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Key Points:
- Antarctic Bottom Water (AABW) temperatures in the Vema Channel are highly variable
- AABW in the Vema Channel has been warming since the early 1970s
- Warming rate in AABW in the Vema Channel waters may be increasing

Supporting Information:
Supporting Information may be found in the online version of this article.

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Warming Trend in Antarctic Bottom Water in the Vema Channel in the South Atlantic

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Abstract The excess heat absorbed from the atmosphere has increased the temperature in the upper layers of the ocean (<2,000 m). In the abyss, infrequently repeated ship sections, deep Argo float measurements, and sparse moored observations have found signs of warming in the Southwest Atlantic, possibly linked to changes in the Weddell Sea. We present a new moored temperature time series sampled near the bottom in the Vema Channel, from February 2019 to August 2020. Together with historical data, the combined record confirms the warming of the abyssal waters, with an increase of 0.059°C in potential temperature between January 1991 and August 2020, embedded within intense high-frequency variability. Moreover, the data suggest the possibility of an accelerated warming, with a change in the temperature trend from 0.0016°C yr^{-1}, between the early 1990s and 2005, to 0.0026°C yr^{-1} afterwards.

Plain Language Summary Water is an efficient temperature regulator. Large energy exchange is required to produce small changes in water temperature. Since 71% of the Earth's surface is covered by oceanic water, the ocean plays a fundamentally important role in the climate system. The ocean transports, stores, and exchanges with the atmosphere substantial amounts of heat and freshwater. In this way, the ocean slows down and mitigates temperature variability in the climate system. However, in spite of its high thermal inertia, the ocean is also affected by global warming. More than 90% of the excess energy injected into the climate system in the past century has been absorbed by the ocean. As a result, the ocean has warmed significantly, at all depths. We report results of observations confirming that warming trends observed previously in abyssal regions of the South Atlantic persist into recent years in the Vema Channel, a deep narrow passage in the South Atlantic bathymetry, where most of Antarctic Bottom Water in the South Atlantic flows northward. Our data also suggest that the warming may be occurring with an increasing rate since the early 2000s.

1. Introduction

Studies based on observations have confirmed the warming of ocean waters since the last decades of the 20th century (Johnson & Lyman, 2020; Rhein et al., 2013; Strass et al., 2020; Wu et al., 2020). The rate of warming is mostly observed in the upper 2,000 m (Johnson & Lyman, 2020; Wu et al., 2020). However, a significant increase in temperature has also been observed in the deepest layers (>4,000m) (Coles et al., 1996; Johnson et al., 2014, 2019, 2020; Purkey & Johnson, 2010; Purkey et al., 2019). In the Argentine basin, the warming seems to be related to changes in the Weddell Sea (Coles et al., 1996). More recently, analysis of the 10-year time series of temperature from near-bottom moored instruments in the Argentine Basin indicate intense high-frequency variability and linear warming trends of ~0.002–0.004°C yr^{-1} (Meinen et al., 2020). In the Brazil Basin, a study of the basin-wide temperature, based on WOCE and Deep Argo observations, estimated a warming of 0.0021 ± 0.0004°C yr^{-1} in Antarctic Bottom Water (AABW) (Johnson et al., 2020).

In the South Atlantic, Georgi (1981) described AABW flowing into the Argentine Basin as a thick and relatively homogeneous bottom layer of potential temperature below 0°C. A latter study, based on a combination of different datasets, reported pronounced stratification and heterogeneity in the water masses colder

