Antarctic Bottom Water changes during the last fifty years

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1. Introduction

The formation of deep and bottom water masses in the Southern Ocean plays a significant role in both global ocean circulation and climate. Antarctic Bottom Water (AABW) formation occurs in some specific areas around the Antarctic margins with contribution of different source waters (Carmack and Foster, 1975). The surface forcing for the formation of this dense water can be cooling by heat loss and increase in salinity (e.g., sea ice formation and brine rejection, among other processes; Killworth, 1983). However, recent studies have documented changes in regional climate around the Antarctic continent, such as the evident atmospheric warming (Turner et al., 2005a) and glaciers retreat in the Antarctic Peninsula region during the last 50 years (Cook and Vaughan, 2010). Gille (2002) pointed to a significant increase in temperature (~0.2°C) of intermediate waters of the Antarctic Circumpolar Current during the 1990s. A similar warming trend for Warm Deep Water (WDW; ~0.012 $°C.year^{-1}$) was also noted by Robertson et al. (2002) in the Weddell Gyre, while Jacobs and Giulivi (2010) have found a decrease in salinity (freshening) in the Ross Sea. In addition, Rintoul (2007) documented a rapid freshening of the Antarctic Bottom Water (AABW) in the Indian and Pacific sectors of the Southern Ocean during the 1995-2005 period.

The trends found by those previous studies reveal a complex and variable change in the ocean-atmosphere-cryosphere climate system, which are still barely understood. The purpose of this work is to investigate the space-temporal variability of the deep and bottom water masses properties in the Southern Ocean to infer any temporal trend in the AABW properties.

2. Southern Ocean database and Methodology

The dataset used for this study is derived from three distinct sources: (1) World Ocean Database 2009 (WOD09, Boyer et al., 2009) which consists of bottle, profiling floats, and CTD data spanning from 1958 to 2010; (2) German Alfred-Wegener-Institute (AWI) database gathered in the Antarctic waters from 2003 to 2010; (3) Brazilian High Latitude Oceanography Group (GOAL) dataset from 2003-2005 and 2008-2010 periods. The three sets of data together cover a total period of 52 years. In addition to the quality control included in WOD09, we also avoided the use of duplicated stations and restricted our analysis to the austral summer (November to March) due to the seasonal variability and lack of observation during other seasons. The parameters analyzed in this work were potential temperature (θ), salinity (S) and neutral density (γn). The last was determined according to Jackett and McDougall (1997). Since AABW density values vary around the Southern Ocean, we used the neutral density of 28.27 kg m^{-3}, as considered by Orsi et al. (1999).

In order to avoid problems associated with irregular spatial and temporal coverage, two approaches were considered in this work. The first consisted of a space-temporal selection, in which only data within a 220 km radius around a recent measurement (i.e., collected during the last decade) were considered. The second approach was a geographic bin criterion, in which annual means of properties were calculated for a two-degree grid and then averaged for the entire region. Due to differences between coastal and oceanic hydrographic regimes (regions), the dataset was selected following the isobaths of 1300 m. Linear fitting and p-value were calculated for each time series. The latter indicates if the linear fit is statistically significant, whose value must be lower than 0.05 for the time series can be considered significant at 95% level. The selection excluded all data in the oceanic region collected during 1962, which had the largest standard deviation of the time series. In the shelf region, no data were collected in 1999. Figure 1 shows the distribution of all the data used in this study. Among the most frequently sampled regions were: the oceanic regions of Weddell, Indian and Western Pacific sectors and the continental shelves of the Ross Sea, Weddell Sea, Bransfield Strait, and Prydz Bay.

3. Results and Discussion

The time series of the oceanic regime (Fig. 2) shows warming (0.0037 $°C.year^{-1}$), freshening (-0.0003 $year^{-1}$) and lightening (-0.0012 kg $m^{-3}.year^{-1}$) trends. In the shelf region (Fig. 2) temperature and salinity annual mean values also presented positive (0.0084 $°C.year^{-1}$) and negative (-0.0012 $year^{-1}$) trends, respectively. The consequences of temperature increase and salinity decrease over time lead to a density decrease (-0.0026 kg $m^{-3}.year^{-1}$) over the entire period.

