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Dense bottom layers in the Scotia Sea, Southern Ocean: Creation, lifespan, and destruction

Michael P. Meredith,[1] Peter J. Brown,[1,2] Alberto C. Naveira Garabato,[3] Loïc Jullion,[3] Hugh J. Venables,[1] and Marie-José Messias[2]

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[1] The lower limb of the Atlantic overturning circulation is renewed by dense waters from the Southern Ocean, a substantial portion of which flow through the Scotia Sea. We report dense bottom layers here, with gradients in temperature and salinity comparable to those seen near the surface of the Southern Ocean. These are overlain by layers with much weaker stratification, and are caused by episodic overflows of dense waters across the South Scotia Ridge, and topographic trapping within deep trenches. One such layer was found to be at least 3–4 years older than the water immediately above. The estimated vertical diffusivity to which this layer was subject is substantially less than the strong basin-average deep mixing reported previously. We conjecture that (a) vertical mixing in the Scotia Sea is strongly spatially inhomogeneous, and (b) the flushing of these layers, like their formation, is related to overflow events, and hence also strongly episodic. **Citation:** Meredith, M. P., P. J. Brown, A. C. Naveira Garabato, L. Jullion, H. J. Venables, and M.-J. Messias (2013), Dense bottom layers in the Scotia Sea, Southern Ocean: Creation, lifespan, and destruction, *Geophys. Res. Lett.*, *40*, 933–936, doi: 10.1002/grl.50260.

1. Introduction

[2] The deep oceanic meridional overturning circulation (MOC) derives from dense water sinking in a small number of localities and generalized upwelling elsewhere. The densest waters that participate in the MOC form around the periphery of Antarctica, and their northward spreading cools and ventilates much of the global abyss [*Johnson*, 2008]. The Weddell Sea is a primary site for the production and export of such waters, with Weddell Sea Deep Water (WSDW) transiting both through and around the Scotia Sea (Figure 1) to become the densest component of Antarctic Bottom Water in the Atlantic [*Naveira Garabato et al.*, 2002]. The main route for WSDW to enter the Scotia Sea is via the Orkney Passage, the deepest cleft in the South Scotia Ridge, while the predominant outflow is Georgia Passage, immediately east of South Georgia (Figure 1) [*Naveira Garabato et al.*, 2002]. During its northward flow, WSDW undercuts the predominantly eastward-flowing Antarctic Circumpolar Current (ACC; Figure 1).

[3] The WSDW in the Atlantic has warmed substantially in recent years, at a rate that is potentially significant for sea level rise and global heat budgets [*Purkey and Johnson*, 2010]. The cause is not yet fully understood; however, a spatially structured warming has been demonstrated in the Scotia Sea, with superposed interannual changes caused by variations in overflow across the South Scotia Ridge [*Meredith et al.*, 2008]. Recently, local wind-forced variability has been implicated in controlling the overflow of dense water across this ridge, with an episodic nature highlighted [*Jullion et al.*, 2010; *Meredith et al.*, 2011]. A reversal of the abyssal flow in Georgia Passage was also hypothesized, whereby dense water could enter the Scotia Sea episodically from the northeast [*Meredith et al.*, 2001].

[4] Here we present new evidence that temporal changes in the overflow across the South Scotia Ridge can lead to remarkably strong gradients in bottom layer properties in the Scotia Sea. We demonstrate that such bottom layers can persist for several years, and discuss the implications for the locations, mechanisms, and time scales of modification of dense waters that spread from the Weddell Sea into the Atlantic MOC.

2. Methods

[5] Hydrographic data were obtained from five occupations of a transect in the eastern Scotia Sea, undertaken in April 1995, April 1999, January 2005, April 2010, and April 2012 (Figure 1). Data from the first three have been reported previously (see *Meredith et al.* [2008] for details of data processing, calibration, etc.); the latter two were undertaken from RRS *James Clark Ross*, with data to near-seabed obtained with a SeaBird 911*plus* profiler. Transient tracer data from 2010 are used, specifically concentrations of dichlorodifluoromethane (CFC-12), trichlorofluoromethane (CFC-11), trichlorotrifluoroethane (CFC-113), and sulphur hexafluoride (SF_6). *Meredith et al.* [2010] gives full details; in brief, tracer concentrations were measured using a double purge-and-trap extraction technique, allied to two gas chromatographs with electron capture detectors. This combines the methods of *Smethie et al.* [2000] and *Law et al.* [1994], with a common valve for sample introduction. Water was drawn from Niskin bottles, and concentrations (on the SIO-1998 scale) were calculated relative to an external gaseous standard supplied by NOAA. Blank corrections were applied and duplicate analyses undertaken to determine analytical precision (1.4% for SF_6, 0.7% for CFC-12, 0.5% for CFC-11, and 1.1% for CFC-113). Some tracer data were collected in other years; however, SF_6 is

