ISSN 0001-4370, Oceanology, 2010, Vol. 50, No. 5, pp. 668–674. © Pleiades Publishing, Inc., 2010.
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MARINE PHYSICS

Internal Waves in a High-Latitude Region

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Received August 26, 2008; in final form, February 15, 2010

Abstract—Internal waves are studied in two high-latitude regions of the Kara Sea. The measurements were carried out with a towed CTD profiler and a distributed temperature sensor on a mooring. The lack of internal waves with an M2 tidal period and the presence of high-frequency waves are demonstrated on the basis of the measurements and numerical modeling.

DOI: 10.1134/S0001437010050048

CHARACTERISTICS OF THE INTERNAL TIDE IN THE ARCTIC REGION

It is known that internal tidal waves are generated in the ocean when currents of the barotropic tide flow over irregularities of the bottom topography [2, 4, 9, 12, 25]. It is likely that the first paper in which the linear theory of internal wave generation by tides on a submarine slope was developed is the one published by Rattray [26]. The vertical components of the currents that appear when the tidal current flows over submarine slopes cause periodic displacements of the isopycnal surfaces. The main energetic frequency of the internal tide is the frequency corresponding to the barotropic M2 tide with a period of 12.4 h. The internal tide plays an important role in the dissipation of the tidal energy in the ocean and facilitates mixing in the ocean.

It is shown in [12] that the main dimensionless parameters determining the intensity of the internal tide generation are the ratio of the horizontal amplitude of the tidal displacement of the water particles to the horizontal scale of the bottom topography, the ratio of the bottom slope to the inclination of the beams of the internal tidal waves, and the ratio of the height of the topographic irregularities to the ocean depth.

The measurements in the ocean and the numerical models demonstrate that submarine ridges, continental slopes, and individual mountains mark the main regions of the internal wave generation in the ocean [4, 9, 12, 19]. In the case when the currents of the barotropic tide are directed normally to the submarine ridge, their effect in the sense of the internal tide generation is maximal. It is clear physically that the stronger the currents of the barotropic tide, the greater the amplitude of the internal tide. The generation of internal tides also depends on the geometrical form of the underwater topography. The main factors determining the generation are the angle of the slope and the height (the proximity to the layer of the maximum Brunt–Väisälä frequency) of the submarine elevation [12]. If the inclination of the slope is close to the characteristics of the internal tidal wave determined from equation

$$dx/dz = \sqrt{N^2(z) - \omega^2}/\sqrt{\omega^2 - f^2}, \qquad (1)$$

the maximum generation of internal tides is observed [12]. Here, ω, N, and f are the tidal frequency, the Brunt–Väisälä frequency, and the Coriolis parameter, respectively. The generation effect of the internal tide is intensified if the layer of the maximum stratification is located at the depth of the submarine slope, and the inclination of the bottom coincides with the inclination of the characteristic curve of the internal tide.

Many properties of internal waves depend on the latitude. Let us show this using the example of a simple equation for the vertical velocities w caused by internal waves:

$$\frac{d^2w}{dz^2} + \frac{N^2(z)}{g}\frac{dw}{dz} + \frac{N^2(z) - \omega^2}{\omega^2 - f^2}k^2 w = 0. \qquad (2)$$

This equation was deduced for a flat bottom. The boundary conditions for the vertical velocity at the bottom and the surface are zero. Here, k is the wavenumber. The denominator of the third term of this equation is important for the problems that we shall discuss below. When we approach high latitudes, the difference between the M2 tidal frequency and the Coriolis parameter decreases, and, at a latitude of approximately $\varphi = 74.5°$C, this difference turns into zero, which excludes the oscillatory solution of equation (2) in the linear formulation.