Figure 3 shows the time series of gridded data that are statistically significant according to the linear fitting applied. In the Weddell, Indian and Western Pacific sectors, where data coverage is more consistent, an increase in deep ocean temperature (Fig. 3A) can be noticed for the oceanic region, mainly in the Weddell sector. This temperature trend (0.0167 $°C.year^{-1}$) is one order of magnitude higher than the one calculated using all oceanic data. This trend is probably related to the WDW warming reported by Fahrbach et al. (2004) and Robertson et al. (2002), considering the importance of this water mass to the formation of deep dense water in those regions. The warming of oceanic dense waters can also be related to the rising

SAM index, since it can lead to a more intense WDW upwelling into the shelf break, therefore rising the contribution of WDW to high density water formation (Jacobs, 2006).

Despite the positive (and statistically significant) temperature trend obtained in the shelf region, when all data were used, high dispersion of temperature annual means is found for the gridded data time series (not shown). This is not the case for oceanic data, which presented a homogeneous distribution (and trend) over time. In fact, in the shelf region the temporal trends of water properties were statistically significant mostly in well sampled regions, such as the Ross Sea, Bransfield Strait, and Prydz Bay, where negative temperature trends (Fig. 3A) were observed. The highest rate value (-0.0137 °C.year^{-1}) was found in the West Antarctic Peninsula (WAP) region, which is considered one of the most susceptible areas to climate change (Meredith and King, 2005).

In the oceanic region (depth >1300 m), no trend was observed with the salinity values while freshening is clearly identified in the shelf waters (Fig. 3B). This freshening is observed in the same regions where the cooling of shelf waters was identified, i.e. Ross Sea, Bransfield Strait and Prydz Bay. In that case, the Ross Sea region presented the highest freshening trend (-0.0033 year^{-1}) compared to the Bransfield Strait region (-0.0012 year^{-1}). The freshening and cooling noticed for the Ross Sea in this study have already been reported by Jacobs and Giulivi (2010). The authors calculated a salinity decrease trend of -0.003 year^{-1} for the High Salinity Shelf Water (HSSW) and -0.004 year^{-1} for Modified Circumpolar Deep Water (MCDW) and a cooling rate of -0.0125 °C.year^{-1} for MCDW. Jacobs (2002) stated that this long-term variability is possibly related to ice sheet melting in WAP.

The neutral density time series (Fig. 3C) reflected the changes in both temperature and salinity over the 50-year period. For instance, a decrease in density by -0.0013 kg m^{-3}.year^{-1} has been calculated for the oceanic sectors, which is probably caused by an increase in temperature in those regions. In the shelf region (Fig. 3C), a decrease in neutral density values over time can be found in the Ross Sea, Prydz Bay and next to the tip of the Antarctic Peninsula. Considering the decrease in temperature found for those regions found in this study, the freshening process is probably leading to lighter deep and bottom water masses varieties. Despite the differences of the hydrographic properties of those studied regions, the derived density trends presented similar values in the Antarctic Peninsula and Prydz Bay region (-0.0022 kg m^{-3}.year^{-1}) and in the Ross Sea (-0.0026 kg m^{-3}.year^{-1}).

4. Summary

In this study we investigated the variability of high dense waters of the Southern Ocean using hydrographic data from 1958 to 2010. The dataset was divided into oceanic (depth >1300 m) and shelf (depth <1300 m) regimes. A decreasing trend was found for both salinity and neutral density shelf and oceanic time series. The salinity trends vary regionally in oceanic waters, being more evident in the shelf, with important contributions from dense water mass formation areas (i.e. Ross Sea, Bransfield Strait, and Prydz Bay), as indicated by the spatial trend of the salinity field. In the Ross Sea, several authors have reported a freshening of shelf and dense waters (e.g., Jacobs, 2002, 2006). Jacobs and Giulivi (2010) stated that changes in precipitation, sea ice production, ocean circulation strength and mostly continental ice melting are possible causes of the freshening process reported and are anti-correlated with the rising annual Southern Annular Mode (SAM) index.

