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OCEANOLOGY

Characteristics of Shear Stratified Flows in the Conditions of the Sea of Japan Shelf Based on in-situ Measurements in 2022

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Abstract—The results of analyzing the in-situ data of shear stratified flow measurements on the shelf of the Sea of Japan are presented. Study of critical zones and layers is performed in terms of the dimensionless Froude and Richardson numbers. It is shown that during the propagation of high-intensity internal bores, sufficiently long (up to several hours) time intervals occur, which are characterized by a supercritical Froude regime, when active generation of short-period internal waves of large amplitude is predicted and takes place. The statistics of the Richardson numbers shows that with the lower bound on the probability in the layer of flow measurements during the observation period, shear instability can occur in 15% of cases and can be preserved in 44% of cases.

Keywords: internal waves, Froude number, Richardson number, resonant generation of waves, shear instability

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INTRODUCTION

Monitoring and forecasting of currents, especially in the shelf zone, play a very important role in planning human economic activities, engineering surveys, and predicting potential impacts on the coastal ecosystem. Estimating the parameters of shear stratified flows is necessary not only at the initial stages of design of various hydraulic structures (from oil and gas production platforms to wave energy converters), but also for the subsequent operation of marine infrastructure facilities, since these parameters are input data for models that allow the prediction of loads on structures, potential soil erosion, and the dispersion of pollutants and contaminants.

The problems related to the description of energy cascades, hydrodynamic instability, laminar-turbulent transitions, and the bottom turbulent boundary layer in natural shear stratified flows are fundamental problems in fluid mechanics and ocean hydrophysics, which is of great practical interest. Shear currents on the shelf are formed under the impact of physical environmental factors, such as atmospheric effects, topographical effects, local buoyancy forces, and tidal influxes. The temporal variability and spatial features of the velocity field distribution, as well as maintaining dynamic mechanisms, are important for the study of such currents. The first stage in qualitative understanding of the dynamics of the occurring processes is the use of simple well-known physical criteria of (in)stability, based on models and methods from the theory of linear and nonlinear oscillations and waves. These criteria are based on the dimensionless Froude and Richardson numbers. Here, we use them to perform a preliminary analysis of dynamic processes observed on the shelf of the Sea of Japan in the fall of 2022.

MEASUREMENT DATA

The research into shear stratified flows under the conditions of the Sea of Japan (Peter the Great Gulf) was carried out at the hydrophysical test site of Il'ichev Pacific Oceanological Institute, Far East Branch, Russian Academy of Sciences, schematized in Fig. 1. A detailed description of the field experiments conducted at the test site is provided in [1–3].

For the calculations, we use one-minute average data from the Infinity horizontal flow recorder at three depths and the thermistor string data with a 10-second resolution and CTD profiling data from October 8, 2022, 12:53 p.m. to October 12, 2022, 2:16 p.m., which were obtained by the Pacific Oceanological Institute,

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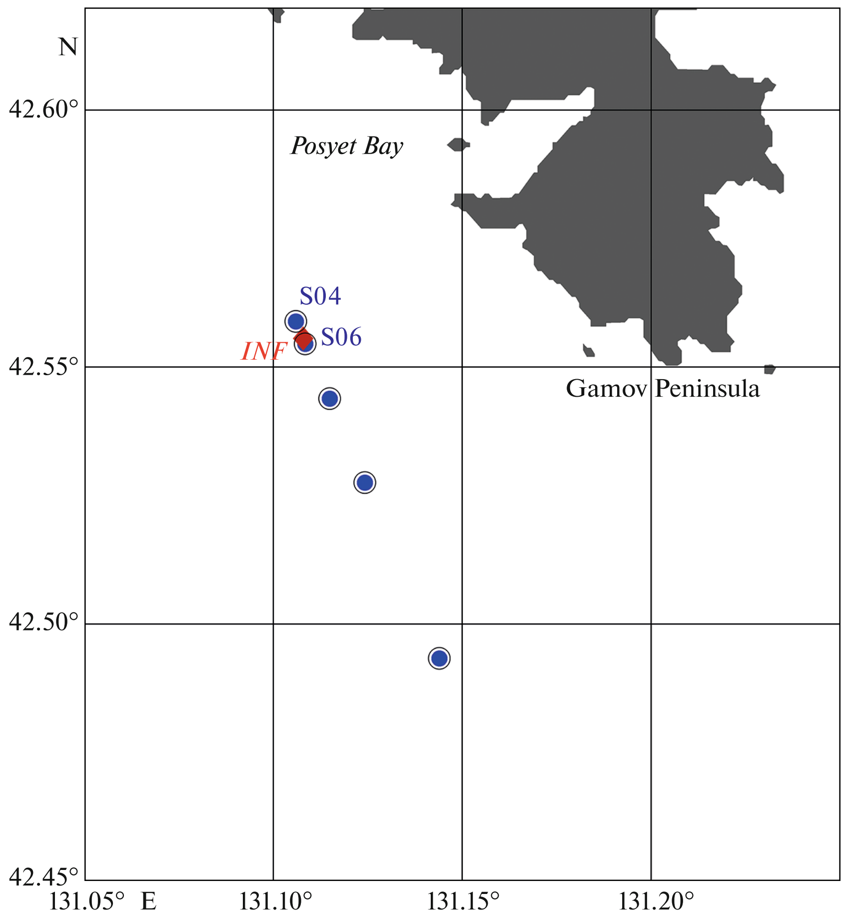

