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Synchronous intensification and warming of Antarctic Bottom Water outflow from the Weddell Gyre

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[1] Antarctic Bottom Water (AABW), the densest water in the global overturning circulation, has warmed in recent decades, most notably in the Atlantic. Time series recorded within the boundary currents immediately upstream and downstream of the most significant outflow of AABW from the Weddell Sea indicate that raised outflow temperatures are synchronous with stronger boundary current flows. These changes occur rapidly in response to changes in wind forcing, suggesting that barotropic dynamics and the response of the bottom Ekman layer are significant. The observed synchronicity indicates that the previously-detected weakening of the export of the colder forms of AABW from the Weddell Sea need not be associated with a reduction in the total flux of AABW exported via this route. These points need careful consideration when attributing the observed AABW warming in the Atlantic, and when determining its contribution to global heat budgets and sea level rise.
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1. Introduction

[2] The Weddell Sea hosts the production of Weddell Sea Deep Water (WSDW), the main contributor to the cold Antarctic Bottom Water (AABW) that permeates much of the global ocean abyss [*Orsi et al.*, 1999]. While AABW in the low-latitude Atlantic is often taken as the ensemble of waters colder than 2°C, WSDW itself has potential temperatures between ~0 and −0.7°C, and forms directly through intense air-sea-ice interaction at the periphery of the Weddell Sea, as well as via upwelling of Weddell Sea Bottom Water [e.g., *Gordon et al.*, 2001; *Meredith et al.*, 2000]. It circulates cyclonically within the boundary currents of the Weddell gyre before being exported across and around the South Scotia Ridge (Figure 1), with Orkney Passage (OP) being the most direct throughflow for WSDW to enter the Atlantic overturning circulation [*Naveira Garabato et al.*, 2002; *Schodlok et al.*, 2002]. Around one quarter of all dense Antarctic-derived waters colder than 0°C flow through OP, after which they flow north and east across the Scotia Sea [*Meredith et al.*, 2001, 2008] and westward in a boundary current toward Drake Passage. They do not, however, penetrate significantly into the Pacific [*Nowlin and Zenk*, 1988].

[3] In recent decades, AABW has warmed significantly in many regions, most strongly in the Atlantic [e.g., *Meredith et al.*, 2008; *Zenk and Morozov*, 2007]. This warming has reached the North Atlantic, where it was interpreted as a slowing in the meridional overturning of Antarctic-derived waters [*Johnson et al.*, 2008]. The warming has a magnitude of potential significance for the global heat budget and calculations of sea level rise [*Purkey and Johnson*, 2010].

[4] There have been a number of investigations of variability of deep and bottom waters in the Weddell Sea [e.g., *Fahrbach et al.*, 2004; *Schröder et al.*, 2002], however the absence of clearly-defined trends in WSDW properties has focused attention on processes that might control its characteristics as it exits the Weddell Sea. Based on hydrographic data from the Scotia Sea, *Meredith et al.* [2001, 2008] proposed that changes in cyclonic wind-forcing over the Weddell gyre could impact on the steepness of isopycnal surfaces in the northern Weddell Sea, and hence on the temperature of the coldest water that crosses the South Scotia Ridge. *Jullion et al.* [2010] used a more comprehensive data set, and found a surprisingly short lag (just a few months) between changes in wind stress curl over the Weddell gyre and temperatures of WSDW exported through OP. If such processes were relevant on decadal timescales, the observed strengthening of winds over the Southern Ocean [e.g., *Thompson and Solomon*, 2002] could plausibly be responsible for the warming of AABW in the Atlantic, due to the coldest classes of WSDW being progressively restricted from crossing the South Scotia Ridge [*Meredith et al.*, 2008]. Here we present observational evidence and dynamical arguments concerning local controls on both the temperature and strength of the outflow of WSDW from the Weddell Sea, and discuss the implications for large-scale water mass properties and ocean climate.

