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Wind-controlled export of Antarctic Bottom Water from the Weddell Sea

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[1] Recent studies suggest that the variability in Antarctic Bottom Water (AABW) properties in the Scotia Sea on time scales up to decadal may be linked to changes in the baroclinicity of the Weddell gyre, with vertical variations in the density structure at the gyre's northern edge acting to control the export of AABW over the South Scotia Ridge and toward the mid-latitude South Atlantic. We test this hypothesis by analysing the AABW properties in fifteen occupations of the SR1b hydrographic section (1993–2009) in eastern Drake Passage alongside possible forcings as derived from atmospheric reanalysis data. We show that variability in the wind stress over the Weddell gyre leads changes in AABW properties in the SR1b section by approximately five months. The sign of the lagged correlation is consistent with the notion of the AABW export from the Weddell Sea being controlled by the gyre's baroclinic adjustment to wind forcing on time scales of several months. Variability in the regional winds is found to be closely linked to the Southern Annular Mode (SAM). These results suggest that there may be a causal relationship between the SAM's positive tendency observed in recent decades and the subsequent warming of AABW detected across much of the Atlantic Ocean.
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1. Introduction

[2] The Drake Passage (Figure 1) is situated north and west of the Weddell Sea (WS), where Weddell Sea Deep Water (WSDW), the main contributor to Antarctic Bottom Water (AABW) [*Orsi et al.*, 1999] filling much of the global ocean abyss, is produced. The WSDW leaving the WS through deep passages in the South Scotia Ridge encompasses the most recently ventilated components of the water mass [*Gordon et al.*, 2001; *Naveira Garabato et al.*, 2002a]. Upon entering the Scotia Sea, WSDW can flow westward toward the Drake Passage [*Naveira Garabato et al.*, 2002b] or northeastward toward the Georgia and Argentine basins [*Meredith et al.*, 2000, 2001; *Naveira Garabato et al.*, 2002b]. The less-recently ventilated components of WSDW can also spread northward by navigating around the eastern side of the island chain at the eastern edge of the Scotia Sea [*Locarnini et al.*, 1993]. Ultimately, WSDW constitutes the densest component of the lower limb of the Atlantic Meridional Overturning Circulation.

[3] In recent years, evidence indicating that the AABW of WS origin has warmed (~0.0025°C yr^{-1}) across the length of the Atlantic Ocean since the 1970s has been mounting [*Coles et al.*, 1996; *Zenk and Morozov*, 2007; *Johnson and Doney*, 2006; *Meredith et al.*, 2008a; *Johnson et al.*, 2008]. However, observations of the evolution of WSDW properties within the WS itself reveal no corresponding warming trend. Specifically, *Fahrbach et al.* [2004] found no decadal-scale change in the temperature of the WSDW in the WS between 1992 and 2002, although they noted a significant warming trend (0.01°C a^{-1}) in the Weddell Sea Bottom Water density class prior to 1998 and a subsequent weakening of the trend. *Robertson et al.* [2002] reported slightly warmer WSDW in the WS in the 1990s compared with the 1970s, but noted that strong interannual variability in WSDW properties prevented them from identifying significant trends.

[4] Seeking to reconcile these two seemingly inconsistent sets of observations, *Meredith et al.* [2008a] hypothesised that the warming of AABW in the Atlantic Ocean abyss has been caused by a decadal-scale change in the range of WSDW density classes exported from the WS, with significant interannual variability superimposed. There is a need to understand this interannual variability so as to enable the correct interpretation of temporally sparse observations, and because the processes controlling WSDW export on interannual time scales may also operate on the decadal time scales pertinent to the AABW warming trend. *Meredith et al.* [2008a] suggested that the interannual variability of WSDW properties in the eastern Scotia Sea was caused by changes in the baroclinicity of the Weddell gyre. A stronger (weaker) Weddell gyre would lead to lighter (denser) water being exported over the South Scotia Ridge, resulting in a change in AABW properties in the Scotia Sea on pressure surfaces (their Figure 10).

[5] Here, we test the plausibility that the "Weddell gyre intensity" hypothesis may underlie the interdecadal warming of AABW observed across the Atlantic Ocean by analyzing the interannual variability in the thermohaline properties of WSDW across eastern Drake Passage. Because of the lack of long-term measurement of the Weddell gyre's baroclinicity, we compare our property time series with the wind stress over the Southern Ocean, believed to be the primary driver of the Weddell gyre intensity [*Martinson and Iannuzzi*, 2003].

