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Between the Devil and the Deep Blue Sea

THE ROLE OF THE AMUNDSEN SEA CONTINENTAL SHELF IN EXCHANGES BETWEEN OCEAN AND ICE SHELVES

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Release of a meteorological radiosonde balloon from RRS *James Clark Ross* in February 2014 to collect a profile of atmospheric properties adjacent to the Pine Island Ice Shelf. *Photo credit: Karen Heywood*

> "Processes on the continental shelf and slope all around Antarctica are crucially important for determining future sea level rise, for setting the properties and volume of exported dense bottom water, and for regulating the carbon cycle. Yet our ability to model and predict these processes over future decades is still rudimentary."

ABSTRACT. The Amundsen Sea is a key region of Antarctica where ocean, atmosphere, sea ice, and ice sheet interact. For much of Antarctica, the relatively warm water of the open Southern Ocean (a few degrees above freezing) does not reach the Antarctic continental shelf in large volumes under current climate conditions. However, in the Amundsen Sea, warm water penetrates onto the continental shelf and provides heat that can melt the underside of the area's floating ice shelves, thinning them. Here, we discuss how the ocean's role in melting has come under increased scrutiny, present 2014 observations from the Amundsen Sea, and discuss their implications, highlighting aspects where understanding is still incomplete.

BACKGROUND

The Antarctic Ice Sheet, which holds a vast reservoir of water—enough to increase global sea level by 58 m (Fretwell et al., 2013)—has been a focus of attention in recent decades because it has been losing mass and thereby making a positive contribution to sea level (Shepherd et al., 2012). The mass discharged to the ocean by the gravity-driven flow of ice from the interior of the continent has been greater than the mass added by precipitation over the ice sheet. The ice sheet in West Antarctica has received most attention because, although considerably smaller than its counterpart in East Antarctica, it rests predominantly on land that lies below sea level and often deepens toward the interior of the ice sheet. Ice at the margins floats free of the bed to form ice shelves, and the flow of ice across the grounding line, which separates the grounded ice sheet upstream from the floating ice shelf downstream, is a sensitive function of the ice thickness there (Schoof, 2007). Thus, if thinning of the ice sheet initiates an inland retreat of the grounding line that takes it into deeper water, the discharge across the grounding line tends to increase, exacerbating the mass imbalance, and the associated positive feedback can lead to rapid and irreversible retreat. The ice shelves play a critical role in regulating the retreat, because as they contact seabed shoals and the sides of confining embayments, the resulting resistance to their flow buttresses the ice upstream. As a result of ice shelf buttressing, the flow of ice across the grounding line is not a monotonic function of the ice thickness there (Gudmundsson, 2013), so the positive feedback can be prevented. However, any changes in buttressing will inevitably lead to changes in discharge from the grounded ice sheet. There is growing evidence that the widespread thinning of ice shelves observed over recent decades (Paolo et al., 2015) has been responsible for the acceleration and thinning of Antarctic outlet glaciers and the associated retreat of their grounding lines (e.g., Park et al., 2013; Mouginot et al., 2014; Rignot et al., 2014).

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report chapter on sea level rise (Church et al., 2013) was the first such report to be able to quantify a likely range of sea level rise during the twenty-first century. This was made possible by recent improvements in our understanding and modeling of ice sheet dynamics, ice-ocean interactions, and climate dynamics. However, it was not possible to provide a very likely range or upper bound of global sea level rise because of the unknown risk of potential collapse of Antarctic ice shelves. There is an increasing rate of ice loss in the Amundsen Sea Embayment in West Antarctica (Paolo et al., 2015). Here, we focus on two vulnerable ice shelves in the eastern Amundsen Sea, Pine Island and Thwaites Glaciers, where ice shelf thinning and glacier acceleration have been observed throughout the past four decades (Mouginot et al., 2014; Rignot et al., 2014). Church et al. (2013) had "high confidence" that the retreat of Pine Island Glacier (if it occurs) would lead to a sea level rise of several centimeters by 2100, but that models were not yet good enough to predict when this might happen. They suggested that Thwaites Glacier may be less prone to undergo ocean-driven grounding line retreat than its neighbor in the twenty-first century, but that this remains uncertain. Modeling results (Joughin et al., 2014) suggest that unstable retreat is already underway for Thwaites Glacier, but that eventual collapse is not likely to occur for hundreds of years.

> "Atmospheric forcing is important for determining ocean conditions and dynamics, for sea ice formation and melt processes, and for surface processes on the Antarctic continent that determine ice mass balance. Despite this, in situ meteorological observations in the Amundsen Sea embayment remain very sparse."

Why are the ice shelves thinning and losing mass? For some Antarctic ice shelves, such as the Larsen Ice Shelf to the east of the Antarctic Peninsula, it is suggested that warmer surface winds are causing the ice shelf to disintegrate (Doake et al., 1998; Elvidge et al., 2016). However, in most other locations around the continent, and especially in the Amundsen, Bellingshausen, and West Antarctic Peninsula sectors, the ocean has been implicated (e.g., Jacobs et al., 2011; Rignot et al., 2013). If relatively warm ocean water extends to the underside of the floating ice shelves, it can begin to melt the ice shelf. The principal source of ocean heat on the Amundsen Sea continental shelf is Circumpolar Deep Water (CDW). This water mass, circulating around Antarctica within the Antarctic Circumpolar Current, has core temperatures of approximately 2°C and is ubiquitous beneath the cold surface layer and broad thermocline that typically occupy the upper few hundred meters of the water column (Schmidtko et al., 2014). The main pycnocline separating CDW from surface waters typically deepens over the Antarctic continental slope to form the Antarctic Slope Front, associated with westward flow around Antarctica in the slope current. The depth of the pycnocline, a key control on exchange across the shelf break, may be strongly dependent on the surface wind stress (Thoma et al., 2008; Spence et al., 2013; Jenkins et al., 2016, in this issue). In the eastern Weddell Sea upstream of the vast Filchner-Ronne Ice Shelf system, the pycnocline characteristically intersects the continental slope well below the shelf break, and the Antarctic Slope Undercurrent flows eastward on the slope (Chavanne et al., 2010). In the Amundsen Sea, in contrast, the pycnocline remains mostly above the level of the shelf break, especially where the shelf edge is cut by troughs (Jacobs et al., 2012). As a result, almost unmodified CDW can cross the shelf break (Jenkins et al., 2010), although shelf break mixing processes reduce the core temperature by about 0.5°C (Jacobs et al., 2012). The undercurrent follows the shelf break and may turn onto the shelf when it encounters crosscutting troughs (Walker et al., 2013). Once on the continental shelf, CDW is thought to follow the glacially carved bathymetric troughs to the ice shelves (Thoma et al., 2008; Jacobs et al., 2011; Nakayama et al., 2013).

