Flow of Antarctic Bottom Water from the Vema Channel

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Abstract: We analyze measurements of bottom currents and thermohaline properties of water north of the Vema Channel with the goal to find pathway continuations of the Antarctic Bottom Water flow from the Vema Channel into the Brazil Basin. The analysis is based on the CTD/LADCP casts north of the Vema Channel. The flow in the deep-water Vema Channel consists of two branches. The deep current flows along the bottom of the channel and the other branch flows above the western wall of the channel. We found two smaller channels of the continuation of the bottom flow. These flows become weak and cease at a latitude of 26°S. The upper current that flows at a depth of 4100-4200 m along the continental slope is balanced by the gravity and Coriolis forces. We traced this current up to 24°S over a distance exceeding 250 km. This branch transports bottom water that eventually fills the deep basins of the North Atlantic.

Key words: Vema Channel; abyssal currents; Antarctic Bottom Water; CTD/LADCP profiles; bottom layer

INTRODUCTION

The Rio Grande Rise separates the Argentine and Brazil basins. It is a topographic obstacle for bottom water propagation to the north. The Vema Channel is a pathway of Antarctic Bottom Water (AABW, θ<2ºC) flow to the north through the Rio Grande Rise (Fig. 1). The depth of the Vema Channel exceeds 4600 m over the background depths of 4200 m (Morozov et al. 2010).

Repeated measurements of temperature, salinity, and velocity at hydrographic stations confirm the prominent role of the Vema Channel for the transport of AABW compared with the Hunter Channel in the east and the Santos Plateau in the west. The θ=2ºC potential temperature isotherm divides large-scale North Atlantic and Antarctic origin flows directed southward and northward, respectively. The transport of AABW through the transect along 31°S in the Vema Channel based on LADCP measurements ranges between 1.6 and 3.5 Sv (Morozov et al., 2010).

Not all the water that flows through the standard section at 31°12'S reaches the northern part of the channel.

The existence of two cores of AABW flow in the Vema Channel was reported in (Tarakanov and Morozov 2015; Tarakanov et al. 2020) (Fig. 2). The research made in (Tarakanov et al., 2020) is related to the study of hydrodynamic properties of the bottom flow and underwater spillways. The bottom core of the flow follows the deepest bed of the Vema Channel. It is a flow of cold dense water formed in the Weddell Sea, which passed the abyssal depths of the Argentine Basin. This flow is governed by the pressure gradient along the Vema Channel. The second core, which is found at a distance of 100–200 m above the western slope of the Vema Channel, is a continuation of the quasi-geostrophic flow of the Deep Western Boundary Current transporting AABW along the continental slope of South America (Morozov et al., 2010).

The objective of this paper is to study the pathways of propagation of the coldest and densest AABW ($\theta < 0.0$°C) into the Brazil Basin north of the Rio Grande Plateau based on the CTD and LADCP measurements. The main goal is to locate these pathways geographically.

BOTTOM TOPOGRAPHY AND DATA

The bottom topography based on satellite altimetry (Smith and Sandwell 1997) was used as the basis of the topography chart. We corrected the depths over the route of our vessels using echo sounders.

Our analysis is based on CTD/LADCP measurements (up to 5 m above the bottom) in 2003, 2009, 2010, 2012, 2013, 2018, 2019, and 2020 conducted in the region of the outflow of AABW from the Vema Channel and also on the data of the WOCE A17 section and quasi-zonal sections A09 in 2009 and 2018 along 24°S (http://cchdo.ucsd.edu). We also used the data of several other stations from the WOD18 database. The locations of our and historical stations are shown in Fig. 3. The barotropic tide was removed from the resulting velocity profiles using the TPXO 9 model (Egbert and Erofeeva 2002).

