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Observations of the Second Mode Internal Waves in the White and Barents Seas

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Abstract
Purpose. The purpose of the work is to describe a comprehensive technique for detecting the second mode internal waves, and to consider the cases of their record during the *in situ* measurements carried out in the coastal areas of the White and Barents seas in summer.
Methods and Results. The initial data were formed based on the series of frequent many-hour CTD measurements performed in the coastal stratified areas in the summer seasons, 2009–2017. The waves, duration of which was 5–60 min and the heights exceeded 1 m, were considered. The observations were processed using the complex of wavelet- and mode-analyses. The cross-wavelet spectrum of the isotherms' vertical displacements demonstrated a statistically significant increase in the cross-spectral power with a complete phase mismatch associated with the second mode of internal waves. The positions of the amplitude maxima of the second mode internal waves on the records of the isotherm oscillations were additionally checked by calculating the hydrostatic normal vertical modes. It is shown that in the near-surface seasonal pycnocline of the White Sea, the second mode internal waves were recorded as the single "convex" ones with average duration 10 min and amplitude 2 m. In the Barents Sea, such waves were observed both as the single "convex" waves, and as the "concave" and "convex" sequential ones with average duration 20 min and amplitude up to 1.5 m. It was established that in the considered areas of the White and Barents seas, the intermittency of the second mode internal waves did not exceed 1 %.
Conclusions. Analysis of the archival data on the six-year-long *in situ* observations has resulted in first description of the cases when the second mode internal waves had been recorded in the White and Barents seas. Having been analyzed, more than 350-hour records of temperature fluctuations permitted to detect only 5 cases demonstrating the second mode internal waves in a form of the "convex" and "concave" ones with their total duration not exceeding 1.5 hours. This indicates that occurrence of such waves is extremely rare in the water areas under consideration.

Keywords: internal waves, second mode, contact measurements, wavelet-analysis, White Sea, Barents Sea

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Introduction

Internal waves (IW) almost always exist in the near-surface pycnocline area (thermocline) with a significant density gradient [1], which is formed in the seas of temperate and subarctic climatic zones during the warm season. Based on the results of the vertical sounding of the water column vertical probing with a high discreteness in time, it is possible to qualitatively estimate the mode composition of IW in the direction of wave crests or troughs on the obtained spatial-temporal panoramas of fluctuations in the characteristics of hydrophysical fields (for example, temperature) [2]. The most common and well-identified IW of the first mode appear as a single oscillation of the water column in the region of the pycnocline (thermocline). Depending on the phase, they are of two types – "up" waves and "down" waves. Internal waves of the second mode are observed in the form of two modifications – these are the "concave" waves and the "convex" waves [3]. In the first case, in the upper part of the water column, an uplift of isopycnes (isotherms) takes place, in the lower part – a deepening. In the second case, on the contrary, in the upper layers, the isopycns (isotherms) descend, while in the lower layers they rise.

Internal waves of the second mode were recorded in many areas of the World Ocean: in the South China Sea [4], in the Indian Ocean [5, 6], in the Andaman Sea [7], on the North American shelf of the Atlantic Ocean [8], near the Russian coast of the Black Sea [9]. The occurrence of such waves in the World Ocean deepwater regions, where the seasonal and main thermoclines are present, is associated with the formation of internal tide beams [10]. In the relatively shallow northern seas of Russia, where the seasonal thermocline is pressed against the surface, the cases of the second mode IWs registration have not yet been described.

