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Key Points:

- A large pool of warm modified Circumpolar Deep Water has been identified on the outer continental shelf near the Totten Glacier
- Shelf break bathymetry varies from 300 to 600 m depth along the East Antarctic Margin with a deeper section offshore Totten Glacier
- Access of modified Circumpolar Deep Water along the East Antarctic Margin is in part controlled by shelf break depth

Supporting Information:

- Supporting Information S1

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Bathymetric control of warm ocean water access along the East Antarctic Margin

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Abstract Observed thinning of the Totten Glacier in East Antarctica has cast doubt upon the stability of the East Antarctic Ice Sheet. Recent oceanographic observations at the front of the Totten Ice Shelf have confirmed the presence of modified Circumpolar Deep Water (mCDW), which likely promotes enhanced melting. Details of how this water accesses the shelf remain uncertain. Here we present new bathymetry and autumnal oceanographic data from the outer continental shelf, north of the Totten Glacier, that show up to 0.7°C mCDW in a >100 km wide and >500 m deep depression within the shelf break. In other parts of East Antarctica, a shelf break bathymetry shallower than 400 m prevents these warmer waters from entering the shelf environment. Our observations demonstrate that detailed knowledge of the bathymetry is critical to correctly model the across-shelf exchange of warm water to the various glaciers/ice shelves of Antarctica for future sea level prediction.

1. Introduction

One of the main uncertainties in estimating future sea level is the behavior of the large ice sheets in Greenland and Antarctic [*Intergovernmental Panel on Climate Change*, 2014]. Remote sensing observations show that parts of the Antarctic Ice Sheet, and especially the West Antarctic Ice Sheet (WAIS), are thinning and losing mass [e.g., *Shepherd et al.*, 2002; *Rignot et al.*, 2008; *Pritchard et al.*, 2009]. The largest ice loss is observed in the Amundsen Sea sector, especially from the Pine Island and Thwaites Glaciers [*Shepherd et al.*, 2002; *Lee et al.*, 2012]. Models suggest that the WAIS in this area might retreat significantly over the next centuries due to marine ice sheet instability conditions [*Schoof*, 2007; *Joughin et al.*, 2014; *Alley et al.*, 2015]. Oceanographic measurements showed that the current ice loss of the large Antarctic ice sheets is primarily driven by melting of the ice shelves caused by intrusions of warmer Circumpolar Deep Water (CDW) that enters the continental shelf and reaches under ice shelves [*Jacobs et al.*, 1996; *Hellmer et al.*, 1998; *Rignot et al.*, 2013]. Detailed studies of the Amundsen Sea sector have revealed that bathymetric troughs provide pathways for modified Circumpolar Deep Water (mCDW) on the continental shelf [e.g., *Nitsche et al.*, 2007; *Walker et al.*, 2007]. When denser than the local shelf water masses, bottom-intensified mCDW will flow down a landward sloping continental shelf along these troughs and reach the grounding zone under the ice shelves where the highest rates of basal melting occur [*Jacobs et al.*, 1996; *Jenkins et al.*, 2010; *Jacobs et al.*, 2012].

For a long time there has been a debate about the stability of the East Antarctic Ice Sheet (EAIS) [e.g., *Sugden et al.*, 1993], but recent geological evidence indicates that the EAIS has been less stable in the past [e.g., *Pingree et al.*, 2011; *Cook et al.*, 2013]. Furthermore, improved subglacial topography reveals several large, potentially vulnerable basins with marine-based ice in East Antarctica [*Fretwell et al.*, 2013]. The most recent generation of ice sheet models, based on this new sub-ice topography, suggests that grounded ice in these basins could retreat and contribute significantly to future sea level rise [e.g., *Mengel and Levermann*, 2014; *Pollard et al.*, 2015]. One of these basins is the Aurora Basin, which drains mainly through the Totten Glacier (Figure 1 inset). *Greenbaum et al.* [2015] estimated that ice equivalent of 3.5 m of sea level rise is flowing just through the Totten Glacier. Satellite data show that the Totten Glacier has been losing mass and thinning at rates of ~1.5 m/y between 2003 and 2008 [*Pritchard et al.*, 2009; *Khazendar et al.*, 2013] and ~0.5 m/yr between 2010 and 2013 [*McMillan et al.*, 2014] and its ice shelf is melting at rates of ~10 m/yr

