Preliminary results of the ice cover drift studies performed in the 2013-2017 winter surveys in the Russian Arctic seas.

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ABSTRACT

The movement of ice floes largely determines the ice loads on hydraulic structures, mode of their operation, choice of supply vessels, an ice control system, etc. During comprehensive winter surveys performed in the interests of Rosneft Oil Company in 2013-2017 on the shelf of the Kara, Laptev and East Siberian Seas, automatic radio buoys with the function of determining and transmitting coordinates were actively used to obtain information on the drift of ice floes. The paper considers the issues of experimental set up and equipment used, presents the main results of the studies. The initial data were analyzed from the point of view of studying the drift of large areas of compacted ice, as well as obtaining the data on the drift velocities of ice formations and its variability (i.e., parameters specified in the documents regulating activities on the Arctic shelf) during periods of maximum development and decrease of ice cover.

KEY WORDS: ARGOS system radio buoys, ice floes, drift and trajectories.

INTRODUCTION

For the design of various types of hydraulic structures and safe operation of hydrocarbon deposits located in the seas of the Russian Arctic, knowledge of ice cover drift parameters is of key importance. The ice cover drift largely determines the ice load on the structure, the mode of its operation, the choice of supply vessels, the ice management system, etc. For many regions of the Russian Arctic shelf, field data on the drift of ice formations are insufficient or not available. Between 2012 and 2017, Rosneft Oil Company together with AARI with the participation of "Arctic Scientific Center" LLC conducted 12 complex expeditions the periods of maximum ice cover extent (4 expeditions 2013-2015 and 2017) and open water seasons (8 expeditions 2012-2017) in the Barents, Kara, Laptev, East Siberian and Chukchee Seas (Fig.1). At the same time, the winter expedition of 2015 became the largest in terms of volume and scope of work of the Arctic expedition in the world over the past 20 years (https://www.rosneft.com/press/news/item/174511/). The study of the drift of icebergs and ice floes in the waters of the Kara, Laptev, and East Siberian Seas was one of the components of the expedition's work programs. During surveys, automatic radio buoys with the function of determining and transmitting coordinates were actively used to obtain the data about the drift of various ice formations. In some areas, radio buoys were used for the first time. The data set collected as a result of these studies is unique in many respects. The information obtained as a result of the analysis allows us to create a plot of the movement of a specific ice formation during the operation of the buoy and to calculate various characteristics of its drift. The main estimates of the drift of ice formations obtained in winter ice research expeditions 2013-2015 in the most general form are given in (Buzin et al., 2016). In (Buzin et al., 2019) preliminary characteristics of iceberg drift in the Russian Arctic Seas were obtained. This paper provides more specialized ice cover drift characteristics.

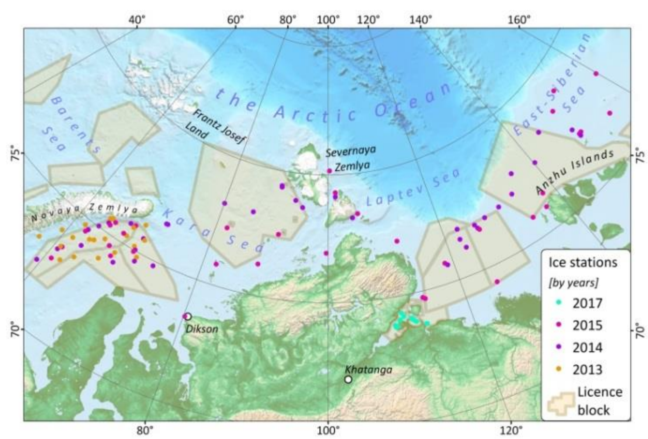


Fig. 1. Areas of winter fieldworks performed for Rosneft Oil Company in 2013-2017, and the positions of the points for complex ice research.

THE USE OF RADIO BUOYS IN ICE DRIFT SURVEY AND RESULTS OBTAINED OVER 2013-17.

The use of radio buoys with the function of determining coordinates and transmitting this information is a proven practice for studying the dynamics of ice formations, both for scientific and practical purposes. Using these devices, the information on the geographical position of the ice formation, as well as a number of related parameters is transmitted via satellite communication systems to consumer. In addition to use for purely scientific purposes (see, for example, the International Arctic Buoy Program, SEDNA - Lei et al., 2016; Hutchings et al., 2010), the use of radio buoys is recommended for collecting information necessary for the design of hydraulic structures, and for use in the composition of the equipment to ensure proper functioning of ice management systems (ISO 35106: 2017; ISO 35104: 2018). All major projects on the Russian Arctic shelf also use this technology, a detailed review of its application and the main results obtained is made in (Buzin, Nesterov, 2018).