Fig. 1. Map of the measurement location indicating the stations at the hydrophysical test site of Il'ichev Pacific Oceanological Institute, Far East Branch, Russian Academy of Sciences.

Far East Branch, Russian Academy of Sciences. The flow was measured at the INF location (Fig. 1, 124 m from the S06 station), bottom depth of 41.5 m. Velocities (meridional and zonal components) were measured at three levels: 2, 8, and 14 m from the bottom (corresponding to the depths of 39.5 m, 33.5 m, and 27.5 m, respectively). The thermistor string at station S06 consisted of 35 sensors, the last sensor being 2 m from the bottom. The density was restored by the TEOS-10 equation of state for seawater, using the salinity profile measured by the CTD probe at station S04.

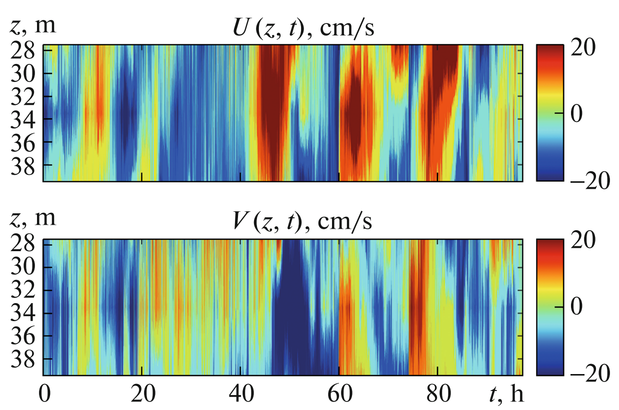

Fig. 2. Zonal and meridional velocity components measured at the INF station.

Figure 2 presents the results of flow velocity measurements in the bottom layer of the sea at the INF station (zonal, U, and meridional, V, components). It shows that the flow velocity is quite significant (in some instances, it exceeds 0.4 m/s), has a pronounced vertical structure, and is also characterized by strong temporal variability in both magnitude and direction. A fragment of the record from 40 to 90 h after the onset of recording is characterized by noticeable quasi-periodicity with dominant long-wavelength components having a near-inertial period for the latitude of the observation site (16–18 h). During the same period, three pronounced internal wave fronts with the same spectral properties were detected in the temperature and density field.

