

Article

Dropped Spectra of Temperature Fluctuations Based on CTD Casts in the Vema Fracture Zone

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Abstract

A strong relationship has been revealed between the topography of the Vema Fracture Zone and spectra of temperature estimated from profiles of CTD casts. Internal waves over rough topography transform the vertical profiles of temperature, as revealed from the data of usual CTD casts. Internal waves generate fine structure in vertical profiles. Variations in the shape of temperature profiles cause variations in one-dimensional spatial spectra of vertical displacements estimated from temperature profiles. Spectral estimates (“dropped spectra”) from profiles over rough topography exceed those estimated over flat topography. In the latter case, they are much closer to the dropped spectra of the Garrett–Munk model.

Keywords: internal tides; CTD; GM model; vertical profiles; dropped spectra; mixing

1. Introduction

Usually, experimental research on internal waves is based on long-term measurements of currents or temperature on moorings. Mooring operations in the ocean require significant funding since the sampling equipment and the expedition onboard research vessels are very expensive and there is a risk of losing instruments. Some oceanographic problems, which require only estimates of the amplitude of internal tides in the given region, can be solved without such specific measurements of internal waves. New approaches to obtain such estimates can be found from the data collected in oceanographic databases. In this paper, we use CTD casts to compare the spectral estimates with the GM-72 model [1]. With this in mind, we have selected measurements in the Vema Fracture Zone in the tropical Atlantic Ocean where we conducted research in January 2022, January 2024, and the period of December 2025–January 2026. The results of the field experiment conducted in 2022 are reported in [2].

The influence of bottom topography on internal waves has been reported in many publications. Strong mixing occurs in the regions of steep topography. Van Haren and Haas [3] report that seafloor topography influences turbulence by means of breaking internal waves over critical slopes. They used mooring data to study turbulence. Measurements in the ocean revealed that turbulence generation induced by internal wave breaking at approximately 5% of the entire ocean floor maintains density stratification. The strongest turbulence contribution is found over supercritical slopes.

Van Haren et al. [4] report on the observation of extremely long Kelvin–Helmholtz billow trains in the Romanche Fracture Zone. Rapidly flowing bottom water over the transversal sill slope of the fracture causes shear-induced turbulent mixing with the overlying water masses. Internal tide currents induce mixing in the upper part of quasi-steady shear flow. This process generates billow trains that vary between 5 and 100 m in vertical scale.



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Klymak et al. [5] studied internal wave breaking over a continental slope. Internal tide breaking leads to the generation of smaller internal waves, turbulence, and the formation of fine structure.

Klymak et al. [6] report how internal tides and nonlinear lee waves interact with steep underwater ridges. This process leads to the breaking of internal tides and generation of smaller structures. Wave breaking induces highly energetic turbulent mixing (up to several thousand times greater than that in the open ocean). Localized internal hydraulic jumps are also generated. The authors emphasize that internal waves generated over steep topography break almost immediately. The mechanics of this breaking reported in the publication include: nonlinear lee waves that break in the lee of the obstacle; under specific conditions, the wave behaving like a hydraulic jump; and overturns that appear. Instead of slowly shoaling, the wave breaks quickly within a single tidal cycle, creating turbulent structures that extend hundreds of meters into the water column.

Martini et al. [7] report on semidiurnal internal tides on the Oregon continental slope with variations in energy during spring and neap periods.

Lamb [8] reports a review on internal waves on the continental shelf/slope. Their breaking provides an important dissipation and mixing mechanism with implications for biological productivity and sediment transport. Breaking mechanisms associated with internal solitary waves include bottom boundary layer instabilities, shear instabilities in the interior of the water column, and wave overturning as they shoal.

Yang et al. [9] report that the waves generated by tides flowing over topography modify the pressure around the topography and thereby exert an additional force that affects tidal energy losses.

Alford et al. [10] use observations and numerical models and show that internal waves in the South China Sea begin as sinusoidal disturbances; they exist as 200m high waves in the region of generation and then break, giving rise to smaller internal waves and turbulence that is 10,000 times higher than that in the open ocean.

The generation and breaking of internal tides into smaller-scale internal waves that influence vertical stratification and turbulence was also studied in [11–16].

Tippenhauer et al. report in [17] that diapycnal mixing in the deep ocean is much stronger in the regions of rough topography of mid-ocean ridges than above abyssal plains. They realized deep ocean horizontal profiling using a microstructure probe attached to an autonomous underwater vehicle to study the spatial distribution of the dissipation rate of turbulent kinetic energy near the Mid-Atlantic Ridge. The study was focused on a channel with unidirectional sill overflow.