BOTTOM CURRENTS AND THERMOHALINE PROPERTIES OF BOTTOM WATER

The data of CTD/LADCP sections occupied across the Vema Channel in the northern part of its extension demonstrate the existence of two types of the coldest AABW ($\theta<0.2$°C). The less saline type of AABW follows the deep channel bed of the Vema Channel. The minimum potential temperature of this type of AABW in the northern region of the channel (26º43.2'S, 34º12.1'W) was recorded in 2003 ($\theta=-0.094$°C). It is noteworthy that there is a positive trend in the bottom potential temperature in time (Zenk and Morozov 2007). Potential temperature at the same point in 2020 was already θ=-0.067ºC. A more saline type of AABW was found over the gentle northwestern slope of the channel. Its core with the minimum potential temperature (θ=-0.084°C) was located at a depth of 4100 m, i.e. approximately 200 m shallower than the core of the less saline type of AABW.

Let us first consider the deeper currents near the outflow of AABW from the Vema Channel based on our CTD/LADCP casts in 2010-2020. The measurements showed that the continuation of AABW flow over the deep bed of the channel is no longer tied to a deep channel, but it spreads as a wider fan-shaped stream, in which two bottom jets of cold-water currents are distinguished. One of the jets (θ=-0.087°C) is directed initially to the east with a slight deviation to the northeast. The second jet with warmer water (θ=-0.063°C) is directed almost to the north. The flow is confined to the feet of higher mountains, while on the outer side of the flow there is a flatter elevation, and the channel is deepened about 200-250 m below the elevation. Usually, the channel width is ~10 km.

We searched for the continuation of the Vema Channel to the northeast of the channel. The stations were made in a quasi-zonally oriented valley nearly at 26°30'S east of 33°30'W, which seemed to be a topographic continuation of the Vema Channel (Fig. 3). Despite the fact that the sill depth at 33°30'W is slightly shallower than 4500 m, the CTD measurements at the stations occupied to the east of this sill showed that such topographic blocking is sufficient to stop the cold water current so that extremely cold water cannot pass to the valley located east of 33°30'W. The vertical temperature gradient at the bottom (0.46°/50 m) is very strong so that potential temperature at station 2527 (26°37.2'S, 33°39.6'W) at a distance of 50 m above the bottom is θ~0.4°C (Fig. 4) unlike θ=-0.034°C at the bottom (4554 m). The flow with potential temperatures below 0.2ºC, is confined to a thin bottom layer 40 m thick. The continuation of the flow turns to the north because of the existence of this barrier.

Along with the eastward continuation of the AABW flow in the Vema Channel there is also a branch of this stream directed to the north (approximately along 34ºW). The northern channel is about 70 m deeper than the relatively flat plain in the west. Thermohaline properties of water in this current are similar to the water properties in the Vema Channel.

The CTD/LADCP measurements in this channel revealed a northerly current with a velocity of approximately 5 cm s^{-1} (Fig. 5). The water in this current is characterized by the thermohaline properties similar to the water in the Vema Channel although it was slightly warmer (-0.063°C) compared to the water (-0.086°C) measured in the eastward flow.

We continued our measurements in the region to find the continuation of the flows from the Vema Channel to the north. A zonal section of four stations was occupied along 33°30'W nearly at 25°34’S where a small channel was found based on the digital database (Smith and Sandwell 1997). The channel is approximately 150-200 m deep relative to the surrounding plateau (4700 m). The width of the channel here is about 7 km at a level of the 4800 m isobath, the maximum depth is 4950 m (Fig. 5).

The measurements of the velocity component normal to the section in this channel show the presence of a high-speed (more than 35 cm s^{-1}) velocity core of the bottom flow approximately 100-150 m thick, which is displaced to the western slope of the channel. Station 2710 (25º34.0’S, 33º29.5’W) was located exactly in the velocity core of this flow. This layer with high velocities is located approximately below the θ=0.62°C isotherm. As usual in the Vema Channel, the core of cold fresher water is displaced to the eastern slope (i.e. to the right of the flow direction) with the formation of the sharpest deep thermocline over it. We estimated the transport in the bottom layer below θ<0.62°C as 0.150±0.007 Sv. This transport of bottom water is more than one order of magnitude smaller than the estimates of the total AABW flow through the Vema Channel through the standard section at 31°12'S.