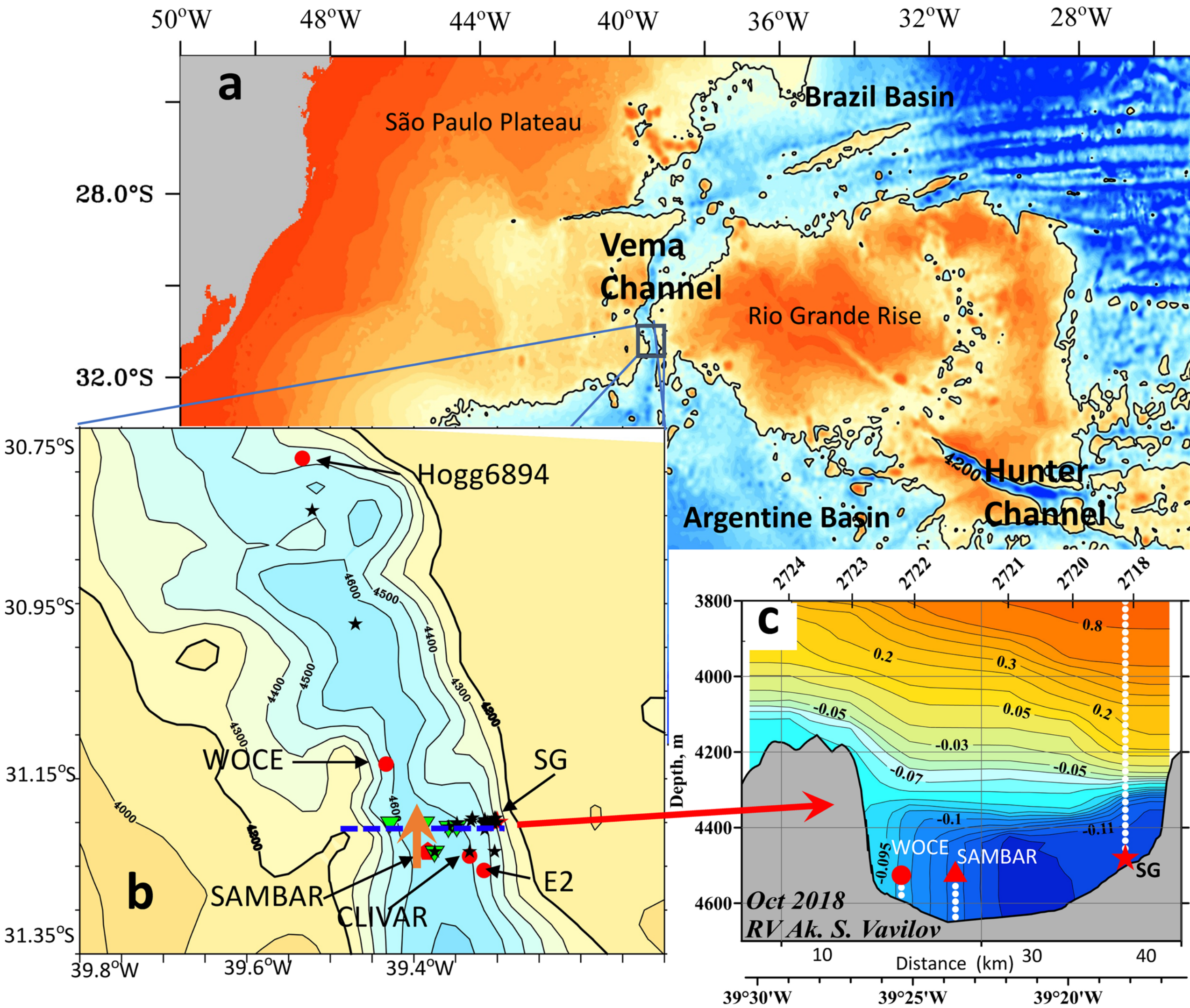

Figure 1. (a) Bottom topography of the Southwest Atlantic around the Vema Channel. In (b), the red symbols indicate the location of five mooring sites described in Table 1. The black stars mark the location of CTD stations used to compare with the moored data. The green inverted triangles are CTD stations near the SAMBAR site. SG represents the nominal position where most of the CTD data were recently sampled by Russian and German ships. The orange vector indicates schematically the long-term mean direction of the flow measured at the SAMBAR site (see Supporting Information S1). The lower-right panel (c) shows a vertical section of potential temperature along 31.2°S (dashed blue line in b), based on data collected in October 2018 (see also Table 2 and Figure 3).

than 0°C in the Argentine Basin (Coles et al., 1996). From the Argentine Basin, the Vema Channel (Figure 1) is the main pathway for the northward flow of AABW (Hogg & Zenk, 1997; Hogg et al., 1982, 1999; Morozov et al., 2018, 2020; Zenk & Hogg, 1996). This makes the Vema Channel a key location to observe variations in the properties of AABW, as indicators of the effects of global warming on the deeper ocean.