At the same time, in this paper we want to show that the measurements made using CTD casts may also be used for the analysis of certain spectral internal wave properties over topography. Strong mixing is generally caused by vertical motions that become more intense over steep slopes where the currents of the tide obtain a vertical component. Hence, isopycnals are displaced up and down, which generates internal waves and leads to the formation of fine structure.

The goal of this study is to show the relation between rough topography and temperature fluctuations measured by CTD casts. The intensity of the fluctuations is reflected in the estimates of the vertical wave number spectra. We identify the regions in the Vema Fracture Zone where fine structure in vertical profiles is significant. The regions of fine structure are associated with rough bottom topography.

The objective of this study is to show that spectral analysis of CTD casts can reveal differences between measurements over flat and rough topography, which can be compared to the background GM-72 model.

2. Data and Methods

The experiments were conducted in the Vema Fracture Zone in the tropical West Atlantic during three cruises in 2022, 2024, and 2025–2026. We occupied CTD sections in the zonal direction along the Vema Fracture Zone approximately following 10°48' N. The distance between stations varied between 5 and 20 nautical miles in different years and locations. A map of the region is shown in Figure 1. The positions of casts along the temperature section in 2025–2026 are shown in Figure 2. We calculated spectral densities from the data of all profiles in the Vema Fracture Zone: those over a flat bottom and those over a rough bottom. Profiles over a flat bottom and those over a rough bottom result in different levels of spectral densities.

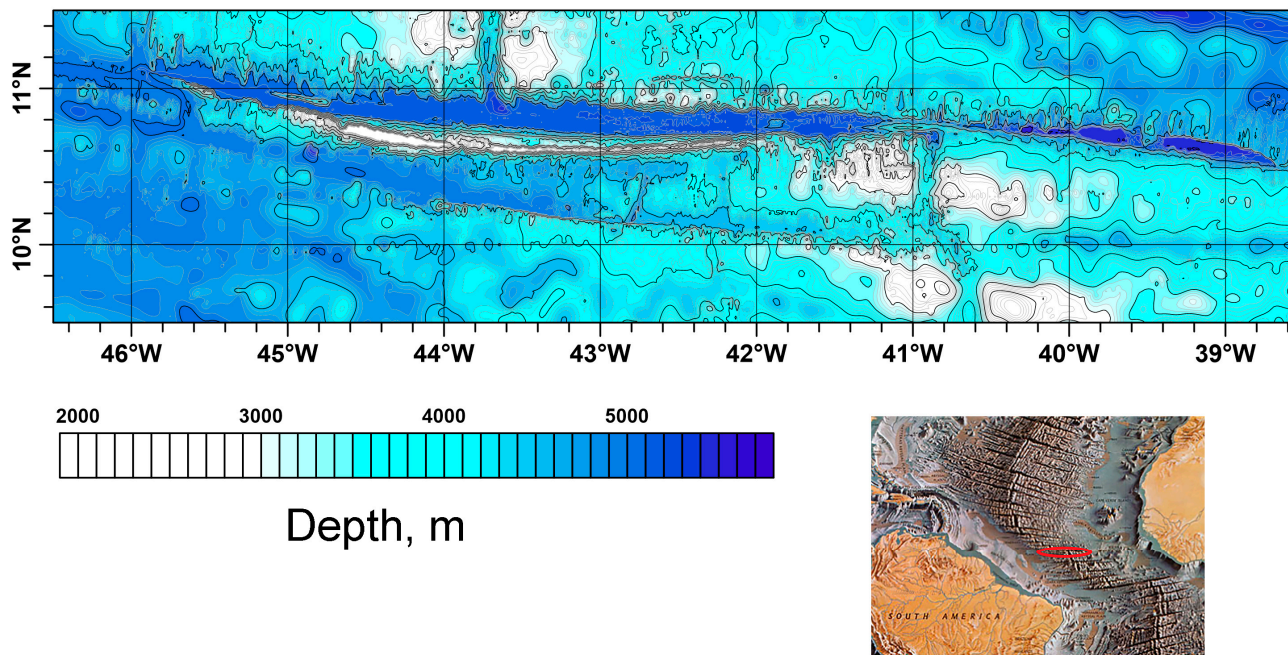


Figure 1. A topographic map of the region (top panel). The location of the region is shown in red on a map of the Atlantic in the bottom panel.