Thus, a latitude close to 74.5° is critical for semidiurnal ($T = 12.4$ h) internal waves. Equation (2) has no solutions; therefore, internal waves with frequency M2 cannot exist in the Arctic Basin as free waves north of the critical latitude. However, the process of their generation at high latitudes does not differ from the similar process at low latitudes. Namely, the currents of the barotropic tide flow over underwater slopes and periodically displace the isopycnal surfaces up and down due to the appearance of the vertical components of these currents near submarine slopes. The differences are in the fact that, in the region of super-critical latitudes, internal waves with frequency M2 would be forced waves over a submarine slope and would not be able to spread from the slope as in the case of lower latitudes. One of the possible mechanisms of the energy transport that could be transferred from the barotropic tide to a forced wave with period M2 is the breaking of this wave and the generation of a packet of short-period waves for which there is no limit for their existence in the polar latitudes.

It is shown in [30] that, if the nonlinearity of the wave process is weak, no effective generation of internal tidal waves occurs at the critical latitude. The nonlinearity is determined by the parameter ε introduced in the paper by Gerkema and Zimmerman [13]:

$$\varepsilon = \frac{l}{L}\frac{h}{H},$$

where l is the horizontal amplitude of the tidal displacement of a water particle, L is the horizontal scale of the topographic variability, h is the vertical scale of the topographic variability, and H is the ocean's depth.

At latitudes close to the critical one, the length of the internal tidal waves and, correspondingly, the phase velocity increase and tend to infinity. Therefore, the vertical displacement of the isopycnals would not create significant slopes of the isopycnal surfaces far from the slopes [30]. Hence, the internal tide would not break due to the large amplitudes and slopes of the isopycnal surfaces.

However, the displacement of the isopycnal surfaces can be significant over steep underwater slopes if the currents of the barotropic tide are strong and, correspondingly, the vertical components are significant. The steep elevation of the isopycnal surfaces can lead to the instability of the long-period waves, their breaking, and the generation of short-wave packets [10, 11].

Despite the fact that free internal waves with a tidal period cannot exist north of the critical latitude, such waves were observed [3, 8, 17, 24, 27, 28]. The authors of [1] made an attempt to explain the existence of such waves due to a decrease in the effective Coriolis frequency by negative vorticity. In this case, the effective critical latitude for the waves with frequency M2 displaces to the north, and the existence of internal tides is possible north of the theoretical critical latitude. The authors of [28] give estimates of the vorticity formed by real currents in the Arctic region. It is shown that the observed horizontal gradients of the currents form a vorticity sufficient for the propagation of internal tides with frequency M2 as far as the North Pole. The theory of the variation of the frequency range for the existence of internal waves was developed in [14, 15, 16, 18]. The local Coriolis frequency f varies due to the vorticity $\xi = \frac{\partial U}{\partial y} - \frac{\partial V}{\partial x}$ formed by the horizontal gradient of the mean current velocity (U and V). The effective Coriolis frequency is written as $f_{eff} = \sqrt{f(f+\xi)}$ or approximately as $f_{eff} = f + \xi/2$.

A qualitatively new explanation of internal tide generation in the high-latitude region is given in [30]. The authors demonstrate that such generation is possible if the problem has a nonlinear formulation. They suggested a numerical nonlinear model that allows the generation of an internal tide at high latitudes and its breaking into packets of short-period internal waves during a specific phase of the internal tide when the conditions for its breaking are formed.

The analysis of the nonlinearity influence on the generation of internal waves is given in [23]. The authors demonstrate that the time variations in the tidal currents are responsible for the generation of internal lee waves. Their horizontal scale is close to the horizontal scale of the topography variation. During the phase of the tidal currents increase, lee waves are generated at the lee side of the submarine obstacle. Their amplitude increases. During the phase of the tidal currents decrease, the lee waves propagate opposite to the flow. Their length is much shorter than the length of the tidal waves, and the appearance of wave packets corresponds to the tidal cycle.

In the regions near the arctic coast of the Kara Sea located slightly south of the critical latitude (for example, the Kara Gates Strait at 70°–71°N), the effect of the critical behavior of the internal waves should be manifested. The geographical location of the arctic shelf of the Russian seas at latitudes north of 70°N is close to the critical latitude. The authors of this paper published in [5, 6, 7, 21] the results of the investigation of internal waves in the Arctic Basin. One of the possible mechanisms for the energy removal that is transferred by the barotropic tide to the forced internal waves is the generation of short-period internal wave packets during each phase of the internal tide. Such a mechanism was considered in [30]. In this work, we shall show the existence of such packets of short-period internal waves based on the measurements in two studied regions.

