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Key Points:
- Comparison of 1989–1995 shipboard to 2019–2020 Deep Argo data reveals Brazil Basin Antarctic Bottom Water warming of 2.1 (±0.4) m °C yr^{-1}
- Comparison of Deep Argo data to a multidecadal (1955–2017) climatology also shows bottom water warming and no change in deep water above
- Bottom-intensified warming, with no trend in overlying Lower North Atlantic Deep Water, reduces abyssal stratification by 1% per decade

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Antarctic Bottom Water Warming in the Brazil Basin: 1990s Through 2020, From WOCE to Deep Argo

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Abstract A warming trend of 2.1 (±0.4) m °C yr^{-1} in bottom waters (4,500 to 5,900 dbar) spreading north from Antarctica through the Brazil Basin is quantified by comparing 2019–2020 data from a new Deep Argo regional pilot array to 1989–1995 data from full-depth zonal and meridional hydrographic sections occupied across the basin before and during the World Ocean Circulation Experiment (WOCE). Additionally, float temperatures are about 0.046°C warmer than those from a long-term climatology in those same bottom waters. Lower North Atlantic Deep Water in the basin shows no detectable warming, but Upper North Atlantic Deep Water exhibits evidence of warming in both analyses. The bottom-intensified warming results in a reduction in vertical density stratification between the bottom and deep waters of about 1% per decade. This change is in contrast with the effects of surface-intensified warming, which tends to increase vertical density stratification.

Plain Language Summary Surface waters around Antarctica become very cold, salty, and dense through atmosphere and ice exchanges. After cascading down the continental shelf to the abyssal ocean, they spread northward as "Antarctic Bottom Waters." Widespread warming of these waters over the past few decades has been detected by analyses of data from decadal occupations of a set of worldwide, transoceanic research cruises. The better to monitor and understand these and other deep ocean changes, international oceanographers are working together to deploy arrays of oceanic robots (Deep Argo floats) that collect oceanographic data from the sea surface to its floor and report them in real time. We analyze data from one of these arrays, recently deployed in the Brazil Basin. By comparing the Deep Argo data collected from 2019 to 2020 with data collected from 1989–1995 during research cruises in the region, we quantify the warming trend of Antarctic Bottom Water as 0.002°C yr^{-1} over that time period, which is about one seventh the global sea surface temperature warming trend from 1989–2019. Furthermore, since the bottom waters are warming, but the deep waters above them are not, the density difference between them is lessening over the decades, potentially influencing ocean mixing and circulation.

1. Introduction

The international World Ocean Circulation Experiment (WOCE) occupied a global set of high-quality, coast-to-coast, full-depth hydrographic sections during the 1990s. Accuracies of the data from the CTD (conductivity, temperature, and depth) instruments used during WOCE (and during many sections occupied during the 1980s prior to WOCE) are quite high: roughly ±3 dbar for pressure, ±0.002°C for temperature, and ±0.003 PSS-78 for salinity. A subset of these baseline sections with data of at least that accuracy have been occupied at roughly decadal intervals during the 2000s under the auspices of CLIVAR and CO_2 programs, and again in the 2010s under GO-SHIP, allowing analyses of changes in temperature, salinity, oxygen, nutrients, carbon system parameters, and other water properties around the globe (Talley et al., 2016).

Comparisons of repeat hydrographic section temperature data from the 2000s to data from the baseline sections occupied in the 1980s and 1990s revealed a nearly global pattern of warming in the abyssal (pressures >4,000 dbar) ocean (Kouketsu et al., 2011; Purkey & Johnson, 2010). This warming was strongest around Antarctica where Antarctic Bottom Water (AABW) is formed in multiple locations (Orsi et al., 1999), but it extended into the abyssal North Pacific Ocean, western Atlantic Ocean, and much of the Indian Ocean, all regions where AABW influences are strong in abyssal waters (Johnson, 2008). An update of this analysis confirmed that the abyssal ocean warming continued into the 2010s (Desbruyères et al., 2016).

