TRANSLATION

The influence of heavy shipping traffic on structure and dynamics of sea ice in the southwestern Kara Sea

Tatiana A. Alekseeva[1,2]✉, Sergey S. Serovetnikov[1], Evgenii I. Makarov[1], Vladimir A. Borodkin[1], Dmitry M. Ermakov[2,3], Vasiliy V. Tikhonov [2,1,4], Alexey V. Kuzmin[2], Ekaterina V. Afanasyeva [1,2], Vladimir D. Kotelnikov[1], Daniel Y. Yuskaev[1], Evgenii V. Kozlovsky[1]

[1]*Arctic and Antarctic Research Institute, Saint Petersburg, Russia*

[2]*Space Research Institute RAS, Moscow, Russia*

[3]*Kotelnikov Institute of Radioengineering and Electronics RAS, Fryazino Branch, Fryazino, Moscow Region, Russia*

[4]*Institute for Water and Environmental Problems SB RAS, Barnaul, Russia*

✉ taa@aari.ru

For citation: Alekseeva T.A., Serovetnikov S.S., Makarov E.I., Borodkin V.A., Ermakov D.M., Tikhonov V.V., Kuzmin A.V., Afanasyeva E.V., Kotelnikov V.D., Yuskaev D.Y., Kozlovsky E.V. The influence of heavy shipping traffic on the structure and dynamics of sea ice in the southwestern Kara Sea. *Arctic and Antarctic Research*. 2024;70(3):323-337. (In Russ.) https://doi.org/10.30758/05552648-2024-70-3-323-337

Abstract. The development of the Northern Sea Route as well as the beginning of year-round transit shipping require not only the production of new icebreakers and ice-class vessels, but also the development of a specialized hydrometeorological support system for ice shipping. For the analysis of satellite data and the development and validation of ice forecasts, actual field data on the ice cover is required. This data can only be obtained from shipboard observations; however, scientific expeditions are rarely organized during the winter. In order to obtain new data over the area of intensive shipping, two expeditions were organized on board of nuclear icebreakers in 2023 and 2024 in the southwestern Kara Sea ("LED-SMP" expeditions). Specialized hydrometeorological maintenance of ice shipping in the southwestern Kara Sea together with the scientific expeditions “LED-SMP” carried out in the same place and time on board the nuclear icebreakers revealed the influence of the technogenic factor on the sea ice structure and dynamics. In winter and spring, two main routes are used for navigation in the southwestern Kara Sea: through the Kara Gate Strait and north of Cape Zhelaniya. In April 2024, a unique situation occurred when, due to the difficult ice conditions east of the Kara Gate Strait, the entire ship traffic was directed north of Cape Zhelaniya. In preparing a long-term ice forecast, it was noted that after the redirection the natural development of ice processes changed. At the beginning of the winter

period 2024, the sea ice conditions developed in a way similar to those observed in the selected homologous years (years with similar scenarios of the sea ice conditions development), however, at the end of the winter period they became different from what was typical of this water area. In performing shipboard observations, significant changes were noted in the sea ice structure along the entire route from Ob Bay to Cape Zhelaniya, which could also affect the speed of ships in such ice. The paper reports preliminary findings from analysis of the data obtained during the LED-SMP-1/2024 expedition. Also, a description is given of a concurrent field/satellite experiment the results of which should later enable us to determine the technogenic impact on the microwave radiation of the sea ice surface.
Key words: ice forecast, technogenic factor, microwave radiometry, sea ice navigation, sea ice structure, shipboard ice observations, field experiment concurrent with satellite survey

Introduction

High-quality specialized hydrometeorological support is a necessary component for the efficiency and safety of ice navigation along the Northern Sea Route (NSR). Many countries are interested in cargo shipping along NSR as an alternative to the route via the Suez Canal [1-3]. Currently, the most important aspects to develop specialized hydrometeorological support are both the improvement of the existing and development of new long-term ice forecasts, which provide the advance planning of marine operations. Despite the fact that new powerful nuclear icebreakers and ice-strengthened carriers have been put into operation, the year-round transit navigation along NSR is still not carried out [4, 5]. Along the entire NSR, there are several sections with unfavorable ice navigation conditions in the winter-spring period for any type of vessel. Long-term ice forecasts of optimal navigation routes allow for advance prediction of periods when openings in ice are expected in difficult areas, as well as the absence of ice compression. Such forecasts are mostly required for the areas and periods which are not provided by specialized *in situ* shipboard data on ice navigation conditions and needed for validating forecasts.

In 2023, the Arctic and Antarctic Research Institute (AARI) began a series of expeditions on board nuclear icebreakers in the southwestern part of the Kara Sea [6]. The purpose of these expeditions was to train young specialists for enlarging the expeditionary staff and to share the experience in special ship ice observations. The system of the observations was developed in AARI in the mid-20th century. Since 2004, AARI ice observations consist of two types of work: continuous visual ice observations of the sea ice characteristics along the route and in the area of ship movement [7] and measurements of ice thickness and snow depth using a ship television complex (STK) [8 ,9].

Concurrently with the process of training specialists during the first expedition in 2023, a need for a comprehensive revision of the entire system of special ship ice observations was revealed. The observations should be carried out in close connection with the tasks of developing specialized hydrometeorological support. The new approach should be based on a planned experiment, that means that the form and structure of information received on board should depend on the requests of specialized hydrometeorological support (for example, for prompt ice forecasts refinement). This, in turn, requires further modernization of STK for gathering data on ice structure during the ship movement, which enables the development of a new scientific direction, namely identifying the main and local scenarios of the sea ice formation. Detailed results of the developments implemented in the first expedition LED-SMP-1/2023 are presented in the paper [6].

