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ПОТОК АНТАРКТИЧЕСКОЙ ДОННОЙ ВОДЫ В КАНАЛЕ ВИМА. ОБЗОР

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Дается обзор наших многолетних исследований потока донных вод в канале Вима в Южной Атлантике. Канал Вима является главным путем распространения Антарктической донной воды из Аргентинской котловины в Бразильскую котловину и далее на север. Канал характеризуется высокими скоростями распространения донного потока. В потоке наблюдаются высокие скорости течений до 60 см/с, хотя обычно скорости находятся в пределах 25—40 см/с. Перенос Антарктической донной воды через канал Вима меняется в пределах от 1.6 до 4.0 (±0.2) Св. За счет придонного экмановского трения ядро холодной и менее соленой воды (θ = −0.120°C) обычно прижато к восточному склону канала. Мы использовали численную модель Института вычислительной математики РАН для моделирования потока донных вод в канале Вима. Это σ-модель на основе полной системы уравнений гидродинамики с приближениями гидростатики и Буссинеска. которая лучше моделирует придонные потоки чем *z*-модели. Численное моделирование подтверждает измерения в океане и показывает пространственную структуру поля скорости в канале.

Ключевые слова: Канал Вима, абиссальный поток, Антарктическая донная вода, поле скоростей, профили температуры, солености и скорости (CTD, LADCP).

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FLOW OF ANTARCTIC BOTTOM WATER IN THE VEMA CHANNEL. A REVIEW

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We present a review of our long-term research of the bottom water flow in the Vema Channel in the South Atlantic. The Vema Channel is the main conduit for Antarctic Bottom Water between the Argentine and Brazil basins and further to the north. This channel is characterized by strong bottom flow. The bottom velocities are usually in the range 25—40 cm/s. The maximum measured velocities were as high as 60 cm/s. The total transport of Antarctic Bottom Water through the channel ranges from 1.6 to 4.0 (±0.2) Sv. The core of the coldest (θ = −0.120°C) and low salinity (34.665 psu) water is usually displaced to the eastern wall due to the Ekman friction. We used the numerical model for ocean circulations developed at the Institute of Numerical Mathematics to simulate the bottom flow in the Vema Channel. This is a σ-model based on the full system of thermo-hydrodynamic equations with the hydrostatic and Boussinesq approximations, which describes bottom currents more adequately than the *z*-models. Numerical simulations confirm the field measurements and reveal significant variability in the intensity and spatial structure of the velocity field in the channel.

Key words: Vema Channel, abyssal flow, Antarctic Bottom Water, velocity field, CTD and LADCP profiles.

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Introduction. It is generally accepted that Antarctic Bottom Water is the water mass that occupies the bottom layer of the Atlantic with potential temperature less than 2°C. This definition is given by Wüst [1]. Antarctic Bottom Water originates from Antarctic Shelf Water, which is formed in the cold seasons along the Antarctic shelf due to cooling of the relatively fresh Antarctic Surface Water and salinification due to ice formation. Antarctic Bottom Water is formed over the Antarctic slope as a result of mixing of the cold and heavy Antarctic Shelf Water with the lighter, warmer, and more saline Circumpolar Deep Water. In the Atlantic Ocean this process generally takes place in the Weddell Sea. If the salinity of the mixed waters is relatively high and the temperature is low, the resulting water mass reaches the ocean floor, thus forming Antarctic Bottom Water.

The pathways of Antarctic Bottom Water spreading in the Atlantic are confined to the depressions in the bottom topography. Antarctic Bottom Water from the Weddell Sea propagates through several passages in the South Scotia Ridge. Then, its pathway to the north into the Argentine Basin occurs through the Falkland Gap in the Falkland Ridge [2]. Part of this water propagates in the Argentine Basin and reaches the Vema Channel before its further transport to the north. Actually, the water flow of bottom waters to the Brazil Basin occurs along three pathways: in the Vema Channel, in the Hunter Channel, and over the Santos Plateau. The measurements in these channels provide evidence that the Vema Channel is the most important pathway in the transport of Antarctic waters compared to the other passages [3]. A scheme of AABW flow is shown in Fig. 1.