One of the first observational programs in the Vema Channel was carried out between December 1979 and March 1981, which found a mean potential temperature of −0.157°C at 4,641 dbar (Hogg et al., 1982). In 1991–1992, as part of the World Ocean Experiment (WOCE), temperature measurements indicated a mean potential temperature of −0.145°C and a warming of 0.021°C, at 50 m above the seafloor in AABW flowing through the Vema Channel over a period of one year (Zenk & Hogg, 1996). Since then, the warming of AABW has been confirmed by data collected by other moored observations and repeated hydrographic cruises (Hogg & Zenk, 1997; Morozov et al., 2018, 2020; Tarakanov et al., 2020; Zenk, 2008; Zenk & Visbeck, 2013). Here, we report the analysis of recent temperature time series in combination with historical data. The results confirm a persistent warming trend of AABW flowing through the Vema Channel.

Table 1
Summary of the Data Sets Used in This Study and Mean Values and Standard Deviations of Potential Temperature Sampled in the Four Mooring Sites

Data set name	Location	Seafloor depth (m)	Sensor depth (m)	Pressure (dbar)	Period of sampling	Mean **θ** ± (°C)	Std_dev (°C)	Ref
Hogg6894	30.7845°S 39.5335°W	4,656	4,560	4,641	March 22, 1980 to March 14, 1981	−0.157	0.009	Hogg et al. (1982)
WOCE	31.1373°S 39.4333°W	4,675	4,425	4,503	January 12, 1991 to December 05, 1992	−0.145	0.016	Zenk and Hogg (1996)
CLIVAR	31.2383°S 39.3333°W	4,580	4,527	4,612	April 21, 1998 to March 08, 2000	−0.135	0.007	Zenk (2008)
E2	31.2547°S 39.3160°W	4,544	4,479	4,557	May 31, 2005 to May 18, 2007	−0.123	0.008	Zenk and Visbeck (2013)
SAMBAR	31.2333°S 39.3833°W	4,630	4,529	4,610	February 01, 2019 to August 29, 2020	−0.086	0.012	This work
CTD_I	See Table S1				1972 to 2018	–	–	Morozov et al. (2018), Tarakanov et al. (2020)
CTD_II	31.20°S 39.30°W	4,390 4,448	4,385 and 4,440	4,462 and 4,518	January 03, 2020 and March 28, 2020	−0.105 −0.107	–	Morozov and Frey (2021)
CTD_II	31.20°S 39.34°W	4,458	4,553	4,634	March 28, 2020	−0.105	–	Morozov and Frey (2021)
CTD_II	31.20°S 39.39°W	4,605	4,599	4,682	March 28, 2020	−0.100	–	Morozov and Frey (2021)

Note. **θ** stands for potential temperature.

2. Material and Methods

On February 01, 2019, as part of the project Variability of the Meridional Transports across the SAMOC Basin-wide Array (SAMBAR), a mooring was deployed at 31.233°S, 39.383°W (Figure 1). The mooring was composed of an Aanderaa SeaGuard current meter (CM) and a conductivity-temperature recorder (microCAT SBE 37SM). None of the instruments had a pressure sensor but their depths were estimated using accurate depth finding and mooring wire lengths. The MicroCAT (MC) was placed at 101 m above the sea floor (Table 1, Figure S2). Given the local depth of 4,630 m, the MC depth of 4,529 m was used to estimate the pressure level (4,610 dbar), using the EOS-80 formulation (Saunders, 1981) to maintain compatibility with the older data. The mooring was recovered on August 29, 2020 and the data were subjected to the quality control process described in the Supporting Information S1 section. The moored record yielded a temperature time series with a 30-min sampling interval from February 01, 2019 to August 28, 2020.

