Transformation of baroclinic tidal waves in the conditions of the shelf of the Far Eastern seas

P D Kuznetsov, E A Rouvinskaya, O E Kurkina and A A Kurkin*

Nizhny Novgorod State Technical University n a R E Alekseev, Nizhny Novgorod, 603950, Russia

E-mail: *aakurkin@gmail.com

Abstract. This work is devoted to the study of the regimes of transformation of baroclinic tidal waves under the conditions of the Far Eastern seas within the framework of a fully nonlinear numerical model. Two sections were selected to study the features of wave dynamics – in the Sea of Okhotsk (Sakhalin Island shelf) and in the Bering Sea (near Cape Navarin). On the basis of the performed calculations, regional and seasonal features of the transformation of baroclinic waves and the structure of the flow induced by them were revealed. It is shown that the dynamics in the winter season is less intensive. The rotation effect on the formation of solibore in the studied conditions is analyzed. The obtained estimates of wave amplitudes and velocities are consistent with the published data of field observations in the Sea of Okhotsk. For the Bering Sea, the conditions are shown to be favorable for the generation of intensive internal waves, which indirectly confirms the hypothesis of influence of such waves on the formation of underwater sand dunes.

1. Introduction

One of the classical and predominant mechanisms for internal waves generation is the transformation of a tidal wave over the seafloor topography [1]. In this sense, the Far-Eastern seas, rich in various natural resources, both mineral and biological, are a favourable environment for the implementation of this scenario. They are stratified in density: most of the year have a pronounced layered structure (e.g., four layers are distinguished in the Sea of Okhotsk waters [2; 3], mainly two or three – in the Bering Sea [4]). They are exposed to a barotropic multicomponent tide, and have complex bathymetry. As a result, short-period intensive internal waves are generated, that is confirmed by the scarce data of satellite observations and field measurements (see, e.g., [5; 6] and others (a database of observations of internal waves, including those in the Far Eastern seas, is presented on the website of our laboratory: https://lmnad.nntu.ru/ru/gwatlas/)). Such waves play an important role in the ecosystem of the stratified sea shelf. And although internal waves are rarely taken into account in the design of hydraulic structures in our country, study of the typical regimes of their generation is an urgent task that has engineering applications. For quantitative assessments of dangerous dynamic effects from short-period internal waves and their further consideration in engineering surveys, it is necessary to perform regional investigation of scenarios of long baroclinic wave transformation to estimate the probability of occurrence of internal waves of extreme amplitudes. Such assessments were started for certain areas of the White Sea, the Barents Sea and the Sea of Okhotsk in [7; 8; 5]. Field and satellite observations indicate a high activity of
this type of waves in some areas of the Sea of Okhotsk (e.g., see [9] for satellite sensing data) and the Bering Sea, however, the amount of such data is limited. Therefore, therefore, it is necessary to resort to numerical modeling, in order to study the scenarios of transformation of baroclinic waves in such water areas.

Within the framework of this study, we selected several vertical “sections” (corresponding to the direction of propagation of the prevailing component of the barotropic tide) in the shelf zone of the Bering Sea and the Sea of Okhotsk. The first of them was chosen on the northeastern shelf of Sakhalin Island. It crosses the Kaigansko-Vasyukansko-Sea oil and gas condensate field, while similar hydrological conditions are typical for the Odoptu-Sea field zone (Sakhalin-1). According to the data of field observations in this area of the northeastern shelf of Sakhalin Island, trains of short-period internal waves with amplitudes from 2 to 10 m at a depth of about 50 m were observed, while the horizontal velocities of currents induced by these waves reached 40 cm/s [10]. Manifestations of short-period internal wave trains are also observed by means of remote sensing [6].

The second cross-section is selected in the northwestern part of the Bering Sea from the Aleutian Basin to the Koryak-Kamchatka coast south of Cape Navarin. This region is poorly studied in the context of the dynamics of internal waves, because direct contact measurements of internal waves are technically difficult and economically expensive at high latitudes. However, there is a hypothesis that internal waves are responsible for the formation of large sand waves in the underwater canyons on the northern continental slope (moreover, the horizontal spatial scales of the discovered bottom dunes coincide with the lengths of the observed short-period waves (see, e.g., [11; 12])). According to satellite radar images, the zone of the Bering Sea south of Cape Navarin is characterized by high activity of short-period internal waves [13]. At the same time, this region is interesting for Russia both from an economic and an ecological point of view.