During the analysis of the data from LED-SMP-1/2023, a number of questions arose that required to set new research tasks. The research program of the next expedition LED-SMP-1/2024 in April-May 2024 was expanded: an upgraded version of STK was used to test a new technology for the ice structure data acquisition during the ship movement, as well as a new experiment on concurrent satellite and *in situ* surveys was conducted. The specific features of the spring navigation in 2024 in the southwestern part of the Kara Sea also contributed to review the research program. Due to difficult navigation conditions in the Kara Gate Strait, the entire ship traffic from the Barents Sea to the ports of the Kara Sea and back passed through Cape Zhelaniya. Unique conditions for the sea ice formation occurred in the area of the main navigation routes due to the technogenic impact of the large traffic of cargo ships and icebreakers. This caused changes in both the ice structure in the southwestern part of the Kara Sea and dynamics of the ice cover and, as a result, affected the accuracy of ice forecasts. The aim of this paper is to present the primary findings from analysis of special ship observation data obtained during LED-SMP-1/2024, as well as to describe the experiment on *in situ* measurements concurrent with satellite observations ("concurrent field/satellite experiment") as a basis for further study of the changes in ice and hydrological regimes associated with intensive shipping in the southwestern part of the Kara Sea.

Expedition LED-SMP-1/2024

In 2024, special ship ice observations were carried out on board the nuclear icebreaker *Yamal*. The expedition route is shown in Fig. 1. The expedition LED-SMP-1/2024 was conducted during seven voyages of the icebreaker from the Gulf of Ob to Cape Zhelaniya and back during the icebreaker routine escort operations along the Northern Sea Route (NSR).

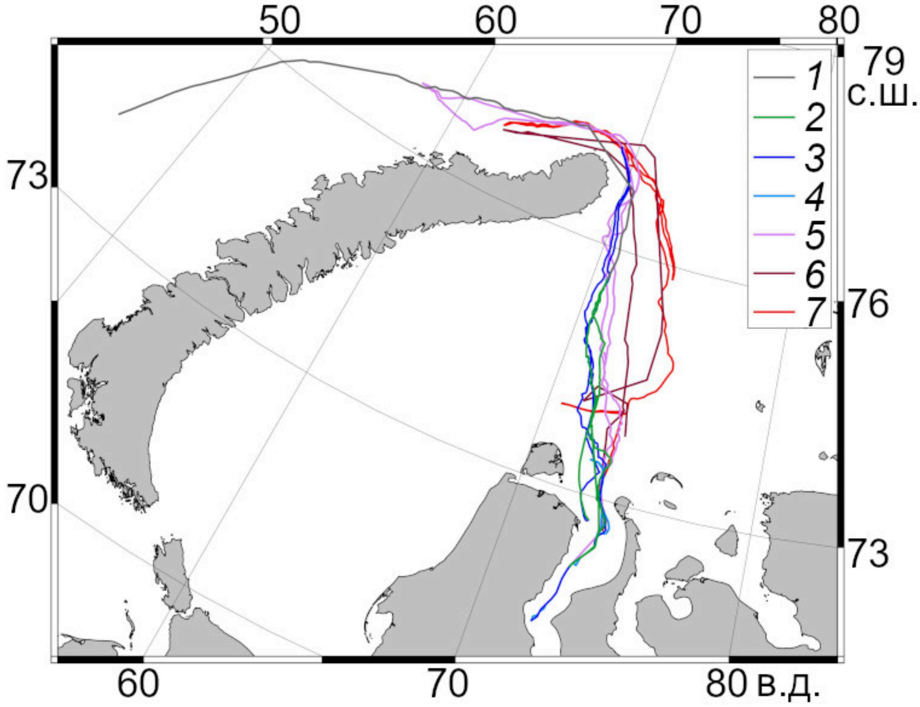

Fig. 1. The routes of expedition on board the nuclear icebreaker *Yamal* in the southwestern Kara Sea during the period of April 19 to May 20, 2024 (routes of *Yamal*: No. 1 – April 19-21, No. 2 – April 22-26, No. 3 – April 26-29, No. 4 – April 29-30, No. 5 – May 01-06, No. 6 – May 07-13, No. 7 – May 16-20, 2024)

Navigation specifics in 2024 in the southwestern part of the Kara Sea

Since April 2024, a unique navigation situation has developed in the southwestern part of the Kara Sea, which has not been observed since the beginning of year-round navigation without icebreaker support in the southwestern part of the Kara Sea over the past 20 years. Information on the location of ships is regularly received and analyzed in AARI. The information is based on daily routine reports from ice-class ships operating on the NSR as well as from various AIS (Automatic Identification System) sources (https://www.marinetraffic.com/ and https://maritime.scanex.ru/). On April 1, 2024, the tanker *Mikhail Lazarev* left the Kara Sea for the Barents Sea through the Kara Gate Strait, moving from the Gulf of Ob to the port of Murmansk. After this voyage, all ship routes passed through Cape Zhelaniya, because unfavorable conditions for ice navigation developed in the Kara Gate Strait in April.

