INTERNAL WAVES ON A SHELF

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The paper considers the contemporary review of internal waves on a shelf based on thirty year's experience of studying internal waves in Russian Seas. The frequency spectra of internal waves are presented and analyzed in shallow-water seas, with those waves being generated by different sources. A strong variability in the spectra differs from the Gurret-Munk one. The main processes which are enumerated lead to the generation of intense internal waves on a shelf. The characteristic features of the observed waves are described, including those of the second mode. Wide possibilities of the acoustic Doppler current profiler (ADCP) are demonstrated for studying internal waves in a sea.

INTRODUCTION

During the last decade, internal waves have attracted high-levels of attention because they strongly influence sound propagation in shelf zones. Internal waves on a shelf or shallow-water sea (those terms being nearly identical) are more complicated for modeling than those in the deep ocean. This fact is explained by a high variety of water dynamics in shelf zones. Here, we present general descriptions of internal waves in shelf sea zones, based on our thirty-year-long study in Russian seas.

1. SPECTRA OF INTERNAL WAVES

The spectrum proposed by Gurret and Munk (G-M) [1] describes the background field of deep ocean internal waves with some accuracy. However, this spectrum is hardly applicable to internal waves of shallow-water seas. Nowadays, attemps are undertaken at finding an analoge of the G-M spectrum for a shelf zone. To that end, the main features of shallow-water internal waves are considered, including the data of our many-years-long measurements.

Fig. 1 presents an example of a typical frequency spectrum for internal waves on a shelf. That spectrum is obtained from the data of long-term measurements in the Sea of Japan by using line temperature sensors (it is possible to read about line temperature sensors in [2-4]). The spectrum has two quite noticeable peaks at frequencies of the semidiurnal tide (a period of 12.4 hrs) and 3.8 cycle/hour in the domain of short-period internal waves. At the shelf of the sea, trains of intense short-period waves moving towards the coast are exhibited. They can be observed every 12 hours. When they are passing, the background spectral levels and the peaks at the high-frequency domain essentially increase, and the level of the G-M spectrum (dashed curves in Fig. 1) is exceeded.

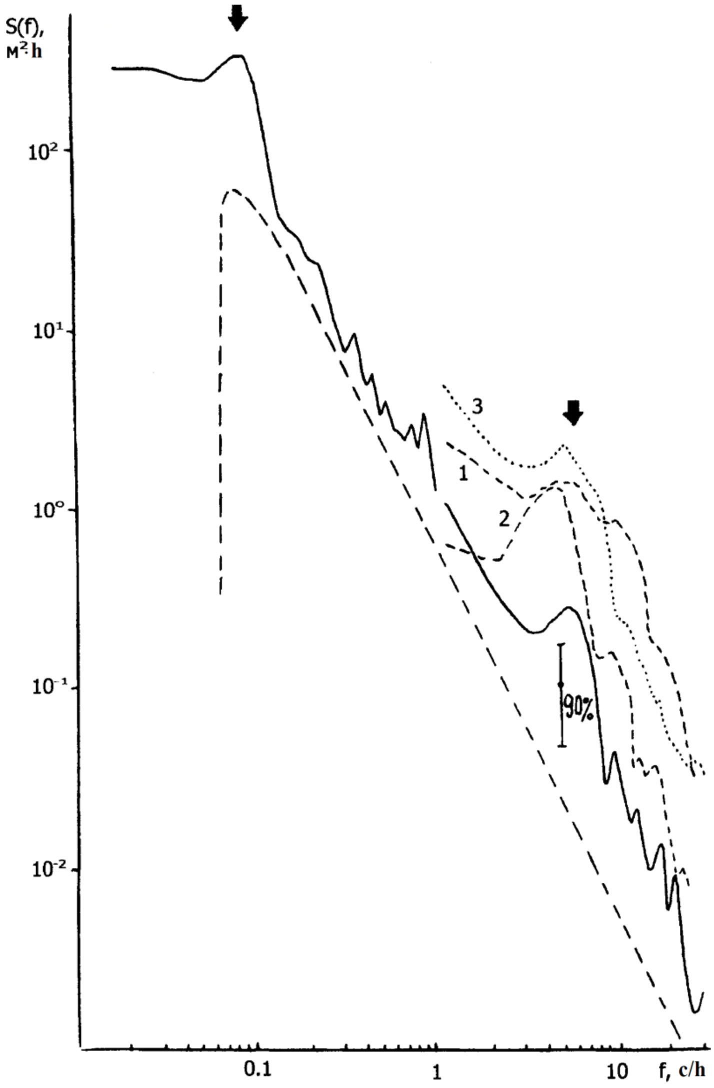

Fig. 1. Frequency spectrum of internal waves in a shallow water of tidal sea. The solid line shows the average spectrum, the dashed lined presents the G-M spetrum. The spectra of the trains of intense waves are denoted as 1 – 3.

