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On the warm inflow at the eastern boundary of the Weddell Gyre

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ABSTRACT

The Weddell Sea plays an important role for the global oceans and climate by being one of the biggest production and export areas of Antarctic Bottom Water (AABW). Circumpolar Deep Water (CDW) enters the Weddell Gyre (WG) at its eastern boundary. Then called Warm Deep Water (WDW), it is a major contributor to the formation of deep and bottom waters due to ocean-ice shelf interactions in the southern and southwestern Weddell Sea. Hydrographic data collected between 0 and 30°E on the *RV Polarstern* cruise ANT XX/2 reveals a two-core structure for the eastern inflow of warm water at roughly 20°E but not further downstream at the Greenwich meridian (GM). Model results and climatological fields suggest that the two cores represent two separate modes of warm inflow. One mode is driven by eddy mixing in the northeastern corner of the WG and the other one is an advective mode, forming the southern branch of the inflow which extends beyond 30°E before turning westward. Both pathways are likely to carry waters from different origins within the Antarctic Circumpolar Current ACC, where more ventilated CDW is found at the Southern Boundary SB compared to the centre. The southern route shows considerable interannual variability in the model. A variable inflow of two types of CDW together with admixed recirculated and cooler waters from the Weddell Sea can potentially contribute to the observed variability and warming trend of WDW over the last decade at the GM.

1. Introduction

The oceanic meridional overturning circulation plays an important role in the global climate system by transporting heat, salt, and other properties around the globe. The Weddell Sea contributes to this circulation by producing and exporting Antarctic Bottom Water (AABW) (Carmack, 1977; Orsi et al., 1999), which is the coldest and most voluminous water mass in the world oceans. Johnson (2008) suggests that the total volume of AABW is about twice as much as that of the North Atlantic Deep Water (NADW). Although many studies in the past have revised the contribution of the Weddell Sea to the total AABW formation, it is still regarded as a major source region by contributing roughly 40%, followed by inputs from the Ross Sea, Adélie Land and Cape Darnely (Meredith, 2013).

A schematic of the circulation in the Weddell Sea and the adjacent Southern Ocean is shown in Fig. 1. The Weddell Gyre (WG) is a mainly wind-driven, cyclonic ocean gyre. The northern border is given by the Antarctic Circumpolar Current (ACC) which flows completely around Antarctica. Within the ACC, several oceanic fronts (light grey lines in Fig. 1) are known and are associated with sharp gradients in the isopycnals which are generally rising towards Antarctica (Deacon, 1937). For a detailed description of oceanic fronts in the Southern Ocean the reader is referred to Orsi et al. (1995). The WG boundaries are predominantly specified by topography, except in the east, where intense water mass exchanges between the gyre and the ACC take place (Schröder and Fahrbach, 1999; Gouretski and Danilov, 1993). Warm and saline water is injected at the eastern boundary (marked in yellow) originating from Circumpolar Deep Water (CDW) (Orsi et al., 1993; Deacon, 1979; Gouretski and Danilov, 1994), which is called Warm Deep Water (WDW) once entering the WG. Along its way in the gyre, WDW is modified by upwelling into and mixing with the surface layer to compensate the heat loss at the surface. This water mass, then called modified Warm Deep Water (mWDW) (red dotted line), makes its way to the southern Weddell Sea crossing

Abbreviations: AABW, Antarctic Bottom Water; ACC, Antarctic Circumpolar Current; ADCP, Acoustic Doppler Current Profiler; BRIOS, Bremerhaven Regional Ice Ocean Simulations; CARS, CSIRO Atlas of Regional Seas; CDW, Circumpolar Deep Water; CFC, Chlorofluorocarbon; GM, Greenwich meridian; HSSW, High Salinity Shelf Water; LCDW, Lower Circumpolar Deep Water; mWDW, modified Warm Deep Water; NADW, North Atlantic Deep Water; NCEP, National Centers for Environmental Prediction; OMP, Optimum Multiparameter; PF, Polar Front; SACCF, Southern ACC Front; SAM, Southern Annular Mode; SB, Southern Boundary; SWT, Source Water Types; UCDW, Upper Circumpolar Deep Water; WDW, Warm Deep Water; WG, Weddell Gyre; WOCE, World Ocean Circulation Experiment; WSBW, Weddell Sea Bottom Water; WSDW, Weddell Sea Deep Water.