2. Data Sources

[5] Data were obtained from two *in situ* instruments, one in the northern Weddell Sea, and one in the southern Scotia Sea (Figure 1). The former was the uppermost instrument on mooring M2 of the Consortium on the Ocean's Role in Climate: Abrupt Climate Change Studies (CORC-ARCHES) program [e.g., *Gordon et al.*, 2010]. M2 was deployed at 62°38′S, 43°15′W in water depth ~3059 m, with the uppermost instrument (a Sea-Bird SBE37 Microcat temperature/conductivity recorder) located 2580 m below the surface. The latter was the Multi-Year Recording Tide

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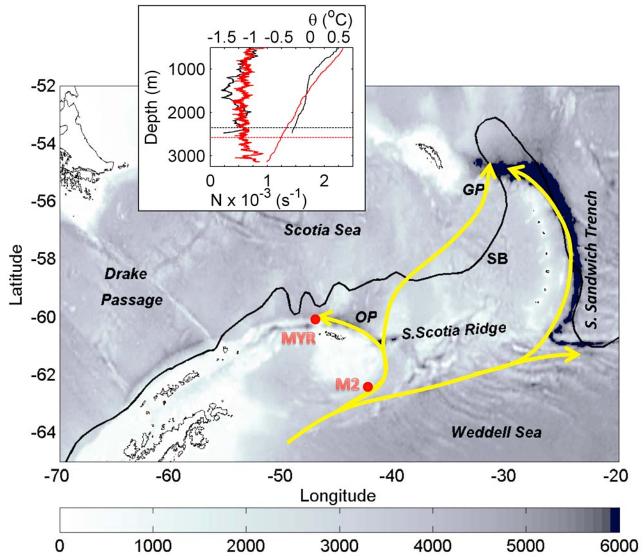

Figure 1. Locations of M2 and MYRTLE in the northern Weddell Sea and southern Scotia Sea (red dots). Yellow arrows depict the primary flow paths of WSDW through the region: Orkney Passage (OP) on the South Scotia Ridge and Georgia Passage (GP) at the northeastern Scotia Sea are key throughflows. The Southern Boundary (SB) of the Antarctic Circumpolar Current is marked. Background shading is depth (m). Inset shows typical potential temperature and buoyancy frequency profiles from the location of M2 (red) and close to the site of MYRTLE (black). The depths of the MYRTLE and M2 temperature sensors used here are marked.

Level Equipment (MYRTLE) [*Spencer and Foden*, 1996], a long-duration bottom pressure recorder deployed on the seabed at 60°03′S, 47°10′W (~2350 m depth) between late 1999 and late 2003. The MYRTLE temperature sensor was not calibrated for absolute temperature, so only anomalies are used; these are precise to 0.001°C. We also use wind stress data from the ERA-Interim reanalysis (http://www.ecmwf.int/products/data/archive/descriptions/ei/index.html).

3. Results

[6] MYRTLE and M2 temperature anomalies correlate well for much of their length with a lag of 120 days (M2 leading MYRTLE; Figure 2a), specifically during 2002 and 2003 for which the correlation at this lag (0.6) is significant at the 95% level. (Note that MYRTLE is scaled by 0.7 in Figure 2. M2 data were obtained from the uppermost instrument on a long mooring, whilst MYRTLE data were obtained with a bottom lander and hence came from closer to the core of the bottom-intensified boundary current). For a path length between the two sites of ~500 km (Figure 1), this 120 day lag equates to a flow speed of ~4.8 cm s^{-1}, somewhat less than the 7.9 cm s^{-1} quoted by *Nowlin and Zenk* [1988] for boundary current speeds at ~2000 m depth to the west of MYRTLE. However, considering the full period of data overlap suggests that ~4.8 cm s^{-1} may underestimate the true long-term mean. Specifically, during 2001, the lag of 120 days shows poor agreement between MYRTLE and M2 (Figure 2a), whereas 60 days yields significantly better agreement. (For this section of data, a 120 day lag gives a correlation of 0.2, compared with 0.55 for 60 days). This shorter lag equates to a flow speed of ~9.6 cm s^{-1}. For comparison, long-term current meter records at M2 give a mean speed of 8.3 cm s^{-1} [*Gordon et al.*, 2010], though no such data are available from M2 for 2001 itself.