After the passing of the train of waves, the high-frequency part of the spectrum decreases; this phenomenon can be explained by the relatively weak oscillations of the thermocline between the approaching trains. When the thermocline transforms from modes of the background to the trains, the short-period spectral level of the peak becomes 1.5 – 2, ordering higher in the spectral density. Nearly the same increase is observed in the peaks of the intense trains in comparison to that of the model spectrum. The decrease of the average background part of the spectrum can be rather well approximated by model one (the decrease proportional to the squared frequency) but exceeds it by a factor of 2 - 3 in its level.

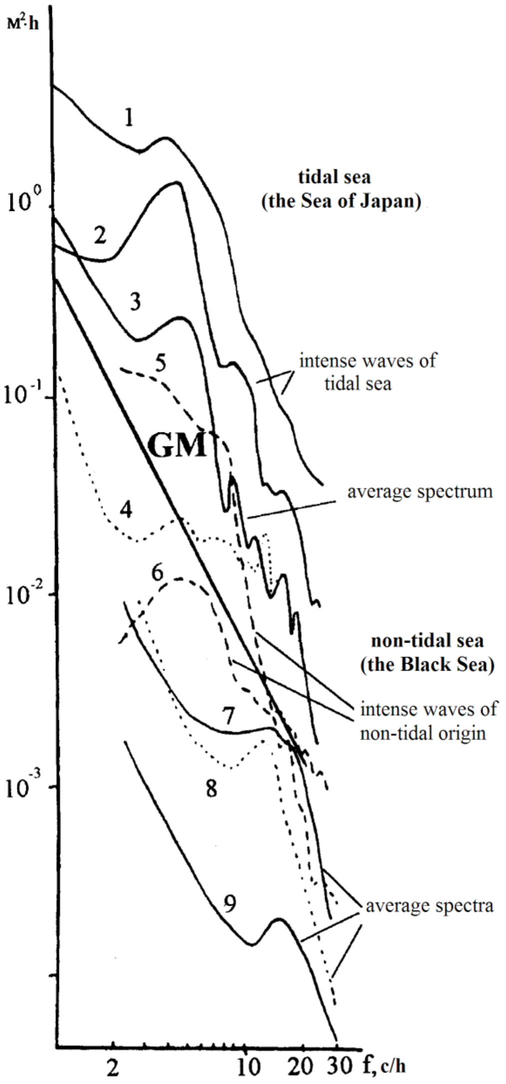

Fig. 2. Spectra of the short-period internal waves measured in the tidal (1 - 4) and nontidal (5 - 9) seas. Typical modes of the thermocline oscilations are presented for a shelf zone.

Now let us consider the range of short-period internal waves in more detail. Fig. 2 presents an enseble of the spectra of internal waves in that range. Those spectra show the variaty of typical modes for modes of oscillations of the thermocline at a shelf. The grouping of the spectra for the tidal Sea of Japan and nontidal Black Sea [5-6] evidently demonstrate the difference in their levels. That difference emphasizes the role of tides as intense sources of short-period internal waves on a shelf. Both the average spectra and those of the most intense internal waves of the tidal sea noticeably (up to two orders of magnitude) exceed their analogs in a nontidal sea. That feature can be put down to the fact that the tidal mechanism is the main source of generating internal waves on a shelf. To conclude this chapter, let us consider the wide range of the scatter of spectral intensities of internal waves on a shelf. They, for a tidal sea, are in mean higher than the G-M spectrum, while lower for the shelf environments. Numerous pieces of evidence obtained in detailed mesurements of internal waves [7-8] led us to conclude that the peak of short-period waves in their spectrum for shallow-water seas are mainly formed by nonlinear waves.

2. GENERATION OF INTERNAL WAVES ON A SHELF

There are many sources of generating intense internal waves on a shelf. Among them, the barocline tide is the main one. The barocline current collides with the continental slope and generates tidal internal waves propagating towards the coast. In propagating over the shelf, a nonlinear transformation of internal tides occurs, thus leading to a generation of intense soliton-like waves [9, 10]. Fig. 3 shows a record that exhibits the power of nonlinear internal tidal waves propagating on the North-West Shelf of Australia [11].

