Dense waters of the Weddell and Scotia Seas: recent changes in properties and circulation

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The densest waters in the Atlantic overturning circulation are sourced at the periphery of Antarctica, especially the Weddell Sea, and flow northward via routes that involve crossing the complex bathymetry of the Scotia Arc. Recent observations of significant warming of these waters along much of the length of the Atlantic have highlighted the need to identify and understand the time-varying formation and export processes, and the controls on their properties and flows. Here, we review recent developments in understanding of the processes that control the changing flux of water through the main export route from the Weddell Sea into the Scotia Sea, and the transformations of the waters within the Scotia Sea and environs. We also present a synopsis of recent findings that relate to the climatic change of dense water properties within the Weddell Sea itself, in the context of known Atlantic-scale changes. Among the most significant findings are the discovery that the warming of waters exported from the Weddell Sea has been accompanied by a significant freshening, and that the episodic nature of the overflow into the Scotia Sea is markedly wind-controlled and can lead to significantly enhanced abyssal stratification. Key areas for focusing future research effort are outlined.

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1. Introduction

The dense waters that form around the periphery of Antarctica are key components of the global ocean circulation [1]. They are produced via intense air–sea–ice interaction over the continental shelf regions, including exchanges with the Antarctic ice sheet [2,3], and are subsequently exported northward to cool and ventilate much of the global ocean abyss [4,5]. Often collectively termed Antarctic Bottom Water (AABW), the flow of these waters constitutes much of the lower limb of the three-dimensional global ocean circulation. AABW can represent a large reservoir for heat and other tracers such as carbon dioxide, the changing volumes of which can be significant for modulating planetary climate [6,7].

Over the past several decades, perceptions have changed concerning where the dominant sources of AABW are located; however, the Weddell Sea (figure 1) is still considered to be volumetrically the most significant and has a particular relevance to Atlantic climate because of its role in renewing the densest layers of the Atlantic Meridional Overturning Circulation (AMOC) [8–10]. The broad shelves to the southwest and west of the Weddell Sea are key regions for dense water production, because brine-enriched waters can pool here for a number of seasons before descending into the deep ocean as part of the AABW mixture [2,9,11]. Similarly, the Filchner-Ronne and Larsen ice shelves that fringe the southwestern and western Weddell Sea, respectively, offer potential for the cooling of dense shelf waters below the surface freezing point, hence preconditioning the waters prior to their inclusion in AABW [11–13]. In addition to these sources located within the Weddell Sea, it has been demonstrated that a significant flow of AABW enters the basin from the east [14], and it was recently shown that this component of AABW forms predominantly near Cape Darnley due to the very intense sea-ice production there, without the requirement for an ice shelf or a broad continental shelf region [8]. There has been a suggestion of significant intermixing of AABW varieties from their different source regions as they penetrate the lower latitude basins [15], thus variability in the properties and export of AABW from the Weddell Sea has the potential to influence deep ocean properties around a large sweep of the Southern Hemisphere.

Within the Weddell Sea, AABW can recirculate within the Weddell Gyre, or, if it is sufficiently light, can escape to the north through gaps in the South Scotia Ridge or by flowing around the South Sandwich Islands at the eastern edge of the Scotia Sea (figure 1). The route through the Scotia Sea is the most direct, with AABW entering this basin predominantly via Orkney Passage (the deepest cleft in the South Scotia Ridge), and then flowing to the northeast to exit via Georgia Passage immediately to the east of South Georgia [16,17]. A further branch of AABW also flows westward as a boundary current towards Drake Passage (figure 1) [16].

One of the most marked changes in ocean climate in recent decades has been the warming of the deep ocean throughout much of the globe, with implications for sea level and the planetary-scale heat budget [18]. This warming has been especially marked in the southwest Atlantic [19,20], i.e. the region where deep waters are renewed predominantly from the Weddell Sea via the Scotia Sea, though this branch of warming has extended also into the North Atlantic at least as far as 24°N [21]. The causes of this warming are not yet well established, and attribution is challenging due to the possibility of planetary wave signals being superposed on the advective signals (cf. [22]), and the complications introduced by aliasing of temporally sparse hydrographic sections [23]. However, it has been hypothesized to be due to a reduction in the export of AABW and an associated slowdown of the lower cell of the AMOC [21], and, if verified, this would have significant implications for the long-term stability of climate and deep ocean ventilation. This highlights the need to understand better the drivers and controls on AABW properties, circulation and changes.

