Stratified flows and internal waves in the Central West Atlantic

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Abstract. In this paper, we study stratified flows and internal waves in the fracture zones of the Mid Atlantic Ridge. The results of measurements carried out in the 39th and 40th cruises of RV Akademik Sergey Vavilov in the autumn of 2014 and 2015 are presented. Hydrophysical properties of the near-bottom flows are studied experimentally on the basis of CTD- and LADCP profiling. Theoretical analysis involves mathematical formulation of stratified fluid flow which uses CTD-data obtained from field observation in the Vema Fracture Zone region. Spectral properties and kinematic characteristics of internal waves are calculated by finite element method.

1. Introduction
Deep basins of the Atlantic Ocean are filled with the water of an Antarctic origin which can spread to the mid-latitudes of the Northern Hemisphere [1, 2]. This water is usually called the Antarctic Bottom Water (AABW) which means [3] the water mass limited from above by an isotherm of potential temperature 2.0°C. Abyssal water exchange between basins occurs through the fractures of underwater ridges [2]. The bottom topography data show that the inflow of AABW into the channels of the fractures is most likely localized in a few passages. They include the equatorial Romanche and Chain fracture zones in the Mid-Atlantic Ridge and the Vema Fracture Zone in the Central West Atlantic. These fractures provide the transportation of cold abyssal waters from the West Atlantic to the equatorial region of the East Atlantic.

The fractures and underwater slopes present an active zone in which a sharp increase in the intensity of the turbulent mixing occurs [4]. Internal waves play significant role here due to the wave breaking which intensifies the mixing. Most interesting wave structures arise in powerful cataract flows near the sills of the fractures. These orographic obstacles disturb descending gravity currents by forced lee waves, attached hydraulic jumps, mixing layers etc. All these effects were observed by the authors in the Romanche and Chain fracture zones during the cruises of the RV Akademik Ioffe in the equatorial Atlantic [5]. Strong mixing in the sill region often leads to the splitting of inclined continuously stratified flow into the jets with different water densities [6]. In addition, shear flows over the obstacles can form critical layers which separate the flow of bottom cold water from opposite overflow. Such critical layers can reflect...
or absorb internal waves generated by the topography, so the upward propagation of these perturbations is blocked [7, 8].

In this paper we analyze the results of our measurements carried out recently in the abyssal channels of the Mid-Atlantic Ridge located in the Central West Atlantic. We investigate kinematic properties of short-period internal waves on the basis of the thermohaline characteristics of waters in the Vema Fracture Zone [9]. In this case, the mathematical formulation reduces to the solution of homogeneous eigenvalue problem, which is solved numerically by finite element method as a problem of the modal analysis.

2. Near-bottom stratified flows in the southern part of the Northern Mid-Atlantic Ridge

In the autumn of 2014 and 2015, the expeditions onboard the RV Akademik Sergey Vavilov carried out measurements of current velocities and thermohaline properties of bottom water in several quasi-zonal fractures in the southern part of the Northern Mid Atlantic Ridge (see Figure 1). These fractures connect deep basins of the West and East Atlantic, they include the Vema Fracture Zone (FZ) (10°50′ N) and a group of sub-equatorial fractures: Doldrums (8°15′ N), Vernadsky (7°40′ N), Bogdanov (07°09′ N) and Nameless fracture at 7°30′ N. The estimates of bottom water (θ < 2.0° C) transport through this group of minor fractures based on our measurements are approximately 0.40 Sv (1 Sv = 10⁶ m³/s), which is close to 33% of the transport estimate through the Vema FZ (1.20 Sv) obtained in the same expeditions. The coldest bottom water temperatures among the investigated fractures were recorded also in the Vema FZ.

![Figure 1. Fractures in the southern part of the North Atlantic Ridge](image-url)
Hydrological measurements were carried out using the SBE-19plus temperature, salinity, and pressure profiler and acoustic current profiler LADCP (RDI Workhorse Sentinel, 300 kHz). The profiling stations were carried out almost to the bottom (3-5 m to the bottom) from a ship that maintained its position at a station point with an accuracy to 100 m. The echo sounder survey was initially carried out along the meridional section and then on the ship’s route from one station to another. A chart of the bottom topography in the region of the Vema Fracture Zone is shown in Figure 2.

