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REMOTE STUDY OF OCEANIC PROCESSES IN POLAR REGIONS

Characteristics of Short-Period Internal Waves in the Kara Sea Inferred from Satellite SAR Data

I. E. Kozlov[a, b, *], V. N. Kudryavtsev[a], E. V. Zubkova[a], A. V. Zimin[a, c], and B. Chapron[d, a]

[a] *Russian State Hydrometeorological University, St. Petersburg, Russia*
[b] *Klaipeda University, Klaipeda, Lithuania*
[c] *Shirshov Institute of Oceanology, Russian Academy of Sciences, St. Petersburg Branch, St. Petersburg, Russia*
[d] *Institut Francais de Recherche pour L'exploitation de la mer, Brest, France*
**e-mail: igor.eko@gmail.com*

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Abstract—In this paper we present the results of short-period internal wave (SIW) observations in the Kara Sea on the basis of satellite ENVISAT ASAR data between July and October 2007. Altogether, 248 internal wave (IW) packets and solitons are identified in 89 SAR images. Detailed spatial statistics of IW signatures and their properties in the Kara Sea is presented. The primary regions of IW activity are the areas near the Kara Gates Strait, the southeastern part of the Novaya Zemlya Trough, and in the vicinity of Cape Zhelaniya. We identify the regions where large IW packets are observed with wavelengths up to 2–3 km and the front length exceeding 200 km. The mean interpacket distance for observed IWs is about 20 km, but it may reach 50–60 km. Consequent IW packets are observed to travel up to 500 km from the presumed generation points. The results of satellite observations are compared with results of previous studies.

Keywords: short-period internal waves, SAR imaging, the Kara Sea

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INTRODUCTION

The study of internal waves (IWs) in the Arctic seas is an important scientific problem and is of great value for a wide range of applications (*Poverkhnostnye i vnutrennie volny...*, 2002). Information about the spatial distribution of IWs and their main characteristics (amplitude, wavelength, etc.) may be very important, e.g., for submarine navigation security and activity related to underwater propagation of acoustic signals. The importance of IW studies in the Arctic seas is also caused by the intensive development of mineral resources on the Arctic shelf and building concerned with it.

Until recently, there has been little information about the IW characteristics in the Arctic basin. Some information about the IW characteristics in the Kara Sea may be found in monograph (*Poverkhnostnye i vnutrennie volny*, 2002), which presents the first summarized results of IW studies in the Arctic seas. Those results were obtained on the basis of numerical simulation and ship observations. The following papers (Morozov et al., 2003; Morozov et al., 2008) present analyses of peculiarities of IWs generation and propagation in the Kara Gates Strait.

It's well known that the critical latitude effect is important for IW studies in the Arctic. In the vicinity of critical latitude internal baroclinic tides M2 (the most energetic tidal frequency) are suppressed and cannot freely propagate from their generation sites. The last fact leads to the destruction of the internal tide and of generating packets of short-period internal waves (SIWs), which can easily propagate at high latitudes and further transfer the tidal energy.

With lower periods than the internal tidal waves, SIWs may represent intensive nonlinear IWs with high amplitudes and lead to a high variability of hydrological characteristics and mixing of stably stratified waters (Sabinin et al., 2004). For existing models, a numerical presentation of SIW generation, propagation, and transformation processes is rather complicated, since such processes are usually "subgrid," even for high resolution models, and require considerably reducing the calculation grid size (*Poverkhnostnye i vnutrennie volny*, 2002; Morozov, Pisarev, 2002). Therefore, there are very few results of numerical calculations of characteristics for the considered kind of waves in the Arctic seas (Pelinovsky et al., 2002); and the basic information about existing SIWs is mainly based on the results of sparse and irregular ship observations (Kozubskaya et al., 1999; Sabinin and Stanovoy, 2002; Stanovoy and Shmel'kov, 2002; Morozov and Paka, 2010; Morozov et al., 2008; Zimin, 2012). It is, therefore, still much to discover about the role and hotspots of SIW generation in the Arctic seas as a whole and in the Kara Sea particularly.

Table 1. Basic characteristics of satellite radar observations of IWs in the Kara Sea

Month, 2007	Number of radar images		Number of IW packets
	IMM	WSM	
July	0	8	0
August	0	11	44
September	4	48	118
October	14	4	86
Totally	89		248

Since recently, methods of ocean remote sensing from space and, primarily, using synthetic aperture radars (SAR) made it possible to figure out the problem of ocean IW studies in a new way. Satellite observations of the IW surface signatures enable to determine their spatial parameters and allocate the areas of their regular occurence, as well as analyze the possible mechanisms of their generation and evolution (Apel, 1985; Jackson, 2004; Zhao et al., 2004b; Bondur et al., 2008; da Silva et al., 2011; Lavrova et al., 2011a). Utilization of satellite SAR data now became a standard technique for investigation of IWs all over the World Ocean (Jackson, 2004) and in Russian seas (Lavrova et al., 2009; Lavrova et al., 2011b; Dubina and Mitnik, 2007; Kozlov et al., 2010; Kozlov et al., 2014).

As SIW generation is often associated with the evolution of the internal tide (Sabinin and Serebryany, 2007; Jackson et al., 2012), especially near the critical latitude (Morozov and Pisarev, 2002; Vlasenko et al., 2003; Morozov and Paka, 2010), satellite observations of SIWs may indicate the main areas, or hotspots as defined by (Sabinin, Serebryany, 2007), of propagation and maximal activity of internal semidiurnal tides.

Despite the presence of ice cover in the Arctic seas, satellite data can be effectively used for studying the SIW field characteristics during the summer–autumn period. Nevertheless, there are only few results of radar observations of IWs in the Arctic seas (Dikinis et al., 1996, 1999; Kozlov, 2008; Kozlov et al., 2010; Kozlov et al., 2014). Some results are available for the Barents Sea (Kozlov et al., 2010) and the White Sea (Zimin et al., 2014; Kozlov et al., 2014). As far as we know, corresponding studies for the Kara Sea were not performed.

This paper presents the results of the SIW field analysis in the Kara Sea on the basis of Envisat ASAR images aquired during the summer–autumn period of 2007. We present the general statistics of SIW occurrences in the Kara Sea and the spatial distribution of their main characteristics. The main areas of the IW generation and propagation were also determined. In addition we also performed a comparison of satellite observations with the results of the previous studies.

DATA AND PROCESSING METHODS

For an analysis of spatial variability of IWs in the Kara Sea, we used Envisat ASAR C-band images acquired in WSM and IMM mode with spatial resolution of 150 × 150 m at VV and HH polarizations. Satellite radar images were obtained from the rolling archive of the European Space Agency (ESA). In total, 89 SAR images were analyzed. Table 1 shows summary data of the number of the processed radar images for different months in 2007. As may be seen from Table 1, the maximal number of images was available for September (52 radar images) and October (22 radar images), which are the months with the minimum ice cover. Figure 1 shows (online version of the paper is available at the site www.elibrary.ru) a map of the SAR data coverage of the Kara Sea during the entire period of observations. As may be seen from the map, the sea area is covered rather evenly; the average number of acquisitions is about 30 SAR images per water-area unit and reaches up to 50 images in the northeastern part.

It is well known that propagation of IWs is accompanied with periodic horizontal currents on the sea surface (Gargett and Hughes, 1972). The interaction between wind waves and these surface currents leads to the generation of the IW surface signature in the form of contrasts of the sea-surface roughness. It is quasi-specular reflection from breaking waves and resonant scattering from short wind waves at the Bragg wavenumber that makes sea surface signatures of internal waves well visible in SAR images. For moderate incidence angles, the wavelength of short Bragg waves corresponds to the length of the radiowave. It's usually supposed that Bragg wave amplification/attenuation occurs in the surface currents convergence/divergence zones. On SAR images IW usually manifest in the form of alternating bright and dark bands (see Fig. 2).

Procedure of SAR image analysis was carried out using INTERWAVE software (Kozlov and Myasoedov, 2012) developed by the authors. This software enables to perform preprocessing and visualization of radar images, select image part of interest, draw a transect across the IWs packet, and determine their basic characteristics: value of radar-signal modulation (of IW signature), as well as all the information associated with characteristics of SAR imaging geometry, local depth, and near-surface wind. Information about the bottom topography was taken from the data base IBCAO Ver. 3.0 (Jakobsson et al., 2012).