The difference in the temperature profiles along the meridional channel (Fig. 4) shows gradual deepening of the isotherms (up to ~400 m) in the bottom layer from the Vema Channel Extension (station 2496) to the section (station 2710 at 25°34’S) especially notable in the layer colder than 0.60-0.65°C. Since the cold water flows out of the Vema Channel the motion of the bottom flow to the north in the meridional channel is determined by the pressure gradient. This small channel is a continuation of the deepest bed of the Vema Channel. As the bottom flow propagates to the north its temperature increases and thickness of the layer decreases, which leads to a decrease in the transport of coldest water.

Let us now consider the upper current of Antarctic Bottom Water. The pathway of the upper cold AABW flow is located over the western slope of the Vema Channel. Such an isolated core over the western terrace of the Vema Channel found on the standard section (along 31°12’S) was observed in the temperature distributions in 1984 (-0.15°C), 1991 (-0.16°C), 1992 (-0.13°C), 2006 (-0.10°C), 2009 (-0.10°C), 2017 (-0.06°C), 2018 (-0.08°C), and 2020 (-0.06ºC). Instrumental measurements of velocity in this core range within 30-36 cm s^{-1} (Morozov et al., 2010).

In 2009, a CTD-section along 24°S was occupied by British scientists. The section was repeated in 2018. Two individual cores of low bottom temperatures were found on this section with potential temperatures in the first core ranging between -0.04°C and -0.05°C at 33°50'W (approximately at a depth of 4650 m) and in the second core at 31°25'W (in the depth range 5000-5200 m) the potential temperatures were between -0.03°C and -004°C. The temperature section along this line (24º S) is shown in Fig. 5.

It is clear that the two jets considered above could not have such a cold continuation because the upper core was located higher than these two jets and the lower core was strongly colder than the temperatures in the previous jets.

It is likely that these two regions of relatively cold bottom temperature could be associated with the continuation of the upper current of AABW from the Vema Channel that was initially spreading above the western wall of the channel. There is no other source of such cold water because the potential temperature of bottom water in the two channels continuing the Vema Channel bed is not as cold as the one recorded on the 24°S section. The measurements in 2009 and 2018 were made at a distance of 300 km north of the channel. The inclination of the continental slope in this region is rather small: approximately 1:100. A jet of cold water in the motion can maintain its position on the slope balanced by the gravity and Coriolis forces. Shallow depressions on the continental slope (~50-100 m) were found exactly in the region of the location of cold-water cores, which could be eroded by the bottom water flow. The potential temperature of the two flows that are the continuations of the flow above the channel (θ~0.0°C) are warmer than the water found at 24°S; the cold water found at this longitude is located at shallower depths (~4600 m) than the two continuation flows (~4700 m) from the deep Vema Channel bed. The potential temperature of the two continuations of the flow is close to zero already at a latitude of 25°30'S. The temperature of the cold water found at 24°00'S, 33°42'W at a depth of 4626 m was -0.049°C. We emphasize that there are no sources of such cold water other than the Vema Channel. Hence, this water arrives here with the upper jet of AABW. In 2018, 2019, and 2020 we made stations to locate the upper jet north of the Vema Channel and confirmed its location at a latitude of 25°34'S. We also found this jet closer to the Vema Extension at 26°20'S, 34°30'W.

Figure 2 shows that a zonal canyon is located at 24°45'S; the canyon becomes wider approximately at 33°00'W. As seen from the distribution of temperature at the bottom from the historical data set (Fig. 3), this canyon widens the flow of the coldest AABW. This canyon diverts part of the cold-water flow down from the upper, quasi-geostrophic core of the AABW flow because the gravity force component directed normal to the flow increases over the steep slope of the canyon. Taking into consideration the geometric parameters of the canyon and its orientation across the geostrophic flow we conclude that the geostrophic balance fails below the edges of the canyon. In this case, a geostrophically uncompensated gravity current appears in the direction of the pressure gradient down the canyon. Thus, the canyon will operate as a channel that separates and diverts part of the bottom water from the upper, quasi-geostrophic stream of AABW to the abyssal depths of the Brazil Basin.