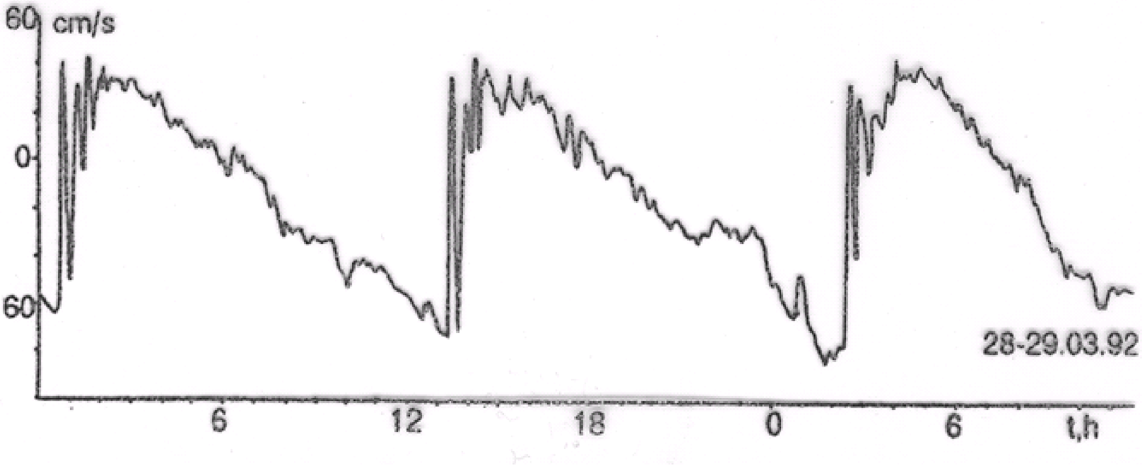

Fig. 3. Internal tidal waves on the NW Shelf of Australia propagating to the shore with 12-hour periodicity experience strong nonlinear transformation in shallow water and transform into huge internal bores (a record of the horizontal velocity of the current near the bottom is shown). Soliton-like waves are generated on the front slopes of the internal tides.

Another frequent source of generating soliton-like waves are long internal waves whose periods are close to the inertial ones [12], and the out-coming to the shelf of internal seiches [13]. Both of them occur after an intense impact on the sea of meteorological factors (passing cyclones, etc.). Fig. 4 shows an example of the intense internal waves of the inertial period (17 hours) on the coastal zone of the Black Sea, with the generation of soliton-like waves at the front slope of the inertial internal wave. In fact, internal waves are often generated by local hydrological fronts moving over a shelf. Among the revealed and observed processes of a similar type, the waves generated of set-down and up-down processes occur [12]. The analogous effect comes from the moving of the freshened surface intrusions of near-coast waters [14, 15]. Our earlier studies show new possible mechanisms of generating intense internal waves on a shelf. Those mechanisms are attributed to a collision of currents and to passing the near-cost anticyclonic eddy at the periphery of the coastal shelf [16].

