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CHARACTERISTICS OF SHEAR STRATIFIES FLOWS IN THE CONDITIONS OF THE SEA OF JAPAN SHELF BASED ON IN-SITU MEASUREMENTS IN 2022

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Abstract. The article presents some analysis results of in situ data of shear stratified flow measurements on the shelf of the Sea of Japan. The study of critical zones and layers is performed in terms of dimensionless Froude and Richardson parameters. It is shown that during the passage of high-intensity internal bores, sufficiently long (up to several hours) time intervals exist, which are characterized by a supercritical Froude regime, when active generation of short-period internal waves of large amplitude is predicted and occurs. The statistics of the Richardson number shows that with the lower probability estimate in the near-bottom layers during the observation period, the occurrence of shear instability is possible in 15% of cases, and its preservation is possible in 44% of cases.

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

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INTRODUCTION

Monitoring and forecasting of currents, especially in the shelf zone, plays a very important role in planning human economic activities, engineering surveys, and predicting potential impacts on the coastal ecosystem. Estimates of parameters of sheared stratified flows are necessary not only at the initial stages of designing various hydraulic engineering systems (from oil and gas production platforms to wave energy converters) but also for the further operation of marine infrastructure facilities, as these parameters are input data for models that allow predicting loads on structures, potential soil erosion, and the spread of impurities and pollutants.

Tasks related to the description of energy cascades, hydrodynamic instability, laminar-turbulent transitions, and the bottom turbulent boundary layer in natural sheared stratified flows constitute fundamental problems of fluid mechanics and ocean hydrophysics, which are of great applied interest. Shear flows on the shelf are formed under the influence of a complex of physical environmental factors, such as atmospheric impacts, topographic effects, local buoyancy forces, and tidal flows. The temporal variability and spatial features of the velocity field distribution, as well as the dynamic mechanisms supporting them, are of great importance in the study of such currents. The first stage of a qualitative understanding of the dynamics of ongoing processes is the use of simple well-known physical criteria of (in)stability, which are based on models and methods of the theory of linear and nonlinear oscillations and waves. These criteria are built on the dimensionless parameters of Froude and Richardson. Here we use them for a preliminary analysis of the dynamic processes observed in the autumn of 2022 on the shelf of the Sea of Japan.

MEASUREMENT DATA

Studies of sheared stratified flows applied to the conditions of the Sea of Japan (Peter the Great Bay) were carried out at the hydrophysical test site of the Pacific Oceanological Institute of the FEB RAS, the

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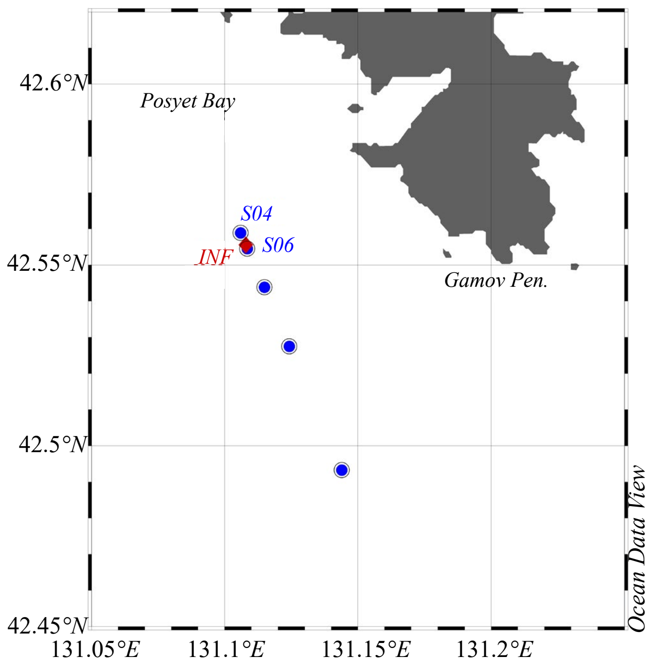

Fig. 1. Map of the measurement area indicating the stations of the hydrophysical testing site of POI.

scheme of which is presented in Fig. 1. A detailed description of the field experiments carried out at the test site is presented in papers [1-3].