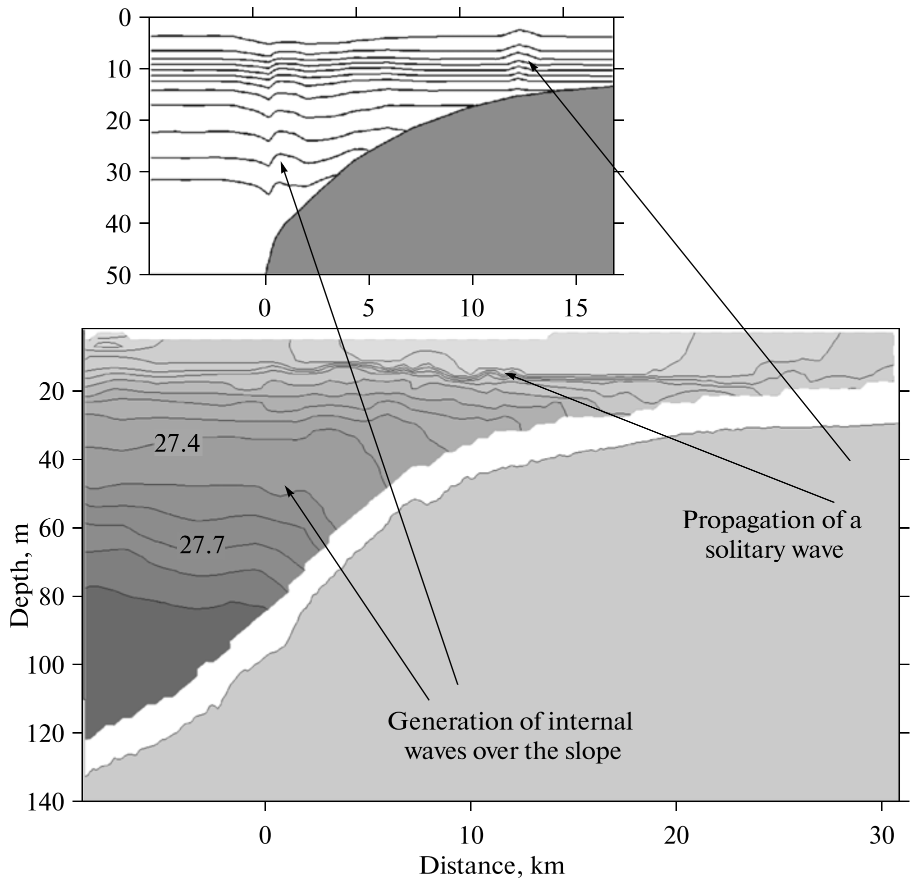

Fig. 1. Field of the isopycnal surfaces along the section west of Yamal according to the numerical model developed by Vlasenko [29] (above) and the distribution of the potential density along the section using a towed profiler. The isopycnals are shown with an interval of 0.1 (below). The gray color shows the bottom topography.

INTERNAL WAVES ALONG THE YAMAL SECTION

The Yamal section was located at a small distance south of the critical latitude for M2 internal tidal waves (71°–72°N). However, the close proximity of the critical latitudes (74°–75°N) should influence the generation and propagation of internal tides. When the barotropic tide wave is incident on the western slope of the Yamal Peninsula, the currents of the barotropic tide obtain a periodic vertical component during their motion up and down the slope. If the amplitude and, consequently, the energy of the internal tide increases, its energy can be transferred to the short-period waves in a higher frequency range of the spectra, for which there is no limit for free propagation. Then, the packets of short-period internal waves or solitary waves can play the role of the barotropic tide energy removal from the region of submarine slopes, where the energy is transferred to the internal waves. Such packets can propagate both to the open sea and to the coast.