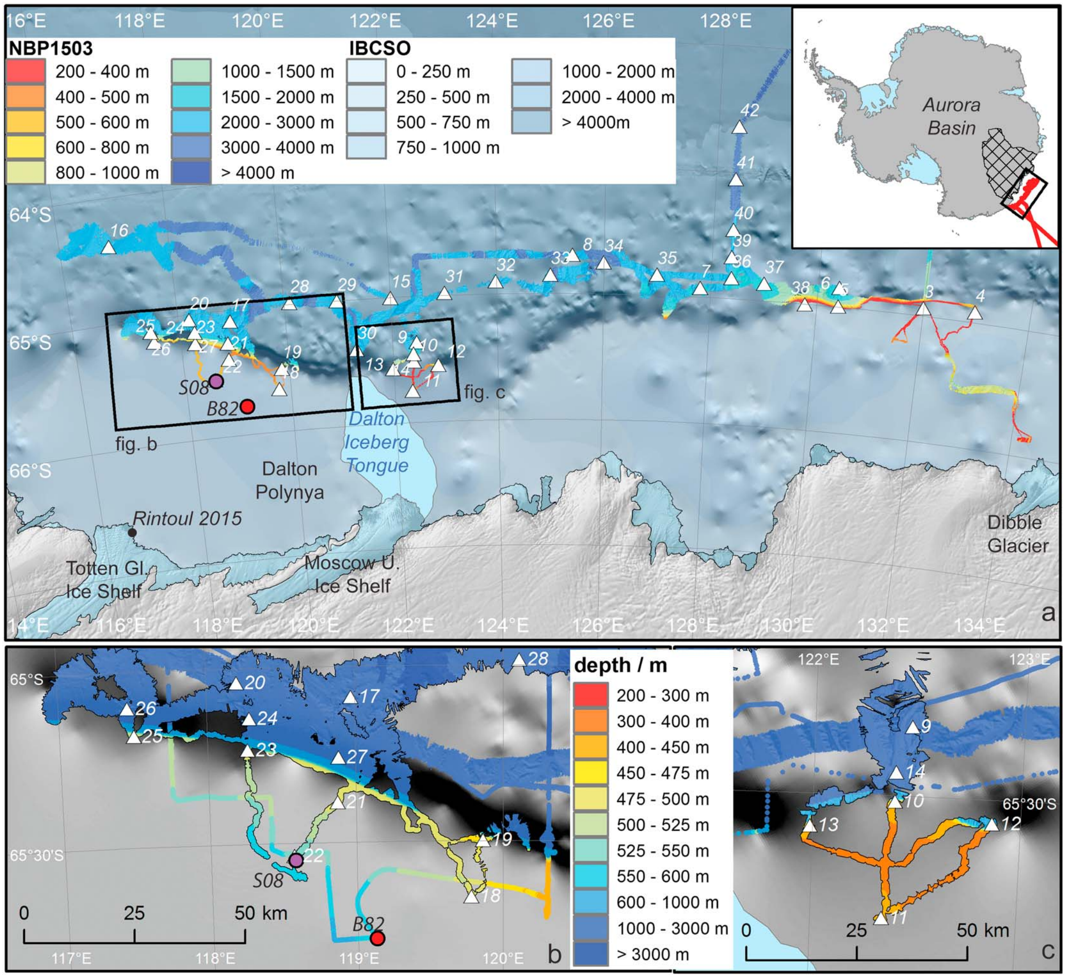

Figure 1. (a) Overview of the swath bathymetry data collected on the continental shelf north of the Totten Glacier showing new EM122 multibeam bathymetry data (color) with IBCSO v1 bathymetry [*Arndt et al*., 2013] as background. MODIS/LIMA Image for land [*Bindschadler et al*., 2008]. Note the smooth IBCSO areas that are interpolated from the few existing data points. New CTD stations are marked by white triangles. S08 and B82 are older CTD stations. Inset shows NBP1503 cruise track, the Totten Glacier drainage basin, and location of the study area. (b) Details of the bathymetry of the Totten Trough with scale emphasizing the depth around 500 m (new NBP1503 data are marked by black border) and older echosounder data (c) Details of bathymetry near Dalton iceberg tongue for comparison with same color scale as Figure 1b.

[*Khazendar et al*., 2013; *Miles et al*., 2013], although a longer-term record shows strong decadal variations without any significant trend in ice shelf thickness [*Paolo et al*., 2015]. The Totten Glacier grounding line retreated 1–3 km over 17 years [*Li et al*., 2015, 2016]. These studies suggest that the cause for the observed thinning and retreat is enhanced melting of the ice shelf and grounded ice due to the intrusion of ocean water with temperatures well above the in situ melting point onto the continental shelf, similar to the process observed in the Amundsen Sea.

Before 2014 there were few direct oceanographic measurements to verify these hypotheses. The two CTD stations on the continental shelf that existed indicated a bottom-intensified layer of warmer mCDW on the continental shelf [*Bindoff et al*., 2000; *Williams et al*., 2011]. In 2015 an Australian survey observed dense, −0.405°C (2.2°C above freezing point) warm water in a 1097 m deep trough in front of the Totten Ice Shelf (Figure 1), confirming that mCDW is reaching the Totten Ice Shelf [*Rintoul et al*., 2016]. Measurements from the Dalton Polynya east of the Totten Ice Shelf (Figure 1) showed abundant mCDW below 500 m on a southward dipping slope [*Silvano et al*., 2017]. Despite these observations, the source of this warmer water and what controls its access to the continental shelf near the Totten Glacier and other parts of the East Antarctic Margin remained uncertain due to the lack of oceanographic and detailed bathymetry data from the outer continental shelf break region.

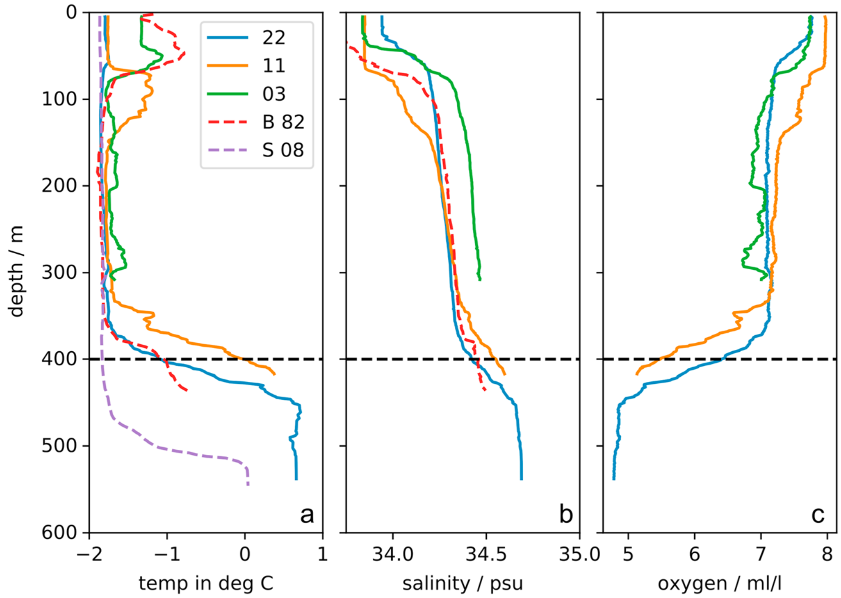

Figure 2. Temperature, salinity, and oxygen profiles of CTD stations 22 (Totten), 11 (Dalton), and 03 (Dibble) (see Figure 1 for location); black dashed line indicates 400 m depth. Previous CTD station from BROKE96 (B82) and SIPEX (S08) is plotted as reference (red and purple dashed lines).

