RUSSIAN JOURNAL OF EARTH SCIENCES
vol. 20, 4, 2020, doi: 10.2205/2020ES000733

Semidiurnal internal tide in the Atlantic Ocean

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Abstract. Analysis of the generation of internal tides over submarine ridges in the Atlantic Ocean based on numerical modeling and measurements on moorings is considered. It was found that energy fluxes of internal tides from submarine ridges are many times greater than those from the continental slopes because generally the barotropic tidal flow is parallel to the coastline. If submarine ridges are normal to the tidal flow, they form an obstacle to the tidal currents and induce generation of large internal waves. Energy fluxes were estimated from many submarine ridges. These estimates were compared with the measurements on moorings. Numerical estimates and measurements on moorings resulted in a map of internal tide amplitudes in the Atlantic Ocean. Large amplitudes of internal tides were found over the slopes of the Mid-Atlantic Ridge in the South Atlantic, Walvis Ridge, Great Meteor Bank, in Biscay Bay, and in the Strait of Gibraltar.

This is the e-book version of the article, published in Russian Journal of Earth Sciences (doi:10.2205/2020ES000733). It is generated from the original source file using LaTeX's **ebook.cls** class.

1. Introduction

Continuous research of many scientists brought us to the commonly accepted result that internal tides are generated when the currents of the barotropic tide overflow the slopes of bottom topography [*Baines,* 1982; *Morozov,* 1995, 2018; *Sjöberg and Stigebrandt,* 1992]. When the currents of the barotropic tide flow over underwater slopes a vertical velocity component appears and displaces isopycnal surfaces. The frequency of these displacements is tidal. Vertical velocity components generate oscillations of isopycnal surfaces, and a result, the generated internal tidal wave propagates from the submarine slopes.

Baines [1982, 2007] used the following approach. He solved the system of hydrodynamic equations and obtained a solution of the generation of internal tides by a mass force over sloping topography. Baines calculated the energy flux of the semidiurnal internal tide generated over continental slopes in the ocean. Numerical solutions of the problem of internal tide generation were studied in the publications by *Vlasenko* [1992] and *Gerkema and Zimmerman* [1995].

Submarine ridges are important regions of internal tide generation [*Morozov,* 1995; *Sjöberg and Stige-*

brandt, 1992]. The generation of internal tides over the slopes of ridges exceeds many times the generation over continental slopes. This result was reported by *Morozov* [1995]. Since then, many of the results were revised and improved. This study is a progressive report about the geographical distribution of the internal tide in the Atlantic Ocean. The goal of this research is to apply numerical modeling to understand the distribution of internal tide amplitudes in the ocean where measurements on moorings were not previously carried out.

2. The Model

In this research the fully nonlinear non-hydrostatic model of the baroclinic tides developed by *Vlasenko* [1992] is used. The model is described in detail in *Vlasenko et al.* [2005]. A two dimensional (x, z) flow in a continuously stratified rotating ocean of variable depth is considered. The model is two-dimensional, it is based on a full set of primitive equations. In addition, the author introduces the equation for the V-component of velocity normal to the x, z plane to account for the effects of rotation. However, the V-component is considered constant. Numerical simulations were performed along sections normal to the submarine ridges and continental slopes.

The model is forced by specifying periodical changes in the stream function. The wave perturbations of vorticity, stream function, and density are assumed zero at the lateral boundaries located far from the bottom irregularities at the submarine ridge. The simulations are terminated when the wave perturbations reach the lateral boundaries. Since the phase velocity of the perturbations does not exceed 2–3 m/s it is possible to continue the calculations for a large number of time steps. The calculations start from a state of rest when the fluid is motionless, and the isopycnals are horizontal.

The vertical step in the model varies with depth but the number of levels does not change with the changing depth. The thickness of the layers is reduced in the depth intervals with strong stratification. A semi-implicit numerical scheme with a rectangular grid with second order approximations to the spatial derivatives and first order approximation of the temporal derivatives in every temporal semi-layer is used.

The density field unperturbed by internal waves corresponding to the vertical distribution of the Brunt-Väisälä frequency $N(z)$ is specified. The model simulates the following physical phenomenon. A long barotropic tidal wave propagates from the open ocean to the continental slope or submarine ridge. The tidal currents flow over the topographic obstacles and obtain a vertical component. Periodically oscillating vertical components with a tidal period displace water particles; thus, a tidal internal wave is generated. The input parameters of the model are stratification, bottom topography, and stream function of the tidal current. The model outputs the fields of density and velocity over the domain of calculations.

