DEVELOPMENT OF THE METHOD OF SPECIAL SHIP ICE OBSERVATIONS

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Summary

Since the middle of the 20th century, the specialists of the Arctic and Antarctic Research Institute (AARI) carry out special ship ice observations in the Arctic and other freezing seas. Field data on the main sea ice parameters are necessary for developing and validation of sea ice forecasts and satellite information. In accordance to the technical achievements and new scientific and practical challenges, observation methods are constantly evolving. In spring 2023, sea ice observations were organized by the AARI's specialists onboard the nuclear icebreaker "*50 let Pobedy*" in the south-western part of the Kara Sea. The paper presents new recommendations to the procedure of special ship ice observations, which were developed during the expedition. They involve sending operative and forecast hydrometeorological information from AARI to the ship with the request to transfer data processing results back to AARI in the areas of predicted high deformation of ice cover along the route, as well as upgrading of ship television complex in order to receive information about ice layers and structure.

Key words: optimal route, ice navigation, hydrometeorological support, ice observations, ship television complex, ice structure, Northern Sea Route.

Introduction

Currently there are three methods of visual ship ice observations in the world, these are the AARI methodology, the protocol for Antarctic Sea-ice Processes and Climate (ASPeCt), (http://www.aspect.aq) and the protocol for Arctic Ship-based Sea Ice Standardization (IceWatch/ASSIST) (http://icewatch.gina.alaska.edu). The principle of all ship-based observations is to visually record the parameters of sea ice cover during the movement of a ship. In the international practice, ship-based visual observations are carried out once every 1–3 hours as the ship moves, which does not provide complete information on sea ice cover along the route.

The system of special (dedicated) ship-based ice observations of AARI was developed in the middle of the 20th century. The first generalization of the experience of ship-based ice observations was made by Ya. Gakkel[1] in 1944, later a number of works describing the methodology were published, and the last guidance was compiled by S. Frolov[2] in 2011.

The main principle of the AARI special ship ice observations is continuous recording of sea ice cover parameters and data on operational performance of a ship both along the ship route and in the area of the ship movement. All parameters were observed visually until 2004; since 2004, visual observations have been supplemented by instrumental measurements of ice thickness and snow depth using the Ship-based Television Complex (STK).

Ship-based monitoring of sea ice conditions is necessary for the development of the high-quality recommendations on the optimal ship route in ice, as well as for validation of satellite information and sea ice forecasts.

In recent years, it becomes necessary to review the methods of special ship ice observations for a number of reasons:

1. A large amount of remote sensing data in open access makes it possible to make an information environment for recording the evolution of sea ice processes with high degree of reliability.

2. Unlimited communication and data upload have become available onboard the ships.

3. Scientific and ship equipment has been improved.

4. There is sufficient data to provide a new understanding of the natural mechanisms of ice cover dynamics.

5. There is a need for developing and improving both short- and long-term ice forecasts for navigation in the Arctic and other frozen seas.

The above reasons set out new requirements for the methodology of special ship ice observations, which should include:

1. Providing daily operational and forecasting data and instructions from the Expedition control center (ECC) for the areas requiring more detailed ship-based observations.
2. Mostly automated gathering of data on ice cover characteristics, rapid onboard integrated analysis of all obtained data and rapid transfer of both data and processing results to ECC. The system should work regardless of the number of ice observers, even if only one specialist is on board.
3. As a result of improvement of the procedure of special ship ice observations, a new system of ice data cumulation on the ice maps or other data mappers should be developed, that can reveal the forming mechanisms of ice cover dynamics.

In May 2023, the AARI specialists together with the consent and help of FSUE Atomflot organized a research expedition on board the nuclear icebreaker "*50 let Pobedy*" during the regular

[1] Instructions for making ice observations from the ship. Ya.Ya. Gakkel. Moscow: Izd. Glavsevmorputi, 1944, 42 p.
[2] Guidance to special shipborne ice observations. Ed. S.V.Frolov. SPb: AARI, 2011, 42 p.

operation of the icebreaker for assisting ships on the route in the southwestern part of the Kara Sea; in the course of the expedition the main provisions of the new methodology of the AARI special ship ice observations were identified and tested, which are presented in this paper.

The aim of the work is to develop an update the methodology for special ship ice observations for the subsequent implementation in expedition activities and operational practice.

Current methods of special ship ice observations

Nowadays, the main source of information on sea ice cover characteristics is data from the artificial Earth satellites, but satellite data do not provide detailed characteristics of the ice cover, which indicate its state. In this regard, ship-based ice observations occupy an important place in the study of sea ice cover. The main purpose of special ship ice observations is to obtain new *in situ* data to identify the patterns of small-scale variability of the ice cover characteristics that significantly affect the efficiency of navigation [1].

