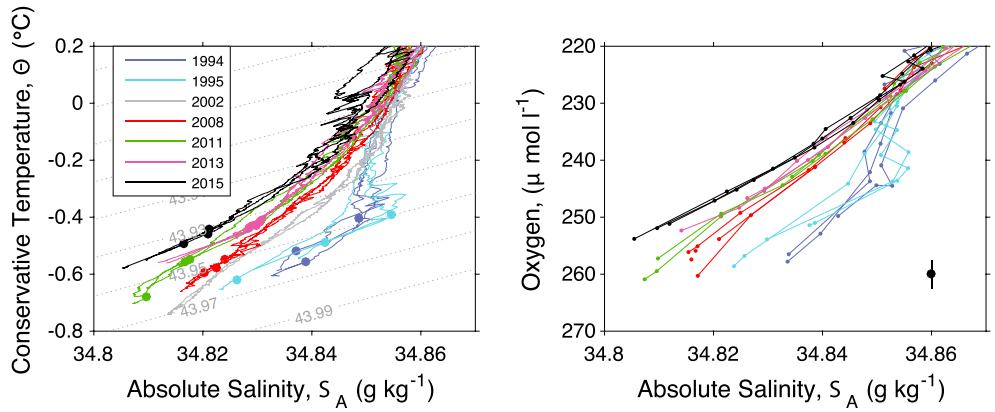

Figure 4. Absolute salinity (g kg^{-1}) versus (a) conservative temperature (°C) and (b) oxygen (μmol l^{-1}) within the Adélie Land Bottom Water core (along the SR3 repeat line (140°E) between 63.2°S and 64.4°S) from 1994 to 2015. Note, observations from 1993, 2003, and 2012 (Figure 3) are missing due to lack of oxygen measurements. Dashed grey lines indicate potential density surfaces referenced to 3,500 dbar ($\sigma_{3,500}$, kg m^{-3}). Note, vertical axis for oxygen is inverted and the black dot in the lower right corner shows the analytical uncertainty in the oxygen measurements. Colored dots in (a) indicated the location 100 m off the bottom.

After calving, deep convection in the polynya continues to produce DSW (Figure 2), albeit of lower salinity and density. The oxygen content of the new, lighter DSW remains high as a result of direct communication with the atmosphere during deep convection. The oxygen content of the ALBW declines after calving (by 5–7 μmol L^{-1}, about twice the analytical uncertainty of 1%). The small reduction in oxygen could reflect mixing with lighter, lower oxygen ambient fluid, consistent with the inference drawn above from the Θ-S_A profiles, or an increase in entrainment of low oxygen water over the slope. Regardless, in each year the maximum oxygen content is found in the densest bottom water, confirming that ALBW continues to ventilate the abyssal ocean.

4. Conclusions

Observations and models show large variability of DSW and ALBW properties prior to calving (Figure 3; e.g., Cougnon et al., 2013; Kusahara et al., 2011a; Lacarra et al., 2014; Shadwick et al., 2013; van Wijk & Rintoul, 2014; Williams et al., 2010). While these studies suggest that variations in sea ice production can explain much of the variability, other processes also likely contribute, including wind-driven changes in circulation (e.g., Spence et al., 2017), changes in freshwater input (e.g., Aoki et al., 2017), variability in cross-shelf exchange, changes in entrainment (and stratification, e.g., Shimada et al., 2012), and conditioning by summer stratification (Marsland et al., 2004). A combination of these factors may explain the relatively fresh DSW present on the shelf in January 2001 (Shadwick et al., 2013; Williams et al., 2010) and the particularly cold, dense, and thick layer of ALBW observed in 2002. While DSW and ALBW properties vary with time prior to calving, the step change in density after the MGT calving exceeds the range of variability observed prior to calving, is statistically significant at the 95% level and has persisted on interannual time scales unlike the precalving variability. This supports our conclusion that the reduction in sea ice formation after calving caused a decrease in the density and volume of DSW (halving the seasonal cycle amplitude of DSW density) which in turn drove a decrease in density and volume of the local variety of bottom water. However, the observational record is too sparse to resolve the full spectrum of variability and we cannot rule out the possibility that other factors may have driven comparable changes in DSW and ALBW in the past.

ALBW ventilates and sets the deep stratification in the Australian-Antarctic Basin and spreads to low latitudes of the Indian and Pacific Basins (Mantyla & Reid, 1995; Nakano & Suginohara, 2002). The sudden freshening of the Adélie Land DSW postcalving is equivalent to 20 years of the long-term trend observed in the Ross Sea and 90 years of that in the Weddell Sea (Schmidtko et al., 2014). Surprisingly, the sharp reduction in salinity (hence density) of the DSW causes large warming of ALBW because the less dense DSW mixes along isopycnals with lighter, warmer ambient CDW as it descends the slope. The DSW remains high in oxygen, and the ALBW continues to ventilate the abyssal ocean, however, at reduced density. The formation of less dense ALBW after calving led to a 275 m contraction of the layer denser than $\sigma_{3,500}$ = 43.93 kg m^{-3} (or neutral density 28.33 kg m^{-3}) at 140°E, equivalent to about 30 years of the precalving trend in isopycnal descent (van Wijk & Rintoul, 2014).

Given the widespread nature of the multidecadal trends in abyssal water properties observed prior to calving, we anticipate that the large and rapid changes in ALBW after calving will influence abyssal properties on basin scales, as suggested by Menezes et al. (2017). Previous studies have linked changes in the Adélie Land icescape and buoyancy forcing to DSW properties (Kusahara et al., 2011b; Lacarra et al., 2014). Our study is the first to provide direct observations of how changes on the continental shelf propagate downstream into the ALBW core. These results confirm that regional changes in icescape and associated changes in surface forcing can have substantial impact on the properties of AABW. The response to the MGT calving event highlights the potential sensitivity of AABW to future change, induced by either natural or anthropogenic perturbations.

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