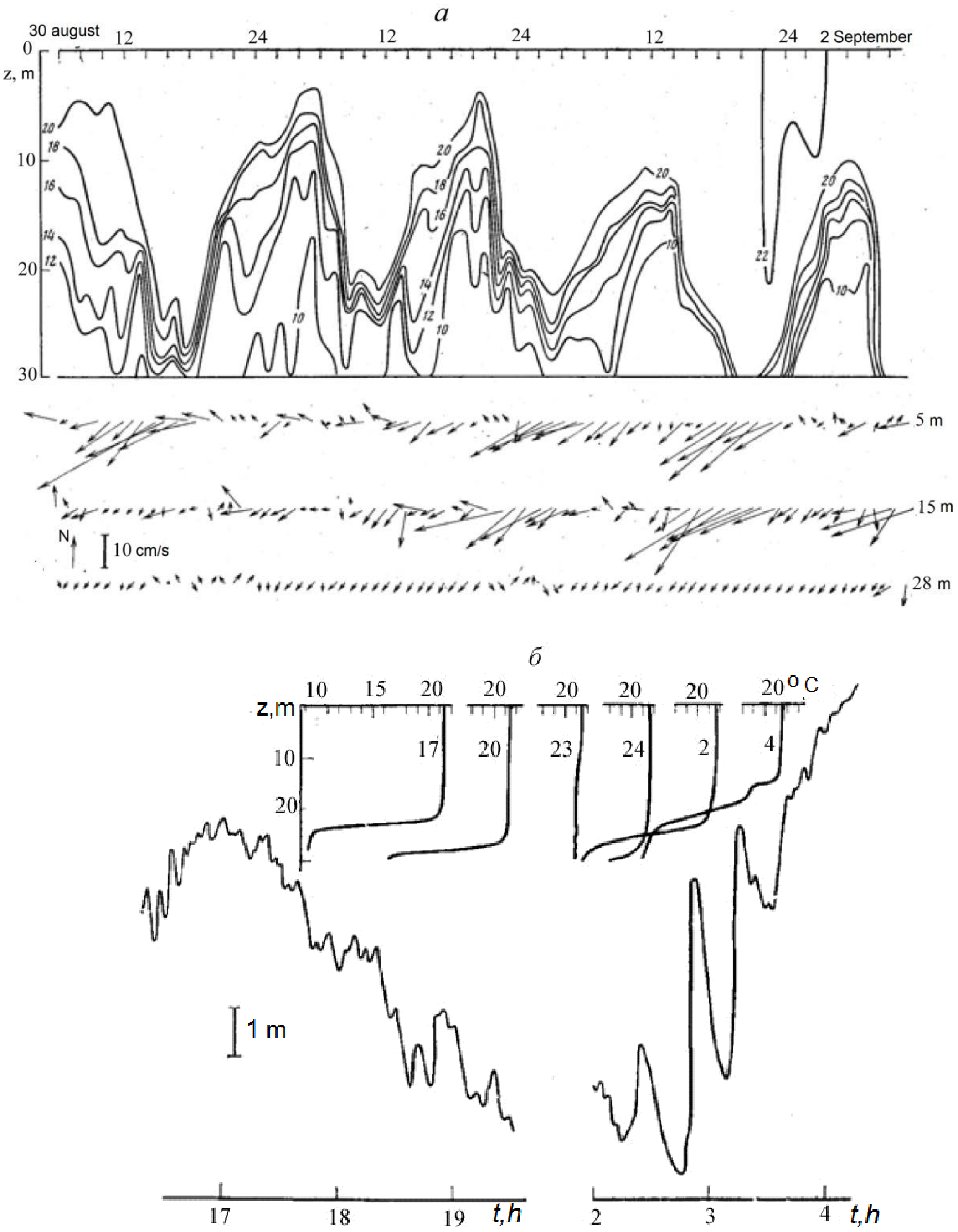

Fig. 4. Generation of internal solitons by near-inertial internal waves. Observation in coastal zone of the Black Sea [12].

3. FEATURES OF INTERNAL WAVES ON A SHELF

A specificity of internal waves on a shelf is consistent with a prevalence of nonlinear waves. The trains of the generated internal waves propagate in a narrow waveguide that is often close to the bottom or to the surface of the sea. Such a phenomenon leads to a rapid accumulation of nonlinear affects in the waves. The waves take a characteristic shape of solitary depressions or elevations (the vertical asymmetry of the waves, see Fig. 5). The power nonlinearities that frequently occur at a coastal zone increase the steepness of the front or the back side of a wave (the horizontal asymmetry) [7, 17], this phenomenon frequently leading to the breaking of the waves.

