Strait of Kara Gates: A Region of Strong Internal Tides in the Arctic Seas

E. G. Morozov*,1 and D. I. Frey1

[1] Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia
* **Correspondence to:** Eugene Morozov, egmorozov@mail.ru

Abstract: This is a review paper about measurements of internal tides in the Kara Gates Strait. Kara Gates is one of the straits where intense internal tides are generated by tidal currents overflowing the transversal sill of the strait. Tidal currents are superimposed on a constant current from the Barents to the Kara Sea. Field studies of internal waves in the strait were carried out in 1997, 2007, and 2015. Analysis of measurements on moorings and towed CTD in scanning mode is presented. Field studies are supported by model simulations of generation and propagation of internal tides.

Keywords: Kara Gates, internal tides, model simulation, towed CTD, moorings

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Introduction

Straits in the ocean are strong generators of internal tides. The problem of studying strong internal tides in straits with a two-layer current has long been of interest to physical oceanographers. The existence of two layers of currents in the Strait of Gibraltar was found in the 19th century. *Carpenter and Jeffreys* [1871] found it using a drogue at 300 m depth from a small boat. They observed a westerly drift of the boat against the wind and surface current. Russian Admiral S. O. Makarov found a two-layer current in the Strait of Bosporus in 1881 [*Shokalsky*, 1959]. Such currents and generation of internal tides are best known in the Strait of Gibraltar [*Bryden et al.*, 1994; *Watson*, 1994] and Bab-el-Mandeb Strait [*Jarosz et al.*, 2005; *Murray and Johns*, 1997]. A strong flow of the barotropic tide, flowing around a ridge crossing the Strait of Gibraltar from north to south (Camarinal Sill), causes intense internal waves with an amplitude of up to 150 m. The superposition of a two-layer current and barotropic tide creates a complex dynamic system in the strait. A similar phenomenon is observed in the Kara Gates Strait between the Barents and Kara seas. The water in the Barents Sea, heated by the inflow of warm Atlantic waters, is much warmer than the water in the Kara Sea. In the narrow strait of the Kara Gates, a two-layer flow system is formed.

According to the most common classification of the waters of the Barents Sea near the Kara Gates [*Dobrovolsky and Zalogin*, 1982; *Terziev et al.*, 1990] the following waters occupy the region of the Kara Gates Strait on the Barents Sea side: 1) Atlantic waters transported from the west by the surface currents and from the north and northeast from the Arctic basin; 2) Arctic waters with temperatures below zero and low salinity entering as surface currents from the north; 3) coastal waters formed under the influence of continental runoff; 4) Barents Sea waters with low temperature and high salinity, formed within the sea as a result of mixing of water masses transported from outside and their transformation under the influence of local conditions. On the Kara Sea side, the waters are determined by the mixing of the water masses of the surface water of the Arctic Basin, coastal runoff, and Atlantic water penetrating through the troughs.

Investigations of internal waves in the straits of cold seas are especially important as they are observed not only in the Arctic [*Morozov and Paka*, 2010], but also in the straits

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of the Southern Ocean [*Frey et al.*, 2023; *Khimchenko et al.*, 2020], where they influence local ecosystems of cold seas. Tides in the Kara Gates Strait are described in a modeling publication by *Kagan and Timofeev* [2015].

Currents of the barotropic tide flow over the transversal sill of the strait and displace isopycnals with tidal periodicity, thus generating internal waves of tidal period [*Hibiya*, 1990; *La Violette and Arnone*, 1988; *Lacombe and Richez*, 1982]. The Kara Gates Strait is one of such straits where strong tides cross the sill and generate internal tides. A warm surface current is directed through the Kara Gates Strait to the east due to the density difference. A weaker surface cold current is directed along the southern coast of the Novaya Zemlya to the Barents Sea. The minimum depth of the transversal sill in the Kara Gates Strait is only 30 m; however, several fractures deeper than 100 m break the sill and provide transport of water in both directions [*Morozov et al.*, 2003a]. We have investigated this region and especially internal tides in the strait in 1997, 2007, and 2015. This is a review paper summarizing the research on internal tides.

Moored measurements

Internal tides in the Kara Gates Strait were previously analyzed by *Morozov et al.* [2003a,b, 2008, 2017] based on moored measurements, numerical modeling, towed CTD, and satellite images.