For the calculations, 1-minute averaged data from the Infinity horizontal current recorder from three horizons and data from thermal chains with a frequency of 10 seconds and CTD sounding during the period from 12:53 on October 8 to 14:16 on October 12, 2022, obtained by POI FEB RAS, were used. The current was measured at point INF (see Fig. 1, 124 m from station S06), the bottom depth was 41.5 m. Velocities (meridional and zonal components) were measured at three levels: 2, 8, 14 m from the bottom (corresponding to depths of 39.5 m, 33.5 m, 27.5 m). The thermal chain at station S06 consisted of 35 sensors, with the last sensor located 2 m from the bottom. Density was reconstructed using the TEOS-10 seawater equation of state with a salinity profile measured by a CTD probe at station S04.

The results of current velocity measurements in the lower sea layer at station INF are shown in Fig. 2 (zonal, U, and meridional, V, components). It can be seen that the current velocity is quite

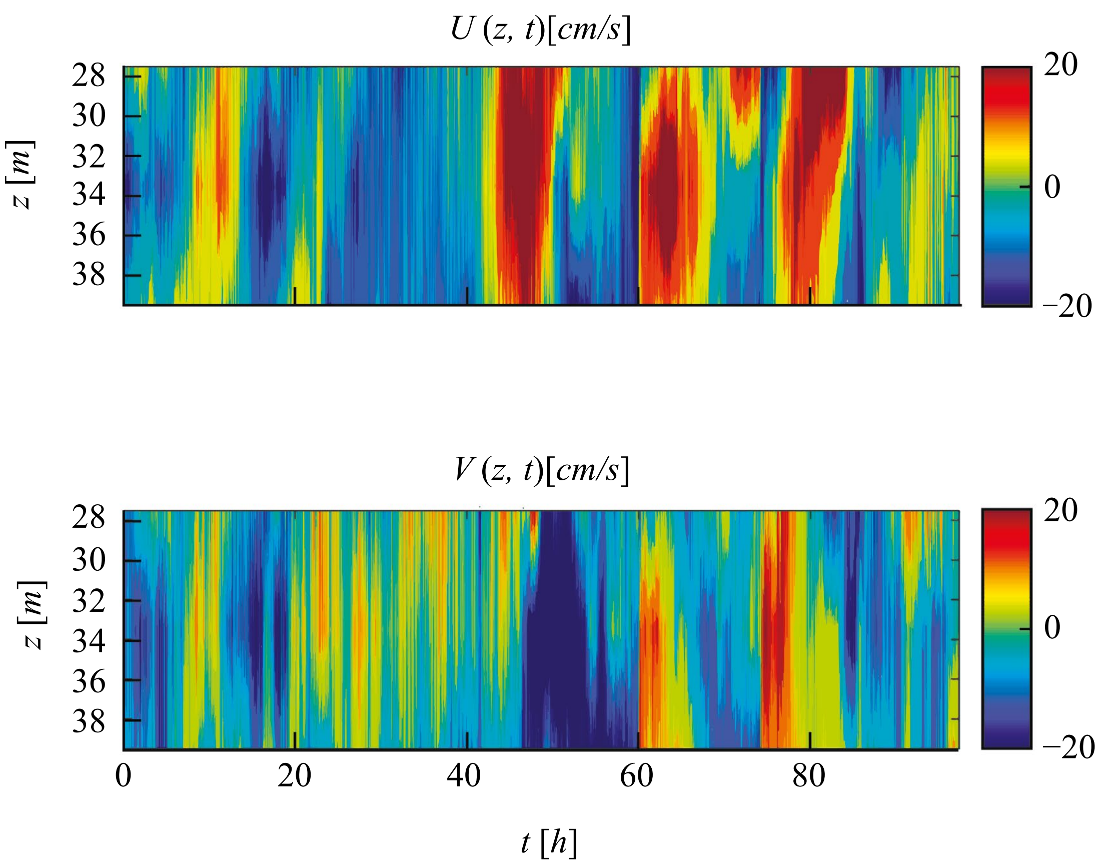

Fig. 2. Zonal and meridional velocity components measured at station INF.

significant (exceeding 0.4 m/s at certain times), has a pronounced vertical structure, and is also characterized by strong variability over time, both in magnitude and direction. The recording fragment during the period from 40 to 90 hours from the beginning of the recording is characterized by noticeable quasi-periodicity with predominance of long-wave components with a period close to the inertial period for the latitude of the observation site (16–18 hours). In the temperature and density field during the same period, three pronounced internal wave fronts with the same spectral properties were identified.