Special ice observations following the AARI methodology are carried out from the navigation bridge continuously during the entire movement of the ship in ice both along the route (in the area along the ship course, the width of which is equal to 6 times the width of the ship's hull and the length is 3 times the length of the ship's hull) and in the area of movement (within the limits of horizontal visibility). Each homogeneous ice zone is separated from the previous one in case when at least one ice parameter changes by 0.5-1 points.

The observations along the route include a visual gauging of the following characteristics: total and partial sea ice concentration, age, size of ice fields, ice thickness and snow depth, ice topography (hummocks and ridges), rafted ice concentration, melt stage, the presence and intensity of ice compacting, behavior of the icebreaker channel, as well as presence of dangerous ice phenomena and dangerous ice formations. The observations in the area of movement include visual gauging of total and partial concentration, age, size of ice fields, ice topography, orientation type of ice openings.

All ice characteristics are gauged according to their description in regulatory guidance [1-3] and recorded in the ship journal (paper copy or electronic).

The Ship-base Television Complex (STK) is a video observation system designed to capture overturned ice blocks near the shipboard for further calculation of ice thickness and snow depth; if necessary, STK is supplemented with peripheral cameras for photo recording of ice conditions along the route of the ship. The main objective of STK is to conduct continuous 24-hour observations and to eliminate the impact of a human factor on the sustainability of observations. In recent years, STK has become an integral part of the AARI special ship ice observations. The STK consists of two modules: a photo recording module and a hardware-software module for data processing. The recording module continuously shooting the sea ice near the shipboard and ensures the time and geographical referencing of the imagery. The hardware-software module archives the obtained data and selects images which are appropriate for measuring ice parameters. A detailed description of STK is given in papers [4, 5].

Expedition "LED-SMP-1/2023"

In May 2023, the Department of ice regime and forecasts of AARI organized the experimental and training expedition "LED-SMP-1/2023" in the southwestern part of the Kara Sea on board the nuclear icebreaker (NIB) "*50 let Pobedy*". The objectives of the expedition were as follows: to monitor the ice cover along the tracks of the Northern Sea Route (NSR), determine the current condition of sea ice cover and its impact on the icebreaking capability, train ice experts and observers, cooperate with navigators for developing a system of specialized hydrometeorological support. Observations were carried out during four voyages of NIB "*50 let Pobedy*" while assisting ships to the Gulf of Ob (Fig. 1).

