Currents and water structure north of the Vema Channel

E. G. Morozov[1], R. Yu. Tarakanov[1], D. I. Frey[1], and D. G. Borisov[1]

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We consider measurements of currents north of the Vema Channel with the goal to find continuations of the bottom water flow after Antarctic Bottom Water leaves the Vema Channel and discharges to the Brazil Basin. We found two smaller channels of the continuation of this flow, one of which is directed to the east and the other to the north. The flow of the coldest water and the magnitudes of its velocity are important for the sedimentation processes, which occur in this region. We analyze the hydrology of the bottom water needed to compare the conditions of environment and the structure of sediments. *KEYWORDS:* Abyssal currents; Vema Channel; sediments; CTD casts; LADCP profiling.

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Introduction

The Vema Channel is the deepest of the existing routes of AABW flow to the north from the Argentine to the Brazil Basin in the region of the Rio Grande, and therefore, the coldest bottom waters flow through this channel. The depths of the Vema Channel exceed 4600 m, while the depth of the Santos Plateau is approximately 4200 m. The channel is a narrow passage between two terraces. In the narrowest part, its width slightly exceeds 15 km. The Vema Channel has been eroded for many millions of years by the abyssal currents of Antarctic Bottom Water [*Gamboa et al.,* 1983]. The topography of the Vema Channel is shown in Figure 1.

Intense studies of the bottom water flow through the Vema Channel were carried out on the standard section across the channel, which runs along the latitude 31°12′ S [*Morozov et al.,* 2008, 2010]. Bottom water flows from the channel to the Brazil Basin in the region of 27°40′ S. Comparison of our measurements over the standard section and over the section in the northern part of the Vema Channel shows that not all the water that flows through the standard section reaches the northern part of the channel. The bottom friction prevents free flow of water, and the bottom water, not being able to completely flow through the channel, finds other pathways. The conclusion that not all the current flowing in the Vema Channel flows into the Brazil Basin was made earlier [*McDonagh et al.,* 2002]. The scheme suggested by these authors shows that in the region of latitude 27°30′ S the stream turns to the west and makes a large anticyclonic loop, which diverts about 2 Sv of the water transport. Our measurements of the currents at the Vema Channel in 2009 showed the presence of a counter current of Antarctic Bottom Water to the south above the level of 4200 m.

Field Measurements of Water Structure and Currents

In 2003, a CTD section without current measurements was made across the Vema Channel in its northern part (approximately at 26°40′ S). In

[1]Shirshov Institute of Oceanolgy RAS, Moscow, Russia

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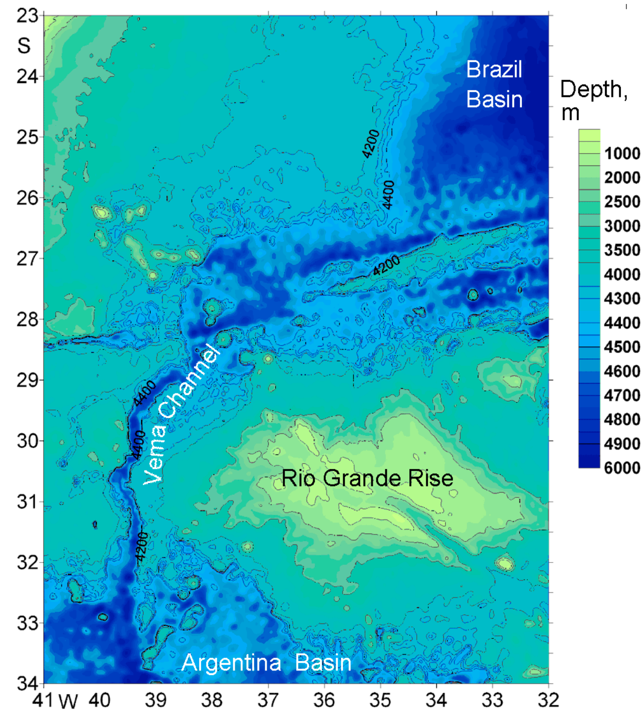

Figure 1. Bottom topography in the region of the Vema Channel based on ETOPO data.

2009–2014, the casts were made with the LADCP profiler; therefore, the velocities and transports from the Vema Channel were estimated at a latitude of about 26°30′ S. Sampling of sediments was also made in this region. A map of stations is shown in Figure 2.

The mean velocities of the current with minimum temperatures on the standard section through the Vema Channel, which was occupied repeatedly (31°12′ S), are 23 cm/s, and in the northern section (26°40′ S) they decrease to 11 cm/s. Another jet of Antarctic Bottom Water with higher temperatures flows above the western slope of the channel at speeds exceeding 20 cm/s.