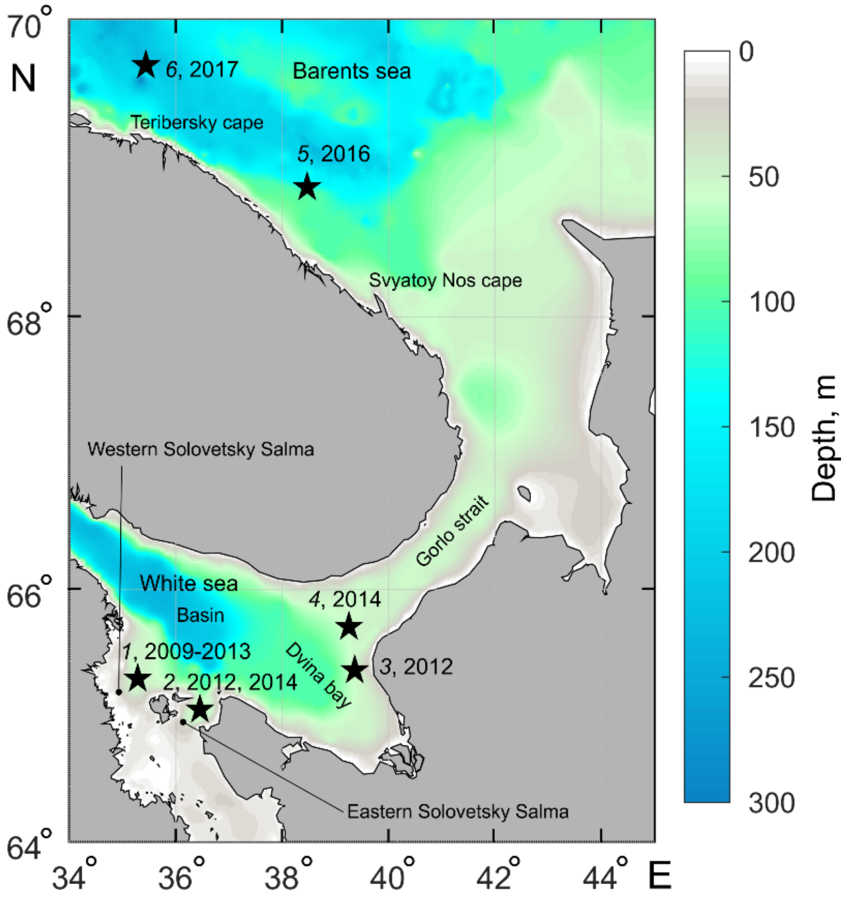
The purpose of this work is to describe the cases of second-mode internal waves registration in the White and Barents Seas based on the analysis results of a long-term archive of data from expeditionary studies of the St. Petersburg Branch of the Institute of Oceanology using an original technique.

Materials and methods of their processing

The materials for this work are the results of long-term (14–80 h) high-resolution (in time and depth) contact measurement of the temperature and seawater density variations. The measurements were carried out in the White Sea [11] in June–August 2009–2014 (areas *1–4* in Fig. 1) and in the Barents Sea [12, 13] in August 2016–2017 (areas *5*, *6* in Fig. 1). In the White Sea, the measurements were carried out at 40–65 m depths from an anchored vessel, and in the Barents Sea, at 100–150 m depths from a drifting vessel (drift speed did not exceed 0.2 knots). The observations included repeated probings (scans) of the water column from the surface to a given horizon. CTD probes SBE-25 (USA) and CTD90M (Germany) were used at the polygons in the White Sea, and CastAway probes (USA) and SBE-25 were used in the Barents Sea. One scanning cycle "descent – ascent" of the probe took 1–2 min, depending on the depth range covered.

In the records of temperature fluctuations, the manifestations of the second mode IWs were previously visually recorded as oscillations of isotherm groups occurring in antiphase in the pycnocline region. For the selected sections of characteristic isotherms, their location depths, which were then subjected to wavelet analysis to check the coincidence of the antiphase of the oscillations, were estimated. The complex Morlet wavelet was applied as the basis function. The estimates of the wavelet coherence power served as a measure of the local relationship, similar to how it was done in [14].

