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# Characteristics of Short-Period Internal Waves in the Laptev Sea and Adjacent Regions of the Kara and East Siberian Seas Based on Satellite Radar Data during Summer-Autumn Period of 2019

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**Abstract**
This paper presents the results of short-period internal waves (SIWs) observations in the Laptev Sea and adjacent areas of the Kara and East Siberian Seas based on analysis of satellite synthetic aperture radar (SAR) Sentinel-1 A/B data between July and October 2019. Analysis of 639 SAR images allowed identifying 2081 surface manifestations (SM) of SIWs. Main regions of SIW observations were determined and their spatial characteristics mapped. More than 60 % of registered SIWs were identified in September, and the lowest number of manifestations (9 %) was registered in July. Maximum number of SIW observations was found near the Arctic Cape, over the large area of the continental slope and in the northeastern shelf of the Laptev Sea. It is shown that the total number of SIW identifications in 2019 was much higher than in 2011, and the principal regions of SIW observations expanded. Moreover, new regions of regular SIW generation were determined in the Shokalsky Strait, between the New Siberian Islands and over the deep sea regions. The most intensive generation area was determined north of the Kotelny Island, between 50 m and 200 m isobaths. In this region, the total number of SIW detections exceeded 15 cases. While a significant increase in the number of SIW detections is observed in 2019, the overall range of the values of SIW spatial characteristics in 2019 is almost the same as in 2011.

**Keywords**: short period internal waves, Laptev Sea, Kara Sea, East Siberian Sea, satellite radar images, tidal currents

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# Характеристики короткопериодных внутренних волн в море Лаптевых и прилегающих районах Карского и Восточно-Сибирского морей по данным спутниковых радиолокационных наблюдений в летне-осенний период 2019 года

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**Аннотация**
Представлены результаты наблюдения короткопериодных внутренних волн в море Лаптевых и прилегающих районах Карского и Восточно-Сибирского морей, полученные на основе анализа измерений спутниковых радиолокаторов с синтезированной апертурой *Sentinel*-1 *A*/*B* с июля по октябрь 2019 г. Анализ 639 радиолокационных изображений позволил идентифицировать 2081 случай поверхностных проявлений короткопериодных внутренних волн. Определены основные районы наблюдения короткопериодных внутренних волн и построены карты распределения их основных пространственных характеристик. Более 60 % случаев наблюдения короткопериодных внутренних волн пришлось на сентябрь, а наименьшее количество проявлений – на июль (9 %). В исследуемый летне-осенний период максимальное количество поверхностных проявлений короткопериодных внутренних волн зарегистрировано в районе м. Арктического, а также на обширной области континентального склона и северо-восточной части шельфа моря Лаптевых. Показано, что общее число случаев регистрации короткопериодных внутренних волн в 2019 г. на порядок выше, чем в 2011 г., а районы обнаружения короткопериодных внутренних волн существенно расширились. Кроме того, обнаружены новые районы регулярной генерации короткопериодных внутренних волн в прол. Шокальского, между Новосибирскими о-вами, а также в глубоководной части акватории. Наиболее интенсивный район генерации поверхностных проявлений короткопериодных внутренних волн располагался в области между изобатами 50 и 200 м, севернее о-ва Котельный. На данном участке акватории максимальное суммарное количество поверхностных проявлений короткопериодных внутренних волн превышало 15. Отмечается, что при значительном увеличении общего количества наблюдений короткопериодных внутренних волн в 2019 г. диапазон изменчивости значений их основных пространственных характеристик в 2019 г. примерно такой же, как и в 2011 г.

**Ключевые слова**: короткопериодные внутренние волны, море Лаптевых, Карское море, Восточно-Сибирское море, спутниковые радиолокационные изображения, приливные течения

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## Introduction

The Laptev Sea is a marginal water body of the Arctic Ocean (AO), characterized by active generation of sea ice and formation of polynyas [1]. The hydrological regime of the water area is characterized by intense river runoff.