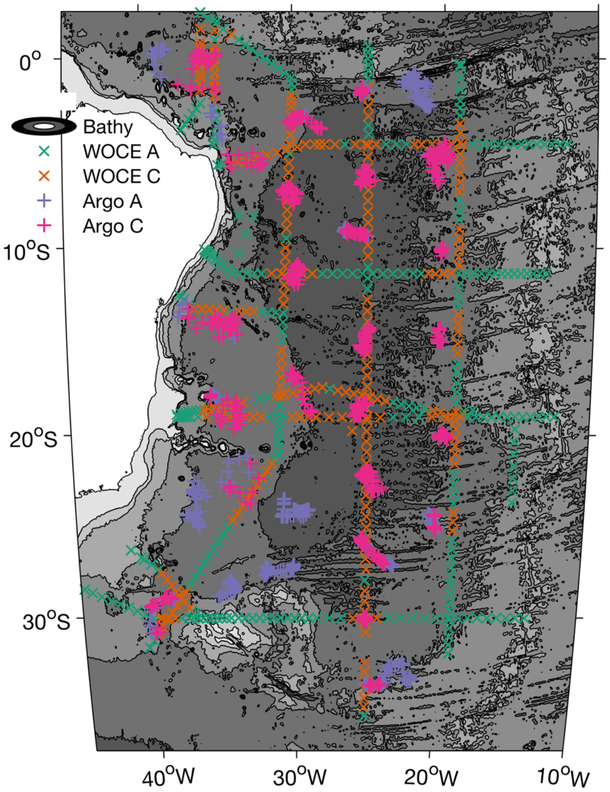

Figure 1. WOCE station positions (x's) with green signifying not used in the 4,000-dbar WOCE-Argo comparison, orange signifying used. Deep Argo profile positions (+'s) with lavender signifying not used and magenta signifying used. Bathymetry (increasingly gray with increasing depth with contours at 1,000-m intervals) is ETOPO1 (Smith & Sandwell, 1997).

Here we focus on bottom water warming in the Brazil Basin of the western south Atlantic Ocean, which is a crossroads for water masses (Tsuchiya et al., 1994): Relatively cold, fresh bottom water from the Antarctic, properly termed Weddell Sea Deep Water for its formation region, along with Lower Circumpolar Water just above it, spread northward there. These are hereafter referred to colloquially as Antarctic Bottom Water (AABW), signifying a relatively vertically homogenous layer of the coldest, densest waters in the region. Overhead lie warmer, saltier deep waters from the North Atlantic, properly referred to as Lower, Middle, and Upper North Atlantic Deep Water (NADW), which spread southward. There is a strong vertical temperature gradient between the AABW and the NADW. Above the NADW fresher, and in many regions relatively colder (e.g., exhibiting a local vertical temperature minimum) Upper Circumpolar Water and Antarctic Intermediate Water spread northward, and so on.

The Argentine Basin lies immediately upstream of the Brazil Basin along the northward spreading route of AABW in the western South Atlantic Ocean. Warming of AABW in the Argentine Basin between the 1970s and 1980s was apparent from an analysis of changes in roughly colocated repeat hydrographic sections taken in those decades (Coles et al., 1996). The warming was quite evident in the Argentine Basin, and in the Brazil Basin it "clearly appeared to have penetrated north of the 25°S section by 1988", "its influence seems to have affected the (1989) 18°S section", but there "was no evidence that it reached, ..., 10°S." The Vema Channel is the main passage for the flow of AABW from the Argentine Basin into the Brazil Basin, and a time series of bottom temperatures there suggests a rather uncertain and relatively sluggish warming rate from 1972 to 1991, followed by a more rapid and better constrained warming trend of 2.8 m °C yr^{-1} over the next 15 yr (Zenk & Morozov, 2007). Within the Brazil Basin warming of about 2 m °C yr^{-1} at pressures exceeding 4,500 dbar was evident along a meridional section at nominal longitude 25°W, first between the 1989 and 2005 occupations (Johnson & Doney, 2006), and again between the 2005 and 2014 occupations (Johnson et al., 2014). The main exit route for abyssal water of Antarctic origin from the Brazil Basin is the equator. There a substantially more rapid warming (0.09°C from 1993 to 1999) was observed in bottom temperatures from a few stations along a frequently reoccupied 35°W section across the equator (Andrié et al., 2003).

