ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2018, Vol. 82, No. 11, pp. 1435–1438. © Allerton Press, Inc., 2018.
Original Russian Text © I.N. Ivanova, V.S. Shlychkov, 2018, published in Izvestiya Rossiiskoi Akademii Nauk, Seriya Fizicheskaya, 2018, Vol. 82, No. 11, pp. 1573–1576.

Internal Waves on the Black Sea Shelf

I. N. Ivanova[a], * and V. S. Shlychkov[a]
[a]*Faculty of Physics, Moscow State University, Moscow, 119991 Russia*
**e-mail: ivair@yandex.ru*

Abstract—Internal waves on the Black Sea shelf are analyzed using in situ data. Inertial waves with different mechanisms of generation are identified. The phase velocity of short-period internal waves is estimated. Internal waves of the second barocline mode, whose mechanism of generation is probably determined by the decay of inertial waves, are observed. The existence of a train of second-mode internal waves is shown.

DOI: 10.3103/S1062873818110114

INTRODUCTION

Internal waves in stratified water reservoirs, lakes, and seas can seriously affect the structures of the velocity fields and parameters of water composition, and the dynamics of systems of stratified currents and upwellings. They affect the mean state of a system through mixing, along with the horizontal and vertical transport of momentum and energy. The source of their origin can be tides, atmospheric pressure oscillations, wind impact, underwater earthquakes, the flow of currents around bottom irregularities, anthropogenic effects, and so on [1]. The Black Sea is unique in that it provides an opportunity to study the main types of internal waves and the mechanisms of their generation without the participation of tidal potential. Of special interest is studying the second-mode internal waves with the unique ability to transport mass along interface boundaries in stratified fluids [2]. The aim of this work was to study the temporal and spatial characteristics of internal waves in the shelf zone of the Black Sea, and to examine their mechanism of generation.

EXPERIMENTAL

The analyzed results were provided by the Russian Academy of Sciences' Marine Hydrophysical Institute in the city of Sevastopol. The measurements were made on the Institute's Katsiveli stationary oceanographic platform from August 1 through 31, 2017. An iceTC60/40 thermistor chain 29 m long with 19 attached sensors was used to continuously measure water temperature T. From the surface to a depth of 11 m, the sensors were spaced at 1 m; below 11 m, the spacing was 2 m. We also recorded the vertical profiles of current velocity U, water temperature T, and electrical conductivity C on August 14–15 using an RCM-9 Doppler current profiler (Aanderaa Instruments). The direction and speed of the wind in the area were also considered.

Processing the data, we identified the position of the thermocline over the entire period of measurements. The spectra of thermocline oscillations and temperature were calculated for all levels. We used a fast Fourier transform to determine the periods of temperature oscillations at different levels.

INERTIAL WAVES

Inertial oscillations are the ones that are most intense. Their period $T = \frac{12\ \text{h}}{\sin\varphi}$ is determined by the Coriolis force, where φ is the width of an area; for the Black Sea, it ranges from 16.7 to 18.2 h. Inertial oscillations recorded during the first days of August were distinguished by the typical form of solitary deepening waves with sharp bottoms and flat rises. At the beginning of August, we recorded five such waves at depths lower than 16 m. The height of three central waves was more than 10 m, allowing us to classify them as intense internal waves. In [3], the emergence of such waves was attributed to meandering of the Black Sea Rim Current caused by an earlier negative surge. With our measurements, there was a similar situation: offshore western or southwestern winds dominated from July 28 to 31, and solitary internal waves were observed from August 2 to 4 after the onshore wind had settled.

The second type of inertial oscillations was recorded from August 21 to 24. The oscillations had an almost symmetrical form, reaching heights of 10–12 m—more than in [4]. Figure 1 shows the oscillations of the isotherms through all depths for the period of August 21–24. Since the direction of the wind varied during these oscillations, we may assume they were caused by drift current oscillation [3], which creates upsurges when the wind is directed onshore and negative surges when it is directed opposite.