The Vema Channel was discovered during the German expedition of R/V Meteor in 1925—1927. Initially, the Vema Channel was known as the Rio Grande Gap (for more details see [4]). Later, this channel was given the name of Vema in recognition of the intense work done by the former research vessel Vema (USA).

The goal of this publication is to review the previous research of the flow of Antarctic Bottom Water in the Vema Channel.

Topography and history of research. The bottom topography around the Vema Channel based on the ETOPO digital topography is shown in Fig. 2. The Vema Channel is the deepest passage for the further spreading of Antarctic Bottom Water in the South Atlantic. The channel is narrow; its width in the narrowest part is 15 km. The depth of the Vema Channel exceeds 4600 m against the background depth of 4200 m. A small sill across the channel (Vema Sill) is located at 31°12' S. The deepest spot of the Vema Sill is 4614 m [4].

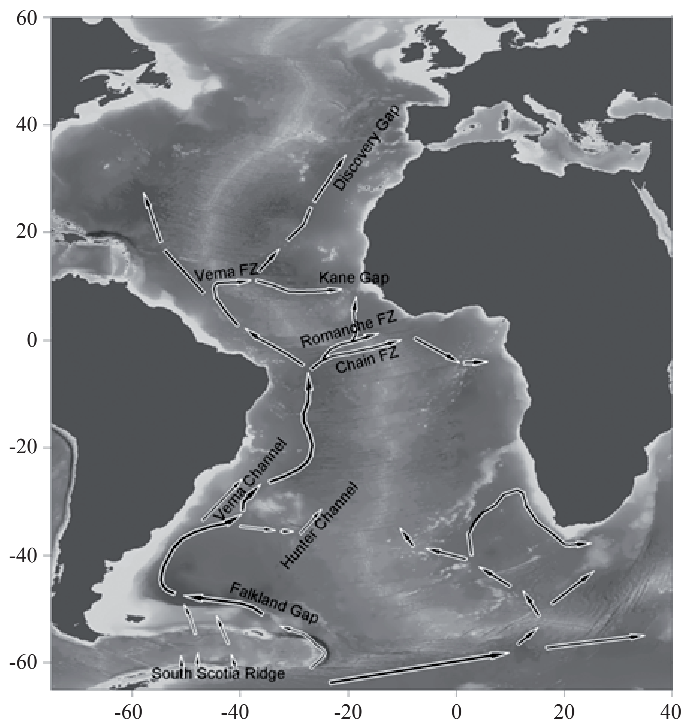

Fig. 1. Scheme of Antarctic Bottom Water flow in the Atlantic. Names of the abyssal channels are indicated.

Рис. 1. Схема потока Антарктической донной воды в Атлантике. Указаны названия абиссальных каналов.