ANALYSIS OF MEASUREMENT RESULTS

Identification of critical zones and layers in the measured flow fields was performed using the classical approach based on Froude and Richardson number calculations [4–6]. In the most common understanding, the Froude number *Fr* represents the ratio of velocities with which two processes, namely, advective and wave, transfer information about disturbance in the medium. Locally, the Froude number also represents the ratio of kinetic and potential energy of the flow and defines the flow as subcritical or supercritical. For stratified fluids, there are many formulations of this criterion, including depending on the type of wave process (see, in more detail in [7]). The Froude number for a stratified flow measured at a point in the presence of internal waves can be calculated as:

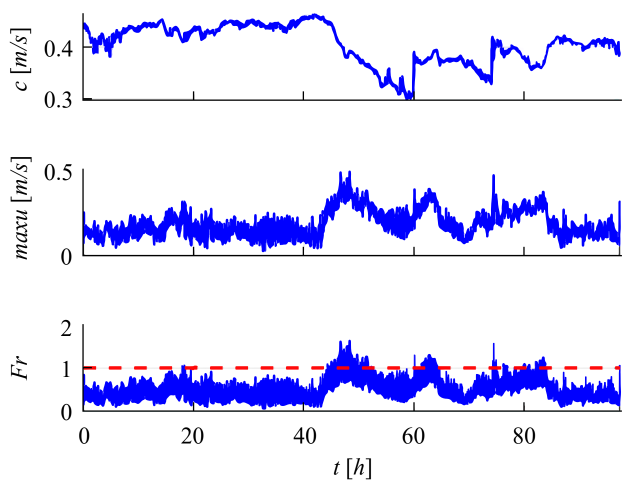

Fig. 3. From top to bottom: phase velocity of long linear internal waves of the first mode, maximum velocity of stratified flow, and Froude number for observational data at stations S06 and INF. On the lower panel, the critical value of the Froude number *Fr* = 1 is shown by the red dotted line.

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

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

The Froude number and the values necessary for calculating this parameter, according to measurements at stations S06 and INF, are shown in Fig. 3. From this figure, it can be seen that there are quite extended time intervals for which the supercritical regime is characteristic. These time intervals correspond exactly to the passage of high-intensity internal bores, on which short-period internal waves of large amplitude are generated.

The gradient Richardson number (*Ri*) for our problem is defined by the relation:

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

where

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

here *N* is the buoyancy frequency, *z* is the depth, *g* is the acceleration of gravity, ñ is the water density, *Sh* is the modulus of the vertical current velocity shear, *V* and *U* are the northern and eastern components of the current velocity, respectively. The parameter *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], and for nonlinear stability, a necessary and sufficient condition is $Ri > 1$ [19]. According to the glossary data [20], there is an assumption about hysteresis: a laminar flow becomes turbulent at $Ri < 0.25$, but a turbulent flow can exist until $Ri = 1.0$ before becoming laminar.

Calculations of auxiliary quantities for computing the gradient Richardson number *Ri* : the square of buoyancy frequency $N^2(z, t)$ based on observational data at station S06 and values $\frac{\partial U}{\partial z}$ and $\frac{\partial V}{\partial z}$ based on observational data at station INF show that the numerator and denominator of *Ri* have the same order of magnitude – 10^{-4} 1/s,

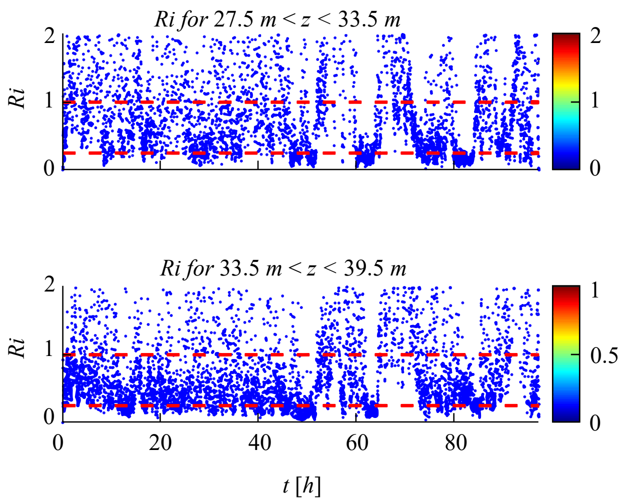

Fig. 4. Gradient Richardson number *Ri* based on observational data at stations S06 and INF. Critical values $Ri = 0.25$ and $Ri = 1$ are shown by red dotted lines.