To estimate the long-term variability and evolution of the temperature, the SAMBAR data were merged with five ancillary data sets (Table 1). Four of them are temperature time series sampled by sensors moored at nearby locations: (a) Hogg6894, that is, the record 6894 from the mooring at 30.7845°S, 39.5335°W reported by Hogg et al. (1982); (b) the WOCE ACM12 mta01767 (Zenk & Hogg, 1996); (c) the "Quasi CLIVAR" Vema Mooring V389105 MicroCat (Zenk, 2008), and (d) the E2 (Zenk & Visbeck, 2013). The fifth historical data set is the time-series of temperature from repeated hydrographic cruises composed of two parts: CTD_I and CTD_II. The first (CTD_I) covers the period from 1972 to 2018 and is described in Tarakanov et al. (2020). The second (CTD_II) contains data sampled during two recent visits by the Russian vessel *Akademik Mstislav Keldysh*, in January and March of 2020 (Morozov & Frey, 2021). The CTD data were obtained at different locations around the SAMBAR mooring site. However, the most recent observations were specifically sampled at 31.233°S; 39.383°W, which is the coldest part of the flow based on previous observations. In March 2020, a section was carried out across the channel along 31.2°S, indicated by the dashed line

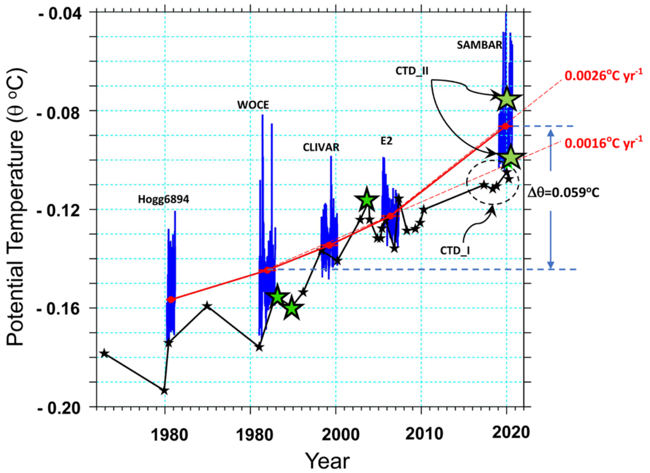

Figure 2. Bottom potential temperature variation in the Vema Channel over 50 years. The black line connects the potential temperature sampled near the bottom during hydrographic visits, indicated by the small black stars. The blue lines indicate the potential temperature derived from the moored instruments, with the red solid line connecting the mean values. The trends from 1990 to 2008 (0.0016°C yr^{-1}) and from 2008 to 2020 (0.0026°C yr^{-1}) are indicated by thin red dashed lines. The last five black stars, within the dashed circle, are CTD measurements at the site CTD_I. The black-contoured green stars indicate CTD temperatures sampled near the location of the SAMBAR measurements (CTD_II).

in Figure 1b. The two stations nearest to the SAMBAR site (at 39.4283°W and 39.3837°W) are used in the comparison with the SAMBAR data.

3. Discussion

We have merged highly resolved temperature observations from five intervals covering the period from 1980 to 2020. Plotting all data sets together shows the observed temperature variability of AABW flow via the Vema Channel (Figure 2). CTD profiles were collected at the time of deployment and recovery of each of the first three moorings (Hogg6894, WOCE, and CLIVAR). Three CTD profiles were collected while the E2 mooring was in place, from May 2005 to May 2007. The last two hydrographic surveys were conducted in January 2020 and March 2020, within the period the SAMBAR moored instruments were sampling.