Here we provide new ship-based bathymetry and oceanography observations that show mCDW near and on the continental shelf of this section of East Antarctica and discuss how bathymetry controls the access of these waters to the continental shelf.

2. Materials and Methods

As the primary objective of scientific cruise NBP1503 with the RVIB *NB Palmer* in 2015, we collected detailed multibeam bathymetry and oceanographic data along the continental slope and outer continental shelf of the East Antarctic Margin from 117°E–134°E (Figure 1). The sea ice conditions during this late season cruise (end March to early May) only allowed access to the outer continental shelf in most places.

Multibeam bathymetry data were collected using an EM122 swath sonar system and corrected for ship motion and sound velocity variations obtained from CTD casts. Bad or unreliable soundings were edited manually using CARIS Hips and Sips software and converted into 30 and 40 m resolution grids following standard procedures [e.g., *Caress and Chayes*, 1996]. To get the most complete overview of the regional bathymetry, the new data were combined with available existing bathymetry information including multibeam bathymetry data acquired during *NB Palmer* cruise NBP0101 obtained through the Marine Geophysical Data System (http://www.marine-geo.org) and single beam echosounder data from the expeditions BROKE96, AU9604, AU9407, and OB3B1957 obtained from the National Centers for Environmental Information (www.ngdc.noaa.gov).

In addition to the bathymetry data, we obtained oceanographic CTD data at 42 stations on the outer continental shelf and slope (Figure1). For each cast we used two Seabird 911 systems with redundant temperature, salinity and SBE 43 oxygen sensors. CTD data used here are from the downcasts only, binned in 1 m intervals, and adjusted using precruise and postcruise sensor calibration values as well as discrete salinity samples analyzed with Portasal salinometers.

3. Results

The bathymetry data show large regional variations in shelf break depth along the margin—ranging from ~300 m near the Dibble polynya to ~400 m near the Dalton Iceberg Tongue to over 450–550 m north of the Totten Glacier (Figure1). North of the Totten Glacier (between 117°E and 120°E), the shelf break manifests into a deep depression over 100 km wide and 450–500 m deep from which the seafloor slopes gently (<1°) poleward (Figure 1b). This trajectory of deepening seafloor toward the inner shelf region is confirmed by older echo sounder data from the BROKE expedition 1996 (Figure 1b) and greater depths reported in the Dalton Polynya [*Silvano et al.*, 2017]. East of this outer shelf depression, the shelf break rises again to ~400 m depth and shallower (Figure 1b). The new bathymetry data do not cover the western limit of the depression, but older echo sounding data with depth < 300 m and a line of grounded icebergs near 116°E show a shallower outer shelf break there (Figure S2 in the supporting information).

NBP1503 oceanographic measurements show significant variation of temperature data along the continental margin. The bottom temperatures on the continental shelf north of the Totten Glacier and Dalton Iceberg Tongue are around 0.6° and 0.3°C, respectively (Figures 2 and 3a). In contrast, bottom temperatures on the relatively shallower (~300 m deep) outer continental shelf near the Dibble Glacier were significantly cooler with temperatures around -1.7°C (Figure 2, CTD 03).

CTD cross sections perpendicular to the shelf break show a core of warm ($T > 0.5$°C) water close to the continental shelf north of the Totten area (Figure 3a). The E-W cross section shows that this water occupies the entire >100 km wide depression (Figure 4a). Salinity of these water masses is also high with 34.5–34.7 practical salinity unit (psu) (Figures 2b, 3b, and 4b); oxygen is low (Figures 2c, 3c, and 4c) and density is above 27.7 kg/m^3 (Figures 3d and 4d).

4. Discussion

The NBP1503 CTD data that partially bridge the crucial gap between the continental shelf and the Southern Ocean, and, along with other recent studies [*Rintoul et al.*, 2016; *Silvano et al.*, 2016, 2017] result in an improved and more complete picture of the distribution of water masses reaching the Totten Glacier. Our new observations that show a deep and extensive pool of water with maximum temperature of ~0.7°C are entering the outer continental shelf over a wide bathymetric depression at depth below 400–500 m. The relatively warm temperature, salinities above 34.62 psu, and depleted dissolved oxygen suggest that this water represents mCDW [*Emery and Meincke*, 1986]. The density is above 27.7 kg/m^3, which is slightly less than the neutral density suggested for CDW by *Whitworth et al.* [1998] but the same that *Silvano et al.* [2017] identified for mCDW on the middle and inner continental shelf. Measurements to the southeast (inland) earlier in the same season by *Silvano et al.* [2017] find similar salinities but slightly cooler (0.4°C) mCDW bottom intensified on the midshelf in bathymetric depressions below 500 m. In front of the Totten ice shelf, *Rintoul et al.* [2016] observed mCDW near the 1000 m bottom with -0.4°C, which is cooler than water observed near the shelf break or on the midshelf, but is still significantly above the melting point at this depth and contains enough heat to explain the observed melting and thinning of the Totten Ice Shelf. This strongly indicates that the mCDW observed on the outer shelf continues to the inner shelf following bathymetry, as observed in Pine Island and Thwaites Glacier system [*Jacobs et al.*, 2012]. In the Amundsen Sea the shelf break depth varies from 400 to >600 m depth and CDW crosses the shelf break where it is deeper than ~500 m. Similar to our new data, the outer shelf depressions in the Amundsen Sea have a low (<1°) landward dipping slope [*Nitsche et al.*, 2007], which is sufficient to guide the denser CDW toward deeper troughs in the inner continental shelf [*Jacobs et al.*, 2012]. This pattern of a low landward gradient on the outer shelf connecting to more deeply eroded glacial troughs in the inner shelf is typical for glacially eroded cross-shelf troughs around Antarctica [*Arndt et al.*, 2013] and provides a probable scenario for the Totten Glacier as well, although there are no bathymetry data between our data and the observation near the Totten Ice Shelf to confirm this.