The calculations performed using the model developed by Vlasenko [22, 29] demonstrate that an internal tide is generated at the arctic latitudes. The generation conditions are determined by the bottom topography, stratification, and currents of the barotropic tide over the submarine slope. The model calculations start from the state of rest. The currents of the barotropic tide spin-up the development of internal waves. After the growth of the internal tidal wave amplitudes ceases, a packet of short-period internal waves is generated at each phase of the internal tide with a solitary wave of high amplitude running before the packet. Such a wave packet and leading wave were recorded during the measurements with a towed profiler in a scanning regime on the Yamal slope. A CTD profiler (Idronaut 316) was towed at a low speed while its depth was periodically changed by lowering and lifting the instrument using a winch.

The calculations using the numerical model with a horizontal resolution of 100 m and 20 vertical layers are shown in Fig. 1. A section of the density obtained

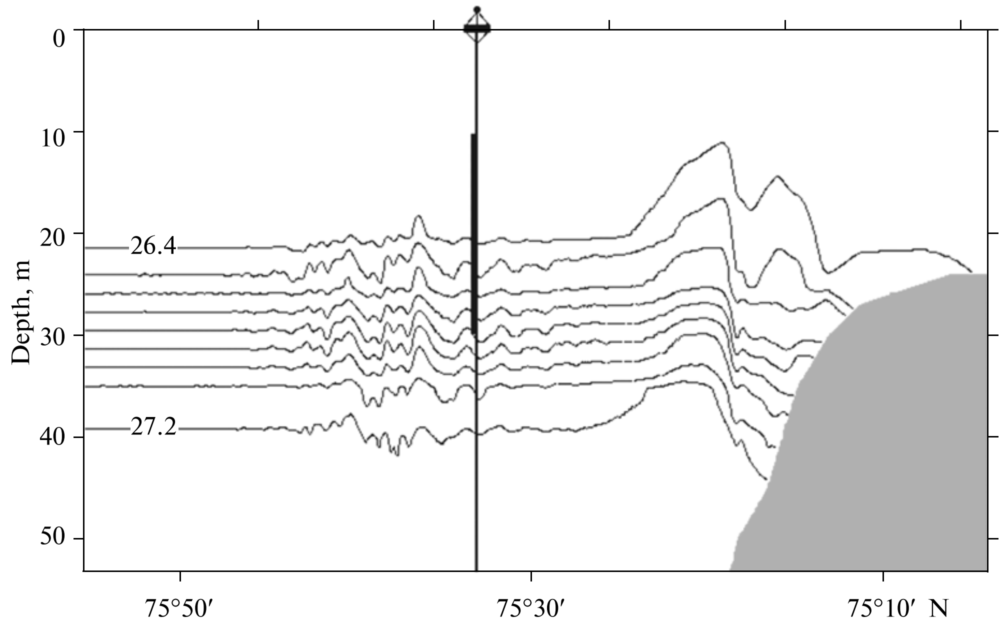

Fig. 2. The calculated field of the isopycnal surfaces (26.4–27.2) perturbed by the generation of the internal tide over a slope. A packet of short-period waves propagates from the slope to the north. The vertical line at the latitude of 75°33′ shows the location of the mooring with the distributed temperature sensor. The distributed sensor recorded the integral temperature in the layer of 10–30 m.

from the towed scanning profiler is also shown in this figure. The distance scales in the figure are the same. The fluctuations of the isopycnal surfaces, as well as of the temperature and salinity, on the seaside of the slope are caused by the internal tidal wave generated there. The fluctuations of the temperature, salinity, and density caused by the propagation of a solitary internal wave are seen over the flat slope from the shelf side. These fluctuations decay closer to the coast, because the energy of the internal wave is not high enough to pass over large distances.

The measurements using a towed profiler cannot resolve the short-period internal waves over the shelf, because the horizontal resolution of such measurements is approximately 500 m. Radar observations of the sea's surface from the ship were carried out simultaneously with the towed measurements [20]. The presence of short internal waves over the shelf is confirmed by the radar observations of the surface. The manifestation of internal waves at the surface is recorded by the radar as a band normal to the slope and the ship's heading. A band of increased intensity in the backscatter signal characteristic of the surface manifestation of internal waves is seen on the radar screen. This band is displaced as the ship moves. The front of the internal wave is practically normal to the ship's heading.

