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Key Points:

- Comparing 1972–1998 historical to 2021–2022 Deep Argo data reveals Argentine Basin Antarctic Bottom Water warming of 2.1 (±0.2) m°C yr^{-1}
- Enhanced warming rates at the southern boundary of the Argentine Basin suggest a reduction in velocity and transport of bottom water
- Observed reduction of AABW volume, with the 0°C isotherm falling ~200 m in 34.5 years, implies a 0.6×10^6 m^3 s^{-1} reduction in transport

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Antarctic Bottom Water Warming and Circulation Slowdown in the Argentine Basin From Analyses of Deep Argo and Historical Shipboard Temperature Data

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Abstract A decadal warming trend of 2.1 (±0.2) m°C yr^{-1} in Antarctic Bottom Water within the western Argentine Basin is found by comparing Deep Argo temperature profiles from 2021 to 2022 to nearby historical shipboard data from 1972 to 1998. This trend is similar in magnitude, but about 10 times more certain, than a previously published trend in the eastern Argentine Basin estimated using repeat hydrographic section data (World Ocean Circulation Experiment Section A16S) from 1989, 1995, and 2014. The present analysis also detects a warming rate in the coldest water entering the basin about double that in the interior. The observed reduction in deep meridional temperature gradient indicates a reduction in geostrophic shear, consistent with a reduced flow rate, and transport, of the coldest, deepest water entering the basin. The falling isotherms in the basin are consistent with an 0.6×10^6 m^{-3} s^{-1} reduction in inflow of the coldest waters to the basin.

Plain Language Summary The coldest, densest waters that sink to the ocean floor around Antarctica and spread northward have been warming in recent decades, as observed in much of the global ocean by shipboard oceanographic surveys since the 1990s. However, large portions of the ocean are unsampled by these surveys, which are only repeated at decadal intervals. Quantifying the warming of the deep ocean, the sea level rise that this warming drives, and associated changes in ocean currents are important for validating projections of future warming and understanding climate change impacts. As a result, regional pilot arrays of freely drifting robotic profiling floats capable of measuring temperature and salinity from the sea surface to the seafloor, called Deep Argo floats, are being deployed to demonstrate their capabilities and build toward a global array. We compare data from Deep Argo floats recently deployed in the Argentine Basin of the western South Atlantic Ocean to historical temperature profiles measured from ships prior to the year 2000. By doing so, we quantify the warming rate of these bottom waters over the bottom 1.5 km of that basin with about 10 times more certainty than by previously published studies using shipboard data alone.

1. Introduction

The cold, dense bottom waters around the global ocean warmed substantially and statistically significantly between the 1990s and the 2000s, both globally averaged and in a majority of deep ocean basins (Kouketsu et al., 2011; Purkey & Johnson, 2010). The overall warming pattern was toward bottom-intensification and stronger warming trends closer to the Antarctic Bottom Water formation regions. Data assimilation results suggest that this warming is associated with a reduction in the formation rate of Antarctic Bottom Water and is propagated by planetary waves (changes in horizontal velocity) over decadal time-scales (Masuda et al., 2010). This mechanism allows much more rapid adjustments than the centennial to millennial residence times of bottom and deep waters (Khatiwala et al., 2012) might suggest. Furthermore, detailed analysis of the data assimilation first reported on by Masuda et al. (2010) also suggests that this warming is associated with an associated slow-down in the northward flows of bottom waters, at least in the western Pacific and western Atlantic Oceans (Kouketsu et al., 2011). Updates of observational analyses of repeat hydrographic sections suggest that the warming trend continued relatively steadily from decade to decade over two recent decades (Desbruyères et al., 2016).

