AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL081463

Key Points:
- Buoyancy forcing drives the upwelling of modified Circumpolar Deep Water (mCDW) in the southeastern shelf region
- Deep convection entrains sensible heat from the warm mCDW at mid-depths into the surface layer during the freezing season
- Sensible heat from mCDW causes a 45% reduction in sea ice production in the Davis Polynya region

Supporting Information:
- Supporting Information S1

Correspondence to:
G. Guo, J. Shi, and L. Gao,
guoguijun@fio.org.cn;
shijiuxin@ouc.edu.cn;
gaolb@fio.org.cn

Citation:
Guo, G., Shi, J., Gao, L., Tamura, T., & Williams, G. D. (2019). Reduced sea ice production due to upwelled oceanic heat flux in Prydz Bay, East Antarctica. *Geophysical Research Letters*, *46*, 4782–4789. https://doi.org/10.1029/2018GL081463

Received 27 NOV 2018
Accepted 19 MAR 2019
Accepted article online 25 MAR 2019
Published online 2 MAY 2019

Reduced Sea Ice Production Due to Upwelled Oceanic Heat Flux in Prydz Bay, East Antarctica

Guijun Guo[1,2,3], Jiuxin Shi[2,3], Libao Gao[1,2], Takeshi Tamura[4,5,6], and Guy D. Williams[6,7]

[1]Center for Ocean and Climate Research, First Institute of Oceanography, Qingdao, China, [2]Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, [3]Key Laboratory of Physical Oceanography, Ocean University of China, Qingdao, China, [4]National Institute of Polar Research, Tachikawa, Japan, [5]SOKENDAI, The Graduate University for Advanced Studies, Tachikawa, Japan, [6]Antarctic Climate and Ecosystem Cooperative Research Centre, University of Tasmania, Hobart, Tasmania, Australia, [7]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia

Abstract The coastal shelf region of East Antarctica is hypothesized to be shielded from the offshore heat of Circumpolar Deep Water (CDW) due to the dynamic barrier of the Antarctic Slope Front. Yet modified CDW (mCDW) intrudes into the coastal environment in key locations, with impacts on dense shelf water formation and ocean/ice shelf interaction that remain largely unquantified. Using moored measurements and conductivity-temperature-depth-instrumented seal hydrographic data collected in Prydz Bay, East Antarctica, we find buoyancy-driven upwelling of mCDW into the subsurface (~50 m) layer of the southeastern embayment. Wintertime convection extends as deep as 300 m, entraining heat of the upwelled mCDW to the surface. Accumulated sensible heat supply to the surface through deep convection during June–July reduces the potential sea ice production by 45% in the Davis Polynya, demonstrating that stronger/warmer mCDW intrusions onto the shelf will likely reduce the shelf water density and threaten Antarctic Bottom Water formation.

Plain Language Summary Sea ice formation in key coastal polynyas (areas of open water or newly formed thin ice in the middle of the extensive pack ice) around Antarctica is critical to Antarctic Bottom Water (AABW) production. The intrusion of warm, modified Circumpolar Deep Water (mCDW) onto the continental shelf in East Antarctica conveys heat toward the shelf region at intermediate depth, capable of impacting sea ice formation in coastal polynyas. Here we use moored measurements and conductivity-temperature-depth-instrumented seal hydrographic data to shed new light on the interaction between sea ice formation and the heat flux from these mCDW intrusions. Due to the buoyancy contrast with the cold, dense shelf water, the warmer mCDW upwells to shallower depths in the coastal regions. When the winter freezing season begins, surface cooling and brine rejection due to sea ice formation drive convection, deepening the mixed layer and entraining heat of the upwelled mCDW to the surface, which results in a negative feedback that reduces sea ice production. The processes identified in this study have strong implications for AABW production, given the projected increase of mCDW intrusions in the future.

1. Introduction

The mixing of modified Circumpolar Deep Water (mCDW) and Dense Shelf Water (DSW, also referred to as High Salinity Shelf Water) is one of the crucial processes in the formation of Antarctic Bottom Water (AABW), which is a key component of the Southern Ocean's meridional overturning circulation that transports cold and ventilated water to lower latitudes (Foster & Carmack, 1976; Orsi et al., 2002). Early thinking suggested that broad shelf regions with large continental ice shelves were necessary to provide the residence time to form cold, saline shelf water with sufficient density to produce AABW, such as Weddell Sea and Ross Sea (Fahrbach et al., 1994; Foldvik, 2004; Jacobs et al., 1970). More recently, coastal polynyas have also been found to support AABW formation through enhanced sea ice production and associated brine rejection, such as those located in Adélie Land (Rintoul, 1998), Cape Darnley Polynya (Ohshima et al., 2013), and Vincennes Bay (Kitade et al., 2014). Prydz Bay (Figure 1) in East Antarctica, characterized by the third largest continental embayment with Amery Ice Shelf (AIS) and multiple polynyas, always presented itself as a likely AABW source (Middleton & Humphries, 1989; Nunes Vaz & Lennon, 1996; Yabuki et al., 2006).