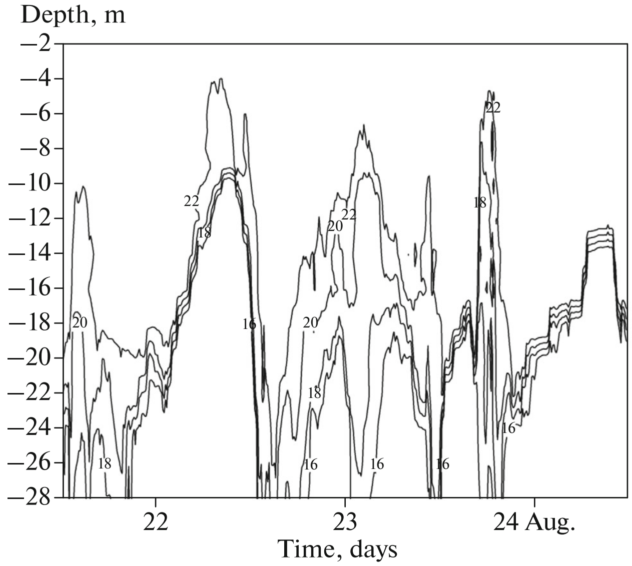

Fig. 1. Cross section of the temperature field over depth and time for August 21–24.

In addition to inertial waves with periods of around 17 h, we detected oscillations with periods of around 6 and 9 h between August 21 and 24. They can be classified as overtones of inertial waves, i.e., waves with periods shorter than an inertial one by a whole number of times [5]. We can see from Fig. 1 that isotherms 20 and 22°C go up (the oscillation occurs at 05:00 p.m), and isotherms 18 and 16°C go down, creating an oscillation with a period of around 9 h. Overtones of inertial waves in the Black Sea had not been observed earlier under in situ conditions.

SHORT-PERIOD WAVES

Short-period waves usually include ones with periods of less than 1 h. One mechanism behind the generation of short-period internal waves is wave-induced fronts in periods of wind stress removal and the reconstructuring of stratification disturbed by an upsurge or a negative surge. This is a quite common mechanism in the coastal areas of seas.

To determine the most frequent short-period waves, we calculated the range of temperature oscillations over all times of measurement, allowing us to discover waves at depths below 25 m that oscillated in the range of 5 to 14 min. Figure 2a shows a wide peak that covers the range of 0.07 to 0.2 cycle/min, conforming to periods of 5 to 14 min.

The electrical conductivity of water was measured in parallel on August 14–15 with an RCM-9 probe. Knowing the water density distribution, we estimated phase velocity c_w of internal waves and distribution of Brunt–Vaisala frequency N, which characterizes the stability of stratification. Phase velocity is usually determined in an approximation of a thin pycnocline