These new data also suggest that the warmest mCDW from the shelf break is not reaching the deep canyon near the Totten Ice Shelf identified by *Rintoul et al.* [2016]. Instead, the water appears to be modified further, e.g., by mixing or blocked by a yet unidentified bathymetric sill between the outer shelf and the Totten Ice Shelf. Detailed knowledge of such a barrier, especially its exact depth, would be critical for models to determine under what circumstances warmer mCDW, which is currently diluted or blocked by such a sill, would reach the base of the ice shelf or grounded ice where it could increase current melt rates. A ridge under the Pine Island Ice Shelf is partially blocking some of the warmest CDW from reaching the grounding line there [*Jenkins et al.*, 2010]. Older echosounder data show another >600 m deep basin near 114°E, east of the shallower ridge (Figure S2) that could provide alternative access of mCDW to the Totten Ice Shelf, but we have no oceanographic observation to confirm the presence of warm water there, and it is less likely to provide mCDW on the midshelf observed by *Silvano et al.* [2017] near 119°E.

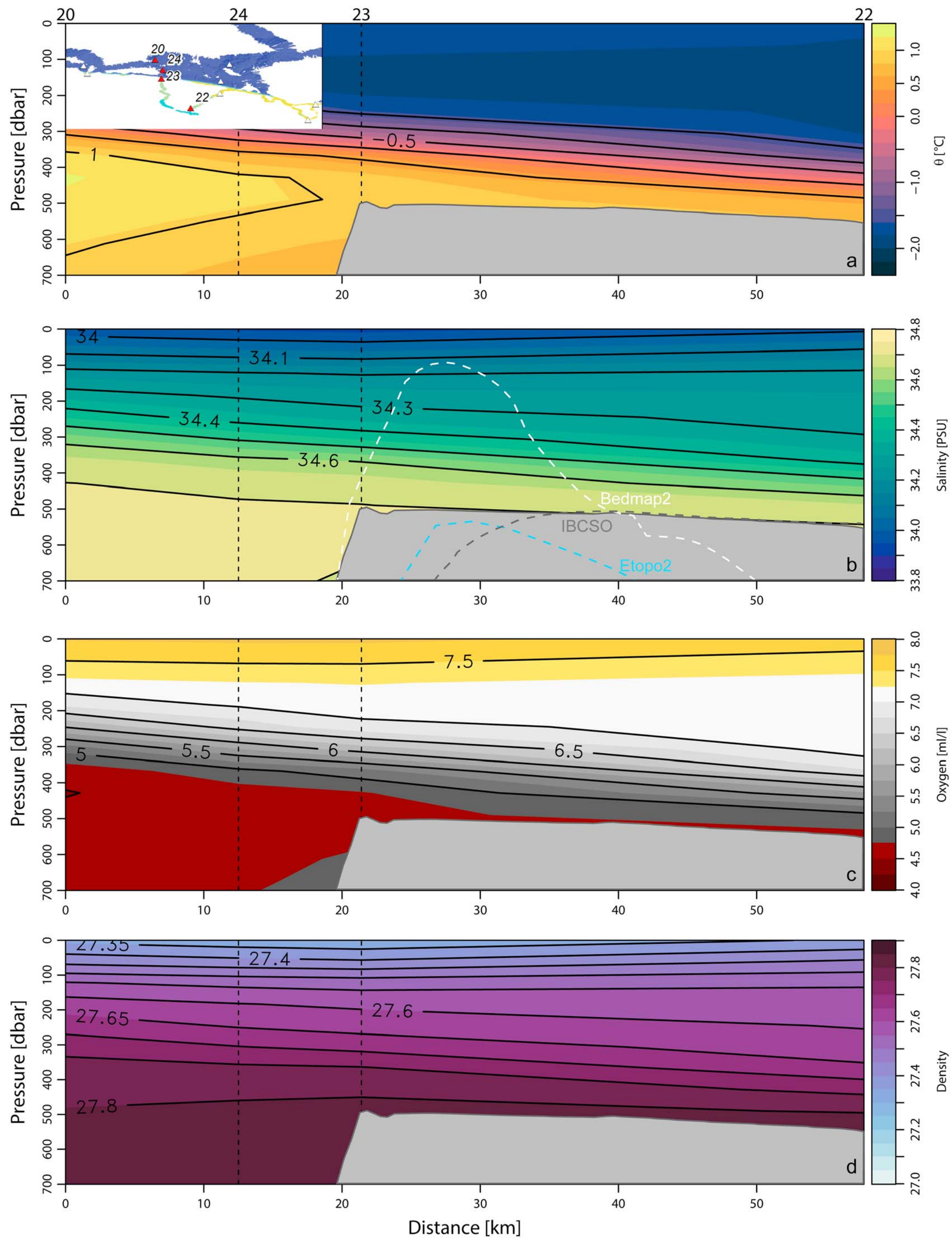

Figure 3. Oceanographic cross sections of (a) temperature, (b) salinity, (c) oxygen, and (d) density perpendicular to the continental slope along the outer continental shelf (see inset and Figure 1 for location). Numbers on top list CTD stations. Dashed lines show BEDMAP2, IBCSO, and ETOPO compilations.