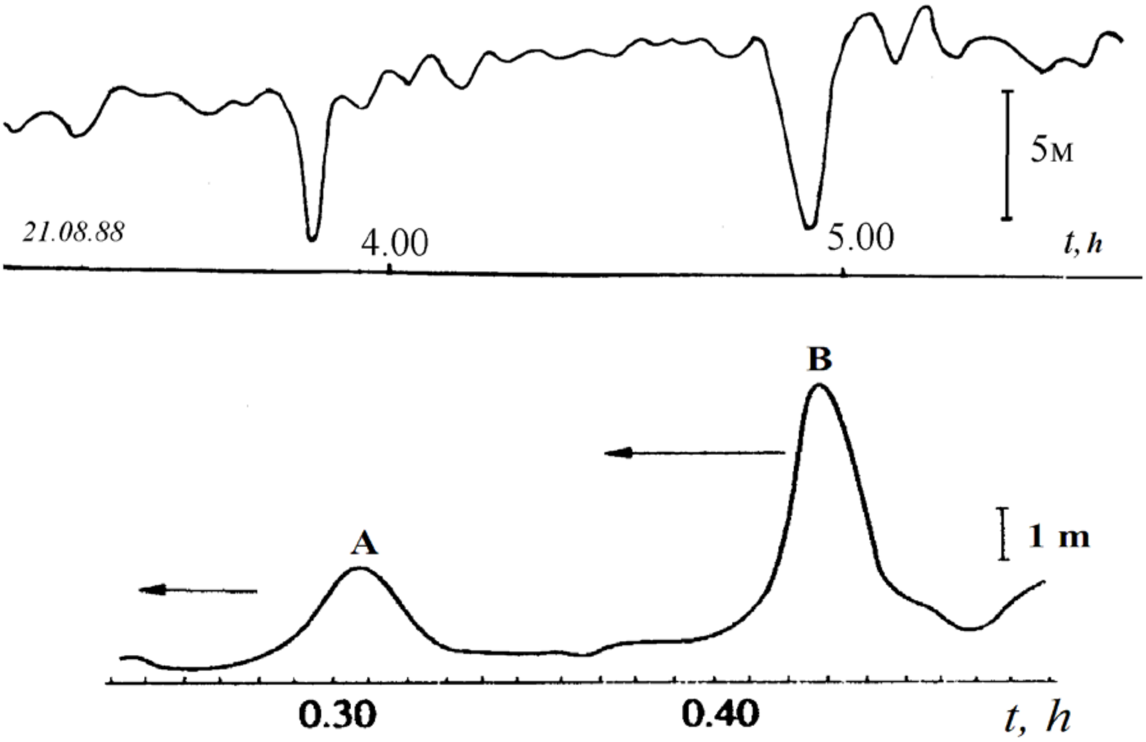

Fig. 5. Characteristic examples of nonlinear internal waves moving on the subsurface thermocline (the upper figure, the shelf of Kamchatka, the Pacific Ocean) and near the bottom thermocline (in the lower figure, the shelf of the Caspian Sea). In the both cases, the sea depth is about 40m, and the waves of 6-8m in height propagate towards the coastline, but with different polarity.

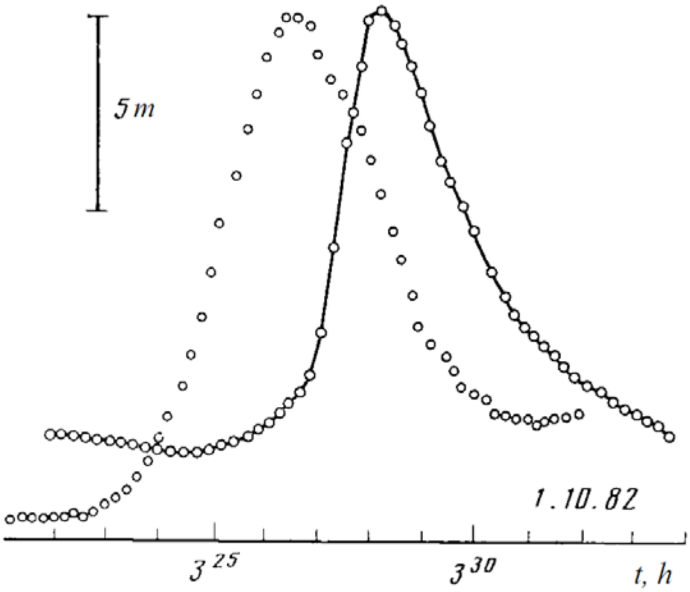

Fig. 6. Horizonal assymetry of internal waves.

We have grounds to assume that the effect of a “change of internal wave polarity” on a shelf are quite common. Such a change occurs when the waves propagate from sea areas where the thermocline is closer to the sea surface than those where the thermocline is close to the bottom [7, 19]. The intense waves propagating to the coast, which have a shape of depression, pass a turning point in the coastal zone. The effect of changing the polarity was first observed in 1982 in Russian waters off the shelf of the Sea of Japan [6, 9], (Fig. 7). After that, the effect was found in measurements in the Mediterranean Sea [18]. Recently, the effect

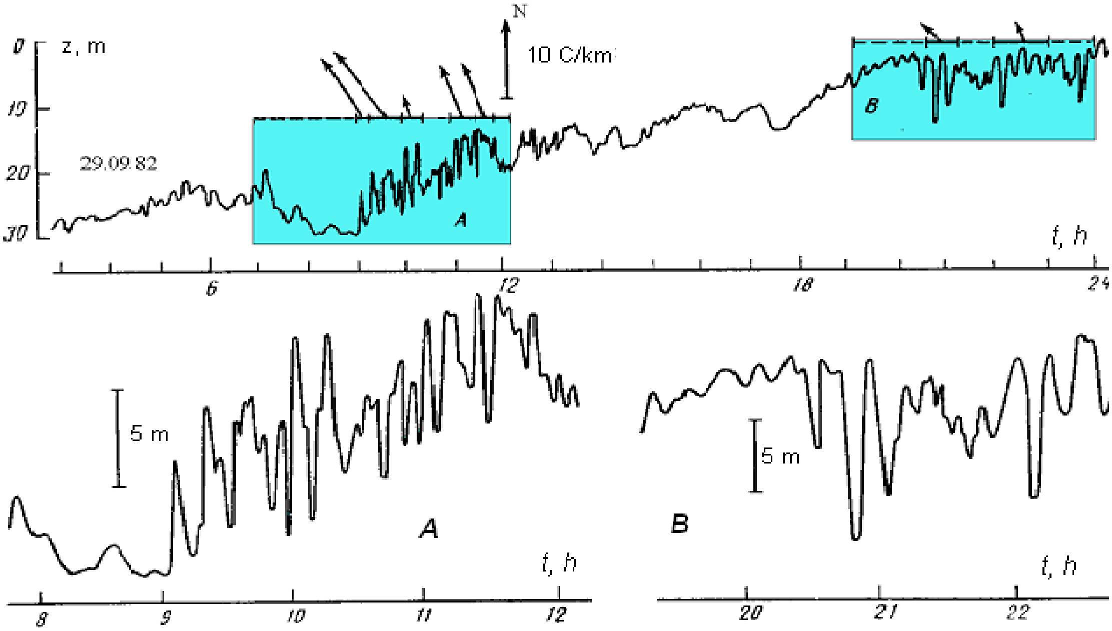

Fig. 7. Example of the observed changes in polarity of amplitudes in the internal waves in the coastal zone of the Sea of Japan, September of 1982. Measurements made by line temperature sensors.