[7] Significantly, temperature anomalies during the period of shorter-lag correlation (2001) were higher than those during the period of longer-lag correlation (2002 and 2003) (Figure 2). The length of the transition between these two periods is hard to quantify precisely, but cannot exceed a few months (Figure 2).

[8] The depths of M2 and MYRTLE data were different, at ~2580 m and 2350 m respectively. Recent multi-beam echo sounder data (not shown) give a sill depth of ~3600 m for the narrowest part of OP, and depths ~2500 to ~3350 m along a shallower ridge immediately upstream. This indicates that WSDW passing the top of M2 can cross the South

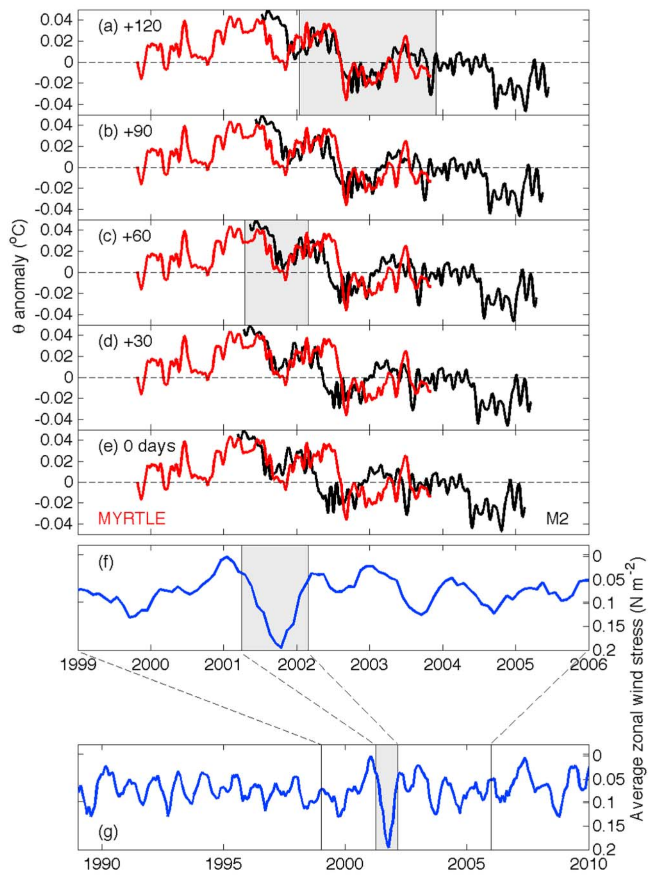

Figure 2. (a–e) Temperature anomaly at M2 (black) and MYRTLE (red), for lags of 0 to 120 days. MYRTLE and M2 correlate well at 120 days lag, except for the first ~9 months, during which a 60 day lag yields the highest correlation (shaded boxes in Figures 2a and 2c highlight these periods). (f) Zonal wind stress averaged over the northern Weddell Sea (area of averaging marked in Figure 3a). Curve is a five-point running average of monthly-mean values, plotted inverted. Shaded box is as per Figure 2c, during which period wind forcing reached a record-length extreme. (g) As for Figure 2f, but for the full length of ERA-Interim.

Scotia Ridge relatively unimpeded, although it will sink and mix as it does so. That the M2 and MYRTLE temperature anomalies show strong similarities indicates vertical coherence in temperature, given this sinking and mixing and the shallower location of MYRTLE compared with M2.

4. Discussion

[9] Coincident with the period of shorter-lag correlation between MYRTLE and M2, zonal wind stress along the South Scotia Ridge was anomalously strong during the latter part of 2001 (Figures 2f, 2g, and 3), with the end of this period matching closely the transition to the longer-lag relationship between MYRTLE and M2 (Figures 2a and 2c). This echoes the timescale of just a few months for the response of WSDW to winds found previously [*Jullion et al.*, 2010]. Given the rapid and synchronous response of WSDW temperature and speed to changes in forcing, we suggest that the key mechanism involved is the response of the bottom Ekman layer to barotropic changes in the strength of the deep boundary current that flows along the sloping topography of the northern Weddell Sea.