2. Changes in the Antarctic Bottom Water of the Weddell Sea: recent findings

Motivated by the large-scale warming of AABW and reports of its reducing flux along much of the length of the Atlantic [21], an obvious starting point is to examine changes of the dense
Figure 1. Schematic of dense water circulation within the Weddell Gyre (red), with primary export routes into and around the Scotia Sea, and into the southern Indian Ocean. Dense water injection into the gyre occurs at the periphery of the southwestern and western Weddell Sea (blue arrows), and there is inflow of deep waters from the east (purple arrow). Green lines denote locations of repeat hydrographic sections referred to in the text, using their original WOCE identifiers. Orkney Passage (OP) and Georgia Passage (GP) are marked.

waters within the Weddell Sea itself. The most comprehensive information relating to gyre-wide changes derives from the sustained programme of repeat hydrographic measurements on the Greenwich Meridian [24]. This has indicated a relatively invariant potential temperature for Weddell Sea Deep Water (WSDW, the component of AABW in the Weddell Sea that is light enough to be exported from the basin) during 1985–2000, followed by a rapid rise in temperature thereafter (figure 2). For the denser component of AABW in the Weddell Sea (Weddell Sea Bottom Water (WSBW), which is too dense to leave the Weddell Gyre directly), the changes are better characterized by a drop in temperature during the 1990s compared with the time immediately before or after. These changes were ascribed to variations in wind forcing over the Weddell Gyre, whereby changes in the intensity and shape of the gyre circulation could influence the inflow of warm, saline water from the Antarctic Circumpolar Current (ACC) and its reprocessing on and adjacent to the shelves into the cold, dense waters that form AABW [24]. However, it is not straightforward to relate the time scales of the temperature changes in the Weddell Sea waters with those observed downstream in the Atlantic. For example, at Vema Channel, the most significant throughflow of AABW from the Argentine Basin to the Brazil Basin in the South Atlantic, the bottom water has warmed at a relatively constant rate since the 1970s [20]. In this context, it is important to note that the bulk water mass changes within the Weddell Sea do not necessarily reflect well the changes in the boundary current systems that feed the overflow routes for AABW across the South Scotia Ridge, and that ultimately supply AABW to the lower cell of the AMOC in the Atlantic. Indeed, while some similarity between the properties of the AABW that recirculates within the Weddell Sea and that which is rapidly exported may be expected on long time scales, it is not the case that a strong correlation need exist between them on all time scales.

In the northwestern Weddell Sea, the boundary current upstream of the most significant outflow of AABW from the Weddell Sea (Orkney Passage; figure 1) has been monitored with moorings since the late 1990s [25,26]. From these data, a marked seasonal signal in the WSBW component has been detected [25], with significant interannual variability superposed [26]. Both of these have been linked to changing atmospheric circulation, with the latter related to large-scale modes of climate variability that can affect both the production of dense shelf water and
its export into the deep ocean. Seasonal and longer period changes in Weddell Sea dense water outflow and transports have been investigated using numerical models, and the role of wind forcing in controlling both the export of dense water from the shelves and the intensity of the gyre circulation on these time scales was highlighted [27, 28]. In the presence of significant seasonal and interannual variability, it is clear that the existing monitoring efforts need to be sustained in order to determine better the nature and cause of long-period (decadal) changes.

One branch of AABW that has shown a clear warming signal is the inflow at the eastern edge of the Weddell Gyre (figure 1). This water is believed to be a significant contributor volumetrically to the AABW found in the Weddell Sea, having formed further east (in the vicinity of Cape Darnley) and spread westward along the continental margin to penetrate into the Weddell Gyre [8, 29]. Based on repeat occupations of the World Ocean Circulation Experiment (WOCE) I6S line at around 30° E, a distinct warming of this AABW since the early 1990s was demonstrated [30]. Using transient tracer (chlorofluorocarbon) and other data, it was argued that this is due to a greater entrainment of warm, mid-depth waters of the ACC into the plumes of dense water that descend from the shelf in its formation region, ultimately caused by a climatological southward shift of the southern edge of the ACC [8, 30]. The expected salinification that would accompany the warming under this process was not observed, but separately a freshening of much of the AABW to the east of the Weddell Gyre has been detected, and it is likely that these factors were (to some extent) mutually compensating [30].