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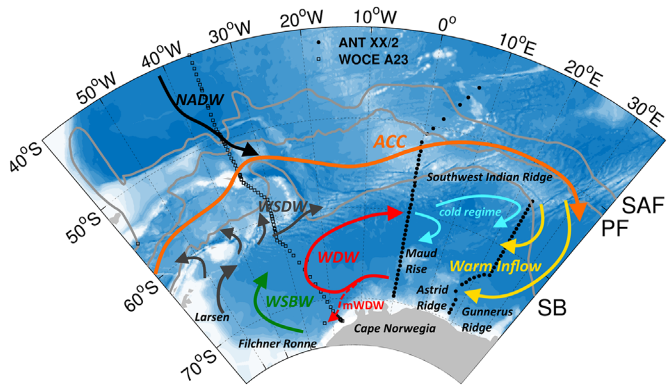

Fig. 1. Schematic circulation of the Weddell Gyre. Black dots are stations along the eastern and Greenwich section from ANT XX/2 and black squares show stations from the WOCE A23 cruise. The light grey lines indicate oceanic fronts (after Orsi et al., 1995), which are labelled on the right hand side (SAF=Subantarctic Front; PF=Polarfront; SB=Southern Boundary). (For interpretation of the references to colour in the text, the reader is referred to the web version of this paper.)

the shelf break towards the Filchner–Ronne Ice Shelf (FRIS) and the Larsen Ice Shelf (LIS). Cooling of the intruded mWDW and brine rejection due to sea ice formation during winter form High Salinity Shelf Water (HSSW) (Nicholls et al., 2009). HSSW is the key water mass contributing to the Weddell Sea Deep Water (WSDW) and Weddell Sea Bottom Water (WSBW), and ultimately the AABW formation. These waters follow the continental slope to the north as part of the cyclonic gyre circulation and the light enough ones exit the basin through several gaps within the South Scotia Ridge System (dark grey arrows) (Naveira Garabato et al., 2002; Palmer et al., 2012; van Caspel et al., 2015). However, there are fractions of WDW which are not involved in dense water formation and follow the general circulation back to the northeast of the WG. On its way the water cools significantly so that the densest class of CDW forms the so-called 'cold regime' (Gordon and Huber, 1984) west of the Greenwich meridian (GM) (light blue), which is characterised roughly by potential temperatures (Θ) between 0 °C and 0.5 °C. This water partly recirculates at the open eastern boundary and mixes with the incoming warm water. Along with the term 'cold regime', the warm inflow in the south is called 'warm regime' and comprises waters with temperatures of 0.5–1.5 °C. Because of the importance of the deep and bottom waters for the global thermohaline circulation, variations in bottom water formation in the Weddell Sea have been an ongoing research topic in the past. Repeated measurements along the GM (Smedsrud, 2005; Fahrbach et al., 2011) are used to monitor the inflow of WDW. Significant variations of water mass properties for the Weddell Sea Deep and Bottom Waters as well as the WDW were detected, accompanied with a positive trend (1984–2008) in the average temperature and salinity of the whole water column (Fahrbach et al., 2011). Variations of the water mass properties were attributed to variations in the inflow of CDW at the eastern boundary, being caused by asymmetric wind forcing at the northern and southern limb of the gyre. Furthermore, Fahrbach et al. (2011) state that redistribution of heat and salt by internal processes is responsible for the long-term increase of temperature and salinity of the WDW.

