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Original article

Characteristics of Short-Period Internal Waves in the Kara Sea in Summer 2022 Based on Satellite Sentinel-1 Data

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Abstract
Purpose. The study aims to investigate the spatiotemporal variability and characteristics of short-period internal waves in the Kara Sea during summer 2022.
Methods and Results. A total of 374 Sentinel-1A synthetic aperture radar (SAR) images acquired from July to September 2022 were analyzed. Processing of these images revealed 2835 surface manifestations of internal waves in the Kara Sea. The highest number of manifestations (1595) was recorded in August, while the lowest (451) occurred in July. Short-period internal waves were rarely observed in shallow coastal zones influenced by strong river runoff. In contrast, they were widespread in the western, southwestern and northwestern parts of the sea, as well as in the Kara Gate and Vilkitsky Straits. Manifestations were detected across extensive areas, including the Central Kara Plateau, deep-water regions and the slopes of the Saint Anna and Novaya Zemlya Troughs. The largest internal wave packets, with areas reaching up to 2000 km^2, were observed over the Saint Anna Trough. Packets with leading crest lengths exceeding 100 km^2 were recorded near Vize Island.
Conclusions. During the warm season, nonlinear short-period internal waves are generated and propagate over most of the Kara Sea, particularly in areas with prough bottom topography. Some of these regions are also characterized by intense tidal and/or background currents. However, numerous wave packets form even where total current velocities are low (0.1–0.2 m/s). In such cases, the primary factor driving short-period internal wave generation is the presence of irregular bottom relief with sharp depth gradients. The propagation direction of these waves is often aligned with background currents, which exhibit significant seasonal variability in both speed and direction in certain areas.

Keywords: short-period internal waves, generation hotbeds, tidal currents, uneven relief of sea bottom, satellite radar images, Sentinel-1, Kara Sea, Arctic Ocean

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Introduction

In recent years, significant changes in climate and hydrological conditions have been observed in the seas of the Russian Arctic zone, manifested by increasing air temperatures, a reduction in ice cover area and the duration of the ice season, a weakening of vertical stratification, and an intensification of currents as a result of the so-called “atlantification” of this sector of the Arctic [1–3].

The significantly larger seasonal ice-free area of substantial parts of the Arctic basin in the last decade allows for the observation and study of hydrophysical processes in the upper ocean layer in a number of new areas previously covered by ice [4, 5]. The active development of the Arctic shelf and the Northern Sea Route underscore the relevance of researching processes that potentially affect sea ice, horizontal and vertical transport of biogeochemical elements and pollutants, underwater navigation, and acoustics.

One such process is short-period (high-frequency) internal waves (SIWs) – an important element of the ocean's dynamic structure, influencing the transfer of mass, momentum, and energy in the marine environment. Free SIWs in the Arctic often manifest as packets of intense nonlinear soliton-like internal waves of large amplitude [6–9]. Their generation does not occur uniformly across the sea area but is confined to specific "hotspots" [10]. One of the primary reasons for the formation of SIWs is the interaction of tidal currents with rough bottom topography, either directly [11] or during the evolution and disintegration of baroclinic internal tidal waves (hereinafter referred to as internal tidal waves) [12–14].

The investigation of the mechanisms and "hotspots" of SIW generation, their propagation features, and their influence on the hydrological conditions of the Arctic basin is highly relevant, which explains the consistent interest in this subject in recent years [8, 15–20].

In this regard, the water area of the Kara Sea, considered in this paper, is no exception [21–26]. A preliminary analysis of the SIW field characteristics in the Kara Sea based on a rather limited dataset of 89 images from the Envisat ASAR synthetic aperture radar was performed for the summer period of 2007 [27], which identified the main SIW generation areas and their propagation features in the sea area. However, a study has recently appeared that used a broader dataset (320 images) from the Sentinel-1 SAR for the summer-autumn period of 2022 [26]. In that study, besides identifying the formation areas and characteristics of SIWs within a two-layer approximation, an estimate of the observed internal wave amplitudes was also provided based on the use of climatic data on vertical stratification.

