Title
Mode-2 internal waves: observations in the non-tidal sea

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Mode - 2 internal waves: observations in the non-tidal sea

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Abstract

The results of observations of mode - 2 internal waves on the shelf of the tide - free Black Sea are presented. Observations were carried out from the stationary platform in July 2011. The platform is situated on the Southern coast of Crimea (Katsively, Yalta), where sea depth is about 30 m. Continuous registration with thermistor chain as well as hourly CTD yo-yo soundings of water bulk with mini-profiler during 10 days were performed. ADCP were used for measurements of currents. Intense mode - 1 and mode - 2 internal waves with a period close to the local inertial (17.3 hrs) were registered. The heights of observed waves reached 10 - 15 m. Firstly mode - 1 oscillations with inertial period were observed which than transformed in mode - 2. The appearance of mode - 2 internal waves were occurred when a mean position of thermocline had a tendency to move deeper. In all cases the mode - 2 waves had the character of the convex type. As far as we know the presenting data is the first observation of mode -2 internal waves in the Black Sea.

Introduction

Until recently it was believed that the higher modes of internal waves, which existence is predicted by the theory, almost never appear in the nature ocean. In fact it was reported only about ubiquitous observations of the mode - 1 internal waves in the ocean. In the last years the situation has changed and there were reports on observations of mode - 2 internal waves, for example in the Indian Ocean (Konyaev et al 1995, da Silva et al 2011, 2015) and in the South China Sea (Yang et al 2009, Ramp et al 2012). All of these cases are according to tidal generated internal waves. Inertial internal waves of mode - 2 were observed after influence of the hurricane on shelf of Atlantic (Mayer et al 1981). We suddenly have faced with mode - 2 internal waves in measurements at the shelf of the Black Sea in 2011. The Black Sea as a closed sea is almost free of tides and therefore has a relatively low amplitudes of typical internal waves (Ivanov and Serebryany 1982). Nevertheless intense quasi - inertial and short - period internal waves are observed in it. The origin of the short-period internal waves is connected with a number of nontidal generation mechanisms (Serebryany and Ivanov 2013). In discussed data long-period oscillations of mode - 2 inertial internal waves were observed. Short - period mode - 2 internal waves also were registered.

1 Methods and site of measurements

From July 9 till 18 of 2011 we performed observations of vertical and temporal variability of temperature, sound velocity and currents from stationary platform of Marine Hydrophysical Institute RAS. The platform is situated on the shelf zone of the Southern coast of Crimea in 600 m from the shore, where sea depth is about 30 m. Platform provides an opportunity to perform long-term measurements of hydrophysical characteristics of the sea. Hourly yo-yo soundings were conducted with mini-profiler SVP of the Valeport Company, which was equipped with a sound-speed, temperature and pressure sensors. Measuring the current velocity was carried out with the use of the ADCP Rio Grande 600 kHz that was mounted at the lower part of the platform and fixed looking down. In addition, the record was also performed with a vertical chain of thermistors consisted of 10 sensors DST-centi of the Starr-Oddi Company, with a period of 30 s in their samplings.

2 Observations of intense internal waves of mode - 1

Before the beginning of our studies the phenomenon of upwelling of the coastal waters took place at this region. Due to this untypical hydrological structure with the value of surface temperature near 17 - 19 ^{0}C and subsurface thermocline were observed. From July 9 the weather was calm that caused gradual warming of the water column, which was manifested in monotonous deepening of the mean position of the thermocline. During this conditions surface temperature has grown from 17^{0}C up to 26 ^{0}C and near-bottom temperature has increased from 10 up to 13 ^{0}C. During the observation period the velocity currents changing insignificantly (within 20 - 30 cm/s). Figure 1 presents temporal variability of vertical structure of temperature for the whole period of measurements from July 9 till 18.