Although the ocean has been implicated in the thinning and acceleration of ice shelves, it is too simplistic to state that the ocean is warming globally and that the ice shelf is melting like an ice cube in a warm bath; rather, ocean dynamics have an important role to play. For example, Antarctic sea ice is not undergoing the decline that is seen in the Arctic (Turner et al., 2015). Although the precise combination of atmospheric, oceanic, and cryospheric processes responsible is still debated, the observed increase in total Antarctic sea ice extent is consistent with the predictions of coupled climate model experiments when perturbed with an addition of meltwater from the Antarctic Ice Sheet (Richardson et al., 2005). Nonetheless, there is evidence that the waters of the Antarctic Circumpolar Current are warming (Gille, 2008). Available data, though sparse, suggest statistically significant warming and shoaling of the CDW core, particularly at the West Antarctic Peninsula and on the Bellingshausen and Amundsen Sea continental slopes (Schmidtko et al., 2014); further long-term observations are required to clearly distinguish trends from decadal variability. On the Antarctic continental shelf, the temperature of the water at the seabed (often the warmest location in the water column) shows a decadal warming trend in the Bellingshausen Sea and freshening in the Ross Sea (Jacobs et al., 2002; Jacobs and Giulivi, 2010; Schmidtko et al., 2014). For much of Antarctica, however, there are insufficient data to inspire confidence in any decadal trends or variability.

Even if the ocean temperature were to remain generally the same, a greater volume of warm water could be transported onto the continental shelf, a greater proportion could reach the ice shelf front (perhaps by reduced diapycnal mixing occurring on the shelf, or perhaps by a more direct route), and/or a greater flux of water could enter the ice shelf cavity (Jacobs et al., 2011). The variability in the volume flux and/or heat flux crossing the continental slope is difficult to estimate from existing observations (Walker et al., 2007; Assmann et al., 2013), but the thickness of the CDW layer at the shelf break has been used as a proxy (Thoma et al., 2008; Dutrieux et al., 2014). Such studies suggest the importance of the large-scale wind forcing in determining the cross-slope flow, with particular emphasis on the zonal (east-west) winds at and north of the shelf break (Walker et al., 2007, 2013; Thoma et al., 2008; Assmann et al., 2013; Spence et al., 2014). St-Laurent et al. (2015) put forward another alternative: that variability in the heat content on the continental shelf is primarily driven not by the amount of CDW that crosses the Antarctic Slope Front but by the air-sea interaction processes occurring in polynyas (open water regions surrounded by sea ice) on the continental shelf.

Ocean-atmosphere interactions are complex in the Amundsen Sea; it has been hypothesized that both zonal wind anomalies at the shelf break (Thoma et al., 2008) and large wintertime heat fluxes in coastal polynyas (St-Laurent et al., 2015) can alter glacial melt rates. Zonal winds at the shelf break are influenced both by the annual longitudinal cycle of the Amundsen Sea Low from the Ross Sea in winter toward the Amundsen Sea in summer (Hosking et al., 2013) and by larger-scale climate variability associated with the El Niño-Southern Oscillation and the Southern Annular Mode (Fogt et al., 2012; Steig et al., 2012; Turner et al., 2013). The Amundsen Sea exhibits the greatest interannual variability in mean sea level pressure field in the Southern Hemisphere (Connolley, 1997). Atmospheric forcing is important for determining ocean conditions and dynamics, for sea ice formation and melt processes, and for surface processes on the Antarctic continent that determine ice mass balance. Despite this, in situ meteorological observations in the Amundsen Sea embayment remain very sparse. Reanalysis products are therefore the only source of gridded, homogeneous meteorological records; Jones et al. (2016) show that while all such products contain biases, ERA-Interim is the most accurate in the Amundsen Sea when compared with the sparse in situ observations available.

iSTAR FRAMEWORK

The UK's Ice Sheet Stability Program (iSTAR, http://www.istar.ac.uk) contributes to international efforts to better understand the causes and variability of melting of the Amundsen Sea ice shelves. Improved understanding of melting processes is a prerequisite for their incorporation into coupled climate models, a key step if we are to improve our ability to predict sea level rise. The iSTAR program aims to investigate the stability of the West Antarctic Ice Sheet, with particular focus on the Amundsen Sea and the Pine Island Glacier, ice stream, and ice shelf system. Four multi-institutional projects are funded through the program. Two undertook glaciological fieldwork based on the ice stream using an innovative tractor train, iSTAR C (*Dynamic Ice*) and iSTAR D (*Ice Loss*). Two undertook oceanographic fieldwork based on a voyage of the UK's RRS *James Clark Ross* in 2014 (Figure 1). Here, we describe some early new results from the two oceanographic elements of the program, iSTAR A (*Ocean2ice*, led by the University of East Anglia) and iSTAR B (*Ocean Under Ice*, led by the British Antarctic Survey) and provide some perspectives for future research. *Ocean2ice* seeks to understand processes and variability of ocean heat transport toward the ice shelves in the Amundsen Sea embayment, while *Ocean Under Ice* seeks to understand the circulation and