The paper presents results of numerical modeling of internal wave fields evolution in realistic conditions in the framework of program complex intended for numerical modeling of propagation and transformation of such waves in the ocean. The goal of this paper is to study regional and seasonal features of baroclinic wave transformation and the structure of the flow induced by them on the basis of the performed calculations under the conditions of the shelf of the Sea of Okhotsk and the Bering sea.

2. Initialization of mathematical model for simulation of dynamics of the internal gravity waves in the conditions of the Bering Sea and the Sea of Okhotsk

The study of internal wave dynamics was carried out by means of the program complex intended for numerical modeling of propagation and transformation of such waves in the ocean, that implements a procedure of numerical integration of fully nonlinear two-dimensional (vertical plane) system of equations of hydrodynamics inviscid incompressible stratified fluid in the Boussinesq approximation, taking into account the influence of barotropic tide [15; 14]:

\[
\vec{V}_t + (\nabla \vec{V}) \vec{V} - f \vec{k} \times \vec{k} = -\nabla P - k \rho g,
\]

\[
\rho_t + \nabla \rho = 0,
\]

\[
\nabla \vec{V} = 0,
\]

\[
\rho = \frac{\rho_f - \rho_0}{\rho_0},
\]

where \(\vec{V} (u, v, w)\) is the velocity vector, \(\nabla\) is the three-dimensional vector gradient operator, subscript \(t\) denotes the time derivative, \(\rho_f\) – the density of sea water, \(\rho_0\) – the average or characteristic density (introduced owing to the Boussinesq approximation that assumes that the density \(\rho_f = \rho_0 (1 + \rho)\) only changes insignificantly in the basin and \(\rho\) is a nondimensional quantity that has a meaning of density anomaly), \(P\) is the pressure, \(g\) is the acceleration due to gravity, \(f\) is,
as above, the Coriolis parameter and \( \vec{k} \) is the unit vector along the \( z \)-direction. The waves propagate in the \( x \)-direction, \( y \)-axis is perpendicular to the wave motion and \( z \) is the vertical coordinate.

The normal to the wave propagation (cross-section) velocity is included in the model, but no variation along the \( y \)-coordinate is allowed. This is realized by neglecting the partial derivatives with respect to \( y \) in the basically three-dimensional equations (1–4). The equations are transformed to a terrain-following coordinate system (so-called sigma-coordinates) and are solved over a domain bounded below by the bathymetry \( h(x) \) (prescribed by the user) and covered by a rigid lid at the surface.

To initialize the model, it is necessary to prescribe undisturbed horizontally homogeneous density field of water masses \( \rho_{\text{mean}}(z) \) as well as the velocity distribution in the barotropic tidal field in the computational domain. The steps of the numerical scheme in space and time are chosen to satisfy the Courant–Friedrich–Levy criterion for stability.

To determine water depth, we defined sections between points with coordinates 60°30’N 177°30’E and 62°30’N 177°21’E (in the Bering sea); 54°31’N 145°32’ E and 53°59’N 143°16’ E (in the Sea of Okhotsk) using GDEM data (figure 1). Section lengths are approximately 160 km and 220 km respectively. The direction of the section is determined in accordance with the pattern of internal gravity waves radiation from the tidal front.

![Figure 1. Geographical location of cross-sections in the Sea of Okhotsk and the Bering sea.](image)

Since horizontally-homogeneous density field is used in our numerical model, the density profiles from the outer edges of the cross-sections have been taken, that are obtained by approximating data from GDEM climatology for winter and summer. Detailed description of algorithm of this stage is presented in [16].

An important condition for initialization of the model is barotropic tide. The horizontal velocity \( u_{\text{btr}} \) in the barotropic tide is given by:

\[
 u_{\text{btr}} = \frac{H}{r(x)} \sum_i U_{\text{max},i} \sin(\sigma_i t + \phi_i) = \sum_i \frac{Q_i}{r(x)} \sin(\sigma_i t + \phi_i),
\]

\[
 Q_i = U_{\text{max},i} H,
\]
where $Q_i$ – the maximum cross flux of water for the corresponding component of the tide, $r(x) = H - h(x)$ – the local depth of the fluid, $\sigma$ – the frequency of the tidal component, $\phi$ – its initial phase, and the $i$-index indicates the various tidal components (M2, S2, K1, O1, P1, Q1). From the continuity equation we obtain the expression for the vertical velocity of the barotropic tide

$$w_{br} = \sum_i Q_i \frac{r'(x)}{r^2(x)} (z - H) \sin(\sigma t + \phi_i). \quad (7)$$