Thus, we conclude that the coldest type of AABW (θ<0.0°C) flows to the north in the Vema Channel as two jets, one of which is located in the deep channel bed and the other approximately

200 m above over the western slope of the channel. The deep channel bed of the Vema Channel does not end in the region 26°40’S, 34°00’W but continues as a widening to the north in the Brazil Basin. This flow generally diverges into two bottom flows along smaller channels. The potential temperature of the flow increases in the course of water spreading. Approximately at 25°30’S, the temperature becomes warmer than 0°C. The potential temperature of the upper jet remains negative even at 24°S. Measurements north of this latitude also revealed negative potential temperatures of the flow. This can be a continuation of the AABW jet described in (Sandoval and Weatherly 1999).

Fig. 7. Bathymetry of the study region based on (Smith and Sandwell 1997) and corrected with our echo-sounder measurement in 2010-2014. Locations of CTD/LADCP casts are shown. Brown dots show our stations in 2003. Green dots show the stations of the WOCE A17 section in 1994. Red dots show the station with negative potential temperatures of the A09 section in 2009. Small red dots show our stations in 2018-2020. Bottom potential temperatures are indicated with the same color as the station locations. The yellow arrows show the directions of currents and their velocity (vectors). White numbers at the dots of stations indicate potential temperature at the bottom. Blue colors emphasize deep water regions, especially the canyon at 24°40’ S. The magenta lines show a scheme of the pathway of the upper jet of AABW flow. Thinner lines show the pathways of the continuation of the deep flow from the bed of the channel.

Thus, we can construct a scheme for the continuation of the Vema Channel based on our and historical measurements north and northeast of the Vema Channel (Fig. 7). The pathways of upper AABW stream are shown with magenta lines in Fig. 7.

CONCLUSIONS

The most important result of our expedition studies in the region of AABW outflow from the Vema Channel is that the deep channel bed does not end here but initially has a quasi-zonal continuation to the east and another continuation to the north. The bottom potential temperatures demonstrate that this flow is related to the coldest part of AABW. The core of the coldest AABW that flows along the channel splits into two parts, one of which turns to the north and the second continues the motion in the eastern direction but also turns to the north because it cannot overflow a barrier at 33°30’ W.

The upper jet spreads further to the north than the bottom flows in the small channels. It is balanced on the continental slope by the gravity and Coriolis forces. This jet has been repeatedly identified on the continental slope of South America. Hence, this is exactly the jet that transports AABW farther to the north eventually filling the deep basins in the North Atlantic.

- **Availability of data and material**

  Field data set for this research is available from PANGAEA Data Archiving & Publications (https://doi.pangaea.de/10.1594/PANGAEA/903812).

- **Competing interests**

  The authors claim that they do not have any conflict of interest.

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- **Authors' contributions**

  Eugene Morozov, Dmitry Frey, and Roman Tarakanov participated together in many cruises. All three participated in field measurements and data analysis. Eugene Morozov was head of the expeditions and wrote the text consulting both co-authors

