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Northwestern Weddell Sea deep outflow into the Scotia Sea during the austral summers of 2000 and 2001 estimated by inverse methods

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Abstract

The northward outflow of cold, dense water from the Weddell Sea into the world ocean basins plays a key role in balancing the global heat budget. We estimate the geostrophic flow patterns in the northwestern Weddell Sea using box inverse methods applied to quasi-synoptic hydrographic data collected during the Brazilian DOVETAIL 2000 and 2001 austral summer cruises. The analysis is focused on the variations of the deep Weddell Sea outflow into the Scotia Sea within boxes that bound the main deep gaps over the South Scotia Ridge. To determine the geostrophic volume transports in each box, mass, salt, and heat are conserved within neutral density layers that are not in contact with the atmosphere. Implementing the inverse model and using property anomaly equations weighted by the flow estimate uncertainty our results are consistent with those reported in the literature. A bottom triangle extrapolation method is introduced, which improves the estimated property fluxes through hydrographic sections. In the austral summer of 2000 the transports of Weddell Sea Deep Water (WSDW) through the Philip Passage, Orkney Passage, and southwestern Bruce Passage are 0.01 ± 0.01, 1.15 ± 0.33, and 1.03 ± 0.23 Sv ($1\,\mathrm{Sv} = 10^6\,\mathrm{m^3\,s^{-1}}$, >0 is northward), respectively. After extrapolation within bottom triangles these transports increase to 0.12 ± 0.03, 3.48 ± 1.81, and 1.20 ± 2.16 Sv. Analysis of the hydrographic data reveal distinct oceanographic conditions over the Philip Passage region, with evidence of mesoscale meanders, warmer and saltier Warm Deep Water (WDW) and colder WSDW observed in 2001 than in 2000. Despite these differences the WSDW transport does not present a significant variation between 2000 and 2001. The WSDW transports through the Philip Passage in 2001 are 0.012 ± 0.001 and 0.113 ± 0.001 Sv after extrapolation within bottom triangles. The circulation derived from the inversion in the austral summer of 2001 suggests a sharp weakening of the barotropic cyclonic flow in the Powell Basin, which may be due to northerly and northeasterly winds associated with an atmospheric low-pressure center located west of the Antarctic Peninsula. We suggest that similar variations in atmospheric forcing may explain changes in the intensity of the cyclonic flow observed in the northwestern Weddell Sea and Powell Basin.

Keywords: Northwestern weddell sea; Weddell sea deep water; Inverse methods; DOVETAIL; Deep outflow variations

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1. Introduction

The Antarctic region represents an important scientific record of past climate and its variations through the evolutionary history of the Earth. Formation, sinking, and northward transport of deep and bottom waters in the Southern Ocean play a key role in the global thermohaline circulation. Dense waters originating in the Southern Ocean spread in the ocean basins further north and contribute to the global heat and freshwater budgets. Recent studies suggest that part of the dense outflow exported from the Weddell Sea into the Scotia Sea upwells because of the high turbulence in this region, which acts as a 'blender' to mix ocean water masses. As the Scotia Sea may be a significant contributor to the 'missing mixing' required to balance the global ocean overturning circulation (e.g. Heywood et al., 2002), it is important to better quantify how much dense deep water enters the basin through the South Scotia Ridge, which separates the Weddell Sea from the Scotia Sea. In addition, improved estimates of the northward transport of deep Southern Ocean waters will lead to a better understanding of global climate and its variability.

Antarctic Bottom Water (AABW, $\theta < 0\,^{\circ}\mathrm{C}$) is the densest water mass associated with the thermohaline circulation of the world ocean (Orsi et al., 1999). AABW is produced in the southwestern and western Weddell Sea in the Atlantic sector and in the Enderby Land coast and the western Ross Sea in the Indian–Pacific sector (Whitworth et al., 1998). Based on the oceanic chlorofluoro-carbon budget, Orsi et al. (1999) diagnosed that 60% of the circumpolar production of AABW occurs in the Atlantic sector. Several studies suggest that the deep outflows from the Weddell Sea represent the most important contributions to the ventilation of the oceans (Deacon, 1933; Reid and Lynn, 1971; Mantyla and Reid, 1983; Yaremchuk et al., 1998; Schröder and Fahrbach, 1999; Muench and Hellmer, 2002). However, recent studies suggest that the Ross Sea and Adélie Land coast are also significant regions of AABW formation, possibly as large as the Weddell Sea (Rintoul, 1998; Bindoff et al., 2000).

Several studies attempted to map the outflow routes of the deep and bottom waters formed in the Weddell Sea and to quantify the transports that connect the Weddell Sea to the world ocean basins (see Rintoul, 1991; Locarnini et al., 1993; Orsi et al., 1999; Gordon et al., 2001; Naveira Garabato et al., 2002a, b; Matano et al., 2002; Schodlok et al., 2002). Estimates of Weddell Sea Deep Water (WSDW) outflow from the Weddell Sea through the South Scotia Ridge are 6.7 ± 1.7, 4.7 ± 0.7, and 6.4 Sv ($1\,\mathrm{Sv} = 10^6\,\mathrm{m^3\,s^{-1}}$, e.g. Naveira Garabato et al., 2002a; Schodlok et al., 2002). The bulk of these transports (4.3 ± 0.6, 5.6 ± 0.1 and 4.2 Sv, respectively) occur through the Orkney Passage, which is the deepest gap on the ridge. Nevertheless, deep water outflow estimates through some of the main deep gaps of the ridge present a wide range of variation. For instance, WSDW outflow estimates through the Philip Passage are 0.7 ± 0.4, -0.1 ± 0.3, and 2.2 Sv (e.g. Naveira Garabato et al., 2002a; Schodlok et al., 2002). These discrepancies can be attributed to sampling differences, methodologies of flow analysis, or real-time variability. Robertson et al. (2002) pointed out that the warming trend of WSDW, in recent decades is comparable to the global averaged surface-water warming (Levitus et al., 2000). Their study suggests that the deep water warming in the Weddell Sea has important implications for AABW formation, pack ice melting, regional ocean–atmosphere heat transfer, and the global thermohaline circulation. Given the differences in transport estimates through the South Scotia Ridge and the reported variations in water-mass properties in the Weddell Sea (Fahrbach et al., 1998; Robertson et al., 2002; Schröder et al., 2002), we wish to further investigate the deep outflow through the ridge and its associated variability.

The oceanographic conditions of the Weddell Sea were the focus of several international programs carried out during the 1980s and 1990s (Gordon and Huber, 1984; Fahrbach et al., 1994; Gammelsröd et al., 1994). The Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) Program (Muench and Hellmer, 2002) was designed to map the routes and quantify the rates of deep and bottom waters recently ventilated in the Weddell Sea and exported across the Weddell–Scotia Confluence. As part of the Brazilian contribution to DOVETAIL, two cruises were conducted during the austral summers of 2000 and 2001 focused on monitoring the variability of the thermohaline structure in the northwestern Weddell Sea. This work aims to describe the water mass characteristics and circulation and to estimate the outflow of deep waters through the main deep gaps of the South Scotia Ridge during summer 2000 and 2001. It provides the first snapshots of these deep