In terms of hydrological and ice regime, the Kara Sea is divided into two contrasting parts, namely the southwestern and northeastern. In the southwestern part, medium first-year ice (with thickness range 70–120 cm) is predominantly observed in winter, and the Novozemelsky ice massif is formed in summer. In the northeastern part of the sea, medium and thick first-year ice (with thickness over 120 cm) is predominantly observed in winter, and the Severozemelsky and Kara

Northern ice massifs are formed in summer [10]. The geographical boundary between the parts follows the line connecting Cape Zhelaniya and Dikson Island. The natural boundary also goes here, connecting the northern tip of the Novaya Zemlya archipelago and the shallow part of the Ob-Yenisei area, where openings and leads are often formed in the meridional direction [11]. This feature of the ice and hydrological regimes of the Kara Sea is always used when navigating in ice on the routes from the Gulf of Ob and the Yenisei Gulf through Cape Zhelaniya. However, in April and May 2024, the navigation was realized exclusively along this route. Thus, the ice cover along the route was affected by greater technogenic impact than in previous years, which necessitated a study of the impact of this phenomenon on the ice-hydrological regime of the entire Kara Sea.

In AARI, the "Method of specialized forecast of ice-operational characteristics of icebreaker-free navigation of modern types of vessels along the NSR with up to 1 month in advance" was developed and approved by the Central Methodological Commission for Forecasts of Roshydromet in 2020 (https://method.meteorf.ru/cmkp/2020/dec20.pdf). The method is used for making long-term forecasts of ice navigation conditions based on identifying of homologous years [12]. By applying this method, several homologous and antipodal years were chosen and analyzed for the ice navigation conditions in spring 2024. Figure 2 shows sea ice concentration maps retrieved with the ASI algorithm (AMSR-E and AMSR2 radiometers, version 5.4, resolution 6.25 km, https://data.seaice.uni-bremen.de/databrowser/) for April 22, 2024, homologous years 2006 and 2015, and antipodal year 2023.

Figure 2 shows that the homologous years (2006 and 2015) demonstrate the main feature of the ice and hydrological regimes of 2024, which is the absence of pronounced dynamic structures in the southwestern part of the Kara Sea. In 2023, the structures in the southwestern part of the Kara Sea are well defined. Figure 3 presents the same data for June.

Figure 3 clearly shows that in June, none of the homologous years reveal the same dynamics of the sea ice cover as in 2024. At the same time, there is good spatial correspondence in the distribution of the sea ice concentration. That is, the dynamics of the sea ice in the southwestern part of the Kara Sea until April 2024 followed the scenario of the homologous years, and then, in June, after the intensive shipping along the single navigation route, the scenario changed. The observed changes led us to hypothesize that there is technogenic factor affecting the ice and hydrological regimes of the Kara Sea.

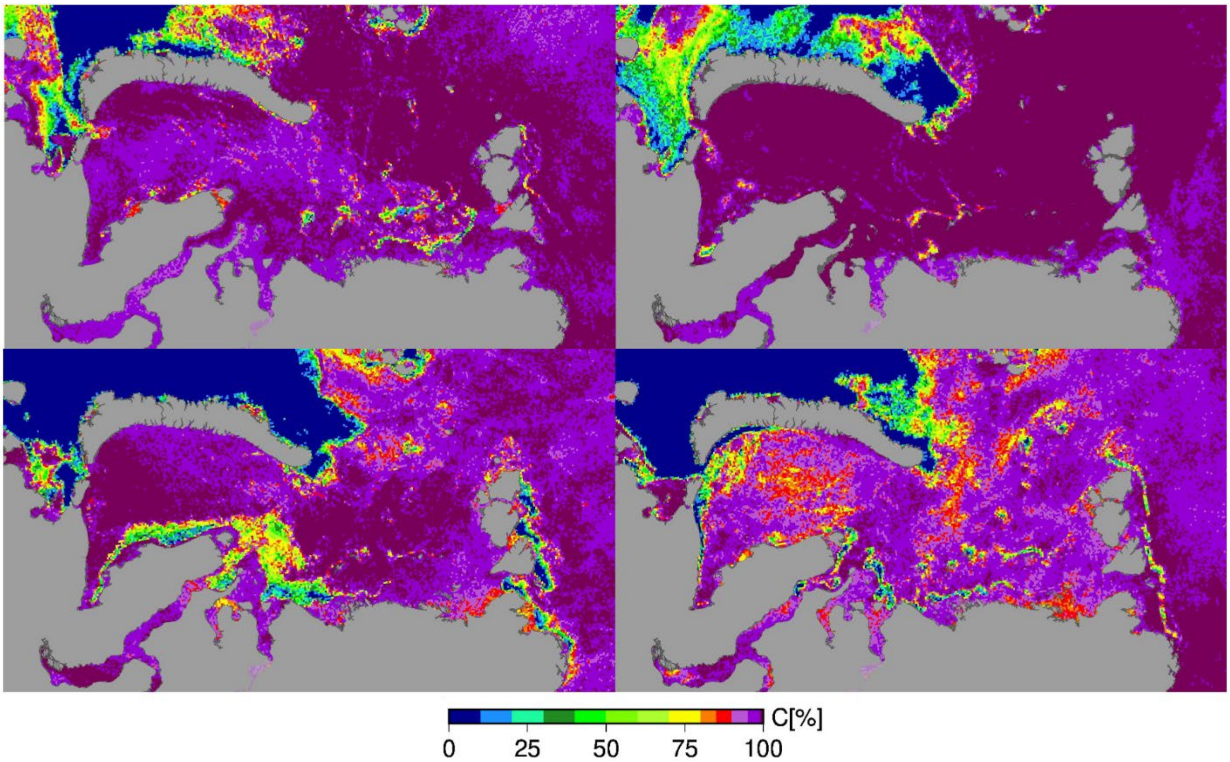

Fig. 2. Sea ice concentration maps (https://data.seaice.uni-bremen.de/databrowser/) on April 22 of 2024 *(а)*, 2006 *(б)*, 2015 *(в)* (homologous years), and 2023 *(г)* (antipodal year)