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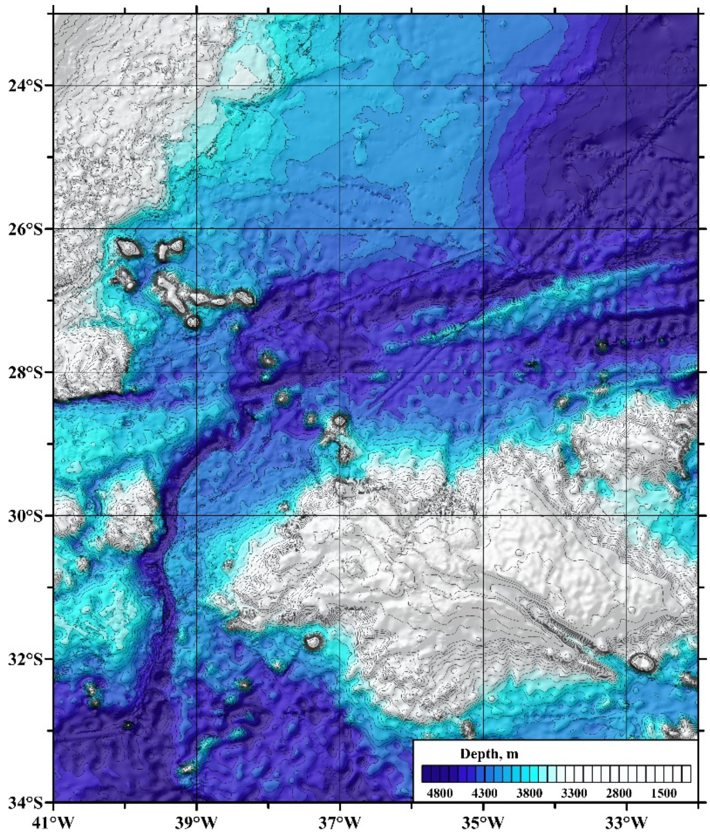

Fig. 1. Topography of the Vema Channel and its continuation

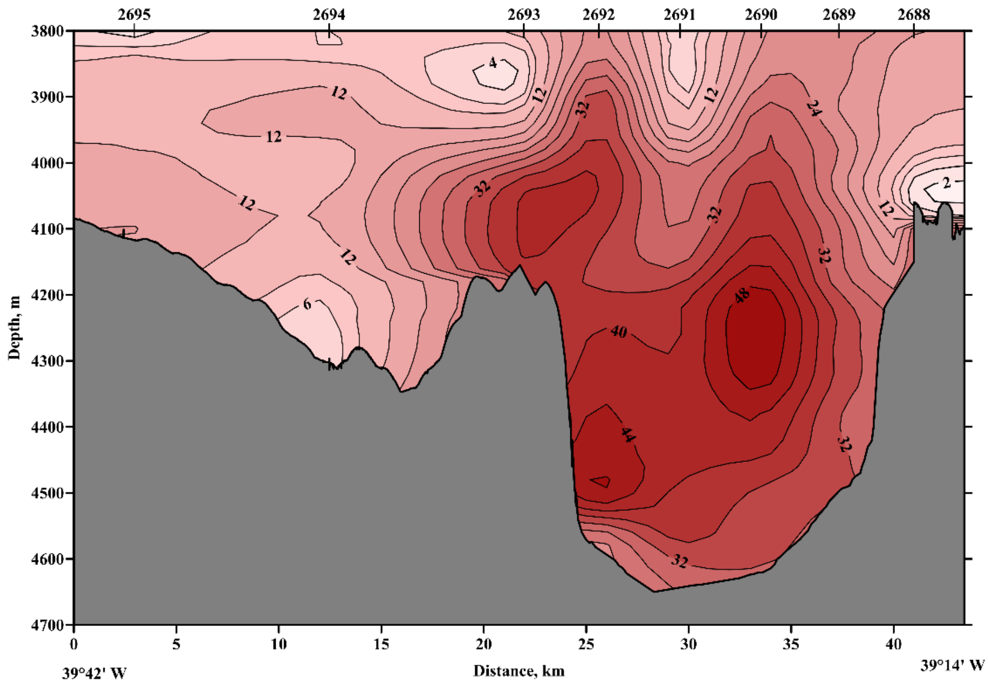

Fig. 2. Section of the meridional velocity component across the Vema Channel at 31º12'S in April 2017. Contour lines are indicated in cm s^{-1}. Numbers of stations are shown along the top axis.