INTERNAL WAVES ALONG THE OB SECTION NORTH OF THE CRITICAL LATITUDE (74.5°)

Calculations using the numerical model in [29] were performed to estimate the amplitudes of the internal waves. The fluctuations of the isopycnal surfaces over a bottom slope on the Ob section were considered in the region of the bottom deepening from 20–30 m to 50 m and the further slow increase in the depth to the St. Anna Trench down to depths of 380 m. Depth variations over the slope from 25 to 50 m were specified in the model at latitudes of 75°10′–75°20′N, which corresponds to the real topography of the section.

The results of the calculations for the velocities of the barotropic tide of 20 cm/s are shown in Fig. 2. At such velocities of the barotropic tide generating an internal wave on the slope, the energy excess leads to the generation of a packet of short-period waves, which is propagates to the north. According to the model, at lower velocities of the barotropic tide, such a packet is almost not formed.

A mooring with a distributed temperature sensor was deployed in this region to record the internal waves. The coordinates of the mooring are 75°33′N, 72°33′E. The distributed sensor recorded an average temperature in the depth interval from 10 to 20 m, while two point sensors recorded the temperature at the ends of the distributed sensor. The depth of the

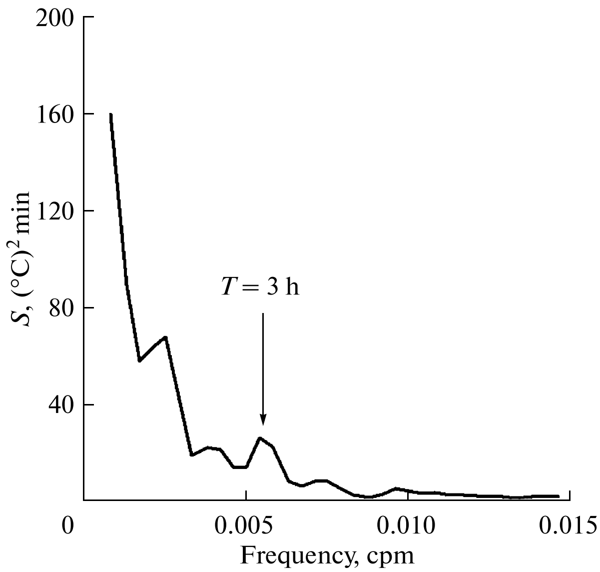

Fig. 3. Spectra of the temperature fluctuations based on the measurements using the distributed temperature sensor in the low-frequency range.

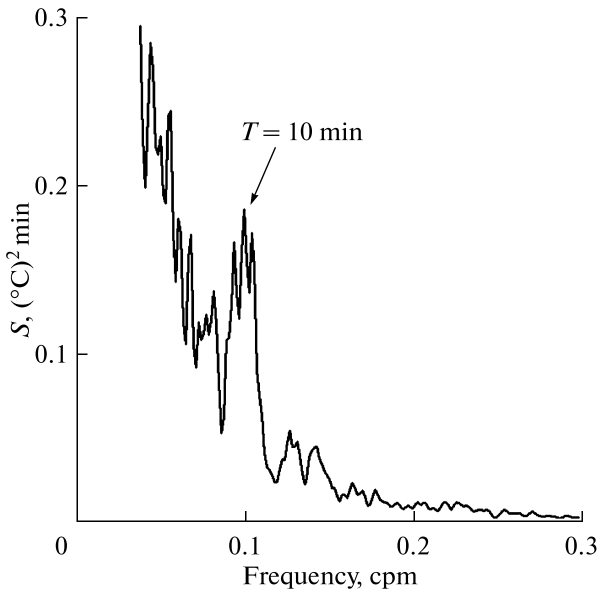

Fig. 4. Spectra of the temperature fluctuations based on the measurements using the distributed temperature sensor in the high-frequency range.

deployment was 105 m. The time interval of the measurements was 10 s.

The instrument recorded fluctuations of long periods (6 and 3 h) and also periodically appearing fluctuations of short periods. The dominating periods of the perturbations can be distinguished in the short-period range corresponding to internal waves with periods of approximately 10 min. No oscillations with periods of 12.4 and 12.0 h were recorded. This was expected because such internal waves can exist only as forced waves over a steep slope. The mooring was deployed north of such a slope over small inclinations of the bottom.