To confirm the fact of the possibility of the second mode IW existence at selected depths from a density profile averaged over several hours, hydrostatic normal vertical modes were calculated using a finite-difference algorithm with the rigid lid conditions, flat bottom, and arbitrary stratification [15, 16]. In the presence of antiphase oscillations of isotherms at the depths corresponding to the amplitude maxima of the second mode IWs, it was assumed that the manifestations of such waves were correctly registered in the record.

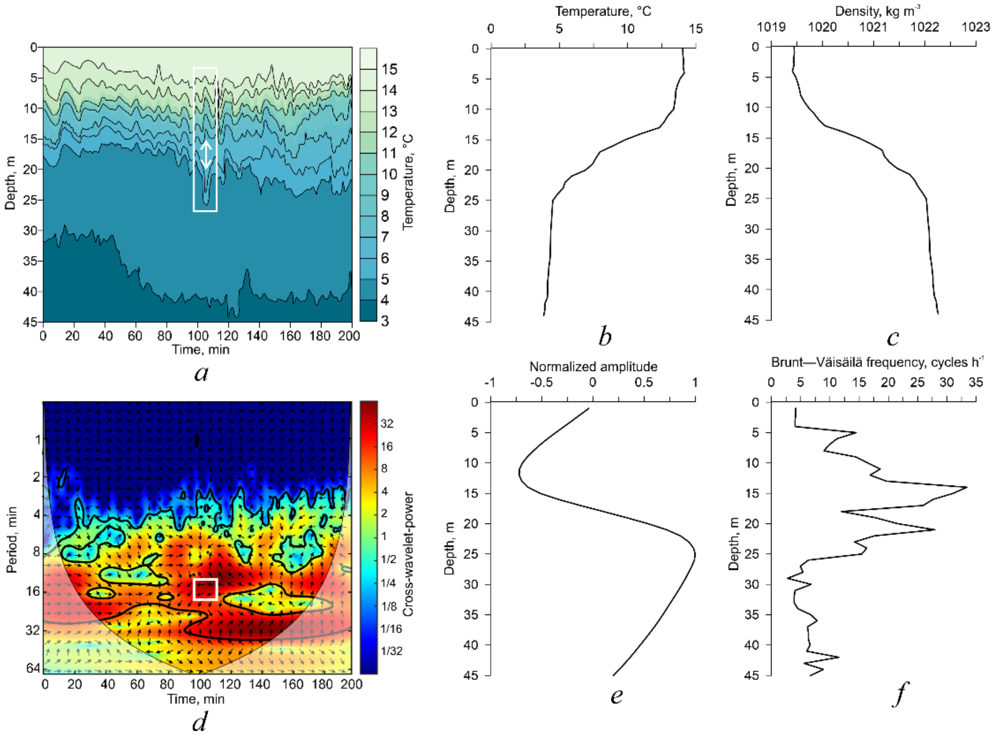


F i g. 1. Scheme of the location of the measurement areas (*1–6*, denoted by the asterisks) in the White and Barents seas combined with the depth map

For each oscillation selected this way and associated with the second mode IW, the height and duration were determined. The method for calculating the characteristics of the IW was similar to that used in [17] for the analysis of the first mode IW, according to which oscillations with a duration of 5–60 min and heights of more than 1 m were considered. Then, the IW temporal intermittency was calculated as the ratio of the second mode IW lifetime to the total recording time at each measurement point, as a percentage. Along the way, for a comparative assessment, on the same polygons where the presence of the second mode IW was detected, the temporal intermittency of the first mode IW was estimated. Their presence was also assessed according to the technique from [17].

Field observations of the second mode IW

Manifestations of the second mode waves in the form of single oscillations or groups of two oscillations were recorded in the seas under consideration. An example of the second mode IW registration based on the data of observations in the White Sea based on the method described above is given in Fig. 2.