The barotropic tide velocity $v_{br}$ in the transverse direction with respect to our section is given by:

$$v_{br} = \sum_i \frac{fQ_i}{\sigma r(x)} \cos(\sigma t + \phi_i). \quad (8)$$

In accordance with (5) – (8), the initial velocity field is initialized as follows (there are no internal waves at the initial time):

$$u = \sum_i \frac{Q_i}{r(x)} \sin(\phi_i), \quad (9)$$

$$v = \sum_i \frac{fQ_i}{\sigma r(x)} \cos(\phi_i), \quad (10)$$

$$w = \sum_i Q_i \frac{r'(x)}{r^2(x)} (z - H) \sin(\phi_i). \quad (11)$$

The amplitudes and phases of barotropic tide components are determined from the TPXO 8 (A TOPEX/Poseidon Global Tidal Model) model based on satellite altimetry data [17].

3. Internal waves in cross-section 1 in the Sea of Okhotsk: results and discussion

The total calculation time was 65 h, which corresponds to approximately 2.5 cycles of the prevailing diurnal component of the tide (it was noted in [1] that the full periodicity of the process is reached after approximately 2–3 tidal cycles). The fields of the vertical and horizontal components of the velocity in the computational domain, as well as the modulus of the total velocity and the density distribution at different stages of the process were constructed and analyzed. Temporal changes in the spectra of isopycnes located at different depths were analyzed. Algorithms for calculating energies (kinetic, potential and APE – Available Potential Energy – the difference between pseudo-energy and kinetic energy [18]), bottom velocities, Froude number (defined as $\text{Fr} = u_{max}/c$, where $c$ is the phase velocity of long internal waves of the lowest mode, and $u_{max}$ is the velocity of the barotropic tide at a given point on the path) were implemented. For the near-bottom and near-surface velocities, the exceedance probability was additionally calculated.

The initial stage of the modeled process is the formation of a long internal wave over the shelf with an amplitude of about 7 m and a length of about 15 km. The next stage of the process (after about 6 hours of the calculation time) is the steepening of the front of the long baroclinic wave. The velocities inside the baroclinic flow increase. After another 12 hours, short internal waves begin to emerge from the long wave. This can be characterized as the formation of a solibor (regimes of solibor generation for different signs of nonlinear coefficients within the framework of the Gardner equation are described in our article [19]). The horizontal velocity field above the continental slope has a complex alternating structure – a positively directed (towards the coast) "stream" stands out parallel to the slope. The maximum horizontal velocities, as well as the maximum values of the modulus of the total velocity, are achieved in the area of formation of solibor on the surface of the sea.

After about 8 hours, 4–5 short waves are discernible on the ridge of solibor. Above the deeper part of the path, the formation of baroclinic tidal waves also becomes noticeable. The evolution of a
barotropic tide into a baroclinic tide with the subsequent generation of short-period internal waves can be traced in more detail on the $x$-$t$ diagram, for example, for an isopycn shown in figure 2, which is located at a depth of 130 m in an undisturbed state. This graph reflects the classic pattern of long-to-short wave evolution over the shelf: after about 4 semidiurnal cycles, a sequence of "solitary" waves (lower right corner of the graph) begins to emerge from the long wave, which can be identified by the "bands" (constant velocity) on the diagram.

According to the amplitude spectrum for the selected isopycn along the spatial coordinate $x$, one can see the "overflow" of energy into high-frequency (relative to tidal) components.

![Figure 2](image1.png)

**Figure 2.** $x$-$t$ diagram of the displacement of the isopycnic surface [m], which is in an undisturbed state at a depth of 130 m.

From the analysis of the induced near-bottom and near-surface velocities, it can be concluded, that the contribution of the baroclinic component is significant, especially to the near-surface velocities. In the area of the steepening of the internal wave, both the bottom and near-surface velocities exceed 0.3 m/s in absolute value (reaching even 0.4 m/s), while the barotropic component on average makes a contribution of about 0.1 m/s. Graph of the exceedance probability for near-surface velocities is shown in figure 3. It is worth noting that this result is in good agreement with the observations, published in the article [10].