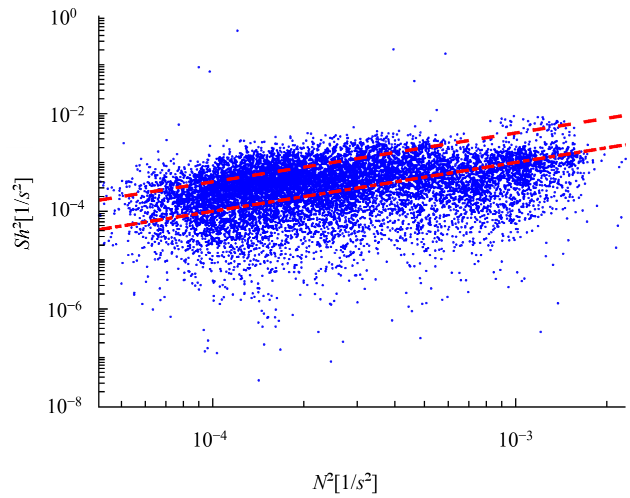

Fig. 5. Scatter diagram $N^2 - Sh^2$, calculated from observational data at stations S06 and INF. Critical values $Ri = 0.25$ and $Ri = 1$ are shown by red dotted and dash-dotted lines, respectively.

therefore unstable regimes can occur in the measurement area. This is also confirmed by Fig. 4, which shows the parameter *Ri* over time (along with critical values $Ri = 0.25$ and $Ri = 1$) for the upper (27.5 m < z < 33.5 m) and lower (33.5 m < z < 39.5 m) bottom layers, where current measurements were conducted at station INF. The probability of meeting the necessary instability condition $P\,(Ri < 0.25)$ for shear flow in the lower layer is 16%, and in the upper layer, 15%. Fig. 5 shows the scatter diagram $N^2 - Sh^2$, calculated from observational data at stations S06 and INF. Accounting for two critical values shows that in the current measurement layer, turbulent kinetic energy generation is possible in approximately 15% of cases, and its preservation in 44% of cases.

It should be noted that the canonical instability criterion $Ri < 0.25$ is based on the assumption of a plane-parallel stratified shear flow. Laboratory experiments and numerical modeling have shown that the criterion for curved stratified shear flow during the passage of short-period internal waves can be modified to $Ri < 0.1$ [6]. The probability of meeting this condition in our case $P(Ri < 0.1)$ is only 1.7% in the lower layer and 1.2% in the layer above it. Most likely, such events are associated with waves of high steepness and amplitude.

The main problem of using *Ri* to estimate vertical turbulent mixing parameters from small-scale measurement data is its strong dependence on the depth increment (z) at which the corresponding derivatives are calculated:

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

or, in other words, on the resolution capability of instruments. In [16], it is shown that according to observational data in the Black Sea, the probability of reaching critical values of the Richardson parameter $Ri < 0.25$ decreases exponentially with increasing z, decreasing from 20% at $z = 0.5$ m to 3% at $z = 6$ m. This indicates that in marine conditions, the fulfillment of the instability criterion is more common at small scales. In our case, current measurements were conducted with a vertical resolution of $z = 6$ m, therefore we obtain only a lower estimate of the probability of possible instability zones appearing.

CONCLUSION

In this paper, we analyzed data from simultaneous measurements of density stratification and bottom stratified currents in the Sea of Japan (Posyet Bay, Peter the Great Bay) at the hydrophysical testing site of POI FEB RAS in October 2022. The results of processing the field experimental data showed that during the observation period of about 25 hours, there are quite extended (up to several hours) time intervals characterized by a supercritical regime, when resonant interaction of long internal waves with shear flow occurs, which is consistent with the observed active generation of short-period internal waves of large amplitude during these time periods. Although the considered criteria for (in)stability emerged from the analysis of linear equations and asymptotic analysis of harmonic wave disturbances of small amplitude, when approaching zones and layers where these criteria are violated, rapid generation of higher vertical modes and wave harmonics occurs, linear description is not applicable here even for waves of small amplitude, and to correctly describe the ongoing processes, it is necessary to solve the complete system of hydrodynamic equations .