These recent observations of mCDW on the continental shelf north of the Totten Glacier are all from 2015. Two oceanographic stations on the outer shelf collected in 1996 [*Bindoff et al.*, 2000] and 2001 [*Williams et al.*, 2011] as part of the BROKE (summer) and SIPEX (late winter) expeditions, respectively, also showed bottom-intensified mCDW on the outer continental shelf (Figure 2) and thus suggest that such mCDW incursions onto the continental shelf have happened in previous years and seasons. Studies from the Amundsen

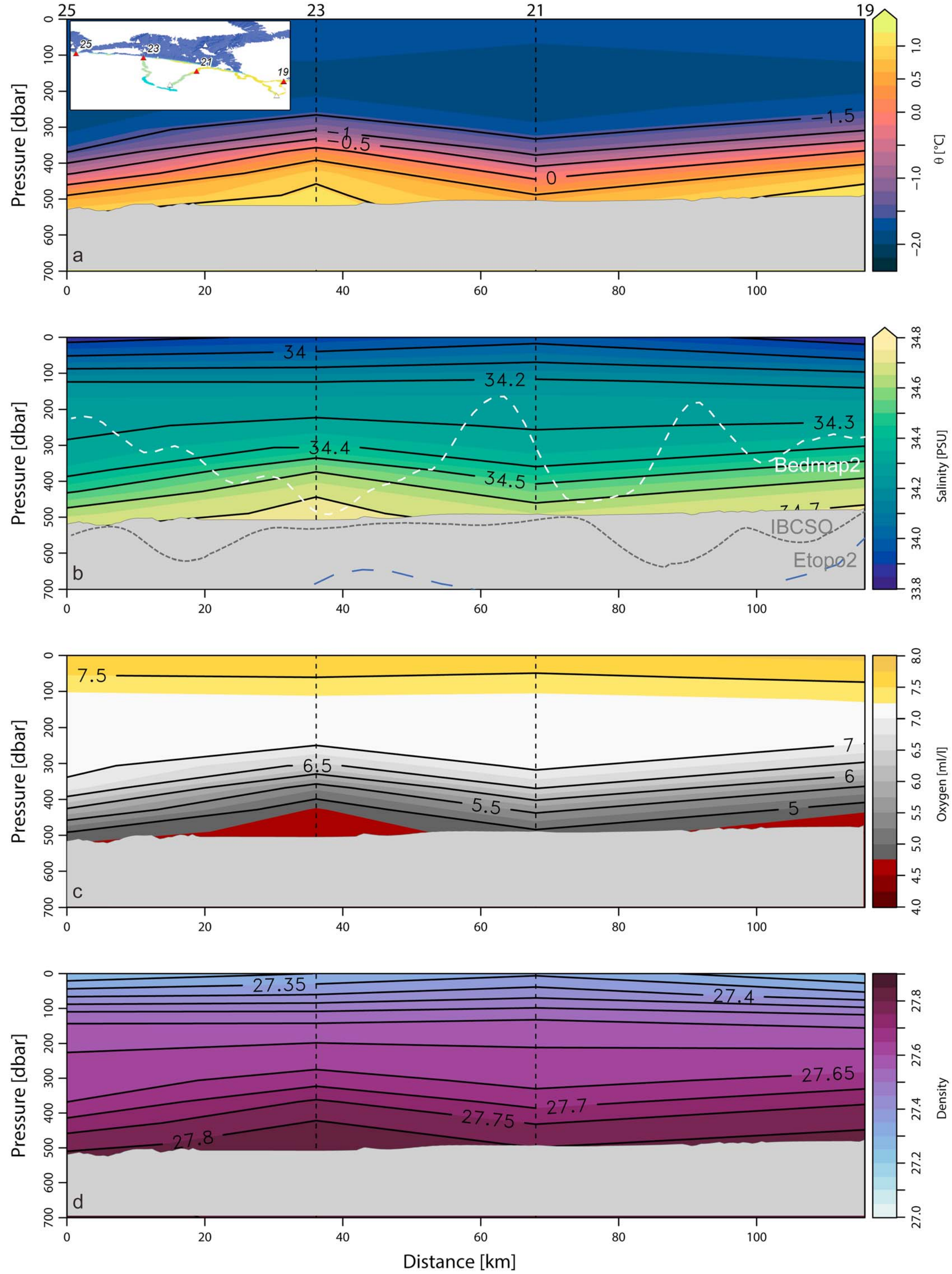

Figure 4. Oceanographic cross sections of (a) temperature, (b) salinity, (c) oxygen, and (d) density parallel to the shelf break along the outer continental shelf (see inset and Figure 1 for location). Numbers on top list CTD stations. Dashed lines show BEDMAP2, IBCSO, and ETOPO compilations.

Sea have shown that the amount of CDW (and related bottom temperature on the continental shelf) can vary seasonally and annually due to changes in wind and current patterns in response to atmospheric conditions [*Dutrieux et al.*, 2014; *St-Laurent et al.*, 2015; *Jenkins et al.*, 2016], but longer time series are necessary to identify such variations in the Totten area.

Bathymetry data from the neighboring Dalton Iceberg Tongue show the shelf break there at ~400 m depth (Figure 1c). The mCDW reaches the shelf break there as well but does not get onto the shelf (supporting information Figure S3). We observe mCDW on the outer continental shelf only where the shelf break is deeper than ~400 m. This highlights that, at least in this section of the East Antarctic Margin, mCDW reaches the continental shelf at a depth where the actual shelf break morphology is a critical threshold that controls access to the shelf and, thus, to any marine-based parts of the EAIS in this section.