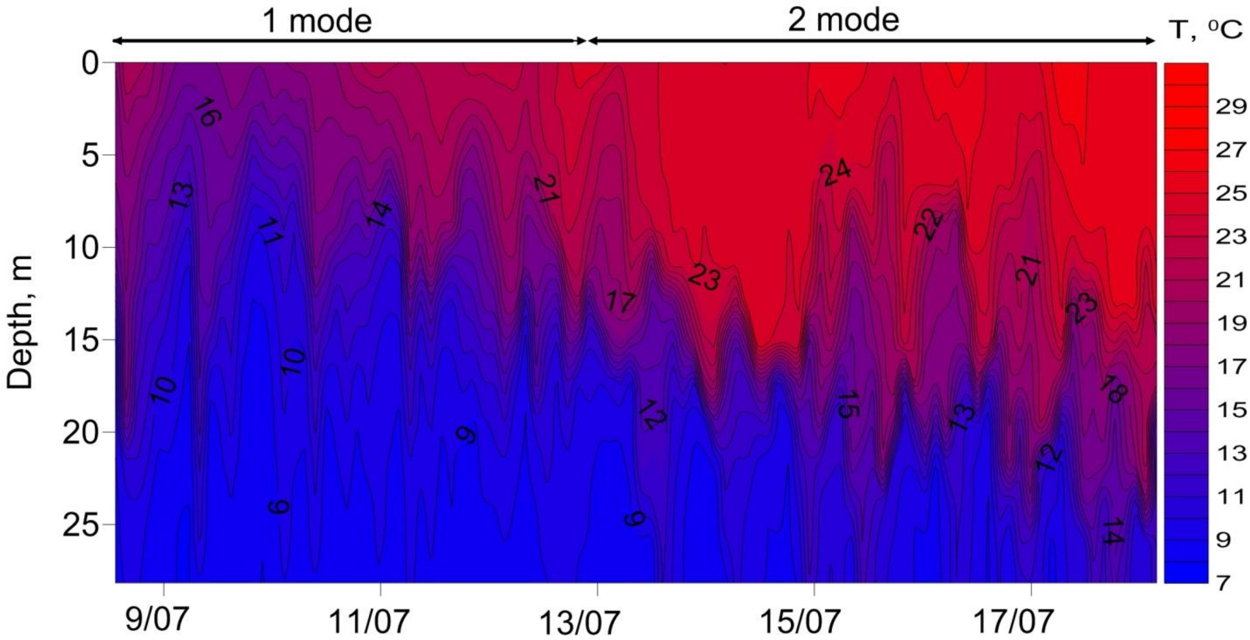

Figure 1: Temporal variability of vertical structure of temperature according to hourly temperature soundings, 9 - 18 July of 2011

For the first few days of observations it was registered typical displacements of thermocline along the entire thickness of water bulk with a period close to the local inertial period, which for this area is 17.3 hours. We mentioned that the character of thermocline fluctuations has changed on July 14 when the average position of thermocline depth has reached the middle of the water column. The evidences of the mode - 2 oscillations were revealed since this time. Consider the first part of our observational period. Figure 2 shows temporal variability of vertical structure of temperature according to hourly yo-yo soundings for 38 hours from July 9. It is clear seen that vertical motions of the water column move with 17-hour period, that indicating the approach of the mode - 1 internal waves to the coastal zone (as well as vertical profiles of velocity currents at individual moments of time). The record shows sharpened troughs of long waves that indicates their nonlinearity. The heights of thermocline oscillations are reach as much as 15 - 20 m. Such synchronous fluctuations were observed during 5 cycles, after that the behavior of inertial oscillations sharply changed.