F i g. 2. An example of a record of the second mode IW in the White Sea in region *1*: *a* – fragment of the temperature fluctuations recorded on 18.07.2012 (white rectangle marks fluctuations of the second mode IW); *b* – temperature vertical profile averaged over two hours; *c* – density vertical profile averaged over two hours; *d* – cross-wavelet power spectrum of the 7°C and 6°C isotherms' oscillations; *e* – calculated profile of the 2nd normalized vertical mode of IW with the 15 min duration; *f* – vertical profile of the Brunt-Väisälä frequency

From Fig. 2, *a* it can be seen that approximately at the 100th minute from the start of measurements, pronounced antiphase oscillations of isotherms, affecting the water column within the range of 5–25 m, are recorded. The amplitude of oscillations is minimal at ~ 15 m depth and increases in the up and down direction reaching the maximum of 2 m at 12 and 24 m depths. The duration of antiphase oscillations is ~ 15 min. Until the moment of the second mode IW registration, insignificant fluctuations of isotherms with an amplitude of ~ 1 m are observed.

The vertical temperature and density profiles shown in Fig. 2, *b*, *c* indicate the presence of a pronounced thermocline in 10–25 m layer, which coincides with the pycnocline.

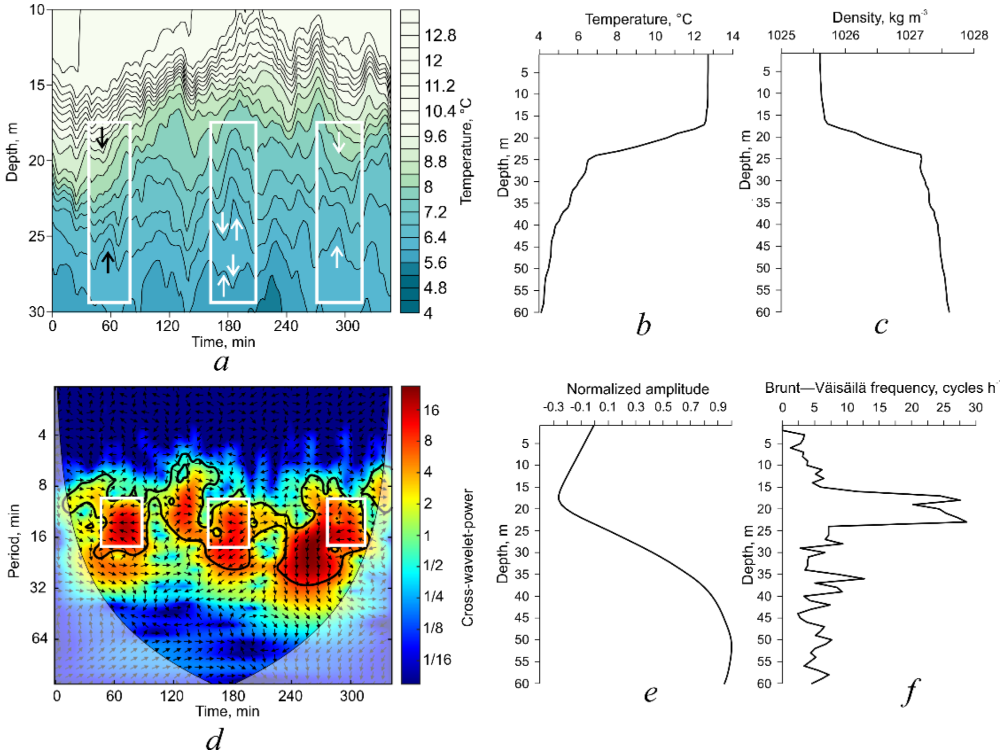
Fig. 2, *d* shows the results of applying the wavelet analysis to the fluctuations of the 6 and 7°C isotherms: solid black lines separate the regions of edge effects, the thick lines limit the regions with a mutual cross-wavelet spectrum and wavelet coherence different from zero at a significance level of 0.95 with respect to red noise. The arrows in the figure show the relative phase of the oscillation: to the right – the oscillations are in phase; to the left – the oscillations are in antiphase. Calculations of the cross-wavelet spectrum of vertical displacements of isotherms show a statistically significant increase in the mutual spectral power with a total phase mismatch of ~ 15 min duration approximately at the 100th minute of measurements, which, according to the accepted method, indicates the registration of the second mode IW (the region is indicated in Fig. 2, *d* with a white rectangle).