In general, the spatial trends show a warming in the Weddell, Indian and Western Pacific oceanic sectors. Besides the warming of WDW reported by Robertson et al. (2002) and Fahrbach et al. (2004), the warming of oceanic dense waters can also be related to the rising SAM index.

The combination of freshening in shelf waters and warming of oceanic water masses leads to the AABW density decrease over the 50-year period analyzed here, with a trend of 0.0026 and 0.0012 kg m^{-3}.year^{-1} for shelf and oceanic waters, respectively. Kerr et al. (2011) also indicated that recent shelf waters freshening trends around the Antarctic continent, based on model outputs, are likely to be related to changes in the AABW outflow rates.

The results reported here not only emphasize that shelf waters are becoming fresher (e.g. Jacobs and Giulivi, 2010; Hellmer et al., 2011), as earlier reported for several regional areas (Weddell, Ross and Adelie Land shelves) around the Southern Ocean, but also that the AABW, produced and consequently exported to the global ocean, are becoming lighter.

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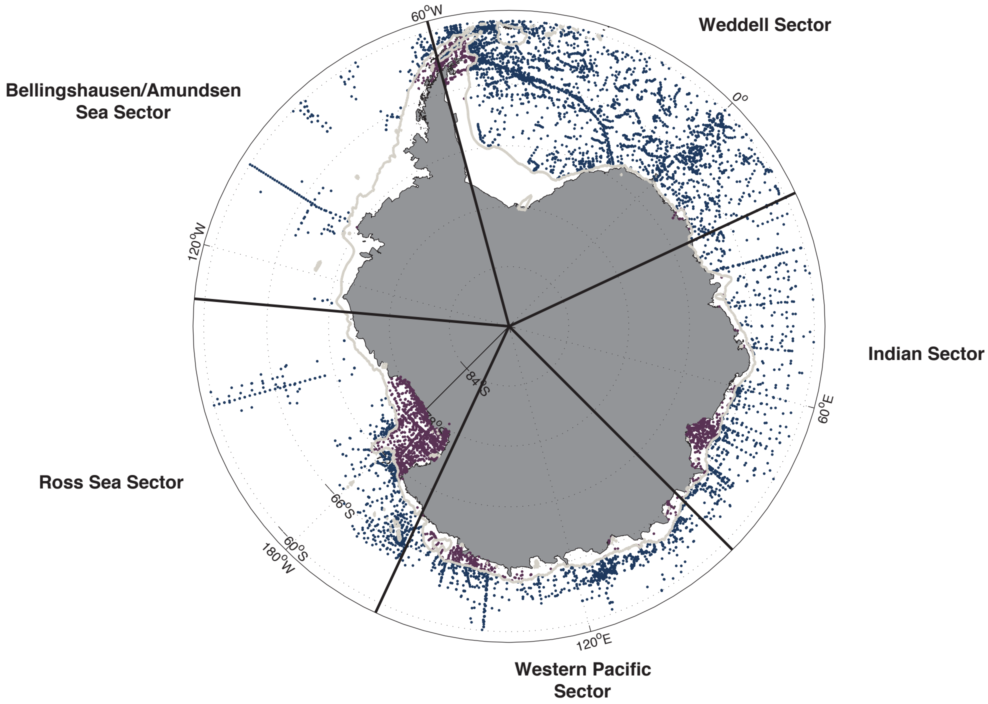

Fig 1: The distribution of observational data in the Southern Ocean. Dots in magenta represent data in the shelf regime (depth <1300 m) while blue dots are in the oceanic region (depth >1300 m). Gray lines indicate the 1300 m isobath and black lines delimit the hydrographic sectors of Weddell Sea, Indian Sector, Western Pacific, Ross Sea, and Bellingshausen/Amundsen Sea (as defined by Cavalieri and Parkinson, 2008).