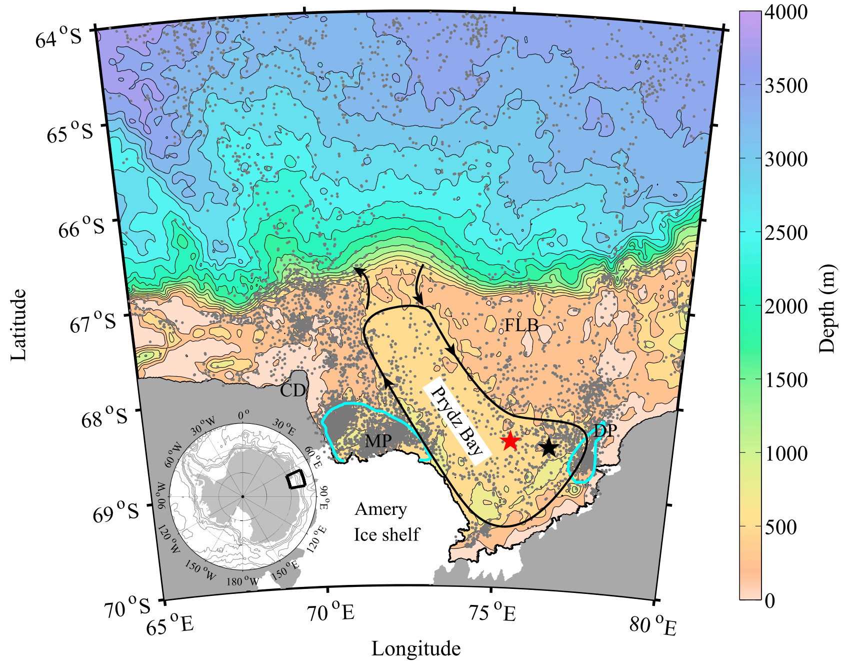

Figure 1. Bathymetry of Prydz Bay from Bedmap2 with 250-m contour intervals. The red and black stars represent the mooring locations M10 and M03, respectively. The gray dots on the background show the locations of seal conductivity-temperature-depth records for April–September used in this study. CD: Cape Darnley; FLB: Four Ladies Bank. Locations of the Mackenzie Polynya (MP) and Davis Polynya (DP) are shown as cyan lines following Williams et al. (2016). General circulation in Prydz Bay is shown as black lines.

However, it was not confirmed until conductivity-temperature-depth (CTD) data from instrumented elephant seals in Mackenzie Bay Polynya and the outflow region of Prydz Channel were shown to be sufficient to make a contribution, albeit fresher due to AIS basal melt, to Cape Darnley Bottom Water (Williams et al., 2016).

Four main water masses are known to occupy the shelf of Prydz Bay: Summer Surface Water (SSW, -1.8 °C $< T <$ 2.1 °C, 30.6 $< S <$ 34.2), DSW (-1.95 °C $< T < -1.85$ °C, $S \geq$ 34.5), Ice Shelf Water (ISW, $T < -1.95$ °C), and mCDW (-1.85 °C $< T < -0.5$ °C with a potential density between 27.72 and 27.85 kg/m^3; Herraiz-Borreguero et al., 2015, 2016; Wong et al., 1998). The bay receives relatively fresh shelf water input via a westward coastal current from the West Ice Shelf (Nunes Vaz & Lennon, 1996; Smith et al., 1984). The costal current merges with the southern perimeter of the Prydz Bay Gyre (PBG) in the southeastern region of the embayment and continues westward along the face of AIS (Nunes Vaz & Lennon, 1996; Smith et al., 1984). Before joining the cyclonic PBG, the coastal current flows through two polynyas, namely, the Barrier Bay Polynya and Davis Polynya, with their respective satellite-derived annual ice production of 93 and 26 km^3 (Tamura et al., 2016; Williams et al., 2016). The salinity of the relatively fresh coastal current water should increase due to the brine-rejection in the Barrier and Davis polynyas during the freezing season. However, mooring results in 2001 indicated that the salinity of the coastal current water east of the AIS did not increase until July (Herraiz-Borreguero et al., 2015), implying that the expected salinity increase was hindered, either by the freshening impact of AIS basal melt or a reduction in sea ice growth due to the sensible heat from warm mCDW intrusions.

Although the Antarctic Slope front (ASF) acts as a strong dynamical barrier to the inflow of CDW across the shelf in East Antarctica (Spence et al., 2014; Thompson et al., 2018), intrusions of mCDW have been observed in the sea ice growth season (March–August), entering Prydz Bay over Four Ladies Bank (FLB) and occupying the eastern side of the bay following the cyclonic PBG and are directed toward the eastern flank of the AIS (Herraiz-Borreguero et al., 2015; Liu et al., 2018; Williams et al., 2016). The interaction of the AIS with mCDW heat transport has been clarified by several studies (Herraiz-Borreguero et al., 2013, 2015; Wong et al., 1998), and the AIS net basal melt rate driven by mCDW inflow was estimated at

1.0 ± 0.4 m/year (Herraiz-Borreguero et al., 2016), reducing local shelf water density and suppressing its potential contribution to AABW formation (Williams et al., 2016). Earlier studies showed that the heat flux from mCDW intruded onto the Ross Sea continental shelf can inhibit sea ice formation in coastal polynyas (Jacobs & Comiso, 1989; Pillsbury & Jacobs, 1985). In the Mertz polynya, the sensible heat contribution of mCDW was estimated to be much smaller than the latent-heat component (Bindoff et al., 2001; Williams & Bindoff, 2003). However, the exact volume reduction of sea ice production (SIP) from mCDW intrusions remained unknown. In Prydz Bay, Massom et al. (1998) suggested that upwelling of warm, deep water might contribute to the formation of the Davis Polynya, but observational evidence quantifying the effect of upwelled sensible heat on sea ice formation is also lacking in coastal polynyas.