The amplitude maxima of the second mode IWs (Fig. 2, *e*) are located at 12 and 25 m horizons, very close to the location of the maxima of the vertical amplitude of the antiphase oscillations recorded from the data of contact observations, which, based on the technique assumptions, confirms the correctness of registering the oscillations as the second mode IW. Note that Fig. 2, *f*, where the Brunt–Väisälä frequencies are greater than 5 cycle/h (at which the waves with a duration of 15 min can exist) are observed in the depth range of 10–25 m.

The analysis given above allows us to assert that in the layer of the near-surface pycnocline (thermocline) of the second mode IW appears in the form of a single "convex" wave.

Fig. 3 demonstrates the examples of the second mode IW registration in the Barents Sea.

The record shown in Fig. 3, *a* is interesting in that it is the only one of those considered where antiphase oscillations of the isotherms are recorded three times: at the 60th, 180th, and 300th minutes from the start of the measurements. At the 60th minute, a pronounced single "concave" oscillation, which can be traced in 18–28 m depth range, is recorded. The minimum amplitude is recorded at ~ 22 m depth, and the maximum value of the amplitude, which is 1 m, is reached at 18 and 27 m horizons. The duration of antiphase oscillations is ~ 20 min. Approximately at the 180th minute of measurements, a less pronounced "concave" oscillation is first recorded, and then a pronounced "convex" oscillation. The amplitude of these oscillations is minimal at 26 m horizon, and the maximum amplitude value, which is 1.5 m, is observed at 20 m horizon. Despite the pronounced antiphase nature of the oscillations, the position of the second amplitude maximum cannot be revealed, most likely due to the narrow coverage range of the water column (10–30 m) by the probing data to achieve an interval between the probings of ~ 1 min. The duration of antiphase oscillations, as in the 60th minute of measurements, is ~ 20 min. At the 300th minute, a single "concave" oscillation is recorded, similar in characteristics to the oscillation at the 60th minute: the amplitude minimum is recorded at ~ 23 m depth, and the maximum amplitude value of 1 m is reached at 19 and 26 m horizons. The oscillation can be traced within the depth range of 18–28 m, its duration is ~ 20 min.



F i g. 3. An example of a record of the second mode IW in the Barents Sea in region *5*: *a* – fragment of temperature fluctuations recorded on 15.08.2016 (white rectangles mark fluctuations of the second mode IW); *b* – the temperature vertical profile averaged over the recording period; *c* – density vertical profile averaged over the recording period; *d* – cross-wavelet power spectrum of the 5.8°C and 6.4°C isotherms' oscillations; *e* – calculated profile of the 2nd normalized vertical mode of IW with the 20 min duration; *f* – vertical profile of the Brunt-Väisälä frequency

Vertical temperature and density profiles in Fig. 3, *b*, *c* indicate the presence of a high-gradient thermocline in 20–25 m layer, which coincides with the pycnocline.

Fig. 3, *d* demonstrates the results of applying the wavelet analysis to 5.8 and 6.4°C isotherms fluctuations. Calculations of the cross-wavelet spectrum of vertical displacements of isotherms show a statistically significant increase in the mutual spectral power with a total phase mismatch in the range of durations of 10–20 min in the vicinity of the 60^{th}, 180^{th}, and 300^{th} minutes of measurements, which indicates the registration the second mode IWs. The areas of phase mismatch are marked in Fig. 3, *d* with white rectangles.