The satellite data from the TPXO.7.1 global inverse tidal model with the Ocean Tidal Prediction Software (OTPS) algorithm (http://volkov.oce.or st.edu/tides/otps.html) was used to estimate the currents of the barotropic tide [*Egbert and Erofeeva,* 2002]. Then, horizontal velocities normal to the underwater slope were recalculated into stream function. The water transport by tidal currents in the open ocean was found as follows:

$$Q = \omega H S$$

where, H is the ocean depth, S is the horizontal displacement of water particle in the tidal flow during half of the tidal period.

The horizontal displacement of water particles was estimated as:

$$S = \frac{2u_0}{\omega} \sin\theta$$

where u_0 is the mean amplitude of the horizontal barotropic tidal currents, θ is the angle between the direction of the barotropic currents and the ridge crest.

The energy fluxes from all major submarine ridges of the Atlantic Ocean were estimated. The bottom topography was taken from the ETOPO digital database of ocean bottom relief (http://www.ngdc.noaa.gov/mgg/global/global.html). Stratification of the ocean was calculated from the CTD database World Ocean Database 2013.

The amplitudes of internal tides generated by the barotropic tide over submarine ridges were estimated. The energy flux for a wide class of waves is given by *Gill* [1982]:

$$E_f = \int_0^z pu \cdot dz$$

In the case of the energy flux from the barotropic tide the energy flux per meter of the continental slope or ridge is given by:

$$E_f = \tilde{E} \cdot c_g$$

where E_f is the energy flux vector from a linear meter (W m^{-1} or J/m s), $\tilde{E}$ is the vertically integrated energy density, c_g is the group velocity. The group velocity can be estimated from the following equation [*Garrett and Munk,* 1979]:

$$c_g = \frac{k k_z^2 (N^2 - f^2)}{\omega (k^2 + k_z^2)^2}$$

where k is the horizontal wave number, k_z is the vertical wave number. It is known that generally in the ocean $N \gg f$ and $k_z \gg k$; hence, we write the following expression leaving only the significant terms:

$$c_g = \frac{k N^2}{\omega k_z^2}$$

We used the wavelengths estimated from the spatiotemporal spectra in various study sites to determine k and correspondingly k_z [*Morozov,* 2018]. The energy density according to *Gill* [1982] is as follows:

$$\tilde{E} = \frac{1}{2}\rho_0 \left(\frac{\tilde{w}_0}{\cos\varphi} \right)^2$$

where $\cos\varphi$ is found from the dispersion relation for internal gravity waves [*Phillips,* 1977]:

$$\frac{\omega}{N} = \cos\varphi$$

Here, we introduced the following notations: $\tilde{w}_0$ is the amplitude of the vertical velocity.

We integrate over the vertical and obtain:

$$E = \frac{\rho V^2}{2} H$$

where V is the vertically averaged amplitude of the orbital velocities of water particles. Then, the mean amplitude of the vertical velocity would be written as follows:

$$w_0 = V \cdot \cos\varphi$$

and the vertical displacements during a half period are written as:

$$\zeta = \frac{2w_0}{\omega}$$

The maximum energy fluxes of internal waves appear at the ridges located normal to the propagation of the barotropic tidal wave. If the crests of the ridge are shallow and the ridge is surrounded by deep waters, the energy flux increases. The Mid-Atlantic Ridge, the Great Meteor Bank, and the Walvis Ridge are the examples of such ridges. The estimated total energy flux in the Atlantic Ocean calculated as a sum of the fluxes from most of the ridges is approximately 4.0×10^{11} W.

Large energy fluxes from the submarine ridges can be explained as follows. The currents of the barotropic tidal wave M_2 are generally directed along the slopes normal to the cotidal lines [*Schwiderski,* 1983]. Since the wave is very long (its length is or the order of 5000 km), its refraction to the coast is not significant. Thus, only a small part of the mass flux associated with the barotropic tide is directed to the coast and crosses the slope line. Only this small portion of the mass flux propagates normal to the slope and generates tidal currents normal to the shore. These currents are responsible for the tidal sea level elevations on the shore and generation of internal tides over the continental slope.