The poleward wind shift in the Southern Ocean is projected to persist through the 21st century (Fyfe et al., 2007), which will facilitate CDW intrusion onto the shelf and lead to an intense and rapid warming of subsurface Antarctic coastal waters (Schmidtko et al., 2014; Spence et al., 2014). Many recent studies are examining the impact of mCDW on ocean-ice shelf interactions, and the likely impact of increased oceanic heat supply to the continental shelf. Silvano et al. (2018) discussed how there is a likely positive feedback between mCDW and freshwater input from ice shelves. Williams et al. (2016) highlighted the impact of this enhanced freshwater input on AABW. This study examines a parallel issue, the impact of oceanic heat supply from mCDW on SIP. All three mechanisms need to be understood clearly in order to consider the future of AABW. Here we focus on reduction of SIP along the eastern flank of Prydz Bay due to the upward heat flux from mCDW intrusions. We use instrumented seal CTD data collected during the freezing season (April–September), and mooring observations deployed along the pathway of mCDW inflow. Given the enhanced CDW upwelling and intrusion onto shelves in the Southern Ocean, this study provides new insights into potentially negative effects of CDW heat on SIP and shelf water density around East Antarctica.

2. Observations and Data

In 2015 the CHINARE (Chinese National Antarctic Research Expedition) research program sent the R/V Xuelong to conduct an CTD survey of Prydz Bay and deployed moored instruments in key regions relating to the inflow of mCDW. A mooring (M10 in Figure 1) was deployed with temperature and conductivity recorders (RBR solo T, concerto CT, and Sea-Bird MicroCATs) in late February 2015 and recovered in December, collecting data at 30-min intervals. The mooring location (75°22.7′E, 68°28.6′S, 612 m) was selected near the expected pathway of mCDW intrusion, in the southeast part of Prydz Bay. Conductivity and temperature data were obtained at 200 and 300 m to identify water mass modification due to seasonal ice production and mCDW intrusion. Temperature was also recorded at the deeper depths of 400, 450, and 600 m. Additional temperature and salinity data obtained from instrumented elephant seals from April to September across 2011–2015 were used to illustrate mCDW intrusion during ice formation season (Figure 1). The calibration procedure for the seal CTD data is described in Roquet et al. (2014), with the accuracy of data estimated to be within 0.03 °C for temperature and 0.05 for salinity. Nearby historical Anderaa current measurements from 1985 (Reeve, 1999), collected at 300 m from an Australian mooring at 76°29.4′E, 68°31.3′S (M03 in Figure 1), are used in this study to augment the water mass times series and estimate transport rates on the shelf. Hourly current data were collected from January through July by M03. Satellite-derived SIP and ice thickness in 2015 are estimated from heat flux calculation during the freezing period following Tamura et al. (2016).

3. Results

3.1. Intrusion and Upwelling of mCDW on the Shelf

In order to capture the vertical distribution of the initial inflow of mCDW into Prydz Bay, we define a section using available seal temperature data for the month of April across 2011–2015 (Figure 2). The section is defined across the FLB from the open ocean to the southeastern inner shelf, along the pathway of intruded mCDW, which is shown to initially move onto the shallow FLB from the deep ocean and then become directed toward the eastern AIS front (Herraiz-Borreguero et al., 2015; Liu et al., 2018; Williams et al., 2016). The isotherm extending from the shelf break rises northward to the base of the SSW layer, indicating the existence of the ASF. Moving southward across the shelf break, there is a warm tongue of water (> −1.7 °C) that also rises into the subsurface layer. This southward elevation of the isotherm describes