of the “change of internal wave polarity” was observed in different regions of the World’s Ocean, and it was studied in detail in many in-sea experiments by different researchers (for example, in the South China Sea [20]). Comparison of the data of detailed measurements of internal waves with the use of spatially-distributed arrays of temperature line sensors, with models of solitons, in many cases confirms the soliton-like behavior of the waves existing on shelves of seas [7, 8].

4. INTERNAL WAVES OF THE SECOND MODE ON A SHELF

When we speak of the mode content of internal waves at a shelf, we often mean waves attributed to the wave of the first mode. The majority of observations of internal waves on a shelf show the wave of the first mode. However, recent evidence shows that often internal waves of the second mode are observed too. It is especially characteristic in the South-China Sea region. We also recently observed internal waves of the second mode in our measurements in the Black Sea [21].

In the measurements in the coastal area of the Black Sea, from the platform of the Marine Hydrophysical Institute of National Academy of Sciences of Ukraine, in the July of 2011, long-period oscillations of the thermocline were observed throughout the observations, with a period of 17 hrs. Such a phenomenon is evidence that quasi-inertial internal waves existed in the region. However, the most interesting features of the measured data were passing from the synchronous vertical displacements of whole water columns to the regime of the second mode. During the initial 7 days of measurements, the first mode was observed and all the layers of water bulk synhronious vertical displacemets occured. Then the behavior of the oscillations sharply changed: the upper and lower water layers began moving in an anti-phase; such a phenomenon showing the occurrence of the second mode of the internal inertial waves. The signs of oscillations of the first and second modes were evidently seen both in the data tracking the sound speed, and in those of the thermistor chain.

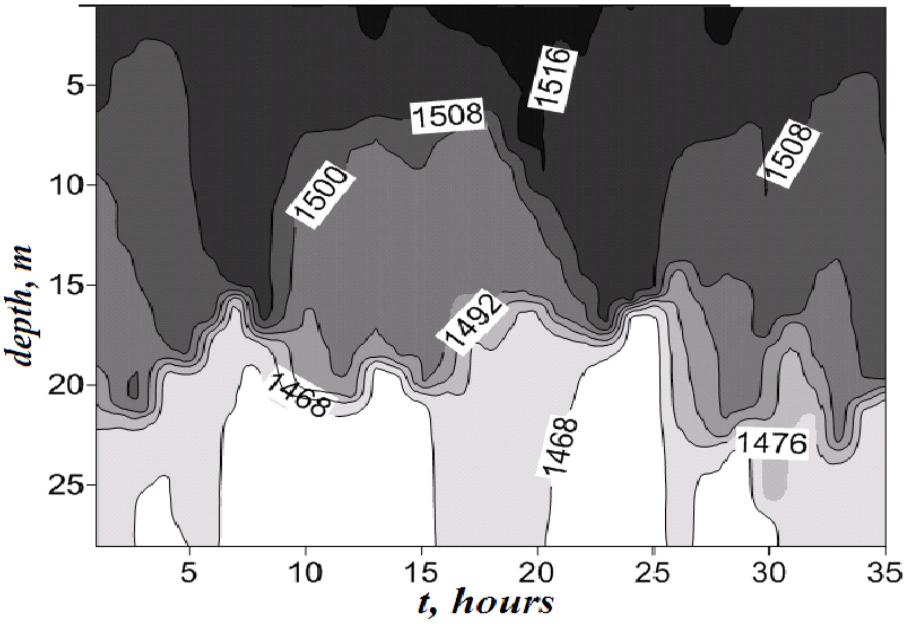

Fig. 8. Second mode internal inertial waves of 17-hour period observations, on a shelf of the Black Sea, by hourly soundings of miniSVP profiler from stationary platform [21].

Fig. 8 presents a fragment of the in-time changing in the sound-speed isopleths from the data during the passage of the quasi-inertial waves of the second mode from 7 to 24 hours in July, 17, 2011. The isopleths of the sound speed are plotted on the base at every-hour, sensing from the surface to the bottom of the sea. It is evidently seen that, with a 17-hour period, from a depth of 16m, the water layers elevate to approximately 7-8m, and then the deepening of the waters occurs to their initial position. Simultaneously, the water layers deepen from a depth of 17m to 21m, and then they elevate. In that process, the oscillations of the sound speed at individual horizons reaches 20 m/s. Here, we presented an example of the inertial internal wave of the second mode. However, we observed short-period internal waves of the second mode as well.