Deep Argo is a relatively new mission of Argo to measure the 50% of the ocean volume below the reach of the 2,000-dbar maximum profiling pressure of Core Argo floats (Roemmich et al., 2019). There are two designs of Deep Argo floats presently capable of profiling between the surface and 6,000 dbar, which allows about 99% of the ocean volume to be measured (sampling to the sea floor in all but the deepest abyssal plains and trenches). The global array design calls for 1,228 Deep Argo floats to afford approximately one float per 5° latitude × 5° longitude bin in ocean regions with bottom depths exceeding 2,000 m that are ice free at least some part of the year (Johnson et al., 2015). Presently, there are regional pilot arrays in several basins where a bottom water warming signal has been previously identified (Roemmich et al., 2019). The Deep Argo regional pilot array in the Southwest Pacific, with two early instruments deployed in 2014, and deployments in earnest in 2016, has already allowed quantification of recent bottom water warming rates in that basin (Johnson et al., 2019).

Here we compare data from the latest Deep Argo float regional pilot array deployed in the Brazil Basin with other data sets to assess deep and abyssal regional ocean temperature trends over the past few decades (Figure 1). The float data were taken between May 2019 and August 2020. We compare those data to collocated 1989–1995 high-quality WOCE and pre-WOCE section data (Figure 1) to estimate a profile versus pressure of temperature trends between the two time periods. We also calculate a profile of mean temperature differences between the float data and the World Ocean Atlas 2018 (WOA-18) multidecadal (1955–2017) climatology.

2. Data and Methods

The Deep Argo float data used here were downloaded from an Argo Global Data Assembly Center (GDAC) in August 2020. There were 31 deployments of Deep Argo floats in the Brazil Basin between May 2019 and February 2020, with one of those being a redeployment of a previously deployed, recovered, and repaired float. Another float was recovered for repair but had not yet been redeployed as of this writing. One float never profiled beyond 1,000 dbar before developing a disabling CTD float communication issue. Another three floats successfully completed multiple deep profiles but then stopped reporting after a few profiles with anomalous engineering data. As of this writing, all the floats deployed had reported 835 profiles reaching pressures of 4,000 dbar or more, and there were 25 floats successfully reporting full-depth profiles on 10-day cycles in the Brazil Basin.

For comparison we downloaded CTD data collected during WOCE cruises across the Brazil Basin (Figure 1 and Table 1) from the CLIVAR and Carbon Hydrographic Data Office (CCHDO; https://cchdo.ucsd.edu/), along with data from two SAVE (South Atlantic Ventilation Experiment) cruises occupied in 1989 (Tsuchiya et al., 1994) that were later designated as WOCE A16. We also downloaded the WOA-18 multidecadal long-term gridded mean fields from the NOAA/National Center for Environmental Information website (https://www.nodc.noaa.gov/OC5/woa18/). These fields are constructed from means of six decades (1955–1964, 1965–1974, ..., 2005–2017). However, in locations where there are no data in a decade, the values for that decade default to the first-guess field, which is the mean over all data regardless of year (T. Boyer, personal communication, 10 April 2020).

For the analysis we first calculated absolute salinity (S_A) and conservative temperature (C_T) from all the datasets and pressure from depth for WOA-18 using TEOS-10 (Feistel, 2012). We then linearly interpolated the C_T and S_A values to a regular 10-dbar pressure grid for each Deep Argo float profile. Since these particular floats were set to sample continuously from the surface to 2,000 dbar then at approximately 10-dbar intervals from there to within 2–3 dbar of the sea floor, the grid is well matched to their vertical data distribution. We interpolated C_T and S_A from WOCE CTD stations that were close in location to float profiles (every station within a 1.5° radius of a float profile location) to the same 10-dbar pressure grid. We also linearly interpolated WOA-18 C_T and S_A values onto that grid at the geographical location of each float profile.