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REFERENCES

1. *Kosheleva A.V., Yaroshchuk I.O., Shvyrev A.N., Samchenko A.N., Pivovarov A.A., Korotchenko R.A.* Experimental studies of background internal waves in the coastal part of Peter the Great Bay // Physics of Geospheres. 2019. P. 110–113.
2. *Yaroshchuk I., Kosheleva A., Lazaryuk A., Dolgikh G., Pivovarov A., Samchenko A., Shvyrev A., Gulin O., Korotchenko R* . Estimation of Seawater Hydrophysical Characteristics from Thermistor Strings and CTD Data in the Sea of Japan Shelf Zone // Journal of Marine Science and Engineering. 2023. V. 11(6). P. 1204.1–24.
3. *Yaroshchuk I., Liapidevskii V., Kosheleva A., Dolgikh G., Pivovarov A., Samchenko A., Shvyrev A., Gulin O., Korotchenko R., Khrapchenkov F.* Observation and Modeling of Nonlinear Internal Waves on the Sea of Japan Shelf // Journal of Marine Science and Engineering. 2024. V. 12(8). P 1301.1–20.
4. *Stepanyants Yu.A., Fabrikant A.L.* Wave propagation in shear hydrodynamic flows // Success in Physical Science. 1989. V. 159. No. 9. P. 83–123.
5. *Polzin K.* Statistics of the Richardson number: Mixing models and finestructure // Journal of Physical Oceanography. 1996. V. 26(8). P. 1409–1425.
6. *Chang M.H.* Marginal instability within internal solitary waves // Geophysical Research Letters. 2021. V. 48(9). P. e2021GL092616.
7. *Mayer F.T., Fringer O.B.* An unambiguous definition of the Froude number for lee waves in the deep ocean // J. Fluid Mech. 2017. V. 831. P. R3.1–9.
8. *Holloway P., Pelinovsky E., Talipova T., Barnes B.* A nonlinear model of internal tide transformation on the Australian North West Shelf // J. Phys. Oceanogr. 1997. V. 27(6). P. 871–896.
9. *Kurkina O.E., Talipova T.G., Soomere T., Kurkin A.A., Rybin A.V.* The impact of seasonal changes in stratification on the dynamics of internal waves in the sea of Okhotsk // Estonian Journal of Earth Sciences. 2017. V. 66(4). P. 238–255.
10. *Vlasenko V., Stashchuk N., Hutter K* . Baroclinic tides: theoretical modeling and observational evidence. Cambridge University Press. 2005. 350 p.
11. *Kurkina O.E., Talipova T.G* . Huge internal waves in the vicinity of the Spitsbergen Island (Barents Sea) // Nat. Hazards Earth Syst. Sci. 2011. V. 11. P. 981–986.
12. *Munk W., Anderson E.* Notes on a theory of the thermocline // J. Mar. Res. 1948. V. 3. P. 267–295.
13. *Pacanowski R.C., Philander S.G.H.* Parameterization of vertical mixing in numerical models of tropical oceans // J. Phys. Ocean. 1981. V. 11. P. 1443–1451.
14. *Redekopp L.G.* Elements of instability theory for environmental flows //Environmental stratified flows. Boston, MA: Springer US. 2001. P. 223–281.
15. *Galperin B., Sukoriansky S., Anderson P.S.* On the critical Richardson number in stably stratified turbulence // Atmospheric Science Letters. 2007. V. 8. P. 65–69.
16. *Morozov A.N.* Statistics of Richardson numbers based on observational data from an oceanographic platform // Ecological Safety of Coastal and Shelf Zones of the Sea. 2018. No. 2. P. 39–46.
17. *Miles J.W.* On the stability of heterogeneous shear flows // J. Fluid Mech. 1961. V. 10 (4). P. 496–508.
18. *Baines P.G.* Topographic effects in stratified flows. Cambridge university press. 1998. 498 p.
19. *Abarbanel H.D.I., Holm D.D., Marsden J.E., Ratiu T.* Richardson number criterion for nonlinear stability of three-dimensional stratified flow // Physical Review Letters. 1984. V. 52. P. 2352–2355.
20. American Meteorological Society, 2023: critical Richardson number. Glossary of Meteorology, http://glossary.ametsoc.org/wiki/critical_Richarson_number .