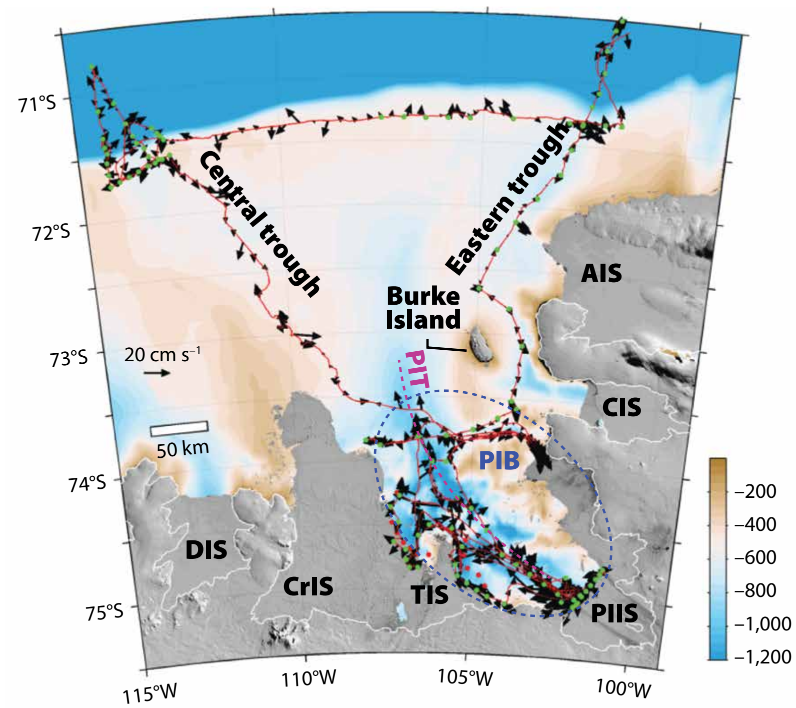

FIGURE 1. Map of the eastern Amundsen Sea showing the track of RRS *James Clark Ross* in February/March 2014 (red line), 105 Ice Sheet Stability Program (iSTAR) CTD stations (green dots), and shipboard acoustic Doppler current profiler currents (black arrows, average current over the upper 40 m). Bathymetry is shown in color shading. Ice information (gray shading) was provided by a MODIS Terra satellite image dated January 27, 2014. The blue dashed oval denotes Pine Island Bay (PIB), and the red dashed curve denotes the axis of Pine Island Trough (PIT). Ice shelves identified are Pine Island (PIIS), Cosgrove (CIS), Abbot (AIS), Thwaites (TIS), Crosson (CrIS), and Dotson (DIS).

melting beneath these ice shelves.

The iSTAR research cruise took place in February/March 2014 (Figure 1). Over 100 CTD stations were occupied together with current velocity from a lowered acoustic Doppler current profiler (LADCP). Tracer measurements and profiles of turbulent microstructure were also acquired. Low sea ice cover on the continental shelf (Figure 2) provided the opportunity to collect hydrographic sections in the eastern Amundsen Sea's bathymetric troughs, which provide channels for relatively warm water to reach the vulnerable Pine Island and Thwaites Ice Shelves. We were able to repeat a quasi-meridional section across the shelf to the east of Burke Island that had been occupied only once before (Jacobs et al., 1996). Our hope to reoccupy the zonal section collected by R/V *Polarstern* in 2010 (Nakayama et al., 2013) was thwarted by extensive sea ice over the northern Amundsen Sea shelf, but we were fortunate that low sea ice cover allowed sections to be undertaken across the front of Pine Island Glacier ice front (adding to a time series of such sections taken every few years) and around the front of the pack ice surrounding Thwaites Ice Shelf. The exciting data set will allow investigation of processes of interaction between ocean, ice, and atmosphere, for example, providing the first ever comprehensive surveys of turbulent mixing and of noble gases, as well as advancing our understanding of the temporal and spatial variability of water masses in the region. Although it was mid-summer, conditions in the Amundsen Sea were challenging. During the research cruise, the air temperature was frequently below −10°C, and there were several extended periods of strong off-ice wind when work was being carried out in Pine Island Bay. Average temperatures close to Pine Island Ice Shelf were 2°C below the 1981–2010 February mean, and the northward component of the wind was more than 1 m s^{-1} stronger than usual (Figure 2). In late February, a sustained period of northward winds combined with low temperatures caused formation of frazil and pancake ice and northward transport of small icebergs toward the continental shelf break.

SEALS AS OCEANOGRAPHIC RECRUITS PROVIDE NEW PERSPECTIVES

The continental shelf of the Amundsen Sea is one of the most remote locations on Earth. It takes a ship about a week to reach the region from any of the nearest ports, and it is even beyond the reach of most marine satellite communication systems. Nonetheless, there have been several forays to the region since the first oceanographic surveys in the 1990s (Jacobs et al., 1996). These expeditions include, for example, the research led by South Korean and Swedish scientists onboard the icebreaker *Araon*, described in a recent collection of papers in *Deep Sea Research II*, and the US ASPIRE program onboard RVIB *Nathaniel B. Palmer* (Yager et al., 2012). The distribution of all accessible historical CTD profiles on the continental shelf between 135°W and 100°W from 1994 until 2014 (1,025 profiles; Figure 3) reveals clusters of observations around the Getz, Dotson, Thwaites, and Pine Island Ice Shelves, and more sparse coverage elsewhere. Note that this region is completely inaccessible to vessels during the winter (April to October) because of extensive sea ice.

To obtain temperature and salinity profiles in winter, we enlisted the help of seven southern elephant seals (*Mirounga leonine*) and seven Weddell seals (*Leptonychotes weddellii*) as part of a multidisciplinary study to characterize the seals' environment. CTD-Satellite Relay Data Loggers (tags; Boehme et al., 2009) that were glued onto the seals' fur in February transmitted CTD profiles until October/November. The tags were discarded during the seals' next molt. In just those few months, the seals provided an order of magnitude more hydrographic profiles than the entire historical data set (Figure 3): 10,838 profiles with either temperature or salinity, or both, passed quality control, including 8,852 that passed quality control with both temperature and salinity. Furthermore, the seal tags provided data during the period when sea ice covered much of the region, between April and September. The seals obtained an unprecedented snapshot of the ocean properties in one year, with data spread across much of the Amundsen Sea continental shelf. The tagged seals provided relatively few profiles from the shelf break

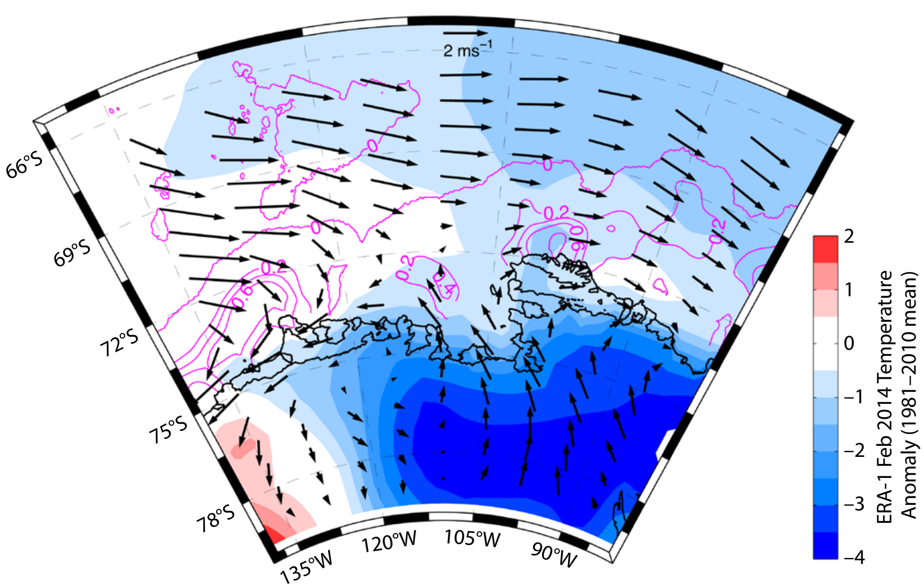

FIGURE 2. Near-surface atmospheric temperature anomaly (shading), 10 m wind vector anomalies, and sea ice concentration (magenta contours) for February 2014, based on ERA-Interim reanalyses and the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA, 1/20th degree). The anomalies are from the 1981–2010 February mean.

and the deepest part of the Pine Island Trough. Like the ships, the seal profiles tend to cluster around the edges of the Getz, Dotson, Thwaites, and Pine Island Ice Shelves, presumably because there are sources of food there in the coastal polynyas adjacent to the ice edge, possibly sustained by micronutrients delivered by the glacier as explored during the ASPIRE program (Yager et al., 2012).