[10] As described by *Garrett et al.* [1993] and *Brink and Lentz* [2010] amongst others, any along-slope geostrophic flow over sloping topography gives rise to a bottom Ekman layer that displaces isopycnals away from their equilibrium depth and that is ultimately arrested by buoyancy forces. The arrest time for a downwelling-favorable along-slope geostrophic flow such as the deep boundary current in the northern Weddell Sea (or, in other words, the time scale on which a change in the along-slope geostrophic velocity is balanced by an adjustment of the bottom Ekman layer) is estimated by $t_{arrest} = 0.5\ c_d^{-1}\ N^{-1}\ S^{-3/2}$, where c_d is the frictional bottom drag coefficient, N is the buoyancy frequency, and $S = N^2 f^{-2} \sin^2\theta$ is the Burger number based on the bottom slope (tan θ) and the inertial frequency f [*Garrett et al.*, 1993]. Using values typical for the northern Weddell Sea boundary current ($c_d \approx 2.5 \times 10^{-3}$, $N \approx 10^{-3}$ s^{-1}, $f \approx 10^{-4}$ s^{-1}, $\theta \approx 2°$, $S \approx 0.12$), we obtain $t_{arrest} \sim 54$ days, broadly consistent with the baroclinic adjustment time scale suggested by the observations.

[11] That the bottom Ekman velocity anomaly associated with the adjustment process is sufficiently large to produce the observed change in WSDW temperature may be shown using the relationship between the Ekman layer velocity v_{Ek} and the along-slope geostrophic speed U_g, i.e., $v_{Ek} = 2.5\ c_d^{1/2}\ U_g$, where the reduction in the Ekman flow resulting from buoyancy effects has been neglected for simplicity [e.g., *Brink and Lentz*, 2010]. An approximate halving of the boundary current speed from ~0.1 m s^{-1} in the last 9 months of 2001 to ~0.05 m s^{-1} thereafter is suggested by observations, implying a reduction in v_{Ek} of ~6 × 10^{-3} m s^{-1}. If such a reduced Ekman flow acted adiabatically on a topographic slope $\theta \approx 2°$ over a time scale $t_{arrest} \sim 54$ days, the implied uplift of isopycnals would be ~900 m, well in excess of the ~100 m suggested by observations. In practice, this isopycnal displacement is a gross overestimate, due to the assumption that the Ekman flow on the slope proceeds unimpeded by buoyancy forces, and serves simply to quantitatively illustrate the plausibility of the proposed mechanism of baroclinic adjustment.

[12] Other potential mechanisms do not seem able to explain our rapid synchronous changes in WSDW outflow temperature and strength. For example, at typical rates of O(10 m y^{-1}), local forcing by anomalous surface Ekman pumping/suction would take several years to displace isopycnals vertically by ~100 m, the amount required to change the temperature of the coldest WSDW exported by the ~0.04°C observed [e.g., *Gordon et al.*, 2001]. Further, changes in the formation properties of WSDW such as have been inferred [e.g., *Fahrbach et al.*, 2004] are unlikely to have the rapid timescale that characterize the shifts in both temperature and flow speed that we have observed, nor are they likely to have such a short-period relationship to changes in local atmospheric forcing.

[13] We hypothesized previously that large-scale cyclonic wind forcing over the extent of the Weddell gyre may control the northward export of WSDW across the South Scotia Ridge [*Meredith et al.*, 2001, 2008]. Our new observations do not preclude this, however it is important to note that classical gyre-wide baroclinic adjustment at high latitudes is characterized by time scales of decades [e.g., *Anderson and Gill*, 1975], which would result in a significantly longer response timescale than that observed here. We thus suggest that any comparatively slow changes in outflow due to changes in large-scale cyclonic forcing will have more rapid (and potentially larger) changes superposed on them due to barotropic and Ekman processes near the outflow itself.