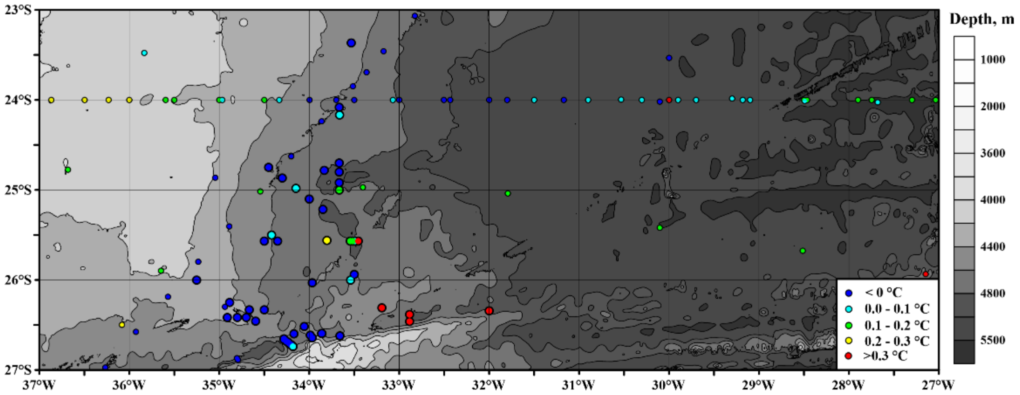

Fig. 3. Bathymetry of the study region north of the Vema Channel based on (Smith and Sandwell, 1997). Locations of our CTD/LADCP casts in 2003–2020 (large circles) and historical stations (small circles) are shown. The corresponding potential temperatures are shown in color.