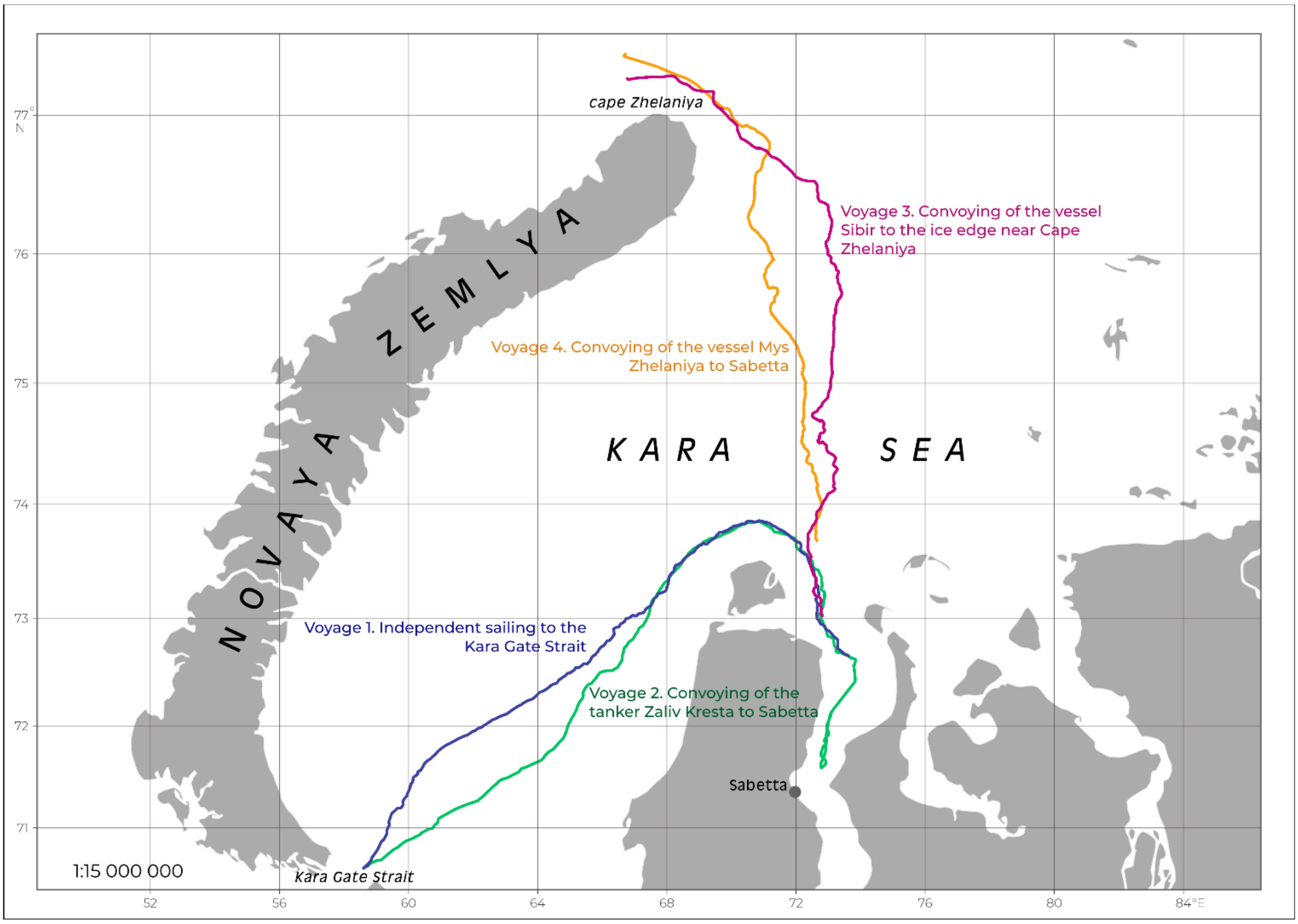

Fig. 1. Map of the voyages "ICE-NSR-1/2023", where special ship ice observations were carried out onboard NIB "*50 let Pobedy*" in May 2023

On the first voyage, NIB 50 let Pobedy moved independently, and on the second, third and fourth voyages it convoyed the Arc4 vessels *Zaliv Kresta*, *Mys Zhelaniya* and *Sibir*. Visual ice observations were conducted along four sailing routes, ice thickness and snow depth were measured using STK, and ship radar images were recorded using the Ice Vision equipment. Before and during the expedition, the new procedure for making special ship ice observations was developed and tested. Prognostic information about the specific conditions of ice navigation and the optimal ship route was received from AARI. Ice observers on board the ship promptly processed and analyzed all received data and sent them back to AARI in graphical and text form for the forecast validation.

At the same time, experimental data were obtained for the subsequent use of STK in order to provide information about the ice structure. For this purpose, images of the overturned ice blocks near the shipboard were made using STK together with synchronous capturing with a photographic camera to obtain high-resolution images.

Development of the procedure for making special ship ice observations

1. Interpretation and prediction of wave dynamics of sea ice cover

The basis of the new approach is the planned experiment. Planning is based on an assessment of the expected result of observation. This is ensured only if we understand the formation mechanism of the dynamics of sea ice cover and, therefore, have the ability to predict its evolution in a specific area at a specific time. Planning itself is carried out by processing previously accumulated information and agreeing it between experimenters.

In the Ice Navigation laboratory of AARI, selecting the optimal navigation route is carried out according to the methodology approved on December 16, 2020 by the Central Methodological Commission of Roshydromet ("Method of specialized forecasting of ice-operational characteristics of independent navigation of modern types of vessels along the NSR routes up to 1 month in advance", the authors of the method are E.I. Makarov, S.V. Frolov, V.E. Fedyakov, E.B.Sapershtein). The brief summary of the method is given below.

The mechanism of formation of ice cover structures, which are indicators of the dynamic processes within the ice, is based on the wave concept of movement of the aquatic environment [6]. The wave structure of such movements is a soliton-like wave. An analog representation of such dynamics is the Poincaré tidal waves. Fig. 2a presents an example of the field of Poincaré tidal waves (standing waves) [7].

Fig. 2a also shows a regular grid of intersecting straight lines (lattice) connecting the antinodes (crests) of standing waves. The shape of the grid cells depends on the following boundary conditions of the water area, namely size of water area and morphological characteristics of the bottom and coastline. It is assumed that the cells in the Arctic Ocean should be close to the square shape.

Satellite radar surveys in the Arctic support the actuality of the proposed water and ice dynamics pattern. Fig. 2b provides an example of such data.