2. Data Set

2.1. Hydrographic Data

[6] We have compiled fifteen repeats of the SR1b Conductivity-Temperature-Depth (CTD) section conducted

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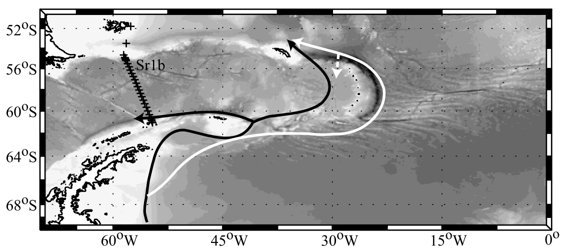

Figure 1. Map and bathymetry of the Drake Passage. The position of the SR1b hydrographic repeat section is shown (black cross). The simplified circulation of light WSDW overflowing the South Scotia Ridge (black arrows) and of dense WSDW circumnavigating the South Sandwich Islands (white arrows) is adapted from *Naveira Garabato et al.* [2002b].

across the eastern Drake Passage (Figure 1) between 1993 and 2009 (one section every austral spring/summer except for the summers of 1994/95 and 1998/99) by scientists of the National Oceanography Centre, Southampton, and the British Antarctic Survey. The sections were occupied as part of the World Ocean Circulation Experiment (WOCE) and post-WOCE repeat hydrographic programme. Instrumental and sampling (resulting from undersampling in the horizontal and in the vertical) errors are estimated to be 0.001°C and 0.002 for Θ and S respectively. A description of how these uncertainties are calculated is detailed in the work of *Naveira Garabato et al.* [2009]. In order to avoid spurious signals introduced by ACC frontal meandering and to look at water mass properties, the CTD data are re-gridded in neutral density/dynamic height (at 400 dbar relative to 2000 dbar, ϕ_{2000}) coordinates as in the work of *Naveira Garabato et al.* [2009].

2.2. Ancillary Data

[7] To attempt to establish a link between changes in AABW properties and climate variability over the Southern Ocean, we examine a range of ancillary data sets. Monthly zonal and meridional wind stress anomalies (anomalies are calculated by removing the annual cycle at each grid point) are extracted from the ECMWF ERA-Interim reanalysis (http://data-portal.ecmwf.int/data/d/interim_moda/) for the 1989–2009 period. The El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) (Figure 2, bottom) are the two dominant modes of large-scale climate variability in the Southern Ocean [see, e.g., *Marshall et al.*, 2004; *Turner*, 2004, and references therein]. We use the Bivariate EnSo Timeseries (BEST) ENSO index (http://www.cdc.noaa.gov/people/cathy.smith/best/) and an observation-based SAM index (http://www.antarctica.ac.uk/met/gjma/sam.html) to study their respective impacts on the Weddell/Drake Passage regional climate.

3. Interannual Variability of AABW Properties

[8] We compute the mean potential temperature, salinity and neutral density of the densest class of AABW (γ_n = 28.28–28.32 kg m^{-3}) regularly present in the SR1b section (Figure 2, top). Focussing on this density class provides statistical advantages, for the regional residence time of the denser AABW classes exported to the Scotia Sea has been estimated to be ~1 year [*Meredith et al.*, 2008a], thus allowing consideration of our sections as mutually independent. In practice, our results are qualitatively insensitive to the choice of density class.

[9] Figure 2 shows that the AABW in the SR1b section is subject to pronounced interannual variability (of amplitude ~0.1°, 0.01 and 0.01 for potential temperature, salinity and neutral density, respectively). Between December 2004 and December 2006, there is a strong cooling and freshening of the AABW, reaching minima of $\Theta \sim -0.26$°C and S ~ 34.666. Two other cold and fresh pulses occur around 1996 and 1999 ($\Theta \sim -0.22$°C and S ~ 34.666), although gaps in the time series limit the resolution of those events. No significant decadal trends are detected. This is perhaps to be expected given the relatively short length of the time series and the proximity to the AABW source, which results in the magnitude of the observed interannual variability in Drake Passage AABW temperature being much larger than the AABW warming trend reported in the South Atlantic (on the order of 0.0025°C yr^{-1}).