5. STUDYING INTERNAL WAVES WITH ADCP

The “Rio Grande 600 kHz” ADCP occurrences are so convenient for studying internal waves that, in our experiments, in many cases, we begin to ignore the traditional sensors, such as the line temperature sensors. The advantages of the acoustic profiler consist in the possibility of simultaneously recording the speed of water currents, including the orbital movements in internal waves, and the positions of the sound-scattering layers in the backscattering patterns. Intense internal waves with a height of 5m and more are firmly recorded by the “Rio Grande 600 kHz” by using the vertical size of the bin 0.5m (see Fig. 9).

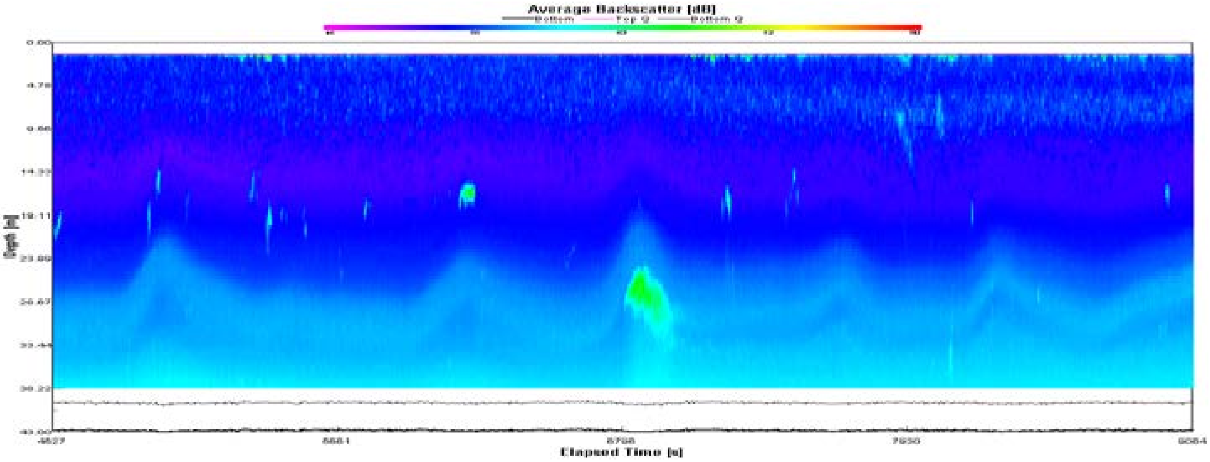

Fig. 9. Example of a record made by ADCP “Rio Grande 600 kHz”. Observations were carried out from an anchored small vessel on the shelf of the Sea of Japan. It is clearly seen that internal wave-elevations are propagating on the bottom thermoclne.

In addition to recording the main parameters of internal waves (their lengths, heights an so on), we can reveal some other phenomena that are directly associated with the internal waves. We also observed the instability of Kelvin-Helmholtz when creating overturned internal waves. In other measurements, we recorded the influence of soliton-like internal waves on dune-like formations at the bottom. Apart from those measurements, we obtained rare data of two new mechanisms of generating intense internal waves in the sea. Those mechanisms consist of generating the waves as a consequence of the collision of currents at the shelf of the Sea of Japan and those caused by the anti-cyclonic eddy at the shelf of the Black Sea [16]. In the both cases, the generated internal waves have amplitudes close to 10m and propagated towards the coast. In many cases, the ADCP-measured internal waves and the effects associated with them are presented in [22]. Therefore, here we restrict ourselves by several examples shown in Fig 10 and 11.