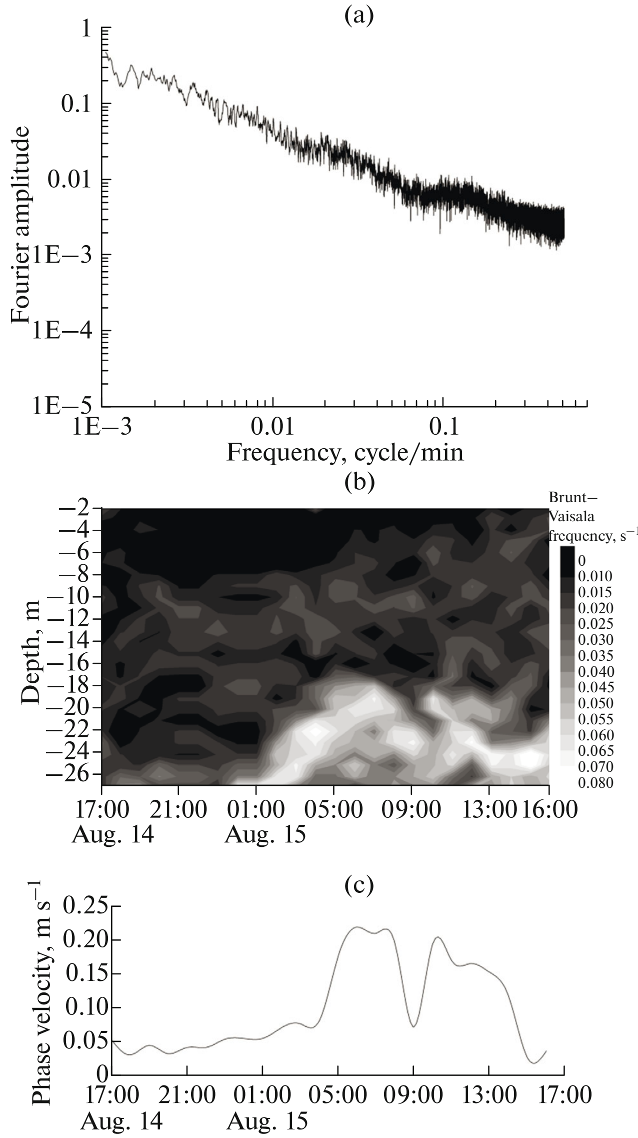

Fig. 2. (a) Fourier spectrum of temperature oscillations; time distributions of (b) Brunt–Vaisala frequency N and (c) phase velocity c_w.

that can considered an interface boundary; it is calculated using expression [6] in a long-wave approximation ($kh \ll 1$ and $kH \ll 1$)

$$c_w = \pm\sqrt{\frac{g\Delta\rho}{\rho}\frac{hH}{h+H}}, \quad (1)$$

where h is the thickness of the upper layer, H is the thickness of the bottom layer, and $\Delta\rho$ is the difference between the densities of layers above and below the pycnocline. The Brunt–Vaisala frequency is calculated as

$$N = \sqrt{-\frac{g}{\rho}\frac{d\rho}{dz}}, \quad (2)$$

where g is gravitational acceleration, ρ is the density of the water, and z is the depth.

The short-period waves of August 15 were observed in the interval from 03:20 to 06:40 a.m. at a depth of 20 m. Figures 2b, c show the distribution of the frequency of buoyancy and the temporal behavior of the phase velocity. The Brunt–Vaisala frequency was highest in the area of wave existence: 0.065–0.07 s^{-1}. The phase velocity of short-period waves varied within 0.1–0.2 m s^{-1}; the periods were ~5 min, and the waves were ~70 m long.

SECOND-MODE INTERNAL WAVES

Second barocline mode waves are solitary disturbances that are symmetric with respect to interface boundaries. They are divided into two types: compression (concave) and tension (convex) [6, 7]. They are interesting because they transport mass at fairly high amplitudes (they are also referred to as waves with captured cores) [8, 9]. Along with the first-mode internal waves, second-mode waves of the tension type were also recorded during our measurements. They can be identified on our temporal temperature record from the characteristic discrepancy between isotherms that stretch from a thermocline in different directions. Figure 3a presents the temperature distribution from August 1 to 3. It shows that the wave motion affected almost an entire water layer 22 m thick: the temperature rose at all levels below 14 m (the deepening of the isotherms) and it fell at the levels between 14 and 6 m. This wave was recorded during the passage of an upsurge front.

Other cases of the second-mode internal waves (a total of four) were recorded between August 22 and 27. Figure 3b shows that as in the first case, a water layer around 20 m thick participated in the motion. A specific feature of the first two waves was that their upper segments formed an inertial wave with a period of ~17 h, and the bottom segments split this wave into two. Inertial oscillations therefore existed at depths of more than 20 m; below 20 m, we recorded an overtone of these oscillations with a period of ~8 h. The third wave differed from previous ones in that the overtone appeared at a depth above 20 m; below 20 m, the structure of a 17-h wave was preserved.

The decay of an inertial wave during interaction with the bottom in shallow waters could thus have been the mechanism of second-mode internal wave generation between August 22 and 27. A unique feature of this process was the generation of overtones, but we could find no description of such interaction in the literature.