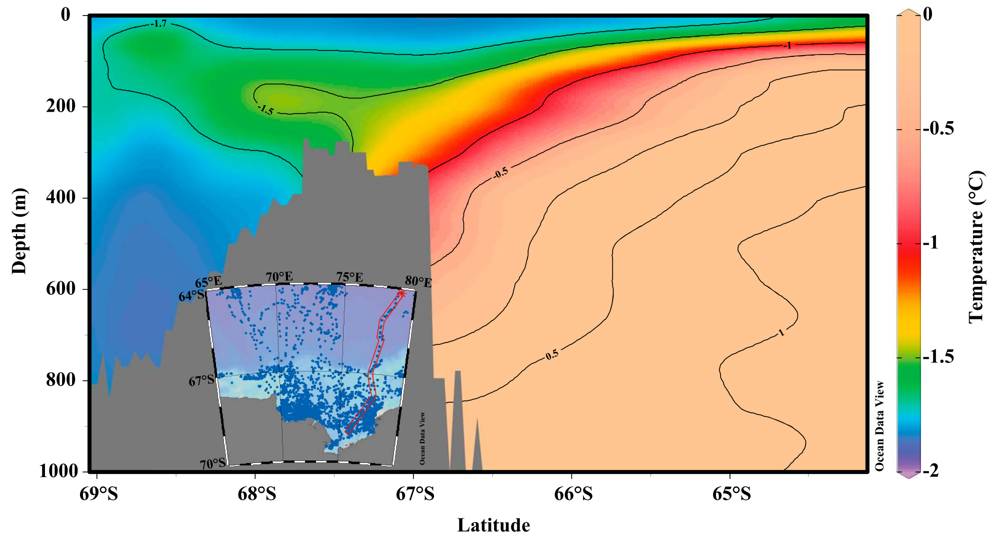

Figure 2. Vertical section of temperature from seal conductivity-temperature-depthrecords in April (blue dots in the inset map) from open ocean to inner shelf. Section location is shown in the inset map (red box), which is defined along eastern side of Prydz Bay to highlight modified Circumpolar Deep Water intrusion.

the mCDW intrusion and its upwelling in the southeast region of Prydz Bay, where relatively warm mCDW encounters cold DSW. The local upwelling is ascribed to the lower density of the warm mCDW relative to colder DSW. The buoyancy difference between these two water masses pushes the warm mCDW upward, causing upwelling in the southeast embayment. Figure 2 shows that the −1.7 °C isotherm (about 0.2 °C above freezing temperature) rises to depth of approximate 50 m, providing a large amount of heat that will become available to the surface when surface convection is initiated at the beginning of the freezing season.

3.2. Convection of Subsurface Heat at the Onset of the Freezing Season

We examine the time series of temperature and salinity data at fixed depths recorded by the mooring M10 (Figure 3), whose location is close to the inflow pathway of mCDW, to verify that this heat supplied by the upwelling mCDW is transported to the surface during the freezing season. The temperature at 200 and 300 m undergoes a substantial increase of 0.1 °C in late February (Figures 3a and 3b), marking the onset of the warm mCDW intrusion. Following this rapid temperature rise, the temperature of the upper most layer is maintained at −1.8 °C, approximately 0.1 °C above freezing temperature (−1.89 °C) from April through May. Then an abrupt decrease in temperature occurs in late May that approaches the freezing temperature, while warming is still clearly present below and becomes stronger (Figure 3b), which implies that the mCDW intrusion above 300 m is still ongoing. This rapid decrease of temperature at 200 m is therefore attributed to the arrival of cold saline surface water through deepened convection due to surface cooling and sea ice formation, which is verified by the corresponding increase in salinity (Figure 3a). Salinity increase at 200 m in June indicates increasing polynya activity due to latent heat loss at surface, agreeing well with the increase of SIP rate in Davis Polynya across June (Figure 3d), which is activated by a cooler atmosphere and stronger katabatic winds in winter.

Warming below 200 m after late May, peaking at a maximum temperature of −1.81 °C in mid-June at 300 m and early July at 400 m (−1.85 °C) and 450 m (−1.86 °C), indicates that the mCDW intrusion is persistent and continues to supply heat to depths greater than 400 m for more than 4 months. By contrast, the deepest water on the shelf is free of mCDW influence, with the observed temperature at 600 m absent of any warming signals (Figure 3c). The simultaneous occurrence of temperature maxima at 400 and 450 m implies that the deepest warm water on the shelf is unaffected by this mixing process and can still access the AIS following PBG. It is noteworthy that the SIP rate in the Davis Polynya shows a distinctly quiet period from July through mid-August (Figure 3d), while thin ice still exists in the polynya with a monthly mean thickness of ~0.1 m (Figure S1). This is counterintuitive because this is the heart of winter. This is ascribed to the

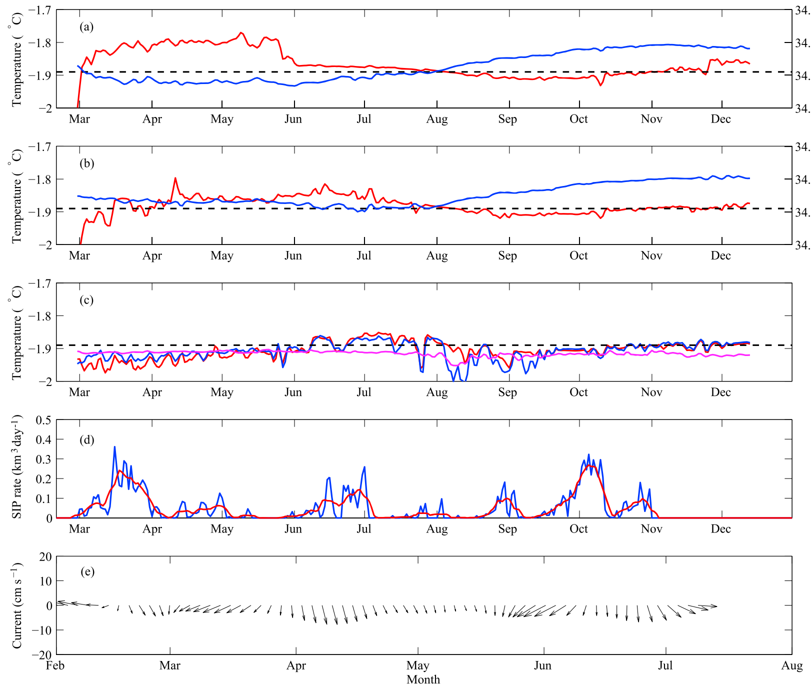

Figure 3. (a and b) The 48-hr running mean of temperature (red) and salinity (blue) records from M10 at depths of (a) 200 m and (b) 300 m. (c) The 48-hr running mean of temperature records from M10 at depths of 400 m (red), 450 m (blue), and 600 m (magenta). (d) Daily SIP volume (blue) and 7-day running mean (red) in Davis Polynya in 2015. (e) Current vectors at 300 m (30 days low-passed) from M03 from February through July. The black dashed line in a–c depicts surface freezing temperature of −1.89 °C.