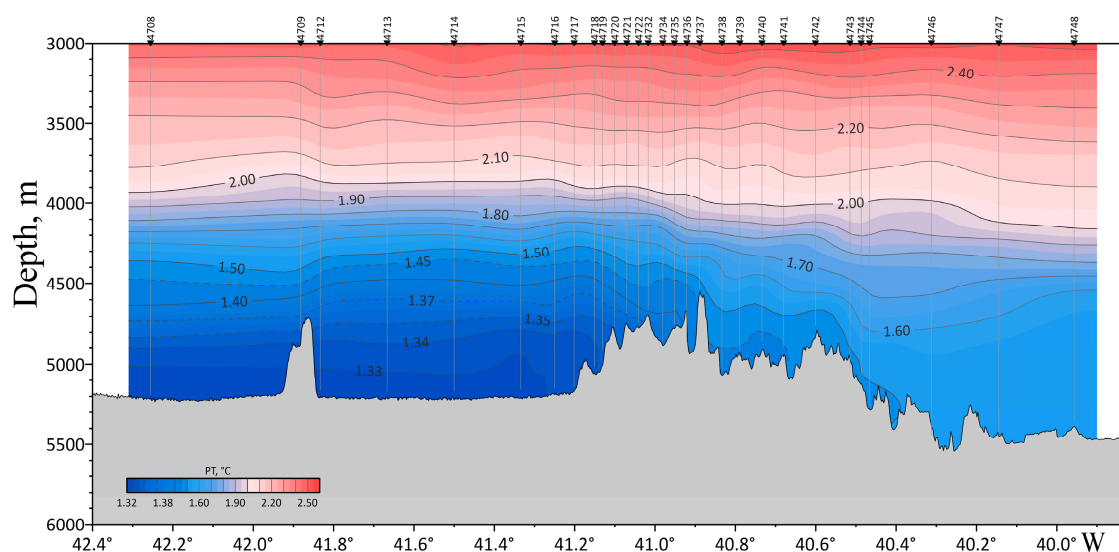


Figure 2. A section of potential temperature along the Vema Fracture Zone in December 2025–January 2026. All CTD stations are indicated on the top axis. Western longitude is laid off along the bottom axis. Vertical gray lines indicate stations of CTD casts.

The speed of lowering the CTD instrument was approximately 1 m/s. We used several CTD instruments: an Idronaut Ocean Seven 320Plus (Brugherio, MB, Italy), Daowan DW1616D (Qingdao, China), and AML-3 LGR (Dartmouth, NS, Canada). Intercalibration among these three instruments revealed little difference in the specified accuracy. The instruments were lowered in pairs mounted on one carousel platform. In this research we calculated the spectra from the Idronaut Ocean Seven 320 Plus data. After processing, the vertical distance between each measurement was either 2 or 1 m.

The Vema Fracture Zone is divided into two parts by a transverse sill. West of the sill at 41.2° W, the bottom of the fracture is relatively flat. East of 41.2° W, the topography is rough with many ridges and steep slopes. The bottom topography is shown in Figure 3. We selected two segments of the section: flat topography between 41.8° and 41.2° W and rough topography between 41.2° and 40.4° W. During the three cruises, 24 CTD casts were made in the western (flat) part of the fracture and 39 stations in the eastern (rough) part of the fracture.

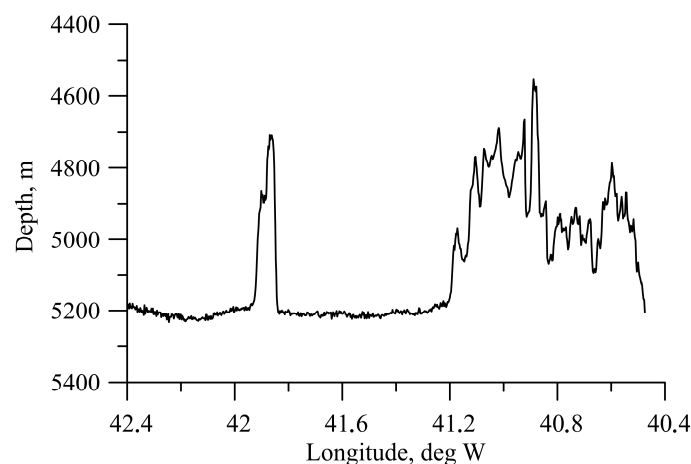


Figure 3. Bottom topography along the Vema Fracture Zone.

In the flat region the mean depth is 5210 m, fluctuating between 5196 m and 5224 m with a standard deviation of 6 m. The mean depth of the rough topography region is 4897 m, fluctuating between 4551 m and 5166 m with a standard deviation of 122 m.

We selected several casts in the flat and rough topography regions made during three expeditions. In the flat segment at 41.8° – 41.2° W, the numbers of casts for analysis were 8, 10, and 6 in 2022, 2024, and 2025–2026, respectively. In the rough segment between 41.2° and 40.4° W, the amounts of casts were 14, 8, and 17 in the different years, respectively.