The fourth and final second-mode wave was a wave train (Fig. 3c). The head wave had an amplitude of ~20 m; the next, an amplitude of ~10 m. Both were followed by two small waves with amplitudes of ~2–4 m, the last of which was probably a second-mode wave.

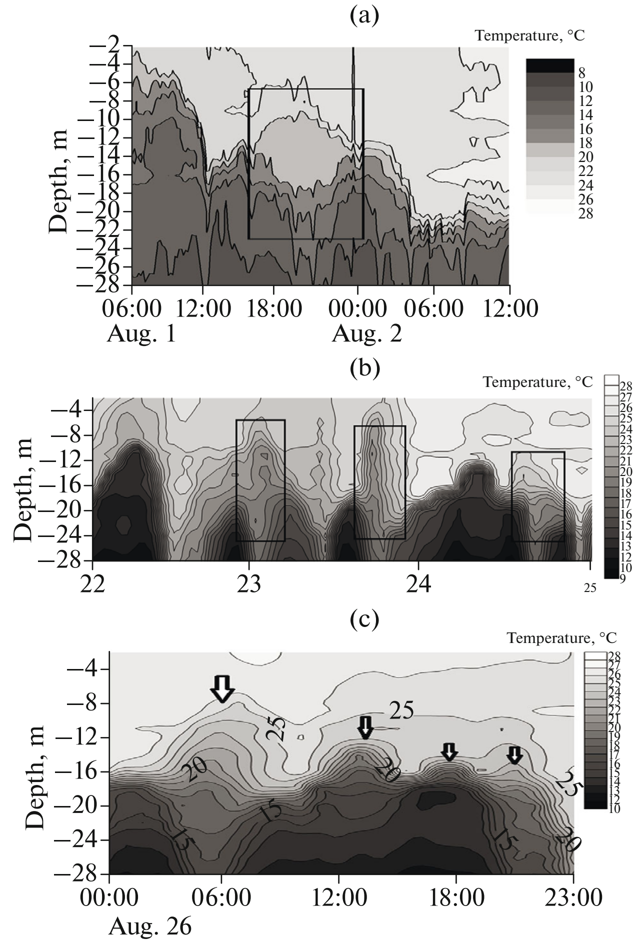

Fig. 3. (a) Second-mode internal wave; (b) generation of second-mode internal waves through the decay of inertial oscillations; (c) train of second-mode internal waves.

CONCLUSIONS

Our study allowed us to identify certain characteristic features of internal waves on the Black Sea shelf around the Marine Hydrophysical Institute's stationary oceanographic platform. Special attention was given to two segments of the spectrum: inertial and short-wave. Periodic oscillations with periods of ~17 h, the overtones of these oscillations, and solitary internal waves approaching the platform with intervals of ~17 h were recorded in the inertial segment. Short-period (~10 min) oscillations were also detected during the action of wind-induced fronts. After comparing our results and those of earlier years, we proposed mechanisms of the generation of inertial and short-period internal waves.

In addition to first-mode internal waves, we observed second-mode waves, all of which were of the tension type. Their emergence was due first to an upsurge front (one wave was observed), and second to inertial oscillations (four waves over six days). The generation of second-mode internal waves by inertial oscillations lasting 17 h produced overtones with periods of ~8 h. Along with second-mode generation, the authors of [10] considered the decay of first-mode waves as they propagate in shallow waters, but said nothing about the decay of a principle wave into overtones.

Yet another recorded second-mode wave was a train of four waves with sequentially falling amplitudes. The first two waves were second-mode. We could find no references to in situ observations of trains of second-mode internal waves in the literature.

We list our main results below:

(1) Internal inertial waves with different mechanisms of generation were observed.

(2) Short-period internal waves with periods of 5–10 min were recorded, the mechanism of their generation by wave-induced fronts was confirmed, and wavelength λ was estimated at ~ 70 m.

(3) Second-mode internal waves probably generated by the decay of inertial waves were identified, and the generation of the principal wave overtones was accompanied by the occurrence of second-mode waves.

(4) A train of second-mode internal waves of the tension type was observed.

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Translated by L. Mukhortova