Short-period internal waves (SIWs) are an important element of the dynamic structure of the ocean, which largely determines horizontal and vertical transfer of matter, momentum, and energy. Due to the increase in the rate of development of the shelf of the Arctic seas, the issue of studying the mechanisms and areas of SIW generation, the features of their distribution and the impact on the hydrological regime of the Arctic Basin is becoming more acute [2]. An important influence on the formation of SIWs is exerted by tidal currents and their interaction with inhomogeneities of benthic topography in the shelf zone and in areas of submarine slopes [3–5].

It is known that, according to satellite observation data, it is possible to determine the main areas of generation and propagation of surface manifestations (SM) of SIWs [3, 6]. In general, there are not so many works on the study of SIWs in the Laptev Sea based on satellite data. Previous work in this area using satellite data for 2007 and 2011 showed that SIW packets are regularly observed in the water area [7, 8]. In the same works, it was noted that the detected internal waves, apparently, were mainly of a tidal nature of formation and spread in certain areas of the shelf and continental slope.

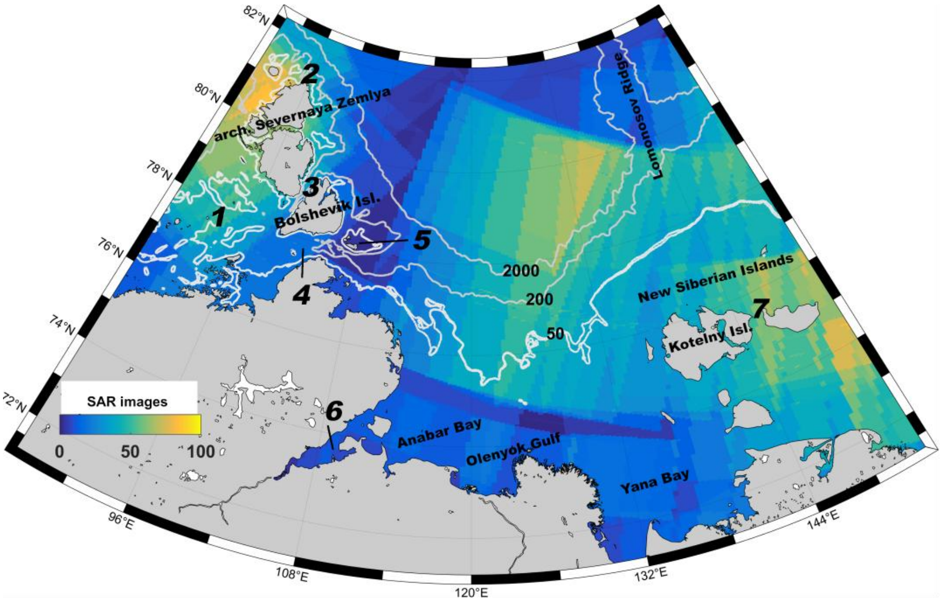
This paper analyzes a vast array of Sentinel-1 A/B satellite radar data (RD) for the summer-autumn period of 2019 and presents the results of a study of the characteristics of the SIW field in the Laptev Sea and partially adjacent water areas of the Kara and East Siberian Seas. In the course of the work, the main areas of SIW generation and propagation in the water area were identified, their main spatial characteristics for the indicated period were determined and mapped.

## Data and methods

The study of the spatial distribution of SIWs and their characteristics in the waters of the Laptev Sea was carried out based on the analysis of data from Sentinel-1 A/B satellite synthetic aperture radars (SAR), launched in 2014–2016. Regular SAR imaging makes it possible to obtain data with a high frequency (every 1–2 days) in a wide swath (about 250 km) and a spatial resolution of 40–90 m.

Processing of satellite data and identification of internal wave surface manifestations in radar images (RI) were carried out in accordance with the technique described in [6].

Fig. 1 shows a map of the study area covered by the SAR survey. As can be seen, the coverage of the radar imagery is quite uneven: most of the images are in the western part of the water area (west of the Arctic Cape), the central deep-water part, and the region near the New Siberian Islands. The least data-rich areas are in the Vilkitsky Strait and the coastal part of the Laptev Sea, as well as near the Anabar Bay, Khatanga Gulf, Olenyok Gulf and Yana Bay.