The spectra were calculated using the Fourier transformation of the correlation function as described by Blackman and Tukey [18].

3. Results

3.1. Application of the Garrett and Munk Model to Spectra of CTD Profiles

Garrett and Munk [1] developed a model of the universal spectrum for internal waves in the deep ocean. They made the following assumptions: The fluctuations observed in the ocean in the spatiotemporal range of internal waves are strictly caused only by internal waves, not by any other processes. The field of waves observed in the ocean is composed of linear internal waves. The scale of these waves is wide and the phases and amplitudes of the waves are random. The energy of the waves is distributed over the wave numbers and frequencies, and this energy is not related to the modes of internal motion; the fluxes of wave energy are the same in the upward and downward directions, while the waves are horizontally isotropic. One of the main assumptions is that the wave field at different

locations in the ocean and at any time is almost the same. Thus, a universal internal wave field is present in the deep ocean, while fluctuations of not very high energy appear sporadically over this background.

In order to correlate the observed data with these assumptions the authors of the model restricted their analysis to the depths of the ocean, excluding water layers with a thickness of several hundred meters from the surface and bottom. In addition, they excluded the equatorial and polar latitudes; they also excluded the tidal frequencies where a strong energy input into internal waves exists.

They composed a dimensionless energy spectrum that depends on the frequency (ω) and wave number (k_x, k_y, k_z). If in the expression for the energy spectrum we specify a constant wave number, we get a frequency-dependent spectrum. These spectra are usually calculated from moored measurements where time series of temperature, currents, and other parameters are recorded. These measurements are most frequently considered in the analysis of internal waves. The peaks on the frequency spectra calculated from time series are associated with the dominating frequencies of fluctuations, and the level of the spectral densities is compared with the background Garrett–Munk model [1,19]. The authors termed these spectra “moored spectra”.

If we set to zero both the frequency and the vertical wave number, then the energy spectrum depends only on the horizontal wave number. Experimental results from towed sensors (provided that the towing speed is significantly greater than the phase velocity of internal waves) are usually compared with this type of spectrum, which is called a “towed spectrum”. The analysis of towed measurements is not performed so often as the analysis of moored records. The peaks on these spectra are associated with the wavelengths (wave numbers) of the dominating processes if we also consider the Doppler effect.

If in the model we set both the frequency and horizontal wave number equal to zero, the spectrum depends only on the vertical wave number. The authors of the GM-72 model call these spectra “dropped spectra” since they are derived from the vertical profiles of temperature and other parameters obtained by lowering a CTD probe from a ship. This type of model spectrum has been analyzed in only a few publications [20,21]. The physical differences between the model and measured spectra depend on the different levels of fine-structure steps in the profile. Smooth profiles of temperature and profiles with steps and strong vertical gradients differ because the latter are affected by breaking internal waves. Fine structure is also formed in the regions of oceanic fronts, but other processes may also be involved (diffusion, convection, salt fingers, winter cooling, etc.).

Garrett and Munk correlate the horizontal $k(k_x, k_y)$ and vertical k_z wave numbers with the mode number j (1, 2, ...) and frequency ω by means of the following relations:

$$k = j\pi(\omega^2 - \omega_i^2)^{1/2}, \text{ and}$$

$$k_z = j\pi n(z),$$

where $n(z)$ is the dimensionless Brunt–Väisälä frequency, and ω_i is the inertial frequency. Then the corresponding vertical component of the root mean square velocity is written as $\omega^2 Z^2$, with Z denoting the vertical displacement. Under the assumption of horizontal isotropy, the vertical wave number energy spectrum is expressed as

$$\int \int E(k_z, \omega) dk_z d\omega = E$$

where $E = 2\pi 10^{-5}$ is a dimensionless constant corresponding to the energy of the waves in a unit-square water column. Then, Garrett and Munk write the spectrum for vertical displacements using the measurements from CTD profilers as

$$\int Z^2(\omega)E(k_z\omega)d\omega$$

The model by Garrett–Munk assumes a power-law dependence of the spectra of fine-structure inhomogeneities of the vertical wave number calculated from the vertical profiles:

$$DS_{\xi}(k_z) = 0.078(1 - f/N)^2 k_z^{-2}, \quad (1)$$

where vertical wave numbers are expressed in cycles per meter. The coefficient 0.078 was calculated from several dimensionless constants introduced in the model. The Coriolis parameter f and the Brunt–Väisälä frequency N are expressed in cycles per second.