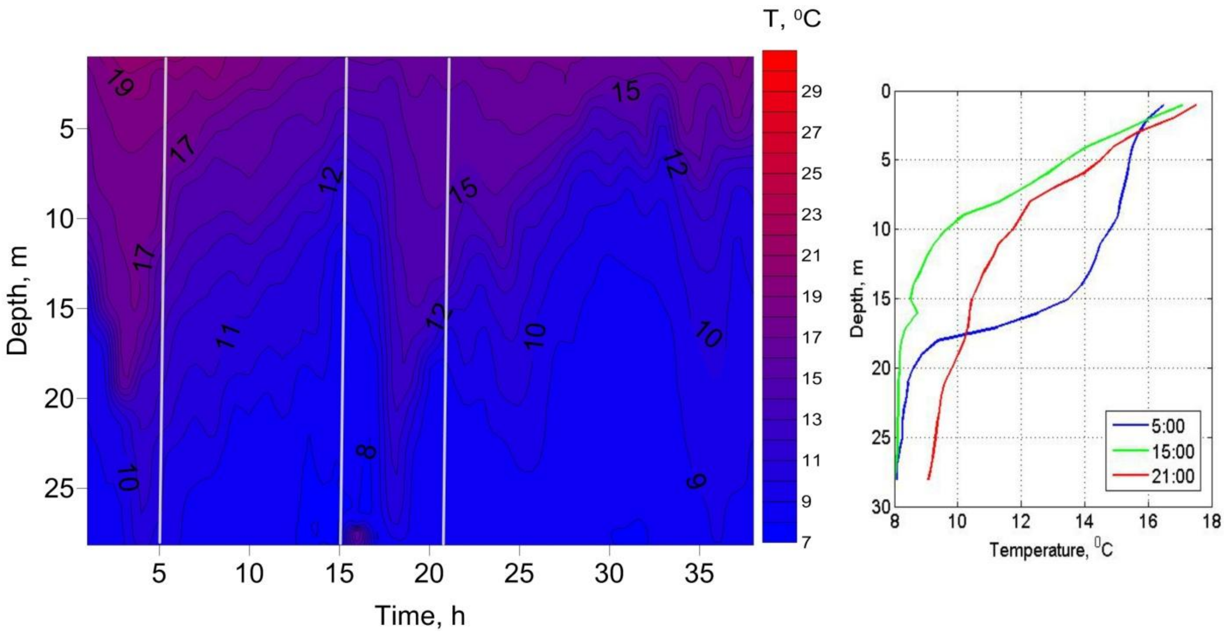

Figure 2: The evidenceof mode - 1 inertial internal waves . Vertical oscillations of temperature for July 9 - 10. At the right, vertical temperature profiles for characteristic times of July 9 are shown

3 Observations of intense internal waves of mode - 2

The changes of thermocline character was as follows. From July 13 thermocline continues its movements with inertial periods, but the upper and lower layers of the water bulk became displacing out-of phase. Traces of these oscillations are evidently seen in both the data of sound-speed, temperature and in the records of currents velocity. This phenomenon has been an evidence of appearing of the second mode in the inertial (quasi-inertial) internal waves. It should be mentioned that before transformation of thermocline oscillations from mode - 1 to mode - 2, some features of vertical out-of phase displacements were registered (see, for example, figure 2 on the wave of July 10).

Figures 3 and 4 show examples of long-period temperature oscillations with 17 - hours inertial period of mode - 2 for 13 - 14 and 16 - 17 of July. Starting from 8 h figure 3 depicted raising of the water layers from 15 - 16 m depth up to 7 - 8 m during inertial period and after that deepened to its starting position. The movement down below 15 m is weak. But in the next inertial cycle a movement of the water bulk became more significant in the lower part and became less in the upper part.