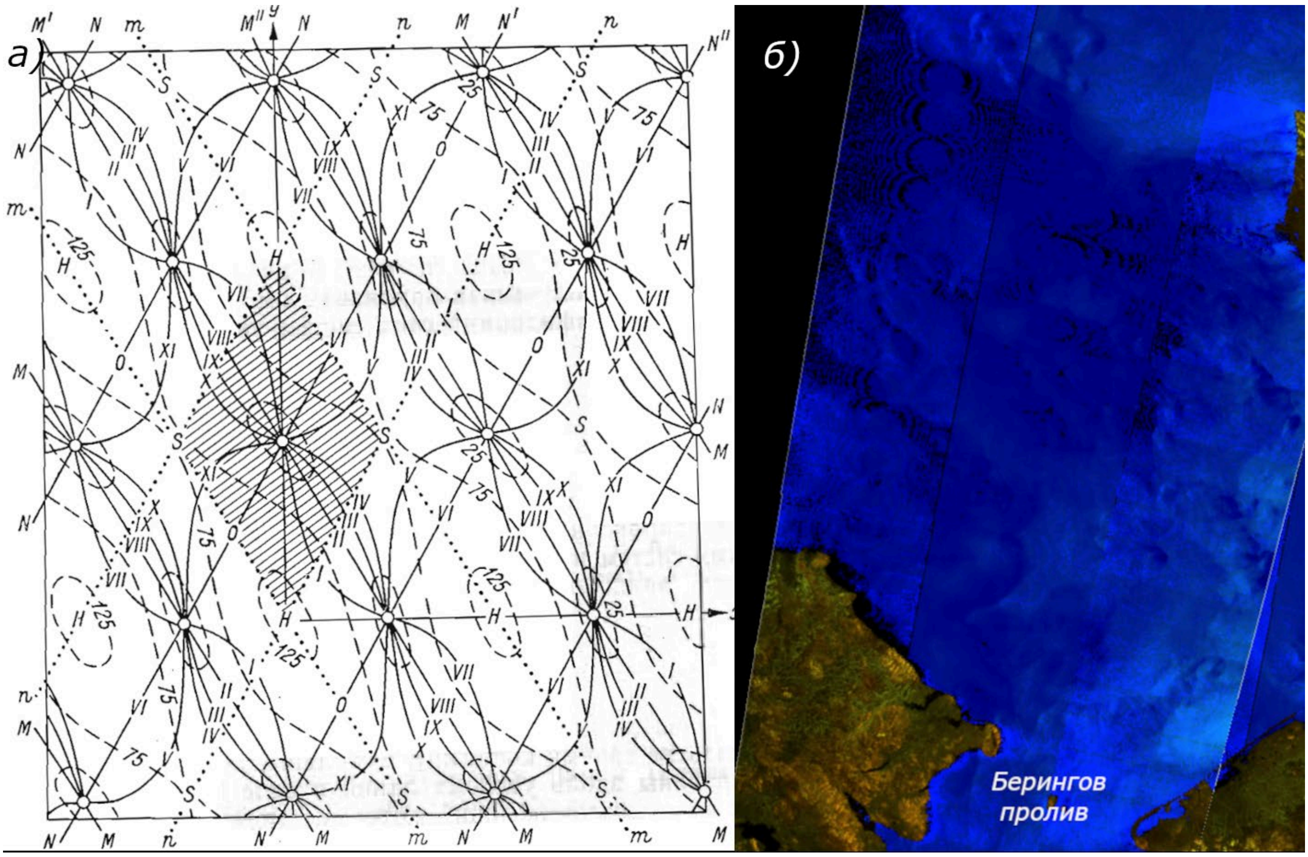

Figure 2. A – the result of oblique interference of standing waves. The Poincaré tidal wave field is a classic example of soliton-like water dynamics [7]. B – Sentinel-1 satellite image (https://apps.sentinel-hub.com/) of the Chukchi Sea in September 24–27, 2023

Fig. 2b shows that the water area is completely covered with soliton waves. The figure also demonstrates that wave crests and troughs form a regular grid.

The above provisions are applied for analog interpretation of the wave structures [6, 8] on the sea ice concentration maps of the University of Bremen (https://seaice.uni-bremen.de/sea-concentration/modis-amsr2/) calculated from MODIS-AMSR2 microwave images of the Arctic Ocean. An example of the interpretation is shown in Fig. 3.

Considering the fact that the dynamics of soliton waves have the lowest energy consumption and the waves themselves are long-period waves, there is reason to expect high stability of the formed wave structures. The high stability of structures provides a basis for their reliable identification and forecasting.