Figure 2 presents an example of the IW packet identification in Envisat ASAR image acquired on 27.08.2007 in the area to the east from the Kara Gates Strait. To reduce speckle noise typical for SAR images of sea surface, the normalized radar cross section value along the transect was calculated as a mean value taken over ten parallel lines. Then, using the signal profile along the transect, its orientation, and the image itself, we determined the following IW characteristics: max-

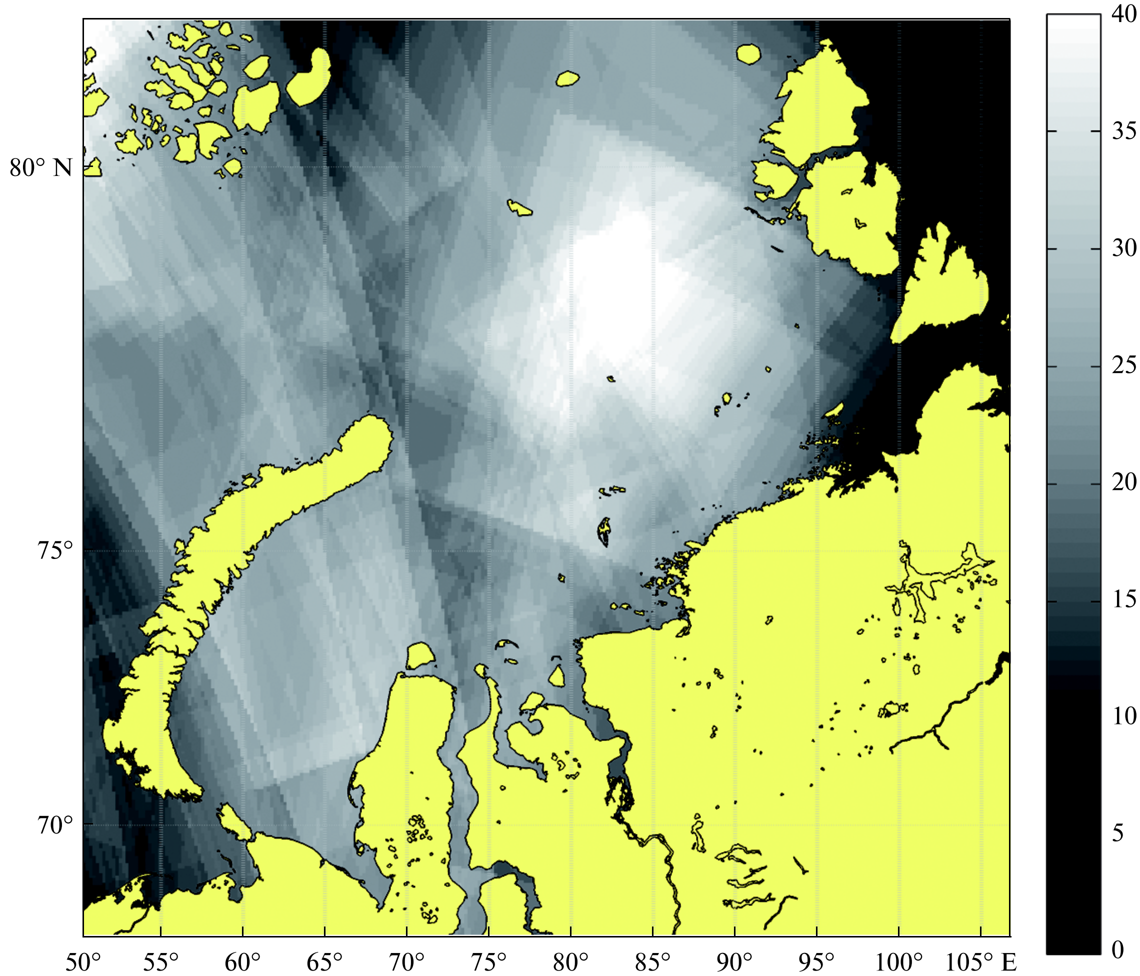

Fig. 1. Map of SAR data coverage of the Kara Sea for July–October 2007.

imal and minimal wavelengths in the packets, crest length of the leading wave, number of waves in the packets, packet area, direction of IW propagation, and distances between the consequent packets.

After all the radar images were processed, we plotted total maps showing spatial distribution of mean values of different IW characteristics. The mean value for the each IW parameter was determined for the grid cells 0.45° N × 1.8° E with the total grid size 30 × 30.

RESULTS OF SATELLITE OBSERVATIONS

In total, after processing of 89 SAR images, we identified 248 IW packets. Most of IW packets (~80%) were detected in September and October (see Table 1). It should be noted that IWs appeared more often in October than in September; one image in September contains two IW packets on average, while in October about five IW packets on average were identified in one image.

Figure 3 shows a map of spatial distribution of IW packets in the Kara Sea. For the clearance, only crests of leading waves in the IW packets were plotted on the map. The maximal number of IW observations (about 60% of total number of the identified packets) is concentrated in southwestern part of the sea: from the Yugorski Shar Strait, then to the East of the Kara Gates Strait, and to the middle of the Novaya Zemlya Trough (see Fig. 3b). IWs were also frequently identified in the area to the northeast from Cape Zhelaniya, as well as to the east and west from southern part of the Central Kara Upland.

IWs were also observed in the northern areas of the sea to the north from 80° N between Vize Island and Ushakova Island, as well as to the north of Shmidt Island ($\theta = 81.6°$ N). In summer time, these regions are usually covered with ice, but there was minimum ice cover area in the Arctic during summer–autumn 2007, which enabled us to carry out the observations.

It should be mentioned that, during the entire period of observations, IWs were not observed in shallow sea areas (up to 50 m depth), including shelf zones in the vicinity of the Ob’ and Yenisei rivers, excluding some areas in northern part of Yenisei Bay, to the North of Sibiryakova Island and in the vicinity of Sver-

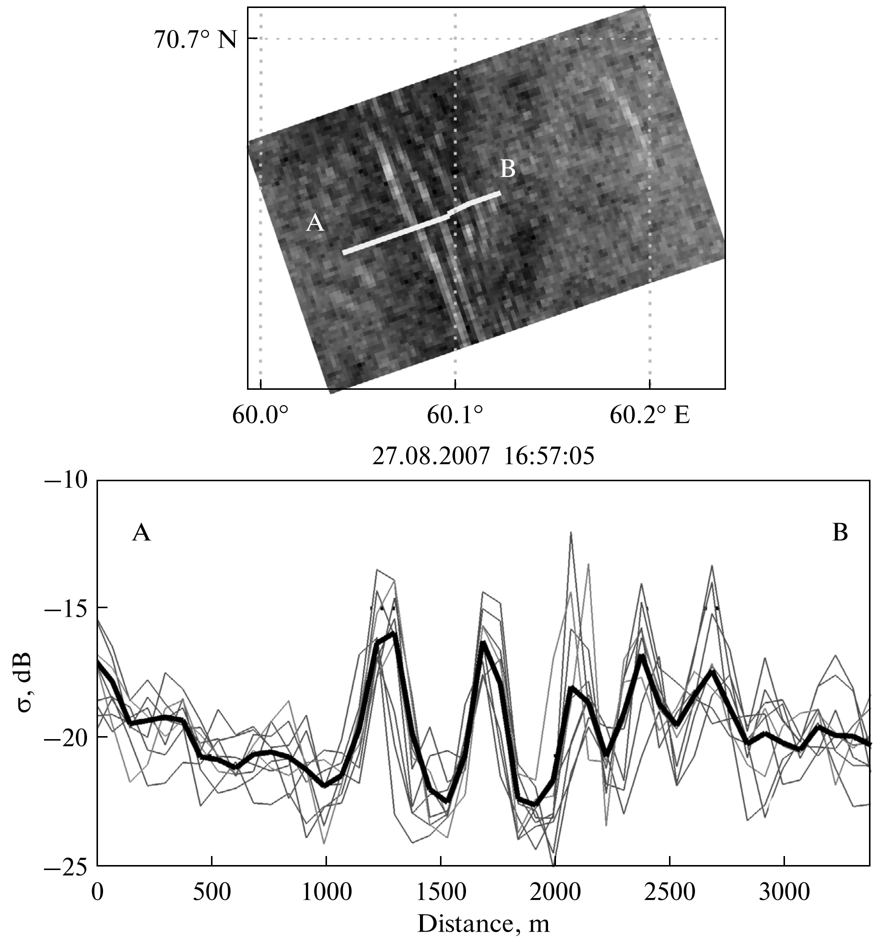

Fig. 2. An example of IW packet identification and extraction of transect crossing internal waves in a region to the east of the Kara Gates Strait in Envisat ASAR image acquired on 27.08.2007 using INTERWAVE software ©ESA ©INTERWAVE.

drup Island (see Fig. 3a). Most of the observed IW packets are located over the deeper sea parts and close to the abrupt topography changes from 100 to 200 m.

Figure 4 shows a map and histogram of the IW observational frequency distribution in radar images of the Kara Sea. The value of IW observational frequency was obtained as the ratio of the general number of IW packets at each sea sector to the total number of radar images of this sector. The IW observational frequency indicates how many IW packets on average correspond to one radar image of the region. To determine this value, we used all the available radar images of the Kara Sea. As may be seen in Fig. 4, the most frequently IWs were observed in the Kara Gates Strait, along the eastern coast of Yuzhnyi Island (Novaya Zemlya Archipelago), at the outer boundaries of the Matochkin Shar Strait, and to the east from Cape Zhelaniya. In these regions, the IW frequency attains a value of 0.5; i.e., at least one IW packet might have been observed at the each second radar image of the sector. At the rest part of the sea, IWs were observed less frequently; the average value of relative observational frequency was about 0.1.

Table 2 shows statistical parameters of some measured IW characteristics. We should mark some peculiarities of the results represented in Table 2. On the radar images, IWs were observed in the form of internal solitary wave trains, two to three waves on average (11 waves maximum) per packet, with an average (maximal) packet length of about 1.5 km (14 km). In some rare cases, they appeared as single solitary waves.