In 2012, measurements in the northern part of the Vema Channel were continued. The main task of these works in the northern part of the Vema Channel (26°44′ S, 34°10′ W) was to determine the position of the continuation of the Vema Channel and the pathways of the bottom water flowing from the channel. The criteria for detecting the continuation of the Vema Channel were the cold temperature of the bottom flow (potential temperature less than 0°C) and its direction in the northeastern quadrant.

The potential temperature of the coldest water (with negative temperatures) at the sections and stations, which have been carried out since 2003 in the regions of 26°45′ S, 34°11′ W, was in the range from −0.075°C to −0.094°C.

The measurements north of the Vema Channel showed that the flow of Antarctic Bottom Water is no longer tied to a deep channel, but it spreads as a wider stream, in which two bottom jets of currents are distinguished. A more intense jet with colder water ($\theta = -0.087$°C) is directed to the east with a slight deviation to the northeast and apparently flows around the northern slope of the Rio Grande Rise. The second less intense jet with warmer water ($\theta = -0.063$°C) is directed almost to the north [*Morozov and Tarakanov,* 2014]. The echo sounder showed that the continuation channels in the northern part of the Vema Channel are confined to the underwater mountains. 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 5–6 miles.

In our expeditions to this region in 2009, 2010 and 2012, the CTD casts were accompanied by measurements of the flow velocity with the help of LADCP (LADCP, RDI WHS 300 kHz). Due to the high transparency of the deep waters of the subtropical Atlantic, the estimates of velocities based on the LADCP data in the entire water column at most stations were not reliable. Therefore, only the LADCP data near the bottom (bottom track

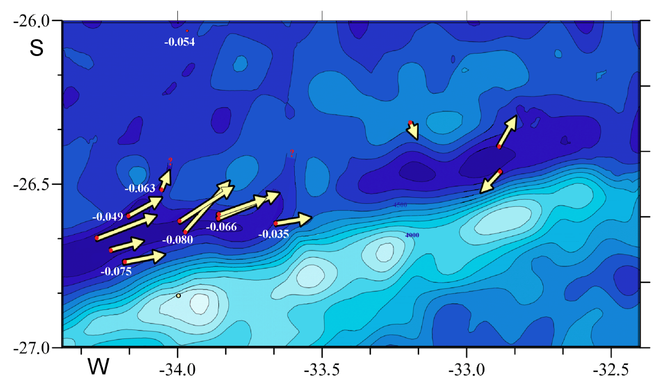

Figure 2. Bathymetry of the study area based on Smith & Sandwell database and corrected with our echo-sounder measurements in 2010–2014. Locations of CTD/LADCP casts (red dots) are shown. The yellow arrows show the directions of currents and their velocity (vectors). White numbers at the dots of stations indicate potential temperature at the bottom. The yellow dot shows the location of sediment sampling site.

data) were considered reliable. The deep channel does not end here, but has a quasi-zonal continuation to the east. In addition to the echo sounding, this was confirmed by measurements of the bottom temperature and velocities at the bottom in 2009, 2010, 2012 and 2013. The velocities were directed to the east, and their maximum reached 20 cm/s. At the same time, the potential temperature at the bottom was negative. Thus, the core of the coldest AABW flow in the channel spreads further to the east.

The measurements in 2012–2013 showed that 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. On the western side of the hill with the center at 26°30′ S, 33°48′ W, the vessel three times crossed a channel oriented approximately from the south to the north. The channel is approximately 4 km wide and 70 m deeper than the relatively flat plain in the west. The slope of the walls of this small channel is up to 7–11%. Measurements at stations in such small channels usually show a current with a velocity of approximately 5 cm/s. Thermohaline properties of water in this current are similar to the water properties in the Vema Channel.

In 2009, a CTD-section along 24°S has been occupied by British scientists. Two individual cores of low bottom temperatures were found on this section with potential temperatures $\theta \sim -0.04$°C at 33°50′ W and $\theta \sim -0.005$°C at 31°25′ W. It is possible that these two regions of relatively cold bottom temperature could be associated with the continuation of the bottom flows of AABW from the Vema Channel, although the measurements in 2009 have been made at a distance of 300 km north of the channel. The slope angle of the continental rise in this region is rather small: approximately 1 : 500. A jet of cold water in the motion can maintain its position on the rise balanced by the gravity and Coriolis forces [*Zhmur and Nazarenko,* 1994]. Shallow depressions on the continental slope ($\sim 50 - 100$ m) were found exactly in the region of the location of cold water cores, which could be eroded by the bottom water flow [*Morozov and Tarakanov,* 2014]. However, a distance of 300 km is too large to make a conclusion that these two cores are exactly the continuations of the two flows that we found.

