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Source water distribution and quantification of North Atlantic Deep Water and Antarctic Bottom Water in the Atlantic Ocean

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ABSTRACT

The distribution and quantification of the source waters of the *North Atlantic Deep Water* (NADW) and the *Antarctic Bottom Water* (AABW) in the Atlantic Ocean were investigated using 40 years of climatology data (1973–2014) constructed from the dataset available in the 2013 World Ocean Database. The quasi-interdecadal variability of NADW and AABW source waters spanned the late 1980s until early 2010 in the analysis of three World Ocean Circulation Experiment sections (WOCE A05, A10 and A16). The study was performed by applying optimum multiparameter analysis to quantify the mixture of six NADW and AABW source waters (four for NADW and two for AABW). The NADW source waters decrease their contributions from north to south, except for the region between 30°S and 45°S where the *Labrador Sea Water* (LSW) contribution suggests an upper NADW deepening. In addition, *Iceland-Scotland Overflow Water* (ISOW) and LSW contribute to the southernmost boundary of NADW in the Southern Ocean. The AABW source waters were observed as far as 45°N with a 15% contribution, with significant recirculation in equatorial regions and higher contributions in Argentine and Brazil basins. The *Denmark Strait Overflow Water* (DSOW) and ISOW showed the highest temporal variability (±20%) not only near their formation region but also in the South Atlantic. The AABW source waters did not present high temporal variability, although temporal changes were found near their formation region. Based on their spatial distribution, the Argentine and Brazil basins were noted as the main locations to use for investigating this issue. The results provide new insights into the mixing inside the deep Atlantic Ocean and the global circulation cell; the results also specify the source water masses that present higher temporal variability and the suitable locations to observe these changes.

1. Introduction

Deep and bottom water masses are formed in few locations around the world and are primarily formed at high latitudes (Foster and Carmack, 1976; McCartney and Talley, 1984). The *North Atlantic Deep Water* (NADW) and *Antarctic Bottom Water* (AABW) are formed in the North Atlantic Ocean (e.g., Swift, 1984; Zenk and Armi, 1990; Dickson and Brown, 1994) and the Southern Ocean (e.g., Carmack and Foster, 1975; Rintoul, 1998; Orsi et al., 1999), respectively, through oceanic processes of deep ocean convection, subsurface mixing (Ivanov et al., 2004; Steinfeldt et al., 2009; Jullion et al., 2014) and interaction with the cryosphere (e.g., ice shelf and/or sea ice; Rahmstorf, 2006; Nicholls et al., 2009). The properties of the newly formed deep and bottom waters are transported throughout their formation region supplying nutrients, heat, salt and gases to the deep ocean (another minor source is hydrothermal activity). Analyzing both conservative and semi-conservative properties, it is possible to identify the distribution of the water masses and to infer how they spread within the global deep ocean (Talley et al., 2011).

The source water masses of NADW and AABW are well identified near their formation areas. NADW is composed of fractions of a mixture of *Labrador Sea Water* (LSW; occupying a layer of ~2000 m), which occupies the subpolar North Atlantic Ocean (Rhein et al., 2002; García-Ibáñez et al., 2015) and spreads southwards mainly with the Deep Western Boundary Current (Rhein et al., 2015) and basin interior pathways (Gary et al., 2012). *Denmark Strait Overflow Water* (DSOW) and *Iceland Scotland Overflow Water* (ISOW), which are found at greater depths (~3000 m to the bottom) and sourced in the subpolar North Atlantic Ocean (García-Ibáñez et al., 2015). And *Mediterranean Water* (MW) that enters the North Atlantic Ocean and occupies

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intermediate to deep depths (700–1800 m, Zenk and Armi, 1990; Bashmachnikov et al., 2015).

AABW is primarily composed of fractions of a mixture of dense/high salinity shelf and ice-shelf waters and *Circumpolar Deep Water* (Orsi et al., 1999). Several AABW varieties are formed around the continent, which ultimately compose the AABW export to the global ocean. *Weddell Sea Deep Water* (WSDW) and *Weddell Sea Bottom Water* (WSBW) are the main AABW varieties found in the Weddell Sea (1000 m to the bottom, Kerr et al., 2009a) that spread to the South Atlantic Ocean (Pardo et al., 2012; van Sebille et al., 2013).

The Atlantic Ocean has two main characteristics: it connects both of Earth's subpolar regions and is the formation area of a young deep water mass (NADW), while in the Pacific and Indian Oceans the deep waters are primarily composed of upwelled bottom waters (Talley, 2013). Furthermore, the Atlantic Ocean water mass structure promotes a unique circulation cell feature of the Global Overturning Circulation and the Atlantic Meridional Overturning Circulation (AMOC) (Broeker, 1991; Lumpkin and Speer, 2007; Talley, 2013) that transports a substantial amount of heat and is important for the maintenance of the global climate.

The AMOC is composed of three main cells: the upper, deep and bottom cells. In general, the upper cell transports warm waters northwards reaching the subpolar North Atlantic, where these waters lose heat and sink to originate the deep cell (composed mainly of NADW). The deep branch moves southwards up to the Southern Ocean, where part of NADW will be transformed into AABW (Talley, 2013; Orsi et al., 1999). The bottom cell (AABW), flows northward and is incorporate into NADW in the North Atlantic Ocean. These cells are kept in motion due to the formation, upwelling and advection of water masses; hence, any changes in these processes could lead to a change in the whole ocean circulation system. For example, the strength of the AMOC is believed to have been extremely reduced in past ages due to extreme climate changes and may have even interrupted the process of deep water formation (e.g., the formation of *Glacial North Atlantic Intermediate Water* instead of NADW during the Last Glacial Maximum (24 ka – 19 ka) until 17 ka - 13 ka, Marson et al., 2014; Lippold et al., 2016).

