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Precursors of Antarctic Bottom Water formed on the continental shelf off Larsen Ice Shelf

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ABSTRACT

The dense water flowing out from the Weddell Sea significantly contributes to Antarctic Bottom Water (AABW) and plays an important role in the Meridional Overturning Circulation. The relative importance of the two major source regions, the continental shelves in front of Filchner-Ronne Ice Shelf and Larsen Ice Shelf, however, remains unclear. Several studies focused on the contribution of the Filchner-Ronne Ice Shelf region for the deep and bottom water production within the Weddell Gyre, but the role of the Larsen Ice Shelf region for this process, especially the formation of deep water, remains speculative. Measurements made during the Polarstern cruise ANT XXIX-3 (2013) add evidence to the importance of the source in the western Weddell Sea. Using Optimum Multiparameter analysis we show that the dense water found on the continental shelf in front of the former Larsen A and B together with a very dense water originating from Larsen C increases the thickness and changes the θ/S characteristics of the layer that leaves the Weddell Sea to contribute to AABW.

1. Introduction

The Southern Ocean is the source of the Antarctic Bottom Water (AABW). This water mass fills most of the global ocean abyss and thus plays a crucial role in the Meridional Overturning Circulation. As a key feature for the global circulation, changes in the production rates or in the main characteristics of the AABW may impact the circulation in all oceans (e.g., Lumpkin and Speer, 2007).

The most important fraction of AABW comes from the Weddell Sea Deep Water (WSDW) (e.g., Orsi et al., 1999). This water mass is formed by the mixing of Warm Deep Water (WDW) with Weddell Sea Bottom Water (WSBW) or with dense shelf waters. The continental shelf in front of Filchner-Ronne Ice Shelf (FRIS) is described as the main region where WSDW and WSBW are formed (Foldvik and Gammelsrød, 1988; Foldvik et al., 2004; Nicholls et al., 2009).

Nevertheless, there is multiple evidence that the Larsen Ice Shelf (LIS) area also contributes, at least intermittently, to WSDW (Gordon et al., 1993, 2001; Fahrbach et al., 1995; Gordon, 1998; Schröder et al., 2002; Nicholls et al., 2004; Absy et al., 2008; Huhn et al., 2008; Jullion et al., 2013). Understanding how the WSDW from different sources contributes to AABW is an important step to comprehend the changes that occur in the deep ocean (e.g., Azaneu et al., 2013; Purkey and Johnson, 2013).

Dense waters formed on the LIS continental shelf are found at shallower levels of the open ocean water column than those originated from FRIS, 1000 km further upstream (Fig. 1 in Gordon et al., 2001). Because of bathymetric constraints, this water can leave the Weddell Sea easier. The passages connecting the Weddell Sea and the Scotia Sea are less than 3500 m deep and restrict the flow into the Scotia Sea (Naveira Garabato et al., 2002; Franco et al., 2007). A high variability was observed in waters able to cross the South Scotia Ridge to produce AABW (Schröder et al., 2002), the authors suggest that the changes were caused not only by temporal fluctuations but also by the intermittent contribution of dense water masses from the Larsen region.

Fahrbach et al. (1995) compared a section in front of Larsen C and one close to the tip of the Antarctic Peninsula (AP) and observed a freshening and warming of the deep and bottom water found on the slope of the northern section. They argued that these changes were caused by a mixture of LIS shelf waters with WDW. Gordon et al. (2001) observed a fresher and more ventilated type of WSDW (VWSDW) and WSBW (VWSBW) south of the South Orkney Plateau both formed by the interaction between shelf water from the Antarctic Peninsula and WSDW. The authors suggest that the VWSBW is produced at a site more to the south with a stronger component of WSDW than the VWSDW.

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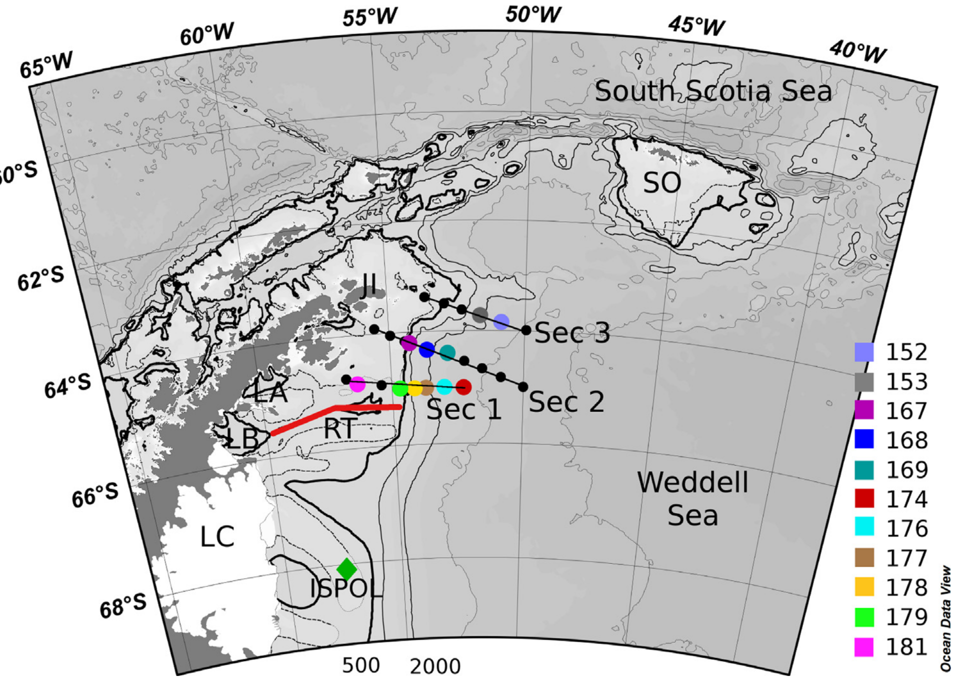