In some practical cases the “−2.5” power law suits the dependence better than the decay described by the “−2” power law. The temperature spectrum calculated from the data is normalized by the mean local vertical gradient of potential temperature. In this case, the internal wave energy per square unit (E) and the equivalent number of modes (j^*) are equal to $2\pi 10^{-5}$ and 5 or 6, respectively.

When deriving the model, Garrett and Munk [1] assumed that the vertical profiles should be measured by free-falling temperature probes. Specifications of the speed of descent of various free-falling temperature probes manufactured by different companies indicate that the velocity of descent should be approximately 1 m/s. We also performed our CTD casts with a vertical speed of 1 m/s. The only difference between the data that we used and the data from free-falling sensors is that the lowered CTD was connected to the ship by an electric cable. The ship was rocking, which sometimes caused upward motion of the instruments. During the CTD cast, the ship kept its position so that the cable was always vertical. Processing of the CTD data excluded upward motion (due to heaving, rocking, rolling, and pitching) of the sensors (the loop edit approach). The loop edit performed during processing excluded upward motion, leaving only the deepening of the instrument.

3.2. Analysis of Data

In order to study the variations in internal waves we processed several CTD casts from along the Vema Fracture Zone in the tropical Northwest Atlantic, measured on three cruises.

Below, we will show that the CTD temperature profiles are influenced by internal waves. This influence follows from the spectral analysis of temperature profiles and their vertical gradients. When estimating the spectral densities of temperature profiles, we find that the energy level of the spectral densities is higher for the profiles measured in the region of rough topography, where intense generation of internal waves occurs. This is caused by fine-structure steps in the profile. When we analyze temperature profiles we obtain the spectral distribution of inverse thickness of homogeneous layers. In the analysis of vertical gradients, we obtain the spectral distribution of inverse distances between interfaces with high vertical gradients. The difference between the spectra of temperature and spectra of temperature gradients is not very significant. Depending on the specific case we can select either the temperature profiles or those of the temperature gradients to obtain the best demonstration of the influence of internal waves.

Since we are interested in the influence of the bottom topography on the generation of internal waves and mixing and we wish to find the correlation between the bottom topography and mixing in the ocean, we shall analyze the fluctuations in the interval of measurements 2000 m above the bottom. We need quite a long spatial series of measurements for statistical spectral estimates; thus, we selected a spatial series length of 2000 m.

We estimated the spectra of the vertical displacements that were calculated as fluctuations of temperature divided by the corresponding vertical temperature gradients. Before estimating the spectra we performed high filtering of the series that eliminated all long

wave fluctuations with vertical wave numbers less than 0.007 m^{-1} . Thus, fluctuations approximately longer than 100 m were filtered off. After filtering, the remaining series appeared as fluctuations with respect to zero. In other words, we subtracted the smoothed curve from the initial series. We estimated the running vertical temperature gradient along the curve by the difference between the values separated by 50 m. This value was selected to exclude negative gradients so that the temperature at deeper levels did not exceed upper ones. Vertical displacements were obtained by dividing temperature fluctuations by the vertical temperature gradient.

In previous work by the author, the spectral densities estimated from the temperature profiles measured near submarine ridges appeared greater than those estimated from profiles over flatter topography [22]. As an illustration of the differences between vertical profiles of temperature, we show an example of two vertical temperature profiles taken in the Vema Fracture Zone (Figure 4).

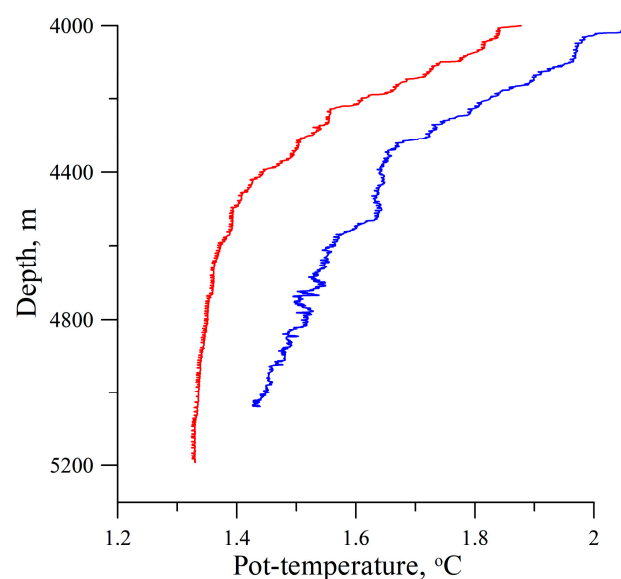


Figure 4. Vertical profiles of potential temperature at stations 4713 (41.66° W) (red) and 4738 (40.83° W) (blue); see Figure 2 for locations.