In September–October 1997, we performed moored measurements of currents and temperature fluctuations in the Strait of Kara Gates. Three moorings were deployed in the strait for a few days at 70°22′ N, 57°38′ E; 70°18′ N, 57°58′ E; 70°17′ N, 58°11′ E (Figure 1). The bottom topography is based on the digital database [*Smith and Sandwell*, 1997]. Within the transverse ridge the depths of the sea in the database are underestimated. Cross-section with echo sounder measurements [*Morozov et al.*, 2017, Figure 6] showed that there are four fractures in the ridge, up to 210 m deep. The Novaya Zemlya Archipelago is a continuation of the Ural Mountain Ridge separated by the strait 56 km wide. Judging by the depth at the mooring locations (230 m), the depth south of the towing tack is even greater.

Temperature measurements at moorings deployed in the strait show strong fluctuations. To isolate the tidal component with the M_2 period (12.4 hours), we used a second-order bandpass elliptical filter [*Parks and Burrus*, 1987]. The bandpass filter was tuned

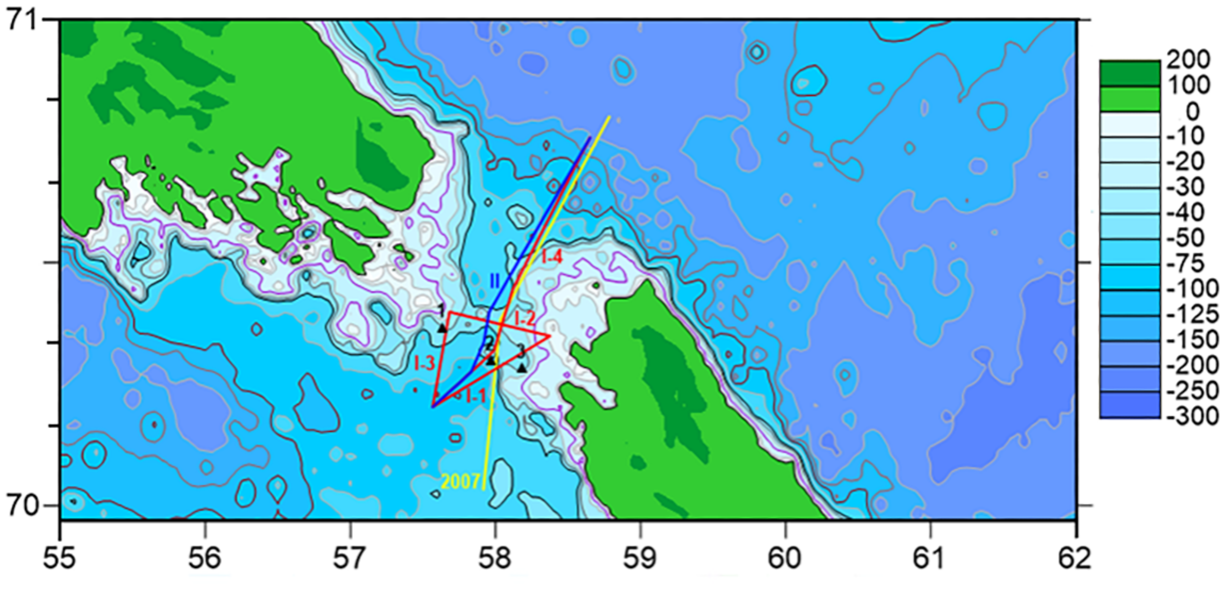

Figure 1. Bottom topography in the Kara Gates based on *Smith and Sandwell* [1997]. The moorings in 1997 (1, 2, 3) are shown with black triangles. Tacks with towed CTD are shown with lines of different color: yellow in 2007, blue and red in 2015.

to the M_2 frequency (1/12.42 per hour) with a bandwidth from 1/12.37 per hour to 1/12.47 per hour. Temperature fluctuations with the M_2 period reach ±0.2 °C.

We interpolated the temperature measured every 15 min by the instruments on the mooring to the levels of 65, 90, 115, 140, 165, 190 and 215 m. Fluctuations of isotherms −0.3 °C and −0.4 °C appeared the most representative, since their fluctuations did not exceed the range of the depths of sensors on the mooring. Time evolution of vertical displacements of isotherms is shown in Figure 2.