CIRCUMPOLAR DEEP WATER: THE ULTIMATE SOURCE OF HEAT

Temperature and salinity at 300 m from the seal tags and the historical CTD database (Figure 3) reveal water mass circulation; the core water masses are most easily identified in the iSTAR ship-based hydrographic section from the shelf edge to the Pine Island Ice Shelf (Figure 4). This section retraces the CTD stations occupied in 1994 during the first scientific expedition to this region (Jacobs et al., 1996). Offshore, the CDW is identified by its temperature maximum at a depth of ~500 m. The CDW layer is relatively saline and has low dissolved oxygen concentrations (Figure 4) because it has been out of contact with the atmosphere for a long time. This layer flows onto the continental shelf through a series of shelf-edge depressions that are at depths of 500–600 m. The processes by which the water crosses the continental slope and associated slope current system are not yet fully understood, and their variability only partially documented (Assmann et al., 2013; Wåhlin et al., 2013), but are thought to include wind forcing (Thoma et al., 2008), onshore transport in bottom Ekman layers (Wåhlin et al., 2012), and the topographically steered undercurrent (Walker et al., 2013). Regional high-resolution modeling studies have shed light on these and other mechanisms thought to determine the variability of ice shelf melting, such as surface heat fluxes and polynya location (e.g., Schodlok et al., 2012; Nakayama et al., 2014).

Seasonal processes of sea ice formation and melt, and heat loss to and freshwater gain from the atmosphere, dominate the properties of near-surface water masses. Salinification from brine

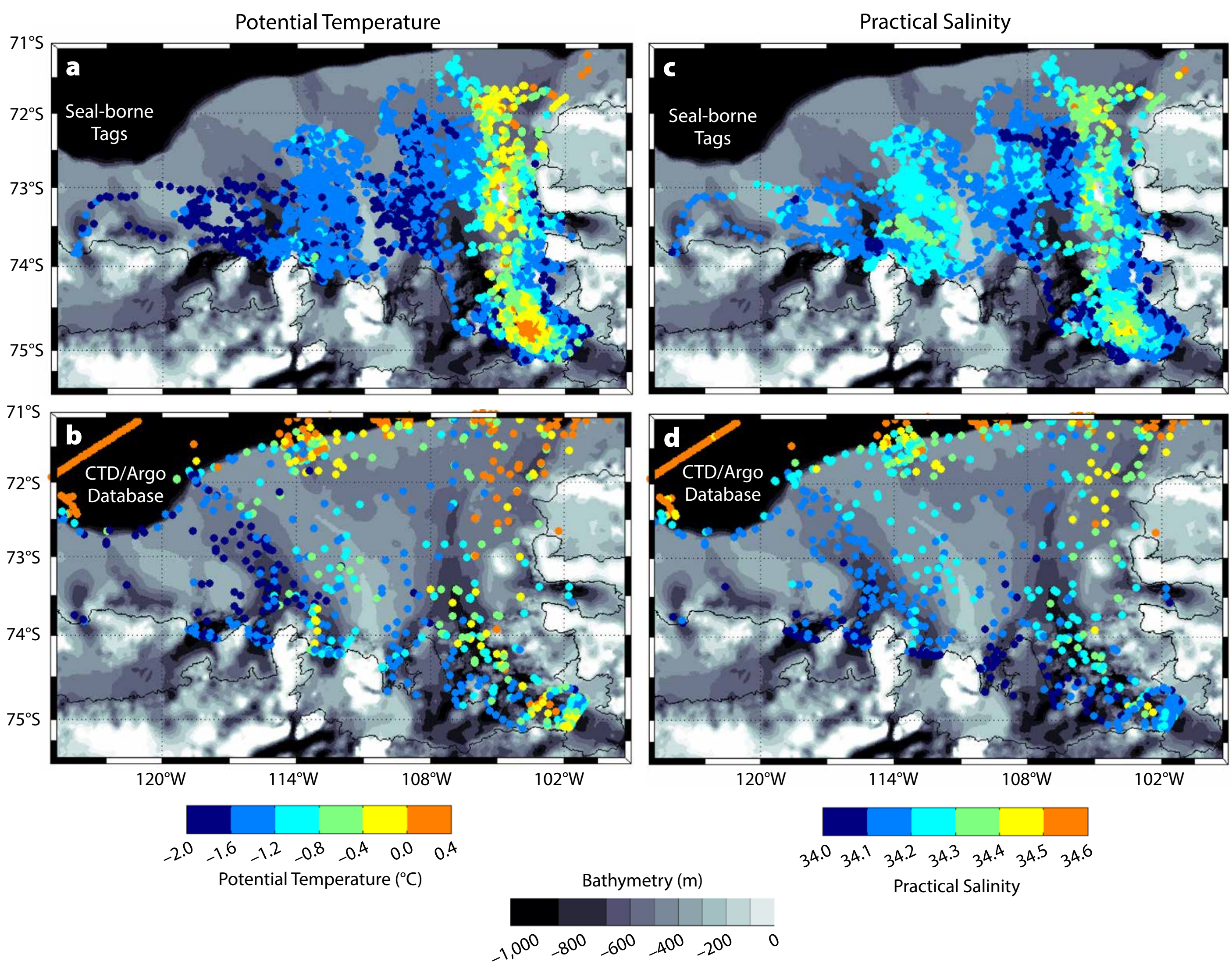

FIGURE 3. Measurements at 300 m of potential temperature (a,b) and practical salinity (c,d) from seal-borne CTD tags (a,c) and from historical CTD and Argo float data between 1994 and 2014 (b,d). Bathymetry from IBCSO (Arndt et al., 2013) is shaded in gray.

rejection during sea ice formation in autumn, and surface cooling, combine to create a winter mixed layer that extends to 100–200 m depth on the Amundsen Sea continental shelf. During summer, this layer becomes stratified, primarily by sea ice melt at the surface, but also by solar radiation. The remnant of the winter mixed layer below is known as Winter Water, and is identified by its temperature minimum (Figure 4). These near-surface layers exhibit high dissolved oxygen concentrations, near the values expected for air saturation under corresponding temperature, salinity, and atmospheric pressure conditions.