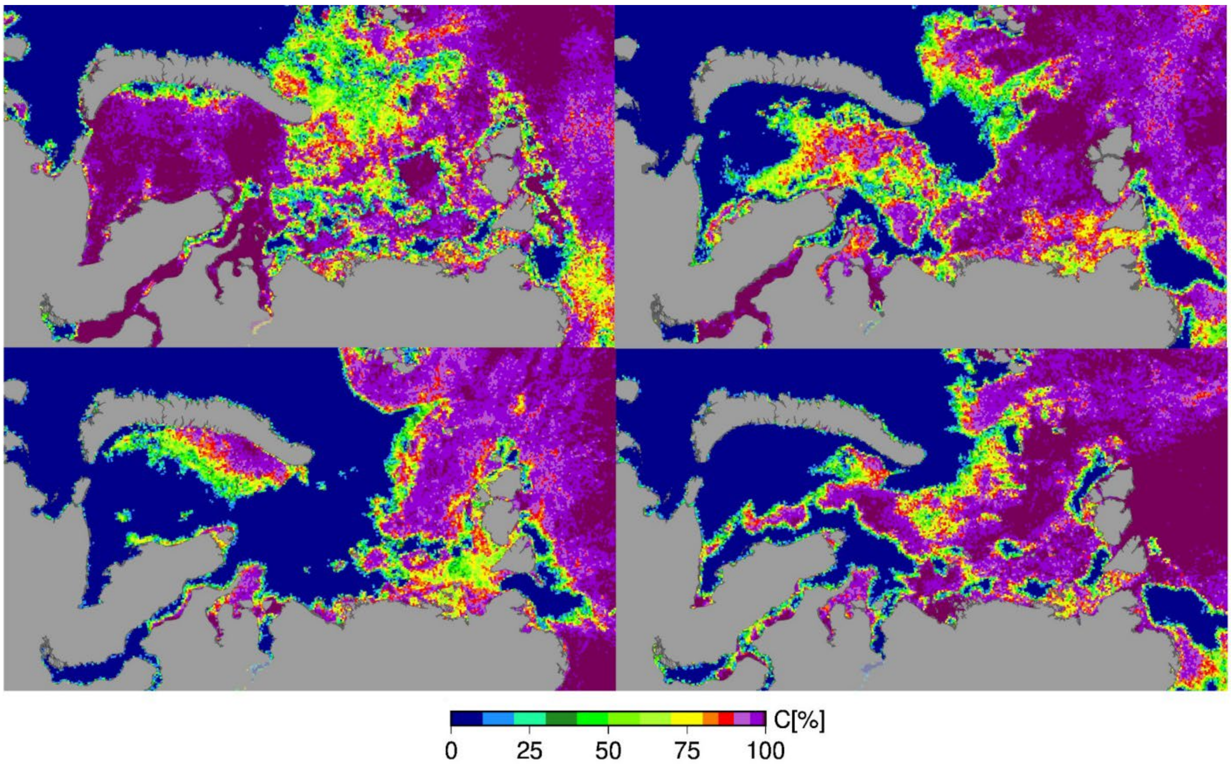

Fig. 3. Sea ice concentration maps (https://data.seaice.uni-bremen.de/databrowser/) on June 22 of 2024 *(а)*, 2006 *(б)*, 2015 *(в)* (homologous years), and 2023 *(г)* (antipodal year)

The first mention of the technogenic impact on the Kara Sea ice cover associated with a significant increase in shipping in the port of Sabetta in winter-spring period was made in 2018 in the context of the ice and hydrometeorological support for winter-spring marine operations throughout a discussion with navigators of the navigation specifics. It was noted, that the dynamics of the sea ice cover on the routes through Cape Zhelaniya did not correspond to its natural features, but resembled a modified technogenic environment. In fact, 2018 is not a natural homologous year for 2024, but analyzing the conditions of ice navigation in 2018 showed homologies in the response of the ice and hydrological regimes to the technogenic impact. Similar manifestations were expected in subsequent years, but they were most clearly manifested and proved by specialized *in situ* data from on board the nuclear icebreaker in 2023 and 2024. To illustrate the intensification of shipping in the southwestern part of the Kara Sea, Figure 4 shows the shipping routes in 2015, 2023 and 2024 for the month-long period of the LED-SMP-1/2024 expedition (April 19 – May 20). The year of 2015 was chosen as an earlier homologous year with less intensive shipping. In 2023, the shipping intensity increased significantly, but shipping routes were evenly distributed along two navigation routes, either through the Kara Gate Strait or through Cape Zhelaniya. In 2024, all routes passed through Cape Zhelaniya, except for the only voyage of the tanker *Mikhail Lazarev,* mentioned at the beginning of the section.

The prevailing conditions resulted in the formation of a stable, difficult-to-pass ice belt between 73–76° N and 71–73° E. Ships moved through the repeatedly broken, crushed and frozen ice with a significant decrease in speed to values less than 4 knots, jamming in ice and ramming.