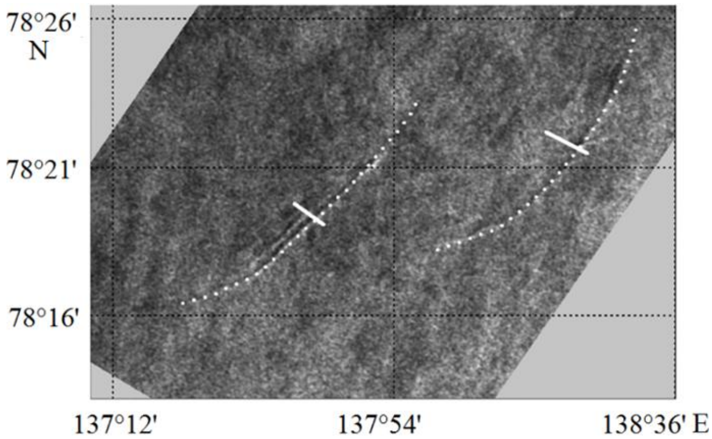

F i g . 1 . Coverage of the Laptev Sea by Sentinel-1 SAR data from 1 July to 31 October 2019. White lines indicate 50-m, 200-m, and 2000-m isobaths. Numbered positions: *1* – Sergey Kirov Islands, *2* – Arctic Cape, *3* – Shokalsky Strait, *4* – Vilkitsky Strait, *5* – Maly Taymyr Island, *6* – Khatanga Gulf, *7* – Blagoveshensky Strait

Analysis of the spatial distribution of surface manifestations of SIWs was carried out using the SNAP program (Sentinel Application Platform). Fig. 2 shows an enlarged fragment of the Sentinel-1 RI for 09.19.2019 (22:50 UTC), which clearly shows manifestations of two SIW packets directed to the southeast.

**Satellite observation results**

In total, during the study, 639 Sentinel-1 A/B radar images were processed for the period from July 1 to October 31, 2019. A detailed study of the received radar images made it possible to detect 30 images with SIW surface manifestations. The largest part of SIW surface manifestations occurred in September (1318 SIW surface manifestations, ~60 %), and the smallest part occurred in July (239 SIW surface manifestations, ~9 %). Variations in the number of identified SIW manifestations for different months can be associated both with the intraseasonal variability of vertical stratification, which determines intensity of SIW generation, and with the variability of wind and ice conditions, which determine the possibility of identifying SIW surface manifestations in satellite data. The table shows the statistics of the analyzed data from July to October 2019.

As a result of processing of 639 radar images, 2081 SIW surface manifestations were found for the summer-autumn period of 2019. The spatial distribution of the leading waves in SIW packets is shown in Fig. 3, *a*. The SIW propagation was observed mainly in the form of solitary wave packets with consistent analysis