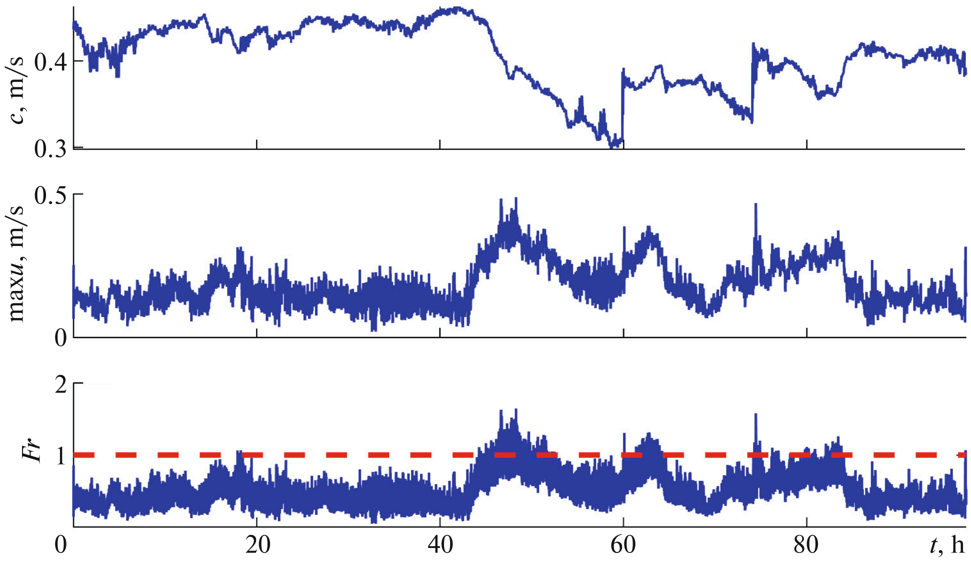

Fig. 3. Top to bottom: phase velocity of long linear internal waves of the first mode, maximum velocity of the stratified flow, and the Froude number for the observation data at stations S06 and INF. The red dashed line in the lower panel represents the critical value of the Froude number $Fr = 1$.

ANALYSIS OF MEASUREMENT RESULTS

We identified the critical zones and layers in the measured fields of flows using a classical approach based on the calculations of the Froude and Richardson numbers [4–6]. In the most common understanding, the Froude number Fr is the ratio of the velocities at which two processes, viz., advection and wave action, convey information about disturbances in the medium. Locally, the Froude number is also the ratio of the kinetic and potential energy of the flow and determines the flow as subcritical or supercritical. For stratified fluids, there are numerous formulations of this criterion, including with respect to the type of wave process (more detailed in work [7]). We calculate the Froude number for the stratified flow measured at the site in the presence of internal waves

$$Fr(t) = \frac{\max_z |\vec{u}(z,t)|}{c(t)},$$

where c is the phase velocity of the long linear first-mode internal waves. The algorithm for calculating this quantity is given, i.e., in [8, 9]. The criterion for linear stability in terms of Froude numbers here is the values of $Fr < 1$. The regime $Fr > 1$ corresponds to the active generation of intense internal waves [10, 11].

Figure 3 presents the Froude number and the quantities required for calculating this parameter according to the measurement data from the S06 and INF stations. It shows the occurrence of quite long time intervals characterized by a supercritical regime. These time intervals correspond to the passage of high-intensity internal bores during which short-period internal waves of large amplitude are generated.

For our problem, we calculate the gradient Richardson number (Ri) from the relationship

$$Ri(z,t) = \frac{N^2(z,t)}{Sh^2(z,t)},$$

where

$$N^2(z) = \frac{g}{\rho(z)}\frac{d\rho(z)}{dz}, \quad Sh^2 = \left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2.$$

Here N is the buoyancy frequency, z is the depth, g is the gravitational acceleration, ρ is the water density, Sh is the modulus of the vertical shear of the flow velocity, and V and U are the northward and eastward components of the flow velocity, respectively. The number Ri is often used in solving problems related to vertical turbulent mixing in a stratified marine environment [12–16]. There are two criteria: for linear instability of a shear flow, a necessary (but not sufficient) condition is $Ri < 0.25$ [17, 18], while for nonlinear stability, a necessary and sufficient condition is $Ri > 1$ [19]. According to the glossary [20], a hysteresis hypothesis is suggested: a laminar flow becomes turbulent at $Ri < 0.25$, but turbulent flow can exist up to $Ri = 1.0$, before it becomes laminar.

The calculations of auxiliary quantities to compute the Richardson number Ri are the following: the buoyancy frequency squared $N^2(z,t)$ based on the observation data from station S06 and the values of $\frac{\partial U}{\partial z}$ and $\frac{\partial V}{\partial z}$ based on the observation data from the INF station indicate that the numerator and the denominator of Ri have the same order of magnitude,

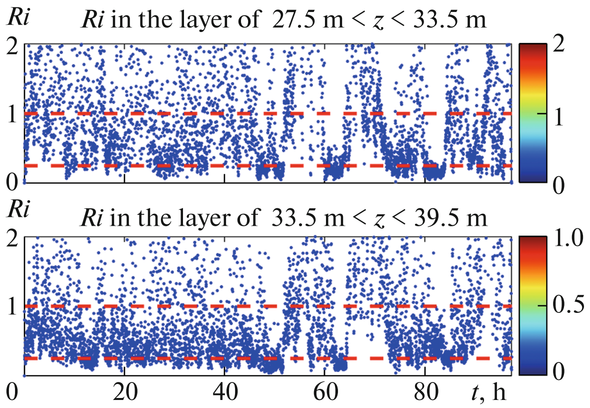

Fig. 4. The gradient Richardson number Ri based on the data of observations at stations S06 and INF. The red dashed line indicates the critical values of $Ri = 0.25$ and $Ri = 1$.