We then computed mean temperature trends (and their standard deviations) for all the float profile data and WOCE station data within a 1.5° radius of each other, where the trends were defined as the difference in temperature divided by the elapsed time for each float profile-WOCE station pair. We similarly computed mean temperature differences (and their standard deviations) between float profile data and the WOA-18 data at each pressure for all data points at which data were available for both data sets. (The deepest WOA-18 values are at 5500 m depth, equivalent to pressures of around 5,600 dbar at the equator and 5,610 dbar at 35°S.)

To compute confidence limits for these means using the standard deviations required estimates of the degrees of freedom. The temporal decorrelation scale for temperature at middepth (1,800 dbar) has been estimated at 62 days using long records from Core Argo floats (Johnson et al., 2015) and the spatial decorrelation length scale at 162 km using repeated long transoceanic section data including WOCE sections and those from subsequent programs (Purkey & Johnson, 2010). Guided by these estimates, we estimated the degrees of freedom for the WOA-18 comparison by counting the number of distinct 60 day × 1.5° latitude × 1.5° longitude bins containing float data used in that comparison. For example, in this analysis there are 722 comparisons of WOA-18 and Deep Argo profiles at 4,000 dbar, yielding 174 degrees of freedom. The counts generally decrease with increasing pressure with two comparisons yielding 2 degrees of freedom at 5,600 dbar. For the temporal trend estimates between the float data and WOCE sections, we made similar counts, but for the temporal dimension we sorted the elapsed time difference between each pair of float and WOCE data into 60-day bins rather than sorting by the time of the float data. This change in the time sorting allowed recognition that sampling of a region by two different WOCE cruises at distinct times are statistically independent. For example, in this analysis there are 4,225 comparison of WOCE and Deep Argo profiles at 4,000 dbar,

Table 1
World Ocean Circulation (WOCE) and Pre-WOCE Hydrographic Sections Used in This Analysis

WOCE section designator	Nominal latitude or longitude	Dates of occupation	Chief scientist(s)
A07	4.5°S	January–February 1993	Morliere
A08	11.3°S	March–May 1994	Mueller
A09	19°S	February–March 1991	Siedler
A10	30°S	December 1992 to January 1993	Mueller
A15	19°W	April–May 1994	Smethie
A16	25°W	January–April 1989	Smethie and Talley
A17	30.5°W	January–March 1994	Memery
A23	39°W	March–May 1995	Heywood and King

Note. See Figure 1 for WOCE station locations.

yielding 203 degrees of freedom. Again, the counts generally decrease with increasing pressure, with 10 comparisons yielding 7 degrees of freedom at 5,900 dbar. We computed 5–95% confidence intervals (90% two-tailed) using the standard deviations and the degrees of freedom estimated as detailed above assuming Student's *t*-distribution. All significance assessments reported here used those confidence limits.

3. Results

The profile of temperature trends between Deep Argo (May 2019 to August 2020; mean time 2020.1) and WOCE (1989–1995; mean time 1992.5) reveals substantial and statistically significant warming in the AABW (Figure 2). Averaged from 4,500 to 5,900 dbar, a region of relatively vertically homogenous bottom water in most of the basin, the warming trend is 2.1 (±0.4) m °C yr^{-1} over the 27.6 yr. There is no statistically significant warming trend from 2,870 to 4,130 dbar, which is within the Lower NADW. But shallower than 2,870 dbar, a warming trend is increasingly strong with decreasing pressure, and by 2,000 dbar, which is within the Upper NADW, that trend reaches 1.3 (±0.4) m °C yr^{-1}. Uncertainties in the trend are smallest, approaching ±0.2 m °C yr^{-1}, at 2,950 and 5,100 dbar, both regions of low vertical temperature gradients. They are large, over ±0.7 m °C yr^{-1}, in the region of high vertical temperature gradient between deep and bottom waters between 3,920 and 4,180 dbar. They are even larger near the very bottom, where there are very few data points, with uncertainties >1.4 m °C yr^{-1}, exceeding the magnitude of the signal, for pressure >5,900 dbar.