fact that the submerged mCDW is mixed up into the surface layer through deepened convection in winter and the continuous sensible heat supply suppresses the sea ice formation in Davis Polynya. mCDW heat in the vicinity of the Polynya has been stripped away by late August when the warm signal of the mCDW intrusion disappears at all observed depths (Figures 3a–3c). So the synoptic SIP in Davis Polynya returns to normal, and brine rejection continues to increase salinity at 200 and 300 m in September and October.

3.3. Reduction of Sea Ice Production

Section properties of temperature across the shelf break (Figure 2), together with the mooring time series (Figure 3), demonstrate how the upwelling of warm mCDW in the southeastern shelf region provides an upward heat flux to the surface layer once deep convection begins in the sea ice growth season. To quantify the accumulated upward heat transport from the intermediate layer to the surface, the volume transport of the mCDW intrusions onto the shelf must be estimated. In April, warm mCDW with potential density larger than 27.72 kg/m^3 exists below the remnant SSW from April through July (Figure S2a), with the maximum temperature of about −1 °C. The absence of this warm signal after July does not indicate the end of mCDW intrusions, but rather the reduction in available seal CTD profiles as the pack ice thickens. The path of mCDW onto the shelf is confined to a relatively narrow longitude range, centered at around 77°E (Figure S2b), corresponding with the previous studies showing that mCDW flows southward along the east perimeter of the PBG toward southern limits of Prydz Bay (Nunes Vaz & Lennon, 1996; Williams et al., 2016).

Given that the temporal coverage of the mCDW intrusions ranges from late February to early August (Figures 3a–3c) and the pathway of the intrusions onto the shelf is centered at 77°E (Figure S2b), the zonal and vertical extent of the intrusions needs to be clarified to estimate the volume of warm water transport. Monthly mean profiles of temperature (Figure 4a) in the southeastern embayment near the mooring locations and Davis Polynya show that warm mCDW exists from the subsurface layer to deeper than 500 m. The mixed layer deepens from near 50 m to deeper than 300 m from April through July, and mCDW heat above 300 m is incrementally removed by deepening convection. The initial entrainment of heat from below the 200 m, into the surface, begins in late May (Figure 3a). Accordingly, we define a

10.1029/2018GL081463

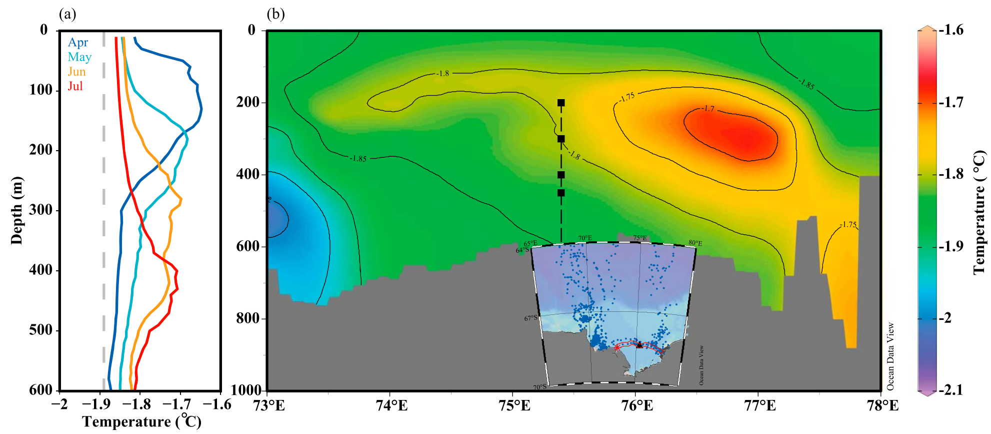

Figure 4. The general pattern of modified Circumpolar Deep Waterintrusion into Prydz Bay. (a) Monthly mean profiles of temperature for April–July (bounded by 68.2–68.7°S, 75.5–77.5°E). The gray dashed line represents surface freezing temperature. (b) Vertical section of temperature across the shelf using seal conductivity-temperature-depth records in June (blue dots in the inset map). The black dashed line and squares represent the mooring line and sampling depths. Location of the zonal section and mooring M10 are shown in the inset map (red box and black triangle).