Figure 2. Bottom topography in the region of the Vema Fracture Zone

The pattern of abyssal currents is governed by the complex bottom topography in this region. Measurements in 2014 showed [9] that the bottom water flow in the Vema FZ directed to the East Atlantic splits into three streams. The northernmost flow is the widest. It flows through the channel which crosses the northern wall of the Vema FZ. The flow in this channel is directed to the northeast. Its width is approximately 10 km along the 3950 m isobath, and the depth of the channel reaches 4350 m (in all fractures we estimated their width along the isobaths close to the depth of the 2.0°C isotherm). Our measurements showed that the minimum potential temperature at the bottom here was 1.38°C, and the velocities of the bottom current in the northeastern direction reached 18 cm/s. An estimate of the AABW transport through this channel based on LADCP measurements is 0.08 Sv.
The main channel of the Vema FZ has latitudinal extension, and this channel is divided by a zonal submarine ridge into the northern and southern parallel sub-channels. The southern channel of the fracture appeared shallower than the northern one. The width of the southern channel along the 3780 m isobath in the region of measurements is close to 4 km and the depth is up to 4500 m. The minimum measured temperature at the bottom was 1.47°C. The velocities of the easterly current were up to 30 cm/s. The AABW transport was estimated at 0.26 Sv.

![Figure 3](image)

**Figure 3.** Structure of stratified flow in the northern channel of the Vema FZ. The cross-section along the longitude 41°01.0’ W is shown: (a) 8 October 2014 and (b) 21 September 2015. Red color shows near-bottom flow directed to the east. Light blue color shows opposite overflow. Violet tones indicate the temperature stratification.

In 2014, we occupied two stations over the sill of the northern channel placed along 41°01.0’ W longitude. The distance between these stations was approximately one mile. The width of the channel along the 3850 m isobath in this place is 7 km and the depth is up to 4690 m. The measurements showed that the minimum potential temperature at the bottom was 1.36°C, and the velocities of the bottom current in this channel reached 34 cm/s. The core of the maximum current velocity in the northern channel was displaced to the right relative to the direction of the flow, and the core of the minimum temperature was displaced to the left. The AABW transport was estimated to be 0.86 Sv. Thus, the total AABW transport through three abyssal channels of the Vema FZ was 1.20 Sv. This amount is more than five times of the transport of fresh water in the Amazon river.

In 2015, we repeated the measurements in the Vema FZ in order to observe the temporal variability of near-bottom stratified flows. It is interesting that the distribution of velocity and temperature changed essentially in northern channel compared to the data obtained in 2014.
Maximal velocity 46 m/s and minimal temperature 1.403°C were found in the deepest part of the northern channel (Figure 3b). This core of Antarctic Bottom Water was shifted to the northern wall in contrast with the flow picture from 2014 (see Figure 3a) which presents the pair of separated AABW jets displaced to the southern wall. The maximal AABW transport in the northern channel was estimated in 2015 to be less than 0.58 Sv. Such a decreasing after one year can be explained by location of intense AABW jet in the wide part of the northern channel in 2014. In general, this example illustrates high variability of intense abyssal flow affected by slight restoring buoyancy force in the presence of extremely weak stratification.

3. Modal characteristics of internal waves

Parameters of internal waves depend strongly on vertical structure of water density in the upper ocean layer, especially on the structure and stratification of the thermocline. Therefore the total density profile should be taken into account starting from the sea surface. Thus, we consider a mathematical model of internal gravity waves of small amplitude in a continuously stratified sea with constant depth $h$. We select the origin of the rectangular coordinate system $(x, y, z)$ on the unperturbed free surface $z = 0$, so the $z$-axis is directed upwards. We assume that the water density in the state of rest depends only on the depth: $\rho_0 = \rho_0(z)$. Linearized equations and boundary conditions describing the dynamics of internal waves in dimensionless form and the approximation of the "rigid lid" are written as [10]

$$v_t + \frac{1}{\rho_0} \nabla p = F, \quad \rho_t + \rho_0 z w = 0, \quad \text{div} \, v = 0, \quad w = 0 \quad (z = 0, \ z = -h)$$

where dimensionless values are related to the dimensional values as

$$(\bar{x}, \bar{y}, \bar{z}, k) = h (x, y, z, \bar{k}), \quad (\bar{t}, \bar{\sigma}, \bar{f}) = \sqrt{\frac{h}{g}} \left( t, \sigma, f \right).$$