Development of methodology for obtaining data on ice structure during ship movement by using STK

The objectives of the expedition included studying some features of ice structure based on STK data in areas with increased number of ice cover destruction due to technogenic impact. During the ship movement, STK took pictures of the overturned ice blocks to record and identify ice thickness and vertical texture pattern of ice, including layered structure (Fig. 5).

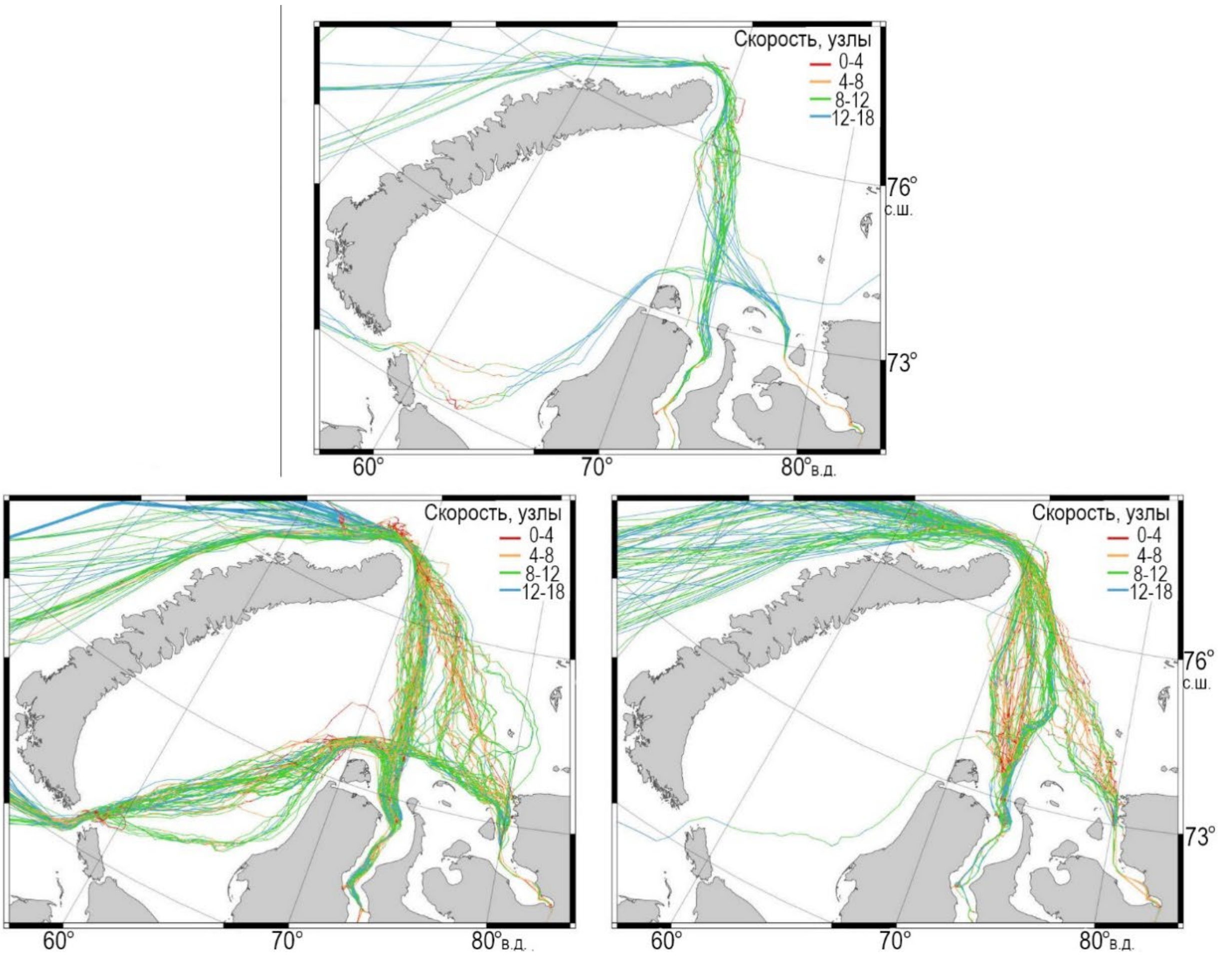

Fig. 4. The routes of icebreakers and Arc7 ice class vessels in the southwestern Kara Sea from April 19 to May 20 of 2015 *(а)*, 2023 *(б)* and 2024 *(в)*

Fig. 5. The photo of ice floes turned up along the hull of the icebreaker *Yamal* during its movement in the southwestern Kara Sea

The photos of the ice vertical sides showed multiplied layers as compared to the natural ice growth in natural conditions, which is clearly due to the technogenic impact in the study area. Regular destruction of the sea ice cover by ships moved along the route and the subsequent freezing of the formed ice fragments stimulates the formation of new layers on the underside of ice as a result of these processes. The presence of water runoff from land plays a significant role in the formation of ice layers, because fresh water displaces saline sea water and forms a layer of desalinated water under the ice. When ship moves, the rotation of the propellers mixes layers of water with different salinity and temperature. These conditions can result in supercooling of water and lead to the formation of intrawater ice and the adhesion of new ice (shuga) to the ship hull. The sticking of shuga occurs not only to the ship hull, but also to the ice bottom surface, making an additional ice layer. It is possible that supercooling in shallow water contributes to the formation of anchor ice, which captures small particles of soil and lifts them to the underside of ice, forming ice layers with mineral inclusions.