Note that until 2013, the main body of instrumental data on ice cover drift characterized mainly the Barents Sea. This is due to the development strategy of the Russian shelf - from west to east (from the relatively mild Barents Sea to harsh Arctic conditions). Thus, the data on ice drift in the Kara, Laptev and East Siberian Seas, collected as a result of the 2013–2017 winter expeditionary work organized by Rosneft Oil Company, characterize water areas where such observations were rare or were not performed at all.

During the winter fieldworks of 2013-2015, various modifications of the Pulsar radio buoys of the ARGOS satellite system manufactured by “ES-PAS” CJSC (Russia) provided with a GPS system and transmitting this information with a 1-hour resolution were installed on ice floes. The error in determining the location using GPS data was ±10 m. The appearance of the buoy is shown in Fig. 2. As a result of the operation of the buoy, hourly information is transmitted about its location, which is displayed on the site of the service provider (in this case, the ARGOS system) and is available to customers of the service. The generated data files contain the measurement time (year, month, day, hour, minutes), coordinates according to the GPS receiver and ARGOS system and additional characteristics of the buoy.

Fig. 2. ARGOS buoy Pulsar mounted on an ice floe, the nuclear i/b Yamal in the background, May 2013 (photo by K. Kornishin).

In winter expeditions 2013-2015 in the waters of the Kara, Laptev and East Siberian Seas, radio buoys were installed on ice floes by 1-2 people at a distance of 300-500 meters from the icebreaker on flat ice areas behind ridges of hummocks. A place, if possible, covered with hummocks on all sides, was chosen for the installation of the device. As a rule, under sections of level ice lying between closely spaced ridges of hummocks, there are powerful ice heels. The installation site chosen in this way during hummocking and summer melting of the ice cover is destroyed last, which in the long run allows us to obtain the maximum possible duration of observations of the drift of each specific ice floe.

During the 2017 winter expedition in the Laptev Sea, radio buoys were placed on ice floes using Mi-8T helicopter, based in the Khatanga Bay at the temporary field base Khastyr deployed on the Khara-Tumus Peninsula.

CHARACTERIZING INITIAL DATA

For the southwestern part of the Kara Sea, 47 trajectories of ice floe drift were obtained in April-August 2013-2015. In the Laptev Sea, data were collected on 48 drifts of ice floes in March-August 2014, 2015 and 2017. In May-August 2014 and 2015 in the East Siberian Sea, 13 ice floes drifted with satellite radio buoys. Ice floe drift trajectories for the period of studies 2013-2017 are presented in Fig.3. A total of 108 ice floe drift trajectories were obtained.

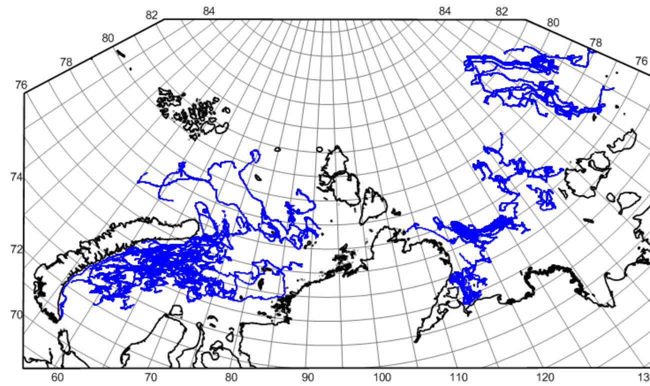


Fig. 3. Ice floes drift trajectories in the surveyed water area in 2013-17.

The materials collected using buoys make it possible to estimate the average speed and direction of drift of ice formations for 1 hour, and the parameters of their trajectories. Available information allows us to estimate the parameters of ice drift under conditions of compact ice cover (April-May), and in conditions of its decay and open water (June-August). Separate results of estimates of ice formation drift parameters are presented in (Neftiyanoye Hoziyastvo, 2015).

ANALYZED PARAMETERS AND ANALYTICAL METHODS

Among the main factors affecting the safe functioning of hydraulic structures on the Arctic shelf is the drift of **large areas of compacted ice (1)** and icebergs (ISO 35104: 2018). For specialized engineering calculations, **data on the drift velocities of ice formations and their variability required (2)** (ISO/FDIS 19906: 2019). To characterize the drift velocities of ice floes, average and maximum velocities, drift repetition in velocity, and average drift vector (defined as a vector whose components are equal to the mathematical expectations of the projections of the observed vectors in a rectangular coordinate system) can be considered.