zonal section across the shelf from the eastern limit of Prydz Bay westward to the AIS front (inserted map in Figure 4b), based on seal CTD records in June, to identify the zonal extent of the warm mCDW inflows. The closed −1.75 °C isotherm with a horizontal width of 64 km characterizes the inflow of the intruded mCDW along the eastern flank of the PBG, whose core temperature at about 300 m is above −1.7 °C. It is notable that warm water outside the closed isotherm of −1.75 °C inferred from the mooring observations (Figures 3a and 3b and 4b) can still supply heat to the surface through convection. As the warm mCDW reaches about 50 m before the new winter surface mixed layer makes contact in April and the mixed layer deepens to greater than 300 m in July (Figures 2 and 4a), it is reasonable to assume that the heat brought by the mCDW intrusion at 50–300 m is transported to the surface through strong convection. This is the case in June and July, while the mCDW thickness influenced by the mixing process before June is relatively smaller and can be neglected. Meanwhile, compared with the upward heat flux (100 W/m^2) when mCDW is entrained to the surface through strong mixing in winter (Jacobs & Comiso, 1989), the downward heat flux of mCDW $\left(F_H = \rho c_p K_v \frac{\partial T}{\partial z}\right)$ is also estimated to be negligible at 0.16 W/m^2, corresponding to a diffusivity of $K_v \approx 10^{-4}$ m^2/s with a vertical temperature gradient of 4×10^{-4} °C/m between 300 and 500 m (Figure 4a). Then the accumulated transport of mCDW heat (H) to the surface can be estimated as

$$H = \rho c_p \left(T - T_f\right)(z_2 - z_1) D v t$$

where ρ is density of mCDW (1,028 kg/m^3), c_p is the ocean heat capacity (4,000 $J \cdot kg^{-1} \cdot °C^{-1}$), T is the typical temperature of mCDW, T_f is the surface freezing temperature (−1.89 °C), z_2 is the maximum depth (300 m) of strengthened convection during ice freezing season, z_1 is the upmost boundary (50 m) of mCDW (Figures 2 and 4a), D is the typical zonal width of mCDW inflow (64 km), v is current speed of mCDW intrusion, and t is seconds for June–July when deep convection reaches the core depth of intruded mCDW (Figures 3a and 4a) and SIP is suppressed by the mCDW heat (Figure 3d). A typical mCDW temperature is taken as −1.64 ± 0.08 °C, mean temperature of warm water confined by the closed isotherm of −1.75 °C, instead of the observed mooring temperature (−1.8 °C), because there is a deviation (~30 km) between the location of M10 and the core pathway of the mCDW intrusion (Figures 1 and 4b).

Current speed of the inflow at 300 m is derived from the historical mooring (M03) measurements (Figure 3e), which provide a mean southward velocity of 4.1 ± 1.6 cm/s from March to the end of the records in mid-July. The dynamic height distribution (Figure S3) shows that M03 is close to the eastern flank of PBG, so the current data records should reflect the actual state of the gyre to some extent, while being somewhat lower in magnitude compared to the core inflow speed. Assuming all of the heat associated with the mCDW above 300 m where deep convection can reach in winter (Figure 4a) is transported into the surface layer via mixing, the accumulated convective heat transport from the mCDW to the surface is estimated to be $3.55 \pm 2.52 \times 10^{18}$ J. By confining the time period to June–July, excluding mCDW with temperature lower than −1.75 °C, and using current data that are outside the core inflow, we expect that this estimate is a conservative lower limit of the total heat entrained to the surface through convection.

Thereafter, the volume reduction (*VR*) of SIP due to convective heat flux can be calculated as

$$\mathrm{VR} = H/\rho_i L_i$$

where sea ice density ρ_i= 920 kg/m^3 and sea ice latent heat of fusion L_i= 3.34×10^5 J/kg. We estimate that 11.55 km^3 of the SIP volume is suppressed by the upward convective heat flux. The satellite-derived annual cumulative SIP in Davis Polynya is 14.1 km^3 in 2015 (Figure 3d), and the multiyear mean value is estimated to be 26 km^3 with interannual variability ranging from 7.8 to 41.4 km^3 (Tamura et al., 2016; Williams et al., 2016). This means that the sensible heat from intruded mCDW reduces 45% of the potential SIP volume in 2015 and contributes effectively to the interannual variability.

4. Conclusions

It has been suggested that the East Antarctic shelf regions are largely shielded from the heat content, and changes therein, of CDW due to the dynamic barrier of the ASF (Schmidtko et al., 2014). However, in this study we show the direct evidence of mCDW intrusions onto the continental shelf region supplying sufficient sensible heat to effectively reduce the local SIP in a coastal polynya. In the southeastern shelf region of Prydz Bay, buoyancy-driven mCDW upwelling lifts the −1.7 °C isotherm as shallow as 50 m in the late summer period, bringing large amounts of heat to the subsurface layer. While the upwelled heat cannot reach the surface directly during the summer/fall period, the onset of winter convection entrains the mCDW heat into the surface layer during the sea ice growth season. The accumulated convective heat transport to the surface during June–July is approximately $3.55 \pm 2.52{\times}10^{18}$ J, impacting the sea ice growth conditions. The volume reduction of SIP during this period is estimated at 11.55 km^3, approximate 45% of the potential SIP volume in the Davis Polynya region. Williams et al. (2016) highlighted the risk to AABW from increased freshwater input from ocean-ice interactions. This study shows that enhanced mCDW intrusions could also have a similar impact on AABW by reducing SIP and DSW formation in coastal polynyas. While historically it was common to distinguish between offshore *sensible-heat* and coastal *latent-heat* polynyas (Massom et al., 1998), the recent decades of observations on the Antarctic margin suggest that many, if not all, are to some degree a hybrid of wind-driven forcing at the surface and some interaction with mCDW heat below, or alternatively upstream. If, as projected, the overall supply of oceanic CDW heat to the Antarctic continental shelf increases into the future due to strengthening and poleward-shift in westerly winds (Spence et al., 2014), the sensible heat component of these hybrid systems will increase, decreasing dense shelf water formation and ultimately, AABW production.