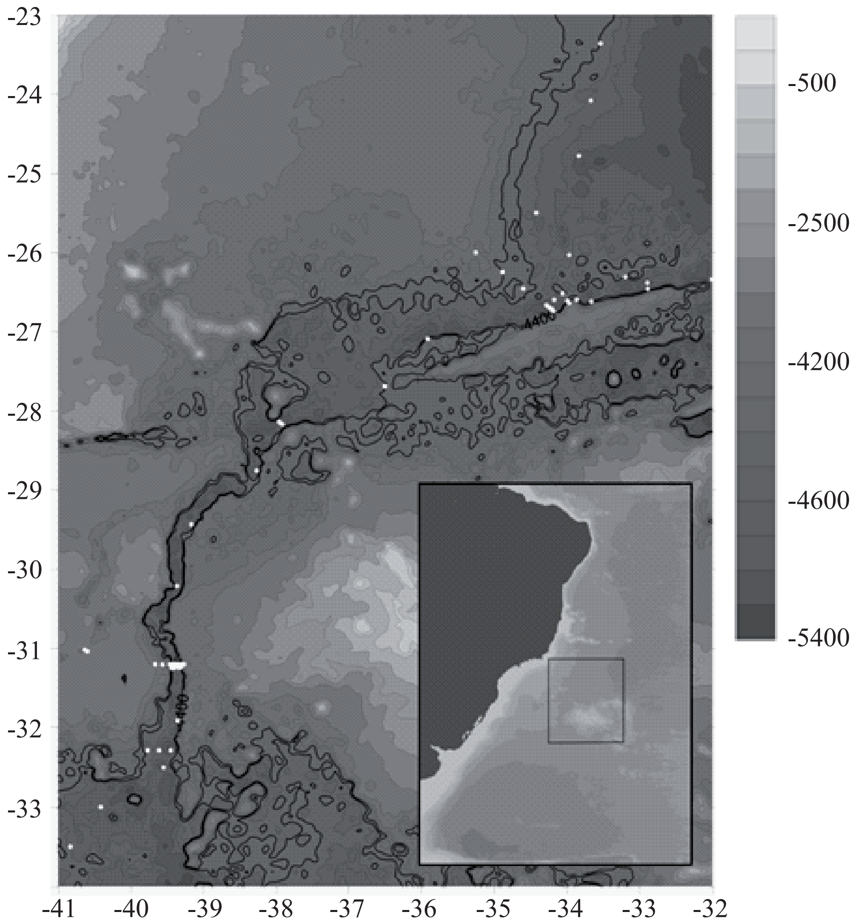

Fig. 2. Bathymetry map in the surroundings of the Vema Channel. Depths are given in meters. A general chart of the South Atlantic and South America with the location of the study region is shown in the inset. White dots indicate locations of stations.

Рис. 2. Батиметрия в районе канала Вима. Глубины указаны в метрах. На вставке показана карта Южной Атлантики и Южной Америки с расположением исследуемого региона. Положение станций показаны белыми точками.

Almost 30 (mainly German, Russian, and British) expeditions with deep water measurements were carried out in this region since 1990. More recently, scientists from Brazil were also involved in the research of the bottom flow through the channel. A new international and multidisciplinary scientific project named SAMBAR started in 2017 to study bottom currents in the South Atlantic. Important component is focused on the variability of the AABW meridional transport in the Vema Channel and across a trans-basin zonal section along 34.5°S, the South Atlantic MOC (SAMOC) Basin-wide Array (SAMBA line).

Structure of the bottom current. Temperature, salinity, velocity. The pressure difference caused by different depths of the upper boundary of AABW in the Argentine and Brazil Basins forces the flow of AABW through the Vema Channel. This difference in the depth of the AABW boundary over the channel is approximately 25 m. The flow of bottom water in the deep Vema Channel occurs in the form of a well-mixed jet. The coldest part of the flow is displaced to the eastern slope of the deep-water channel due to the Ekman friction. This displacement of the jet to the right relative to its motion occurs in the Southern Hemisphere, which is induced by the bottom friction. The secondary helical circulation intensifies the density and temperature gradients above the mixed bottom layer. This effect was confirmed by modeling in [5].

The topographic boundaries of the channel allow the propagation of Weddell Sea Deep Water, which is the densest and coldest component of Antarctic Bottom Water. The thickness of the jet is about 200 m. Within the sections of the jet, the variation ranges of its potential temperature and salinity are 0.1°C and 0.005 psu, respectively. The Weddell Sea Deep Water core is characterized by the minimum potential temperature *q* = -0.110°C (in situ temperature +0.235°C) and a salinity of 34.67 psu.

A section along the Vema Channel was made in November 2003 from the R/V "Akademik Sergey Vavilov" to study the variations in the properties of AABW in the course of its flow through the channel. The CTD casts were located at the bottom of the eastern slope of the channel. These measurements showed that the potential temperature in the jet becomes warmer from south to north. The difference along the channel is as high as almost 0.05 °C and the temperature increase is almost linear [6, 7].

Starting from 1991, thirteen sections across the Vema Channel were made by the German and Russian oceanographers along the standard line at 31°12' S. The scientists of the Shirshov Institute of Oceanology occupied this section in 2002, 2003, 2004, 2005 (March and October), 2006, 2009, and 2017. Examples of the temperature and salinity distributions across the standard section are shown in Figs. 3 and 4.