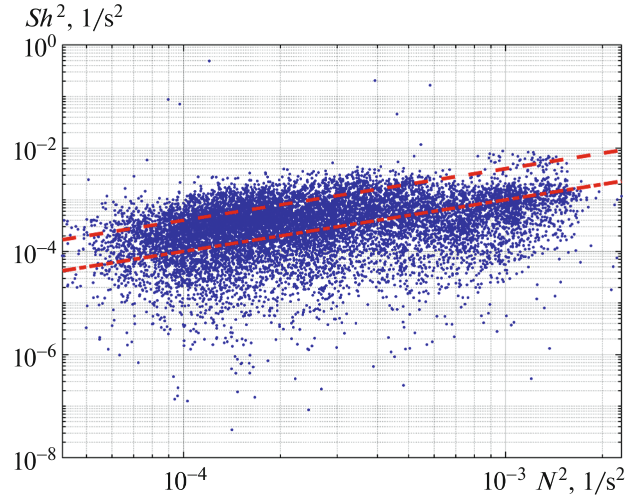

Fig. 5. Scatter plot of $N^2 - Sh^2$ made using the observation data obtained at stations S06 and INF. The red dashed and dot-and-dash lines show the critical values of $Ri = 0.25$ and $Ri = 1$, respectively.

10^{-4} 1/s; therefore, unstable regimes may take place in the measurement area. This is also confirmed by Fig. 4, which shows the parameter Ri versus time (along with the critical values of $Ri = 0.25$ and $Ri = 1$) for the upper ($27.5 \text{ m} < z < 33.5 \text{ m}$) and lower ($33.5 \text{ m} < z < 39.5 \text{ m}$) bottom layers where the flow was measured at the INF station. The probability of fulfillment of the necessary instability condition $P(Ri < 0.25)$ for the shear flow in the bottom layer is 16%, while in the upper layer it is 15%. Figure 5 shows a scatter plot of $N^2 - Sh^2$ made using the observation data from stations S06 and INF. The consideration of two critical values suggests that in the layer where the flows were measured during the observation period, turbulent kinetic energy can be generated in ~15% of cases and can be preserved in 44% of cases.

Note that the canonical instability criterion $Ri < 0.25$ is based on the assumption concerning a plane-parallel stratified shear flow. The laboratory experiments and numerical modeling showed that the criterion for the curved stratified shear flow when short-period internal waves propagate can be modified to $Ri < 0.1$ [6]. In our case, the likelihood that this condition is fulfilled $P(Ri < 0.1)$ is only 1.7% in the bottom layer and 1.2% in the layer above it. Such events are likely associated with waves of high steepness and amplitude.

The main problem with using Ri to assess the parameters of vertical turbulent mixing based on fine-scale measurement data is its strong dependence on the increment of depth (Δz), at which we calculate the corresponding derivatives:

$$\frac{\partial U}{\partial z} = \lim_{\Delta z \to 0} \frac{\Delta U}{\Delta z},$$

or, in other words, on the resolution of the devices. It was shown in [16] that, based on the data of observations in the Black Sea, the probability that critical values of the Richardson parameter $Ri < 0.25$ are reached decreases exponentially with growing Δz and reduces from 20% at $\Delta z = 0.5$ m to 3% at $\Delta z = 6$ m. This implies that the instability criterion is fulfilled more often at small scales under marine conditions. In our case, the flow measurements were taken with a vertical resolution of $\Delta z = 6$ m; therefore, we estimate only the lower bound on the probability of occurrence of potential instability zones.

CONCLUSIONS

This work presents an analysis of the simultaneous measurements of the density stratification and the near-bottom stratified currents in the Sea of Japan (Posyet Bay, Peter the Great Gulf) performed at the hydrophysical test site of Il'ichev Pacific Oceanological Institute, Far East Branch, Russian Academy of Sciences, in October 2022. The results of processing the in-situ experimental data showed that, during the observation period, currents lasting for about 25 h had quite extended (up to several hours) time intervals characterized by the supercritical regime, when a resonant interaction occurred between long internal waves and shear flow, which is consistent with the active generation of short-period internal waves of large-amplitude observed during these periods. Although the study criteria of (in)stability arose during the consideration of the linear equations and as a result of the asymptotic analysis of small-amplitude harmonic wave perturbations, as the zones and layers where these criteria were not fulfilled drew closer, higher vertical modes and wave harmonics were generated rapidly. In this case, a linear description is not applicable even for small-amplitude waves, and accurate description of the ongoing processes requires solving a closed system of hydrodynamic equations.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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