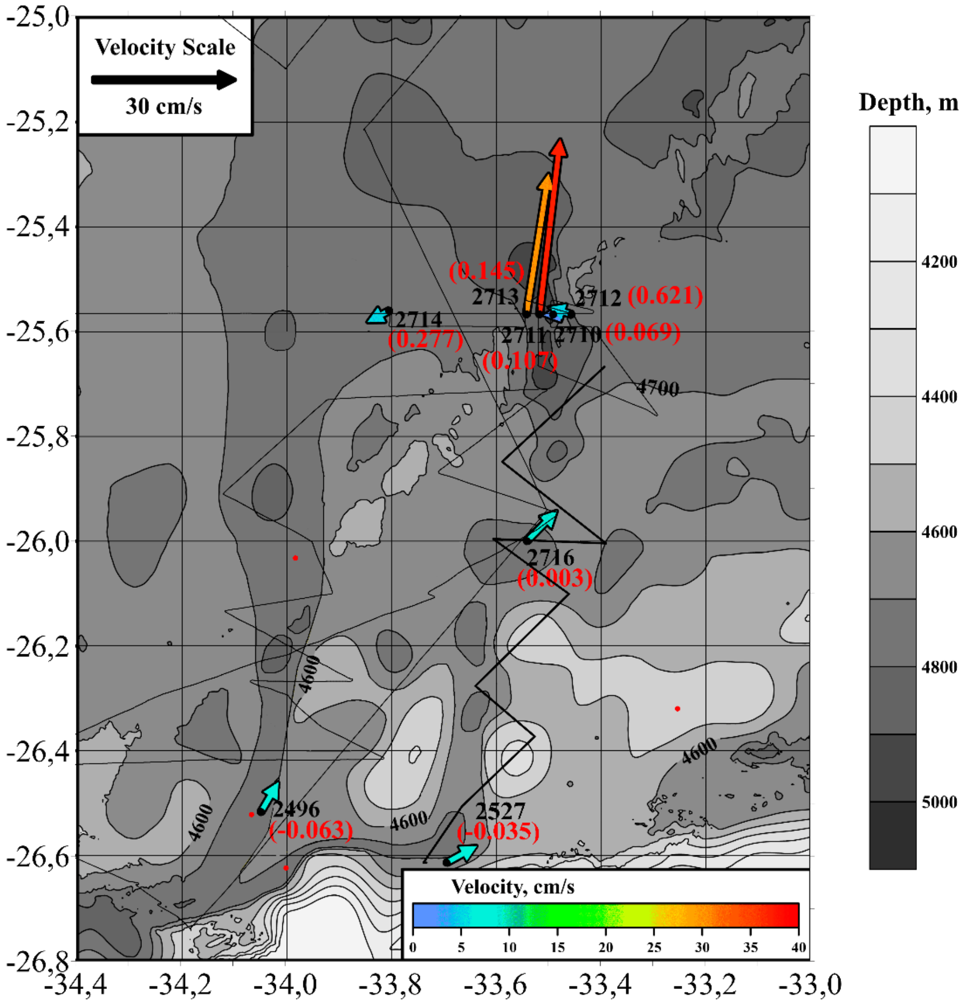

Fig. 4. Locations of important stations north of the Vema Channel. Vectors of the LADCP velocities averaged over the 50-meter bottom layer, and potential temperatures measured at the bottom (numbers in brackets) are shown. Thin lines show the lines of echo-sounder measurements.

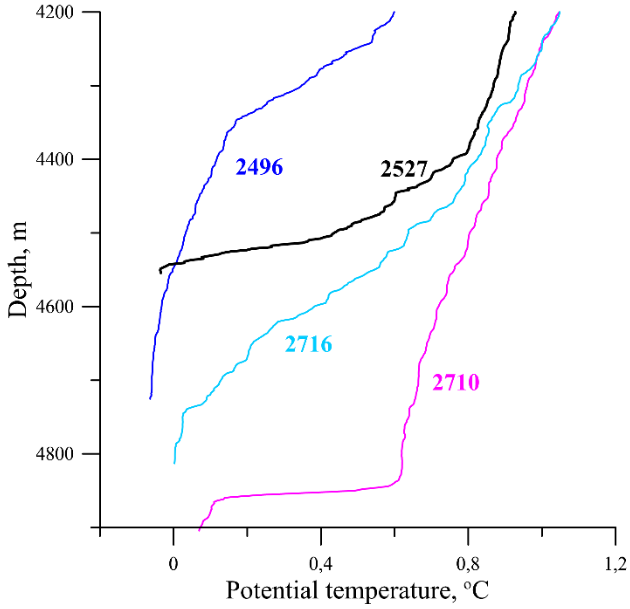

Fig. 5. Profiles of potential temperature in the bottom layer at stations 2496 (26°31.1'S, 34°03.3'W), 2710 (25°34.0'S, 33°29.5'W), 2527 (26°37.2'S, 33°39.6'W), and 2716 (26°00.0'S, 33°32.5'W) in the depressions. The numerals at the profiles correspond to the numbers of stations in Fig. 4.

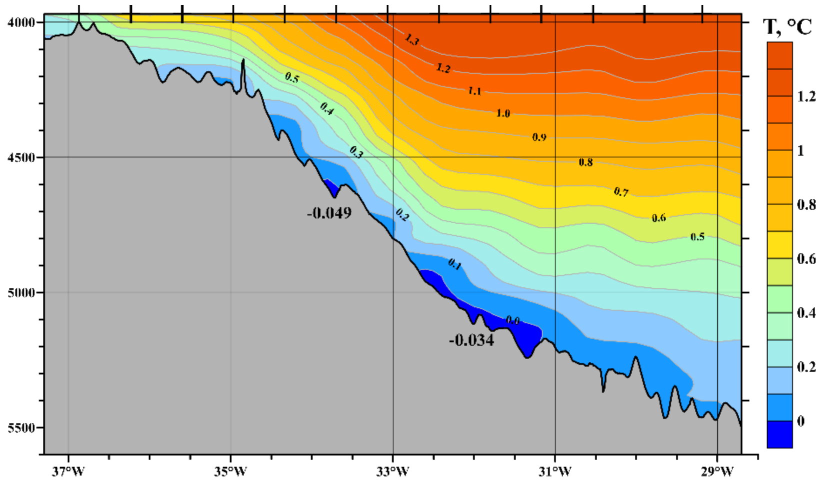

Fig. 6. Distribution of potential temperature over the bottom part of the A09 section (2009) over the continental slope of South America. The potential temperatures at the bottom are indicated.