Approximately at a latitude of 26°30′ S a deep depression exists extending in the eastern direction from 33°20′W to 32°W where the depths of the Brazil Basin reach 5000 m. We thought that the eastern continuation of the flow from the Vema Channel continues along this depression. With this in mind in 2013 we made 4 CTD-casts in this depression, but all of them revealed that no water cooler than 0°C exists here as well as no clearly pronounced easterly flow of bottom water was found. The bottom water temperature was approximately +0.4°C. Hence, a submarine mound exists approximately along the 33°30′ W meridian that prevents propagation of coldest water from the west.

In 2012, investigations north of the Vema Channel were completed at station 2497 (26°35.8′ S, 33°51.7′ W). The potential temperature of water at the bottom was −0.087°C; the current was directed to the east-northeast. In 2013, station 2497 was repeated as station 2526 almost at the same coordinates 26°35.7′ S, 33°51.7′ W. But in 2013, the potential temperature was −0.066°C (in contrast to the colder water in 2012, $\theta = -0.087$°C); we think that this happened because the instrument did not get exactly in the stream of the coldest water, or maybe the water warmed by 0.02°C. The direction of the current did not change. Detailed echosounder measurements in this area showed that the channel bed becomes shallower (up to 4550 m) and in the region of longitude 33°39′ W it turns to the northeast, because shallower topographic obstacles which are located further to the east do not allow the further eastward flow of the bottom water. Station 2527 was occupied at coordinates 26°37.2′ S, 33°39.6′ W at a depth of 4554 m east of stations 2497 and 2526. The current at this station was directed to the northeast (12 cm/s), while the bottom temperature increased to −0.036°C.

The bottom flow ascends to shallower depths and several times crosses the thresholds with a depth of 4550–4560 m. Weddell Sea Deep Water is confined to a thin bottom layer 40 m thick, which is seen on the vertical temperature profile at station 2527 (Figure 3).

Thus, we can construct a scheme for the continuation of the Vema Channel, which is shown in Figure 2. Spreading of bottom water east of 36°30′ is closed. The AABW that is found east of this longitude with a temperature of +0.4°C was transported from the east.

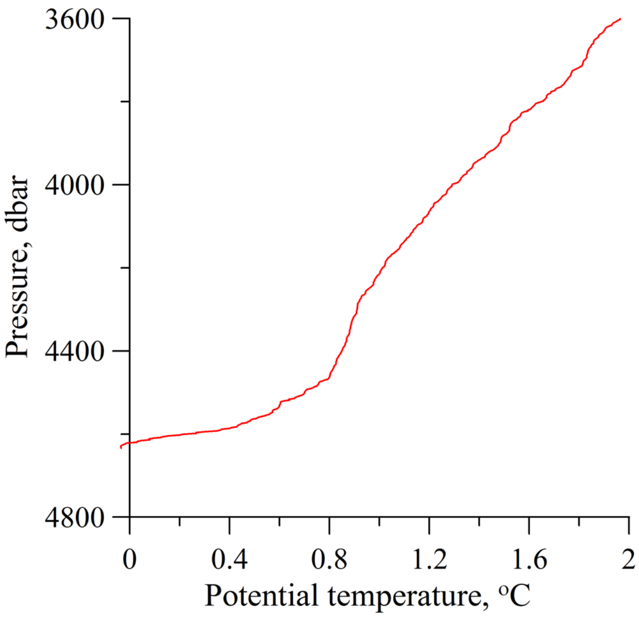

Figure 3. Profile of potential temperature at station 2527 at 26°37.2′ S, 33°39.6′ W. Near the bottom, a strong temperature gradient exists (0.8°/150 m).

Model Simulations of Circulation

In addition to the measurements in the bottom layer, we simulated the currents in this region using the modern three-dimensional ocean dynamics model INMOM [*Frey et al.,* 2017]. The INMOM model is based on a complete system of primitive equations of hydro-thermodynamics in spherical coordinates with the hydrostatic and Boussinesq approximations. The INMOM model has been tested in the Atlantic, including the experiments within the international CORE program [*Danabasoglu et al.,* 2014].

The initial conditions are specified using the temperature and salinity fields from the climatic average monthly data of the World Ocean Atlas [*Antonov et al.,* 2010], the initial velocity field is assumed zero. These data are also used to specify the annual cycle of temperature and salinity at liquid boundaries.