![Figure 3](image2.png)

**Figure 3.** Distribution of the exceedance probability for the near-surface velocities.
To classify the processes of the internal wave generation it is proposed in [1] to use the Froude number magnitude. In the "supercritical" regime Fr > 1, so the generation of strong nonlinear internal lee waves by tide is possible at any latitude, whereas there is no IW generation when Fr ≪ 1 in the region north of the critical latitude. The spatial distribution of the Froude number along the simulated path indicates that no supercritical regime arises under the simulated conditions.

4. Cross-section 2 in the Bering sea: results and discussion

The total calculation time was 72 hours. The transformation regime of the baroclinic wave in section 2 is qualitatively different from that observed for section 1. The following estimates were obtained: the amplitude of long baroclinic waves can reach 20 meters (the generated short-period internal waves have amplitudes of the order of 10–15 m), and the horizontal velocity in the water column can be as high as 0.3 m/s, while the velocities of bottom flows in the upper part of the shelf reach 0.8 m/s, the Froude number exceeds 1 only in the coastal zone of the section at depths less than 150 m ("subcritical" regime is observed at a greater part of the computational domain).

It is shown that the dynamics of internal waves in the studied region also corresponds to the classical scheme of evolution of long barotropic tidal waves into baroclinic ones with the subsequent formation of wave bores. The obtained estimates illustrate dynamics of internal waves not only in the studied section, but also over a significant part of the northwestern shelf of the Bering Sea, where a similar hydrological regime takes place.

For the winter season, the generation of short-period internal waves is less intense. The generated waves have heights of up to 10 m. However, in some areas bottom velocities are still significant. In general, velocities have an amplitude of 0.2–0.4 m/s, reaching peak values of 0.6 m/s very close to the coast (see figure 4).

![Figure 4](image)

**Figure 4.** Distribution of the exceedance probability for the near-bottom velocities in winter.

The second cross-section is located in the region of high, though not critical latitudes (less than 74–75 °, at which, according to the predictions of the linear theory, free semidiurnal internal waves cannot exist (see, for example, [20])). We analyzed how strongly taking into account the Earth's rotation affects the dynamic picture. As expected, an increase in the Coriolis force leads to the fact that fewer short internal waves are generated from a long baroclinic wave, and their amplitudes also decrease (the regime does not change, only quantitative characteristics). It is also worth noting that in the high latitude region, intensive internal waves are often observed, and at the stage of their transformation, shoaling and breaking in the coastal zone, the Coriolis force no longer plays an important role. The simulation results for the second cross-section without rotation, with rotation...
corresponding to 30 °, as well as real rotation at a latitude of about 60 ° are shown in figure 5. For example, at t = 45 h, the maximum amplitude of a short period internal wave on the solibor crest is 20 m in the case of no rotation, 3 m with a rotation corresponding to 30 °, and 1 m with a real one. The number of waves in a wave train during this time period is equal to 7, 4, 2, respectively.

**Figure 5.** x-t diagram of the displacement of the isopycnic surface [m], which is in an undisturbed state at a depth of 200 m (a) without rotation, (b) with rotation corresponding to 30 ° and (c) 60 °.

### 5. Conclusion

This work is the first stage in the creation of an atlas of baroclinic wave amplitudes and associated dynamic effects for the Far Eastern seas. On the example of the selected sections in the Sea of Okhotsk and the Bering Sea, the dynamics of internal waves was simulated. It was shown that in the studied region the classical scheme of the evolution of long barotropic tidal waves into baroclinic ones with the subsequent formation of wave bores is carried out. The observed regimes differ for the selected sections. Estimates of the short period internal wave and long baroclinic wave amplitudes, as well as the velocities induced by them were obtained. For the cross-section in the Sea of Okhotsk, the internal wave amplitudes reached 5–7 m, and horizontal velocities of the currents induced by them were about 0.3–0.4 m/s both on the bottom and on the surface (that is in good agreement with measurements); for the section in the Bering Sea, the wave amplitudes exceeded 20 m, and the velocities exceeded 0.6–0.8 m/s (which theoretically confirms the hypothesis about the influence of the internal waves on the bottom topography). The influence of seasonal changes in density stratification, which leads to a decrease in the amplitudes and velocities of internal waves, was analyzed. Taking Earth rotation into account also has a qualitative effect on the dynamic picture. We calculated and analyzed such parameters as the Froude number, wave energy (APE), exceedance probabilities for near-bottom and near-surface velocities. These criteria, as well as the values of the Shields number (to determine the probability of soil erosion), will be considered in the future to analyze only extreme wave phenomena.