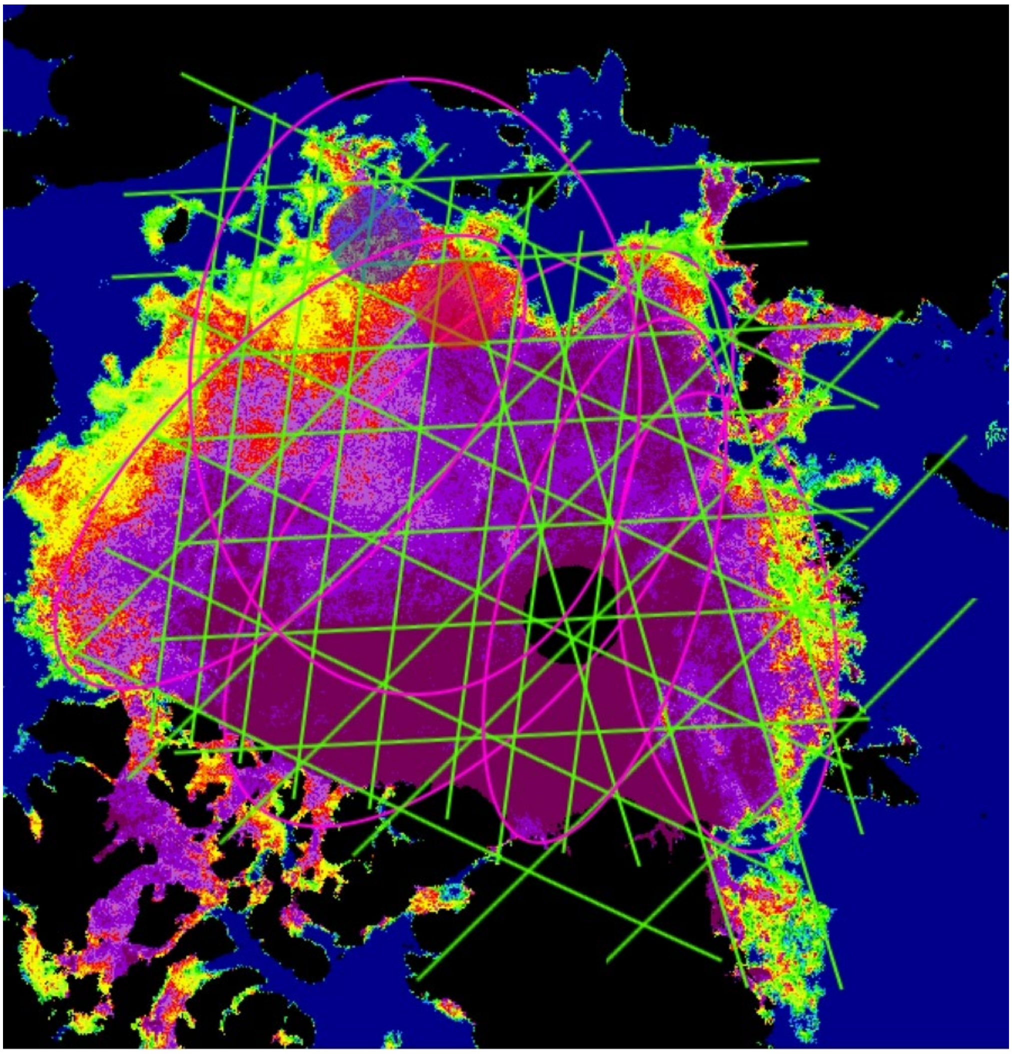

Fig. 3. Structures of the sea ice cover of the Arctic Ocean in the form of soliton waves that determine its dynamics on July 27, 2005 [6,8], superimposed on the MODIS-AMSR2 sea ice concentration map (https://seaice.uni-bremen.de/sea-ice-concentration /modis-amsr2/)

The described features of the scheme for interpreting and predicting the wave dynamics of ice cover were applied during the organization of the scientific and operational expedition on board the NIB *50 let Pobedy*. Microwave satellite data on the Arctic Ocean water area were processed in ECC. Local areas on the planned route of the nuclear icebreaker were selected based on the obtained results. The nodes of regular grid, in which the streamlines of soliton waves were in close proximity, were considered to be the areas of interest along the route. Such areas were considered to be areas of increased ice cover deformation, ridging and compacting. Ice observations in such areas had to be carried out with the greatest possible detail.

An example of wave analysis of the dynamics of sea ice cover in the Kara Sea on May 5, 2023, reported on board the nuclear icebreaker is shown in Fig. 4.