The depth and pathway of the CDW is constrained by bathymetry, by the depth of the overlying layers, and by the strength of the meridional geostrophic flow, which has an associated zonal tilt of the isotherms and isopycnals. The quasi-meridional section from the continental shelf edge to the ice shelf included stations to the east of Burke Island (about 200 km from the ice shelf; Figure 4). The CDW core is noticeably higher to the north and east of the island, and lower to the south. This may indicate strong mixing at the sill south of Burke Island, or it may indicate a convergence of pathways after passing both sides of the island. The map of seal tag temperature at 300 m depth (Figure 3) reveals warm water passing on both sides of the island, but this may be temporally variable.

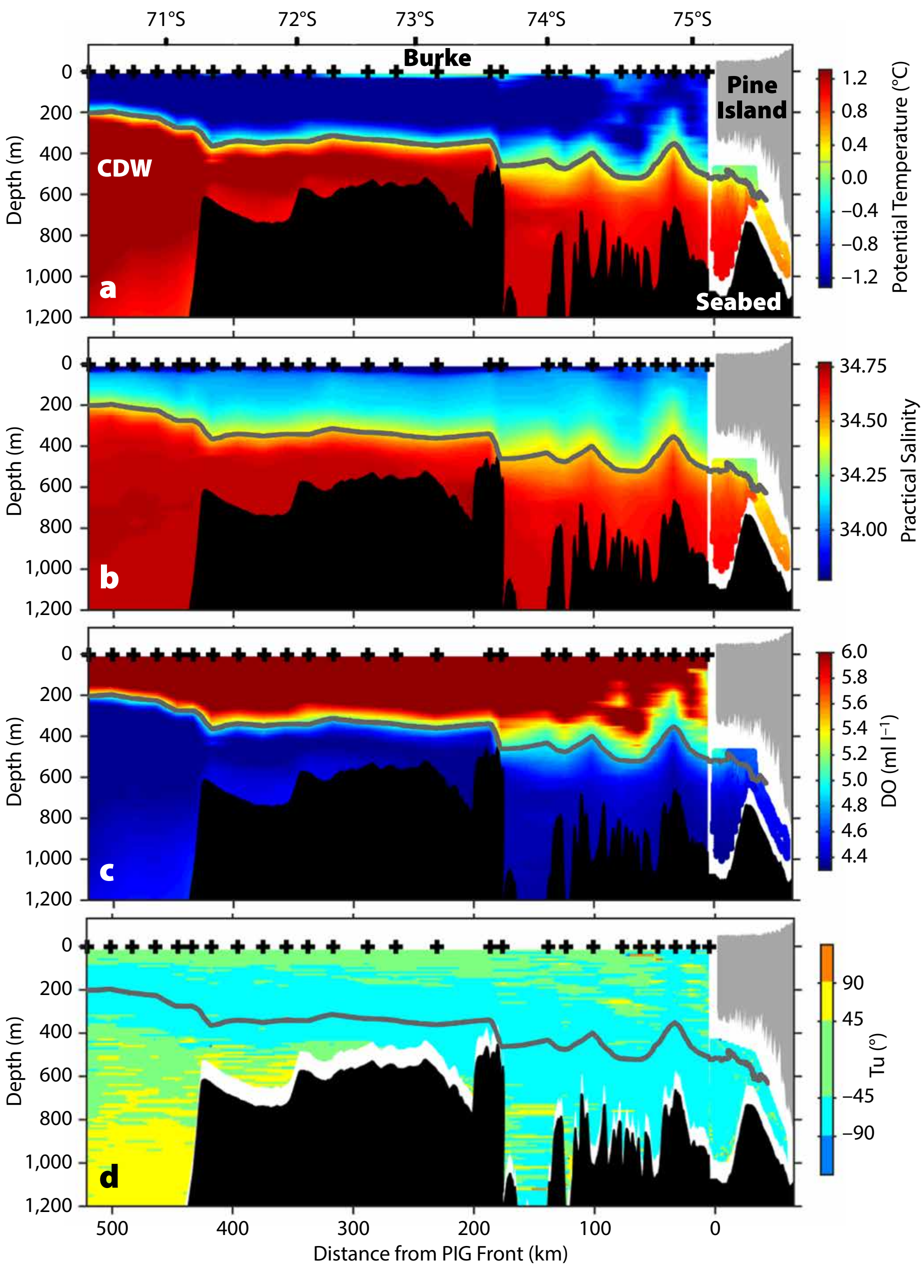

FIGURE 4. Quasi-meridional hydrographic section from the iSTAR 2014 ship-based survey extending from the open ocean to Pine Island Glacier. (a) Potential temperature referenced to the sea surface. (b) Practical salinity. (c) Dissolved oxygen concentration (ml l^{-1}) (d) Turner angle shaded, with mid-thermocline isopycnal superimposed. Contours are interpolated from 2014 ship-based casts (black crosses) in the open ocean, and from *Autosub3* observations underneath the Pine Island Ice Shelf.

At 300 m, the warmest and most saline waters are found in the eastern channel (Figure 3), leading to the Pine Island and Thwaites Ice Shelves. Relatively warm and saline water is also found in front of the Getz Ice Shelf. Pine Island Bay, in front of the ice shelf, hosts an anticyclonic gyre circulation (Thurnherr et al., 2014), clearly identifiable in the doming of the isotherms and isohalines about 30 km from the ice shelf (Figures 3 and 4). This gyre (certainly present in 2012 and 2014 ship-based surveys, and visible in shipboard ADCP velocities, Figure 1) may be a variable feature, and its role in transporting warm water toward the ice shelf cavity remains to be explored.

Figure 5 shows quasi-meridional temperature and salinity sections from the seal tags during February to April 2014, designed to be as comparable in location to the ship-based section (Figure 4) as possible. On the outer shelf, the water mass properties are very similar, and the mid-thermocline isopycnal exhibits a comparable structure. However, in the region of Pine Island Bay, the doming marking the center of the gyre is located some 30 km further north (compare the black and gray contours in Figure 5a). This intriguing observation suggests some temporal variability of the gyre, probably caused by local wind forcing changes; this will be investigated further in future work using the 10-month span of seal-tag observations in the region.