During the LED-SMP-1/2024 expedition, the salinity of seawater was measured. The technical features of the seawater intake unit of the icebreaker provided only mean values of salinity in a layer of 11 meters, which limited the possibility of identifying the water stratification in the study area.

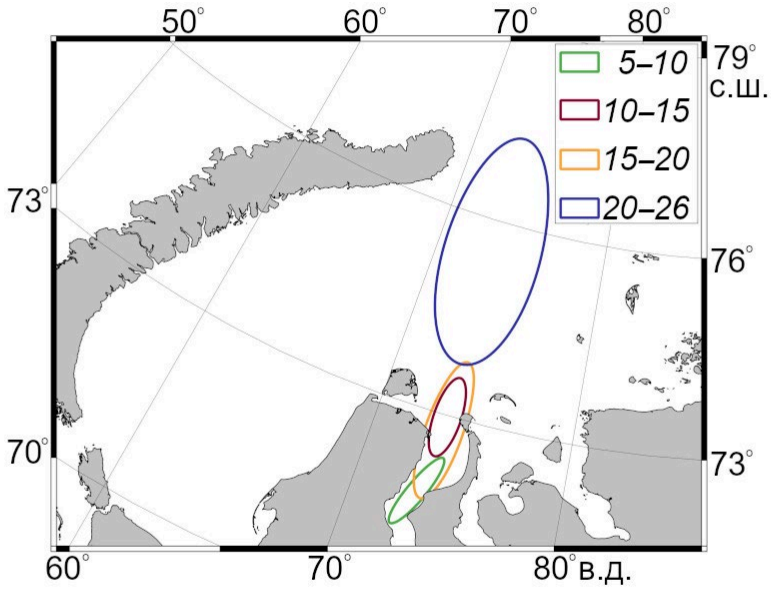

Fig. 6. The areas of different values of sea water salinity (‰)

Primary analysis of the distribution of mean water salinity values (Fig. 6) allows to identify the main areas of salinity impact on differences in ice formation in the study area. Thus, above the latitude of 74° N, the mean water salinity was over 20‰ everywhere, and in the Gulf of Ob it varied from 2‰ to 19‰, increasing from south to north. In the areas of unstable salinity values, the probability of water supercooling and therefore the probability of shuga ice formation during ship movement increases significantly, which resulted in the multiplied layers when the ice freezes from its bottom. In the Gulf of Ob area, vertical side of the ice has more layers than in the central and northern parts of the Kara Sea (Fig. 7). Layers with mineral inclusions are more common.

Preliminary analysis of the obtained data reveals the necessity of considering the following phenomena: the runoff from land; number of the ship voyages in the study water area and frequency of technogenic destruction of the continuity of ice cover; mixing of the underice waters as a result of operation of ship propellers; formation of intrawater ice and its adhesion to the underside of the sea ice, as well as to the hull of ship and the bottom (sticking effect); formation of a layered structure of ice as a single mechanism of the sea ice formation under the conditions of continuous technogenic impact due to transport operations.

Fig. 7. The layered structure of sea ice observed at different latitudes along the route of the "Yamal" icebreaker. The photos were taken at the points of 73.163 N; 73.128 E *(a)*, 74.000 N; 71.419 E *(б)*, and 76.016 N; 70.552 E *(в)*

Considering the above, there is a need to develop a method for studying the sea ice formed under such conditions, as well as gathering data on water temperature and salinity, sea ice structure and its physical properties.

Concurrent field/satellite experiment

Regular monitoring of the state of the arctic sea ice cover on the global scale is based on data of satellite microwave radiometers (SSMIS, AMSR-2, etc.). Currently, more than a dozen algorithms for reconstructing the ice concentration and extent based on satellite microwave radiometry data have been developed and are used in practice [13, 14]. A problem of the satellite data and, hence, of these algorithms is the low spatial resolution of measurements. The variability of the sea ice cover within the resolution of the satellite microwave radiometer can be very large, especially during the intensive processes of ice formation or destruction [15].

To refine the relationships between the characteristics of the natural sea ice cover and the spectrum of the emitted microwave radiation we need to conduct comprehensive *in situ* experiments concurrent with satellite surveys. The main goal of such experiments is to obtain microwave data similar to satellite ones, but with higher spatial detail, together with information on the current state of the ice cover at observation points according to synchronous optical measurements and expert estimates. Thus, the main objective of the concurrent field/satellite experiment during the LED-SMP-1/2024 expedition was to provide microwave radiometric measurements of the surface (sea ice cover and/or open water area) at the frequencies similar to those of satellite radiometers and used in the sea ice concentration reconstructing algorithms. To take into account the contribution of atmospheric radiation, as well as to implement the external calibration procedure of the radiometers, an important task was to carry out regular observations of the atmosphere at various zenith angles.

Successful completion of the experiment provides calibrated, spatially referenced, timed radiometric information, supplemented by optical observations and expert assessments. It makes it possible to solve the following problems:

1) clarify the dielectric characteristics of different types of ice and snow cover in the microwave range (effective emission and reflection coefficients);

2) test and refine the algorithms for reconstructing the following characteristics of the underlying surface based on microwave data: sea ice cover concentration, snow cover thickness, effective thickness and temperature of the layer that forms the upward microwave radiation.