For large sections of the East Antarctic continental shelf, especially between 80°E and 140°E, there are very limited direct bathymetry observations [*Arndt et al*., 2013]. Available data include few, isolated echosounder profiles and limited multibeam bathymetry data collected in 2001 and 2015 as part of NBP0101 and NBP1402 expeditions, respectively [*Leventer et al*., 2006; *Beaman et al*., 2011; *Fernandez-Vasquez et al*., 2014]; the latter focuses mainly on the Mertz Glacier and the Dalton Polynya, but the data are not publicly available yet. As a result, most bathymetry compilations of the East Antarctic Margin are based on predictions from gravity inversions [*Smith and Sandwell*, 1997; *Greenbaum et al*., 2015] or interpolations between sparse echosounder data, e.g., International Bathymetric Chart of the Southern Ocean (IBCSO) [*Arndt et al*., 2013] resulting in uncertainties in seafloor depths of over 100 m (Figures 3b and 4b) [e.g., *Jakobsson et al*., 2002; *Brisbourne et al*., 2014]. By including more of the existing echosounder data, the IBCSO grid is closer to our measured results than ETOPO2 or BEDMAP2, neither of which had access to all prior soundings and rely more on gravity inversion in this region. Such differences of several 100 m are likely to affect the outcome of oceanographic and ice sheet models.

The detailed bathymetry data that now exist for the outer continental shelf and shelf break along the east Antarctic Margin reveals large variability in depth between ~300 m and over 600 m. There are many sections that are too shallow for the observed mCDW to enter the continental shelf. Such limits for warm water access are critical boundary conditions for more accurate model prediction of future ice sheet behavior, which often assume that warm water will reach the grounded ice. Improving these boundary conditions for models requires more complete and accurate depth information for larger sections of the East Antarctic continental shelf.

In addition to detailed bathymetry data, there is also a need of improved oceanographic information. The existence of pathways for warmer mCDW, as deep troughs on the continental shelf, does not mean it is the densest (i.e., bottom intensified) water mass on the shelf, the prerequisite for ultimately reaching the grounded ice and significantly enhancing melting [*Williams et al*., 2011]. For example, although a deep trough exists in front of the Mertz Glacier [*McMullen et al*., 2006; *Beaman et al*., 2011], Dense Shelf Water (by definition denser than CDW) from the intense sea ice formation/brine rejection in the Mertz polynya region relegates the mCDW entering from the shelf break to the midwater column in summer and completely erodes its presence through top-to-bottom convection in winter [*Williams and Bindoff*, 2003; *Williams et al*., 2008]. *Williams et al*. [2011] estimate that the much weaker Dalton polynya has annual sea ice production that is ~25–30% of that in the Mertz region, and therefore, Dense Shelf Water is unlikely to be formed there, something the recent summertime surveys appear to confirm [*Silvano et al*., 2017].

Finally, it is currently not well understood where and when along the East Antarctic Margin mCDW or CDW might be getting close enough to the shelf break to even access the continental shelf. Circum-Antarctic estimates of major ocean currents and frontal system have placed the main CDW near but not exactly next to East Antarctic Margin continental margin [*Orsi et al*., 1995]. Model results by *Hellmer et al*. [2012] suggest that this might change with increasing ocean warming, and *Schmidtko et al*. [2014] report first signs of such a warming trend, although the number of actual measurements from the East Antarctic margin remains insufficient.

5. Conclusions

These new oceanographic and bathymetry data from the Totten Glacier East Antarctic Margin show that warm mCDW (up to 0.7°C) is entering the outer continental shelf through a section of the shelf break over 500 m deep. This substantial pool of water is a potential source of mCDW waters (further modified, i.e., slightly cooler and fresher) that have been observed both on the central continental shelf and in front of the Totten ice shelf.

Our data also show that exact depth of the shelf break can be a critical factor in determining if mCDW can access the continental shelf and, therefore, will be an important factor in improving future ice sheet models. In our study mCDW only enters the continental shelf where the shelf break is deeper than 400 m. The data also show that the shelf break depth varies significantly along the East Antarctic Margin; however, detailed bathymetry is still missing for large sections of the margin, and more data are needed to assess the vulnerability of other sections of East Antarctica.

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Geophysical Research Letters

Supporting Information for

Bathymetric control of warm ocean water access along the East Antarctic Margin

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Contents of this file

Figures S1 to S4

Introduction

Additional figures that provide additional examples or context to the main paper.