The average value of maximal wavelength in the packet (distance between adjacent solitons) was 0.6 km, whereas the average length of the leading wave crest was about 40 km. It should be noted that, in a number of cases, we observed solitons of especially large waves with wavelengths of 2–3 km (2.3 km at maximum) and with a length of the leading wave crest of about 200 km (225 km at maximum), which are comparable with the horizontal dimension of large intensive IWs of high amplitudes (Apel et al., 1985; Jackson, 2004; da Silva et al., 2011). The average area of the packets was about 60 km^2, but for the largest packets it may attain values of more than 700 km^2.

Regular observations of the IW packets in the regions marked above allows to suppose that observed

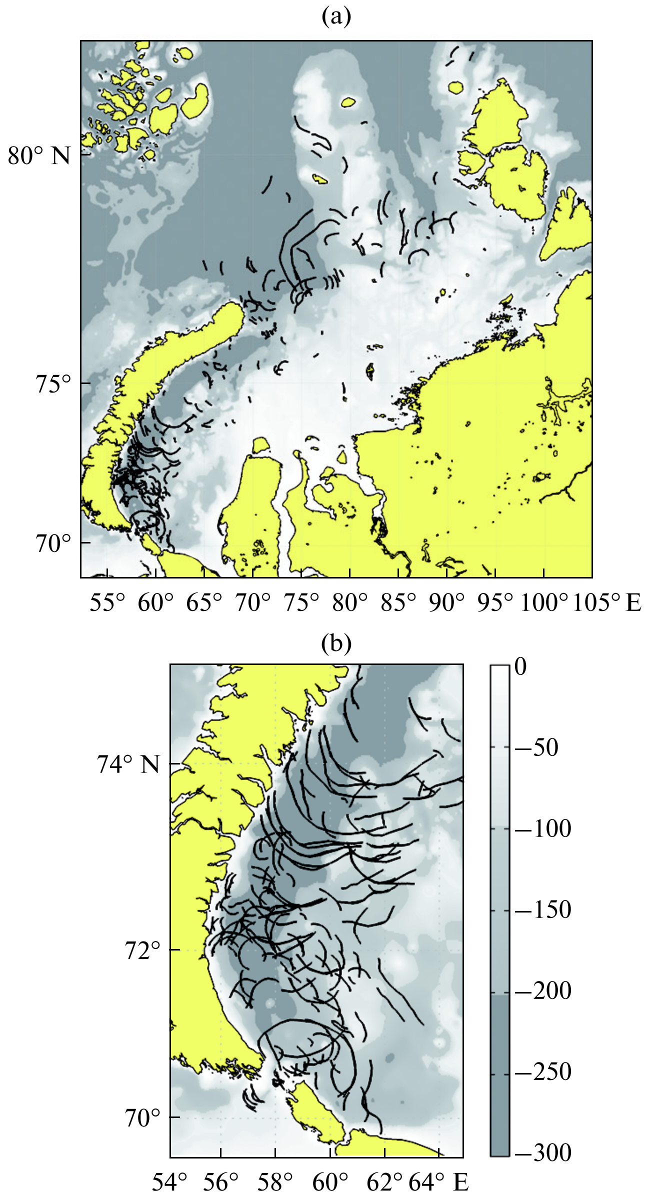

Fig. 3. Spatial distribution of IW packets: (a) for the entire Kara Sea and (b) in the southwestern part of the sea according to Envisat ASAR data in July–October 2007.

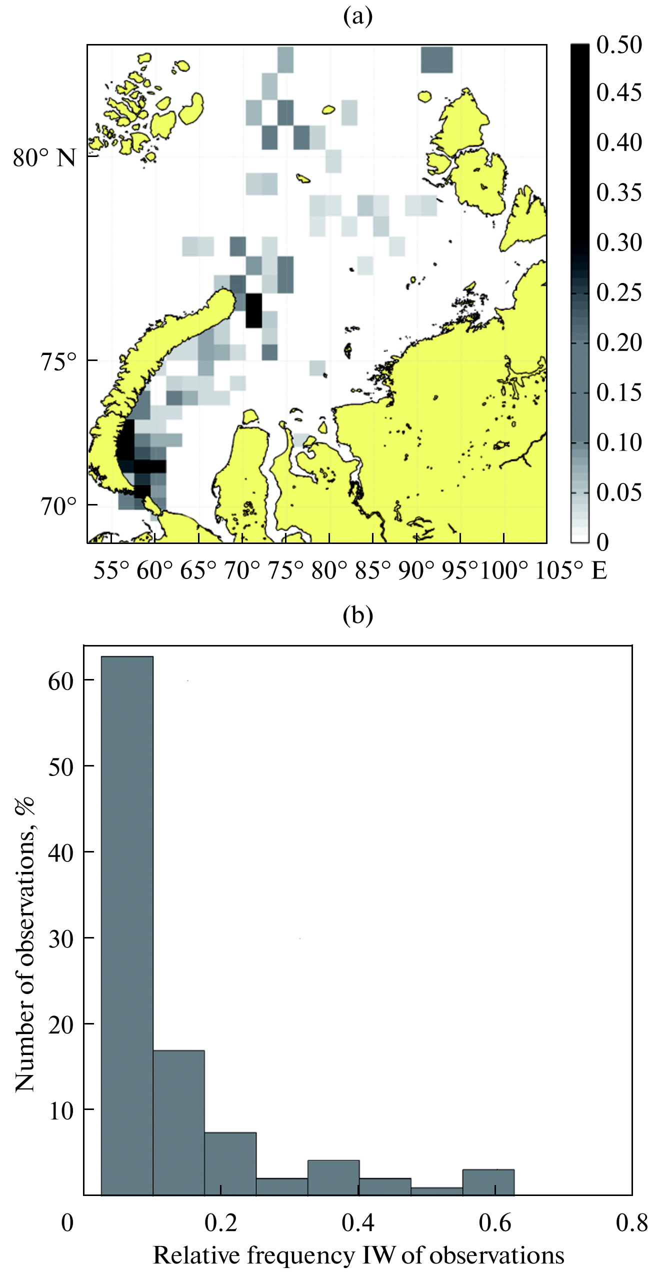

Fig. 4. Relative observational frequency of IW packets in satellite SAR images of the Kara Sea: (a) map of spatial distribution of IW observational frequency; (b) histogram of observational frequency.

IWs are predominantly of tidal origin. In a number of cases, one SAR image contained the entire series of the consequent IW packets, which admittedly have the same region of generation. The maximal number of such packets was five and even more. As is seen from Table 2, the average distance between the adjacent IW packets is about 20 km, but it may reach 50–60 km.

Figure 5 shows a map of spatial distribution of basic IW parameters listed above. As is evident from Fig. 5, there are typically packets with three–four waves per packet. The packets largest in the number of waves (from 8 to 11 waves) were observed over the Central Kara Upland, to the east of Cape Zhelaniya, as well as in the vicinity of the Matochkin Shar Strait (seven waves). The maximal wavelength in the packet (over 2 km) basically appeared in the northern part of the sea, to the north and the east of Cape Zhelaniya (see Fig. 5b). Along eastern coasts of Novaya Zemlya archipelago and in the vicinity of the Kara Gates Strait, the wavelengths were 0.4–0.7 km.

IW packets with a crest length of the leading wave over 100 km appeared to the east of Matochkin Shar Strait and east of Civol'ki Bay, to the northeast of Cape

Table 2. Statistical characteristics of basic IW parameters in the Kara Sea according to satellite SAR observations

IW parameter	Maximum	Minimum	Mean value	Median
Number of waves per packet	11	1	3	2
Maximal wavelength, km	3.20	0.15	0.63	0.54
Front length of the leading wave, km	224.45	4.50	37.06	28.80
Length of wave packet, km	14.47	0.10	1.72	1.28
Packet area, km^2	733.26	1.80	64.45	28.60
Distance between the packets, km	63.26	0.73	18.71	17.52

Zhelaniya (the deepwater part of the sea) and at the northwest of the sea over the southern part of Voronina Trough (see Fig. 5c). IW trains with a maximal crest length of 225 km were recorded over the southern part of St. Anna Trough. We observed shorter wave crests with crest lengths of 50 km at shallow areas of the sea, over the Ob-Yenisei shallow water, the Central Kara Upland, and the shelf areas near archipelagos of Novaya Zemlya and Severnaya Zemlya.

The largest IW packets (see Fig. 5d) were located in the deepwater areas of the sea: to the east of the Matochkin Shar Strait and to the northwest of Cape Zhelaniya (over 200 km^2). On average, the packet area was about 80–100 km^2; the most frequent packets were small, with areas as small as 50 km^2. For Central Kara Upland, packet areas vary in a wide range from minimal to maximal. There are packets with a small area over its central part and packets with large areas over steep slopes and deepwater troughs.

Figure 6a shows a map of the spatial distribution of propagation of IW packet directions (relative to the direction to the north). It should be seen that waves propagate in different directions right up to opposite ones, even in separate areas of the sea. One striking example is the Kara Gates Strait, from which IWs propagate in southwestern direction to the Barents Sea, as well as in east and northeast directions to the Kara Sea (see Figs. 7–8).

Along the eastern coast of Novaya Zemlya Archipelago over the deepwater part of Novaya Zemlya Trough, large systems of consequent IW packets propagating in the southern direction (see Figs. 3, 7) were regularly observed. In the area from the Kara Gates to approximately 73° N, IWs propagating from the trough to the east and northeast were regularly observed. In the northern part of the sea (over 76° N), the western direction of propagation basically dominates, but we should also mark wave packets propagating to the northeast from Cape Zhelaniya to the Central Kara Upland and then to Voronina Trough. Wave packets to the north of Schmidt Island propagate in the northwestern direction. On the whole, the dominant direction of IW propagation is westward (Fig. 6b).