The negligible salinity change in the inflowing AABW from the east of the Weddell Gyre [30] coincided with relatively small changes in bulk AABW salinity along the Greenwich Meridian, with an increase in WSDW salinity during the 1990s and early 2000s reversing after 2005, and a decrease in WSBW salinity in the late 1980s ceasing after the early 1990s (figure 2) [24]. Downstream in the South Atlantic, salinity changes within Vema Channel since the 1970s have been weak [20]. Compared with the marked (and in some places, very strong) AABW freshening trends observed elsewhere around Antarctica, these facts could be deemed surprising [31, 32].

Figure 2. Mean potential temperature (a,c) and salinity (b,d) for WSDW (a,b) and WSBW (c,d) along the Greenwich Meridian in the Weddell Sea. The dashed lines represent the property averages for 1984–1993, 1994–2002 and 2003–2008. (Adapted from [24].)
New findings have changed this perspective. Using data from the WOCE SR1b section in eastern Drake Passage (figure 1), a recent study [33] documented a long-term freshening of AABW since 1993 (figure 3). Although these data were collected outside the Weddell Sea itself, it is well known that this branch of AABW derives from the WSDW that forms in the northwestern Weddell Sea (in the vicinity of the Larsen ice shelves) and then flows northward and eastward to cross the South Scotia Ridge, after which one limb flows westward towards Drake Passage (figure 1). Consequently, it was inferred that the AABW freshening observed in Drake Passage was indicative of freshening of WSDW happening at its formation sites in the western Weddell Sea [33]. Other processes that might potentially have affected the AABW properties, such as changing mixing as it flows over the rough topography of the South Scotia Ridge or changing bottom Ekman layer processes, were discounted as they would have affected the potential temperature–salinity relationship of the water mass in a manner different from that observed [33].

In terms of attribution, it was not the case that a unique process could unambiguously explain the freshening of AABW in Drake Passage; however, observations of a marked freshening of the shelf waters in the northwestern Weddell Sea gave further support to it having its origins there [34]. It was suggested that the collapse of the nearby ice shelves (most dramatically, Larsen B), and the acceleration of the glaciers that were buttressed by the ice shelf prior to its collapse, were instrumental in the freshening of the shelf waters and thus the AABW formed there, though smaller contributions from sea-ice changes and precipitation could not be excluded [33]. Importantly, given that the collapse of Larsen B has been argued to have an anthropogenic cause (specifically an intensification of atmospheric circulation and increase of air temperatures on the eastern side of the Antarctic Peninsula [35]), this is suggestive of an anthropogenic change in abyssal water properties over potentially large scales. Given the putative causes of the salinity decrease, and the potential for its continuation given the current nature of climate change in its formation region (ongoing warming at the Antarctic Peninsula), further freshening of the AABW might be expected, and, if it does occur, it is likely to be progressively traceable along much of the length of the Atlantic. One could speculate that, should further dramatic ice shelf collapses occur at the eastern Peninsula (e.g. of Larsen C [36]), the freshening of shelf waters and AABW could accelerate. Alternatively (and equally speculatively), if the shelf waters become sufficiently fresh that they are too light to convect seasonally to the bottom of the shelf, this mode
of AABW renewal may diminish. Predictive skill concerning when or if such changes may happen is currently lacking.

It should be noted that, contemporaneous with the salinity decrease in the AABW observed in Drake Passage, there was no apparent decrease in the thickness of the AABW layer there (figure 3). While not conclusive in itself, this nonetheless indicates that the postulated volumetric reduction in AABW export into the lower limb of the Atlantic overturning does not feature strongly in these data [33].

Given the changes observed in the dense waters originating in the Weddell Sea, and the great reach of the waters so formed, it is incumbent upon us to maintain long-term monitoring efforts to determine and understand the ongoing climatic variations of the waters, and their impacts. However, this is not sufficient by itself, because the waters can be modified en route to lower latitudes, and understanding the controls on this, and how they change with time, is also key. We will next summarize some recent key findings that relate to the modifications of these waters as they transit northwards towards the Atlantic and place these results in the context of the known large-scale changes in deep ocean climate.

3. Controls on the flow and properties of dense water through the Scotia Sea

In accord with the above, repeat occupations of the WOCE A23 section in the Scotia Sea (figure 1) have demonstrated the presence of a marked AABW warming trend, with significant interannual variability superposed [37]. Indeed, the Scotia Sea appears to be the location where the strong interannual changes observed in the Weddell Sea coexist with the detectable decadal changes that are more readily observed further north in the Atlantic. Given this, and the rugged bathymetry that the AABW must negotiate en route to the Atlantic, the Scotia Sea marks itself as a key region for understanding of controls on circulation and water mass transformations.