The most prominent property of the distribution of potential temperature and salinity across this section is displacement of the core of the coldest and low salinity water to the eastern wall of the channel caused by the Ekman friction.

In the upper part of the flow above the channel, the cold low saline core of the flow is displaced to the west. This phenomenon was observed over the western slope of the channel. Several measurements in this core indicate that the potential temperature in this core was less than -0.04°C and salinity was less than 34.676 psu. At the eastern slope, such values of temperature and salinity are observed at depths greater by 150-200 m. This jet exists due to displacement by the Coriolis force.

Observations of velocities in the channel. In January 1991, several moorings were deployed on the Santos Plateau and in the Vema Channel within the WOCE program. Two of the moorings were located in the Vema Channel. These moorings operated till December 1992. Two moorings were deployed in the Vema Channel in December 2003 and operated till March 2005. The moorings in 1991—1992 and 2003—2005 were operating close to the Vema Sill (at 31°08' S and 31°15' S, respectively) [3].

The records on moorings indicate that below 4000 m the flow was directed by the topography. The unidirectional flow speed increased toward the bottom. A decrease in the flow speed was recorded only by the deepest instruments (26 m above the ground) on the eastern side. The level of no motion between the AABW and North Atlantic Deep Water was approximately 3600 m based on the 3.5 years average of current observations on moorings.

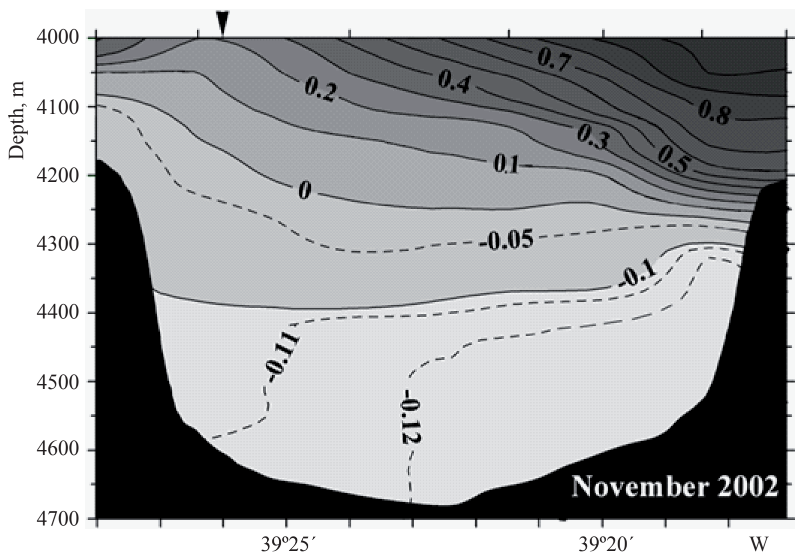

Fig. 3. Section of potential temperature (°C) across the Vema Channel in November 2002 (cruise of R/V "Akademik Ioffe") at 31°12' S. The tics at the upper axis show locations of CTD stations, the triangle show the location of mooring.

Рис. 3. Разрез потенциальной температуры (°C) по широте 31°12' с.ш. в канале Вима в ноябре 2002 года (рейс НИС «Академик Иоффе»). Отметки на верхней оси показывают местоположения станций CTD, треугольник показывает место буя.