Here, $v = (u, v, w)$ is the velocity vector of wave perturbations; $F = (f v, -f u, -\rho/\rho_0)$ is the mass force vector; $p, \rho$ are wave perturbations of pressure and density, respectively; $\bar{f} = 2\Omega \sin \varphi$ is the Coriolis parameter; $\Omega$ is the angular velocity of the Earth; $\varphi$ is the latitude; $g$ is the acceleration due to gravity; $\sigma$ is the frequency of wave oscillations; $k$ is the horizontal wave number. We seek the solution of homogeneous problem (1), (2) as harmonic wave packets propagating horizontally with amplitudes depending on $z$,

$$(u, v, w, p, \rho) = \{U(z), V(z), W(z), P(z), R(z)\} \exp i(kx - \sigma t).$$

Substituting these functions into equations (1) and boundary conditions (2), we obtain the self-adjoint eigenvalue problem with spectral parameter $k^2$ at the given wave frequency $\sigma$,

$$\frac{d}{dz} \left( \rho_0 \frac{dW}{dz} \right) + k^2 \rho_0(z) \frac{N^2(z) - \sigma^2}{\sigma^2 - f^2} W = 0, \quad W(0) = W(-1) = 0.$$

Here $N^2(z) = -g\rho_0 z(\rho_0(z)$ is the dimensionless Brunt – Väisälä frequency. Thus, according to the oscillation Sturm theorem, an infinite set of eigenvalues $k_n^2$ ($n = 1, 2, 3, \ldots$) exists in the case $f < \sigma < \min N(z)$ considered here. These eigenvalues form an infinitely increasing monotonic series, and the complete orthogonal system of the corresponding eigenfunctions $W_n(z)$ (internal wave modes) exists [11].
Figure 4. Termohaline characteristics measured in 2015: (a) station 2569 in the Vema FZ; (b) station 2577 in the Bogdanov fracture

Figure 5. Dispersive curves: (a) station 2569 in the Vema FZ (2015); (b) station 2577 (the Bogdanov fracture, 2015); (c) station 2551 in the Vema FZ (2014)
The code based on finite elements method was used similarly to [12] by numerical solution of the spectral problem (3). We calculated modal characteristics of internal waves for the density profiles $\rho_0(z)$ obtained during the expeditions of RV Akademik Sergey Vavilov in 2014 and 2015. The Figure 4a illustrates the representative profiles of temperature, salinity, density and Brunt — Väisälä frequency obtained in the Vema FZ (station 2569 at 10°48.3 N, 41°01.0 W), and the Figure 4b shows CTD-data measured in the Bogdanov FZ (station 2577 at 07°09.6 N, 34°55.2 W). We note that the thickness of pycnocline at station 2569 is about 70 m. Station 2577 was occupied at a distance of about 200 km southeast of station 2569. The pycnocline there is thicker (approximately 120 m) due to the fresher upper layer.

Figures 5a and 5b show dispersion curves of modes 1-5 calculated by using the CTD-data from stations 2569 and 2577, respectively. In addition, Figure 5c shows dispersive curves calculated from the CTD-data measured in 2014 at station 2551, which was located in the same region in the Vema FZ as station 2569 in 2015. It is clear from this comparison that increased steepening (with respect to frequency) of dispersion curves at station 2577 occurs due to the difference between the density profiles in the upper layer at stations 2569 and 2577. This means that the pycnocline formed in the region of the Bogdanov FZ is an intense wave-guide for short-period internal waves. At the same time, stations 2569 and 2551 located at the same place in 2014 and 2015 show high similarity of dispersive curves despite high temporal variability of the local abyssal flows described in Section 2.

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