In general, despite the different locations of the observations, there is a good agreement (within one standard deviation) between the ship-based measurements (the stars in Figure 2) and the data sampled by the moored recorders during the periods 1980–1981, 1991–1992, 1999–2000 and 2005–2007. Given the lateral temperature gradients between the different locations, we adjusted the temperatures of the mooring data to a single location in the following way. First, we estimated the long-term temperature increase based on the measurements at point 31.2°S 39.3°W close to the eastern wall of the channel because this part of the flow is well mixed, and this is the coldest core of the flow. Then, the bias (due to the across-channel temperature gradient) was estimated between this point and the SAMBAR mooring location at 39.38°W, where potential temperature was higher than near the eastern wall (Table S3). This temperature difference is clearly seen in Figure 3. The temperature difference was estimated based on 14 sections across the channel occupied from 1991 to 2020. The mean value of the temperature difference between these points is 0.0117°C. Potential temperature measurements at the mooring were reduced by this value to fit the long-term curve of temperature variations in Figure 2. The resulting linear trends for the mooring and CTD data (Figure S9) computed for the entire lengths of both time series are very similar: 0.0017°C yr^{-1} and 0.0018°C yr^{-1}, respectively.

The difference between the mean temperatures sampled by the moored sensors in 1991–1992 (WOCE) and 2019–2020 (SAMBAR) is roughly 0.059°C in about 28 years. This corresponds to a warming rate of 0.0021°C per year. The WOCE and SAMBAR moorings were both located farther west than the other time series, close to the 4,600 m isobath (Figure 1b). Note that at any given time, the along-isobath potential temperature variations are small compared to the long-term trends (Zenk & Morozov, 2007; Supporting Information S1).

Both CTD and mooring records can be described by linear fit to the data with similar linear trends calculated with the full length of the data sets (Figure S9). Based on a systematic pattern in the linear fit residuals, we performed a quadratic fit, which reduced the root mean square error by nearly an order of magnitude (Figure S10). We also computed the percent change in the trend between consecutive periods of the mooring data (Table S3). In all cases, the difference is positive and increasing: 18% from 1981–1991 to 1991–1999; 23% from 1991–1999 to 1999–2006; and 62% from 1999–2006 to 2006–2020. This motivated us to choose the E2 mooring as the break point for computing the trends shown in Figure 2.

From 1991 to 2005, the mean potential temperature increased from −0.145°C to −0.123°C, or 0.0016°C yr^{-1}, while after 2005–2007 the rate of warming increased to 0.0026°C yr^{-1}. In contrast, the CTD data suggest a steady warming trend for the entire period from early 1990 to 2020. The mean potential temperature at CTD_I (dashed circle in Figure 2) is noticeably lower than the mean value at the SAMBAR site. A detailed analysis rules out the impact of temperature sensor drift on the SAMBAR measurements. Moreover, as suggested by Hogg and Zenk (1997) more than two decades ago, the apparent inconsistency in the potential temperature trends may be explained by the "substantial cross-channel temperature variations...," which makes it difficult to separate long-term trends from spatial temperature variations. Regardless of