The profile measured at station 4713 over flat topography is smoother than the one at station 4738. The differences between the profiles are clearly seen even visually. The properties of other profiles from the two different regions of the study site are the same.

A high level of fine-structure steps on the profile at station 4738 can be explained by many intrusions, which we consider are mostly induced by internal waves. The vertical motion induced by the barotropic tide over the slope also leads to the generation of intrusions, mixing, interleaving, and fine structure.

The spectral functions were calculated from the data of temperature profiles. Vertical wave number spectra of temperature fluctuations from the measurements on three expeditions are shown in Figures 5–7. In the left panels we show bunches of spectral curves calculated from the measurements in each year with different colors. In the right panels we show the corresponding mean spectral curves: red for the data over flat topography and blue for the data over rough topography.

The vertical displacements were calculated as fluctuations of temperature divided by the mean temperature gradient in the 50 m thick water layer. The temperature gradient decreases with depth. These figures show that the estimates of spectral densities at stations over rough topography exceed the model spectrum. This is caused by the many steps on

the vertical profile due to the existence of fine structure specific to oceanic regions with intense vertical motion.

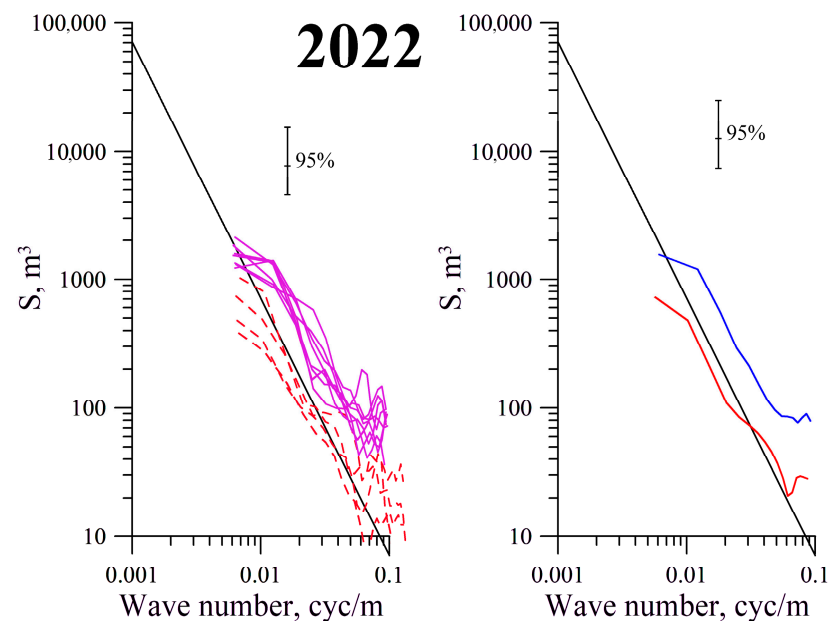


Figure 5. Spectra of vertical displacements in 2022. The (**left panel**) shows bunches of individual spectral curves from the data over flat topography (lower dashed curves of light brown tone) and curves from the data over rough topography (upper solid curves of violet tone). The (**right panel**) shows the mean spectra: a red line for the flat region and a blue line for the rough topography. The black straight line (calculated from Formula (1)) shows the model dropped spectrum from the Garrett–Munk model. The 95% confidence interval is shown.