As the oceanic circulation is directly associated with climate and because of its large capacity for heat transport, an understanding of the water mass distribution and variability is an important tool to investigate the changes in the ocean circulation pattern and, consequently, the Earth's climate (Broecker et al., 1985; Rahmstorf, 2002). Hence, this study aims to contribute to a better comprehension of the mixture of the source water masses in the deep Atlantic Ocean. This understanding would enable a deduction both spatially and temporally of whose source water masses of the NADW and AABW play an active role in the Atlantic-scale distribution of NADW and AABW (Hirst, 1999; Johnson, 2008; Talley, 2013).

To gain these insights, the main goals of this study are (i) to investigate the spatial distribution of the NADW and AABW source water masses, (ii) to quantify the mixture contribution in the deep Atlantic Ocean, and (iii) to determine the variability of NADW and AABW source water masses. Thus, the manuscript is organized as follows: Section 2 describes the properties and distribution of the main source water masses, as well as some aspects of what is known regarding their variability. The database used in this study, the conservative and semi-conservative parameters, and the method applied (Optimum Multiparameter) are explained in Section 3. Section 4 contains the spatial distribution of each source water mass divided by four Atlantic basins and the variability of the source water masses, which was investigated by three repeat World Ocean Circulation Experiment (WOCE) transects. The results are discussed in Section 5 based on the distribution and variability of the source water masses in the Atlantic Ocean. The main results are summarized in the conclusions in Section 6.

2. NADW and AABW source water masses

2.1. Source water mass formation and spreading

NADW differs from AABW because of its higher salinity, temperature and dissolved oxygen (Fig. 1a–c shows the higher values of these properties in the subpolar North Atlantic, which decrease southwards due to the larger contribution of AABW). AABW is traced by its higher nutrient content, which is especially pronounced in the silicate concentration (Fig. 1d). Although the NADW core is found shallower than 4000 m in most of the Atlantic Ocean (e.g., between 2000 m and 4000 m; please see Fig. S1, which is analogous to Fig. 1, but at 3000 m), in the subpolar North Atlantic, the lower NADW (the denser part of NADW) is found at this depth (e.g., Johnson, 2008) with the previous characteristic cited above (compared with waters from the Antarctic). South of this region, the decrease in these properties and the increase in silicate contents indicate an increasing influence of AABW (Fig. 1).

The lighter component of NADW—*Labrador Sea Water* (LSW)—is formed in the Labrador Sea (Fig. 2a) during deep winter convection (Yashayaev, 2007; Talley et al., 2011). LSW is recognized by its relatively low salinity (34.84–34.88) compared with other NADW components (for example, the properties of DSOW, ISOW and MW in Table 1) and high oxygen content (~301 μmol/kg) (Table 1). LSW can be identified in subpolar North Atlantic basins (the Atlantic Ocean and basin subdivisions are identified in Fig. 2a) at depths of 1500 m to 2500 m (Rhein et al., 2002; Jenkins et al., 2014; García-Ibáñez et al., 2015), spreading southward mainly by the Deep Western Boundary Current and interior pathways (Rhein et al., 2002; Yashayaev, 2007; Gary et al., 2011, 2012).

Another component of the upper NADW is the *Mediterranean Water* (MW), which is formed in the Mediterranean Sea and is characterized by maxima in salinity (35.5–36.6) and temperature (9.5–12 °C) (Table 1). Due to its high density, MW occupies intermediate depths from 900 m to 1350 m (Bashmachnikov et al., 2015) after passing through the Strait of Gibraltar into the North Atlantic Ocean. During this trajectory, MW mixes with ambient deep waters through turbulent processes, spreads southwestward of the strait and is fully absorbed by adjacent waters (van Aken, 2000; Talley et al., 2011, p. 292; Bashmachnikov et al., 2015).

The combination of North Atlantic warm waters, Arctic cold waters, and strong surface cooling during winter results in the formation of dense intermediate and deep waters in the Nordic Seas (Mauritzen, 1996; Fogelqvist et al., 2003; Yashayaev and Clarke, 2008). These waters overflow through passages located east of Iceland—*Iceland-Scotland Overflow Water* (ISOW)—and through the Strait of Denmark—*Denmark Strait Overflow Water* (DSOW). ISOW becomes a homogeneous water mass after mixing with Iceland Basin water masses (e.g., *Subpolar Mode Water* and LSW, Yashayaev and Clarke, 2008) and is recognized by its high salinity (34.97) and low temperatures (2–2.7 °C) (Fig. 3). In other subpolar and subtropical North Atlantic basins (e.g., Irminger and West European basins), modified ISOW is identified as *Northeast Atlantic Deep Water* (NEADW; e.g., Yashayaev and Clarke, 2008; García-Ibáñez et al., 2015).

DSOW is found less diluted in the bottom of Irminger Basin (Fig. 2a) (Fogelqvist et al., 2003) since it is the result of the diapycnal mixing within the dense overflow plume that crosses the sill (e.g., composed of *Iceland Sea Intermediate Water*, *Re-circulating Atlantic Water*, *Arctic Atlantic Water*, *upper Polar Deep Water* and *Polar Intermediate Water*; see Fig. 11 and the text of Rudels et al., (2002) for further discussion). Further south, DSOW mixes with other NADW components (e.g., LSW and ISOW, García-Ibáñez et al., 2015). DSOW is identified in the bottom layer of the Irminger (deeper than 2900 m) and Labrador (deeper than 3300 m) basins by its high density ($35.2 > \sigma_{1.5} > 34.82$ kg m^{-3}) and low