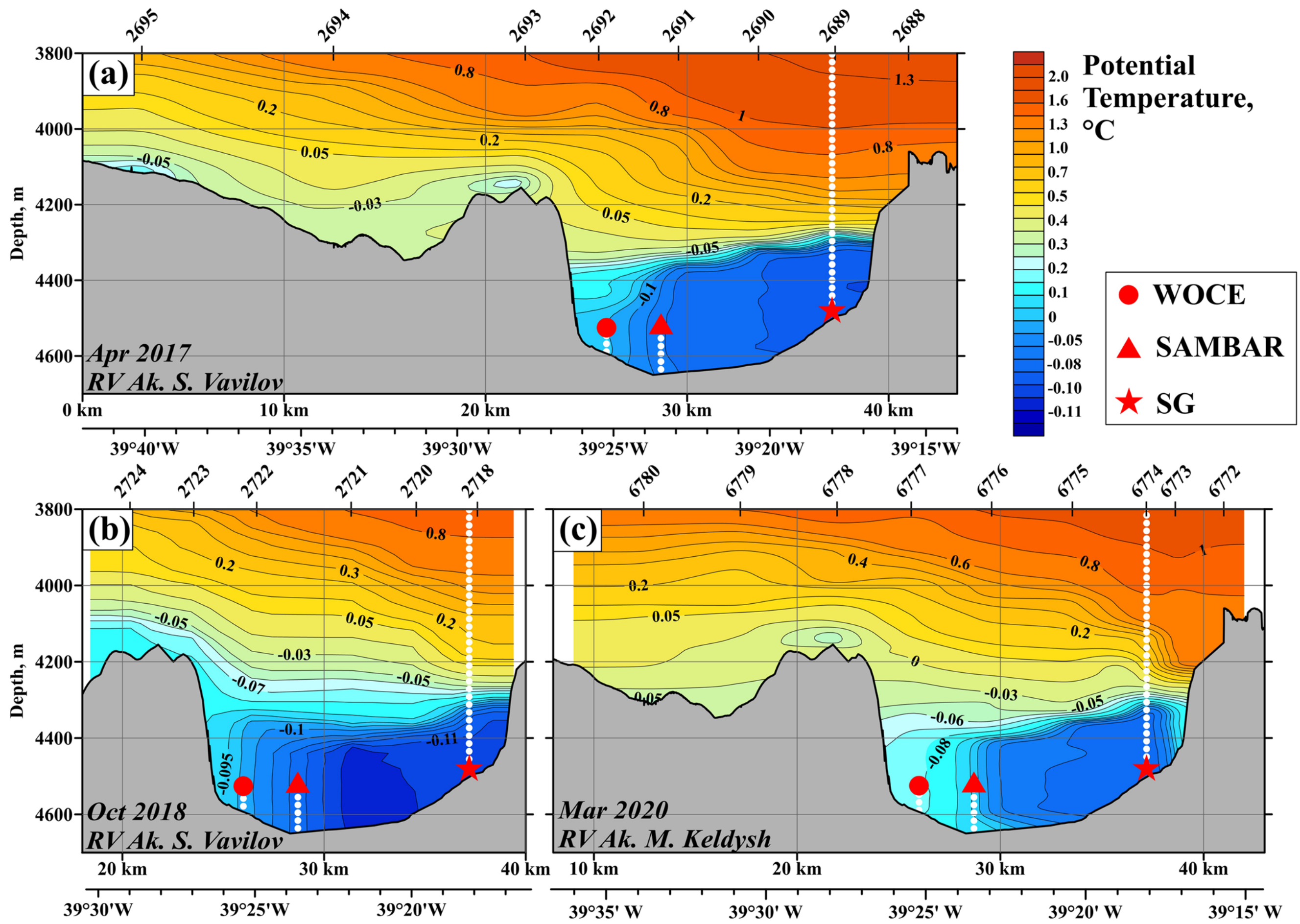

Figure 3. Vertical cross-channel sections of potential temperature along 31.2°S (indicated by the dashed line in Figure 1) plotted with CTD data collected during visits of the Russian research vessels in 2017, 2018, and 2020. The red circle, triangle and star indicate the sites WOCE, SAMBAR and SG (CTD_I), respectively.

whether linear or quadratic fits are used to quantify the temperature changes the warming rate for the entire 1991–2020 period is in good agreement with the abyssal temperature increase of ~0.02–0.04°C per decade reported in earlier studies (Johnson et al., 2020; Meinen et al., 2020; Zenk & Morozov, 2007) and suggests that this warming persists into recent years.

Temperature sections along the axis of the Vema Channel indicate that the near-bottom along-channel temperature gradient is of 0.0002°C km^{-1} (Zenk & Morozov, 2007; Supporting Information S1). In the cross-channel direction, however, there is a stronger gradient (−0.002°C km^{-1}): the waters near the eastern wall of the Vema Channel being colder than in the western side (Frey et al., 2019; Morozov et al., 2018; Zenk & Morozov, 2007). This near bottom east-to-west temperature gradient was well captured during three cross-channel sections along 31.2°S carried out by Russian vessels in May 2017, October 2018, and March 2020 (Figures 1c and 3). The WOCE and the SAMBAR sensors were moored closer to the western side of the channel, in areas with temperatures 0.011–0.012°C higher than those observed over the eastern side of the channel. Thus, while simultaneous measurements at WOCE and SAMBAR sites would be likely to yield similar temperatures, one should expect larger differences between measurements at the SAMBAR and the deeper CTD samples at the SG sites. This was considered when computing the trends, by means of an adjustment to account for abyssal spatial temperature gradients (Table S3, Figure S9). The temperatures at levels of the SAMBAR mooring during the three zonal sections shown in Figure 3 are quantified in Table 2. At the stations at longitudes 39.42 and 39.38°W, which are near the WOCE and SAMBAR mooring sites (less than 5 km), the potential temperatures fall within the range defined by one standard deviation of the