[1]British Antarctic Survey, High Cross, Madingley Road, Cambridge, UK.
[2]School of Environmental Sciences, University of East Anglia, Norwich, UK.
[3]National Oceanography Centre, University of Southampton, European Way, Southampton, UK.

Corresponding author: M. P. Meredith, British Antarctic Survey, High Cross, Madingley Rd., Cambridge, CB3 0ET, UK. (mmm@bas.ac.uk)

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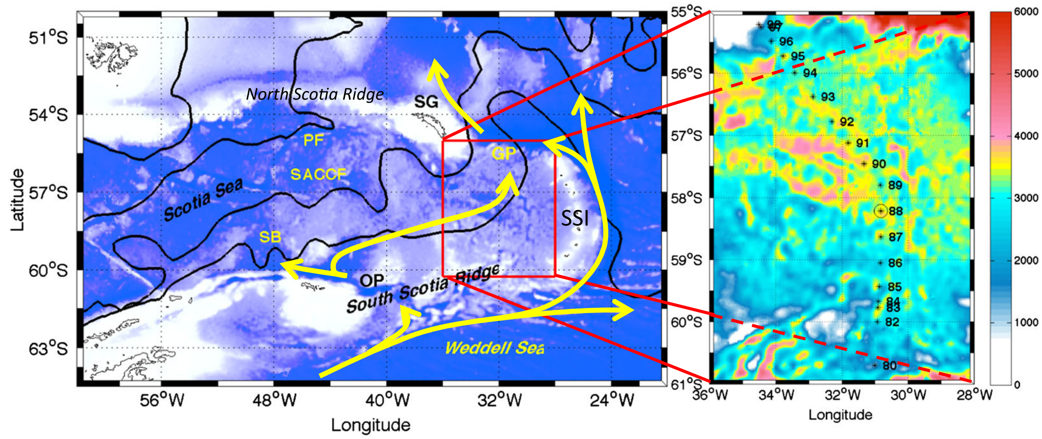

Figure 1. Bathymetry of the Scotia Sea, with South Georgia (SG), Georgia Passage (GP), South Sandwich Islands (SSI), and Orkney Passage (OP) marked. The Polar Front (PF), Southern ACC Front (SACCF), and Southern Boundary (SB) are also marked. The flow of WSDW is shown schematically (arrows). The inset shows detailed topography from the eastern Scotia Sea, with 2010 stations marked. (The same locations were occupied in other years except 2005, which had coarser spatial coverage, and 2012, which had no stations north of 57°S). Station 88 is circled.

the key tracer for our analyses, hence only 2010 data are used here.

[6] Age differences between the bottom of a tracer profile and the overlying water were derived by converting the atmospheric histories for CFCs and SF_6 (*Walker et al.* [2000], *Maiss and Brenninkmeijer* [1998], and updates) to time series of seawater concentrations appropriate to the temperature and salinity of the layers. This assumes a mixing recipe whereby 33% of the Lower WSDW (LWSDW) originates from recently-ventilated shelf waters (with assumed saturation of 0.55 for CFCs and 0.50 for SF_6) and 67% from poorly ventilated warm deep water (assumed saturation of 0.05). These values were derived from established tracer concentrations in shelf waters and deep Southern Ocean waters [e.g., *Huhn et al.*, 2008; *Rodehacke et al.*, 2010, etc.]. Sensitivity studies were conducted, whereby the percentage of recently-ventilated water in the LWSDW was varied by ±10%, and the saturation of SF_6 relative to CFCs varied by ±10%; these are used to determine the range in age differences quoted below.

[7] Because of uncertainties in the exact composition and mixing history of LWSDW, we cannot determine reliable ages for the waters measured. However, the near-linear nature of the SF_6/CFC ratios allows a constraint on the age difference between two parcels of the same type of water to be determined robustly. This is a lower limit to the true age difference, because mixing will decrease the vertical gradients in tracer ratio.