An early assessment of the AABW in the Scotia Sea hypothesized that its interannual-to-decadal changes in temperature could be caused by changes in wind forcing over the Weddell Gyre, with a stronger (weaker) gyre being associated with warmer (cooler) classes of AABW being exported across the South Scotia Ridge [38]. It was conjectured that this may contribute to the decadal warming trend in the Atlantic, because the trend in wind forcing was of the correct sign to induce a long-period withdrawal of the coldest AABW from the bottom of the sills of the ridge crest. This was investigated further using the data from the SR1b section (figure 1) and the role of wind forcing in controlling the temperature of the AABW overflow across the South Scotia Ridge was confirmed [39]. However, it was demonstrated that the lag between wind forcing and bottom temperature response was just a few months, rather than the years or decades that one might expect for a gyre-wide response to large-scale changes in winds, and it was further shown that the changes in AABW temperature were most sensitive to winds in the vicinity of the South Scotia Ridge itself.

These findings were explored further using deep and bottom temperature data from fixed moorings within the boundary current immediately upstream and downstream of Orkney Passage, and the rapid response of bottom AABW temperature and flow speed through the passage to changes in local winds was affirmed [40]. A new concept emerged, in which a wind-forced acceleration/deceleration of the barotropic flow along the South Scotia Ridge would have an associated impact on the direction and/or mixing in the bottom Ekman layer close to Orkney Passage, with a rapid impact on both AABW temperature and flow speed through the passage itself [40]. Given the climatic increase in winds in this region over the past several decades, this has the potential to exert a significant long-term climatic change on AABW properties downstream in the Atlantic similar to that observed. However, the properties of the AABW upstream in the Weddell Gyre are known to be variable on a range of time scales [25,26], and the mechanisms for such changes include wind-forced variability and eddy processes affecting the inflow of dense waters into the deep ocean [27,28,41], so decoupling the locally driven changes in Orkney Passage from those generated more remotely is not straightforward. Overall, it is clear that significant detail is still lacking concerning the exact nature of the key processes inherent in the transfer
of AABW through the deep passages of the South Scotia Ridge, and the transformations that it undergoes upstream and during the transit. Such information is critically needed if fuller attribution and predictive skill are to be generated.

Once having entered the Scotia Sea, there are still considerable topographic obstacles that AABW must negotiate prior to entering the major Atlantic basins to the north. In particular, it should be noted that the denser classes of AABW in the Scotia Sea cannot exit the basin unaltered; instead, they must mix upwards into lighter classes before outflowing. This fact was exploited in a control volume study [42], where the flux of dense AABW across the South Scotia Ridge was used to determine its basin-wide vertical mixing within the Scotia Sea. A very high rate of mixing was derived (around $39 \times 10^{-4} \text{ m}^2 \text{s}^{-1}$), equating to a very short residence time of this water within the Scotia Sea of around 2–3 years. While this calculation did not inform on the relevant processes per se, the strong bottom-reaching flows of the ACC and the rugged bathymetry were mentioned as credible factors in the generation of enhanced mixing [42].

New insight into these factors was recently obtained from repeat occupations of the WOCE A23 section in the Scotia Sea (figure 1). Along these, very strong vertical gradients in abyssal water properties were observed occasionally, caused by water being topographically trapped in trenches of several hundred metres deep (figure 4) [43]. The mechanism proposed to explain the creation of these layers was the episodic overflow of dense water across the South Scotia Ridge, consistent with the episodic nature of the wind-forced variability in the overflow described above. The concept is that, following an anomalously dense water intrusion into the Scotia Sea, this bottom

Figure 4. Potential temperature and neutral density profiles collected from the northern part of the WOCE A23 repeat section in the Scotia Sea (north of the northernmost dogleg in figure 1). Profiles are colour-coded by year. Note, in particular, the very steep gradients in temperature and density close to the seabed in some years; this is that water that is topographically trapped within deep trenches in the basin, and which can reside there for upwards of 2–3 years. (Adapted from [43].)
layer flows northward along the seabed and sinks upon encountering one or more of the trenches. Subsequently, less dense water can then flow in a less constrained manner over the upper surfaces of these layers, and, combined with the temporal changes in the properties of the waters that cross the South Scotia Ridge, strong gradients can be generated at the interfaces [43].