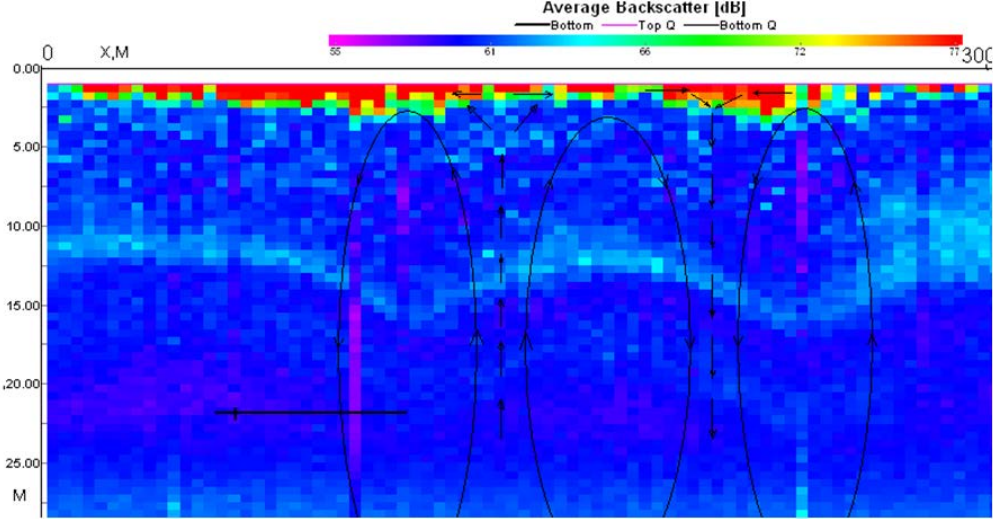

Fig. 10. The effect of internal waves on the layer of subsurface bubbles (red colors). Observations made by ADCP "Rio Grande 600 kHz" in 2003 on the shelf of the Sea of Japan. Picture of backscattering signal is shown.

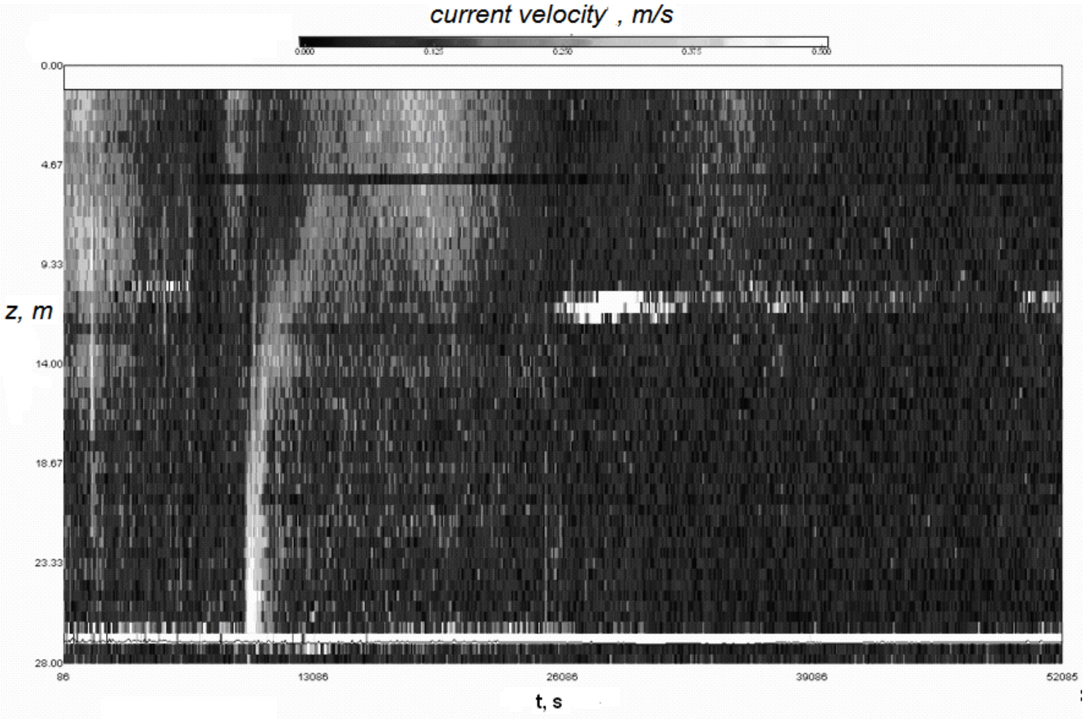

Fig. 11. Internal bore on the shelf of the Black Sea. Observations made by ADCP "Rio Grande 600 kHz" from stationary platform. An intense jet-like current in the near –bottom layer can be noticed.

The first one is a so-called effect of internal waves on a subsurface layer of air bubbles [23] (Fig. 10). The effect consists of a modulation in thickness of the layer of subsurface air bubbles by propagating internal waves. The observed effect can be explained in terms of two mechanisms: the overturning of the surface waves that generate the undersurface bubbles in the field of convergence of the flows, and the downward carrying of the bubbles by the orbital flow in the internal waves.

The second example is a record of strong nonlinear internal waves – internal bore on shelf of the sea (Fig. 11). Measurements were made on August 22, 2005. When the bore approached we observed a sharp increase in the near-bottom current, up to 0.6 m/s, with a sharp change in the direction from east to west.

6. CONCLUSION

As a whole, nowadays, studies of internal waves show a substantial progress in studying the nonlinear waves at shelf zones. The presented experimental data were in main based on two following measurement methods: the use of line temperature sensors, and the acoustic Doppler profiler of currents. In our paper, we did not touch on the important problem of sound propagation in the internal-wave environment. However, a number of interesting results were recently obtained in that sphere.

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