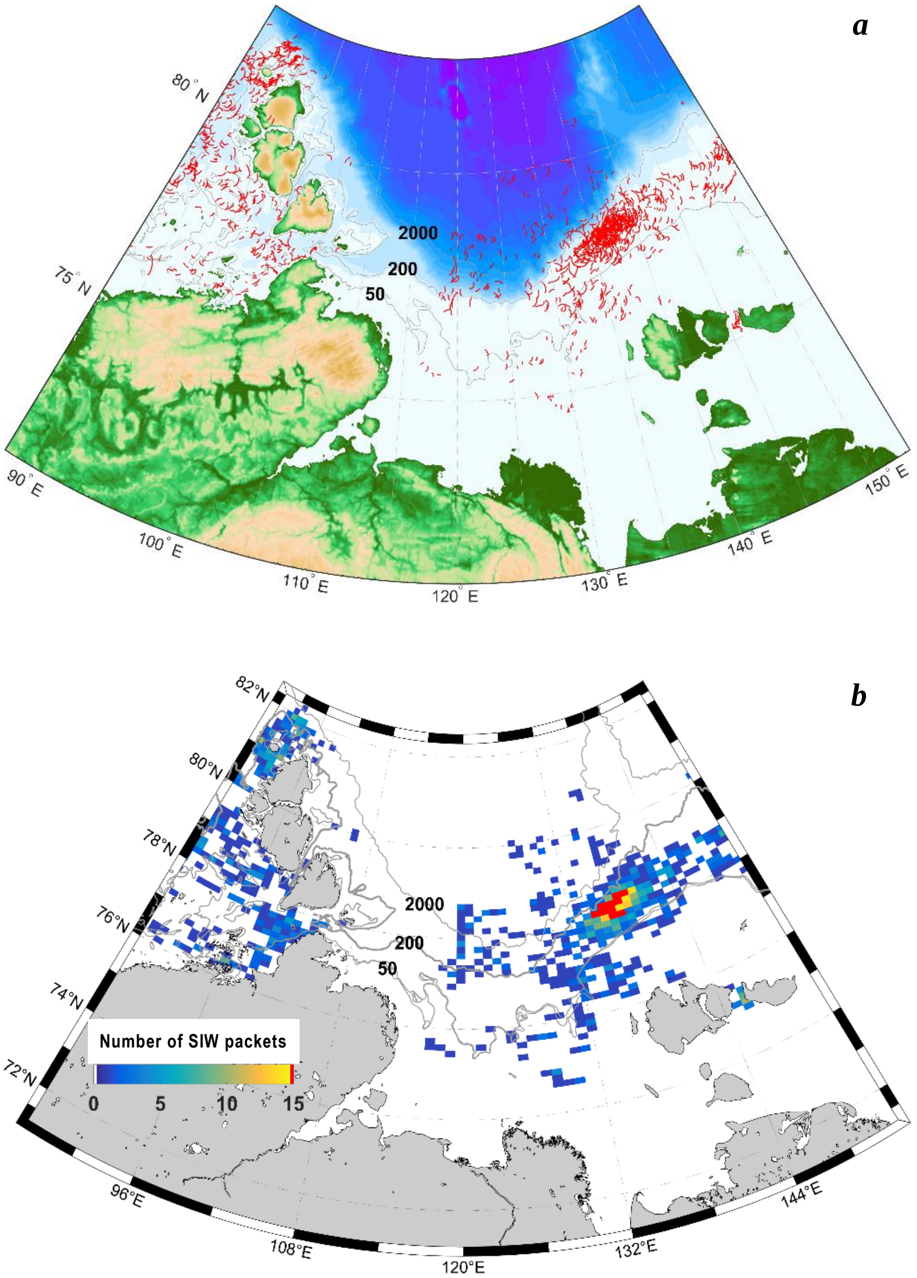

F i g . 2 . An example of manifestation of SIWs in Sentinel-1 SAR image acquired on 09.10.2019 (22:50 UTC) in the Laptev Sea. White dotted lines indicate positions of leading waves in the SIW packets, the white solid line shows wave lengths of the relevant packets

Statistics of analyzed Sentinel-1 A/B SAR data and the number of the SIW SM from July to October 2019

| Month | Number of | | |
|---|---|---|---|
| | analyzed images | images with SIWs | registered SIW packets |
| July | 164 | 4 | 191 |
| August | 147 | 7 | 422 |
| September | 175 | 16 | 1318 |
| October | 153 | 3 | 150 |
| **Total** | **639** | **30** | **2081** |

results; the SIW packets were directed both along the isobaths, towards increasing depths, and towards the shallow shelf. Fig. 3, *a* shows that the distribution of SIW packets over the sea area is uneven.

According to the data analysis of 2011 [7, 8], manifestations of internal waves were most often observed in four key areas: northwest of the Severnaya Zemlya archipelago, east of Bolshevik Island, near the mouths of the Anabar, Lena, and Khatanga rivers, and also north of the New Siberian Islands.