Acknowledgments
This work was supported by the National Key R&D Program of China (2018YFA0605701) funded by the Ministry of Science and Technology of the People's Republic of China (MOST), National Natural Science Foundation of China (41706220 and 41876231), and Basic Scientific Fund for National Public Research Institutes of China (2018S02). G. Williams was supported through the Australian Research Council and Antarctic Climate and Ecosystems Cooperative Research Centre. T. Tamura was supported by funds from the Grant-in-Aids for Scientific Research (17H04710) of the Japanese Ministry of Education, Culture, Sports, Science and Technology. The mooring data of M10 are available at Chinese National Arctic and Antarctic Data Center (http://www.chinare.org.cn). Current measurements from mooring M03 (originally called 85/03) are available from https://data.aad.gov.au/metadata/records/AADC-00044 (Reeve, 1999). Elephant seal hydrographic data were collected and made freely available by the International MEOP Consortium and the national programs that contribute to it (http://www.meop.net).

References

Bindoff, N. L., Williams, G. D., & Allison, I. (2001). Sea-ice growth and water-mass modification in the Mertz Glacier polynya, East Antarctica, during winter. *Annals of Glaciology*, *33*, 399–406. https://doi.org/10.3189/172756401781818185

Fahrbach, E., Peterson, R. G., Rohardt, G., Schlosser, P., & Bayer, R. (1994). Suppression of bottom water formation in the southeastern Weddell sea. *Deep Sea Research Part I: Oceanographic Research Papers*, *41*(2), 389–411. https://doi.org/10.1016/0967-0637(94)90010-8

Foldvik, A. (2004). Ice shelf water overflow and bottom water formation in the southern Weddell Sea. *Journal of Geophysical Research*, *109*, C02015. https://doi.org/10.1029/2003JC002008

Foster, T. D., & Carmack, E. C. (1976). Frontal zone mixing and Antarctic Bottom water formation in the southern Weddell Sea. *Deep Sea Research and Oceanographic Abstracts*, *23*(4), 301–317. https://doi.org/10.1016/0011-7471(76)90872-X

Fyfe, J. C., Saenko, O. A., Zickfeld, K., Eby, M., & Weaver, A. J. (2007). The role of poleward-intensifying winds on Southern Ocean warming. *Journal of Climate*, *20*(21), 5391–5400. https://doi.org/10.1175/2007JCLI1764.1

Herraiz-Borreguero, L., Allison, I., Craven, M., Nicholls, K. W., & Rosenberg, M. A. (2013). Ice shelf/ocean interactions under the Amery Ice Shelf: Seasonal variability and its effect on marine ice formation. *Journal of Geophysical Research: Oceans*, *118*, 7117–7131. https://doi.org/10.1002/2013JC009158

Herraiz-Borreguero, L., Church, J. A., Allison, I., Peña-Molino, B., Coleman, R., Tomczak, M., & Craven, M. (2016). Basal melt, seasonal water mass transformation, ocean current variability, and deep convection processes along the Amery Ice Shelf calving front, East Antarctica. *Journal of Geophysical Research: Oceans*, *121*, 4946–4965. https://doi.org/10.1002/2016JC011858

Herraiz-Borreguero, L., Coleman, R., Allison, I., Rintoul, S. R., Craven, M., & Williams, G. D. (2015). Circulation of modified Circumpolar Deep Water and basal melt beneath the Amery Ice Shelf, East Antarctica. *Journal of Geophysical Research: Oceans*, *120*, 3098–3112. https://doi.org/10.1002/2015JC010697

Jacobs, S. S., Amos, A. F., & Bruchhausen, P. M. (1970). Ross sea oceanography and Antarctic Bottom Water formation. *Deep Sea Research and Oceanographic Abstracts*, *17*(6), 935–962. https://doi.org/10.1016/0011-7471(70)90046-X

Jacobs, S. S., & Comiso, J. C. (1989). Sea ice and oceanic processes on the Ross Sea continental shelf. *Journal of Geophysical Research*, *94*(C12), 18,195–18,211. https://doi.org/10.1029/JC094iC12p18195

Kitade, Y., Shimada, K., Tamura, T., Williams, G. D., Aoki, S., Fukamachi, Y., et al. (2014). Antarctic Bottom Water production from the Vincennes Bay Polynya, East Antarctica. *Geophysical Research Letters*, *41*, 3528–3534. https://doi.org/10.1002/2014GL059971

Liu, C., Wang, Z., Cheng, C., Wu, Y., Xia, R., Li, B., & Li, X. (2018). On the modified circumpolar deep water upwelling over the Four Ladies Bank in Prydz Bay, East Antarctica. *Journal of Geophysical Research: Oceans*, *123*, 7819–7838. https://doi.org/10.1029/2018JC014026