3. Results

[8] South of the Southern Boundary of the ACC (Figure 1), WSDW exhibits subtle potential temperature-salinity inflections at the 28.31 kg m^{-3} neutral density (γ^n) surface in two occupations (Figure 2). This surface defines the boundary between LWSDW and Upper WSDW (UWSDW), with LWSDW being topographically constrained within the Scotia Sea, and needing to mix upward before exiting the basin. The first of these inflections (in 1999) took the form of LWSDW being saltier for a given potential temperature relative to the gradient of the UWSDW curve. This was interpreted as an

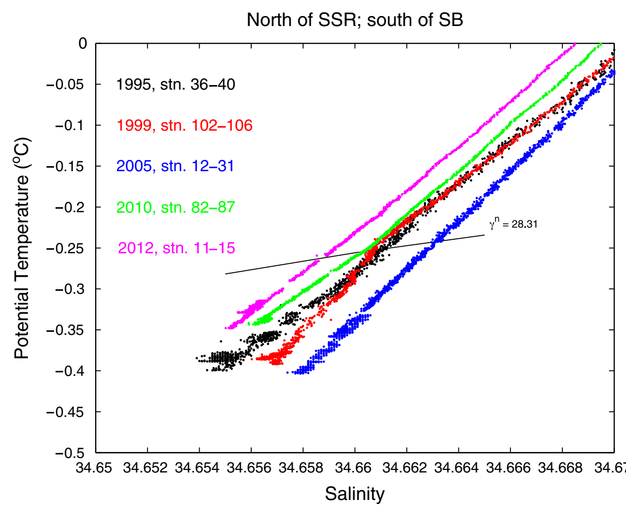

Figure 2. Mean potential temperature-salinity curves for waters south of the Southern Boundary, obtained by averaging the appropriate profiles each year. The 28.31 kg m^{-3} neutral density surface is marked.

incursion of abyssal LWSDW from around the South Sandwich Islands into the Scotia Sea through Georgia Passage, while UWSDW was freshened slightly by waters spilling from the tip of the Antarctic Peninsula [*Meredith et al.*, 2001; *Whitworth et al.*, 1994]. The absence of an inflection in other years was explained by all the WSDW crossing the South Scotia Ridge at those times. The second inflection at γ^n = 28.31 kg m^{-3} occurred in 2010, and is noteworthy because of its opposite sign, with fresher LWSDW for a given potential temperature. This cannot be explained by a reversal in seabed flow through Georgia Passage, which could only explain a relative salinification of abyssal waters in the Scotia Sea.

[9] It is argued here that the inflection in 2010 is caused by the episodic nature of the dense overflow across the South Scotia Ridge. WSDW that flows through Orkney Passage always includes LWSDW classes, and while the spread of salinity seen in Figure 2 is comparable to the measurement uncertainty, it is nonetheless known that dense waters of

Weddell Sea origin exhibit a genuine range of salinity for a given potential temperature [e.g., *Gordon et al*., 2010, and references therein]. Because LWSDW is topographically constrained within the Scotia Sea (unlike UWSDW, which can flow out uninhibited), a vertical gradient in residence time will exist across the $\gamma^n = 28.31$ kg m^{-3} surface. Combined with temporal changes in the potential temperature-salinity relationship of the overflowing water, this can create a marked boundary in properties at this interface.

[10] If the 2010 inflection were caused by intermittency in the dense overflow across the South Scotia Ridge, a question then arises: could the 1999 inflection not be created similarly, without the need to invoke reversals in abyssal circulation through Georgia Passage? Applying Occam's razor, this is indeed a simpler hypothesis that still reconciles all the observations, and hence a more likely explanation.

[11] In the northern Scotia Sea, there are several bottom layers that exhibit strong vertical gradients in hydrographic properties, with stratification comparable to that in the near-surface Southern Ocean pycnocline (Figure 3). These layers occur in different places in different years, and are sometimes absent altogether. When present, they occur in the deep trenches that dissect the northern Scotia Sea, and which can be many hundreds of meters deep (Figure 1). We argue here that these layers are manifestations of the same episodic nature of WSDW overflow at the South Scotia Ridge that causes the inflections further south, i.e., an overflow event allows an anomalously dense class of WSDW to spread through the Scotia Sea, with the densest part becoming trapped in the trenches. Layers with reduced stratification often overlie these dense layers; these are most likely caused as boluses of lighter LWSDW advect over the denser layers. In this respect, they are analogous to layers in the deep Caribbean Sea caused by the strongly episodic dense overflows there [*MacCready et al*., 1999].