As was noted above, in radar images we sometimes observed a series of sequential IW packets, similar in their configurations and propagation direction. Throughout the entire observation period, we identified 55 such packets and measured distances between them. The map and distribution histogram of distances between adjacent packets are shown in Figs. 6c and 6d. In approximately 30% of cases, the distance between the packets did not exceed 10 km; the second peak (~25%) was indicated for 20 km (Fig. 6d). In 10% of observations (about six cases), the distance between the packets exceeded 40 km with the maximum value of 63 km. As may be seen from Fig. 6c, packets with a distance up to 30 km were observed in all main observation areas, whereas IWs with inter-packet distances in the range of 30–60 km were basically identified in the northern part of the sea over abrupt depth changes to the east of Cape Zhelaniya, among the Central Kara Upland and Voronina Trough, as well as in the deepwater part of the sea over St. Anna Trough (the maximal value of 63 km).

It is well known that the generation of SIW packets is often related to internal tide propagation and transformation and the distance between consequent SIW trains may correspond to the wavelength of the internal tide (Jackson et al., 2012). Our estimated interpacket distances of 20–40 km agree well with in situ and model results (Morozov et al., 2003; Morozov et al., 2008). Assuming the generation of SIW packets every tidal cycle (each 12.4 h), we can easily obtain the value range of IW phase velocities. For distances between the packets of 10–60 km, phase velocity values are 0.2–1.5 m/s. According to results presented in (Pelinovsky et al., 2003), the average value of a long linear internal wave propagation velocity in the Kara Sea was 0.3 m/s, which approximately corresponds to the lower limit of our observations.

Figure 7 shows an example of IW packet signatures in the western part of the Kara Sea on Envisat ASAR image taken on September 22, 2007. In a single image, the whole system of IW packets is represented, in total about 14 packets propagating from the north to the south over the deepwater part of Novaya Zemlya Trough. Enlarged fragments of SAR image with IW packets are presented in Figs. 7b–7f. The packets evidently have a characteristic convex form with the number of waves per packet from 2 to 12; they look

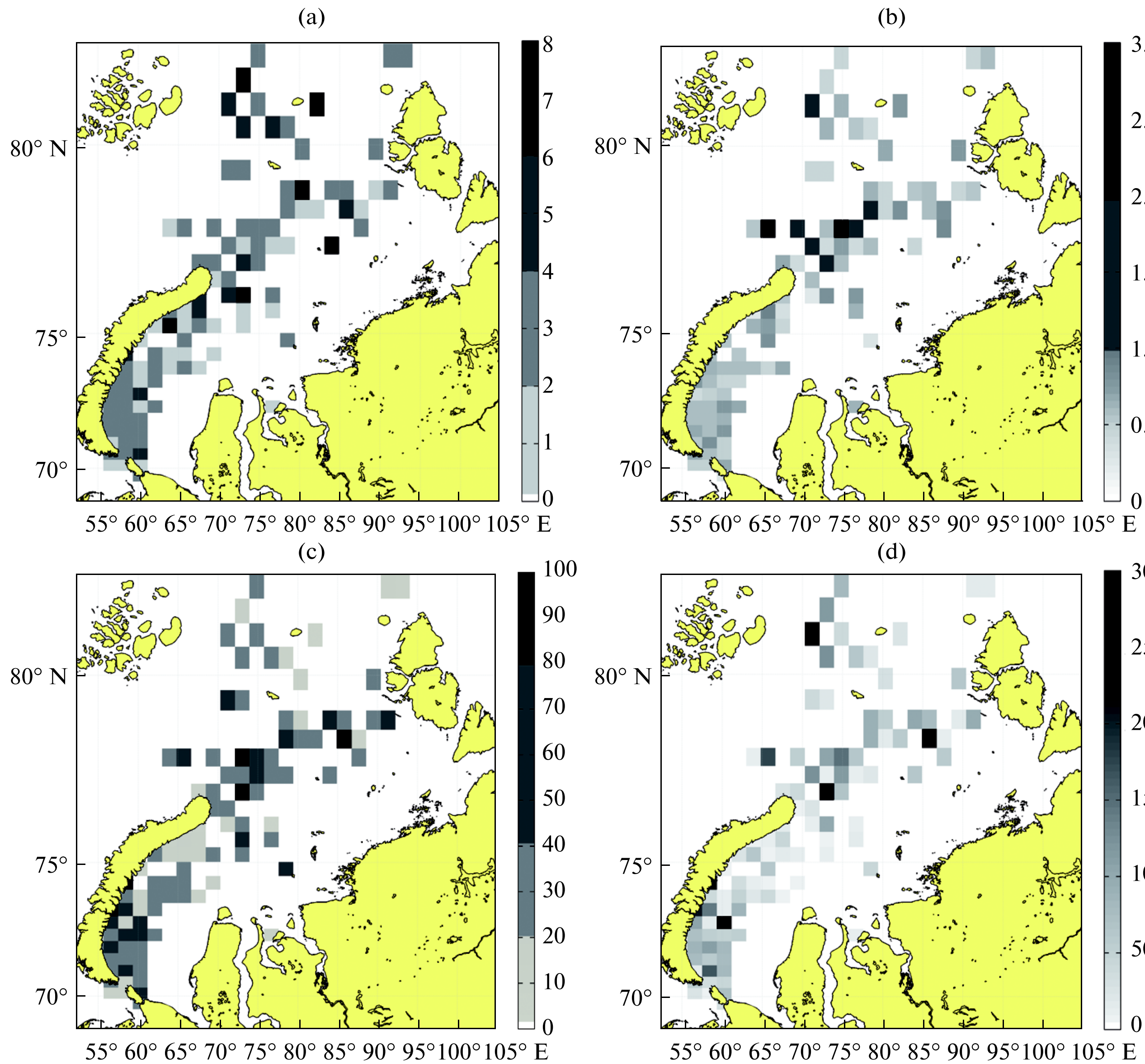

Fig. 5. Maps of spatial distribution of IW parameters in the Kara Sea: (a) number of waves in IW packets, (b) maximal wavelength in IW packets (km), (c) crest length of the leading wave (km), and (d) IW packet area (km^2).

consequential, though in some places their SAR signatures are not very distinct. It is hard to judge from a single SAR image whether all these IW packets originate from the same generation point, however, their form, generic structure of the system, and peculiar increase of the distance between the packets as they propagate to the south are in favour of this assumption. At the top of the radar image, the distance between adjacent packets is about 10 km (Figs. 7b, 7d), but gradually increases up to 25 km (Fig. 7e) at the bottom of the image. The general propagation trajectory of this system of SIWs is represented in Fig. 7a by a white line and is about 500 km (from 74.6° N to 71° N). SIW packets from one generation site are unlikely to overcome such a long distance (from generation source) without dissipation, though some examples are known in literature (for instance, see Kozlov et al., 2014). We can see an inverse scenario on some images: the system of IW packets propagates along the Novaya Zemlya Trough to the north.

It should be noted that, besides the main system of SIWs propagating to the south, the radar image shows a second SIW system that is parallel to the first and is located to the east over depths of 200 m. Some waves of the system are directed to the southeast. However, there are no observed packets overcoming the eastern boundary marked with a black dashed line in Fig. 7a. This line corresponds to peculiar SAR manifestation of surface