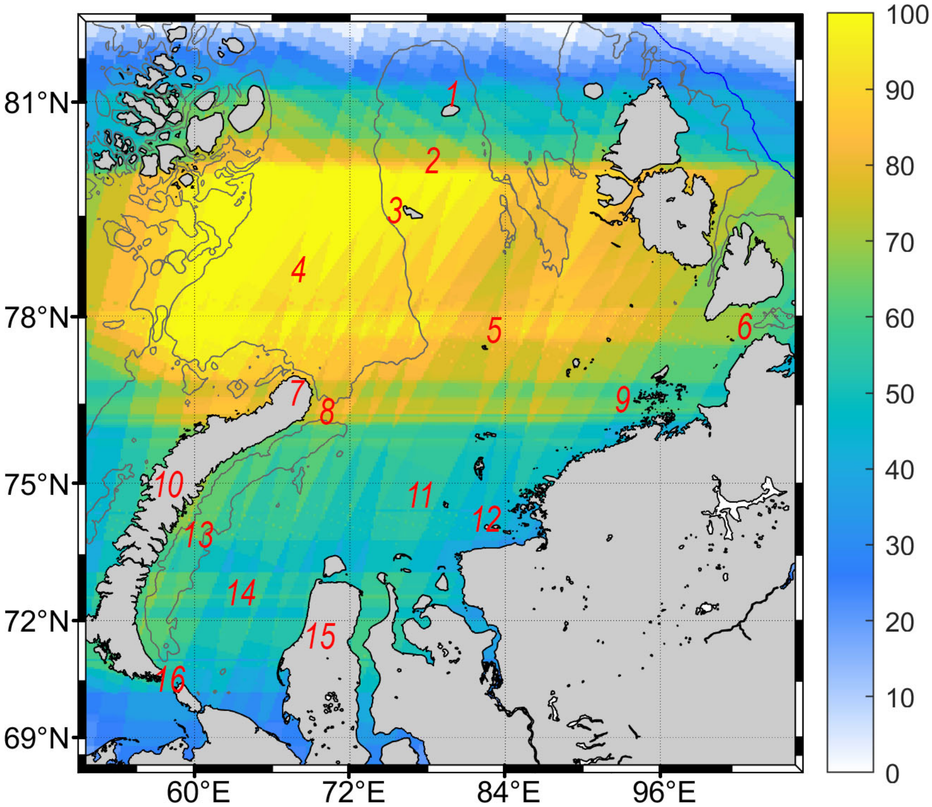
Simultaneously, researchers from Marine Hydrophysical Institute of the Russian Academy of Sciences conducted a similar study using virtually the same initial Sentinel-1 dataset for July – September 2022 – the months with the maximum buoyancy frequency values in the annual cycle of the Kara Sea [22].

The aim of the present paper is to identify and analyze the formation areas and properties of SIWs in the Kara Sea in 2022, to compare these findings with observations from 2007 and to relate the results to those reported in the study [26].

Data and methods

The analysis of SIW characteristics in the water area of the Kara Sea was carried out by processing satellite radar images (SAR) from Sentinel-1A in the Extra Wide Swath (EW) imaging mode, with a swath width of 250 km and a spatial resolution of 90 m. The satellite data were obtained from the archives of the Copernicus Open Access Hub system of the European Centre for Medium-Range Weather Forecasts (https://scihub.copernicus.eu).

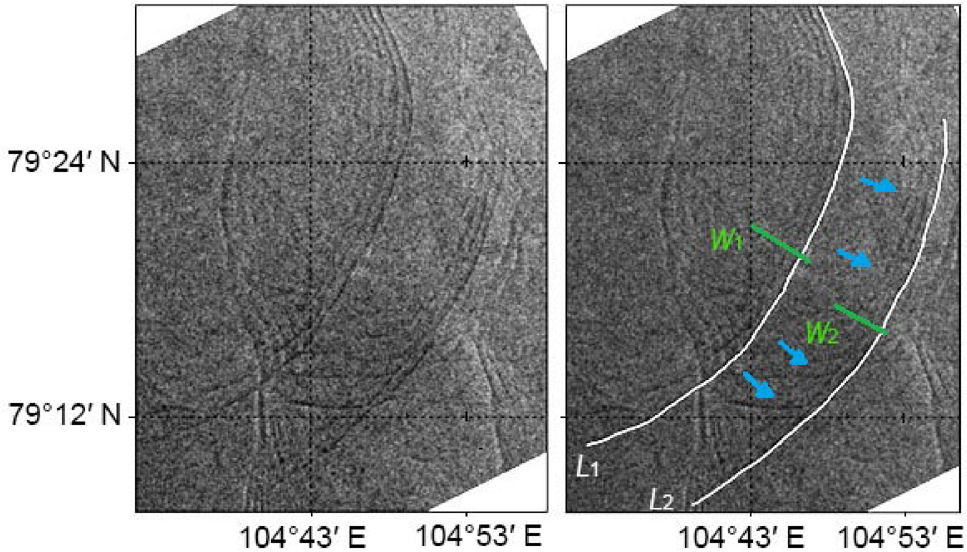
The work involved the analysis of 371 satellite SAR images from July to September 2022, of which 121 images were from July, 131 from August, and 119 from September. Fig. 1 shows a map of the satellite coverage of the Kara Sea water area for the entire observation period. The northern part of the sea, north of 76°N, is covered most extensively by satellite data (more than 70–80 SAR images). The coverage of the southern part is fairly uniform and averages 40–60 images per unit area of the sea surface. The minimum amount of data, 20–30 images, is available for the estuarine areas in the southwestern part of the sea.



F i g. 1. Coverage of the Kara Sea basin with Sentinel-1A data from July 1 to August 31, 2022. Grey isolines show the position of 200 m isobath. Numbered positions: *1* – Ushakov Island; *2* – Central Kara Plateau; *3* – Vize Island; *4* – Saint Anna Trough; *5* – Uyedinenie Island; *6* – Vilkitsky Strait; *7* – Zhelaniya Cape; *8* – Brusilov Rapids; *9* – Nordenskjold Archipelago; *10* – Novaya Zemlya Archipelago; *11* – Yamalo-Gydanskaya Shoal; *12* – Pyasino Gulf; *13* – Novaya Zemlya Trough; *14* – Western Kara Step; *15* – Yamal Peninsula; *16* – Kara Gates

The analysis of satellite images and the identification of surface manifestations (SMs) of SIWs were carried out according to the methodology presented in [17, 18], using the ESA Sentinel Application Platform (ESA SNAP) software. For each identified SIW packet, the coordinates of the leading wave's center, the length of its front, and the width of the wave packet were determined. Further processing of the satellite data analysis results was performed in the Matlab software environment. To construct spatial maps of the distribution of SIW characteristics, their average and total values were determined on a grid of 60 × 100 nodes in latitude and longitude. When constructing histograms of the distribution of SIW parameters, the values were taken for each wave packet.