PROCESSES ON THE CONTINENTAL SHELF

The pathways of water masses across the 400 km wide continental shelf from shelf break to ice front (Figures 1 and 3) are complex and not well known. Nakayama et al. (2013) document the likely merging of the inflows from the two easternmost bathymetric troughs (referred to as the eastern and central troughs). Mixing of the CDW with overlying waters likely influences the heat available for melting that reaches the ice shelf front. Much of the meltwater from the ice shelf cavity is neutrally buoyant at mid-depths, so it lies in the thermocline below the Winter Water (Nakayama et al., 2013; Dutrieux et al., 2014). It is not known how the volume flux or properties of meltwater feed back into the CDW volume flux and properties through mixing. Such mixing is not yet quantified, but we expect greater mixing in regions of rough bathymetry, caused by breaking internal waves and near-boundary turbulence.

In polar regions, diffusion can also play a significant role in diapycnal mixing. The Turner angle (Ruddick, 1983) indicates the stability of the water column and whether temperature or salinity is providing that stability (You, 2002). Turner angles between −45° and −90° (turquoise in Figures 4d and 6d) represent the "diffusive" regime of double-diffusive convection (corresponding to colder fresher water overlying denser but warmer salty water). Much of the thermocline between the Winter Water and the CDW is classified as being susceptible to diffusive mixing. The warm CDW is overlain by colder, fresher Winter Water, so both temperature and salinity increase with depth, resulting in diffusive mixing; however, the temperature gradient in these regions drives the mixing. We do not see strong evidence of a staircase structure in temperature and salinity profiles, which may suggest that the circulation is too strong for such a diffusive regime to be detectable. Turner angles between 45° and 90° (yellow in Figures 4d and 6d) represent the "salt-finger" regime of double-diffusive mixing (corresponding to warmer salty water overlying denser but colder and fresher water). This occurs on the lower boundary of the core of CDW, both as it approaches the continental slope, and on the continental shelf near the seabed, where temperature decreases with depth below the CDW core. The upper few hundred meters, and many regions near the seabed beneath the thermocline, are typically characterized by Turner angles between −45° and 45° (green in Figures 4d and 6d), where stable stratification is provided by both temperature and salinity gradients.

DELIVERING WARM CDW TO THE ICE SHELVES

The iSTAR campaign included deployments of the autonomous underwater vehicle *Autosub3* beneath the Pine Island Ice Shelf to extend the ship-based section into the cavity (Figure 4), comparable with the sections published by Jenkins et al. (2010). The year 2014 was fairly typical compared with historical measurements in terms of the heat content of the Pine Island Trough region (105°W–110°W, 72°S–75°S). While a little cooler than 1994, it was not as warm as observations from the late 2000s. The thermocline was lower in 2014 than in 2009 when more relatively warm water was able to access the ice shelf cavity (Jacobs et al., 2011; Dutrieux et al., 2014). The transport of CDW toward Pine Island and Thwaites Ice Shelves is estimated using the iSTAR ship-based quasi-zonal CTD sections at the shelf edge in the central and eastern troughs (see Figure 1 for locations), as well as the iSTAR ship-based quasi-zonal CTD section across Pine Island Trough south of Burke Island at approximately 73.8°S (Figure 6; see Figure 1 for location). The de-tided shipboard ADCP currents (Figure 1) were used to reference the geostrophic shear using the portion of the water column where the shear calculated from the iSTAR CTD sections matched the directly observed shear. We derive CDW flux by integrating the volume transport from the seabed to a neutral density of 28 kg m^{-3} assumed to denote the upper boundary of CDW (following Walker et al., 2007). Heat fluxes through these sections are calculated using the temperature of the water

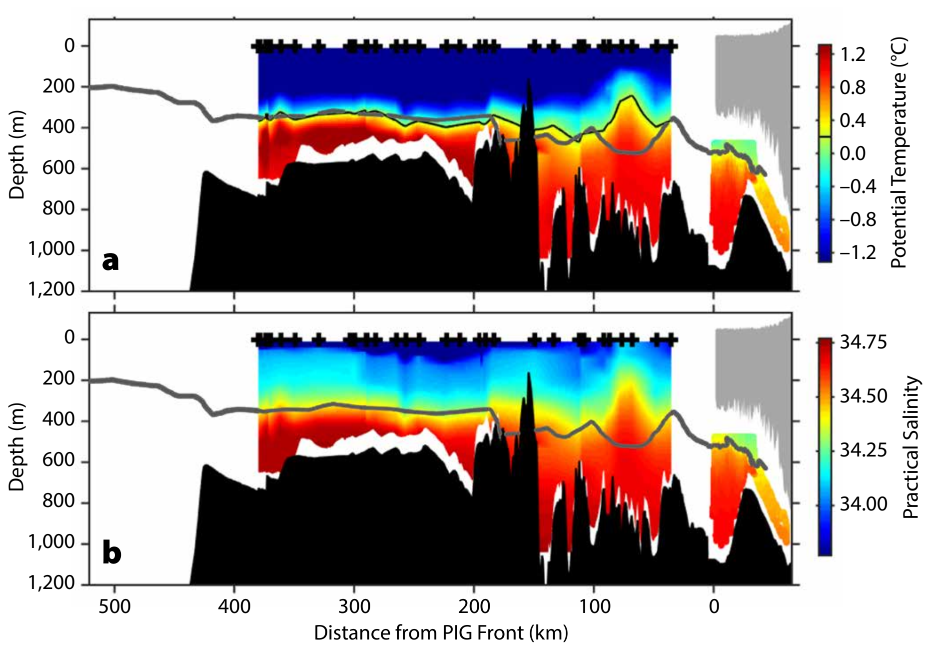

FIGURE 5. As Figure 4, but derived from seal-tag temperature and salinity profiles during February to April 2014. The data beneath Pine Island Glacier are the same as in Figure 4. The gray contour is the mid-thermocline isopycnal from the ship-based data as shown in Figure 4, to enable comparison.

above the in situ freezing point, following the definition of, for example, Walker et al. (2007). This quantity represents the total heat flux available to melt the ice shelves and is therefore useful around the Antarctic margins, but we do not account for the full heat budget of the Amundsen Sea or Pine Island sector, only the portion that flows in through certain sections; we do not have land-to-land sections with no net volume flux across them.