All of the studies mentioned above relied on data from hydrographic sections that were occupied repeatedly at decadal intervals, first during the 1980s and 1990s in the lead up to and during the World Ocean Circulation Experiment (WOCE), then during the 2000s as part of the CLIVAR/CO2 Repeat Hydrography Program, and more recently during the 2010s under the auspices of the Global Ocean Ship-based Hydrographic Investigation Program (GO-SHIP) (Sloyan et al., 2019; Talley et al., 2016). While the globally averaged warming trends from such studies are statistically significantly different from zero, the confidence limits are fairly wide, about half the

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size of the signal over a decade (Desbruyères et al., 2016). The ocean warming trend below 2,000 m accounts for ~9% of the warming in the climate system from 1971 to 2018 (von Schuckmann et al., 2020). Since warming of the climate system is a key metric for validating climate models (Hansen et al., 2011), better knowledge of how fast and where the ocean is warming is societally relevant. Furthermore, deep ocean warming contributes measurably to sea level rise as well (Cazenave et al., 2018), another societally important issue.

Deep Argo is an expansion of the Argo mission to measure the bottom half of the ocean volume below the 2,000 m sampling limit of Core Argo floats (Roemmich et al., 2019). So far Deep Argo has implemented regional pilot arrays in the Southwest Pacific Basin, the Australian Antarctica and South Australian basins of the southeast Indian Ocean, the subpolar gyre and western subtropics of the North Atlantic Ocean, and the Brazil Basin of the western South Atlantic Ocean. Most recently, that last array has been expanded southward into the Argentine Basin. Comparisons of these Deep Argo data to historical shipboard data have so far demonstrated the capability of the pilot arrays to accurately ascertain recent warming rates of bottom waters over spans as short as 4 years in the Southwest Pacific Basin (Johnson et al., 2019), to greatly decrease uncertainties of decadal time-scale warming of bottom waters in the Brazil Basin when compared to historical hydrographic data (Johnson et al., 2020), to allow mapping of the spatial distribution of the evolution of recent changes in bottom water properties in the Australian-Antarctic Basin (Thomas et al., 2020), and to help to quantify decadal variations of temperature in North Atlantic Deep Water masses in the Irminger Sea of the Subpolar North Atlantic Ocean (Desbruyères et al., 2022), amongst other accomplishments.

The volume of the coldest bottom waters in portions of the southern and western Argentine Basin were reduced substantially in 1988 and 1989 relative to the 1970s and early 1980s (Coles et al., 1996). Analysis of a quasi-meridional repeat hydrographic section occupied in the eastern Argentine Basin in 1989, 1995, and 2014 showed that the bottom waters were warming over that time at a rate of 1.9 (±2.2) m°C yr^{-1} averaged from 4,500 to 5,310 dbar (Johnson et al., 2014). Here we analyze decadal time-scale temperature trends on pressure surfaces from nearby pairs of Deep Argo and historical shipboard CTD profiles in the Argentine Basin (Figure 1), finding a similar overall warming trend in the bottom water, but with much greater accuracy, and inferring a slowdown in the flow of bottom water into the basin by regional variations in that overall trend, as well as the descent rate of the 0°C isotherm, the latter following Purkey and Johnson (2012).

2. Data and Methods

The methods used here closely follow those in Johnson et al. (2020), so there is some repetition of that publication in this section. The Deep Argo float data used here were downloaded from an Argo Global Data Assembly Center (GDAC) in May 2022. Only data from Deep SOLO and Deep APEX floats (capable of profiling to 6,000 dbar) were used. Four floats were deployed in the basin in January 2021, another three in March 2021, and two more in February 2022. In the time period analyzed, they collected 388 profiles extending to 4,000 dbar or deeper. The shipboard CTD data used here were downloaded from the World Ocean Database 2018 (https://www.ncei.noaa.gov/products/world-ocean-database) in January 2022. Only data taken prior to 2000 with quality control flags of "good" were used in this analysis, which included 610 profiles from 1972 to 1998 that extended to at least 4,000 dbar.

The float salinity data were corrected for an incorrect characterization of the compressibility of the conductivity cell by the manufacturer of -9.57×10^{-8} $dbar^{-1}$, substituting -12.5×10^{-8} $dbar^{-1}$ instead (Wong et al., 2022). Then absolute salinity (S_A) and conservative temperature (C_T) were calculated using TEOS-10 (Feistel, 2012) from both the float and historical data. Then the data were linearly interpolated to a uniform 10 dbar pressure grid. Since the majority of these particular floats were set to sample continuously from the surface to 2,000 dbar and at approximately 10 dbar intervals from 2,000 dbar to within 2–3 dbar of the sea floor, the grid is well matched to their vertical data distribution. We then computed mean C_T trends (and their standard deviations) as a function of pressure for all the float and historical profiles within a 1.5° radius of each other, where the trends were defined as the difference in C_T divided by the elapsed time for each float-historical station pair.