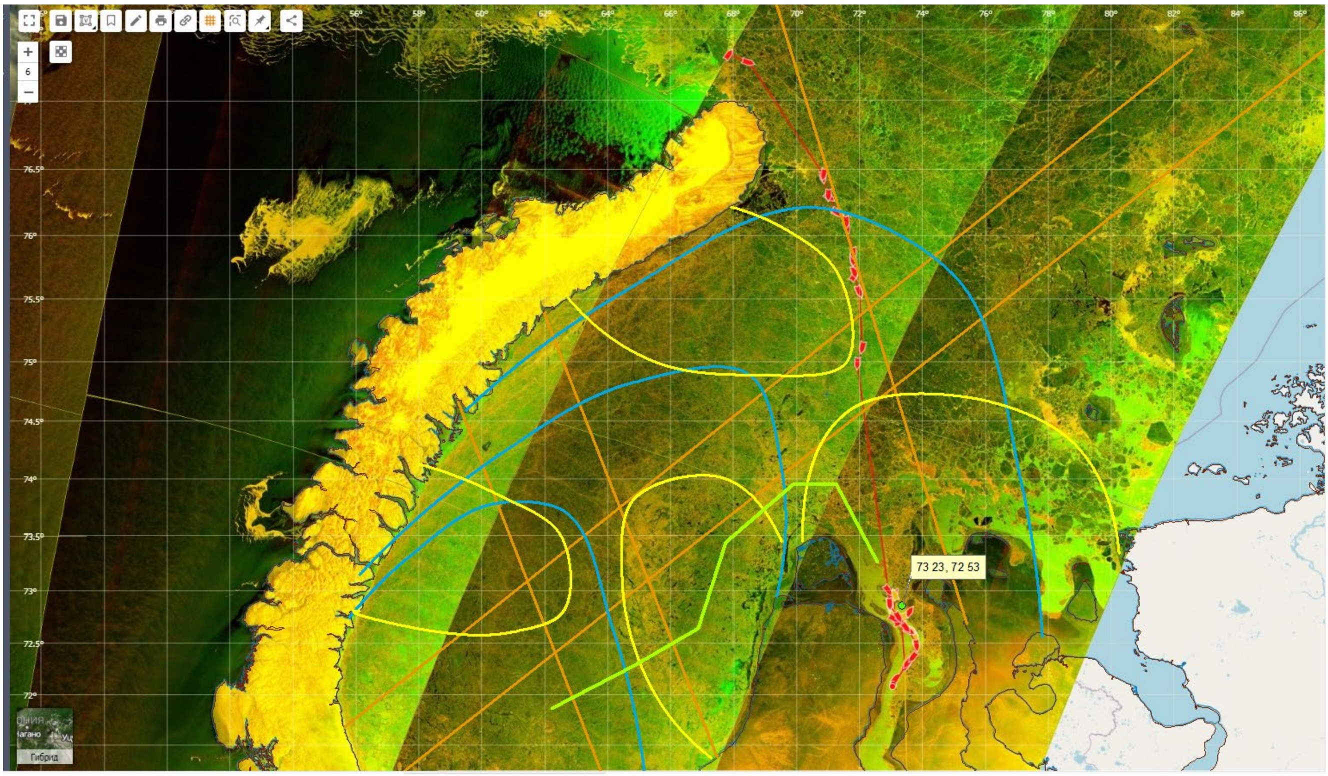

Fig. 4. Interpretation of the wave structures of sea ice cover for the first voyage of the expedition “ICE-NSR-1/2023”. The green line shows the predicted optimal route of navigation. The orange lines depict the “natural grid” of natural oscillations of the water area, blue lines show the propagation of a progressive wave, yellow lines depict reflected waves [6, 8] for the southwestern part of the Kara Sea, May 5, 2023

Special ship ice observations from the icebreaker during the passage through the specified areas of increased deformation of sea ice cover must contain the following information:

- selected ship radar images that are most typical for the specific ice cover in a given area;
- selected STK images for various types of sea ice in the given area;
- panoramic photographs of the homogeneous ice zones along the route, taken from the ship’s bridge;
- generalization of visual ice observation data in the given area both in the table and text form.

Thus, during the expedition “LED-SMP-1/2023” the structure and form of information from the ship was practised to improve the methodology for selecting the optimal ship route. In the future, the form and structure of the information can be supplemented according to the needs of another ice forecasts.

2. Using STK to obtain information about sea ice structure during ship movement

The problem of identifying and recording the structure of sea ice along the ship route is important for understanding the patterns of distribution of ice with different structures and physical properties along the NSR tracks and in the other arctic regions. The composition of level ice, which is the sum of the crystalline structure (ice structure) and the various inclusions within the ice (ice texture), largely determines its physical properties [9]. STK records ice overturn near the shipboard and provides pictures of the overturned blocks that reflect vertical "texture pattern" of the ice floe. During the natural growth of ice all changes in the conditions of ice formation over the entire period of its existence are consistently "recorded" in the ice structure and texture. The structure of ice and the stage of ice condition, i.e. internal changes within the ice due to thermometamorphic processes, directly affect the physical properties of ice, including ice strength, which is important for shipping [10]. Thus, from the pictures of ice overturn alongside shipboard during the ship's movement, it is possible to reconstruct the "life history" of the ice floe under study.