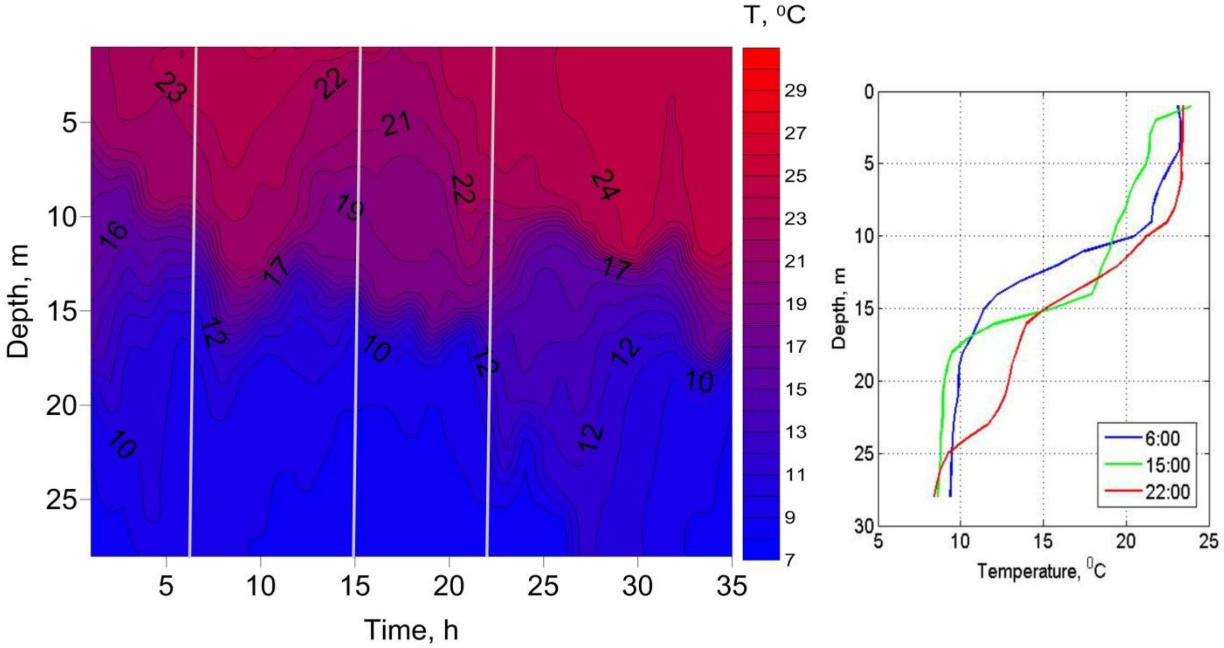

Figure 3: The evidence of mode - 2 inertial internal waves . Vertical oscillations of temperature for July 13 - 14 . At the right, vertical profiles of the temperature for characteristic times of July 13 are shown

During 16 - 17 July mode - 2 oscillations were more pronounced and had more regular character (Figure 4, 5). Amplitude of these oscillations varies up to 7 m. Observed mode - 2 internal waves belong to convex type waves. These type of mode - 2 waves observed most frequently at the ocean shelf.