To compute confidence limits for these means using the standard deviations requires estimates of the degrees of freedom. We use a 60 day temporal decorrelation scale based on analysis of temperature at 1,800 dbar using long records from Core Argo floats (Johnson et al., 2015) and 1.5° latitude and longitude spatial decorrelations based on analysis of repeated long trans-oceanic section data (Purkey & Johnson, 2010). Guided by these results,

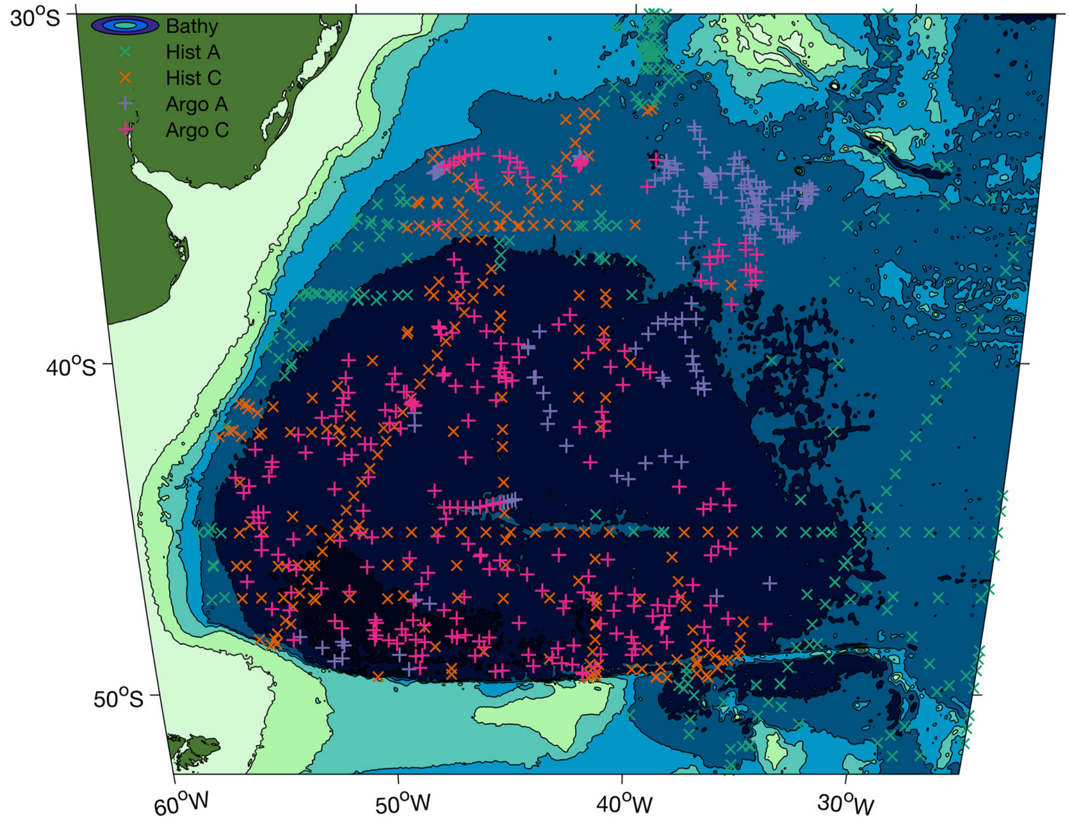

Figure 1. Historical station positions (×'s) with green signifying data not used in the 4,000-dbar Historical-Argo comparison and orange signifying data used. Historical and Argo profiles shallower than 4,000 dbar are not used at this level, but are used at other levels that they sample if they are close enough for comparisons. Deep Argo profile positions (+'s) with lavender signifying data not used and magenta signifying data used. Bathymetry (increasingly blue with increasing depth with contours at 1,000-m intervals) is from ETOPO1 (Smith & Sandwell, 1997).

we estimated the degrees of freedom by counting the number of distinct 60 days × 1.5° latitude × 1.5° longitude bins containing float data used in that comparison. We sorted the time difference between each pair of float and historical data into 60 day bins rather than sorting by the time of either the float data or the historical data. This method of time sorting recognizes that sampling of a region (e.g., a 1.5° latitude × 1.5° longitude area) by either two different historical cruises at distinct times (e.g., at least 60 days apart) compared to a single float profile are statistically independent. It also recognizes that profiles from a single float or different floats in a region sampled at distinct times (e.g., at least 60 days apart) compared to a spatially proximate profile from a historical cruise are statistically independent.