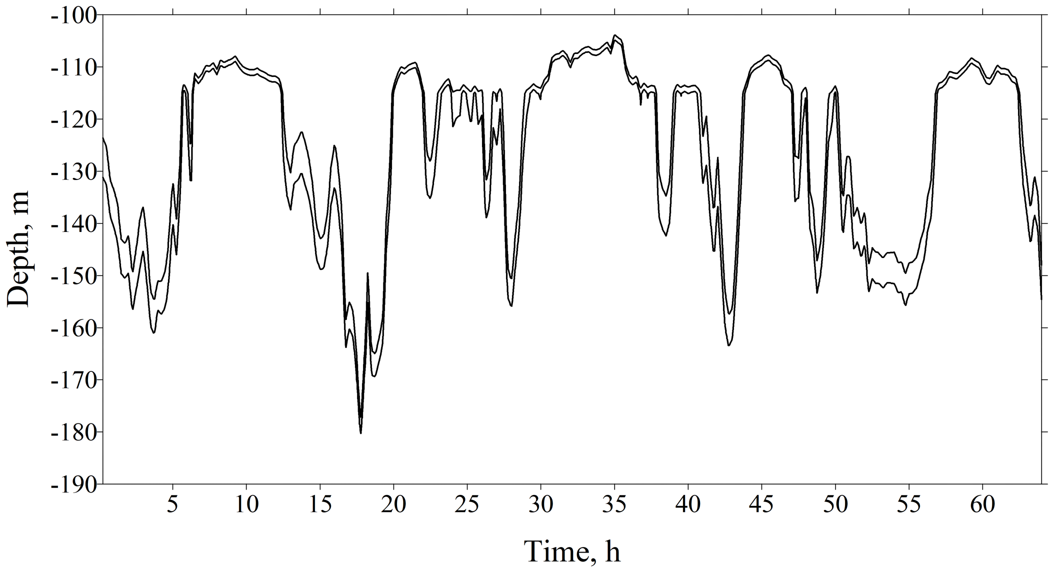

Figure 2. Vertical displacement of the −0.4 °C and −0.3 °C isotherms at the mooring in the Kara Gates Strait. Data from mooring 3 in Figure 1 (October 4–7, 1997).

One can conclude from the figure that the range of fluctuations is very strong. These isotherms oscillate vertically from a depth of 110 m to 180 m at a sea depth of 230 m. A dominating period of 12 h is seen. The amplitude of their displacement from the equilibrium position is about 35 m. The oscillations differ significantly from sinusoidal oscillations, which indicates their strong nonlinearity. The wave partially collapses after reaching its maximum amplitude.

Moored temperature measurements in 1997 show that in the spring phase of the tide the vertical peak-to-peak displacement of isothermal surfaces reached 70 m, while the total depth at the measurement site is 230 m.

While analyzing the data of previous studies [*Morozov et al.*, 2003a,b, 2008, 2017] one can see that the structure of internal tides in the Kara Gates is similar to that in the Strait of Gibraltar and Bab-el-Mandeb Strait. High amplitude internal tidal waves are generated because strong currents of the barotropic tide overflow the slopes of the sill and displace isopycnals with tidal periodicity [*Brandt et al.*, 1996; *Morozov et al.*, 2003b]. A warm current from the Barents Sea to the Kara Sea generated by sea level difference intensifies the internal tide propagating to the southwest [*Morozov et al.*, 2017]. Superposition of the current and barotropic tide flow forms a complex dynamic situation in the Kara Gates Strait. Interaction with the currents intensifies internal tides.

Further measurements are needed for understanding the seasonal variations in the thermohaline structure of the strait and corresponding responses of ocean currents and internal waves to the changes in oceanographic conditions. Direct measurements of oceanographic and kinematic structure in the strait remain extremely rare during the major part of the year. Long-term moored measurements seem to be extremely interesting in this regard.

Measurements with a towed CTD in a scanning mode

The joint application of towed CTD measurements, radar imaging, and numerical modeling is a new approach to investigate internal tides. A scheme of the field works in the strait in 2007 and 2015 is shown in Figure 1. The measurements in 2007 and 2015 coincided with the spring tide; hence they were conducted during strong tidal currents.

We shall analyze filed measurements over a section in the Strait of Kara Gates with a towed CTD. A CTD-profiler Idronaut 316 was towed by a ship in a scanning mode at a speed of 6 kn. The profiler was periodically lowered and raised so that the records were made almost from the surface to the bottom. One cycle of lowering and raising was approximately 5 min long depending on the depth. The horizontal resolution between cycles was a few hundred meters. A scheme of the towing legs is shown in Figure 1. The towed measurements were carried out on September 8–9, 2007, on August 28–29, 2015, and on October 6–7, 2015.