The fields of horizontal velocities, potential temperature and salinity at the sigma levels, and sea surface height are the prognostic parameters of the model. The horizontal resolution is 0.02° by latitude and longitude, which gives about 10 calculation points in the cross section of the Vema Channel with a width of 20 km. The vertical sigma levels are non-uniform; the best resolution is at the bottom. The total number of sigma levels is 33, at a depth of 4850 m, the lower 10 levels are set near the bottom between 4400 and 4850 m with a resolution of 50 m.

Application of sigma levels as a vertical coordinate makes it possible to describe the bottom dynamics of the ocean in an arbitrary range of depths; good resolution at the bottom is gained both in the Vema Channel and in the deep Brazil and Argentine basins. Simulated velocities from the deepest σ-level are presented in Figure 4. Analysis of the simulation results shows that the bottom velocities in the ocean basins are usually low and do not exceed 8–10 cm/s. North of the Vema Channel, the characteristic velocities are about 10–15 cm/s with a general direction to the northeast (Figure 4). The model and measured velocities do not contradict each other.

We also provide graphs of the vertical distribution of the potential temperature and temperature in situ, which affects the composition of the sediments (Figure 5). The temperature graphs are given for two stations: on the slope of the elevation (station 1446 R/V *Akademik Ioffe* in 2003, 26°44.4′ S, 34°10.8′ W) and in the continuation of the Vema Channel (station 2526 R/V *Akademik Sergey Vavilov* in 2013, 26°35.7′ S, 33°51.6′ W), closest to the sediment core site [*Ivanova et ak.,* 2016].

Structure of Sediments

The ocean waters at depths below several hundred meters are aggressive toward calcium carbonate in the sediments. They become more aggressive with increasing depth due to the increase in hydrostatic pressure, decrease in temperature, and carbonate ion concentration. There are two major water depth levels distinguished according to calcium carbonate content in sediments. The lysocline represents a boundary, below which the rate of dissolution of calcite (or aragonite) increases substantially. This boundary marks a dramatic change in preservation of foraminifera tests, pteropodes and coccoliths. The depth of the lysocline is different for each of the indicated types of organisms. The carbonate compensation depth represents the