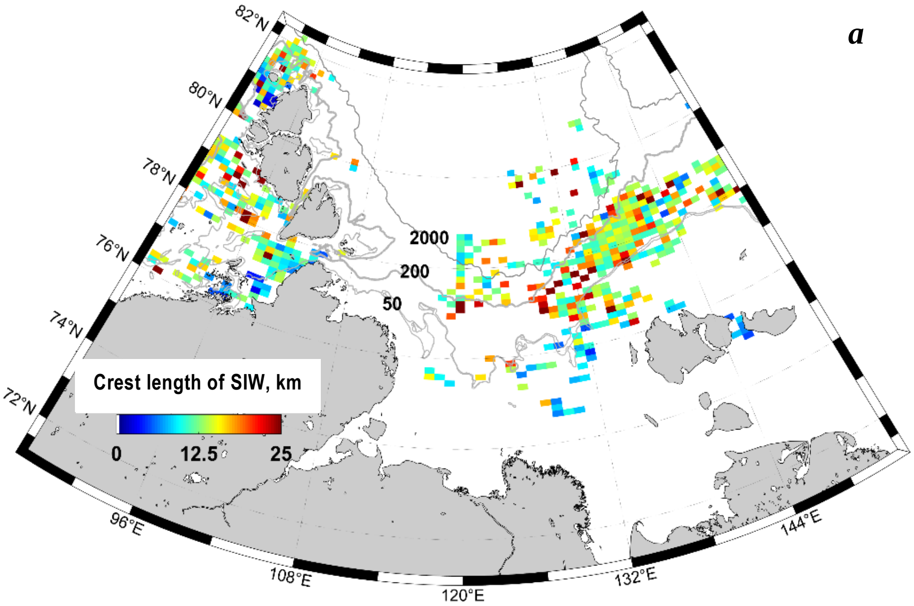

F i g . 3 . Distribution maps of the SIW packets in the Laptev Sea and adjacent regions from July to October 2019: *a* – locations of the leading wave crests in the SIW packets; *b* – total number of SIW surface manifestation. Grey lines indicate 50-m, 200-m, and 2000-m isobaths

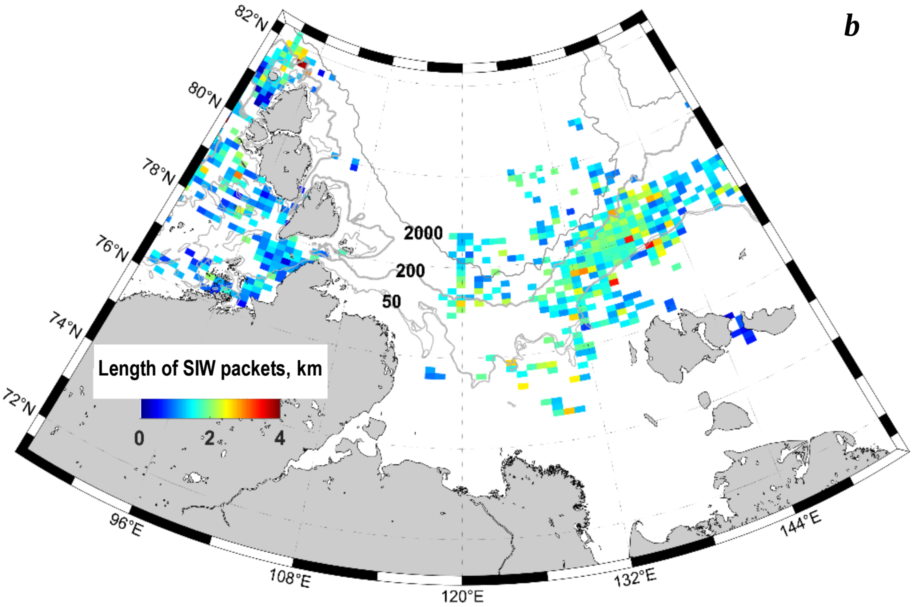
A very similar distribution of SIW SMs was also observed in 2019, with the exception of coastal areas with a pronounced runoff of rivers and to the east of Maly Taymyr Island. This can be partly explained by the fact that the availability of radar images of these areas in 2019 was significantly lower. From July to October 2019, the maximum number of SIW SMs was registered in a vast area of the northeastern shelf of the Laptev Sea. In contrast to the results of 2011, a large number of SIW manifestations is also observed above the continental slope and near the edge of the shelf in the central part of the sea. Also, for the first time, SIW manifestations are observed in large numbers in the deep-water part of the water area southwest of the Lomonosov Ridge. In the western part of the water area, a large number of SIWs were found northwest of the Arctic Cape, as well as west of the islands of the Severnaya Zemlya archipelago. New areas of observation of SIWs were discovered to the northwest of Kotelny Island, in the Blagoveshensky Strait and between Kirov Island and the Nizkiy Cape, including the Vilkitsky Strait from the Kara Sea.