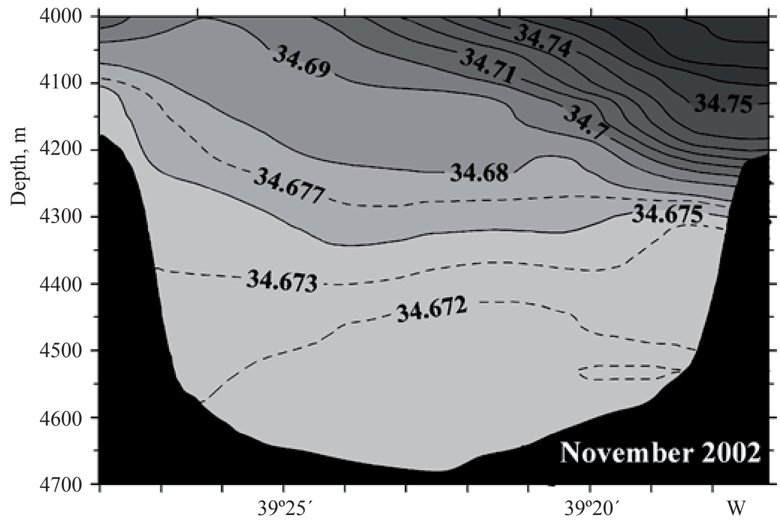

Fig. 4. Section of salinity (psu) across the Vema Channel in November 2002 (cruise of R/V "Akademik Ioffe") at 31°12' S. The tics at the upper axis show locations of CTD stations, the triangle show the location of mooring.

Рис. 4. Разрез солености (епс) по широте 31°12' с.ш. в канале Вима в ноябре 2002 года (рейс НИС «Академик Иоффе»). Отметки на верхней оси показывают местоположения станций CTD, треугольник показывает место буя.

The accuracy of velocity measurements is ±0.5 % of the water velocity relative to the ADCP ±5 mm/s (Teledyne RD Instruments, WorkHorse Sentinel ADCP Installation Guide, http://www.teledynemarine.com/). The errors of the LADCP measurements estimated by the processing program [8] are usually 3—4 cm/s. In the bottom layers due to the bottom track signals, the errors are 1—2 cm/s. The relative errors in the transport calculations are low if the velocities are high. The errors increase at low velocities. We consider that the estimates of transport calculations (based on the velocity errors and errors due to not exact estimates of the square of cross-section) after integrating with respect to depth are within 10 %. We give the transport values with the estimated errors.

The measured velocities in the core of the current usually ranged between 25 and 35 cm/s but the peak values can be as high as 60 cm/s and sometimes decrease to zero. The time series of meridional current measured on a mooring in the channel is shown in Fig. 5.

The measurements of velocity profiles across the Vema Channel using a Lowered Acoustic Doppler Current Profiler (LADCP) made possible the analysis of the velocity distribution across the channel. Usually the core

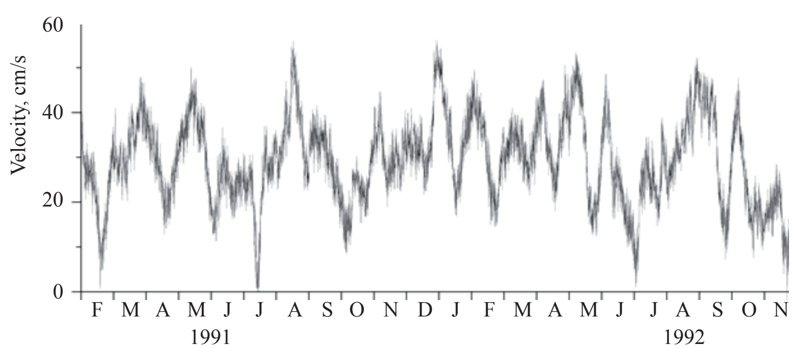

Fig. 5. Time series of the meridional component of velocity measured at the mooring at 31°08' S, 39°26' W at a depth of 4625 m over the ocean bottom at 4675 m from February 1991 to November 1992.

Рис. 5. Временные ряды меридиональной составляющей скорости на буе в координатах 31°08' с.ш., 39°26' з.д. на глубине 4625 м, глубина моря *H* = 4675 м. Измерения проводись с февраля 1991 г. по ноябрь 1992 г.

of the current with high velocities is located in the middle of the channel at depths of 4300 m approximately 300 m above the bottom. The maximum velocities are close to 30—35 cm/s, but in 2017 we recorded extremely high velocities up to 55 cm/s.