The field of isopycnals based on the temperature records in the scanning mode over the section in the strait is shown in Figure 3. This is a snapshot of the displacements of isotherms along the cruise track.

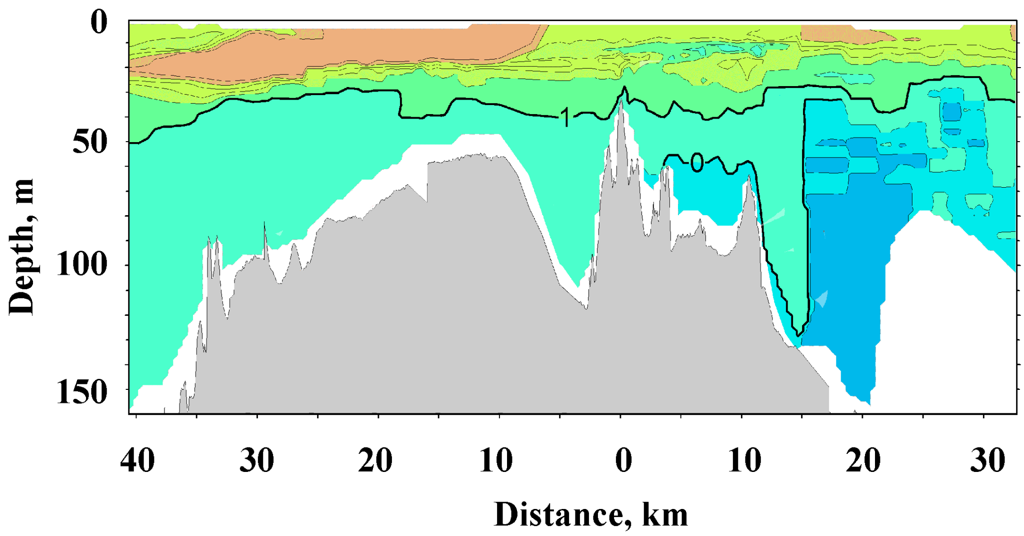

Figure 3. Distribution of temperature over the towed CTD section during the ship motion from the Barents to the Kara Sea. Isotherms are shown with an interval of 1 °C. Thicker lines shows the 1 °C, and 0 °C isotherms to emphasize the observed effect. Gray color shows the bottom profile.

When an internal wave propagates opposite to the current its amplitude increases, and the wave length becomes shorter. If the effect is strong, an internal bore appears. On the other side of the sill, the wave propagates in the same direction as the current. This does not produce a bore. One can see from the figure that an internal bore propagating to the west is located at 18 km from the shallowest crest of the sill. The 1 °C isotherm sharply deepens by 10–15 m at the slope of the sill. Judging from the distances between the maximum depths of isotherms the horizontal size of internal tidal wave (the leading slope of the wave and the bore) is 21 km.

Numerical modeling

We used a non-hydrostatic model developed by V. I. Vlasenko [*Morozov and Vlasenko*, 1996; *Vlasenko*, 1992] to study the generation and propagation of internal tides. Application of this model to the regions of Arctic seas was made in [*Morozov and Pisarev*, 2002]. In this calculation, we used simplified topography based on our echo-sounder survey in the region. Stratification was taken from the CTD data measured in the region during field works. The amplitude of barotropic tidal currents was assumed equal to 18 cm/s based on the TPXO model, which uses satellite altimetry data [*Egbert and Erofeeva*, 2002] and averaging of moored current-meter measurements.

The ellipses of the baroclinic tides M_2 and S_2 on the dates of towed measurements in 2007 across the strait were calculated from the data of satellite altimetry using the OTIS algorithm of the Oregon State University [*Egbert and Erofeeva*, 2002]. The ellipses are shown in Figure 4.

Numerical simulations were carried out using a domain 200 km long with a horizontal step of 75 m and 20 vertical levels. The time step was specified equal to 2 s. The coefficients of horizontal eddy viscosity and density diffusivity as 5 m^2/s over the ridge and 1.5 m^2/s beyond the ridge over the flat bottom in the model. The coefficients of vertical turbulent viscosity and density diffusion were set at 0.001 m^2/s over the ridge and 0.0001 m^2/s beyond the ridge over the flat bottom.