Fig. 3, *b* shows a distribution map of the total number of observed SIW SMs in the waters of the Laptev Sea at the nodes of a grid of 100 × 60 cells. In the most part of the study area, the total number of SIW SMs, on average, did not exceed five cases of registration over the entire observation period. However, in the Blagoveshensky Strait and north-west of the Arctic Cape, the number of SIW recording cases reached ten. The most intense area of SIW SM generation is the area between 50 and 200 m isobaths to the north of Kotelny Island. Here, the total number of SIW SMs in some areas exceeds 15 cases, and on average is at the level of 10–15 cases. This area is characterized by average data availability, while SIW SMs are recorded quite often in it. This confirms that this area is a key place for generation of internal waves in the Laptev Sea. Let us note that this area is characterized by the maximum velocities of tidal currents for the study area, reaching 1 m/s [4, 9].

Comparison of the obtained results with the results of the work of previous years allows us to conclude that the areas of SIW generation can change from year to year. For example, in 2019, the minimum number of SIW SMs was observed in sectors located east of Maly Taymyr Island and north of Bolshevik Island, where, according to 2011 data, it was maximum [7]. On the other hand, the areas north of the New Siberian Islands, in the Vilkitsky Strait and north-west of the Arctic Cape are fairly stable areas for internal wave generation. These areas have expanded significantly in recent years, which may be caused by the so-called atlantification of this sector of the Arctic [10–13]. We also note that the background ice conditions were somewhat different in 2019 and 2011: for the period under consideration, the average position of the ice edge in 2019 was more to the north than in 2011. This fact could affect both formation of more favorable conditions for the generation of SIWs due to the melting of a larger amount of ice, and ability to observe large areas of open water in the northern part of the study area.

Fig. 4 shows maps of distribution of some spatial SIW characteristics – the crest length SIWs (Fig. 4, *a*) and the length of the SIW packets (Fig. 4, *b*).




F i g . 4 . Spatial distribution maps of the SIW characteristics in the Laptev Sea and adjacent regions from July to October 2019: *a* – crest length of the SIW packets; *b* – length of SIW packets. Grey lines indicate 50-m, 200-m, and 2000-m isobaths

Fig. 4, *a* shows that generation of SIW packets with longer crest lengths is noted along the entire shelf of the Laptev Sea. The most extended crests were found in the central part of the water area and northwest of Kotelny Island. In these areas, the crest length reaches maximum values (50–60 km). In the Vilkitsky, Shokalsky, and Blagoveshensky Straits, shorter SIW trains were observed, the value of the crest lengths did not exceed 12 km.

The distribution of SIW packet length values is shown in Fig. 3, *b*. SIW packets with maximum packet lengths up to 3.3 km were found north of Kotelny Island. In the region of the straits, the packet length varies from 0.9 km to 2.1 km. In the area north of the New Siberian Islands, more extended SIW packets are formed. A similar trend is also observed to the north of the Arctic Cape, where the values of the length of SIW SM packets are somewhat smaller. The zone in the Kara Sea basin is noteworthy: there are SIWs with more extended crest lengths, but with smaller packet widths. In the section from the Sergey Kirov Islands to Maly Taymyr Island and along the entire length of the Vilkitsky Strait the generation of SIWs with crest lengths of smaller ranges (7–10 km) at the same packet length is observed. This can probably be explained by the influence of background non-tidal currents, which can affect the spatial characteristics of internal waves depending on the current direction [14, 15].