Fig. 2 (left) shows an example of the propagation of several consecutive SIW packets in the Kara Sea water area on a Sentinel-1A SAR image from August 11, 2022. The internal wave packets marked in Fig. 2 (right), have an arc-shaped structure and are directed east-southeast; however, besides them, packets with western and southern directions are also visible in the SAR image. The white curves show the extent of the wave front of the leading waves (hereinafter referred to as the front length), and the green straight lines show the width of the wave packets. All identified SIW packets were analyzed in a similar manner.



F i g. 2. Example of manifestation (*left*) and identification (*right*) of SIW characteristics in the Sentinel-1A SAR image obtained on 08.11.2022 (02:58 *UTC*) in the Kara Sea. White lines *L*1 and *L*2 indicate the positions of leading wave crests in the SIW packets, green straight lines *W*1 and *W*2 – the SIW packet widths. Blue arrows show the direction of SIW propagation

It is important to note that the identification of SIWs in SAR images is difficult under conditions of strong winds and the presence of ice cover. According to our estimate, the number of SAR images with ice concentration exceeding 50% and high surface wind speeds did not exceed 20% of the total number of satellite images.

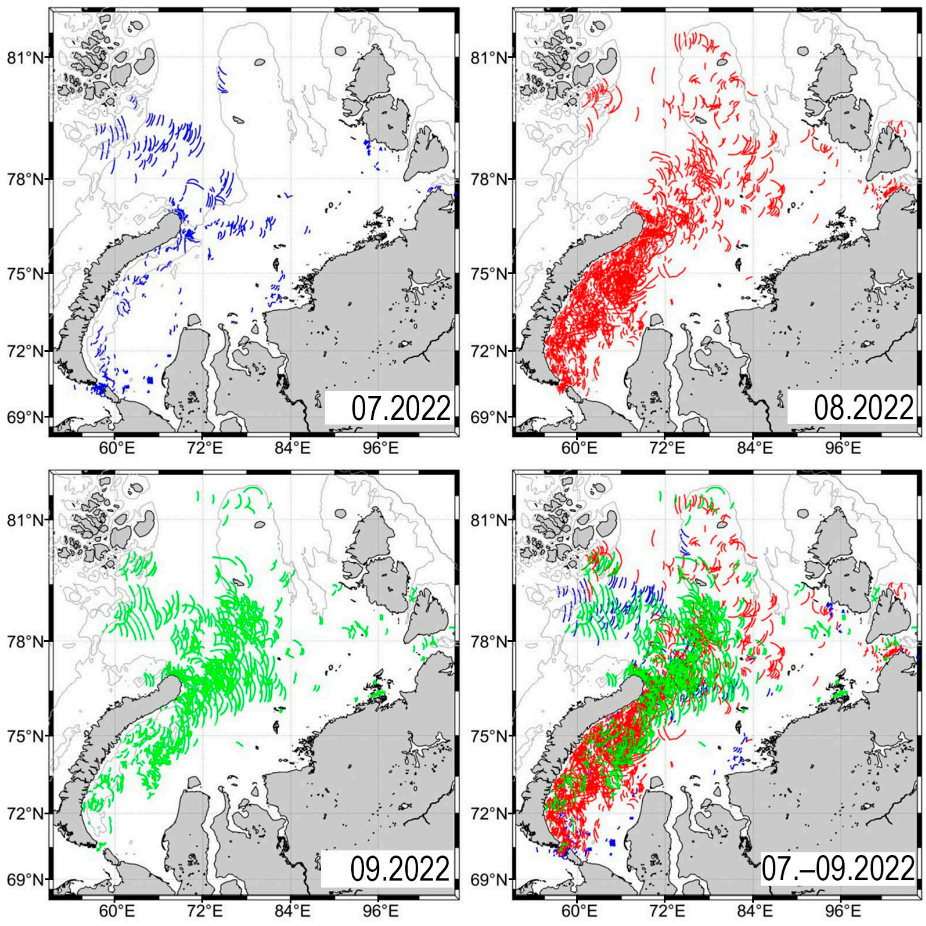
To investigate the potential mechanisms of SIW generation, additional information on bottom topography from IBCAO [28], tidal currents from the *Arc2kmTM* model [1] [29], and surface currents from the CMEMS GLORYS12V4 reanalysis data with a spatial resolution of 0.25° at the 1 m depth level were incorporated into the analysis.

[1] Howard, S.L. and Padman, L., 2021. *Arc2kmTM: Arctic 2 Kilometer Tide Model*. NSF Arctic Data Center. https://doi.org/10.18739/A2PV6B79W

Results of satellite observations

Analysis of 371 Sentinel-1 SAR images for July 1 – September 30, 2022, allowed for the identification of 2835 surface manifestations (SMs) of SIWs. The majority of the recorded SIW packets were observed in August (1551 SIW SMs or ~ 56% of the total), the fewest in July (451), and 789 SIW SMs were recorded in September.