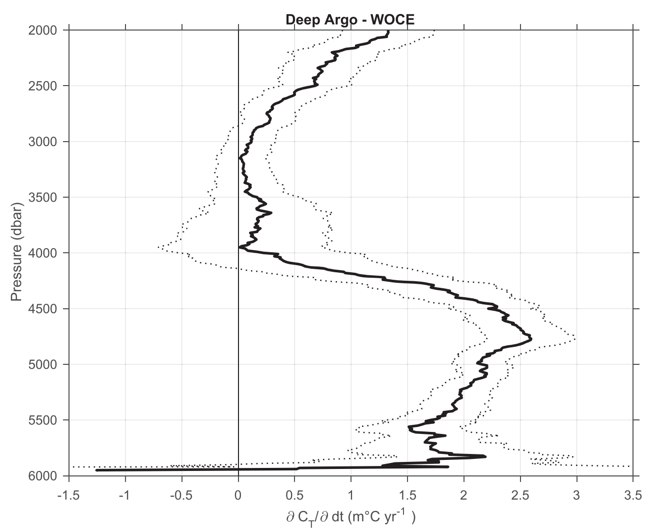

Figure 2. Conservative temperature (C_T) trends (m°C yr^{-1}) versus pressure (dbar) in the Brazil Basin computed by comparing all pairs of Deep Argo profiles reported from May 2019 to August 2020 within a 1.5° radius of WOCE profiles from 1989–1995. See Figure 1 for Deep Argo and WOCE profile locations. Means (solid line) and 5–95% confidence intervals (dashed lines) are shown.

The profile of mean temperature difference between the Deep Argo floats (from 2019–2020) and the WOA-18 long-term climatology (Figure 3) is similar in shape to the temperature trend between Deep Argo and the WOCE data (Figure 2). Within the AABW, the pressure-averaged value of warming from 4,500–5,600 dbar is 46 (±9) m °C. There is no statistically significant difference between the Deep Argo data and the long-term climatology from about 2,650–3,350 dbar, with Deep Argo data being increasingly warmer than WOA-18 with decreasing pressures shallower than 2,650 dbar, reaching a value of 36 (±8) m °C at 2,000 dbar. Uncertainties are larger in the portions of the water column with larger vertical temperature gradients. They approach a minimum of ±4 m °C at 2,950 dbar, where the vertical temperature gradient is relatively small.

4. Discussion

A previous analysis of warming in the Brazil Basin using trends from the three occupations of the meridional WOCE Section A16S (nominally along 25°W) in 1989, 2005, and 2014 found a warming rate of 2.2 (±0.6) m °C yr^{-1} from 4,500–5,900 dbar (Johnson et al., 2014), very similar to the rate found here of 2.1 (±0.4) m °C yr^{-1} for that same pressure range (Figure 2). However, the present

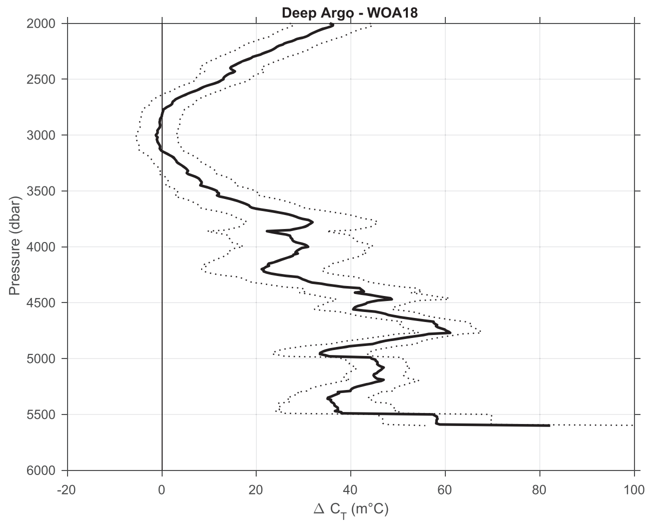

Figure 3. Conservative temperature (C_T) difference (m°C) versus pressure (dbar) between Deep Argo float profile data in the Brazil Basin collected between May 2019 and August 2020 minus values from the WOA-18 long-term (1955–2017) climatology. See Figure 1 for Deep Argo profile locations. Means (solid line) and 5–95% confidence intervals (dashed lines) are shown.

estimate is based on more recent data that are more widely distributed around the basin, making it less susceptible to biases owing to sparse coverage issues (Figure 1), and reducing formal uncertainties slightly. The increasing warming with decreasing pressure, exhibiting substantial, statistically significant values at 2,000 dbar, is also consistent with other analyses of middepth warming in the region using both repeat hydrographic section and core Argo profile data (Giglio & Johnson, 2017).