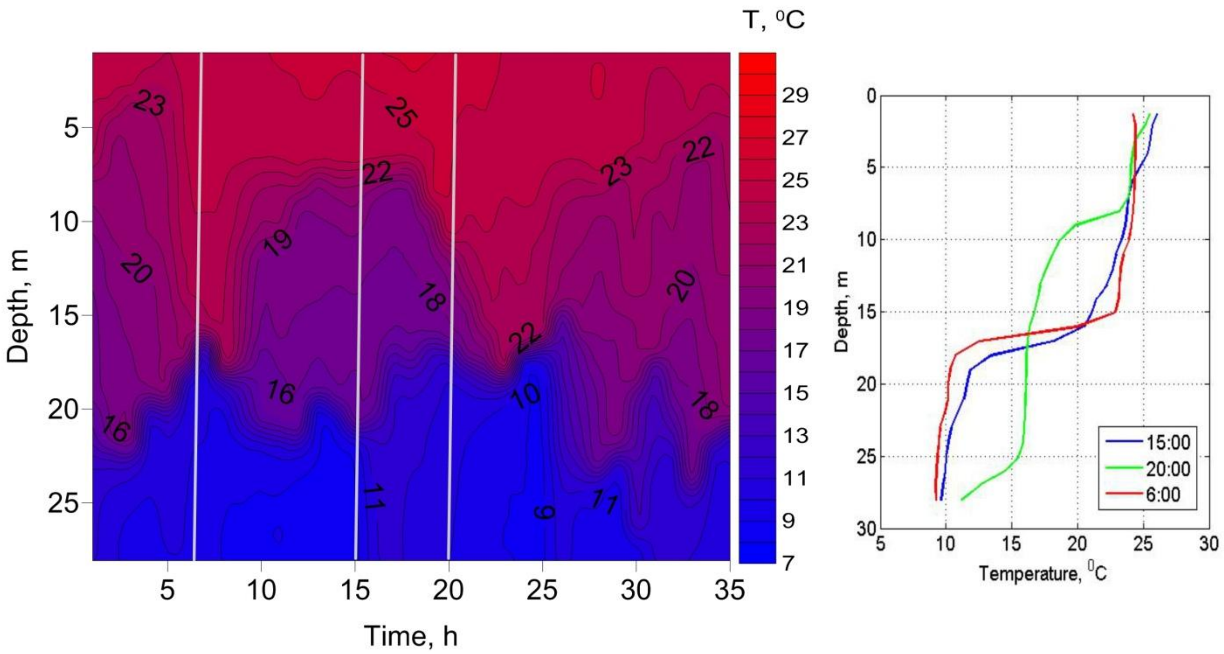

Figure 4: The evidence of inertial mode - 2 internal wave. Vertical oscillations of temperature for July 16 - 17. At the right, vertical profiles of the temperature for characteristic times of July 16 are shown.

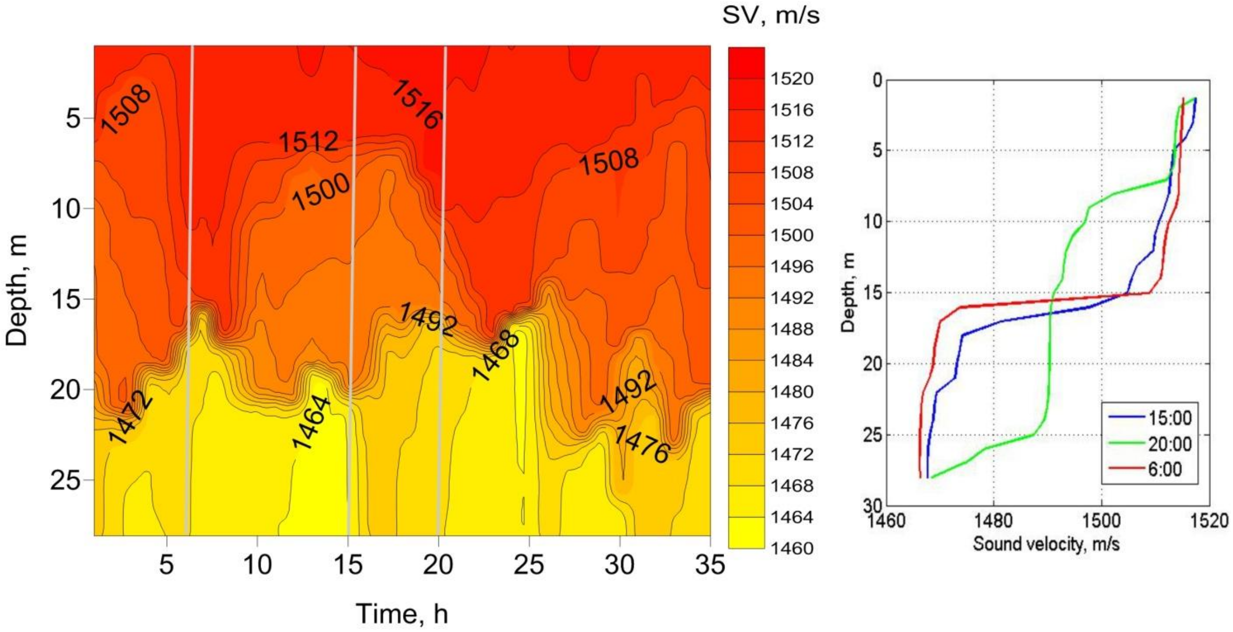

Figure 5: The evidence of mode – 2 inertial internal wave . Vertical oscillations of sound velocity for July 16 - 17. At the right, vertical profiles of the sound velocity for characteristic times of July 16 are shown.

4 Conclusions

The main goal of the paper was to demonstrate the evidence of the existence of a mode - 2 inertial internal waves in the Black Sea. After 2011 we have carried out several similar experiments on observation of internal waves in the Black Sea (Serebryany and Khymchenko 2014). We have also noted mode - 2 evidence of the inertial and short-period (periods from several minutes to tens minutes) internal waves. Following questions naturally arise: what is the cause of its generation and what is the theoretical model for it. This will be the next step for our future work. The observed fact of the appearance of mode - 2 along with deepening of the mean position thermocline could be the key for the explaining of this phenomenon.

Acknowledgements

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