According to the vector-algebraic approach (Volkov et al., 2012), the characteristic of variability of a vector random variable is the root mean square deviation tensor RMS (σ_V) which can be represented by an ellipse with semi-axes $\sqrt{\lambda_1}$ and $\sqrt{\lambda_2}$ ($\sqrt{\lambda_1} > \sqrt{\lambda_2}$), oriented towards maximum variability α (see fig. 4), characterized with linear invariant $\sqrt{I_1} = \sqrt{\lambda_1^2 + \lambda_2^2}$.

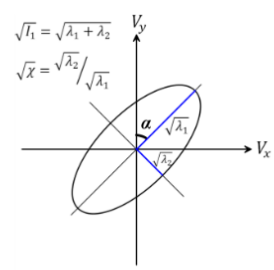


Fig. 4. Root mean square tensor (σ_V) of random vector value

The linear invariant determines the magnitude (intensity) of variability. In orthogonal to the direction α, the variability is minimal. The elongation (anisotropy) of the ellipse describes the invariant $\sqrt{X} = \sqrt{\lambda_2}/\sqrt{\lambda_1}$. The less is $\sqrt{X}$, the more anisotropic is the drift variability, i.e. drifts have great variability in a particular direction. If this parameter is equal 1, the standard deviation takes the form of a circle.

Semi-axes $\sqrt{\lambda_1}$ and $\sqrt{\lambda_2}$ determined through the variance of the drift projection on the axis x and y (D_{V_x} и D_{V_y}) and covariation between them ($K_{V_xV_y}$):

$$\sqrt{\lambda_{1,2}} = \sqrt{0.5\cdot\left\{I_1 \pm \sqrt{\left(D_{V_x} - D_{V_y}\right)^2 + 2\cdot K^2_{V_xV_y}}\right\}} \qquad (1)$$

According to (Bonnemaire, 2005; Nesterov et al., 2009):

- information on the repeatability and duration of low drift velocities;
- information on changes in drift directions;
- radius of curvature of the drift.

also serve as characteristics of ice floe drift variability.

Information on low drift velocities is of interest from the point of view that, after the drift slows down, the movement of ice in any direction is possible.

To characterize changes in the direction of drift (COD - change of direction) we will consider the magnitude of unidirectional change when there is a change in the direction of the drift in one direction (clockwise or counterclockwise). With this definition, a unidirectional change in drift direction can exceed 360°.

In the papers of (Pritchard and DeFranco, 1995; Bonnemaire, 2005), ice drift trajectories are represented as flat lines. At the same time, their curvature is considered as the main characteristic of the lines. Curvature characterizes the curvature of the line at the point in question. The curvature of the line is everywhere equal to zero, the curvature of a circle of radius R is everywhere equal to $1/R$. For any other line, the curvature changes from point to point. The point at which the curvature is zero is called the straightening point. The reciprocal of the curvature is the radius of curvature R. The radius of curvature of a circle is equal to its radius; at the straightening point, the radius of curvature is equal to infinity. To estimate the radius of curvature, the relation is used:

$$R = \frac{V^2}{a_N} = \frac{\left(x'^2 + y'^2\right)^{3/2}}{\left|x'y'' - y'x''\right|} \qquad (2)$$

where a_N – acceleration component normal to the direction of movement, V – velocity of movement, (x,y) – Euclidean coordinates, dashes refer to time differentiation (parameter t).

In engineering applications, the minimum radius of curvature of the ice drift is of primary interest. The simplest way to determine the minimum radius of curvature from the source data depending on the drift velocity is to estimate the maximum value of the acceleration component normal to the direction of motion.

The greatest rotational effect of ice on an object (hydraulic structure, moored vessel, etc.) at the same angular velocities will be observed when the radius of curvature of the drift is comparable to or less than the linear dimensions of this object. Small radii of curvature of ice drift are observed at low drift velocities.

It is assumed (ISO 19906: 2019) that maximum ice loads are observed at drift velocities ranging from 0.003 m/s to 0.1 m/s. At drift velocities above 0.1 m/s, brittle destruction of ice occurs. It is also known (ISO 19906: 2019) that structures with a frequency in the range of 0.4 to 10 Hz are prone to self-oscillations if the total damping of the platform-foundation system does not exceed 3% of the critical value. Self-oscillations can mainly occur in a situation where ice cover drifting at a speed of 0.04 m/s to 0.1 m/s continuously affects structures with vertical faces.

In the absence of comprehensive information on the processes of ice destruction in the study area, it is recommended to increase estimates of ice loads for inclined structures at ice drift velocities of more than 0.5 m/s (ISO 19906: 2019). For conical and inclined structures, the ice velocity of 0.1 m/s is also critical. At this speed, the coefficient of static friction can be five times the coefficient of kinetic friction.