**Acknowledgments**

This study was initiated in the framework of the state assignment in the field of scientific activity (topic No. 0728-2020-0007 “Wave climate of the stratified sea shelf: nonlinear dynamic processes and their impact on the coastal zone and hydraulic structures”) and the grant of the President of the Russian Federation (SP-1225.2019.5).

**References**

[1] Vlasenko V, Stashchuk N and Hutter K 2005 Baroclinic Tides: Theoretical Modeling and Observational Evidence (Cambridge: Cambridge University Press) 372 p

[2] Moroshkin K V 1966 Water masses of the Sea of Okhotsk (Nauka) 66 p

[3] Kruts A A and Luchin VA 2013 Vertical water structure in the Okhotsk Sea *Izv. TINRO* **175** pp 234–253

[4] Dudkov S P 2010 Mezhdgodovye izmeneniya prostranstvennogo sootnosheniya tipov vertikal’noj stratifikacij vod na severo-zapadnom shel’le Beringova morya letom 2005–2008 gg. *Izv. TINRO* **162** pp 306–323
[5] Zimin A V and Svergun E I 2018 Short-period internal waves in the shelf areas of the white, Barents and Okhotsk seas: Estimation of the extreme heights occurrence and dynamic effects in the bottom layer Fund. i Prikladn. Gidrofiz. 11 4 pp 66–72
[6] Mitnik L M and Dubina V A 2007 Proc. Envisat Symp. Spatial-temporal distribution and characteristics of internal waves in the Okhotsk and Japan Seas studied by ERS-1/2 SAR and Envisat ASAR pp 23–27
[7] Svergun E I and Zimin A V 2017 Forecast of the occurrence of intense internal waves in the White and Barents Seas according to expeditionary research Fund. i Prikladn. Gidrofiz. 10 2 pp 13–19
[8] Svergun E I and Zimin A V 2020 Characteristics of Short-Period Internal Waves in the Avacha Bay Based on the In Situ and Satellite Observations in August-September, 2018 Morskoy Gidrofizicheskii Zhurnal 36 3 pp 300–312
[9] Mitnik L and Dubina V 2019 The Sea of Okhotsk: Scientific Applications of Remote Sensing In book: Remote Sensing of the Asian Seas pp 159–175
[10] Rutenko A N and Sosnin V A 2014 Hydrodynamic processes on the Sakhalin shelf in the coastal Piltun area of the grey whale feeding and their correlation with atmospheric circulation Russ. Meteorol. Hydro. 39 pp 335–349
[11] Karl H A Cacchione D A and Carlson P R 1986 Internal-wave currents as a mechanism to account for large sand waves in Navarinsky Canyon head, Bering Sea Journal of Sedimentary Research 56 5 pp 706–714
[12] Lagerlof G S E and Muench R D 1987 Near-inertial current oscillations in the vicinity of the Bering Sea marginal ice zone Journal of Geophysical Research 92 C11 pp 11789
[13] Svergun E I and Kozlov I E 2021 Characteristics of short-period internal waves in the Bering sea in summer 2019 from Sentinel-1 data Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa 18 3 pp 269–276
[14] Tyugin D Yu, Kurkin A A, Pelinovsky E N and Kurkina O E 2012 Increase of productivity of software package for modeling of internal gravity waves IGW Research with the help of Intel® Parallel Studio XE 2013 Fund. i Prikladn. Gidrofiz. 5 3 pp 89–95
[15] Lamb K 1994 Numerical experiments of internal wave generation by strong tidal flow across a finite amplitude bank edge J. Geoph. Res. 99 C1 pp 843–864
[16] Rouvinskaya E A, Kurkina O E and Kurkin A A 2011 Modeling of internal weather in the ecosystem of the stratified sea shelf Ecological Systems and Devices 6 pp 8–16
[17] Egbert G D and Erofeeva S Y 2002 Efficient inverse modeling of barotropic ocean tides J. Atmos. Oceanic Technol. 19 2 pp 183–204
[18] Lamb K 2008 On the calculation of the available potential energy of an isolated perturbation in a density-stratified fluid Journal of Fluid Mechanics 597 pp 415–427
[19] Kurkina O, Rouvinskaya E, Talipova T, Kurkin A and Pelinovsky E 2016 Nonlinear disintegration of sine wave in the framework of the Gardner equation Physica D. 333 pp 222–234
[20] Morozov E G and Paka V T Internal waves in a high-latitude region Oceanology 2010 50 5 pp 668–674.