Fig. 1. Regional map of the northwestern Weddell Sea. ANT XXIX/3 stations are marked with circles, stations mentioned in the text are colored (see label on the lower right corner of the figure). Sections 1–3 are labeled (Sec #). The auxiliary profile obtained from the ISPOL cruise is marked as a green diamond and labeled. The location of Robertson Trough is shown by the red line. Gray shades represent the bathymetry from Rtopo 1 (Timmermann et al., 2010), the isobaths of 400 m (dashed line), 500 m (thick line), 1000 and 2000 m (thin lines), and 3000 m, 4000 m, 5000 m (very thin lines) are drawn. Abbreviations are Joinville Island (JI), Larsen A, B and C (LA, LB and LC, respectively), Robertson Trough (RT), and South Orkney Island (SO). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Measurements made in March 2002 on the shelf just north of Larsen C revealed the presence of water colder than the surface freezing point, originating from the interaction with the ice shelf (Nicholls et al., 2004). Hydrographic data from 2004 to 2005 collected during the Ice Station Polarstern (ISPOL) drift experiment (Hellmer et al., 2008) also showed evidence for dense water production in this region and revealed the presence of lenses of relatively salty and cold waters on the continental slope at a depth of 1600 m (Absy et al., 2008). Optimum Multiparameter (OMP) analysis using temperature, salinity, and noble gas observations together with chlorofluorocarbons (CFCs) as age tracers supported the hypothesis of a nearby source (Huhn et al., 2008).

In this paper we present conclusive evidence for the production of a precursor water type of AABW in the LIS region. Besides, we reinforce the idea that this contribution can be related to two (or more) sources within this area. To do this, we analyzed oceanographic data obtained during summer 2013 on Polarstern Cruise ANT XXIX/3 (Gutt et al., 2013); Polarstern Cruise reports can be found at http://www.pangaea.de/PHP/CruiseReports.php?b=Polarstern.

2. Hydrographic data

The goal of the Polarstern cruise ANT XXIX/3 (January to March 2013) was to perform a multidisciplinary investigation in the area of the former Larsen A and B Ice Shelves together with a krill census. In addition, an extensive hydrographic and bathymetric investigation was planned for the shelf and slope in front of the Larsen C Ice Shelf (Knust, 2012) (http://epic.awi.de/31329/7/ANT-XXIX_1-3.pdf). Unfortunately, the initial plans had to be changed due to the severe sea-ice conditions (Gutt et al., 2013).

The main oceanographic goal was the investigation of dense water production in the LIS area. Therefore, three hydrographic sections were performed in the northwestern Weddell Sea (Fig. 1) almost perpendicular to the continental slope to a depth of 3000 m. Although other casts were performed during the cruise, this work mainly discusses these three sections.

The data analysis is focused on the dense waters, defined here as all waters with a neutral density (γ^n) greater than 28.27 kg m^{-3}. This value was chosen because it was used in other works to define the interface between WDW and WSDW (e.g., Fahrbach et al., 2011), and also the upper limit of AABW originating from the Weddell Sea (Orsi et al., 1999). The γ^n of 28.4 kg m^{-3} was used to separate WSDW from WSBW. Nevertheless, the names WSDW and WSBW are misleading when used for waters found in shallow areas, like the continental shelf. To avoid the depth association we used the terms Neutral Deep Water (DWγ^n) to refer to waters in the γ^n-range from 28.27 to 28.4 kg m^{-3}, and Neutral Bottom Water (BWγ^n) for γ^n higher than 28.4 kg m^{-3}. The new terms are especially useful to discuss the mixing processes occurring at the shelf break and on the slope. The abbreviations used for all water masses are summarized in Table 1.

2.1. Data quality

The hydrographic measurements during ANT XXIX/3 were made using a SBE 911+ CTD connected to a carrousel with 24 bottles of 12 L. The sensors attached to the system were two conductivity and temperature sensors, a pressure sensor, one oxygen sensor, a transmissometer, a fluorometer, and an altimeter. More details about the sensors are found in Gutt et al. (2013).

The conductivity and temperature sensor calibrations were performed before and after the cruise at Seabird Electronics. The accuracy of the temperature sensors is 2 mK. The readings of the pressure sensor have precision and accuracy better than 1 dbar. The conductivity was corrected using salinity measurements from water samples. IAPSO Standard Seawater from the P-series P154 (K15 = 0.99990, practical salinity 34.996) was used. A total of 98 water samples were measured using an Optimare Precision Salinometer OPS 006. On the basis of the water sample correction