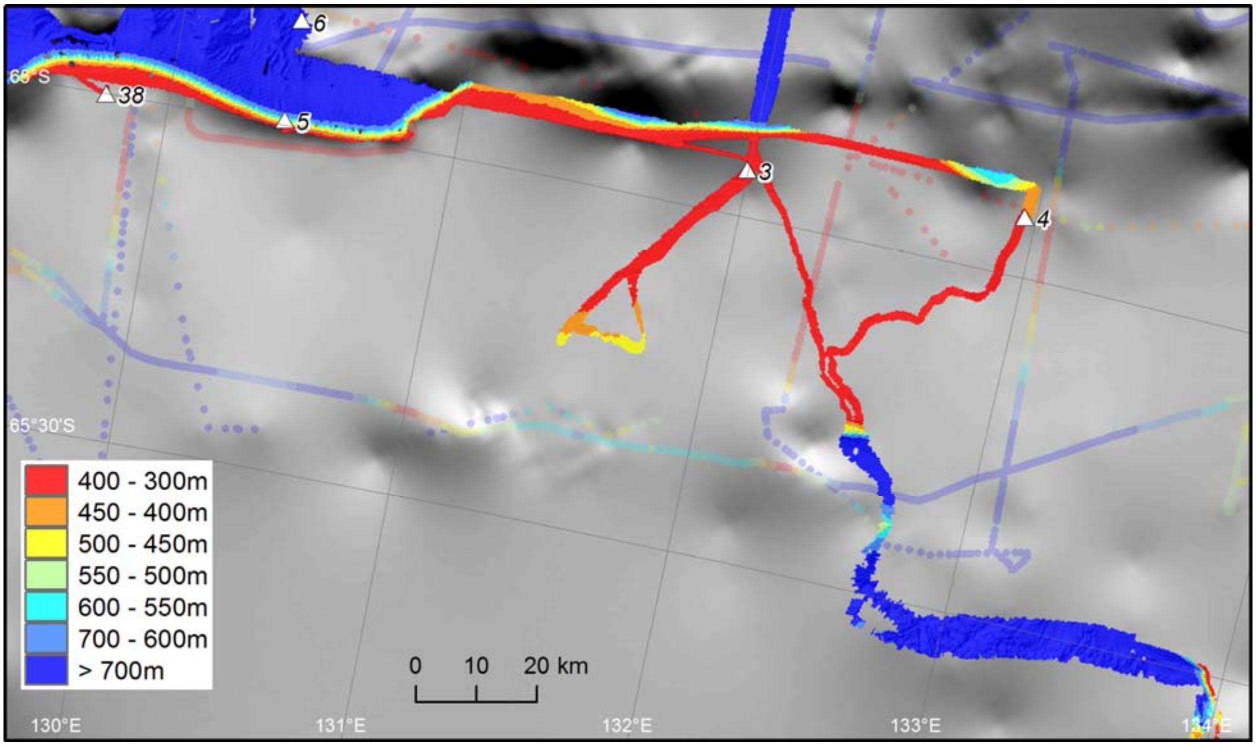

Figure S1. Bathymetry north of Dibble Glacier/Polynya with the same color scale as Figs 1b, 1c and older echosounder data (faded colors). Grey background shows IBCSO v1 bathymetry [Arndt et al., 2013]. Note the smooth IBCSO areas that are interpolated from the few existing data points. New CTD stations are marked by white triangles.

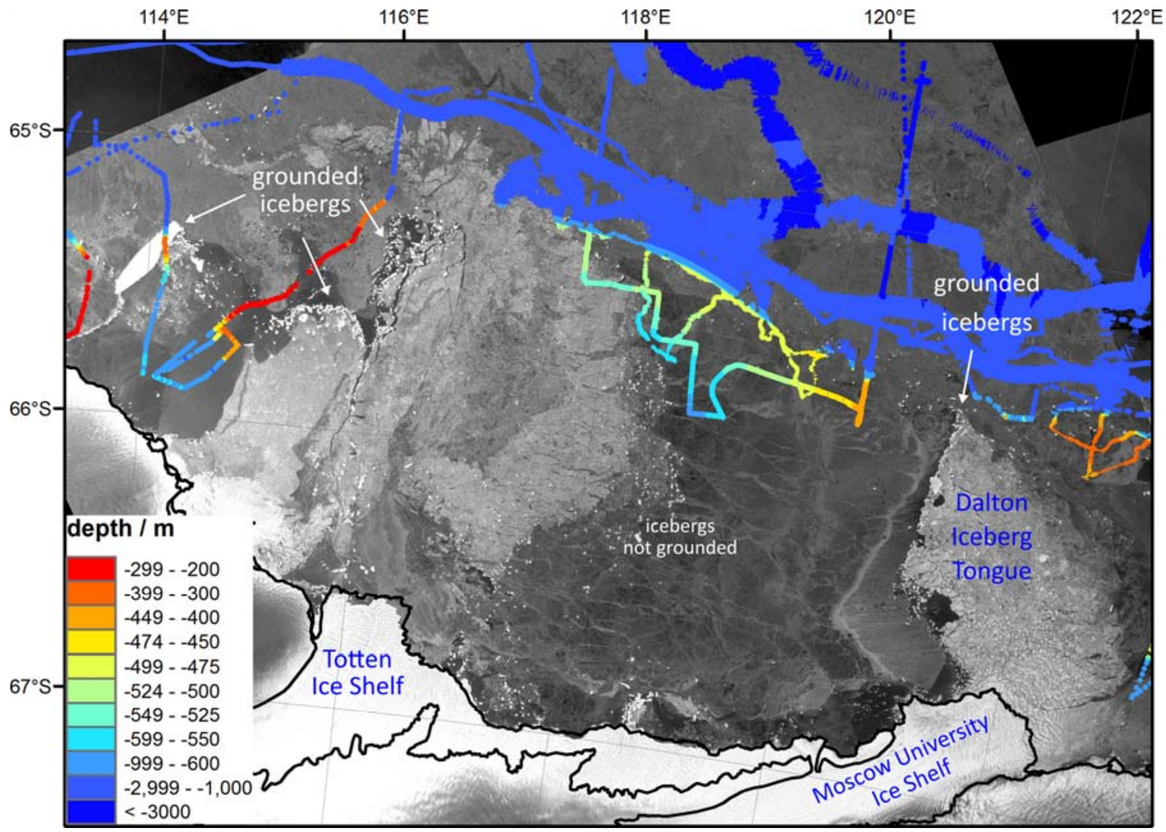

Figure S2. Mosaic of Sentinel radar images (5. Feb, 2. July 2017 from Polarview; http://www.polarview.aq/) with multibeam and singlebeam bathymetry data showing grounded icebergs that indicate shallow (<400m) water depth. West of the study area grounded icebergs around 116°E and west of it are near the <300m deep echosounder data (red points), thus marking shallower water. To the East grounded icebergs at the edge of the Dalton iceberg tongue and the available data indicate shallower seafloor there as well. Iceberg grounding was determined by comparing iceberg positions in multiple radar images. Note the deeper data near 114°E and 66°S indicating another potential, deeper pathway for access to the Totten Ice Shelf.