The zigzagging appearance of the comparison of the Deep SOLO data with the WOA-18 long-term climatology for pressures exceeding 4,000 dbar (Figure 3) may be partially owing to the climatology having no fixed year, so as comparisons in different regions drop out with increasing pressure the difference changes owing partly to a change in time elapsed for the comparison. The assumed mean date for the climatology is circa 1986, although that may be less certain in sparsely sampled areas such as the deep South Atlantic than it would be in better sampled regions such as the shallow North Atlantic.

Using the AABW temperature difference of 46 m °C between the long-term climatology and the floats, and the warming rate of 2.1 m °C yr^{-1} between the float and WOCE dates, one can estimate an approximate mean date of the climatology in the AABW. The result is about 1998. Bottom water warming at the Vema Channel, the entrance to the Brazil Basin, was detected starting in earnest around 1990 (Zenk & Morozov, 2007). Since the bottom waters of the Brazil Basin likely started warming some years after that date, the trends estimated here appear roughly consistent with the difference from the long-term climatology.

The cause of the AABW warming is a subject of some debate. Some studies suggest that less AABW is being produced in recent decades than previously (e.g., Purkey & Johnson, 2012). Others suggest that the same amount of AABW is being produced, it is just fresher, warmer, and less dense (e.g., van Wijk & Rintoul, 2014). In the Ross Sea and along the Adelie Lands this decrease in formation rate, or change in AABW properties, may be linked to freshening along the continental shelves owing to increased marine ice sheet melting rates (Jacobs & Giulivi, 2010). The hypothesis that freshening results in decreased AABW formation rates is supported by at least one modeling study (Fogwill et al., 2015). For the Weddell Sea region a decrease in AABW export or change in properties could be related to enhanced cooling and deep and bottom water production during the Weddell Polynya that occurred in the mid-1970s (Zanowski et al., 2015). No matter its origin, the AABW warming signal is communicated far from its origin on timescales much shorter than those of advection, by relatively rapidly propagating planetary waves (Masuda et al., 2010).

The lack of warming in Lower NADW and the warming of the AABW below results in a reduction in the abyssal thermocline, the strong temperature gradient between the Lower NADW and AABW, in that basin. A local vertical minimum in vertical temperature stratification (not shown) is found in the NADW at 3,000 dbar. At that pressure there is neither a discernible temperature trend when comparing Deep Argo and WOCE data (Figure 2) nor a discernible temperature difference when comparing Deep Argo data to the WOA-18 long-term climatology (Figure 3). The bulk temperature difference between NADW at 3,000 dbar and the near-homogenous AABW layer from 4,500 to 5,900 dbar is 2.1°C. Given the rate of warming in that layer of 2.1 m°C yr^{-1}, the thermal stratification decrease is about 1% per decade. This reduction in stratification as a result of bottom-intensified warming is opposite to the trend in the upper ocean, where stratification increases as the ocean mixed layer warms more quickly than that the water below (Rhein et al., 2013). This reduction in stratification between AABW and NADW is also likely to be linked to both the strength of the abyssal meridional overturning circulation and mixing between these two water masses, but the dynamics that characterize those links are complex, and at present not certain (Cessi, 2019).

As this regional Deep Argo pilot array continues to collect data in the Southwest Atlantic and hopefully expands geographically with deployment of more Deep Argo floats, it will open up several more avenues of investigation into deep and abyssal water mass changes: It will be possible to estimate annual cycles in the deep and abyssal water throughout the region. Hence, a Deep Argo seasonal climatology will be possible, to which historical data can be compared taking into account any effects of that annual cycle, similarly to previous investigations using core Argo data (Roemmich et al., 2012). Estimating trends over shorter timescales than decadal will be possible using the Deep Argo data, as has been done using data from the longer-established Southwest Pacific Deep Argo Regional Pilot Array (Johnson et al., 2019), perhaps allowing improved understanding of deep ocean physics such as the roles of planetary waves in effecting deep water property variations (Masuda et al., 2010). As the array expands, similar analyses will also be possible in adjacent deep basins. When a global array is completed, near real-time assessments of Earth's energy imbalance, a key climate diagnostic, including the deep ocean contribution, which has been about 10% of the total in recent decades (Johnson et al., 2016) will be feasible.