Warm Deep Water: properties and origin: Warm Deep Water ($0\,°C \le \Theta \le 1.5\,°C$), being the only source of heat for the WG (besides solar radiation), originates from CDW which represents, by volume, the most dominant water mass of the ACC. After entering the Atlantic sector via the Drake Passage, the lower parts of CDW are altered by upwelling NADW (black arrows in Fig. 1) at the Antarctic convergence zone, and also by recently ventilated water masses leaving the WG to the north (Whitworth and Nowlin, 1987; Reid et al., 1977; Orsi et al., 1993). As the latter have a higher density than waters found outside the gyre, they sink once leaving the Weddell basin while the lighter CDW is displaced upwards in the water column. The WOCE A23 section shows the interactions between these water masses (Heywood and King, 2002). For orientation, the section is also marked in Fig. 1. According to different hydrographic properties it is common to separate CDW into lower and upper CDW (LCDW, UCDW; see Fig. 2). LCDW is characterised by a salinity maximum due to the influence of the NADW (Patterson and Whitworth, 1990), while the UCDW in the Atlantic sector is classified as the layer with minimum oxygen and maximum nutrient (phosphates, nitrates) concentration (Larque et al., 1997; Saunders and King, 1995; Vanicek and Siedler, 2002), which are properties gained in the Indian and Pacific sectors. CDW enters the WG between 15 and 30°E, a region characterised by meanders and eddies (Schröder and Fahrbach, 1999; Gouretski and Danilov, 1993, 1994) in association with the southward turn of the ACC in the vicinity of the Southwest Indian ridge. Hence, there is no closed boundary in the east and the inflow may be highly variable. Park et al. (2001) show evidence of the eastern boundary extending far beyond 30°E. They speak of two modes of the formation of the warm regime. One is the eddy-mixing between the cold regime and the ACC north of 60°S between 20 and 30°E, where the authors refer to Schröder and Fahrbach (1999). The second mode is based on their findings and is given by direct westward advection along the southern limb of the gyre. It consists of gradually upwelled CDW which can be modified by surrounding Antarctic slope and shelf waters.

The hydrographic data presented in this study shows both

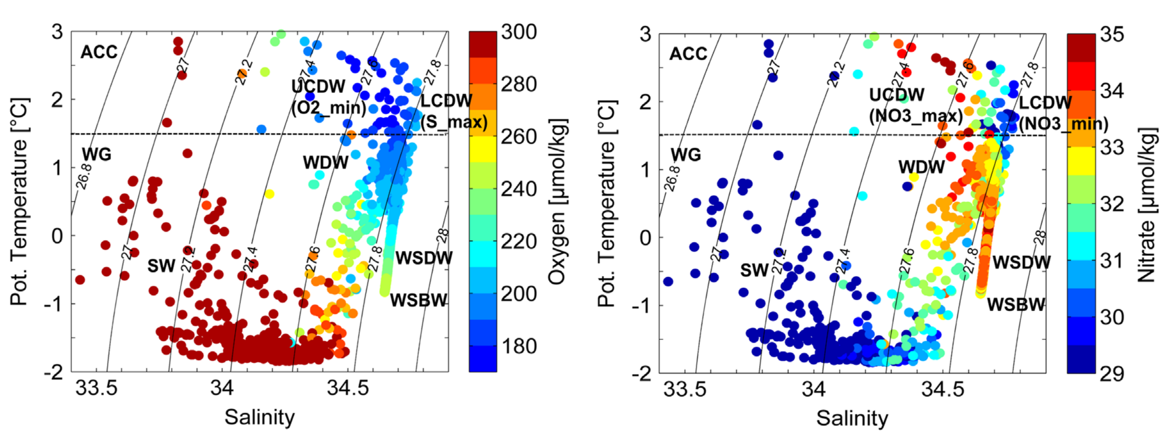

Fig. 2. *T–S* diagram including all bottle data from ANT XX/2 with the colour shading giving oxygen (left) and nitrate (right) values. The dashed line at 1.5 °C indicates the border between ACC and WG waters. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)