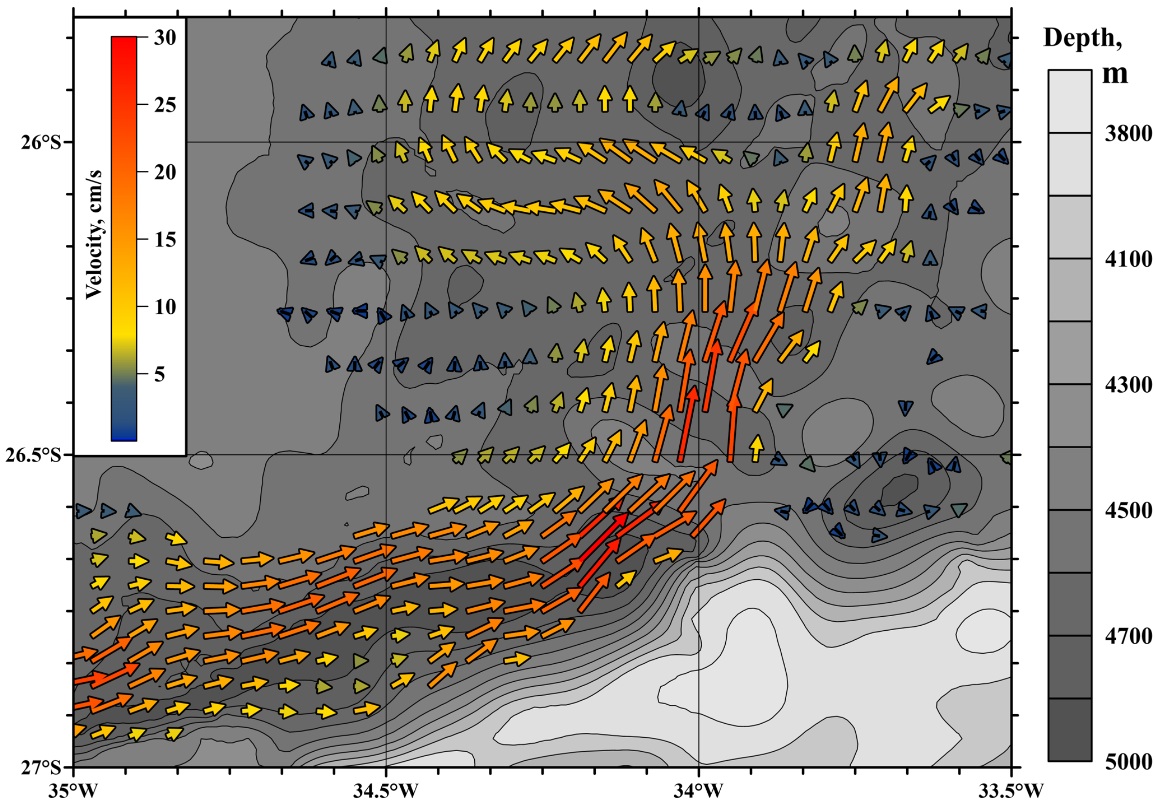

Figure 4. Bathymetry of the study site north of the Vema Channel and modeled velocities in the bottom layer from the deepest σ-level for the depths greater than 4500 m.

depth level, at which the rate of carbonate accumulation equals the rate of carbonate dissolution. The calcite lysocline is considered by several authors to be associated with the boundary between North Atlantic Deep Water and Antarctic Bottom Water [*Berger,* 1968; *Volbers and Henrich,* 2004]. According to [*Melguen and Thiede,* 1974] the foraminiferal lysocline and carbonate compensation depth correspond to water depths of 4050 and 4500 m, respectively. It is assumed in [*Johnson et al.,* 1977] that the carbonate compensation depth in the southern part of the Brazil Basin is 4250 m. Analysis of the sediment core taken on the ridge south of the CTD/LADCP stations revealed significant variations in the lysocline depth during the last 3 Ma (up to 3800–3900 m) [*Ivanova et al.,* 2016].

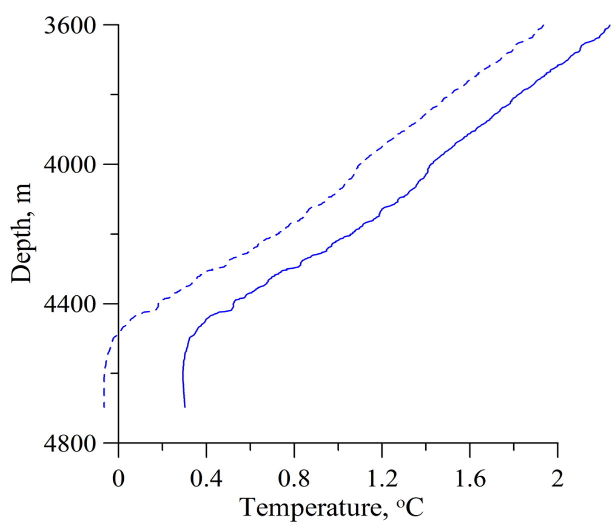

Figure 5. Solid curve shows in situ temperature profiles at station 2526 (26°35.7′ S, 33°51.6′ W, blue line). The dashed line shows the potential temperature.

The 2°C isotherm marking the upper boundary of AABW is traced in the study area at a depth of approximately 3800 m. Good preservation of calcareous microfossils in surface sediments collected south of the CTD/LADCP stations in the depth range 3800–3900 m [*Dmitrenko et al.,* 2012; *Ivanova et al.,* 2016] indicates that the calcite lysocline is associated with the depth level within AABW. Analysis of the sediment core retrieved on the ridge south of the CTD/LADCP stations revealed significant variations in the lysocline depth during the last 3 Ma (up to 3800–3900 m) [*Ivanova et al.,* 2016]. It is likely that the carbonate compensation depth corresponds to the depth range of

4500–4600 m characterized by a rapid decrease in water temperature. The depth levels located below the 0.5°C isotherm correlate well with data published in [*Melguen and Thiede,* 1974].

Conclusions

In the northern part of the Vema Channel, Antarctic Bottom Water flowing from the Vema Channel splits into two branches. The stronger jet with cold water ($\theta = -0.087$°C) is directed to the east. The second jet with slightly warmer water ($\theta = -0.063$°C) is directed almost to the north. Good preservation of calcareous microfossils in the surface sediments collected in the study area indicates that the calcite lysocline is located within AABW below the 2°C isotherm. The carbonate compensation depth is likely to be associated with a zone of dramatic decrease in water temperature down the water column at depths of 4500–4600 m (below the 0.5°C isotherm).

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D. G. Borisov, D. I. Frey, E. G. Morozov, and R. Yu. Tarakanov, Shirshov Institute of Oceanolgy RAS, Nakhimovskii prospect .36, 117997 Moscow, Russia. (egmorozov@mail.ru)