Let us compare the transport across the standard section in the Vema Channel (31°12' S) and across the channel in its northern part (26°40' S, Vema Extension). The velocity sections are shown in Fig. 6. The potential temperature isotherm θ = 0°C is shown in the figure as a heavy line. The channel becomes deeper and narrower in its northern part. The isotherms of temperatures higher than 0°C are located above the slopes of the channel. This means that the flow of AABW (even the flow of Weddell Sea Deep Water) is not confined to the channel but occupies wider space. The available data allow us to compare only the transport of cold water with temperature θ < 0°C. The mean velocities of the current with such temperatures through the standard section are 23 cm/s, while they decrease to 11 cm/s through the northern section. The current of AABW with higher temperatures exceeds 20 cm/s but we do not have measurements over the western slope of the channel to estimate the transport there.

The cross-section area of the standard section below the 0°C isotherm is $6{\cdot}10^6$ m^2, while that across the northern part of the channel is four times smaller ($1.4{\cdot}10^6$ m^2). A large amount of cold water (θ < 0°C) does not reach the northern section because it cannot overflow the numerous sills along the Vema Channel. Part of this cold water mixes with the overlying layers. The transport of water with temperatures below 0°C through the standard section (31°12' S) is 1.4±0.1 Sv, while only 0.16±0.02 Sv is transported through the northern section, which is almost 10 times smaller. One can also see that the θ = 0°C isotherm is much deeper in the northern section.

A conclusion that not the entire volume of water that flows in the Vema Channel (more specifically crosses the standard section at 31°12' S) reaches the exit of the channel at 26°40' S was made earlier [9]. It was suggested that at 27°30' S part of the flow turns to the west and makes a large anticyclonic circulation loop trapping about 2 Sv of the flow. Our measurements at the standard section in 2009 revealed a countercurrent above 4200 m.

We also made zonal sections south of the channel across a wider depression, which is the entrance to the Vema Channel. The sections were made in 2005 along 33°34' S and in 2017 across 32°17' S. The northern velocities over these sections are not high and do not exceed 10 cm/s.

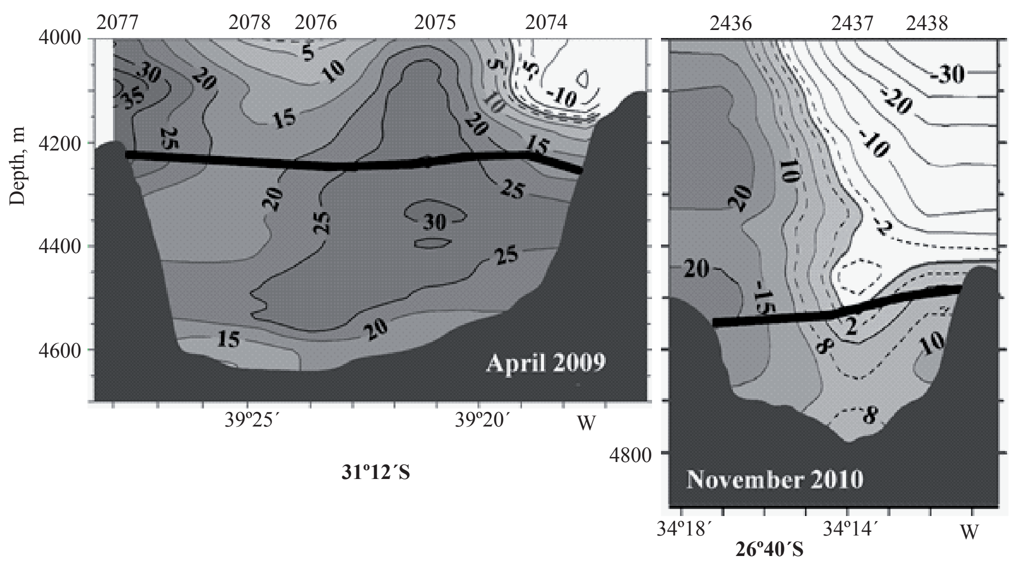

Fig. 6. Sections of meridional velocities across the Vema Channel at 31°12' S and 26°40' S.
Positive velocities (gray color) are directed to the north. The heavy black line denotes the θ = 0 °C isotherm.