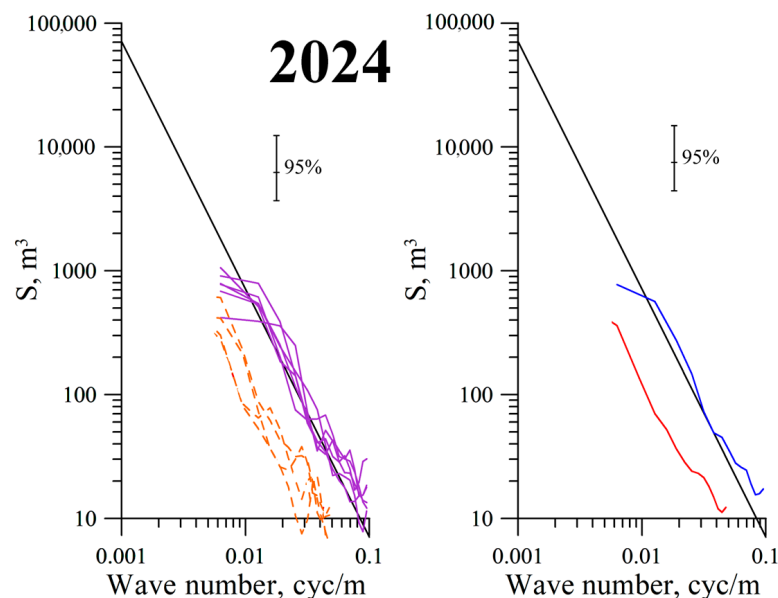


Figure 6. Spectra of vertical displacements in 2024. The (**left panel**) shows bunches of individual spectral curves from the data over flat topography (lower dashed curves of light brown tone) and curves from the data over rough topography (upper solid curves of violet tone). The (**right panel**) shows the mean spectra. The black straight line shows the model dropped spectrum from the Garrett–Munk model. The 95% confidence interval is shown. This figure differs from Figures 5 and 7 by the fact that spectral estimates are lower than the model spectrum. This may be caused by errors in calculating the model spectra and a lower estimate of the buoyancy frequency.

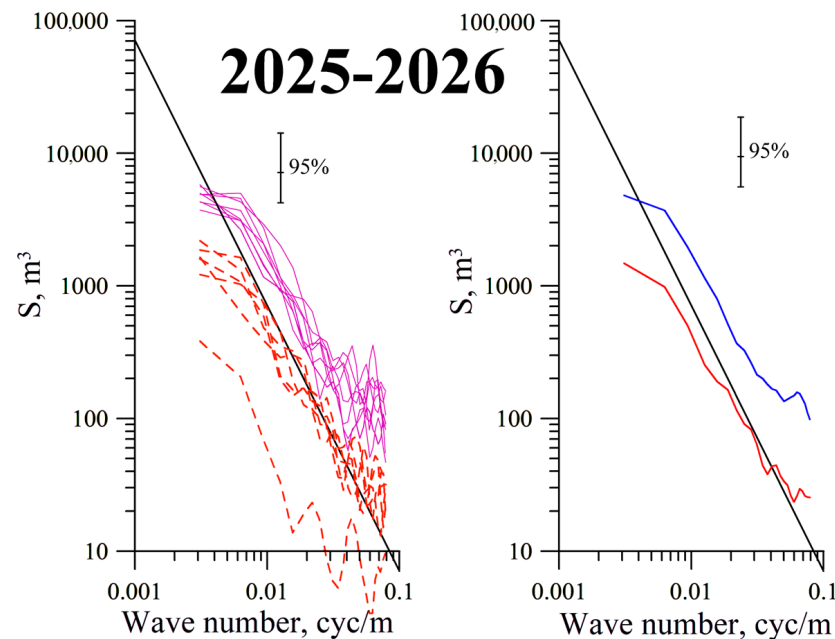


Figure 7. Spectra of vertical displacements in 2025–2026. The (**left panel**) shows bunches of individual spectral curves from the data over flat topography (lower dashed curves of light brown tone) and curves from the data over rough topography (upper solid curves of violet tone). The (**right panel**) shows the mean spectra. The black straight line shows the model dropped spectrum from the Garrett–Munk model. The 95% confidence interval is shown.

4. Discussion

Regions with strong vertical motion and mixing are usually found near steep slopes on the bottom topography [23,24]. The vertical motion is usually associated with barotropic tides, which obtain a vertical component when the currents of the tide flow over the slopes. This leads to the generation of internal tides that can break under critical conditions into packets of short-period waves. However, other processes can also induce vertical motion near abrupt topography.

Cold dense water sinks over Antarctic slopes and flows to the north as the deep limb of the Meridional Overturning Circulation. The currents in the upper layer transport warm water from the tropical regions to the north and south. These waters mix with deeper water by means of internal waves; thus, the existing ocean stratification is maintained. Munk [25] and Munk and Wunsch [26] suggested that bottom topography is extremely important in global mixing. The currents of the barotropic tide flow over the slopes of bottom topography, and this interaction generates the baroclinic tide. Special experiments are conducted in the ocean to study turbulent energy dissipation. One such experiment was conducted near Hawaii. It was called the Hawaii Ocean Mixing Experiment (HOME). This experiment was aimed at investigating the topographic influence on mixing [27].

When internal waves propagate in a stratified ocean they deform the density field, generating fine structure, which includes steps of uniform density and regions of high vertical gradients. When internal waves break over steep topography, the water column may become hydrodynamically unstable; thus, turbulent patches are generated [28]. Enhanced mixing over the topographic slopes was revealed in the abyssal depths [29–31]. Oceanic fine structure consists of vertical temperature, salinity, and density steps ranging from 1 m to 100 m. These layers are primarily formed by internal gravity wave breaking, double diffusion (such as salt fingers), thermohaline intrusions at water mass fronts, and differential advection. In addition to internal waves, the following physical processes form fine structure:

- Internal waves are generated generally by tides. Breaking of internal waves, which occurs very often due to shear instability near rough topography, generates turbulence.
- Double diffusion occurs because heat diffuses 100 times faster than salt.