4. Relationship Between AABW Properties and Wind Stress Over the Southern Ocean

[10] The link between the interannual variability of AABW properties in the SR1b section and the baroclinicity of the Weddell gyre is investigated by calculating lagged correlations between the time series shown in Figure 2 and the monthly zonal wind stress anomalies south of 30°S.

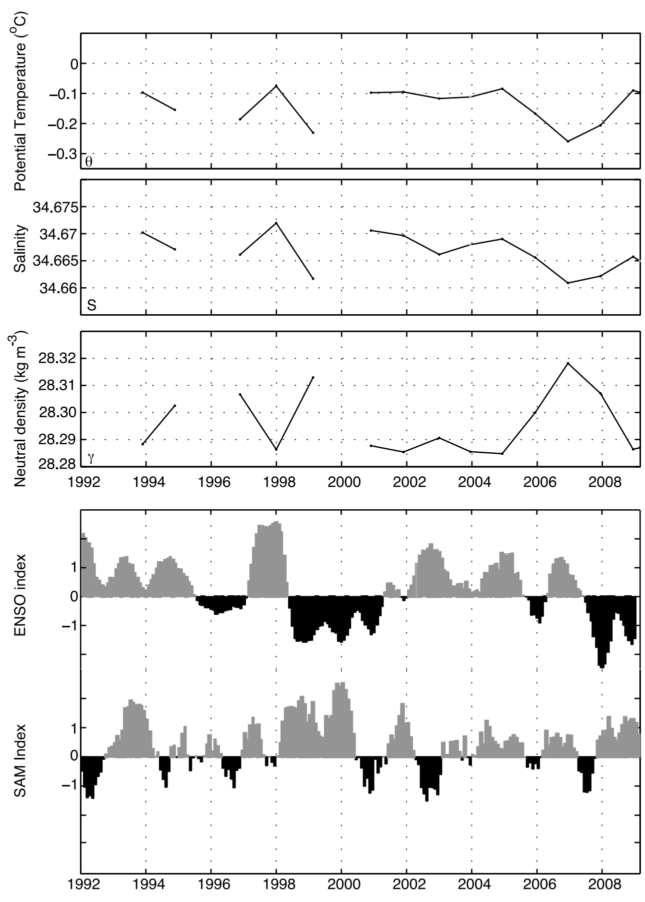

Figure 2. (top) Time series of potential temperature, salinity and neutral density of AABW on Sr1b. (bottom) The 1-year low-pass filtered ENSO and SAM indexes time series over the same period.

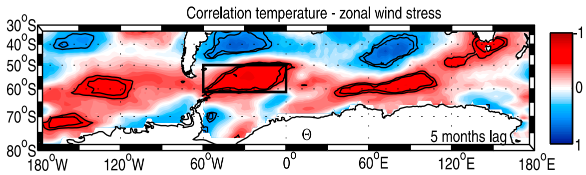

Figure 3. Spatial correlation at 5 months lag between the zonal wind anomalies and potential temperature time series of the densest AABW. The black line are the 90% and 95% confidence interval levels. The black box shows where the correlations of the averaged wind stress anomalies and the SAM and ENSO index are calculated.

High correlations are found with a 5-month lag over the Southern Ocean (Figure 3). The banded nature of the high positive/negative correlations over the Southern Ocean/subtropical region, which evoke a SAM-like pattern, clearly suggests that the variability of AABW properties is significantly influenced by large-scale changes in the wind stress. The circumpolar nature of the high correlations reflects the strong degree of coherence in the variability of the westerly wind stress over the Southern Ocean, mainly associated with fluctuations in the SAM.

[11] These results do not imply a causal relationship between the wind stress over the entire Southern Ocean and the interannual variability of AABW properties, but rather that hemispheric-scale changes in the wind stress co-vary with the winds (and the wind stress curl in particular) over the WS. The focus of our correlation analyses is on wind stress rather than on its curl because the scarcity of observations assimilated by the ERA-Interim reanalysis in the Southern Ocean and the second-order derivative nature of the curl render it very sensitive to errors. Moreover, we argue that because of the predominant zonal direction of the winds over the Southern Ocean, the wind stress curl is primarily driven by the meridional gradient of the zonal wind stress. Therefore, we conclude that the alternating bands in the correlation pattern over the Southern Ocean shown in Figure 3 strongly suggest that the wind stress curl over the Weddell region at five months lag controls the export of AABW out of the WS, likely through changes in the gyre's baroclinicity.