The spectra of the temperature fluctuations in the low and high frequency ranges are shown in Figs. 3 and 4. These spectra demonstrate the existence of fluctuations with periods of 6 and 3 h in the low-frequency range and fluctuations with a period of approximately 10 min in the high-frequency range. Fluctuations with a higher frequency from 10 s to one minute are seen in some time intervals of the record. Such fluctuations do not appear regularly. The fluctuations of the temperature in the interval of intense

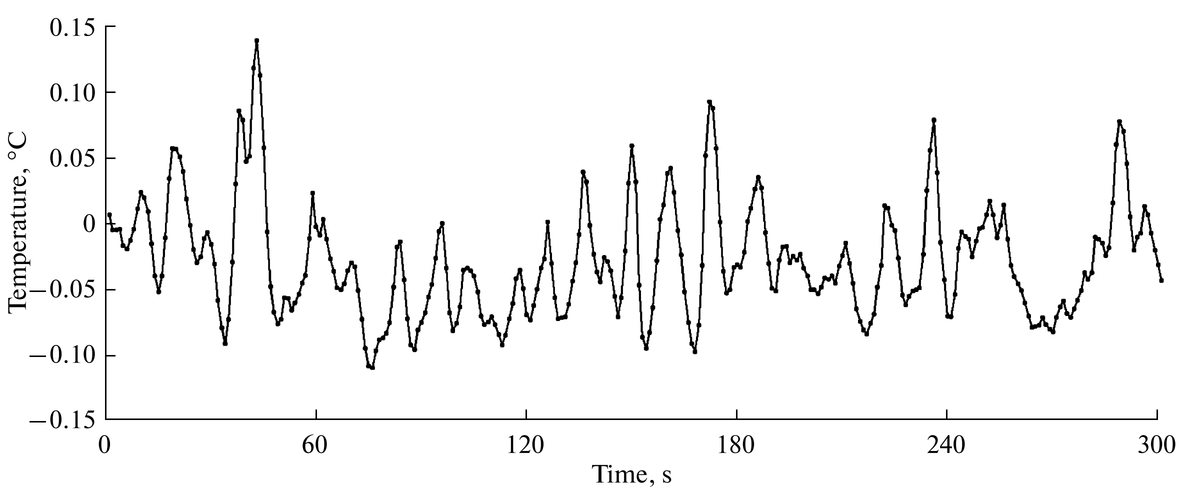

Fig. 5. Temperature fluctuations caused by the propagation of waves based on the measurements using the distributed temperature sensor.

high-frequency fluctuations are shown in Fig. 5. Characteristic fluctuations with a period of approximately 10 s are clearly seen.

CONCLUSIONS

The temperature measurements with a distributed temperature sensor in the thermocline layer on the Ob section at a latitude of 75°33′ demonstrated the existence of temperature fluctuations with a period of a few minutes, which is a response to the propagation of short-period internal waves generated by the internal tidal wave over the shelf break. Packets of short-period internal waves occasionally appear in the region of the measurements. Internal waves with a period of 12.4 h were not recorded because the measurements were carried out a long distance from the steep shelf break. The existence of an internal tide as a forced wave is most likely over steep slopes.

Internal waves propagating from the shelf breaking to the coast were recorded west of the Yamal Peninsula. The existence of internal waves demonstrated by the calculations using a numerical model was confirmed by the measurements of a towed profiler and radar.

The moored measurements recorded fluctuations with periods of 6 and 3 h, as well as fluctuations caused by high frequency internal waves on the shelf break north of the Yamal Peninsula. The fluctuations with such periods appeared spontaneously. Oscillations with a period of 12.4 h and other semidiurnal oscillations were not recorded by the mooring because the measurements were carried out north of the critical latitude.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project no. 08-05-00120), the NWO–RFBR program (project no. 047.017.2006.003), the World Ocean Federal Targeted Program, and Program 17 of the Presidium of the Russian Academy of Sciences (Fundamental Problems of Oceanology: Physics, Geology, Biology, and Ecology).

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