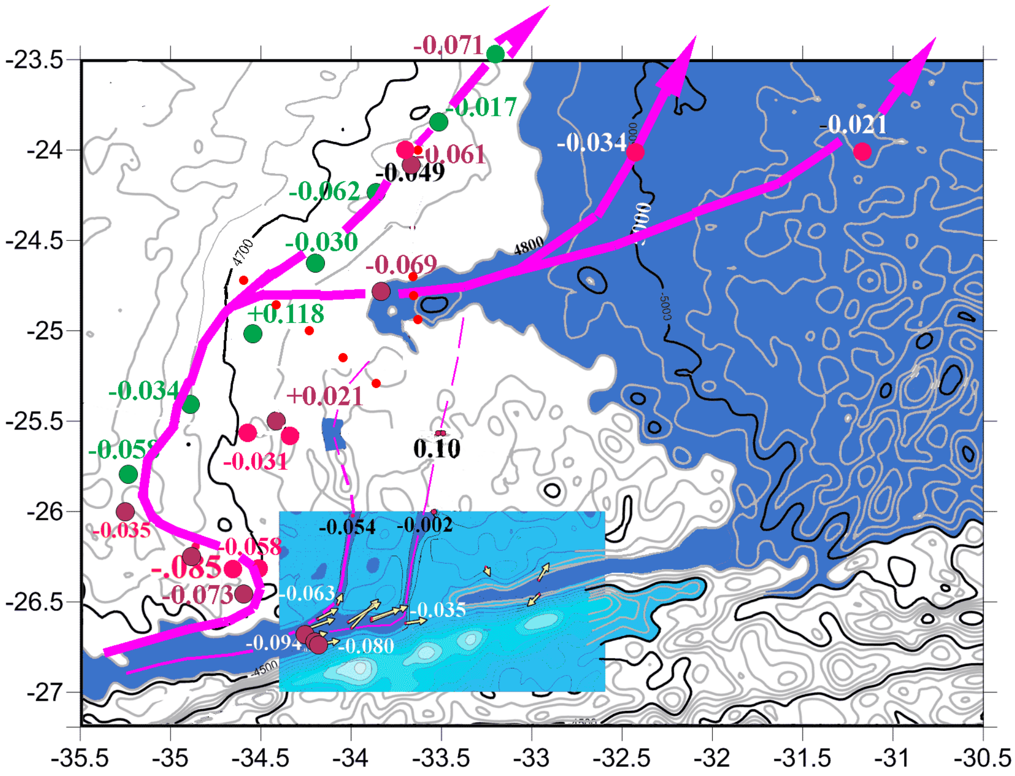

Fig. 7. Bathymetry of the study region based on (Smith and Sandwell 1997) and corrected with our echo-sounder measurement in 2010-2020. Locations of CTD/LADCP casts are shown. Brown dots show our stations in 2003. Green dots show the stations of the WOCE A17 section in 1994. Red dots show the station with negative potential temperatures of the A09 section in 2009. Small red dots show several our stations in 2012-2020. Bottom potential temperatures are indicated with the same color as the station locations. The yellow arrows show the directions of currents and their velocity (vectors). Numbers in color at the dots of stations indicate potential temperature at the bottom. Blue colors emphasize deep water regions, especially the canyon at 24°40’ S. The magenta lines show a scheme of the pathway of the upper jet of AABW flow. Two small deep channels are shown schematically along 33°40’W and 34°05’W.