These processes induce salt fingers and diffusive convection.

Salt fingers appear when warm, saline water overlays colder, fresher water. Heat rapidly diffuses downward and forms descending columns of denser water, leading to a number of well-mixed layers.

Diffusive convection occurs when cold, fresh water overlays warm, salty water. Heat diffuses upward faster than salt, creating density instabilities that induce convective mixing and layered structures.

Thermohaline intrusions appear in frontal zones. This interleaving of different water forms strong lateral and vertical variations; thus, layered fine structure appears.

Vertical motions caused by the current of Antarctic Bottom Water with shear overflowing the rough topography in the Vema Fracture Zone induce vertical motions, internal waves, and mixing. After overflowing, the current descends the slope into a deep depression like an underwater cataract [2].

We compared the vertical wave number spectra of temperature fluctuations in the CTD profiles in the Vema Fracture Zone and revealed that higher estimates of spectra appear from the data of profiles over rough bottom topography. The levels of spectral densities calculated from vertical profiles over the flat parts of the Vema Fracture Zone in 2022–2026 were notably lower than the levels of spectra calculated from the CTD casts over rough topography. We show examples of these spectra in Figures 5–7. These fine-structure steps and high vertical gradients of temperature in the vertical profiles can be caused by stronger internal waves existing over the slopes of rough bottom topography. High-frequency internal waves are generated when intense internal tides break over the regions of steep slopes. These internal waves induce steps and vertical gradients in the vertical structure of the temperature profiles, which can be seen by analyzing usual CTD casts. The temperature fluctuations and the fine structure observed in the vertical profiles cause variations in the one-dimensional spatial spectra of vertical displacements estimated from the CTD casts. Spectral densities estimated from the CTD profiles (the “dropped spectra”) near submarine slopes are greater than those estimated in locations with flat bottom topography. The spectra estimated from the CTD casts over smooth topography are close to the model background spectra described by the Garrett–Munk model.

Usually, the CTD profiles taken near submarine slopes are characterized by a greater presence of fine structure than those taken at larger distances from steep slopes. The level of spectral densities in the case of profiles with fine structure can be higher by one order of magnitude than that of the smooth profiles, whose characteristics are very close to the GM-72 background model spectrum.

The maxima in the spatial distributions of the temperature and its vertical gradient spectral densities are usually observed near steep slopes of the bottom topography. The analysis of spectra from the measurements in the water column 2000 m above the bottom revealed strong correlation between the abrupt topography and temperature fluctuations in the CTD profiles.

We found that the difference between the spectra of fluctuations of vertical displacements measured over rough and flat topography is most pronounced in the lowest and middle ranges of vertical wave numbers of the estimated spectra. This corresponds to a scale of fine-structure steps approximately greater than 10 m. No dominating peaks on the spectra were found at these wave numbers. We think that fine-structure steps of different thickness with a length scale of 10–30 m can be formed during mixing. The vertical step of

our data was 1–2 m. This sampling did not allow us to reveal correlations at smaller scales; such results would not be statistically reliable.

5. Brief Summary

Analysis of data from CTD profiling in the Vema Fracture Zone in the tropical West Atlantic reveals that variations in the vertical structure of the temperature profiles (steps and high gradients) are clearly pronounced over steep bottom topography. These variations can be caused by internal waves generated over steep underwater slopes. The changes can be caused by breaking internal tides and transfer of their energy to internal waves of high frequency, which is associated with the appearance of vertical fine structure. Other processes can also contribute to formation of fine-structure steps, like double diffusion, currents with shear, diffusive convection and intrusions.

Variations in the vertical structure of temperature profiles are reflected when estimated one-dimensional spatial spectra of vertical displacements are calculated from temperature fluctuations. In the regions of smooth bottom relief located far from the regions of wave generation over the topographic slopes, the wave number spectra are much closer to the background Garrett–Munk model spectra. The spectral functions estimated near the slopes and over the slopes exceed the model level. This research is limited to the Vema Fracture Zone, which has two contrasting regions of flat and rough topography. No similar findings could be obtained from our measurements in other fracture zones. A similar comparison of spectra over flat and rough topography was reported in [22]. The spectral level of fluctuations of vertical displacements over the Mid-Atlantic Ridge exceeded the level over deep flat basins of the Atlantic at the same latitude.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The author declares no conflicts of interest.

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