Many of submarine ridges are normal or almost normal to the direction of the tidal currents and form an obstacle that provides intense internal tide generation because tidal currents obtain a significant vertical component. The amplitudes of internal tides in such regions are high. These regions include the equatorial part of the Mid-Atlantic Ridge and almost the entire Mid-Atlantic Ridge in the Southern Hemisphere, the Walvis Ridge, and the Great Meteor Bank. Internal tides of high amplitude were also found in the high-latitude regions of the Atlantic [*Khimchenko et al.,* 2020; *Marchenko and Morozov,* 2016]. Generation of internal tide is strong when the slope of the characteristic surfaces of internal tides is the same as the slopes of the bottom topography at the depth of the maximum stratification [*New,* 1988].

Internal tides with high amplitudes are generated in the Strait of Gibraltar, but unlike the submarine ridges these waves have little influence on the energy budget of the ocean. The Strait of Gibraltar can be considered a point source, and the energy of internal tides dissipates in close vicinity within the strait. Submarine ridges are long linear sources of internal wave generation.

In the regions of the Cabo Verde Basin located far from the ridges and continental slopes the internal tide signal generated by remote intense sources sometimes does not reach the study sites. Russian experiments Polygon-70 and Mesopolygon-85 are located in this deep basin in the tropical Northeast Atlantic. Local generation of internal perturbations occurs over smaller forms of bottom topography in the deep ocean and does not give any strong contribution to the budget of internal wave energy in the entire ocean.

Internal tides are even less intense in the Sargasso Sea. The POLYMODE experiment was organized in the middle of the Sargasso Sea in a deep basin far from large topographic formations. The bottom of the basin is very flat. The signal from remote sources at the Mid-Atlantic Ridge and continental slopes does not reach the moorings. This was confirmed by *Dushaw* [2006] who recorded only weak internal tides in the Sargasso Sea.

Knowing the energy that is transferred from the barotropic tide to internal waves over the slopes of submarine ridges it is possible to construct a chart of the amplitudes of internal tide in the entire ocean. The amplitudes over ridges are calculated from the energy fluxes. Then, dissipation of energy over distance in the course of internal tide propagation is needed to extend the chart from the regions near ridges to the entire ocean. An estimate is needed how amplitudes of internal tides decrease with the distance from the generating source.

These estimates can be based only on the data of measurements. Such data are available in several regions of the Atlantic: near the Great Meteor Banks in the East Atlantic, west of the Iberian Peninsula, and near the coast of Brazil. The moorings in these sites were located in a line approximately normal to the submarine slopes. A decrease in the amplitude was estimated on the basis of these measurements as 10% of amplitude decrease over one wavelength. The energy losses are about 15% over one wavelength [*Morozov,* 2018].

Thus, a chart of the amplitudes of the semidiurnal internal tides over the entire Atlantic Ocean was constructed based on the model simulation and measurements on moorings that were used to verify the model and select correct coefficients of viscosity and diffusion (Figure 1). The chart in Figure 1 is very rough despite the fact that it was improved many times after its first publication by *Morozov* [1995]. The chart does not contain details. It shows only the general pattern