[12] Lagged correlations of local winds show significance at the 95% level with the SAM index at short time lags ($r = 0.496$ at 0 month lag). Correlations of local winds with the ENSO index are marginally significant at the 95% level at very short lags ($r = -0.141$ at 0 month lag), and also at lags approaching 3 years, reflecting the quasi-cyclical nature of this climate mode. Correlations with SAM greatly exceed those with ENSO in magnitude, reflecting the predominance of this mode in determining local winds. During a positive (negative) SAM phase, stronger (weaker) westerlies between 50°S and 70°S increase (decrease) the wind stress curl and predictably spin up (slow down) the cyclonic Weddell gyre, contracting (relaxing) isopycnals and leading to a warmer, saltier and lighter (cooler, fresher and denser) class of AABW being exported to the Scotia Sea.

5. Discussion

[13] We provide evidence that interannual variability in the properties of the AABW exiting the WS toward Drake Passage is driven by the wind stress curl over the Weddell gyre, likely through changes in the gyre's baroclinicity affecting the density classes of the AABW exported out of the WS. The time lag involved (5 months) suggests that the gyre must adjust over time scales of two months (assuming a velocity of 0.1 m s^{-1} [*Nowlin and Zenk*, 1988] results in a transit time of 3 months from the Orkney Passage to Sr1b). Little is known about the extent, controls and time scales of the variability in the Weddell gyre's baroclinic structure, partly because of the lack of wintertime hydrographic measurements. *Meredith et al.* [2008a] discussed some localized observational evidence suggestive of interannual changes in the gyre's baroclinicity. *Beckmann et al.* [1999], in turn, showed that the gyre transport in the BRIOS general circulation model exhibits a marked annual cycle correlated with the local wind stress curl, but did not comment on the modal partitioning of the gyre's response. However,he 2–3 month baroclinic adjustment time scale found here appears short in the context of geostrophic adjustment theory [e.g., *Anderson and Gill*, 1975], which suggests that baroclinic adjustment to changes in wind forcing for a Weddell-sized basin should occur on considerably longer (multiannual) time scales. Some observational evidence indicating substantial wind-forced baroclinic adjustment of a sub-polar gyre on seasonal time scales is available from the high-latitude North Atlantic and Arctic oceans [e.g., *Proshutinsky et al.*, 2002]; however, the mechanistic interpretation of this fast response is unclear and requires further investigation.

[14] We have shown that the variability of the zonal wind stress over the northern WS is modulated by the SAM over relatively short time scales (0–5 months). *Martinson and Iannuzzi* [2003] instead highlighted the possible role of ENSO in influencing the intensity and upper-ocean properties of the Weddell gyre, through changes in cyclonic forcing over the region. Our results suggest that the SAM is the primary climate mode (with a secondary influence of ENSO) regulating the gyre's baroclinicity and the export of AABW out of the WS.

[15] Many previous studies have demonstrated how atmospheric forcing can influence the properties of upper-ocean and intermediate water masses in the Southern Ocean [e.g., *Meredith et al.*, 2008b; *Sallée et al.*, 2008; *Naveira Garabato et al.*, 2009]. Here, we provide rare evidence of a direct, short-term (~5 months) influence of atmospheric variability on the properties and (implicitly) circulation of bottom waters at some distance from their source. This highlights the complex coupled nature of atmosphere/ocean/topography interactions in the Southern Ocean, and emphasizes the challenge inherent in trying to resolve these processes in simulations of the lower limb of the oceanic overturning circulation.

[16] We have observed pronounced interannual variability of AABW properties at a distance from its source. This illustrates the difficulty in reliably determining interdecadal variations in bottom water properties in regions near the water mass formation areas from temporally-sparsed hydrographic measurements. Notwithstanding this, the mechanism we have suggested here to explain interannual changes in AABW property may also underlie the warming trend observed along much of the length of the Atlantic Ocean in recent decades. Indeed, as well as interannual variability, SAM has exhibited a trend toward a more positive state (implying stronger westerly winds over the

Southern Ocean) since the 1960s, due at least partly to anthropogenic causes [*Marshall et al.*, 2004; *Thompson and Solomon*, 2002]. This is the correct sign of change to lead to a warming of the AABW exported from the WS, if the mechanism we have outlined is also in operation on decadal time scales. If proven, this would indicate that the warming observed along nearly the entire length of the abyssal Atlantic in recent decades has a root cause that includes forcing from anthropogenic actions.

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