Рис. 6. Разрезы меридиональных скоростей поперек канала Вима на широтах 31°12' с.ш.
и 26°40' с.ш. Положительные скорости (серый цвет) направлены на север.
Толстая черная линия обозначает изотерму θ = 0 °C.

Warming of the bottom flow. The warming of the cold water core in the Vema Channel since 1972 was first noted in [10]. Time series of potential temperature from the site in the Vema Channel (standard section at 31°12' S) revealed the general warming trend till the last measurements in April 2017. Before 1993, potential temperature at 31°14' S was −0.18°C, while the deviations did not exceed 0.01°C. From 1972, potential temperature has been increasing.

The time evolution of the coldest Antarctic Bottom Water (Weddell Sea Deep Water) along the Vema Channel is shown in Fig. 7. The temperature gradually increases. The first part of the record has already been analyzed in [11]. The authors discussed the temperature rise until 1996. Our measurements show that the temperature increase over the Vema Sill from 2002 to 2017 is 0.014±0.003°C.

This warming may have many causes. It could be related to global warming. The time of AABW propagation to the Vema Channel exceeds 35 years [12]. From 1970 to 1998, the bottom water in the Weddell Sea was becoming warmer near the source of its formation, but the warming trend was not statistically significant. However, from 1998 to 2002 it was negative [13]. The correlation between the temperature increase in the Weddell Sea and the temperature increase in the Vema Channel is not straightforward because the travel time of AABW to the Vema Channel takes a very long.

Numerical modeling of the current. The numerical model for ocean circulations developed at the Institute of Numerical Mathematics (INMOM) was used to simulate the bottom flow in the Vema Channel. This is a σ-model based on the full system of thermo-hydrodynamic equations with the hydrostatic and Boussinesq approximations [14], which describes bottom currents more adequately than the *z*-models. The lower layers in the σ-coordinates, which are also called isobathic, follow the bottom topography more exactly. We adjusted the model for simulations of the bottom current in narrow channels [15]. The selected domain for simulations covered the entire Vema Channel, the Santos Plateau, and the Rio-Grande Rise. The topographic data were interpolated to the modeling grid and smoothed several times using the Tukey filter. The temperature and salinity fields from the climatological Levitus Atlas of the World Ocean [16] were specified as the initial conditions. We specified a zero initial velocity field.

The horizontal resolution was approximately 2.2 km (0.02° by latitude and longitude) over a 20 km-wide transversal section of the Vema Channel. The vertical σ-levels were not specified uniformly; the resolution increased with depth and reached 50 m near the bottom. The total number of σ-levels was 33; almost half of them were specified in the bottom layer, which is 800 m thick.

Based on the numerical simulation the bottom velocities in the oceanic basins around the Vema Channel are quite low and do not exceed 8—10 cm/s. However, strong intensification of currents is observed in the Vema Channel. The maximum velocities reached 35 cm/s in the narrowest part of the channel close to the Vema Sill at 31°S. The characteristic velocity over the entire length of the channel varied from 20 to 30 cm/s. The total transport over the entire length of the channel was directed from south to north. Our direct measurements of

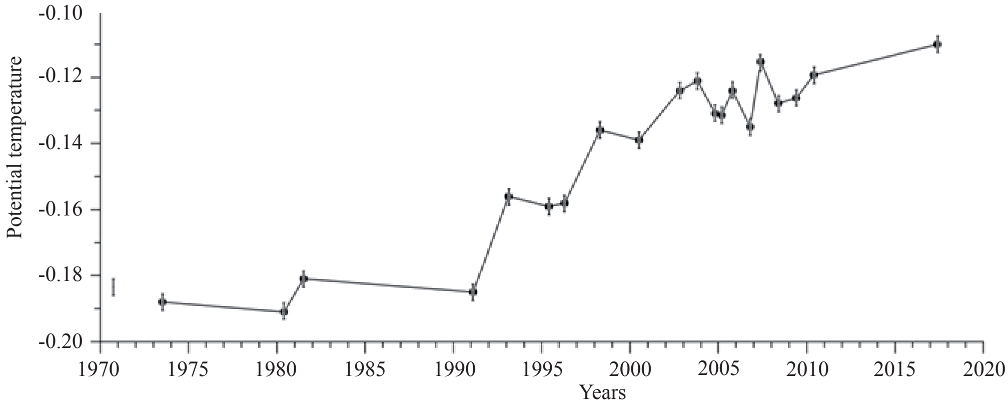

Fig. 7. Warming in the core of the Antarctic Bottom water flow at the standard section across the Vema Channel approximately at 31°12' S, 39°18' W. Temperature errors are indicated.