At the moment, the resolution of the STK camera provides information about the thickness of ice and ice layers. Ice layering mostly occurs in the following cases:

1. Transiting to other genetic type of ice when the conditions of ice formation change, especially in the case of a change in a layer having granular and fibrous structures [9,10].
2. Frontal interrupting of the natural growth of crystals as a result of dynamic processes in the ice cover (hummocking and ridging, ice rafting, ice breaks, formation of fractures and polynyas). As a result of these processes, small fragments and crystals of frazil ice, formed in the water column, arrive at the crystallization front at the lower boundary of the ice. A thin layer of ice with a granular structure appears (though sometimes it can be more significant), below which the natural growth of ice of the previous structure continues.

Figure 5 presents the example of the side surface of the overturned ice block. In the photographs, the texture of the upper layers *a* and *b* differs from the underlying layers, in contrast with the layers *c*, *d* and *e*, which are very probably formed of the same genetic type of ice and the layering occurs due to the dynamic processes in the ice cover, resulted in intermediate bands. We can assume that the area of the ice floe formation is rather dynamic, considering the fact that during the ice floe short existence, judging by the picture, there are at least three cases of disruption of the natural growth of ice due to dynamic processes in the ice cover. Based on the layer thicknesses, which can be determined by STK, and using the rough rate of sea ice growth, the approximate dates of ridging can be calculated.

Developing this methodology initially requires to focus on obtaining high-quality information about the layering of ice from the photographs of the ice overturns. In the future, it is necessary to increase the resolution of STK images to improve the quality of ice texture representation.

Together with the STK survey, it is necessary to provide the following data from the ship:

- data on water salinity in the survey area, since water salinity is one of the fundamental impact factors for ice formation, which results in the formation of different genetic ice types;

- data on the meteorological conditions in the survey area;

- data on water temperature in the area where the ice texture is recorded.

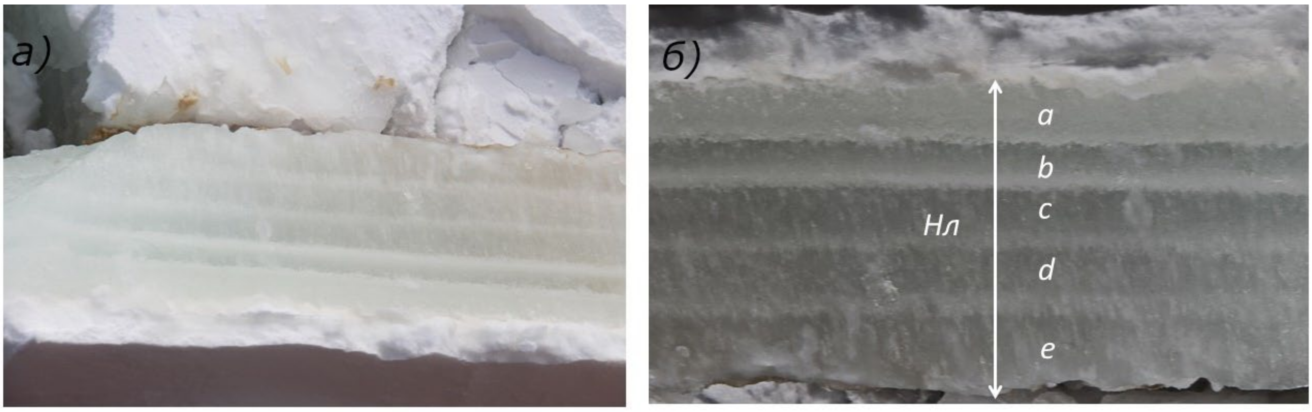

Fig. 5. An example of using the images of the side surface of ice floe for the texture analysis: original image (*a*) and processed image (*b*). The indices placed in the processed image (*b*) reflect a possible interpretation of the layering of ice, where H_l is the ice thickness, layer *a* – the top layer with the granular structure, layer *b* – the layer of unclear crystalline structure (possibly the beginning of the formation of a fibrous structure), layers *c*, *d* and *e* – layers, most likely having a fibrous structure.

In addition to the analysis of the ice structure information, the following materials should be involved:

- currents data (it is necessary to take into account that the initial and further formation of the drifting ice may occur in different places and, consequently, the ice structure that is reconstructed from the texture pattern may not reflect the conditions of ice formation at the place of capturing the image);
- data on ice structure and conditions of ice formation for a given area, taking into account seasonality from other sources. Particular attention should be paid to the ice structure data collected directly in the field [11]. These data can be used as the test data for identifying ice structure data from STK.

