Internal Tidal Fronts in the Coastal Zone of the Japan Sea

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Abstract—Presented are the results of the studies of internal tidal fronts in the coastal zone of the Japan Sea carried out in October 2012 using the anchored buoy stations which were installed on the route situated along the normal to the isobaths of the coastal zone. The analysis demonstrated that there are fast-moving internal tidal fronts in the field of coastal water temperature. These fronts represent the lifting of the thermocline limited in space and reaching 1/3 of the depth of the coastal zone with the steep leading edge and with the nonstationary wave zone adjoining it. This zone is filled with high-frequency pulsations having the periods of 3–5 minutes and amplitudes up to 10 m. It is revealed that internal tidal fronts propagate with the velocity of the first mode of the internal wave and with the frequency of the tidal harmonic $M_2$. They are the highly nonlinear formations (the parameter of nonlinearity is $\sim 0.3$) filled with high-frequency (the frequency $\omega \sim 20$ cycle/hour) amplitude-modulated disturbances with the steepness of the wave front of $\sim 8$ cm/s; their length is $\sim 1$ km.

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1. INTRODUCTION

Flows in the shelf zone and especially in the coastal zone of adjacent seas are often characterized by the presence of high-amplitude internal gravity waves (IGWs). These waves propagate horizontally and wave energy is concentrated in the pycnocline zone. As a rule, they are generated on the boundary of the shelf zone as a result of the interaction between the barotropic tide and shelf edge. This interaction results in the formation of the internal tide that is transformed and split while propagating into the bundles of high-frequency high-amplitude IGWs which are called internal tidal fronts (ITFs). When such fronts propagate in the coastal zone, intensive flows are induced with the horizontal and vertical components of velocity. Tidal fronts initiate the transportation of suspended matter and the start of biological processes in the coastal zone. The flows induced by them exert significant influence on offshore platforms, and the trend of ITFs towards the collapse and formation of the microstructure facilitates the understanding of the mechanism of mixing processes in the coastal zone of the ocean [8].

The internal tidal front is a poorly investigated hydrological phenomenon observed in the coastal zone of the adjacent seas of Russia and associated with the typical density stratification of the coastal water in these seas and with the coming of internal gravity waves with tidal frequency to their coastal zone. The present paper analyzes the data of observations of the internal tide in the coastal zone of the Japan Sea. The observations were carried out on the wave track with the length of $\sim 10$ km located along the normal to the isobaths from the zone of its generation (the depth is $\sim 100$ m) to the zone of intensive collapsing (the depth is $\sim 40$ m). The analysis of the data of measurements in the offshore part of the track demonstrated the presence of tidal disturbances of the pycnocline of a quasiharmonic form propagating along the normal to the isobaths towards the shore with the velocity of the first mode of IGWs with the frequency of the tidal harmonic $M_2$. The evolution of these disturbances was monitored. It was revealed that increase in the inclination of their leading edge takes place in the process of propagation along the track and subsequently high-frequency wave bundles, namely, internal tidal fronts, are formed at the phase of the maximum lifting of pycnocline to the surface.
2. INSTRUMENTS AND METHODS OF RESEARCH

The data of instrumental measurements of temperature and its fluctuations were used for studying ITFs in the coastal zone of the Japan Sea. The measurements were carried out with NOVO thermographs and autonomous digital complexes which were installed at the anchored autonomous buoy stations (ABSs) placed along the wave track situated along the normal to the isobaths of the coastal zone. Besides, a hydrological cross-section was carried out in the middle of the experiment. The scheme of the location of ABSs and the hydrological cross-section is presented in Fig. 1.

The autonomous digital complex (ADC) consisted of the hermetic container with the registration system, power batteries, and the thermistor chain with temperature sensors located at equal distances throughout the depth. The DS18B20 1Wire-enabled digital thermometers giving the 12-bit value of temperature calibrated in degree Celsius were used as temperature sensors. The temperature was measured within the range from –55 to 125°C. The resolving capacity of the complex was equal to 0.06°C and the time of the conversion of one value of temperature was 750 ms [2].

The NOVO autonomous digital thermograph produced by Onset (USA) has the accuracy of 0.21°C in the range from 0 to 50°C and the resolution of 0.02°C at the temperature of 25°C as well as the memory of 64 kilobyte (~42000 of 12-bit measurements of temperature).

To carry out the in situ experiment, four anchored autonomous buoy stations were installed on October 14, 2012 in the area of the Gamov Peninsula in the coastal zone of the Japan Sea. One of these stations was equipped with NOVO thermographs (ABS-I) and the others, with autonomous digital complexes. Figure 1 presents the schemes of the location of stations in the research area with and without account of the bottom topography. Stations ABS-II–ABS-IV were equipped with 12 temperature sensors installed at the distance of 3 m from each other. ABS-I was equipped with six NOVO thermographs located at the distance of 9 m from each other (starting from the bottom). The registration of temperature at all stations was carried out with the discreteness of 1 minute. The duration of measurements amounted to a bit more than six days.

On October 16, 2012, the hydrological cross-section was carried out along the track using the CTD sounding at six stations. The sounding was carried out using the RBR XRX-620 sonde (Canada). The instrument was equipped with the Fast thermometer having the inertia of not more than 0.2 s. After the data processing (taking account of the dynamic error) total errors of measured characteristics were equal to: ±0.15 m for the depth of immersion of the instrument, ±0.005°C for temperature, and ±0.005 psu for salinity. The temperature and electric conductivity were measured from the surface to the bottom at each station.