The counts of comparison pairs of profiles generally decrease with increasing pressure, with 1,445 comparisons of Deep Argo and historical data yielding 453 degrees of freedom at 2,000 dbar, 1,243 comparisons yielding 408 degrees of freedom at 4,000 dbar, and 42 comparisons yielding 15 degrees of freedom at 6,000 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 mean temperature trends in the Argentine Basin from comparisons of Deep Argo to historical data (Figure 2) shows warming statistically significantly different from zero throughout the water column, except for at the minimum warming value of ~0.5 m°C yr^{-1} near 3,600 dbar, for which the 5%–95% confidence limits overlap zero. The trend generally increases with decreasing pressure above 3,600 dbar, reaching almost 3 m°C yr^{-1} at 2,000 dbar. It also increases with increasing pressure from 3,600 to at least to 5,300 dbar, where it reaches

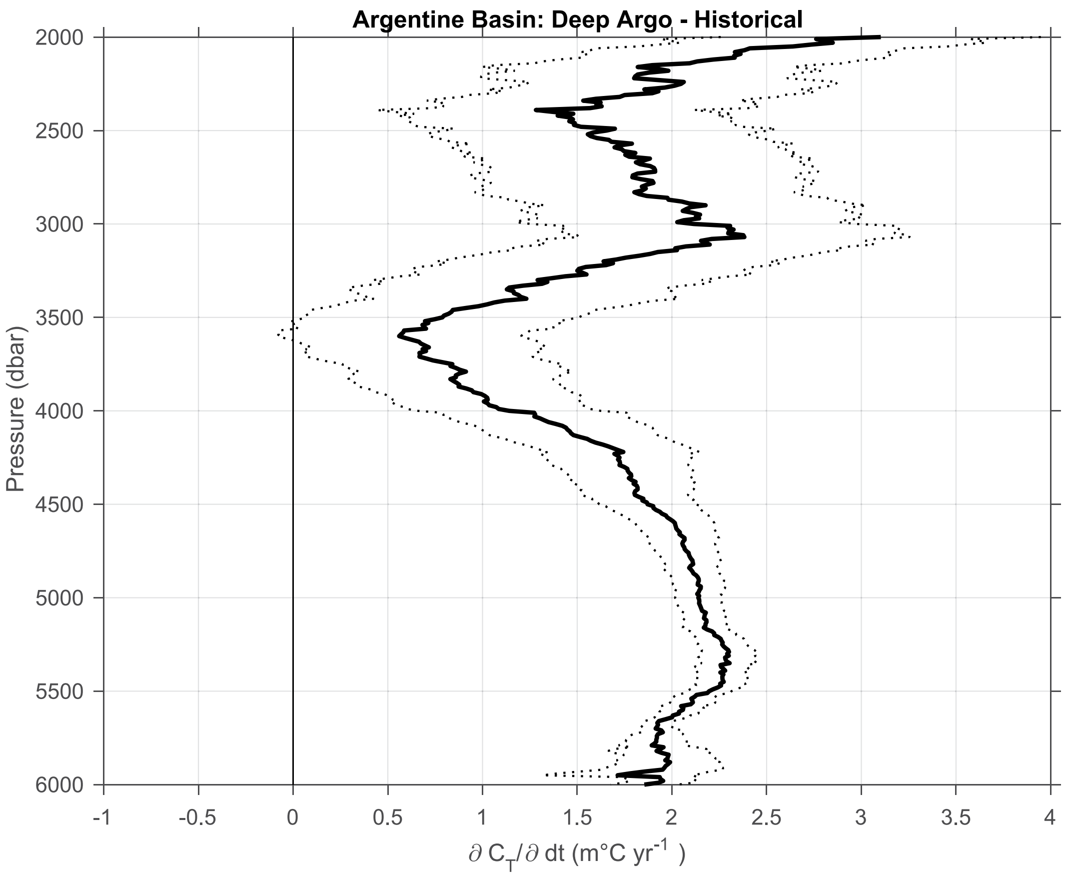

Figure 2. Conservative temperature (C_T) trends (m°C yr^{-1}) versus pressure (dbar) in the Argentine Basin computed by comparing all pairs of Deep Argo temperature profiles reported from January 2021 through April 2022 within a 1.5° radius of historical profiles collected from 1972 to 1998. See Figure 1 for Deep Argo and historical profile locations. Means (solid line) and 5–95% confidence intervals (dashed lines) are shown.

2.3 m°C yr^{-1}. A classic definition of Antarctic Bottom Water is $C_T < \sim 0$ °C (Gordon, 1966). For the historical data used in the comparisons that isotherm is on average at ~4,500 dbar pressure. For the Deep Argo data used in the comparisons, the mean pressure at 0°C is ~4,700 dbar. This is a deepening of 200 dbar in about 34.5 years (given that the mean time of historical samples at 4,500 dbar is 1987.25 and the mean time of the deep Argo data is about 2021.75). The mean warming rate from 4,500 to 6,000 dbar (approximately within the Antarctic Bottom Water) is 2.1 (±0.2) m°C yr^{-1}.