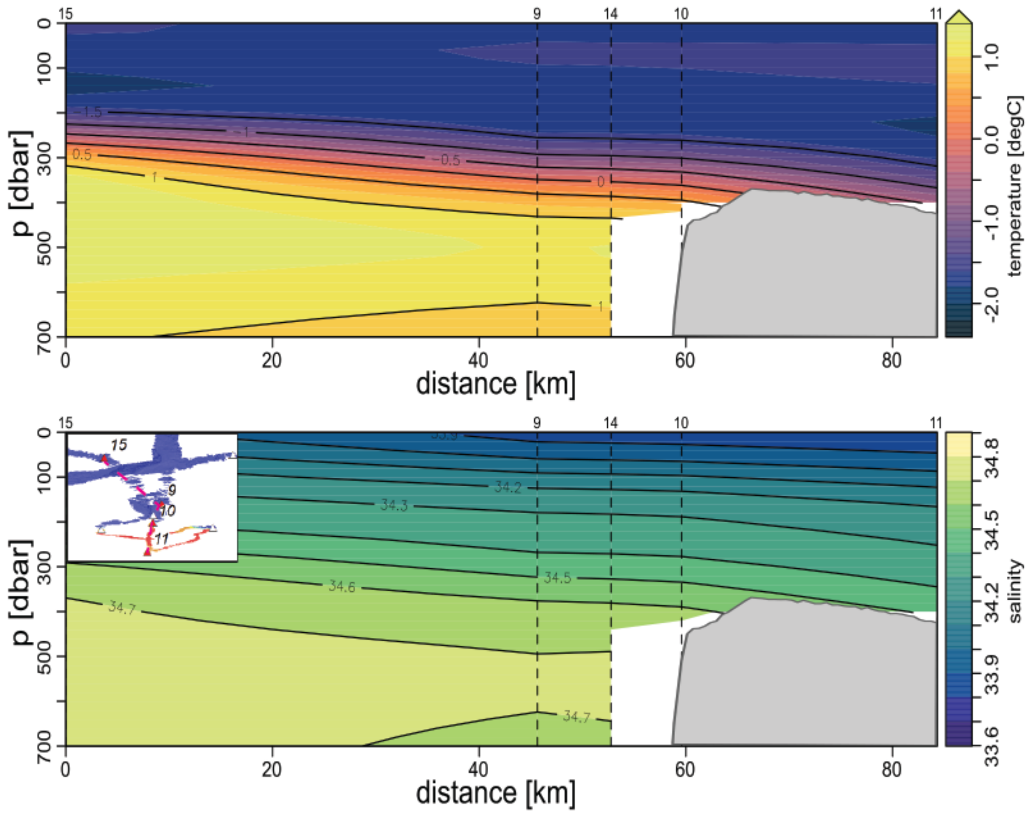

Figure S3. Temperature and salinity cross-section north of the Dalton iceberg tongue. Showing warmer water at the shelf break, but not getting onto the outer shelf.

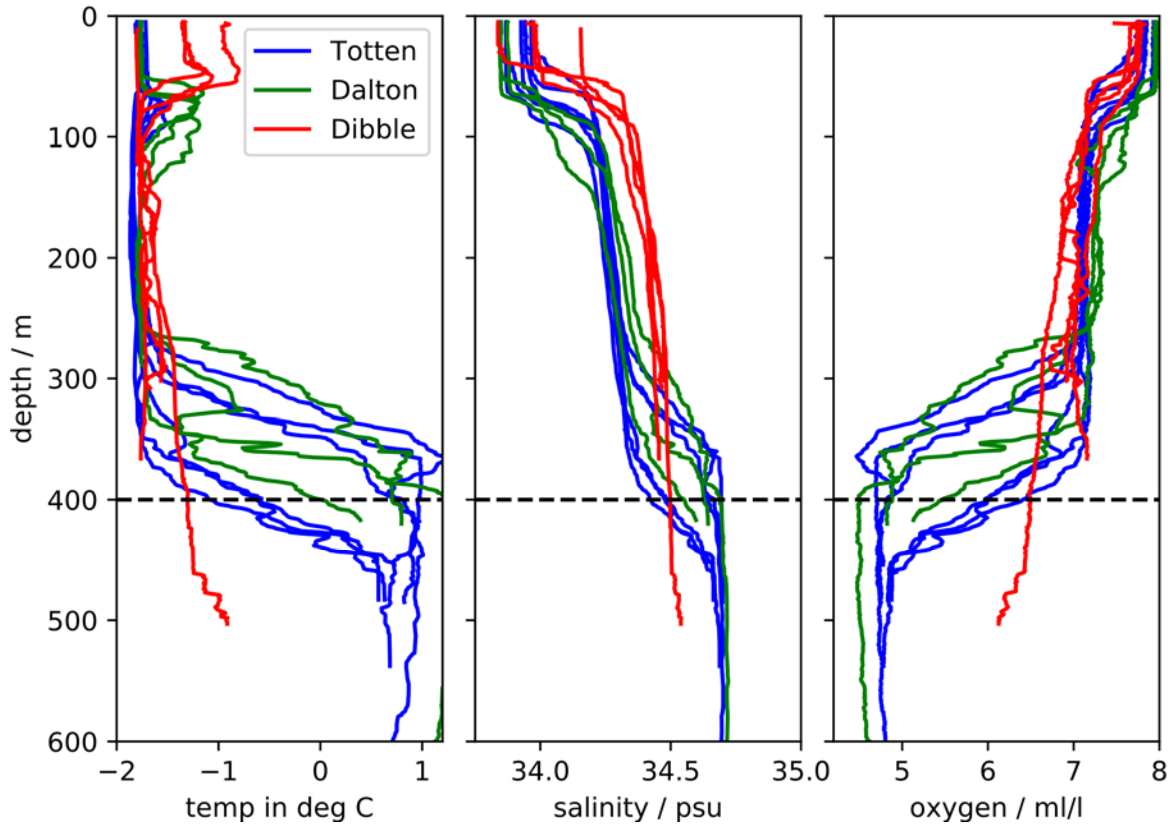

Figure S4. Multiple CTD plots together colored by shelf break near Totten (blue, Stations 18, 19, 21, 22, 23, 25), Dalton Iceberg tongue (green; Stations 10, 11, 14) and Dibble Polynya (red; Stations 3, 4, 5, 38).