The significant difference in the number of SIW SMs across various months could be caused by a combination of factors – intraseasonal variability of vertical stratification, background wind conditions, and surface currents, which affect both the intensity of internal wave generation itself and the detectability of their surface manifestations from space. In our case, the pronounced intraseasonal variability in the number of observed SIW SMs is due to the difference in effective satellite coverage of the region from month to month. The coverage variability is maximum in August and minimum in July, which fully explains the noted difference in the number of SIW observations.



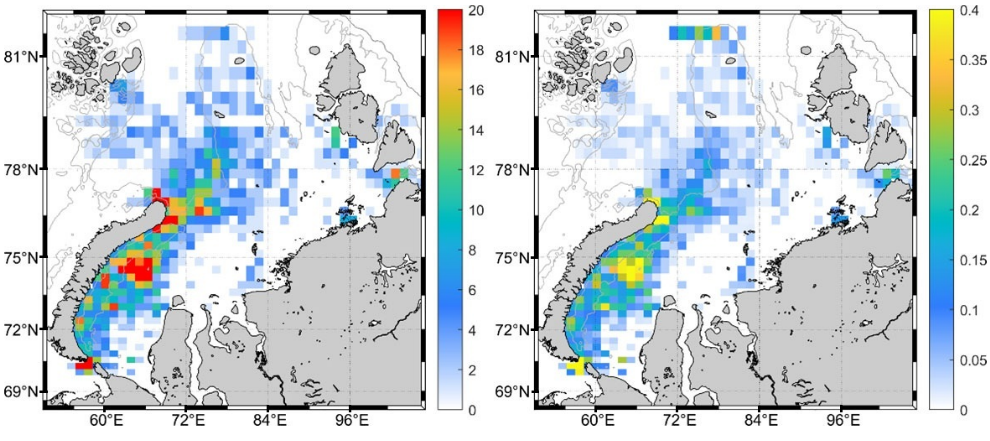
F i g. 3. Map of SIW packet distributions in the Kara Sea. Blue, red and green colors show the locations of SIW packets in July, August and September, 2022, respectively. Grey isolines show the position of 200 m isobath

The final map showing the positions of all SIW manifestations in the Kara Sea basin is presented in Fig. 3, where the positions of SIWs in the summer-autumn period of 2022 are marked with different colors. The internal waves are distributed quite unevenly across the water area.

The fewest waves were observed in the shallow coastal areas of the sea with intense river runoff. Nevertheless, waves were also recorded in some of these areas – to the northwest of the Yamal Peninsula, to the northwest of the Pyasino Gulf, and in the area of the Nordenskjold Archipelago. Among such shallow areas, the strait regions – the Kara Gates and the Vilkitsky Strait – stand out, where the number of SIW manifestations was high.

In the rest of the sea area, especially in its western, southwestern, and northwestern parts, internal waves were observed almost everywhere, including extensive areas of the Central Kara Plateau and the deep-water regions of the Saint Anna Trough and the Novaya Zemlya Trough. Thus, during the summer season, SIW packets form over at least half of the Kara Sea area.

In some sea areas, the dominant direction of internal wave propagation is quite well traced. For example, in the northwestern part, SIWs had a pronounced eastern direction, which may indicate their possible generation on the western slopes of the Saint Anna Trough. To the east of Cape Zhelaniya, internal wave packets propagated mainly eastward. In the vast area between the Novaya Zemlya Trough and the Yamal Peninsula, internal waves propagated predominantly southward (shown in more detail below).