Table 2
Potential Temperature θ at Stations Along 31.2°S During Visits of Russian Vessels to the Vema Channel in 2017, 2018, and 2020

Period	Station	Longitude (° W)	Press. (dbar)	Mean θ (° C)
May 2017	2689	39.3000	4508	-0.1100
	2690	39.3450	4610	-0.1074
	2691	39.3867	4610	-0.1067
	2692	39.4283	4610	-0.0963
October 2018	2718	39.3000	4480	-0.1101
	2720	39.3333	4610	-0.1128
	2721	39.3667	4610	-0.1139
	2722	39.4167	4610	-0.1009
	2723	39.4500	4438	-0.0878
March 2020	6774	39.3067	4518	-0.1070
	6775	39.3450	4610	-0.1067
	6776	39.3867	4610	-0.1053
	6777	39.4283	4528	-0.0762

Note. The stations highlighted in green were occupied a few kilometers from the SAMBAR mooring.

SAMBAR data (the larger green stars with black outline in Figure 2)—the smaller green stars in Figure 2 are stations occupied near the SAMBAR mooring in other cruises. At the SG site (39.3°W), however, the mean potential temperature from the CTD measurements is colder by more than 0.02°C compared to the SAMBAR mean. Considering the short distance between the two locations, there is a gradient of ∼−0.0013°C km $^{-1}$, which is larger than the along-channel gradient reported by Zenk and Morozov (2007). This cross-channel gradient explains the lower temperatures in the recent CTD observations, and the apparent lack of a rate of increase in the warming trend in the CTD data at the SG site, as compared to the moored observations. This also illustrates the importance of assessing the location of observations within the channel when comparing different observations.

Another important feature captured by the moored instruments is the intense high-frequency variability in potential temperature. Rapid changes occur over periods of only a few days in the moored records, with peak-to-peak changes during these rapid events that exceeded the amplitude of the changes/trends we are discussing over decades. The ability to average months of high frequency observations illustrates the potential of the moored data to evaluate trends without aliasing the strong high frequency variability that can complicate analyses of snapshot observations from the CTD profile collected infrequently.

4. Summary

The mean potential temperature sampled during 2019–2020 SAMBAR mooring was −0.086°C, an increase of 0.059°C as compared with the −0.145°C mean of the 1991–1992 WOCE data. The warming trend of ∼0.0021°C yr^{-1} agrees with the most recent estimates in the Argentine Basin (Meinen et al., 2020) and the Brazil Basin (Johnson et al., 2020). Perhaps more crucially, our results suggest that this warming trend is increasing with time, with a possible acceleration beginning around 2005–2007. The moored data also reveal energetic high-frequency variability, as reported by Meinen et al. (2020). Our results underline the need to carry out sustained and more frequent observations to accurately quantify the longer term variation of the abyssal ocean temperature. Deep Argo floats have been proven to be effective in quantifying changes in the deep ocean in near real time over short periods with high accuracy (Johnson et al., 2019, 2020). Despite the uncertainties from the infrequent observations, the recent estimates from Deep Argo in the Brazil Basin (Johnson et al., 2020), falls within our estimate of 00016°C yr^{-1} to 0026°C yr^{-1} in the Vema Channel. Nevertheless, moored observations need to be carried out at selected locations to minimize the impact of the spatial distribution of the near-bottom temperature on the estimate of long-term temperature changes.

Data Availability Statement

All data used in this study are available at https://doi.org/10.17882/80927. Except for the SAMBAR data, all other data sets used in the article are described in Hogg et al. (1982), Zenk and Hogg (1996), Zenk (2008), Zenk and Visbeck (2013), Morozov et al. (2018), Tarakanov et al. (2020), and Morozov and Frey (2021).

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