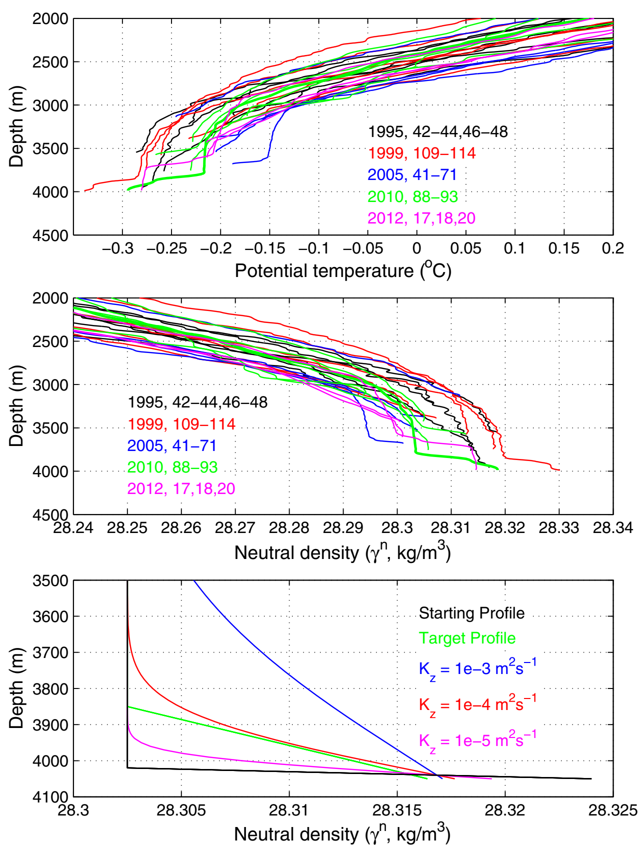

Figure 3. Potential temperature (top) and neutral density (middle) versus depth for stations north of the Southern Boundary. Note the strong abyssal layers in many profiles, overlain by layers with much weaker stratification. Thicker line denotes station 88. (bottom) Calculations to constrain rates of vertical mixing to which the dense layers are subject. Black line is starting density profile; green is the target profile (a close representation of station 88). Blue, red and magenta lines are the results after 3.5 years of vertical mixing with $K_z = 1 \times 10^{-3}$ m^{2}s^{-1}, 1×10^{-4} m^{2}s^{-1}, and 1×10^{-5} m^{2}s^{-1} respectively.

[12] This mechanism implies an age difference between the dense LWSDW layers in the trenches and the less dense layers above; we use the 2010 transient tracer data to demonstrate this. Three profiles that year exhibited dense bottom layers (Figure 3), but only one (station 88) had transient tracer measurements in the bottom layer. Of necessity, we focus on this station, accepting that it is not necessarily indicative of the general situation; it nonetheless usefully constrains the trapping time scale of these layers.

[13] Station 88 displayed SF_6 and SF_6/CFC ratios that decreased with depth through the dense bottom layer (Figure 4). A consequence of the monotonic increases in the atmospheric ratios (Figure 4) is that seawater with reduced ratios must be older. (The other possibility is that the waters formed as a mixture including a smaller percentage of recently-ventilated waters, which is not the case here.) Tracer ratios yield lower-limit age differences of 3.2–3.8 years (SF_6/CFC-113), 3.5–3.7 years (SF_6/CFC-12), and 3.3–3.6 years (SF_6/CFC-11). Overall, we obtain a robust lower limit of 3–4 years to the actual age difference between the dense bottom layer and the overlying water.

4. Discussion and Conclusions

[14] It was argued previously that LWSDW in the Scotia Sea was subject to intense mixing over a wide area, with a mean vertical diffusivity of $39(\pm 10) \times 10^{-4}$ m^{2}s^{-1} [*Heywood et al*., 2002]. For a LWSDW volume of $3.0(\pm 0.5) \times 10^{14}$ m^3,