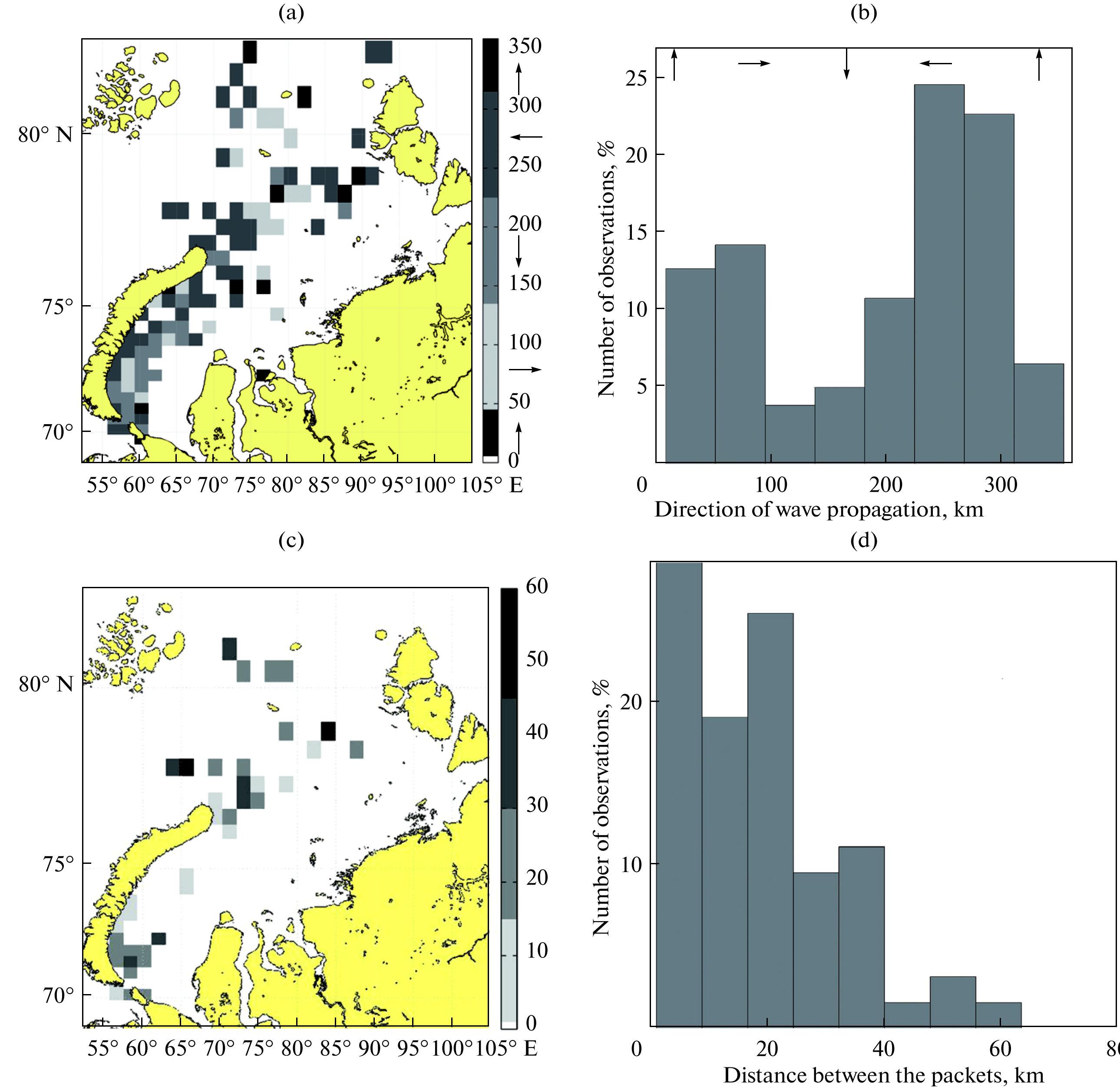

Fig. 6. (a, c) Maps and (b, d) histograms of distribution of IW propagation directions (a, b) and distances between consequent IW packets (c, d). Arrows show the main direction of IW packet for each segment of direction scale.

currents divergence/convergence zones near the boundary between fresh riverine Ob'-Yenisei waters and more dense waters of the western part of the Kara Sea.

We also marked two wave systems of opposite directions on this image near the Kara Gates Strait. The first system of three consequent packets propagates from the Kara Sea towards the strait (Fig. 7h); the distance between the packets is 18–20 km and the front length is 2–5 km. The second system of two packets is directed to the east (Fig. 7g); the distance between the packets is also about 20 km, but the crest length of the leading waves is over 50 km in both packets.

COMPARISON WITH RESULTS OF THE EARLIER STUDIES

In this section, we carry out a comparison of our results with the results of previously published field and model experiments. One of the most interesting regions of the Kara Sea is the Kara Gates Strait. An analysis of internal tide in this region was performed in (Morozov et al., 2003a, 2003b, 2008), which shows that, in the western part of the strait, there is generation of strong internal tide with high amplitude (up to 50 m) directed towards the Barents Sea. Then the internal tide transforms into internal bore followed by

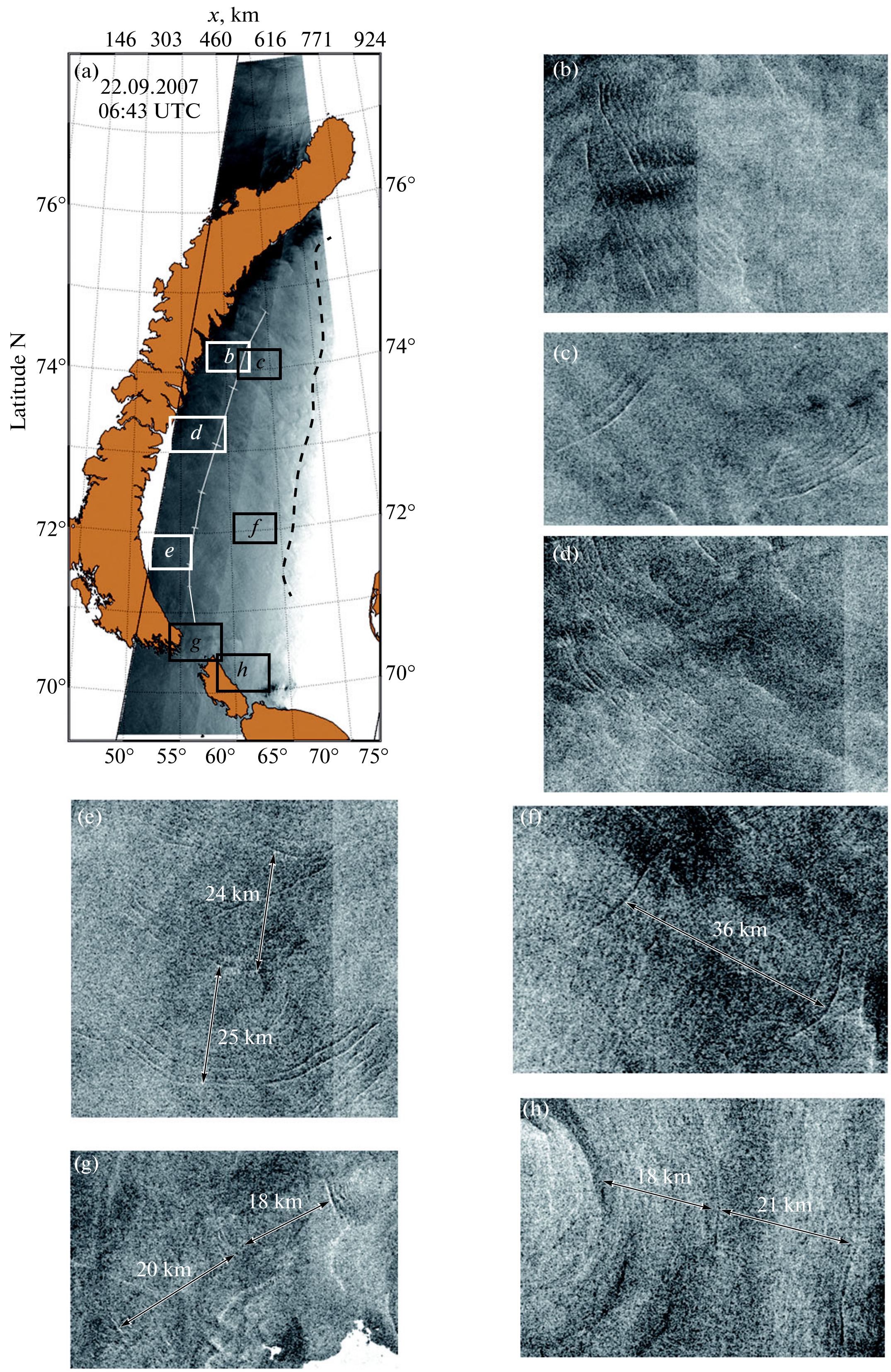

Fig. 7. Example of IW packet manifestations in western part of the Kara Sea in Envisat ASAR image acquired on September 22, 2007, 06:43 UTC: (a) location of SAR image and its corresponding fragments on the map and (b–h) enlarged fragments of SAR image illustrating IW packets manifestations in different parts of the image.