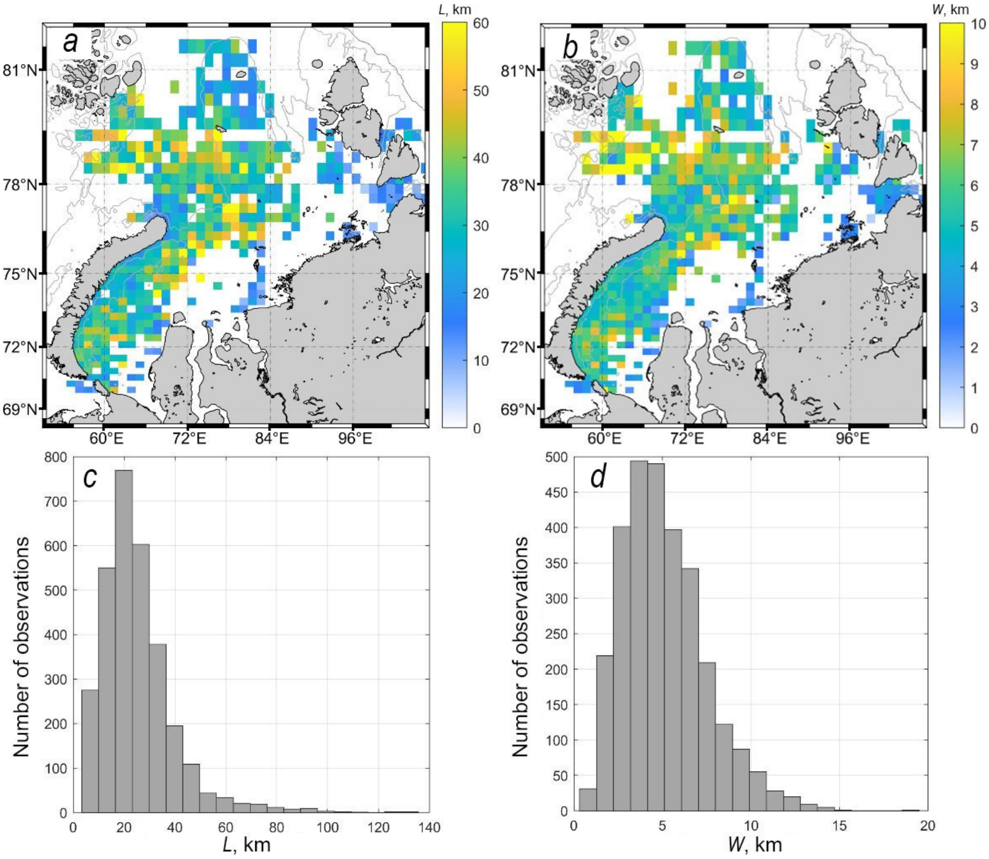


F i g. 4. Maps showing the distribution of SIW total number (*left*) and probability (*right*) in the Kara Sea in July – September, 2022, based on satellite observations

For a more precise determination of the main SIW observation areas (their formation "hotspots"), maps of the total number of SIW observations (Fig. 4, left) and their probability (Fig. 4, right) are provided. The probability was calculated as the ratio of the total number of SIW observations to the total radar imaging coverage of the area on a grid of 60 × 100 nodes. A probability value of 0.4 indicates that SIW packets were recorded in four out of 10 satellite images of a given area.

As can be seen from the figures, both maps generally correspond well t o each other and allow for the unambiguous identification of key SIW generation areas.

The maximum number of SIW manifestations (more than 15) and the maximum values of their probability (greater than 0.3) are observed in the following areas: in the Kara Gates; in at least three generation hotspots in the vast area with depths of 50–150 m, bounded on the west by the eastern slope of the Novaya Zemlya Trough and on the east by the western part of the West Kara Step; in the area of Cape Zhelaniya; in the area of the Brusilov Sill located southeast of this cape. In addition to the indicated areas with similar parameters, it is also important to note the areas of the Vilkitsky Strait and the shelf break to the northwest of Ushakov Island. Thus, at least 8 stable SIW generation hotspots are identified in the Kara Sea water area. There are also many other areas where SIWs form quite regularly, with a probability above 0.1.



F i g. 5. Maps (*a*, *b*) and histograms (*c*, *d*) of the distributions of leading wave crest lengths (*a*, *c*) and SIW packet widths (*b*, *d*) in the Kara Sea in July – September, 2022

The maps shown in Fig. 5 characterize the horizontal dimensions of SIW packets across and along their direction of propagation. From Fig. 5, *a*, *b*, a spatial correlation in the distribution of these parameters across the sea area is evident.

In shallow coastal areas and near islands, the sizes of SIW packets are minimal – the length of the leading wave front does not exceed 20 km, and the width of the wave packets is less than 5 km. As the depth increases, the sizes of the SIW packets also increase. The maximum values of both parameters were observed in the area of the Saint Anna Trough and on its eastern slope (to the southwest of Vize Island), to the west of Uedineniya Island, and along the depth drop-off to the northwest of the Yamal-Gydan Shoal. The largest wave packets, observed over the Saint Anna Trough, had a leading wave front length of 120–125 km, a packet width of 15–19 km, and a wave packet area of more than 2000 km^2.