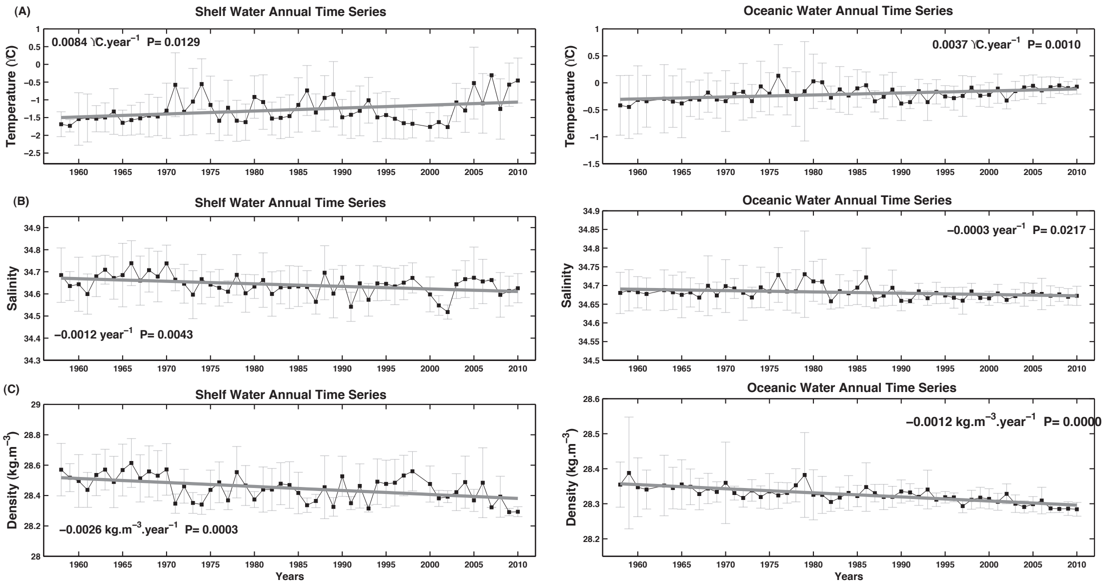

Fig 2: The annual average of potential temperature (upper), salinity (middle) and neutral density (lower) for shelf (left) and oceanic (right) regions, respectively, during the 50-year period. Error bars represent one standard deviation of the values. The gray solid lines represent the linear fit to the average values for each regime (or region). The temporal rate of change and P values are also added to the figures.