There is a distinct spatial pattern in these temperature trends. From about 1,800 to 5,600 dbar a stronger warming trend is discernible near the southern edge of the basin compared with the interior. This southern edge of the basin is the region where cold water entering from the south is banked up against the continental slope as it flows westward (Arhan et al., 1999; Coles et al., 1996, see their Figure 3 for a bottom water circulation schematic in the Argentine Basin). That cold water is warming faster than in the interior of the basin. This distinction is especially pronounced from 5,000 to 5,600 dbar, within the Antarctic Bottom Water, and is shown here at 5,300 dbar (Figure 3). The warming rate computed comparing Deep Argo to historical data from the 1970s, 1980s, and 1990s is clustered around 2 m°C yr^{-1} between 48°S and 40°S in latitude, but tends toward higher values for all three decades south of 48°S (Figure 3a). This pattern of higher values near the southern boundary of the basin appears especially strong for the trends between Deep Argo and historical data from the 1980s and 1990s, but also holds, although perhaps to a lesser extent, for the trends between Deep Argo and historical data from the 1970s. On average, temperatures smoothed in latitude at that pressure are −0.35°C near the southern boundary in historical data and −0.17°C in the Deep Argo data, a warming of +0.18°C (Figure 3b). Further north, in the basin interior between 48°S and 40°S, the warming estimated from differences of Deep Argo minus historical temperatures on that isobath smoothed in latitude ranges from +0.05 to +0.08 °C, less than half of the largest warming rate, which is located at the southern boundary.