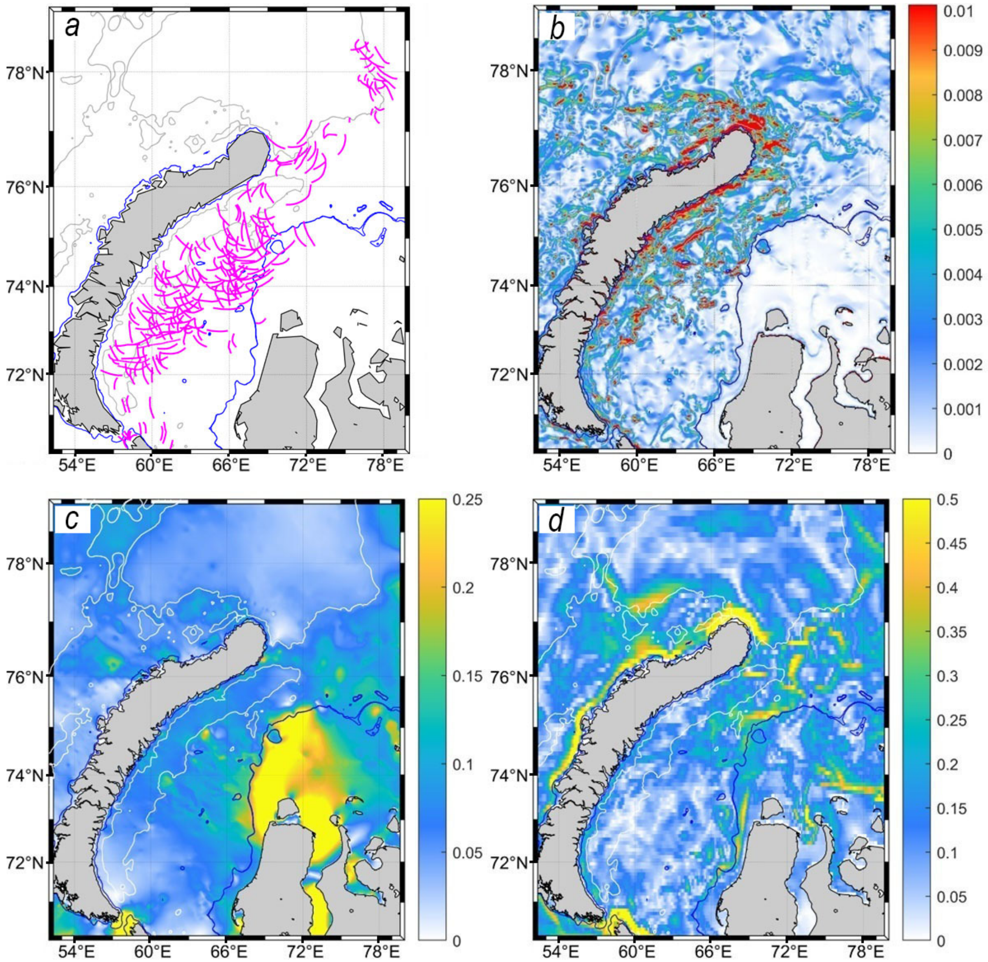
According to Fig. 5, *c*, the range of values for the leading wave front length varies from 5–6 to 125 km with an average value of 35 km. The main peak of observations falls within the 10–30 km range. As noted above, waves with a wave front length greater than 30–40 km were observed in the central and northeastern parts of the water area. The width of the wave packets varied in the range of 0.7–19 km with an average value of ~ 5.5 km. In most observations, the wave packet width was 3–6 km (Fig. 5, *d*). Recall that the wavelengths within the wave packets were not determined in this study, but their general range was 0.1–3.5 km.

Let us consider, using a specific example, the main physical factors influencing SIW generation in the central and southern parts of the water area. For this purpose, Sentinel-1A SAR images from August 13, 2022 (02:43 UTC) with a record number of SIW SMs (239) identified internal waves were selected (Fig. 6, *a*). The SAR image shows three main groups of SIWs: in the vicinity of the 200 m isobath on the southeastern slope of the Saint Anna Trough; to the east of the Novaya Zemlya Archipelago along almost its entire length; in the Kara Gates.

Let us note again that, despite the presence of intense tidal currents (speed ~ 0.5 m/s) in the vast shallow Ob-Yenisei estuarine region (Fig. 6, *c*), surface manifestations of SIWs were not recorded, except for its northwestern periphery, where SIW packets arriving from the north were observed (Fig. 6, *a*). The main reason for this is apparently the lack of suitable topographic conditions.

In the area of the southeastern Saint Anna Trough, the waves are oriented across the isobaths and propagate over the continental slope of 200–400 m (Fig. 6, *b*) predominantly towards the deep water to the southwest, although waves of the opposite direction are also present. The topographic slope in this area is ~ $(3–5)°\cdot10^{-2}$ (Fig. 6, *b*). The formation of internal tidal waves over the continental slope is a common phenomenon in the Arctic basin [7, 30]. In this case, the formation of high-frequency internal wave packets occurs during the disintegration of the internal tide directly over the slope, since low-frequency internal tidal waves with an M_2 period cannot freely propagate near the critical latitude of 74.5°N [13, 31–33]. According to [7, 31], this scenario is possible even with low tidal current speeds (0.1–0.15 m/s). In our case, the speed east of the 200 m isobath was also within this range (Fig. 6, *c*). The amplitudes of internal waves generated over the slope can reach 50 m [7, 8].

The process of formation and characteristics of nonlinear internal waves in the Kara Gates have been studied quite frequently. The strait area is characterized by the presence of a submarine ridge with a series of isolated peaks and high speeds of background and tidal currents (Fig. 6, *c*, *d*) [9, 14, 34]. Here we note only that the generation of SIWs in the strait is possible not only during the evolution of the internal tide formed by the total flow around the submarine ridge [14, 21, 35], but also in the transcritical regime [36]. In the latter case, SIW generation can occur twice per tidal period or 4 times a day, and the direction of internal wave propagation will be determined by the intensity and direction of the total flow during the transcritical regime [11]. According to observations, the amplitudes of nonlinear SIWs in the strait reach 30–40 m [18].



F i g. 6. Locations of the leading waves in SIW packets (*a*), dimensionless sea bottom slope (*b*); tidal (*c*) and surface (*d*) current velocities (m/s) in the Kara Sea on 13.08.2022. Blue and white lines indicate the 40 and 200 m isobaths, respectively

The main and most numerous group of internal waves propagates southward from Cape Zhelaniya and from the eastern slope of the Novaya Zemlya Trough over the West Kara Step (Fig. 6, *a*), which has been noted previously [26, 27]. The generation of SIW packets directly near Cape Zhelaniya is apparently caused by the interaction of an intense (with a speed exceeding 0.5 m/s) jet of the West Novaya Zemlya Current, which rounds the northern tip of the archipelago, with the local topography (Fig. 6, *b*). Tidal current speeds during and shortly before the satellite imaging were low (~ 0.05 m/s, Fig. 6, *c*), although in general the mean barotropic tidal energy flux here is also directed southward [37]. The amplitude of internal waves in this area can reach 50 m [38].