In the 2024 experiment, a microwave radiometric complex (Fig. 8a) was used to provide measurements at frequencies of 5.5 GHz (on alternating vertical and horizontal polarizations), 19 GHz, 22.2 GHz (on vertical polarization), 36 GHz (simultaneously on vertical and horizontal polarizations), 60 GHz, 92 GHz (on vertical polarization). Radiometric measurements were accompanied by video recording of the sea ice parameters in the observation spot with a frequency of 1 image per 2 seconds together with recording of navigation information for accurate coordinate referencing. The measuring complex made it possible to mechanically change zenith angles. In the experiment, the observations were conducted in two main modes, the first mode at an angle of 37° to the surface (angle of 53° to the normal) corresponding to the measurement geometry of the SSMIS and AMSR-2 satellite radiometers [8], and the second one at an angle of 25° to the surface (65° to the normal) corresponding to the measurement geometry of MTVZA-GY [16; 17]. During the regular calibration, mirror angles were set at values of 53° and 65° to zenith, respectively. Additionally, slow scanning of the atmosphere by elevation angle from horizon to zenith was carried out. At the top point, calibration was carried out using standard emitters ("cold" and "hot" loads) at temperatures of about 14°C and 50°C, respectively (Fig. 8b). Viewing angles were continuously monitored using a three-axis inclinometer and recorded synchronously with the recording of other measurements.

The equipment was placed on board the icebreaker *Yamal* at a height of about 17.5 meters above the surface (Fig. 8c), thus, it gave a removal of the center of the observation spot at about 23.2 meters and 35.5 meters from the ship side at the used zenith observation angles (53° and 65° from nadir). The main axes of all radiometric instruments were matched. The observation spot had elliptical shape (elongated perpendicular to the course), the dimensions enlarged with increasing radiation wavelength. In the lowest-frequency channels, it had the following dimensions for the incident angle of 53° from nadir (with an angular size of the antenna directivity pattern at a level of 3 dB): 10.4 meters for 5.5 GHz; 9.0 meters for 19 GHz and 22.2 GHz. At incident angle of 65° from nadir, the dimensions were, respectively, 14.8 meters for 5.5 GHz and 12.8 meters for both 19 GHz and 22.2 GHz.

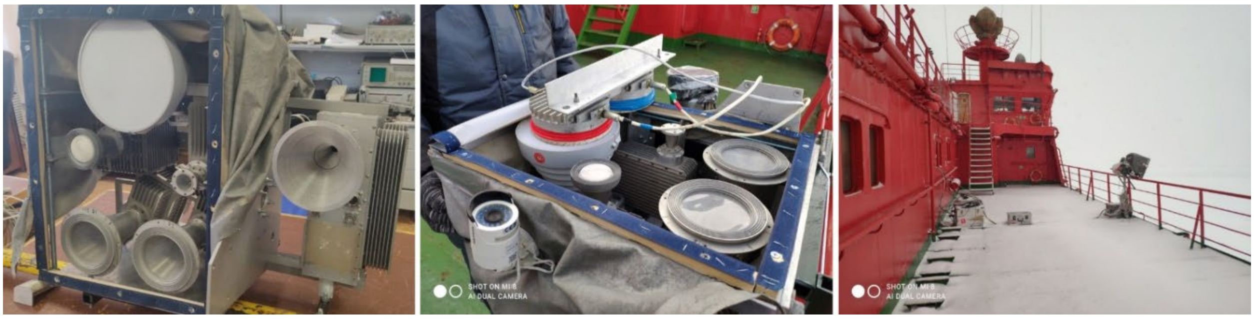

Fig. 8. The complete set of the microwave radiometric complex *(a)*, the complex during calibration using standard emitters ("cold" and "hot" loads) *(b)*, and the complex fixed on board the "Yamal" icebreaker during measurements *(c)*

The experiment was conducted on areas both of relatively untouched ice and heavily deformed ice. Further analysis of the accumulated data will reveal the degree of technogenic impact on the characteristics of microwave own radiation of the ice cover.

Conclusion

The results of the analysis of special ship ice observations obtained during two spring expeditions LED-SMP-1/2023 and LED-SMP-1/2024 allow us to identify significant changes in the ice structure in areas of intensive shipping. Additionally, we reveal a significant impact of technogenic factor on forecasting the dynamics of ice cover and changes in the sea ice structure. The discovered technogenic impact on the formation of sea ice cover brings up a number of scientific and practical questions that need an urgent and detailed study:

1. How does intensive shipping change the sea ice structure, conversely, how does the changed ice cover affect the real icebreaking capability of ships.

2. How does the dynamics of ice cover change in areas of intensive shipping and how should this be taken into account in the ice forecasts.

3. What are the features of imaging of the ice deformed under technogenic impact on satellite images in various ranges of the electromagnetic spectrum?

To provide fully answers for these questions we need to conduct additional experiments and new expeditions, covering the entire period of formation and melting of the sea ice cover in the southwestern part of the Kara Sea, as well as a detailed analysis of satellite information and monitoring of changes and drift of the deformed ice.

Competing interests. The authors declare no conflict of interest**.**

Funding. Visual ice observations, obtaining data on ice thickness using the AARI STK in the LED-SMP-1/2024 expedition, as well as analysis of the impact of man-made factors on long-term ice forecasts, modernization of the STK, analysis of the ice cover structure were supported by the Russian Science Foundation [grant number 23-17-00161] (Alekseeva T.A., Serovetnikov S.S., Makarov E.I., Tikhonov V.V., Afanasyeva E.V., Kotelnikov V.D., Yuskaev D.Yu., Kozlovsky E.V.).