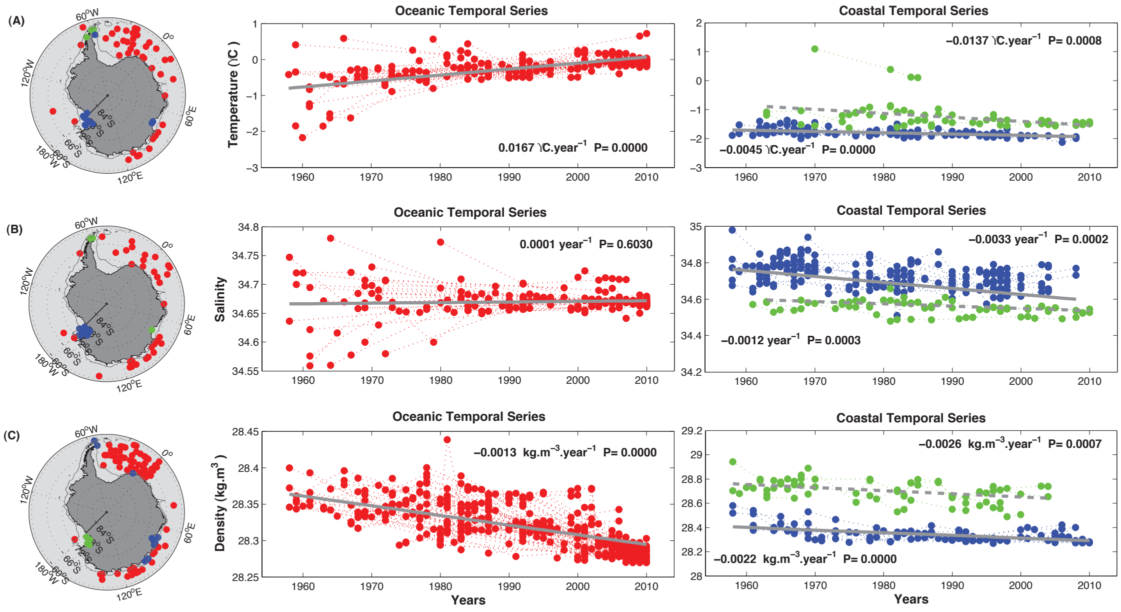

Fig 3: Potential temperature (A), salinity (B) and neutral density (C) time series of the gridded data for oceanic (middle) and shelf (right) waters. The position of each gridded data can be seen on map (left), where the red color denotes oceanic regions and the blue and green denotes shelf regions.

Developing a Vision for Climate Variability Research in the Southern Ocean-Ice-Atmosphere System

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The Southern Ocean region is currently accumulating more heat and anthropogenic carbon than anywhere else in the ocean, which could have global ramifications. Climate models poorly resolve this key region, and produce a wide variety of projected climate states in the future. Ongoing greenhouse gas increases and ozone recovery are both expected to modify Southern Hemisphere wind patterns, with likely implications for ocean heat and carbon uptake (Figure 1). This will exert a strong influence on the global climate system. Much effort has recently gone into improving ocean model representation of the role of eddies, yet these processes are not yet adequately represented in coarse IPCC-class climate models. Improvements to models and our understanding of the role of eddies and air-sea-ice interactions in the Southern Ocean system have been made, but large gaps still exist. To compound this situation, there is a paucity of observations in the Southern Ocean climate system, including ocean circulation/hydrography, air-sea fluxes, and atmospheric properties. The CLIVAR/CliC/SCAR Southern Ocean Panel (SOP) has had a sustained interest in driving forward the observational programmes required in this region, with some notable achievements (e.g. the Southern Ocean Observing System; SOOS).

During 19 - 21 October 2011, the SOP held its seventh meeting (SOP-7) in Boulder, Colorado, USA. The meeting convened experts from three key areas of Southern Ocean research – Southern Ocean carbon, atmospheric processes over the Southern Ocean, and Southern Ocean physics – with the overarching objective to generate an overview of current understanding in these three main areas. Under each of the three themes, invited speakers highlighted to the panel key open questions and discussed gaps in our current understanding. This will ultimately feed into the vision document being developed by the panel: A Vision for Climate Variability Research in the Southern Ocean-Ice-Atmosphere System. The following three sections summarize in turn the main issues highlighted during the meeting across the above three thematic areas.

Southern Ocean Carbon

The Southern Ocean is an important regulator of atmospheric carbon dioxide (CO2). In this region, old, CO2-rich water is ventilated to the atmosphere, and nearly half of the ocean's anthropogenic CO2 is absorbed and stored. It is therefore important to quantify and understand the processes controlling air-sea CO2 exchange in the Southern Ocean, given the implications for the global climate system.

Results based on coarse-resolution ocean models suggest that the physical circulation of the Southern Ocean governs the exchange of CO2 across the air-sea interface, and that changes in the physical circulation have altered the uptake and release of CO2 from the region (Figure 1). However, the community remains concerned about certain aspects of these modeling studies. Central to their concerns are two questions: (1) Can