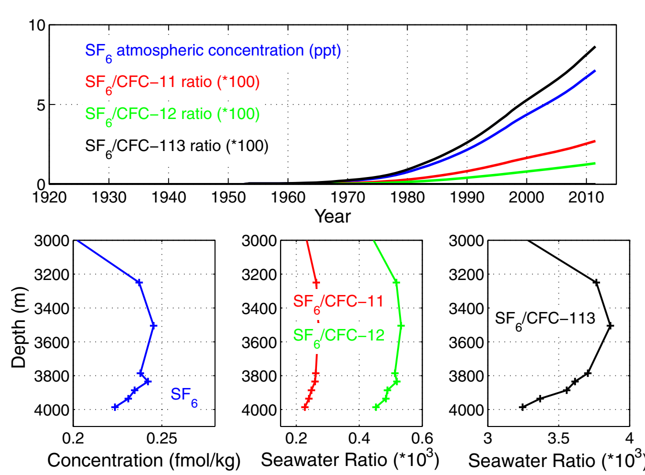

Figure 4. (top) Atmospheric SF_6 as a function of time, and its ratio to CFCs. (bottom) Profiles of SF_6, SF_6/CFC-11, SF_6/CFC-12, and SF_6/CFC-113, from station 88 in 2010.

this yielded a residence time of 2.4±0.5 years; rapid flushing of the deep Scotia Sea was highlighted. While this residence time resembles our constraint on the age of the 2010 dense layer (3–4 years older than the less stratified LWSDW layer above), there are profound differences in implications. First, our constraint for the layer is a lower limit to its true age. Second, our constraint relates to the age of the layer at the time of measurement: it is unknown how much longer it persisted thereafter. It is thus very possible that the layer we measured persisted significantly longer than the flushing time of LWSDW in the Scotia Sea overall. Given that LWSDW must mix upward prior to exiting the basin, this implies a vertical diffusivity for the dense layer smaller than 39×10^{-4} m^{2}s^{-1}. We constrain this further by solving

$$\frac{\partial \gamma^n}{\partial t} = \kappa_z \frac{\partial^2 \gamma^n}{\partial z^2}, \tag{1}$$

where t is time, z is height, K_z is vertical diffusivity, and it is assumed that the layer is largely isolated from its surroundings (advective terms are neglected) and that the vertical gradient of K_z is small. This is solved starting with an extreme density gradient for the layer (Figure 3), and then iteratively mixing for 3.5 years with prescribed K_z and an upper boundary condition that allows for diffusive flux. Different values of K_z were tried, and the similarity of the ending profile to that observed was qualitatively examined: we find that $K_z = 1 \times 10^{-4}$ m^2 s^{-1} can comfortably explain the structure of the layer observed (Figure 3). Given that our age constraint is a lower limit, and that the dense layer was deliberately chosen to have a very strong initial gradient, this represents an upper limit to the true vertical diffusivity to which the layer was subject. Although our calculation is crude, it is clear that the 39×10^{-4} m^2 s^{-1} for basin-average LWSDW mixing derived previously is much greater than the diapycnal mixing to which our layer was exposed.

[15] To understand this difference, it should be recognized that the high basin-average diffusivity reported previously will incorporate regions of stronger and weaker mixing. This raises the question: if our dense layers form in a region of comparatively weak mixing, where in the Scotia Sea is it significantly stronger? The most obvious candidate is the region around Orkney Passage itself, where LWSDW must negotiate extreme changes in topography, and where there have been direct indications of strong mixing previously [*Naveira Garabato et al.*, 2004].

[16] Although our temporal sampling is relatively coarse, there are no clear instances of layers persisting from one transect occupation to the next, despite their multiyear lifespan. Particularly effective in their demise could be overflow across the South Scotia Ridge of water as dense (or denser) than the layer present, with consequent rapid flushing of the trenches.

[17] Layers of the form observed can exist outside the Scotia Sea also: a similarly strong abyssal layer was observed in the Georgia Basin (north of South Georgia) in 2000 [*Meredith et al.*, 2003]. Its origin was not clear at the time, but it now seems likely that episodic overflow across the ridge that extends northeast from South Georgia is the most likely mechanism. Georgia Basin has much smoother topography than the Scotia Sea, and deep diapycnal mixing here is weaker [*Naveira Garabato et al.*, 2004]; nonetheless, it appears that some of the mechanisms controlling the modification of dense WSDW and the time scales of its spreading are similar.

[18] In summary, we have described how episodic overflows of dense WSDW into the Scotia Sea create bottom layers that become trapped by topography in the northern part of the basin, overlain by layers with much weaker stratification. The trapped layers can persist for a number of years, despite the reported strong basin-average deep diapycnal mixing; we hypothesize significant spatial structure in the rates and mechanisms of deep mixing in the Scotia Sea. With similar layers also observed outside the Scotia Sea, comparable controls may exist at other deep gaps along the WSDW spreading route in the Atlantic.

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