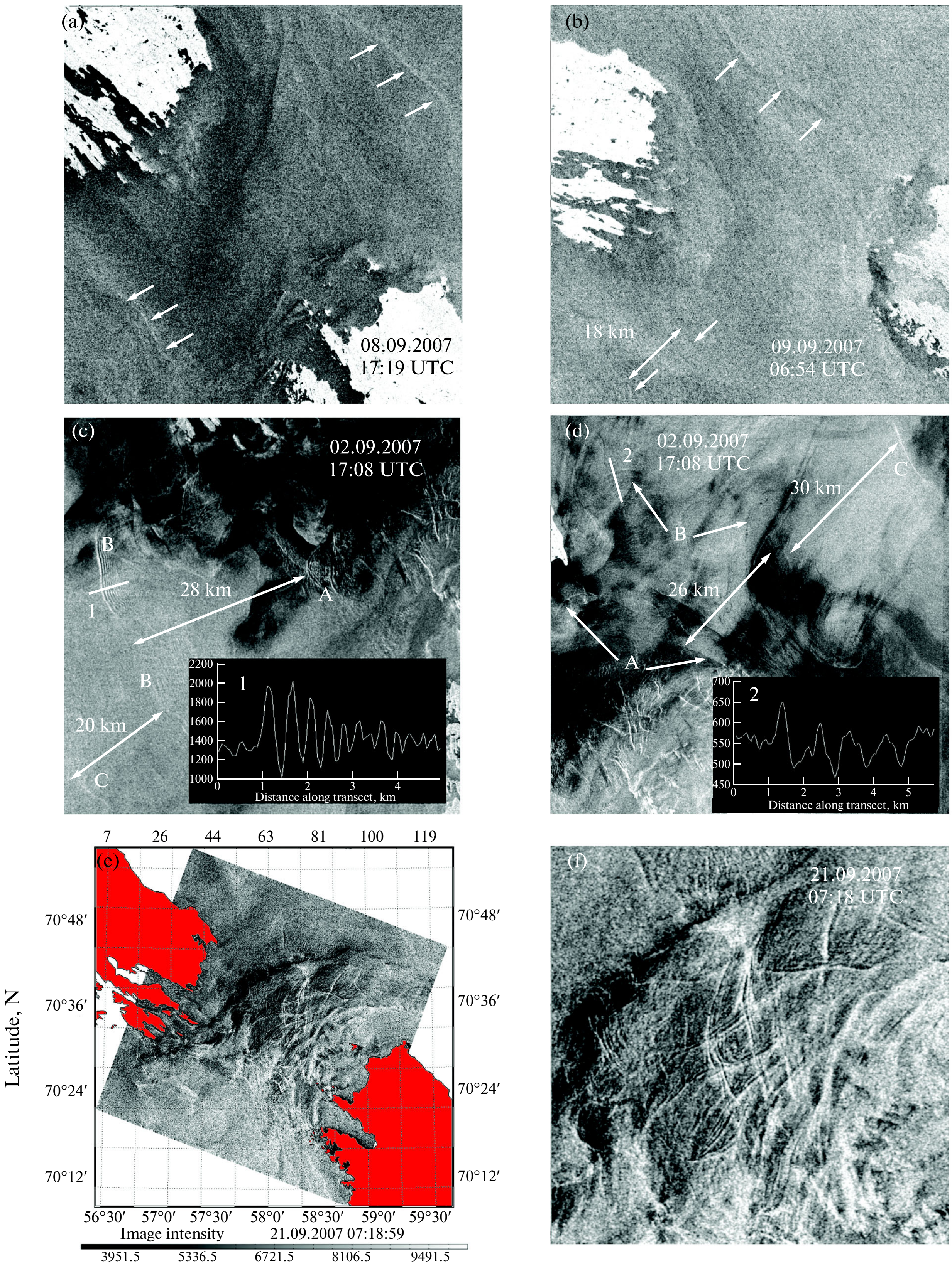

Fig. 8. Examples of IW packet observations near the Kara Gates Strait in Envisat ASAR images: (a) fragment of SAR image taken on September 8, 2007, 17:19 UTC; (b) fragment of SAR image taken on September 2, 2007, 17:08 UTC; (c–d) fragments of SAR image taken on September 2, 2007, 17:19 UTC; and (e–f) location of SAR image on the map and its fragment for September 21, 2007, 07:18 UTC.

a packet of SIWs. On the other side of the strait, an internal hydraulic jump is formed and is directed towards the Kara Sea. Herewith, according to results of model calculations, the IW length in eastern part of the strait (towards the Kara Sea) is longer than that in western part (the Barents Sea). Ship-borne IW measurements in this region were carried out from September 8 (22:20 UTC) to September 9 (06:40 UTC), 2007. For this period, the ESA rolling archive contained two SAR images acquired in the evening on September 8 (17:19 UTC) and in the morning on September 9 (06:54 UTC), 2007. Fragments of these images are shown in Figs. 8a and 8b. In both cases, background wind conditions were not so much favorable for IW detection in SAR images. They contained clear surface signatures of rain cells in the atmosphere; the velocity of near-surface wind was higher than the optimal range of 3–8 m/s.

In an image taken on September 8, 2007 (Fig. 8a), at both sides of the strait, we distinctly see bright stripes presumably related to internal wave manifestation on the sea surface. Analogous IW signatures in the form of stripes of locally enhanced radar backscatter were identified by ship radar during field experiment (Morozov et al., 2008). A visual interpretation of the radar image fragment on September 9 was difficult due to high near-surface wind (about 10 m/s). Nevertheless, in the eastern part of the strait, a signal anomaly in the form of alternating stripes of increased and decreased radar backscatter is seen. From the the Barents Sea side, we observe only weak IW signatures in the form of dark stripes with level of radar signal a bit lower than background. White arrows in Fig. 8b mark approximate boundaries of these packets; the distance between them is about 18 km.

In both images of eastern part of the strait, we observed manifestation of a solitary wave that propagates towards the Kara Sea. These signatures could be a surface manifestation of an internal tide. According to results of numerical simulation (Morozov et al., 2008), propagation of internal tide eastward from the strait is not accompanied by the generation of SIW packets. An analysis of satellite images for different dates indicated that SIW packets were observed to the east from the strait travelling to the Kara Sea. Figure 8d shows a fragment of a SAR image on September 2 (17:08 UTC), 2007. There are three consequent IW packets (marked with A, B and C) directed towards the northeast (see Fig. 8d). The distance between these packets is about 26–30 km and they contain 3–5 waves per packet (see Section 2 in Fig. 8d); the crest length of the first two packets is about 50 km, which is actually equal to the width of the strait. The IWs further propagate to the Kara Sea the more their crest length increases. These crests are formed as semiellipses whose major axis is elongated perpendicular to the main axis of the strait (see Fig. 3b). Such packets initially generated near the Kara Gates Strait were observed down to the area north of the Yugorskiy Shar Strait (Fig. 7i).

Propagation and evolution of the internal tide towards the Barents Sea (Morozov et al., 2003b; Morozov et al., 2008) is well seen in Fig. 8c. At approximately 15 km from central part of the strait, we can clearly see a small SIW packet (marked with A in Fig. 8c) with four to five waves and a front length of about 8 km. The following packet (B) is located at a distance of about 28 km from the first one; it contains 12–14 waves(see Section 1 in Fig. 8c) and its front length reaches 60 km. The distance between the following pair of packets (B, C, and further) is 20–24 km. The observed interpacket distances agree well with the length of internal tidal wave, 24 km, obtained from model and in situ measurements in this region a week after (Morozov et al., 2008). In this SAR image, in total, we observed five consequent SIW packets at the distances of about 140 km to the southwest from presumed generation site in the Kara Gates Strait.

We also should note one peculiarity of SAR signatures of SIW packets propagating from the strait to the Barents Sea. Figure 8c shows that the most distinct manifestation of packet B with maximal radar contrast were observed in upper-left part of the image (see location of section 1), but radar contrasts in the bottom part are much lower. This variation of radar contrast may be related to peculiarities of solitons propagating in conditions of varying stratification and background currents and the corresponding attenuation of their surface manifestation, or result from changes in SAR imaging geometry, for instance, local variation of the angle between radar range and direction of near-surface wind (for instance, see formula (6) in paper of Kudryavtsev et al., 2012). In any case, most SAR images of this region contain SIW packets that are usually located to the north from the main axis of the strait (where the northern part of the packet B is located) and propagate towards the west and the northwest along southwestern coast of Yuzhnyi Island (arch. Novaya Zemlya). It is also plausible that in the southern part these packets simply have weaker surface signatures and hence not apparently detectable, while in fact they may have the shape of semi-ellipses as shown on Fig. 8c.

One example of SIW packets the earlier propagating from the Kara Gates was also identified in Almaz-1 SAR image to the south of Sahaninykh Islands (Dikinis et al., 1999). Although the authors of this paper assumed that there was local generation of IW packets due to interaction of tidal current with local bottom topography, Envisat ASAR images having wide swath enabled us to confirm that IW packets in the vicinity of Sahaninykh Islands originate from the Kara Gates Strait. Inside the strait, we often observed a rather complicated picture of several systems of small IW packets with two–three waves per packet directed along and across the strait (see Figs. 8c–8f).

In paper (Sabinin and Stanovoy, 2002), on the basis of hourly measurements of current field over the

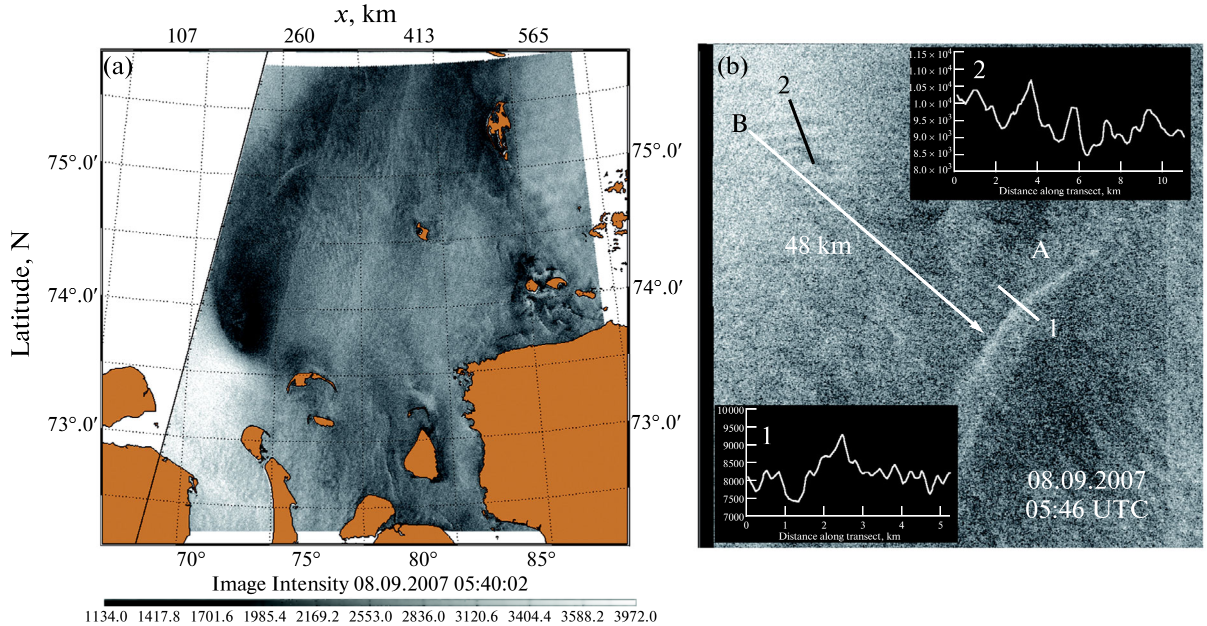

Fig. 9. Example of IWs manifestation of changing polarity in Envisat ASAR image of the southern part of the Kara Sea for September 8, 2007, 05:46 UTC.