Distribution of the average values of the crest length and the length of SIW packets is shown in the histograms in Fig. 5. The crest lengths characteristic of the Laptev Sea vary from 2 to 60 km, with an average value of 15.8 km.

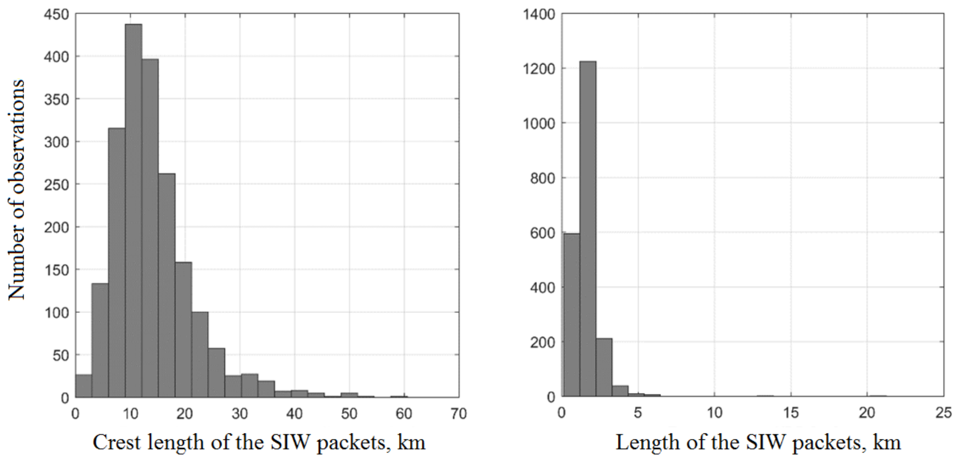



Fig. 5. Histograms of the SIW characteristics in the Laptev Sea and adjacent regions from July to October 2019: *a* – crest length of the SIW packets; *b* – length of the SIW packets

Most often, waves with a length of more than 20 km are observed in the central and eastern parts of the water area. The range of variations in the length of SIW packets is from 400 m to 5.2 km, with an average value of 1.85 km over the entire water area (Fig. 5, *b*).

**Conclusion**

The paper presents the results of a study of the field of short-period internal waves in the Laptev Sea, as well as the adjacent waters of the Kara and East Siberian Seas, obtained during the analysis of the Sentinel-1 A/B satellite data array for the summer-autumn period of 2019. In the course of 639 radar images processing, 30 images with pronounced internal wave surface manifestations were identified. A total of 2081 SIW SMs were registered, maps with the internal wave location and their spatial characteristics were constructed.

In the course of work, it was found that in 2019 the total number of SIW cases was significantly higher compared to 2011. The number of used satellite radar images for the summer-autumn period of 2019 was twice higher than their number in 2011, while the total number of SIW SM cases in 2019 was approximately 20 times higher than their number in 2011. It is interesting to note that with a significant increase in the total number of SIW observations in 2019, the variability range of the values of their main spatial characteristics is approximately the same as in 2011.

It is important that, in addition to the general increase in the cases of SIWs by an order of magnitude, the areas of SIW manifestation also expanded significantly. Besides, new regions of regular SIW generation were discovered in the Shokalsky Strait, between the New Siberian Islands, as well as in the deep-water part of the water area. All these facts indirectly confirm the hypothesis that the observed "atlantication" of the Eurasian sector of the Arctic, which is characterized, among other things, by intensification of currents against the background of a general weakening of vertical stratification, can contribute to an increase in the SIW generation in the Arctic.

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**Alexey V. Kuzmin** – data processing and analysis, article text preparation and revision

**Igor E. Kozlov** – problem statement, data processing and analysis, preparation of visual materials, article text revision

*All the authors have read and approved the final manuscript.*