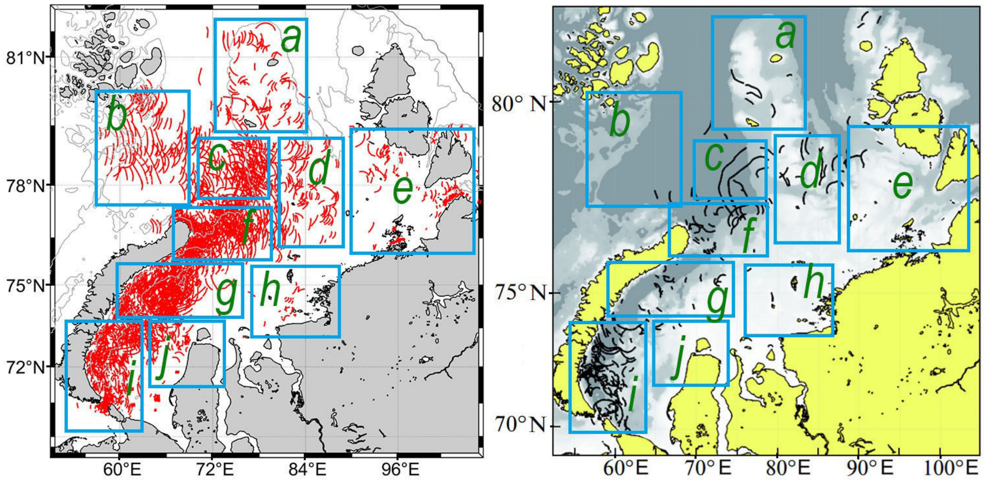
The SIW packets located somewhat further south are formed directly over the Brusilov Sill, where all conditions exist for their generation through the interaction of tidal currents (with speeds of ~ 0.15–0.2 m/s) with the topography of the sill. This area is characterized by local maxima in the field of the mean dissipation rate of barotropic and baroclinic tidal energy and is a hotspot for internal tidal wave generation [33, 39].

The extensive area over the West Kara Step to the east of the Novaya Zemlya Trough is characterized by a large number of fairly narrow local zones of heterogeneous topography with depths in the range of 60–160 m [40] and a dimensionless slope of ~ 0.1 (Fig. 6, *b*). Each such area of topography is essentially a site of SIW generation. Tidal currents here are higher (speed ~ 0.15 m/s) than directly in the deep-water area of the Novaya Zemlya Trough (Fig. 6, *c*). Background currents in the surface layer are more intense (speed greater than 0.2 m/s) north of 74.5°N, but they are weaker than tidal currents in the southern part of this area (Fig. 6, *d*).

An interesting feature is the predominantly southern direction of the SIWs in the indicated area. It coincides with the direction of the surface semidiurnal tidal wave and the mean horizontal transport of barotropic tidal energy, which here amounts to 2000–10000 W/m [37]. Let us consider the features of background currents in this area, as they may also play a significant role in the formation of SIWs. According to the results of field measurements in September 2007 [38], the main currents in this area (the East Novaya Zemlya Current and the northern branch of the Yamal Current) are directed north and northeast, consistent with modeling results for the autumn period [41]. However, in the summer period, the main jet of the East Novaya Zemlya Current, directed northeast along the shores of the Novaya Zemlya Archipelago, recirculates in the opposite direction along the eastern slope of the Novaya Zemlya Trough in the area of 75°N, connecting with the waters of the West Novaya Zemlya Current, which also penetrate southwest during this period [41]. Thus, the formation of southward-propagating SIWs in summer is quite explicable by the superposition of tidal and background currents of southern direction over heterogeneous topography. It is interesting to note that in September, when significantly more intense northeastward currents dominate the upper layer [38, 41], the SIW packets are also directed northeast (Fig. 3, *c*).

Let us once again examine the indicated distribution of SIWs in more detail and compare it with previously obtained results. For comparison, Fig. 7 shows the results of SIW observations in July – September 2022 and in July – October 2007. It is evident that our results (Fig. 7, left) provide a significantly more complete picture of the SIW formation areas. The most significant differences are characteristic for areas *a, b, e, g, h, j,* where waves were either not encountered at all previously, or their manifestations were significantly fewer (Fig. 7, right). The frequency of SIW SMs per SAR image, based on the 2007 survey results, is substantially lower (2.8) than in 2022 (7.64).

Let us compare the results obtained in this work with the results of the QUODDY-4 tidal model [42], based on which four main internal tidal wave generation areas in the Kara Sea were identified – the northern part of the Central Plateau, the western and eastern slopes of the Novaya Zemlya Trough, the Kara Gates, and the area southeast of Cape Zhelaniya. It is reasonable to expect that SIW packets formed during the disintegration of internal tides should also be found in these same areas. From Fig. 7, *a*, it is clearly seen that SIW packets are observed in all these areas and in many others where, according to [42], the amplitudes of internal tidal waves are non-zero, with the exception of the area west of the Yamal Peninsula. However, the question of whether all observed SIW packets are associated specifically with the disintegration of internal tidal waves remains open, as the mechanisms of SIW generation are quite diverse [11].