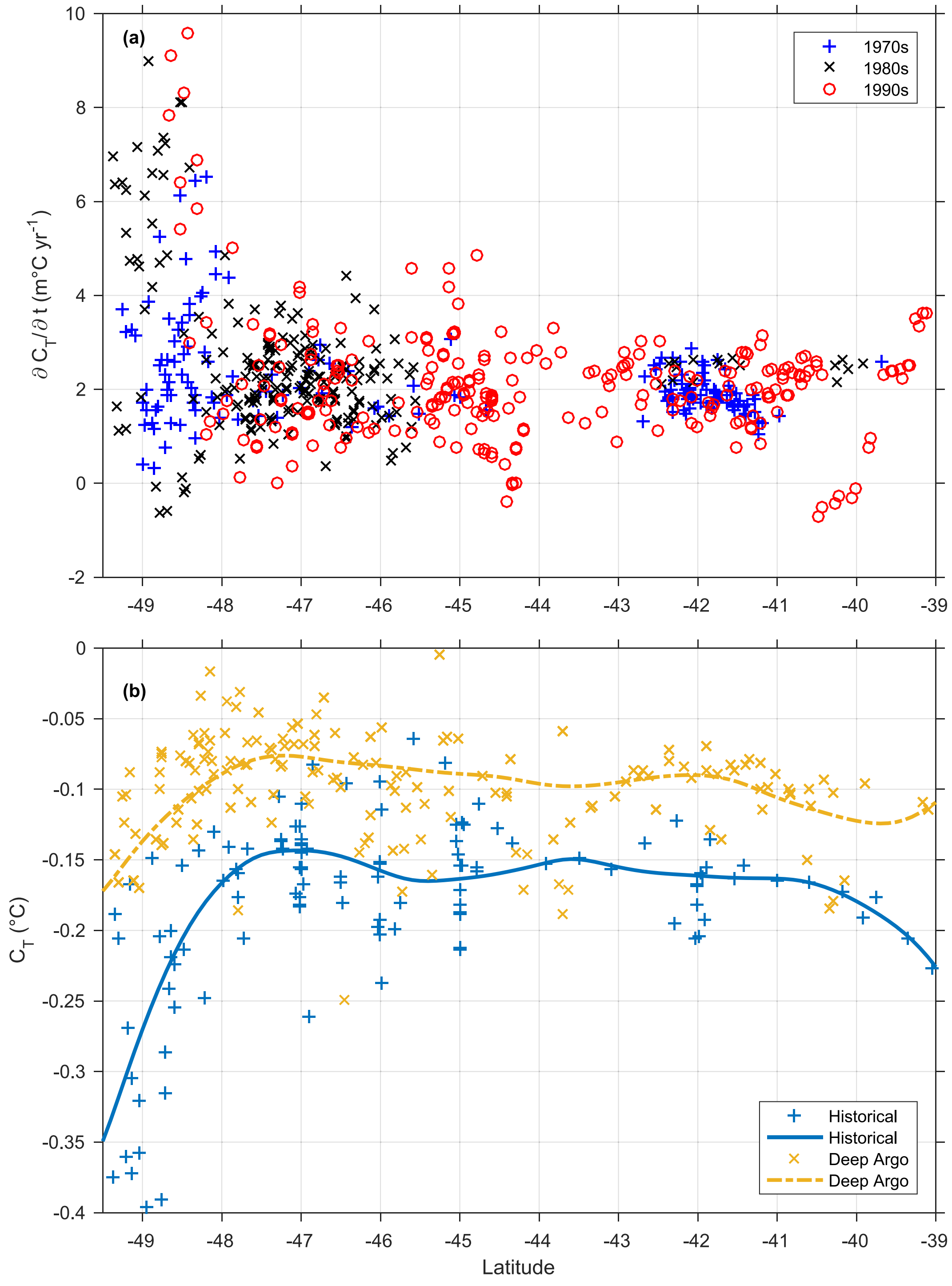

Figure 3. (a) Conservative temperature (C_T) trends (m°C yr^{-1}) at 5,300 dbar versus mean latitude for nearby pairs of Deep Argo float and historical profiles from the 1970s (blue + s'), 1980s (black ×'s) and 1990s (red ○'s). (b) Individual C_T values from those pairs for Deep Argo float (yellow ×'s) and historical data (blue +'s) versus latitude and smoothed applying a Loess filter with a 3° latitude half-power point to Deep Argo float (yellow dot-dashed line) and historical (blue solid line) data.

4. Discussion

The warming rate of 2.1 (±0.2) m°C yr^{-1} of AABW (averaged from 4,500 to 6,000 dbar) found here in the western Argentine Basin is the same size as warming rates found from analysis of a repeat hydrographic section (WOCE A16S) in the eastern Argentine Basin (Johnson et al., 2014). However, the results here have confidence limits that are about 10 times tighter than those from the previous study, which finds a warming rate of 1.9 (±2.2) m°C yr^{-1} (averaged from 4,500 to 5,310 dbar), with the bottom of that range being the deepest pressure at which trends could be estimated. The results here are also more up-to-date, with an average sampling date of 2021.75 for the Deep Argo floats versus 2014 for the latest reoccupation of WOCE A16S. The results presented here also span a longer time period, 34.5 years with a mean time of 1987.75 for the historical data, compared with 25 years for the span of the 1989, 2005, and 2014 occupation years for the WOCE A16S sections.