Data Availability Statement

The WOCE data were downloaded from https://cchdo.ucsd.edu/ website, the WOA18 data from https://www.nodc.noaa.gov/OC5/woa18/ website, and the Deep Argo data from one of the Argo Global Data Assembly Centers (https://nrlgodae1.nrlmry.navy.mil/argo/argo.html).

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References

Andrié, C., Gouriou, Y., Bourlès, B., Ternon, J. F., Braga, E. S., Morin, P., & Oudot, C. (2003). Variability of AABW properties in the equatorial channel at 35 ºW. *Geophysical Research Letters*, *30*(5), 8007. https://doi.org/10.1029/2002GL015766

Cessi, P. (2019). The global overturning circulation. *Annual Review of Marine Science*, *11*(1), 249–270. https://doi.org/10.1146/annurev-marine-010318-095241

Coles, V. J., McCartney, M. S., Olson, D. B., & Smethie, W. M. (1996). Changes in Antarctic Bottom Water properties in the western South Atlantic in the late 1980s. *Journal of Geophysical Research*, *101*(C4), 8957–8970. https://doi.org/10.1029/95JC03721

Desbruyères, D. G., Purkey, S. G., McDonagh, E. L., Johnson, G. C., & King, B. A. (2016). Deep and abyssal ocean warming from 35 years of repeat hydrography. *Geophysical Research Letters*, *43*, 10,356–10,365. https://doi.org/10.1002/2016GL070413

Feistel, R. (2012). TEOS-10: A new international oceanographic standard for seawater, ice, fluid water, and humid air. *International Journal of Thermophysics*, *33*(8–9), 1335–1351. https://doi.org/10.1007/s10765-010-0901-y

Fogwill, C. J., Phipps, S. J., Turney, C. S. M., & Golledge, N. R. (2015). Sensitivity of the Southern Ocean to enhanced regional Antarctic ice sheet meltwater input. *Earth's Future*, *3*(10), 317–329. https://doi.org/10.1002/2015EF000306

Giglio, D., & Johnson, G. C. (2017). Middepth decadal warming and freshening in the South Atlantic. *Journal of Geophysical Research: Oceans*, *122*, 973–979. https://doi.org/10.1002/2016JC012246

Jacobs, S. S., & Giulivi, C. F. (2010). Large multidecadal salinity trends near the Pacific-Antarctic continental margin. *Journal of Climate*, *23*(17), 4508–4524. https://doi.org/10.1175/2010JCLI3284.1

Johnson, G. C. (2008). Quantifying Antarctic Bottom Water and North Atlantic deep water volumes. *Journal of Geophysical Research*, *113*, C05027. https://doi.org/10.1029/2007JC004477

Johnson, G. C., & Doney, S. C. (2006). Recent western South Atlantic bottom water warming. *Geophysical Research Letters*, *33*, L14614. https://doi.org/10.1029/2006GL026769

Johnson, G. C., Lyman, J. M., & Loeb, N. G. (2016). CORRESPONDENCE: Improving estimates of Earth's energy imbalance. *Nature Climate Change*, *6*(7), 639–640. https://doi.org/10.1038/nclimate3043

Johnson, G. C., Lyman, J. M., & Purkey, S. G. (2015). Informing deep Argo array design using Argo and full- depth hydrographic section data. *Journal of Atmospheric and Oceanic Technology*, *32*(11), 2187–2198. https://doi.org/10.1175/JTECH-D-15-0139.1

Johnson, G. C., McTaggart, K. E., & Wanninkhof, R. (2014). Antarctic Bottom Water temperature changes in the western South Atlantic from 1989 to 2014. *Journal of Geophysical Research: Oceans*, *119*, 8567–8577. https://doi.org/10.1002/2014JC010367