From Fig. 3, *e* it can be seen that the amplitude maxima of the second mode IWs are located at 18 and 50 m horizons, the nodal point is at the 25 m horizon. The positions of the upper maximum and nodal point, obtained from the analysis of the temperature fluctuation record, are very close to their theoretical position on the profile of the second normalized vertical mode IWs. The revealed coincidence of the positions of the amplitude maximum and the nodal point of the antiphase oscillations on the theoretical profile and in the data of contact observations can serve as confirmation of the second mode IWs registration. Additional confirmation can be found in Fig. 2, *f*, where the Väisälä–Brunt frequencies are greater than 4 cycle/h (at which the waves with 20 min duration can exist) are observed within a wide depth range of 10–45 m.

Thus, the results of the analysis of contact observations data in the Barents Sea made it possible to reveal the simultaneous presence of both "convex" and "concave" waves in the records of the second mode IW temperature fluctuations.

A similar analysis was performed for the entire array of observations; its results are given in the table, according to which the oscillations identified as the second mode IWs manifested themselves only in two areas, *1* and *5* (Fig. 1). An analysis of the rest of the measurements did not make it possible to distinguish the presence of the second mode IWs, despite the significant duration of the measurements. The second mode IW oscillations in the White Sea were observed only in the area of Zapadnaya Solovetskaya Salma in the form of single waves. In 2009, they were traced in 10–22 m layer, in 2012, in 5–33 m layer; in these years, nodal points with a minimum amplitude were observed slightly below the average thermocline position. In the Barents Sea, near Kharlov Island, the oscillations under consideration were recorded as single or successive waves in the 18–27 m layer.

In the White Sea, all the registered cases of the second mode IWs manifestation, in accordance with the classification given in [3], are the "convex" waves. Both "concave" and "convex" waves were recorded in the Barents Sea. It should be noted that the measurement areas were located at a distance of 15–25 miles from bottom topography inhomogeneities: in the White Sea, this is a sag at the boundary of the Western Solovetskaya Salma and the Basin; in the Barents Sea, it is a continental slope to the north of the Svyatoy Nos Cape. These inhomogeneities can be considered as regions of the second mode IWs generation due to the interaction of the tidal flow with them.

It can be seen from the table that second mode IWs are a rare phenomenon. They were found only in four of the 12 cases of many hours of observations considered. For the identified cases, it turned out that the intermittency of the second mode IWs is 40–120 times less than the intermittency of the first mode IWs, which indicates a very low prevalence of the second mode IWs in the considered areas of the northern Russian seas.

Statistical characteristics and intermittency of the internal waves based on contact measurements

Number of the region under study	Date of measurements	Total time of measurements, min	Average height of the second mode IW, m	Average duration of the second mode IW, min	Intermittency of the second mode IW, %	Intermittency of the first mode IW, %
1	June, 2009	810	2	8	0.9	90
	August, 2010	3105	No oscillations of the second mode are found			
	July, 2011	1080				
	July, 2012	1450	2.5	15	1.0	79
	August, 2012	1350	1	7	0.5	63
	August, 2013	780	No oscillations of the second mode are found			
2	July, 2012	1540				
	July, 2014	1470				
3	July, 2012	1440				
4	July, 2014	1500				
5	August, 2016	4810	2	20	0.6	81
6	August, 2017	4040	No oscillations of the second mode are found			

Conclusion

According to the results of a complex (wavelet and mode) analysis of a long-term archive of CTD measurements with a high discreteness in time, the cases of recording non-linear internal waves of the second mode in the White and Barents Seas were described for the first time. It was determined that the second mode internal waves were predominantly "concave" waves, contained 1–2 oscillations with an average duration of 10 min and an average amplitude of 2 m. The calculation of the intermittency showed that the second mode internal waves in the seasonal near-surface pycnocline are a very rare phenomenon against the background of the wide distribution of internal waves.

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Aleksey V. Zimin – participation in expeditionary research; selection and analysis of literature; scientific supervisor; critical analysis and revision of the text

Gleb V. Zhegulin – participation in expeditionary research; performing calculations of the cross-wavelet spectrum of vertical displacements of isotherms and hydrostatic normal vertical modes

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.