We calculate that a net volume flux of CDW of 270 mSv (1 Sverdrup, Sv = 10^6 m^3 s^{-1}) crossed the shelf break at the central trough in February 2014, but some of this may recirculate locally. This is very similar to that measured by Walker et al. (2007), who calculated 234 mSv from a similar CTD section. Our derived quasi-heat flux from the CDW flowing through this section is 3.3 TW, compared with 2.8 TW in 2003 derived in the same way (Walker et al., 2007). The volume flux and heat flux are greater in 2014 by a similar proportion. A net volume flux of CDW of 85 mSv crosses the shelf break at the eastern trough, through which the warmest waters enter (Figure 3). Our section suggests that less CDW penetrates onto the shelf here than at the central trough; however, the two sections are not directly comparable because they are of different zonal extent. The central trough section mostly spans southward, onshore flow, whereas the eastern trough spans a narrow onshore flow in the east together with a broader region of offshore flow in the west. These two flows from the eastern and central troughs likely merge, and the combined inflow at the shelf break from the central and eastern troughs is 351 mSv. The CDW volume flux across the zonal section south of Burke Island (Figure 6) is 250 mSv, where sloping isopycnals reveal the southward geostrophic flow of the deep waters. Therefore, 100 mSv of the CDW flux at the shelf break does not reach the section south of Burke Island. Some mixing as the CDW travels across the continental shelf will necessarily lead to reduction in the volume of the densest waters. It is likely that some of this CDW enters the cavities under Abbott and Cosgrove Ice Shelves in the eastern Amundsen Sea and becomes less dense through mixing with meltwater. In addition, some CDW may recirculate on the outer shelf, or flow under Abbott Ice Shelf and into the Bellingshausen Sea, although little is known about the flow under this ice shelf.

Comparison of the ship-based zonal hydrographic section (Figure 6a,b) with that derived from the seal tag data for February to April (Figure 7) indicates a similar slope of the isotherms and isohalines. However, the CDW is both warmer and saltier in the seal tag data, suggesting variability in the properties of the CDW approaching the Amundsen Sea ice shelves. Understanding the driving mechanisms behind such variability is a key part of the *Ocean2ice* project.

Circulation and meltwater transport across the Pine Island ice front can be estimated from CTD and LADCP data

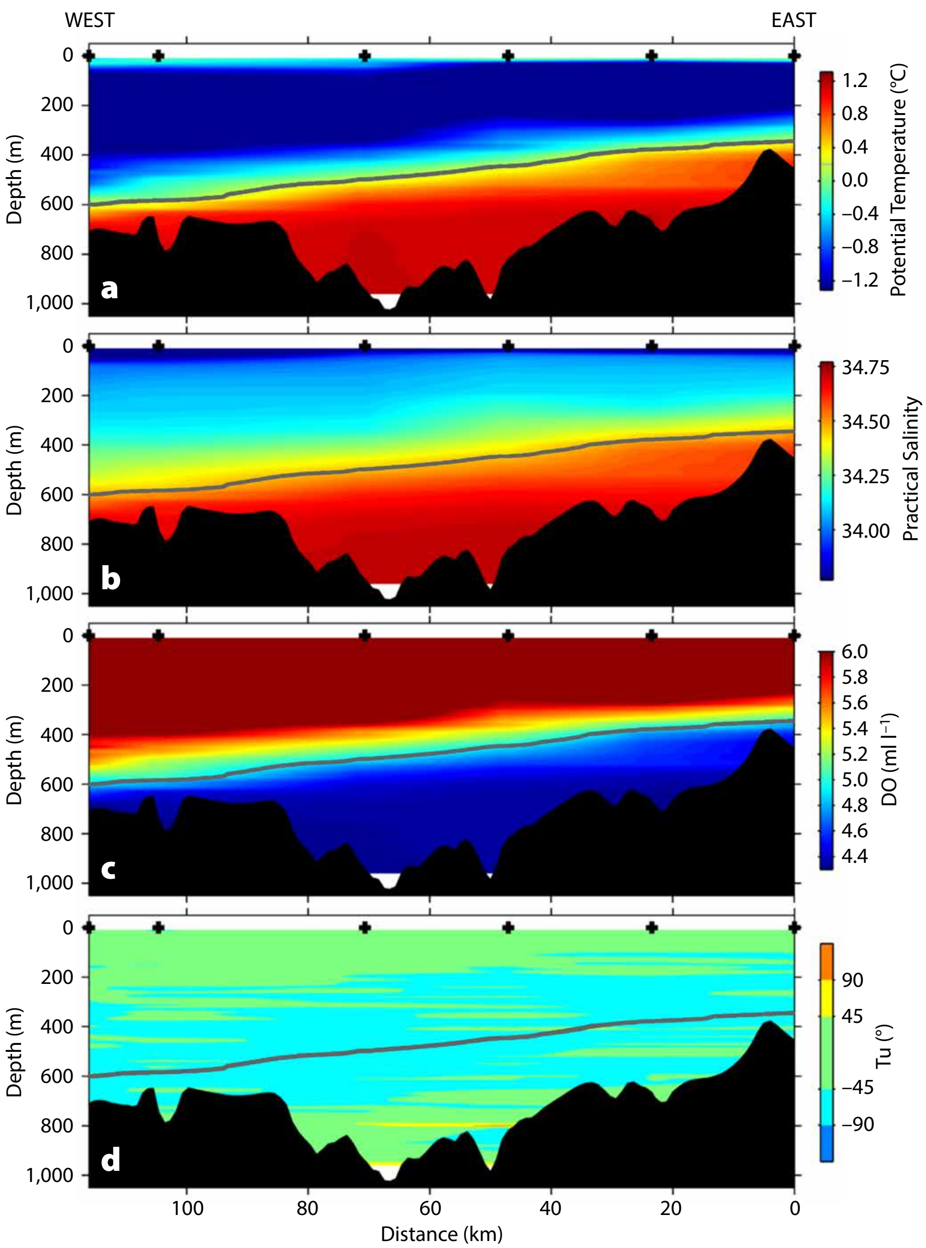

FIGURE 6. Zonal cross section from the iSTAR ship-based survey in 2014 across the Pine Island Trough just south of Burke Island. (a) Potential temperature referenced to the sea surface. (b) Practical salinity. (c) Dissolved oxygen concentration (ml l^{-1}). (d) Turner angle shaded, with mid-thermocline isopycnal superimposed.

using the methods described by Jenkins and Jacobs (2008) and Jacobs et al. (2011). The meltwater export of 40 ± 16 km^3 yr^{-1} is comparable with that estimated from 2012 data (Dutrieux et al., 2014), showing that melt rates considerably lower than those found in the last part of the first decade of this century have been sustained throughout the recent cool period in Pine Island Bay. Cross-ice-front circulation of 0.48 ± 0.09 Sv is comparable with all recent estimates (Dutrieux et al., 2014). Circulation of the warmest waters below 800 m contributes about one-fifth of the total circulation, but the net inflow below that level is indistinguishable from zero. This observation is consistent with the waters below the level of the ridge crest mapped by Jenkins et al. (2010) being confined to the outer cavity seaward of the ridge and not interacting with the ice.