Using transient tracer data (chlorofluorocarbons and sulfur hexafluoride), age constraints were placed on one such layer, and it was determined to be at least 2–3 years old (i.e. it had resided in the trench for at least this long). Using a simple one-dimensional diffusion model, it was inferred that this layer had been subject to a maximum vertical mixing rate of $1 \times 10^{-4} \text{ m}^2 \text{s}^{-1}$ during that period, and probably significantly less. This raises a striking question: how do we reconcile this apparently unexceptional mixing rate from the central Scotia Sea with the very strong basin-average mixing derived previously (around $39 \times 10^{-4} \text{ m}^2 \text{s}^{-1}$) [42]? Possibilities include strong spatial structure in mixing within the basin, such that the locations of unremarkable mixing are compensated by other locations of very much greater mixing, and the high basin-average value is the spatial mean of these. Alternatively, there may by strong temporal variability in mixing, such that mixing is low when the dense bottom layers are present, but higher when they are not, with possible impacts from the formation/destruction processes for the layers. More data are needed to resolve this absolutely, but our current hypothesis is that there is strong spatial structure in deep mixing within the Scotia Sea, and that much of the mixing happens close to the vicinity of the South Scotia Ridge itself, which is characterized by very rugged topography, and where the AABW is forced to negotiate some significant gaps and flow along some convoluted bathymetry as it floods northwards. Future investigations will seek to better resolve these issues, and more fully resolve the key processes responsible for the transformations of AABW as it crosses the South Scotia Ridge and the Scotia Sea en route to entering the lower limb of the AMOC.

4. Concluding remarks

One of the overarching findings of recent work on AABW in the Atlantic sector of the Southern Ocean is that it is far from straightforward to ascribe changes in the low-latitude Atlantic to changes occurring at the formation sites in the Weddell Sea. In some cases, this can be done, such as with the recently observed freshening of this water mass, but in many cases the temporal patterns of the oceanic climate change do not allow easy attribution. This highlights the need to understand both the processes that dictate the changing properties of the water mass as it forms, and those that control its time-varying export and modification as it transits through the complex bathymetric systems en route to the major Atlantic basins. Increasingly, it is being seen that the large-scale properties of the deep and abyssal waters along much of the length of the Atlantic are heavily influenced by small-scale processes that relate to how the water negotiates rugged topography, and by the episodic nature of the flow generated by fluctuating winds.

In this context, much attention has focused recently on gaps in the South Scotia Ridge, and in particular on Orkney Passage, which is now seen not just as a major throughflow site for AABW, but also a critical location where this water mass is transformed, and where such transformations may change climatically into the future. Inevitably, passages such as Orkney Passage are poorly resolved in coupled climate models and even in state-of-the-art forced ocean models, and the processes hypothesized to be responsible for the transformations are misrepresented or absent. Dedicated model-based studies of dense water flow through narrow gaps and passages are making progress with this, but it seems that we are still some way from including the relevant processes in large-scale numerical integrations that can be run for long periods (decades and longer), and this remains a major restriction on our ability to construct projections of future changes. Nonetheless, increasing our predictive skill as it relates to the properties of the large-scale abyssal ocean is increasingly seen as important, because of the role such waters play in determining sea level, global climate and benthic biodiversity. Accordingly, it is incumbent on us to fully determine the key processes and develop ways of representing their effects in coarse resolution models. A critical first step is targeted fieldwork, complemented...
by high-resolution, process-oriented modelling. In tandem, strategies should be put in place for sustained monitoring at key locations, so that the performance of the models that will be generated can be challenged and progressively improved. It should be noted that the process studies needed to understand the mechanisms underpinning long-period variability and change inevitably require multi-year datasets, as single-mission research expeditions are by themselves ineffective at identifying cause and effect relationships.

The ocean beneath the ice-covered seas remains the most challenging environment in the world from which to make sustained, high-quality scientific measurements, and the Weddell Sea contains some of the least-explored regions on the planet. Combined with the critical need to understand the evolving marine climate of this region, this results in such data as are collected being disproportionately valuable, and the sustained time series especially so. Long-term maintenance of these series at a time that is financially challenging for many nations will not be easy, yet scientifically their loss would be ruinous. Greater implementation of marine robotics and the advent of truly autonomous ocean observing will help in future years [44]; however, the series must be maintained in the meantime using proven approaches.

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