northern slope of a bank located to the east of Novaya Zemlya Trough (approximately 71.8° N, 60.2° E), the authors analyzed semidiurnal tidal oscillations. For conditions of almost two-layer stratification, they identified semidiurnal IWs of the lower internal mode. Herewith, the authors noted the obvious nonlinearity of the observed IWs and frequent variation of their propagation direction: waves propagated alternately to the north and south. During an analysis of satellite images, we also observed IWs at various times in this region (see Fig. 3b). They usually propagate as packets moving towards the south, but some images also show packets of northern direction. An example of IW observation in this region is shown in Fig. 7f, where we distinctly see two consequent SIW packets with several waves each, the distance between them being 36 km and maximal wavelength in the packet being 3.2 km. These packets are part of large SIW system propagating from the region over Novaya Zemlya Trough in southern and southwestern directions. Perhaps IWs similar to those observed in satellite images were identified using contact methods. Authors (Sabinin and Stanovoy, 2002) explained existence of these IWs by the lee generation over a bank to the south of the measurement location. At the same time, satellite observations indicate that the generation of southward travelling IW trains most likely occurs over the slope of the Novaya Zemlya Trough, since the whole system originates from there. However, a confirmation of this fact requires a more detailed comparison of collocated satellite and in situ measurements.

As we noted before, IWs were rarely detected in a shallow shelf at the vicinity of Ob' and Yenisei estuaries. In the work by (Pelinovsky et al., 2002) noted that these regions are special zones for IWs propagation and kinematic IW characteristics significantly depend on background current regime. Results of hydrological measurements showed that, in shallow waters of the Kara Sea, buoyancy frequency profiles may have several peaks; and coefficients of quadratic and cubic nonlinearity defining the polarity of short-period solitons alternate in sign. This means that, in satellite radar images, we may expect "unusual" IW manifestation, including IWs of the second mode (da Silva et al., 2011), solitons of elevation, and soliton-polarity changes during its propagation (Zhao et al., 2004a). Without information about local hydrology, we may neglect their signatures in SAR images. One example of such "unusual" (and rather moot) IW signatures is shown in Fig. 9. On the upper-left edge of the SAR image (the section is marked with a square) of the southern part of the Kara Sea to the northwest from Sverdrup Island, we observed radar signal anomalies, very similar to surface manifestation of oceanic IWs. Surface signatures of two possible IW packets are located 45–50 km from each other and, judging from the shape of their crests, directed to the northwest. The packet locations corresponds to depths of approximately 30 and 40 m in the seaward direction. One peculiarity of these signatures is the different sign of their signatures: in the southeastern part of SAR image (packet A in Fig. 9b), the dark stripe precedes the bright one (see transect 1 profile in Fig. 9b), which usually corresponds to elevation solitons of positive polarity, and at the top part of the SAR image fragment there is a traditional manifestation of dark bands on brighter background characteristic for solitons of depression (for instance, see Zhao et al., 2004; da Silva et al., 2011; Jackson et al., 2012). It is quite possible that IW signatures in Fig. 9b are caused by atmospheric impact, since this SAR image fragment covers the northern periphery of the polar low (see Fig. 9a). This is supported by the fact that observed radar signatures are rather unusual for oceanic IWs and have large distances (2–3 km) between adjacent waves in the packets. On the another hand, the observed signatures are located exactly in the vicinity of the region where, according to model calculations (Pelinovsky et al., 2002), we might observe polarity conversion of SIW solitons during their propagation. At the same time, according to the same paper, the IW generation site is located over an abrupt depth change and waves must propagate from the north to the south against the currents. In our case, it is opposite. Nevertheless, this case clearly illustrates possible difficulties for identification of IWs in shallow shelf regions and interpretation of their radar manifestations.

CONCLUSIONS

In this paper we presented results of analysis of the SIW field in the Kara Sea based on processing of satellite Envisat ASAR images for the summer–autumn period of 2007. After processing of 89 satellite radar images, we identified 248 SIW packets and solitons. For the first time, we presented detailed statistics of IW occurrences in the Kara Sea and the spatial distribution of their main parameters.

The most frequently SIW packets appeared in southwestern part of the sea, in the vicinity of the Kara Gates Strait, and over southwestern part of the Novaya Zemlya Trough, as well as to the northeast of Cape Zhelaniya and over the slopes of the Central Kara Upland. Most identified IW packets were located in deepwater parts of the sea, over abrupt depth changes (100–200 m), and near underwater slopes. Observed IW packets propagated both shorewards and seawards. On the whole, the western direction of IW packet propagation dominated.

The largest IW packets with a distance between adjacent waves in a packet of about 2–3 km and crest length of the leading wave of about 200 km were observed to the north of Cape Zhelaniya, over slopes of the Central Kara Upland, between Vize Island and Ushakova Island, and over Novaya Zemlya Trough in the vicinity ofthe Matochkin Shar Strait.

In SAR images, we regularly observed consequent IW packets. The distance between them on average was about 20 km, but in some cases it reached 50–60 km. The maximal number of such packets reached five. We should note separately systems of large IW packets propagating over the deepwater part of the Novaya Zemlya Trough. In this case, the number of consequent IW packets on a single image reached 14. Observation results indicate that IWs propagate up to 500 km from their presumed generation site.

On the both sides of the Kara Gates Strait, SIW packets related to internal tide propagation were regularly observed. Analysis of satellite SAR images jointly with the results of in situ measurements enabled us to identify surface manifestations of internal tide propagating towards the Kara Sea. Without available in situ measurements it would be extremely hard to identify observed anomalies of radar signal as surface manifestation of internal tide. We have also often observed SIW packets traveling from the Kara Sea towards the strait. In the strait itself we observe a complex picture of several systems of small SIW packets directed along and across the strait. These facts indicate the complex structure of the IW field in the region of the Kara Gates Strait and require further investigation.

It is important to note that, during the whole period of observations, SIW manifestations were rarely observed in shelf areas of the sea in the vicinity of Ob' and Yenisei estuaries. Herewith, in situ records (Stanovoi and Shmel'kov, 2002) and model results (Pelinovsky et al., 2002) explicitly indicate its presence in this part of the sea. Shallow pycnocline, presence of fresh water lenses, and plenty of frontal zones (where IWs may have decrease of amplitude or degrade) (Smirnov et al., 2002)- all these may lead to the attenuation of surface IW signatures or formation of "unusual" surface manifestations in SAR images.

To summarize, the basic areas of IW generation and propagation in the Kara Sea are the regions near the Kara Gates, over southeastern part of Novaya Zemlya Trough, and in the vicinity of Cape Zhelaniya. We assume that internal waves observed in these regions might be intensive IWs with high amplitudes generated as a result of tidal flow perturbation over steep topography. The tasks of future studies are to determine the time variability of SIW parameters, identify their relation with the tidal phase, and analyze the physical mechanisms of their generation and vertical structure in regions of regular observations through combination of satellite measurements with field observations and modeling.

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REFERENCES

Apel, J.R., Holbrook, J.R., Liu, A.K., and Tsai, J.J., The Sulu Sea internal soliton experiment, *J. Phys. Oceanogr.*, 1985, vol. 15, no. 12, pp. 1625–1651. doi 10.1175/1520-0485(1985)

Bondur, V.G., Grebenyuk, Yu.V., and Morozov, E.G., Satellite recording and modeling of short internal waves in coastal zones of the ocean, *Dokl. Earth Sci.*, 2008, vol. 418, no. 1, pp. 191–195.

Dikinis, A.V., Ivanov, A.Yu., Mal'tseva, I.G., et al., Deciphering of internal waves on radar images from the Almaz-1 satellite with the help of hydrometeorological and hydrographic data, *Issled. Zemli Kosmosa*, 1996, no. 5, pp. 47–59.

Dikinis, A.V., Ivanov, A.Yu., Karlin, L.N., et al., *Atlas annotirovannykh radiolokatsionnykh izobrazhenii morskoi poverkhnosti, poluchennykh kosmicheskim apparatom "ALMAZ-1"* (Atlas of Annotated Radar Images of Sea Surface Obtained by the Almaz-1 Satellite), Karlin, L.N., Ed., Moscow: Geos, 1999.

Dubina, V.A. and Mitnik, L.M., Internal waves in the Sea of Japan: spatial and temporal distribution characteristics on the basis of remote sensing satellite data, *Issled. Zemli Kosmosa*, 2007, no. 3, pp. 37–46.