In the model simulations we introduced a current from the Barents Sea in the entire depth of the strait. The current was directed to the northeast. The direction of the flow in Figure 5 is from left to right. Its mean velocity was 9 cm/s. A periodical barotropic tidal flow with an amplitude of 18 cm/s was superimposed on this current.

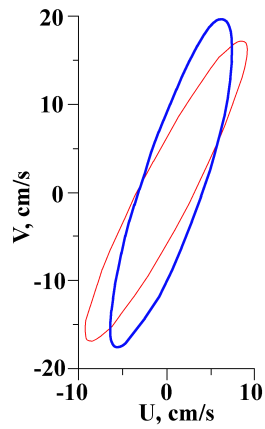

Figure 4. Ellipses of tidal currents at the M_2 tidal frequency on the mooring calculated from the measurements is shown with a blue line [*Morozov et al.*, 2003a]. Ellipse of tidal currents calculated from the satellite data at the M_2 and S_2 tidal frequencies [*Egbert and Erofeeva*, 2002] is shown with a red line.

In 2007 and 2015, the ship was moving from the Barents Sea to the Kara Sea opposite to the propagation of internal tide in the Barents Sea. A reverse ship track was also made in 2015. Their amplitudes on the Kara Sea side are smaller than on the Barents Sea side. The perturbations of the density field induced by the propagating internal tide after four tidal periods (48 h) of simulation are shown in Figure 5. The fluctuations of the density field are not symmetrical relative to the sill that crosses the strait.

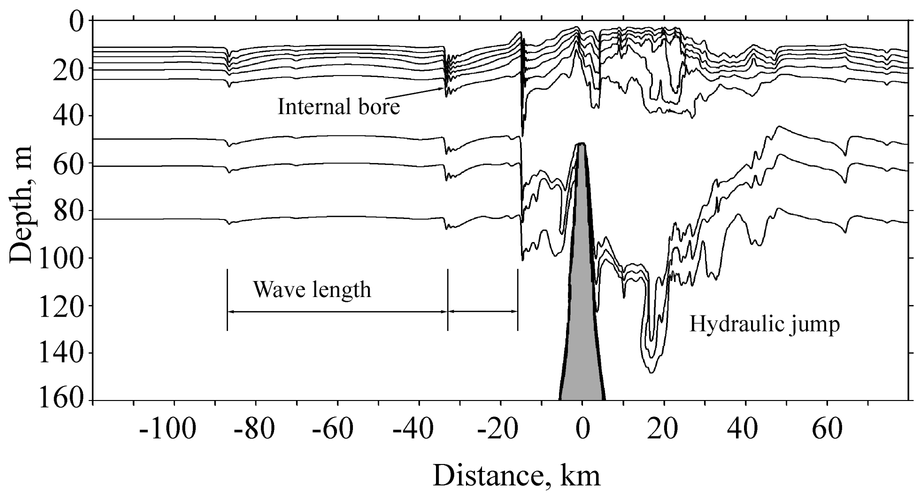

Figure 5. Numerical simulation of the density field perturbed by internal waves in the Kara Gates Strait. The contour lines of density from 1.025 to 1.029 g/cm^3 with a step of 0.0005 g/cm^3 perturbed by the current in the flow and internal waves are shown based on the numerical simulations. Bottom is shown with gray color.

A stronger internal tide should be observed in the Barents Sea because internal waves propagate to the southwest from the sill in the strait in the direction opposite to the current. This is confirmed by the numerical simulation. While internal tide propagates opposite to the current its amplitude increases because the wavelength is shorter compared to the propagation in the same direction with the current. The leading edge of the wave is flat and the trailing edge is steep. Owing to strong non-linear effects and the mean current opposite to the wave propagation internal bore is formed east and west of the sill. The isopycnals sharply deepen to 10–15 m forming a bore. A packet of short-period waves follows the bore.

Conclusions

Analysis of the data of towed measurements in the Strait of Kara Gates shows that the amplitudes of internal tides in the strait are large and occupy a significant part of the ocean depth. The waves propagate along the strait in a stratified flow. Generation of internal tide in the strait occurs due to the periodical displacement of isopycnals by the barotropic tide over the slopes of the transversal sill. A hydraulic jump is formed by the mean current directed to the Kara Sea, which is trapped east of the slope.

Internal tidal is intensified in the western part of the strait because it propagates opposite to the mean current. The wavelength becomes shorter; hence the wave energy concentrates over a smaller spatial scale, and the wave amplitude increases.

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