The development of a microwave radiometric complex at the Space Research Institute and conducting a concurrent field/satellite experiment using it on board a nuclear icebreaker in the LED-SMP-1/2024 expedition was carried out within the framework of the topic "Monitoring" state registration No. 122042500031-8 (Ermakov D.M., Kuzmin A.V.).

REFERENCES

1. Nguyen L.H., Park S-H., Yeo Gi-Tae. Keyword network analysis: Uncovering research trends on the Northern Sea Route. The Asian Journal of Shipping and Logistics. 2021;37(3):231-238. https://doi.org/10.1016/j.ajsl.2021.06.001

2. Gunnarsson B., Moe A. Ten years of international shipping on the Northern Sea Route: trends and challenges. Arctic Review on Law and Politics. 2021;12:4-30. DOI:10.23865/arctic.v12.2614

3. Grigoryev M.N. Development of Transit Potential of the Northern Sea Route. Outlines of global transformations: politics, economics, law. 2021;14(4):81-97. DOI: 10.23932/2542-0240-2019-12-5-109-129

4. Chen S-Y., Kern S., Li X-Q., Hui F-M., Ye Y-F., Cheng X. Navigability of the Northern Sea Route for Arc7 ice-class vessels during winter and spring sea-ice conditions. Advances in Climate Change Research. 2022;13(5):676-687. https://doi.org/10.1016/j.accre.2022.09.005

5. Li X., Otsuka N., Brigham L.W. Spatial and temporal variations of recent shipping along the Northern Sea Route. Polar Science. 2021; 27: 100569. DOI:10.1016/j.polar.2020.100569

6. Alekseeva T.A., Makarov Y.I., Borodkin V.A., Serovetnikov S.S., Saperstein E.B., Sokolova Yu.V., Kotelnikov V.D. Development of the method of special ship ice observations. *Arctic and Antarctic Research*. 2023;69(4):394-406. (In Russ.) https://doi.org/10.30758/0555-2648-2023-69-4-394-406

7. *Observations of sea ice conditions. Saint-Petersburg*. 2009. 360 p.

8. Serovetnikov S.S., Frolov S.V., Klein A.E. Ship-based television complex — the program for automatic sea ice thickness monitoring. *Russian Arctic*. 2018;2:41–55. (In Russ.) https://doi.org/10.24411/2658-4255-2018-00017

9. Afanasyeva E.V., Serovetnikov S.S., Alekseeva T.A., Grishin E.A., Solodovnik A.A., Filippov N.A. Mapping the thickness of sea ice in the Arctic as an example of using data from a ship-based television complex for operational hydrometeorological support of maritime activities. *Arctic and Antarctic Research*. 2022;68(2):96–117. (In Russ.) https://doi.org/10.30758/0555-2648-2022-68-2-96-117

10. Karklin V.O., Yulin A.V., Sharatunova M.V., Mochnova L.P. Climate variability of the Kara sea ice massifs. *Arctic and Antarctic Research*. 2017;(4):37-46. (In Russ.) https://doi.org/10.30758/0555-2648-2017-0-4-37-46

11. Buzuev A.Ya., Dubovtsev V.F., Zakharov V.F., Smirnov V.N. Conditions of ice navigation in ice of northern hemisphere // GUNiO, 1988. 280 p.

12. Sapershtein E.B., Makarov E.I., Alekseeva T.A., Pavlova E.A. New approach to Arctic ice dynamics research and its applications in Arctic shipping. *Transactions of the Krylov State Research Centre*. 2024; Special Issue 1: 168–176 (In Russ.) EDN: QALYWX

13. Tikhonov V. V., Raev M. D., Sharkov E. A, Boyarskii D. A., Repina I. A., Komarova N. Yu. Satellite microwave radiometry of sea ice of polar regions: a review // Izvestiya, Atmospheric and Oceanic Physics. 2016. Vol. 52. No. 9. P. 1012-1030. https://doi.org/10.1134/S0001433816090267

14. Ivanova N., Pedersen L., Tonboe R., Kern S., Heygster G., Lavergne T., Sorensen A., Saldo R., Dybkjaer G., Brucker L., Shokr M. Inter-comparison and evaluation of sea ice algorithms: towards further identification of challenges and optimal approach using passive microwave observations. *Cryosphere*. 2015. V. 9. P. 1797–1817. https://doi.org/10.5194/tc-9-1797-2015

15. Alekseeva T.A., Sokolova J.V., Afanasyeva E.V. et al., The Contribution of Sea-Ice Contamination to inaccuracies in Sea-Ice Concentration Retrieval from Satellite Microwave Radiometry Data during the IceMelt Period. *Izvestiya, Atmospheric and Oceanic Physics*, 2022, Vol. 58, No. 12, pp. 1470–1484, DOI:10.1134/S0001433822120039

16. Boldyrev V.V., Ilgasov P.A., Pantsov V.Yu., Prokhorov Yu.N., Strelnikov N.I., Cherny I.V., Chernyavsky G.M., Yakovlev V.V. Microwave scanner/probe MTVZA-GYA spacecraft "Meteor-M" No. 1. *Questions of electromechanics. Proceedings of NPP VNIIEM*. 2008;107:22-25

17. Chernyavsky G.M., Mitnik L.M., Kuleshov V.P., Mitnik M.L., Streltsov A.M., Evseev G.E., Cherny I.V. Brightness temperature modeling and first results derived from the MTVZA-GY radiometer of the Meteor-M No. 2-2 satellite. *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa*. 2020;17(3):51–65 (in Russ.), DOI: 10.21046/2070-7401-2020-17-3-51-65