Рис. 7. Потепление в ядре антарктического потока нижней воды на стандартном разрезе через канал Вима приблизительно на 31°12' с.ш., 39°18' з.д. Указаны погрешности измерений температуры.

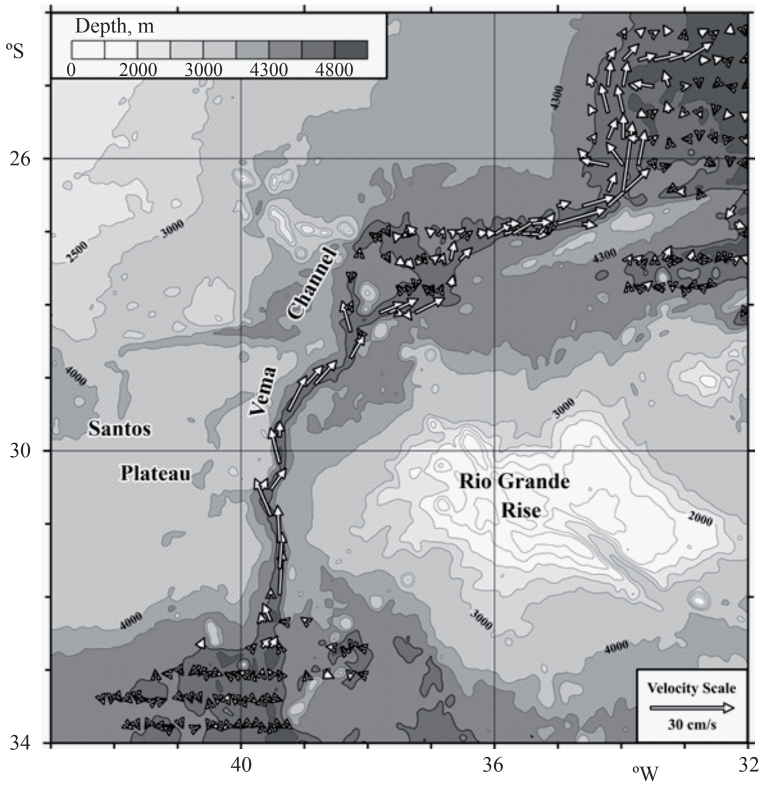

Fig. 8. Simulated velocities in the bottom layer of the Vema Channel presented from the data of the deepest σ-level (approximately 50 meters above the seafloor).

Рис. 8. Модельные скорости в нижнем слое канала Вима по данным самого глубокого σ-уровня (примерно 50 м над морским дном).

currents in the Vema Channel were used as the reference data to verify the results of the numerical simulations. Simulated velocities in the bottom layer of the Vema Channel are shown in Fig. 8.

The measured velocities in the channel with a lowered acoustic Doppler current profiler over the sill (30 cm/s) appeared close to the model estimates. The measured and simulated velocities at the entrance to the channel and at the exit from it were lower with a range from 5 to 10 cm/s. Our simulation shows the existence of a southerly countercurrent at the depths above 4000 m.

Conclusions. We summarize the results of our measurements and modeling of the bottom flow of Antarctic Bottom water in the Vema Channel in the South Atlantic. A flow of high velocity was repeatedly measured in the channel with mean velocities of 25—40 cm/s and the maximum reaching 60 cm/s. The total transport of Antarctic Bottom Water through the channel within the liquid boundaries above the walls of the channel is approximately 3±0.3 Sv. The core of the coldest (θ = −0.120°C) and low saline water is usually displaced to the eastern wall. Numerical simulations confirm the field measurements and reveal the spatial structure of velocity field in the channel.

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