Implementing the above-described methodology for determining ice structure with the help of STK will therefore provide a set of data, which will serve to identify the "main scenario of ice formation" for various water areas. By the "scenario of ice formation" we mean a change of conditions of ice formation, resulting in a gradual growth of ice of various genetic types. The "main scenario" refers to the repeated ice formation scenario from year to year, which reflects both the repeated ice structure and the repeated ice formation conditions for a given water area.

The "main scenario" of ice formation covers large areas; additionally, ice can form according to "local scenarios", which reflect the growth of ice under ice formation conditions different from the main scenario. Such areas of ice cover include coastal ice, ice near ridges and icebergs, as well as sea ice inside leads and fractures. The structure of ice formed under the "local scenario" will differ from the structure of ice formed according to the "main scenario", which will affect the physical properties of ice. Thus, the necessary result of STK survey data analysis is to distinguish data into groups as follows: data on the structure of ice formed according to the “main scenario”, and data on the structure of ice formed according to “local scenario”. Each group will carry corresponding information about the structure of ice that is specific to it, which must be taken into account when analyzing the ice physical properties.

3. Developing a new configuration of STK

First of all, it is necessary to note some branching in the process of improving and modernizing STK. The ship television complex, as a system focused primarily on conducting and improving the scientific observations, enabled in 2018 to develop a project of the ship television-meteorological complex (STMK); the main task of STMK is operational support of the system of specialized hydrometeorological support with standardized reference data on ice and meteorological conditions in the area of ship’s movement [4].

The STMK project is developed for installation on a large number of vessels and primarily focused on the automatic collection of key data, but it does not meet the requirements of scientific research tasks. This is due to the need to standardize STMK equipment in accordance with the regulations of measuring instruments and the maritime register and does not imply active modernization beyond the tasks assigned to the system.

STK remains a constantly evolving research equipment and continues to be improved and modified by developing and introducing new technical solutions.

At the current stage, the STK is being equipped with a set of mobile meteorological stations in order to obtain along-route meteorological information that has specific data collection regime as compared to standard ship weather stations, that make it possible to relate the recorded ice formations to current conditions.

A major step in improving the information content of the collected data is the development of a procedure for obtaining data on ice ridging and hummocking along the ship route based on a combination of data from the thickness gauge and a number of accelerometer sensors. This information together with information about the ship movement makes it possible to evaluate ridges as a relative parameter of the dynamics of the ship’s movement. With this approach, the parameter of ridging characterizes not the areal distribution of ridges and hummocks in the navigation area, but the complex parameter of the dynamic resistance of individual ridges to the movement of the ship along the route.

To ensure a better assessment of the morphology of ice floes, the resolution of the thickness gauge camera is increased, as well as the means of protecting the camera lens are improved to avoid active splashing and freezing of the optics if camera is installed closer to the measurement site.

The hardware-software module is continuously updated with new algorithms that ensure the interaction of all recording elements, as well as automatic preprocessing and obtaining the final results of online processing of streaming date.

It should be noted that complete automation of the STK operation process is impossible due to high percentage of visual observations provided by an ice observer. However, the priority importance within the framework of the development of the system is the continuous increase in the degree of automation of the STK stream information processing, as well as the generation of operational complex data, supplemented by the parameters of the accompanying observation conditions.

One of the serious limiting factors in the process of technical improvement of STK is the maintaining of a high degree of mobility of the system together with versatility of use on different types of vessels during expeditions and special operations.

Conclusion

The updated methodology for special ship ice observations was developed and partially put into practice as a part of the expedition "LED-SMP-1/2023". The basis of the new approach is the planned experiment, which consists of assessing the expected results of observations. The Expedition control center analyzes the dynamics of sea ice cover in the expedition area, compiles an optimal ship route, and identifies the most important areas for the forecast, namely the areas of increased deformation of sea ice cover., The scientific group on board the ship conducts the most detailed observations in the selected areas and, as they pass, analyzes and summarizes the data from special ship ice observations and promptly sends them to the expedition control center.

Data on the structure of sea ice and history of its formation is important to provide more comprehensive information about sea ice cover as the navigation environment. Increasing the resolution of STK camera and improving the means of protecting the camera lens in case of the STK installation closer to the measurement site contribute to gather the data. Recording ice overturns near the shipboard by STK provides photographs of ice side surface that reflect vertical "texture pattern" of the ice floe. Currently, the AARI specialists develop the method for determining the structure of ice with the help of STK, which will make it possible to identify the "main scenario of ice formation" for various water areas.

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

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