F i g. 7. Areas of SIW observations in the Kara Sea (marked with letters) in July – September, 2022 (based on the present study results) – *left*, and in June – October, 2007 (based on the results of [27]) – *right*

Let us now compare our results with the recent results of study [26], performed using an identical dataset. Let us note that, excluding data for October 2022, which were not used in our work, the authors of [26] identified 794 SIW SMs in 235 SAR images for July – September 2022. The frequency of internal wave occurrence over the full sample of used satellite data in this case is 3.38 SIW SMs per SAR image, which is only 20% higher than the 2007 results [27] but 2.3 times lower than our result (7.64 SIW SMs) for the analogous period in 2022.

If we consider not the entire sample, but only the set of SAR images in which surface manifestations of SIWs were observed, the result is analogous. In [26], 834 SIW SMs were identified in 97 SAR images, whereas in our work – 2835 SIW SMs in 128 SAR images, i.e., the underestimation is 2.6 times compared to our results.

Finally, if we compare the number of identified SIW SMs for each month, normalized by the total number of SAR images used in the analysis, it turns out that in July and September we identified 3 times more such SIW manifestations, and in August 2 times more, than in study [26]. The authors of that study also mention that the maximum number of SIW SMs on a single SAR image was observed by them on August 11, 2022, and reached 72, whereas in the present work, 44% more – 104 SIW SMs – were identified. Thus, there is a very significant omission of surface manifestations of SIWs in the satellite data and, consequently, an underestimation of the probability and the main SIW formation areas in the Kara Sea.

Study [26] lacks data on the distribution of SIW SMs in the water area of the Saint Anna Trough in July – September 2022. According to our data, the most significant differences in July are visible in the water area of the Pyasino Gulf and the Novaya Zemlya Trough; in August – in the central part of the sea and the northern regions over the Central Kara Plateau; in September – in the southern part of the Novaya Zemlya Trough and the northernmost part of the sea – in the area of Ushakov Island.

Regarding the spatial parameters of SIWs, only the length of the leading wave front was determined in [26]; the range of observed values was 3–58 km with an average value of 12.5 km. According to our data, the range was 3–125 km with an average value of 35 km (Fig. 5, *c*). As in [26], elevated values of this parameter (more than 40–50 km) were observed to the east and southeast of Cape Zhelaniya; however, the maximum values were recorded over the deep-water area of the Saint Anna Trough (78–79°N), which is clearly visible in Fig. 3, *a* and 5, *a*. These results, as well as the actual observations of SIWs in the indicated area, are absent in study [26].

Conclusion

Analysis of 371 Sentinel-1 SAR images for July 1 – September 30, 2022, allowed for the identification of 2835 surface manifestations of SIWs in the Kara Sea water area. The majority of SIWs were recorded in August (~ 56%).

A general increase in the recorded cases of SIW SMs and a substantial expansion of their observation areas compared to the results obtained in the summer of 2007 are noted. During the summer-autumn season of 2022, SIW packets formed over more than half of the Kara Sea area. The SIW generation areas correlate well with the sea areas where the dimensionless slope of the sea bottom is ≥ 0.01 and the values of tidal/background currents are non-zero. The question of the amplitude and penetration depth of these oscillations remains open; however, individual studies on the Kara Sea shelf show the existence of intense SIWs with heights of 30–50 m. Such waves can lead to intense turbulent exchange both on the shelf and over the continental slope.

At least 8 stable SIW generation centers are identified: the areas of the Kara Gates and Vilkitsky Strait; three generation hotbeds in the vast area bounded on the west by the eastern slope of the Novaya Zemlya Trough and on the east by the western part of the West Kara Step; the areas of Cape Zhelaniya and the Brusilov Sill, as well as the area of the shelf break to the northwest of Ushakov Island. The identified areas may very likely simultaneously be centers of internal tidal wave formation and, consequently, areas of intense tidal energy dissipation in the Kara Sea.

Furthermore, new SIW formation areas were discovered: the southern part of the Saint Anna Trough and its western and eastern slopes, the Central Kara Trough, the Central Kara Plateau, the area east of Severny Island, as well as coastal water areas near the Yamal Peninsula and Bolshoy Island. The fewest waves were observed in the shallow coastal areas of the sea with intense river runoff. The main reason for this is apparently the lack of corresponding topographic conditions.

In general, SIW packets form in various areas of the Kara Sea with pronounced bottom topography heterogeneities, sometimes of quite small scale; some of these areas are characterized by intense tidal and/or background currents. Numerous SIW packets also form in areas where the speed of the total currents is only 0.1–0.2 m/s. The main condition for SIW formation in such areas is the presence of heterogeneous bottom topography with sharp depth gradients. The direction of SIW propagation is often determined by the direction of background surface currents, which in certain areas are very intense and have pronounced seasonal variability in speed and direction.

In shallow coastal areas and near islands, the sizes of SIW packets are minimal. The largest wave packets, with an area exceeding 2000 km², were observed over the Saint Anna Trough, where the wave front length reached 120–125 km and the packet width was 15–19 km.

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