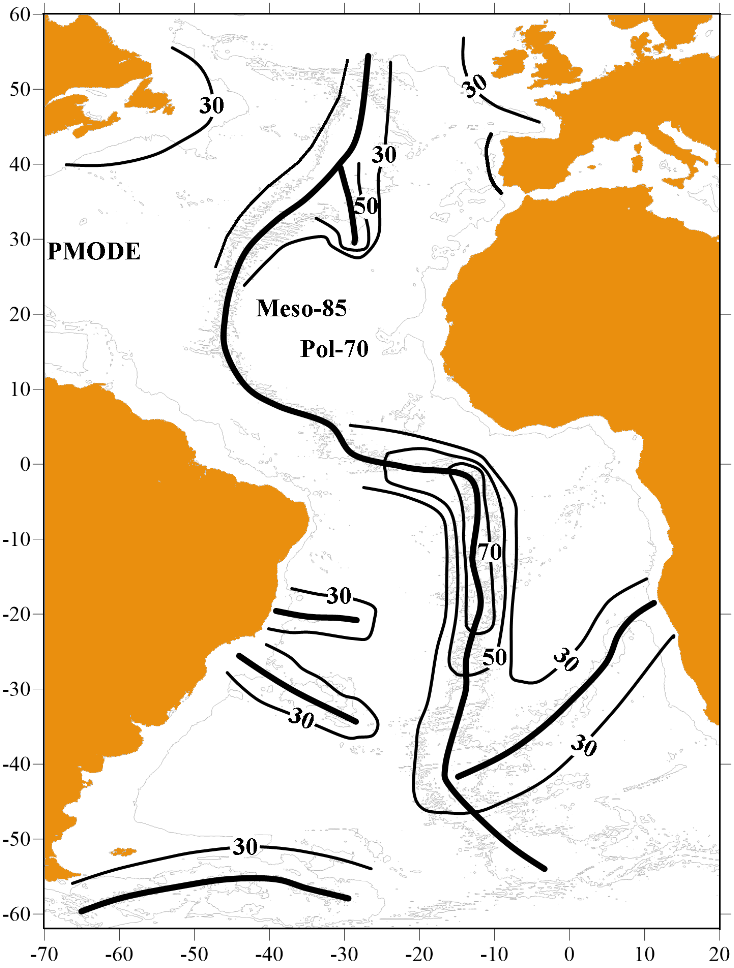

Figure 1. Map of the amplitudes of semidiurnal internal tides (meters) in the Atlantic Ocean. Submarine ridges are shown with heavy lines. Contour lines show the regions of the semidiurnal internal tide amplitudes exceeding 70, 50 and 30 m (peak-to-peak). The regions of the POLYMODE, Polygon-70, and Mesopolygon-85 are shown.

of the amplitude distribution. The amplitudes must be regarded as “vertically averaged” and also “time averaged” with a half month (spring-neap) time scale.

3. Discussion

Internal tides are actually internal waves with tidal frequency. These are internal waves with fixed frequency, high amplitude, and energy. Since internal tides are internal waves of high energy, they can propagate over large distances from the regions of their generation before the energy decreases to the background level.

Internal tides get their energy from the barotropic tide in the regions of large underwater topographic formations: slopes of submarine ridges, seamounts, islands, and continental slopes. The energy fluxes depend on the geometry of the slope, stratification, and water transport by the currents of the barotropic tide. The energy fluxes from the barotropic tide strongly increase if the inclination of the slope is close to the characteristic curve of internal tides, which depends on stratification. The direction of tidal currents relative to the ridge is an important factor of internal tide generation.

The maximum energy fluxes and hence, the maximum amplitudes of internal tide are formed in the regions, in which the currents of the barotropic tide are normal to the crests of the ridges. The energy fluxes are maximal when the crest of the ridge is close to the maximum stratification and the surrounding depths of the ocean are deep.

High amplitudes of internal tides are confined to the regions of submarine ridges. In the deep ocean basins far from submarine slopes and rough topography, internal tides decay to the background level (with amplitudes close to 10 m). The maximum amplitudes are found near large topographic features. For example, near the North Mid-Atlantic Ridge south of the Great Meteor Banks, the amplitude of vertical displacements was as high as 36 m. East of the Great Meteor Banks the amplitudes reached 50 m. However, the largest internal tides exist in the Strait of Gibraltar, where vertical displacements of water particles exceed 200 m.

Moderate internal tide amplitudes within 15–20 m were recorded in the regions of the Polygon-70 and Mesopolygon-85 experiments located at distances of many hundred kilometers from submarine ridges.

In the central part of the Sargasso Sea located very far from large topographic formations, the amplitudes of internal tides are even smaller. Such a distribution of the amplitudes of semidiurnal oscillations over the ocean basin confirms the concept that internal tides are generated over the slopes of topography and then propagate to the other regions of the ocean as free internal waves. Internal tides lose energy while propagating from the locations of generation.

4. Conclusions

1. A chart of the distribution of internal tide amplitudes was constructed on the basis of calculations and measurements. Usually internal tide amplitudes are within 10–30 m, but the maximum amplitudes in the open ocean exceed 100 m.
2. The properties of internal tides in the ocean were determined on the basis of numerical modeling, which was verified using moored measurements.
3. Submarine ridges are the regions of intense generation of internal tides. The energy fluxes from the barotropic tide to the internal tide over submarine ridges were calculated. These fluxes exceed the fluxes to the internal tides from the continental slopes. This occurs because the currents of the

barotropic tide are generally parallel to the continental slopes; hence they do not transport much water across the slope. Tidal currents can flow normal to the ridges and overflow them generating high-amplitude internal tides.

4. As the internal tide propagates over the ocean basins it loses its energy. At large distances from the sources (of the order of 1000–1500 km) the internal tide approaches the background level of internal waves.

Acknowledgments. The work was carried out within the State Task of the Russian Federation 0149-2019-0004; the research was supported by the Russian Foundation for Basic Research (grant 19-57-60001, numerical simulations) and by the Russian Science Foundation (grant 16-17-10149, data analysis). The work of I. Ansorge was supported by the National Research Foundation of South Africa (Grant UID 118901).

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