The intensified warming near the southern boundary shows that the boundary current bringing the coldest AABW into the basin has warmed more than older water in the interior. The geostrophic relation implies a weakening of the bottom-intensified westward flow entering the Argentine Basin in this current as a result. This result is consistent with previous studies in the region, which also noted more warming, hence the more rapid fall of isotherms at the southern boundary of the Argentine Basin (Coles et al., 1996; Johnson et al., 2014). It is also consistent with output of a global data assimilation analysis, which also suggests a reduction of northward AABW flow in the western subtropical South Atlantic in recent decades (Kouketsu et al., 2011). Presumably the rapid warming in the boundary current spreads more slowly into the interior, resulting in the smaller average rate of warming in the deep basin as a whole.

The overall warming of AABW and the reduction of westward flow of AABW entering the basin at its southern boundary are also consistent with the contraction of deep isotherms in the basin. A fall of the 0°C conservative isotherm from ~4,500 to ~4,700 dbar in the Argentine Basin, as seen in this study, occurring over 34.5 years, is roughly equivalent to a volume reduction of 1.7×10^{15} m^3 within the Argentine Basin. Dividing the volume change by the time change gives a volume transport of 0.6×10^6 m^3 s^{-1}. That is about a tenth of the mean northward flow of AABW at 32°S in the South Atlantic estimated from a box inverse model (Lumpkin & Speer, 2007), and on the same order as the reduction in transport of 0.36×10^6 m^3 s^{-1} $decade^{-1}$ below 3,500 m estimated from a data assimilation at that same latitude in the western South Atlantic (Kouketsu et al., 2011). Mapping historical and Deep Argo profiles used in this comparison separately to 49.5°S and 47°S using a 3° half-power point Loess smoother to span the boundary current region, and estimating the westward geostrophic transport from 4,500 to 6,000 dbar between those two latitudes referenced to zero velocity at 4,500 dbar results in a volume transport reduction from 10.0×10^6 m^3 s^{-1} for the historical data to 9.1×10^6 m^3 s^{-1} for the Deep Argo float data, again qualitatively consistent with the reduction in volume of AABW within the Argentine Basin.

The warming trends in bottom waters of the Argentine Basin (Figure 2) also agree well with a similar study of warming trends in the Brazil Basin (Johnson et al., 2020, their Figure 2). However, one might not expect the warming trends as a function of pressure in the two basins to overlap within uncertainties at pressures. First because there is a good deal of mixing of AABW as it flows from the Argentine Basin into the Brazil Basin through the Vema Channel. Second because the lateral temperature gradients with which the hypothesized slow down in circulation interacts to produce much of the warming via lateral heave (e.g., Masuda et al., 2010) vary between and within the basins as well (see Johnson et al., 2014, their Figure 1).

The confidence limits on AABW temperature changes in the Argentine Basin with only nine Deep Argo floats sampling there are half of those in the Brazil Basin using data from about three times more floats (Johnson et al., 2020), even though both float arrays had been sampling for a year or two at the time of the two analyses. The difference arises because floats move much more quickly in the energetic Argentine Basin than the more quiescent Brazil Basin. As noted in a Deep Argo design study, the more the floats disperse, the more accurately changes in water properties can be determined (Johnson et al., 2015). The rapid float motion in the Argentine Basin results in more independent comparisons of float and historical profiles both by increasing distances among profiles and by resulting in more spatial co-locations of float and historical profiles, roughly doubling the degrees of freedom in this study compared to the one in the Brazil Basin.

Data Availability Statement

The WOD18 data used in this study are available at and were downloaded from https://www.ncei.noaa.gov/products/world-ocean-database in January 2022. The Deep Argo data used in this study are available at and were download from one of the Argo Global Data Assembly Centers, https://nrlgodae1.nrlmry.navy.mil/argo/argo.html in May 2022. The ETOPO1 data used in this study are available at and were downloaded from https://www.ngdc.noaa.gov/mgg/global/ in January 2022.

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