Johnson, G. C., Purkey, S. G., Zilberman, N. V., & Roemmich, D. (2019). Deep Argo quantifies bottom water warming rates in the Southwest Pacific Basin. *Geophysical Research Letters*, *46*, 2662–2669. https://doi.org/10.1029/2018GL081685

Kouketsu, S., Doi, T., Kawano, T., Masuda, S., Sugiura, N., Sasaki, Y., et al. (2011). Deep ocean heat content changes estimated from observation and reanalysis product and their influence on sea level change. *Journal of Geophysical Research*, *116*, C03012. https://doi.org/10.1029/2010JC006464

Masuda, S., Awaji, T., Sugiura, N., Matthews, J. P., Toyoda, T., Kawai, Y., et al. (2010). Simulated rapid warming of abyssal North Pacific waters. *Science*, *329*(5989), 319–322. https://doi.org/10.1126/science.1188703

Orsi, A. H., Johnson, G. C., & Bullister, J. L. (1999). Circulation, mixing, and production of Antarctic Bottom Water. *Progress in Oceanography*, *43*(1), 55–109. https://doi.org/10.1016/S0079-6611(99)00004-X

Purkey, S. G., & Johnson, G. C. (2010). Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. *Journal of Climate*, *23*(23), 6336–6351. https://doi.org/10.1175/2010JCLI3682.1

Purkey, S. G., & Johnson, G. C. (2012). Global contraction of Antarctic Bottom Water between the 1980s and 2000s. *Journal of Climate*, *25*(17), 5830–5844. https://doi.org/10.1175/JCLI-D-11-00612.1

Rhein, M., Rintoul, S., Aoki, S., Campos, E., Chambers, D., Feely, R., et al. (2013). Observations: Ocean. In T. F. Stocker, et al. (Eds.), *Climate Change 2013: The physical science basis*, *Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* (pp. 255–315). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Roemmich, D., Alford, M. H., Claustre, H., Johnson, K., King, B., Moum, J., et al. (2019). On the future of Argo: A global, full-depth, multi-disciplinary array. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00439

Roemmich, D., Gould, W. J., & Gilson, J. (2012). 135 years of global ocean warming between the Challenger expedition and the Argo Programme. *Nature Climate Change*, *2*(6), 425–428. https://doi.org/10.1038/nclimate1461

Smith, W. H. F., & Sandwell, D. T. (1997). Global sea floor topography from satellite altimetry and ship depth soundings. *Science*, *277*(5334), 1956–1962. https://doi.org/10.1126/science.277.5334.1956

Talley, L. D., Feely, R. A., Sloyan, B. M., Wanninkhof, R., Baringer, M. O., Bullister, J. L., et al. (2016). Changes in ocean heat, carbon content, and ventilation: A review of the first decade of GO-SHIP global repeat hydrography. *Annual Review of Marine Science*, *8*, 185–215. https://doi.org/10.1146/annurev-marine-052915-100829

Tsuchiya, M., Talley, L. D., & McCartney, M. S. (1994). Water-mass distributions in the Western South Atlantic - A section from South Georgia Island (54S) northward across the Equator. *Journal of Marine Research*, *52*(1), 55–81. https://doi.org/10.1357/0022240943076759

van Wijk, E. M., & Rintoul, S. R. (2014). Freshening drives contraction of Antarctic Bottom Water in the Australian Antarctic Basin. *Geophysical Research Letters*, *41*, 1657–1664. https://doi.org/10.1002/2013GL058921

Zanowski, H., Hallberg, R., & Sarmiento, J. L. (2015). Abyssal Ocean warming and salinification after Weddell Polynyas in the GFDL CM2G coupled climate model. *Journal of Physical Oceanography*, *45*(11), 2755–2772. https://doi.org/10.1175/JPO-D-15-0109.1

Zenk, W., & Morozov, E. (2007). Decadal warming of the coldest Antarctic Bottom Water flow through the Vema Channel. *Geophysical Research Letters*, *34*, L14607. https://doi.org/10.1029/2007GL030340