5. Conclusions

[14] AABW in the Atlantic is warming rapidly, and determining the causes of this is important if the implications for global heat budgets and sea level rise are to be correctly quantified and understood. If, as has been suggested previously, the cause of this warming were a reduction in the northward export of the colder classes of WSDW (as opposed to the same volume being exported with higher temperatures) such calculations will need to account for this to avoid regional overestimates of heat content and thermal expansion. Our findings support the notion of the colder classes of WSDW being progressively restrained from leaving the Weddell Sea, however the synchronous nature of the temperature and export speed of WSDW in response to changing winds adds significant further complexity. Specifically, it now seems possible that a wind-induced reduction in the export of the colder classes of AABW into the Atlantic overturning circulation can be associated with an increase in the export of the warmer classes. The balance between these factors in controlling the overall export flux is presently unknown.

[15] Similar to the AABW in the North Atlantic [*Johnson et al.*, 2008], bottom waters in the North Pacific have also warmed recently [*Fukasawa et al.*, 2004]. The rapid timescale of this warming (order of four decades) was likely accomplished by a fast teleconnection facilitated by internal Rossby and Kelvin waves, which have the action of slowing the deep currents that transport AABW northwards. If true also in the Atlantic, with the perturbations that generated the wave teleconnection being changes in the WSDW outflow of the type described here, the superposition of such fast wave-mediated signals upon slower advective changes would generate significant complexity, and make attribution of measured deep ocean climate change even more challenging. This is compounded by the fact that the outflow

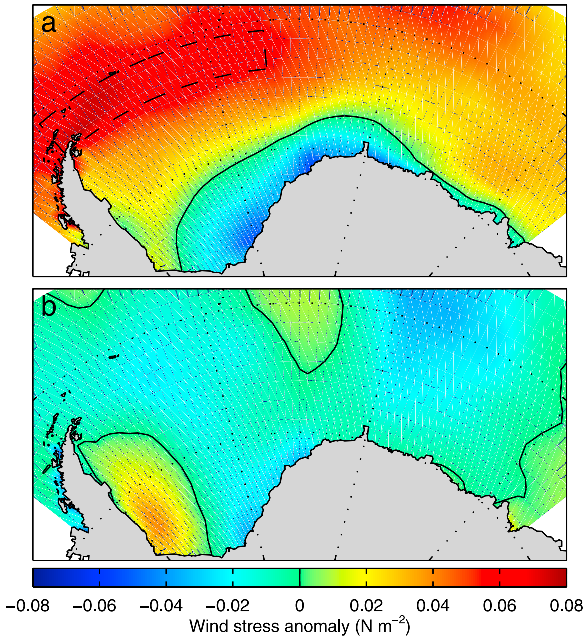

Figure 3. (a) Zonal and (b) meridional wind stress anomalies respectively, for the last 9 months of 2001. The zero N m^{-2} contour is plotted. Note the strong anomaly in eastward wind stress at the northern edge of the Weddell Sea during this period.

processes outlined here are not represented in current climate-scale ocean models.

[16] The changes in WSDW observed here were caused by changes in winds that project strongly onto the pattern of the Southern Annular Mode (SAM), consistent with *Jullion et al.* [2010]. The SAM has moved to a higher-index state in recent decades, associated with anthropogenic forcing from ozone depletion and/or greenhouse gases, resulting in stronger winds over the Southern Ocean [*Marshall*, 2003; *Thompson and Solomon*, 2002]. To the extent that the mechanisms described here are relevant on decadal timescales, this carries the implication that anthropogenic processes may be significant in the abyssal warming along the length of the Atlantic. If the winds over the Southern Ocean continue to strengthen in future years and decades (either via there being a stronger mean, or more frequent events such as that seen in 2001), this could result in warmer classes of WSDW being supplied more efficiently to the lower limb of the global overturning circulation. To detect and correctly attribute such changes, a system capable of monitoring both properties and fluxes is required. Accordingly, we will deploy shortly a comprehensive mooring array in the narrowest part of OP. Sustaining this for several decades will be difficult, but is required to meet the challenges outlined here.

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