Fu, L.L. and Holt, B., Internal waves in the Gulf of California: Observations from a spaceborne radar, *J. Geophys. Res.*, 1984, vol. 89, no. C2, pp. 2053–2060. doi 10.1029/JC089iC02p02053

Gargett, A.E. and Hughes, B.A., On the interaction of surface and internal waves, *J. Fluid Mech.*, 1972, vol. 52, no. 1, pp. 179–191. doi 10.1017/S0022112072003027

Jackson, C.R., *An Atlas of Internal Solitary-Like Waves and Their Properties (2nd Ed.)*, Alexandria, VA: Global Ocean Association, 2004.

Jackson, C.R., Silva, J.C.B., and Jeans, G., The generation of nonlinear internal waves, *Oceanography*, 2012, vol. 25, no. 2, pp. 108–123. doi 10.5670/oceanog.2012.46

Jakobsson, M., Mayer, L.A., Coakley, B., et al., The international bathymetric chart of the Arctic Ocean (IBCAO) version 3.0, *Geophys. Res. Lett.,* 2012, vol. 39, L12609. doi 10.1029/2012GL052219

Konyaev, K.V., Internal tide at the critical latitude, *Izv., Atmos. Ocean. Phys.*, 2000, vol. 36, no. 3, pp. 363–375.

Kozlov, I., SAR signatures of oceanic internal waves in the Barents Sea, in *Proc. of the SAR Oceanogr. Workshop (SeaSAR 2008), January 21–25, 2008, Frascati, Italy*, Netherlands: ESA Publications Division, 2008, ESA SP-656.

Kozlov, I.E., Kudryavtsev, V.N., and Sandven, S., Some results of research on internal waves in the Barents Sea by methods of radar sounding from the space, *Probl. Arkt. Antarkt.*, 2010, no. 86, pp. 60–69.

Kozlov, I.E. and Myasoedov, A.G., INTERWAVE: Determination of the characteristics of oceanic internal waves by their manifestations in satellite radar images of sea surface, Certificate of state registration of computer program no. 2012660637 of November 26, 2012.

Kozlov, I., Romanenkov, D., Zimin, A., and Chapron, B., SAR observing large-scale nonlinear internal waves in the White Sea, *Remote Sens. Environ.*, 2014, vol. 147, pp. 99–107. doi 10.1016/j.rse.2014.02.017

Kozubskaya, G.I., Konyaev, K.V., Plyudeman, A., and Sabinin, K.D., Internal waves at the slope of Bear Island from the data of the Barents Sea Polar Front Experiment (BSPF-92), *Oceanology (Engl. Transl.)*, 1999, vol. 39, no. 2, pp. 147–154.

Kudryavtsev, V., Myasoedov, A., Chapron, B., Johannessen, J., and Collard, F., Imaging mesoscale upper ocean dynamics using SAR and optical data, *J. Geophys. Res.,* 2012, vol. 117, C04029. doi 0.1029/2011JC007492

Lavrova, O.Yu., Mityagina, M.I., and Sabinin, K.D., Manifestation of Internal waves on the sea surface in the northeastern part of the Black Sea, *Issled. Zemli Kosmosa*, 2009, no. 6, pp. 49–55.

Lavrova, O.Yu., Mityagina, M.I., and Sabinin, K.D., Study of internal wave generation and propagation features in non-tidal seas based on satellite synthetic aperture radar data, *Dokl. Earth Sci.*, 2011a, vol. 436, no. 1, pp. 165–169.

Lavrova, O.Yu., Mityagina, M.I., Sabinin, K.D., and Serebryanyi, A.N., Satellite observations of surface manifestations of internal waves in the Caspian Sea, *Issled. Zemli Kosmosa*, 2011b, no. 2, pp. 40–48.

Morozov, E.G. and Pisarev, S.V., Internal tides at the Arctic latitudes (numerical experiments), *Oceanology (Engl. Transl.)*, 2002, vol. 42, no. 2, pp. 153–161.

Morozov, E.G., Parrilla-Barrera, G., Velarde, M.G., and Scherbinin, A.D., The straits of Gibraltar and Kara gates: A comparison of internal tides, *Oceanol. Acta*, 2003a, vol. 26, no. 3, pp. 231–241. doi 10.1016/S0399-1784(03)00023-9

Morozov, E.G., Neiman, V.G., and Shcherbinin, A.D., Internal tide in the Kara Strait, *Dokl. Earth Sci.*, 2003b, vol. 393A, no. 9, pp. 1312–1314.

Morozov, E.G., Paka, V.T., and Bakhanov, V.V., Strong internal tides in the Kara Gates Strait, *Geophys. Res. Lett.*, 2008, vol. 35, L16603. doi 10.1029/2008GL033804

Morozov, E.G. and Paka, V.T., Internal waves in a high-latitude region, *Oceanology (Engl. Transl.)*, 2010, vol. 50, no. 5, pp. 668–674.

Pelinovsky, E.N., Polukhin, N.V., and Talipova, T.G., Simulation of the characteristics of the field of internal waves in the Arctic Ocean, in *Poverkhnostnye i vnutrennie volny v arkticheskikh moryakh* (Surface and Internal Waves in Arctic Seas), Lavrenov, I.V. and Morozov, E.G., Eds., St. Petersburg: Gidrometeoizdat, 2002.

Poverkhnostnye i vnutrennie volny v arkticheskikh moryakh (Surface and Internal Waves in Arctic Seas), Lavrenov, I.V. and Morozov, E.G., Eds., St. Petersburg: Gidrometeoizdat, 2002.

Sabinin, K.D. and Stanovoi, V.V., *Intensivnye polusutochnye vnutrennie volny v Karskom more*, in *Poverkhnostnye i vnutrennie volny v arkticheskikh moryakh* (Surface and Internal Waves in Arctic Seas), Lavrenov, I.V. and Morozov, E.G., Eds., St. Petersburg: Gidrometeoizdat, 2002, pp. 265–279.

Sabinin, K.D., Serebryany, A.N., and Nazarov, A.A., Intensive internal waves in the World Ocean, *Oceanology (Engl. Transl.)*, 2004, vol. 44, no. 6, pp. 753–758.

Sabinin, K.D. and Serebryany, A.N., "Hotspots" in the field of internal waves in the ocean, *Akust. Zh.*, 2007, vol. 53, no. 3, pp. 410–436.

da Silva, J.C.B., New, A.L., and Magalhaes, J.M., On the structure and propagation of internal solitary waves generated at the Mascarene Plateau in the Indian Ocean, *Deep-Sea Res.*, 2011, vol. 58, no. 3, pp. 229–240.

Smirnov, V.N., Shushlebin, A.I., and Korostelev, V.G., Results of field measurements of parameters of surface and internal waves in the Arctic Ocean and Sea of Okhotsk, in *Poverkhnostnye i vnutrennie volny v arkticheskikh moryakh* (Surface and Internal Waves in Arctic Seas), Lavrenov, I.V. and Morozov, E.G., Eds., St. Petersburg: Gidrometeoizdat, 2002, pp. 310–320.

Stanovoi, V.V. and Shmel'kov, B.S., Short-period internal waves in the Kara Sea, in *Poverkhnostnye i vnutrennie volny v arkticheskikh moryakh* (Surface and Internal Waves in Arctic Seas), Lavrenov, I.V. and Morozov, E.G., Eds., St. Petersburg: Gidrometeoizdat, 2002, pp. 280–298.

Vlasenko, V., Stashchuk, N., Hutter, K., and Sabinin, K., Nonlinear internal waves forced by tides near the critical latitude, *Deep-Sea Res., Part I*, 2003, vol. 50, no. 2, pp. 317–338. doi 10.1016/S0967-0637(03)00018-9

Zhao, Z., Klemas, V., Zheng, Q., Li, X., and Yan, X.-H., Estimating parameters of a two-layer stratified ocean from polarity conversion of internal solitary waves observed in satellite SAR images, *Remote Sens. Environ.*, 2004a, vol. 92, pp. 276–287. doi 10.1016/j.rse.2004.05.014

Zhao, Z., Klemas, V., Zheng, Q., and Yan, X.-H., Remote sensing evidence for baroclinic tide origin of internal solitary waves in the northeastern South China Sea, *Geophys. Res. Lett.*, 2004b, vol. 31, L06302. doi 10.1029/2003GL019077

Zimin, A.V., Internal waves on the White Sea shelf according to observations, *Oceanology (Engl. Transl.)*, 2012, vol. 52, no. 1, pp. 11–20.

Zimin, A.V., Kozlov, I.E., Chapron, B., Myasoedov, A.G., Mokhnatkin, F.Yu., and Atadzhanova, O.A., Characteristics of short-period internal waves in the White Sea according to radar satellite data, in *Problemy izucheniya, ratsional'nogo ispol'zovaniya i okhrany prirodnykh resursov Belogo moray / Sb. mater. XII Mezhd. konf. s elementami shkoly dlya molodykh uchenykh i aspirantov, 30 sentyabrya–4 oktyabrya 2013 g., Petrozavodsk, 2013* (Problems in the Study, Rational Use, Protection of White Sea Resources: Proceedings of the 12th International Conference with Elements of School for Young Researchers and Postgraduate Students, September 30–October 4, 2013, Petrozavodsk, 2013, pp. 124–126.

Zimin, A.V., Romanenkov, D.A., Kozlov, I.E., Chapron, B., Rodionov, A.A., Atadzhanova, O.A., Myasoedov, A.G., and Collard, F., Short-period internal waves in the White Sea: The 2012 summer operational subsatellite experiment, *Issled. Zemli Kosmosa*, 2014, no. 3, pp. 1–14.

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