Massom, R. A., Harris, P. T., Michael, K. J., & Potter, M. J. (1998). The distribution and formative processes of latent-heat polynyas in East Antarctica. *Annals of Glaciology*, *27*, 420–426. https://doi.org/10.3189/1998AoG27-1-420-426

Middleton, J. H., & Humphries, S. E. (1989). Thermohaline structure and mixing in the region of Prydz Bay, Antarctica. *Deep Sea Research Part A. Oceanographic Research Papers*, *36*(8), 1255–1266. https://doi.org/10.1016/0198-0149(89)90104-0

Nunes Vaz, R. A., & Lennon, G. W. (1996). Physical oceanography of the Prydz Bay region of Antarctic waters. *Deep Sea Research Part I: Oceanographic Research Papers*, *43*(5), 603–641. https://doi.org/10.1016/0967-0637(96)00028-3

Ohshima, K. I., Fukamachi, Y., Williams, G. D., Nihashi, S., Roquet, F., Kitade, Y., et al. (2013). Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya. *Nature Geoscience*, *6*(3), 235–240. https://doi.org/10.1038/ngeo1738

Orsi, A. H., Smethie, W. M. Jr., & Bullister, J. L. (2002). On the total input of Antarctic waters to the deep ocean: A preliminary estimate from chlorofluorocarbon measurements. *Journal of Geophysical Research*, *107*(C8), 3122. https://doi.org/10.1029/2001JC000976

Pillsbury, R. D., & Jacobs, S. S. (1985). Preliminary observations from long-term current meter moorings near the Ross Ice Shelf, Antarctica. *Oceanology of the Antarctic Continental Shelf*, *43*, 87–107. https://doi.org/10.1029/AR043p0087

Reeve, J. (1999). Prydz Bay current meter data 1985–1986. Antarctic Data Centre - CAASM Metadata. Retrieved from https://data.aad.gov.au/metadata/records/AADC-00044

Rintoul, S. R. (1998). On the origin and influence of Adélie Land Bottom Water. *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin, Antarctic Research Series*, *75*, 151–171.

Roquet, F., Williams, G., Hindell, M. A., Harcourt, R., McMahon, C., Guinet, C., et al. (2014). A Southern Indian Ocean database of hydrographic profiles obtained with instrumented elephant seals. *Scientific Data*, *1*, 140028. https://doi.org/10.1038/sdata.2014.28

Schmidtko, S., Heywood, K. J., Thompson, A. F., & Aoki, S. (2014). Multidecadal warming of Antarctic waters. *Science*, *346*(6214), 1227–1231. https://doi.org/10.1126/science.1256117

Silvano, A., Rintoul, S. R., Peña-Molino, B., Hobbs, W. R., van Wijk, E., Aoki, S., et al. (2018). Freshening by glacial meltwater enhances melting of ice shelves and reduces formation of Antarctic Bottom Water. *Science Advances*, *4*(4), eaap9467. https://doi.org/10.1126/sciadv.aap9467

Smith, N. R., Zhaoqian, D., Kerry, K. R., & Wright, S. (1984). Water masses and circulation in the region of Prydz Bay, Antarctica. *Deep Sea Research Part A. Oceanographic Research Papers*, *31*(9), 1121–1147. https://doi.org/10.1016/0198-0149(84)90016-5

Spence, P., Griffies, S. M., England, M. H., Hogg, A. M., Saenko, O. A., & Jourdain, N. C. (2014). Rapid subsurface warming and circulation changes of Antarctic coastal waters by poleward shifting winds. *Geophysical Research Letters*, *41*, 4601–4610. https://doi.org/10.1002/2014GL060613

Tamura, T., Ohshima, K. I., Fraser, A. D., & Williams, G. D. (2016). Sea ice production variability in Antarctic coastal polynyas. *Journal of Geophysical Research: Oceans*, *121*, 2967–2979. https://doi.org/10.1002/2015JC011537

Thompson, A. F., Stewart, A. L., Spence, P., & Heywood, K. J. (2018). The Antarctic slope current in a changing climate. *Reviews of Geophysics*, *56*, 741–770. https://doi.org/10.1029/2018RG000624

Williams, G. D., & Bindoff, N. L. (2003). Wintertime oceanography of the Adélie Depression. *Deep Sea Research Part II: Topical Studies in Oceanography*, *50*(8-9), 1373–1392. https://doi.org/10.1016/S0967-0645(03)00074-2

Williams, G. D., Herraiz-Borreguero, L., Roquet, F., Tamura, T., Ohshima, K. I., Fukamachi, Y., et al. (2016). The suppression of Antarctic Bottom Water formation by melting ice shelves in Prydz Bay. *Nature Communications*, *7*(1), 12577. https://doi.org/10.1038/ncomms12577

Wong, A. P. S., Bindoff, N. L., & Forbes, A. (1998). Ocean-ice shelf interaction and possible bottom water formation in Prydz Bay, Antarctica. *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin, Antarctic Research Series*, *75*, 173–187.

Yabuki, T., Suga, T., Hanawa, K., Matsuoka, K., Kiwada, H., & Watanabe, T. (2006). Possible source of the Antarctic Bottom Water in the Prydz Bay Region. *Journal of Oceanography*, *62*(5), 649–655. https://doi.org/10.1007/s10872-006-0083-1