PERSPECTIVES

Processes on the continental shelf and slope all around Antarctica are crucially important for determining future sea level rise, for setting the properties and volume of exported dense bottom water, and for regulating the carbon cycle. Yet our ability to model and predict these processes over future decades is still rudimentary. Many of the state-of-the-art coupled climate models used for the 2013 IPCC report show biases in the temperature of water on the Antarctic continental shelf greater than 1°C (Heuzé et al., 2013), which would lead to significant errors in any predicted melt rate of an ice shelf encountering these water masses in the model. The horizontal resolution of climate models is often too coarse to resolve the coastal polynyas critical to setting water mass characteristics through air-sea interaction. St-Laurent et al. (2013) and Stewart and Thompson (2015) both find that a resolution of about 1 km is required to accurately resolve eddies over the continental shelf, and the polynya processes are likely to require a similar scale. Jones et al. (2016) demonstrate that even the meteorology of the continental shelf in the highly sensitive Amundsen Sea embayment is sparsely observed and poorly simulated, with small-scale features such as katabatic winds not well represented. This is the case in many other key regions around the continent, especially where there are no national Antarctic bases to maintain meteorological stations.

Processes at the Antarctic continental slope are particularly challenging to observe. Moorings are difficult to place precisely on a steep slope. The Rossby radius, which determines the mesoscale eddy scale, is only about 1–2 km on the Antarctic continental shelves, and submesoscale processes occur on an even smaller scale. Thus, the Antarctic slope current is narrow and the undercurrent even more so; understanding their driving forces requires extremely closely spaced moorings or hydrographic profiles. Both currents vary in space and on time scales of hours (due to internal waves and tides) to years (due to forcing variability). Therefore, we need to exploit the opportunities provided by new technologies to make the necessary high-resolution ocean observations at the Antarctic shelf break and slope. Ocean gliders, for example, can occupy repeat sections across the slope at sufficiently high resolution to quantify the eddy processes shown to be key in transporting heat toward the continent (Thompson et al., 2014).

Measurements collected during winter are essential for understanding what determines ocean heat content near ice shelves, as well as exchanges of heat, freshwater, and trace gases between the ocean, the ice, and the atmosphere. In the Amundsen Sea, a strategically placed array of moorings, such as that being nurtured by a collaboration of South Korean, Swedish, UK, and US scientists, will begin to provide the information against which numerical models can be tested and improved; such collaborations are being encouraged by the international initiative to design a multidisciplinary and cost-effective Southern Ocean Observing System (SOOS; http://www.soos.aq). The Amundsen Sea shelf and slope are frequently infested with sea ice; while this poses a challenge to ship-based scientists, marine mammals are able to shoulder the burden of monitoring ocean properties during winter. Moorings must be

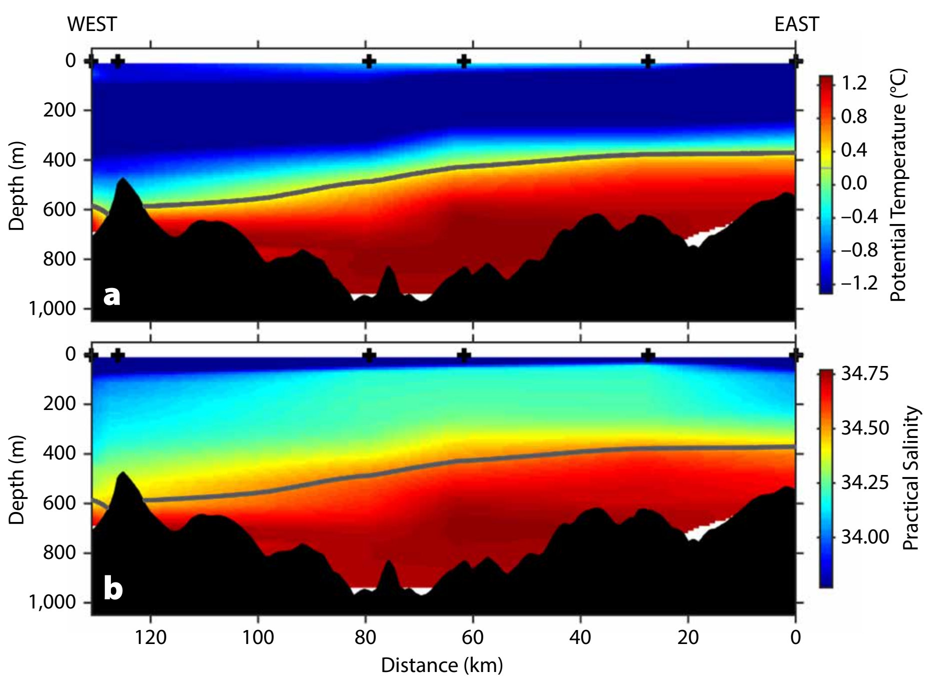

FIGURE 7. As Figure 6, but derived from seal-tag temperature and salinity profiles during February to April 2014. The gray contour is the mid-thermocline isopycnal from the ship-based data as shown in Figure 6, to enable comparison.

designed to withstand icebergs so are unable to carry instruments in the upper few hundred meters; the seals can fill that crucial gap to help us to understand the seasonal cycle in upper ocean stratification and mixing. Already, data sets provided by tagged seals are revealing the circulation of water masses on the Antarctic shelf between continental slopes and ice shelves (Zhang et al., 2016).

Because of their impact on ecology as well as their role in air-sea exchange, polynyas on the continental shelf are likely to be a particular focus of future modeling and observational efforts. We know very little about the processes in such polynyas during early spring, late autumn, or winter. Simultaneous observations of both ocean and atmosphere are needed. These polynyas have been shown in model studies to be important in setting the heat content of waters approaching and entering ice shelf cavities (Nakayama et al., 2014; St-Laurent et al., 2015). Monitoring heat fluxes at ice shelf fronts is perhaps an even greater challenge, and was one of the topics addressed at an international workshop (Keck Institute for Space Studies, 2015). While the logistics and environmental constraints mean that it is a great achievement to occupy even single hydrographic sections along the fronts of ice shelves such as Dotson, Pine Island, or Thwaites during a summer season, we know that this is insufficient. We need to design an observing system that can monitor heat flux into these ice shelf cavities on time scales of days, weeks, months, and years.

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