The drift variability characteristics below are for time scales of 1 hour or more. On a smaller scale, the characteristics will be different. In particular, the estimate of the minimum radius of curvature of the ice drift will be less.

RESULTS OF THE ICE FLOE DRIFT SURVEYS IN 2013-17.

To illustrate the thesis of **"drift of large areas of compacted ice"** as one of the main ice threats on the Arctic shelf (see the previous paragraph), we consider cases of drift of compact ice cover (areas of the Novaya Zemlya ice massif and drift in the East Siberian Sea).

Ice drift in the southwestern part of the Kara Sea, 2013

In the southwestern part of the Kara Sea, a cyclonic water cycle is characteristic; in the spring-summer period, compacted ice is stably preserved here. The annual summer accumulation of compact ice along the Novaya Zemlya islands is distinguished into a special formation - the Novaya Zemlya ice massif. The ice massifs are quasistationary accumulations of ice of high concentration (7-10 points, 70-100%), thickness and hummockiness. The Novaya Zemlya ice massif is formed mainly by ice of local origin and almost always melts during the summer period. Under average conditions, the thickness of the ice in the southwestern part of the Kara Sea at the end of the winter period can reach 1.8 meters, and the ice concentration is 9-10 points. However, these parameters are subject to sufficiently strong interannual variability. In winter, ice drift prevails in this water area (Variability..., 2004; Reference Guide...; Frolov et al., 2007).

Of the three ice seasons of 2013-2015, observations of ice drift in this water area, the most thick and compact ice was observed during the period of maximum ice cover development in 2013 (Fig. 5).

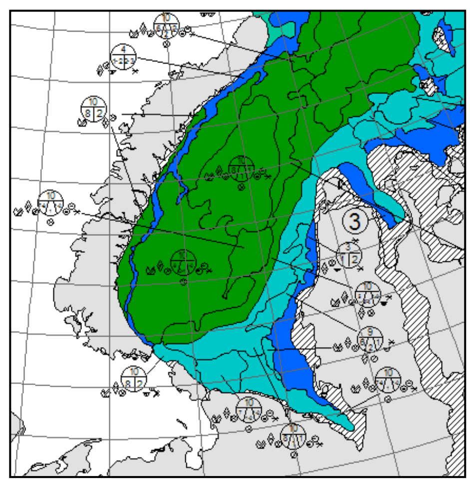


Fig. 5. A fragment of a generalized ice map for the Kara Sea region on May 07, 2013 (www.aari.ru). Thick first year (FY) ice is shown in green, the medium FY ice is blue, and nilas is bright blue.

Fig.5 shows that the dominant ice in this water area was thick first year ice (thickness more than 120 cm) with a concentration of 10 points (100%). The high concentration and thickness of the ice cover were reflected in the drift velocities of individual ice floes. Thus, the average modulus of ice cover drift velocity (i.e., the arithmetic mean value) in 2013 amounted to 0.10 m/s in the southwestern part of the Kara Sea in May, and in 2014 and 2015. - 0.14 and 0.11 m/s, respectively. A similar pattern is also observed for the average drift vector (i.e., average transfer) - 0.01 m/s, 0.02 and 0.02 m/s, respectively.

The drift trajectories of ice floes in the southwestern part of the Kara Sea in May 2013 are shown in Fig. 6. Fig.6 shows that the ice cover in the water area moves mainly synchronously, due to its significant concentration and thickness. The direction of the drift is mainly outwards (i.e., from the SW part of the Kara Sea to the NE), which is well manifested in the subsequent period (see Fig. 7).

The results obtained indicate that in the partially closed water area of the SW part of the Kara Sea, ice drift in the winter-spring period occurs mainly along the SW-NE axis.

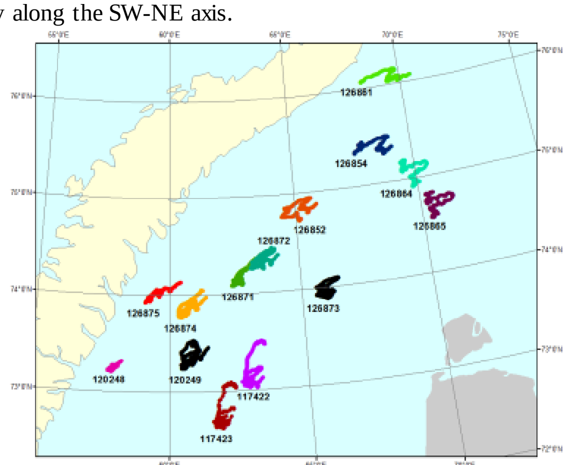


Fig. 6. Drift trajectories of individual ice floes in a compacted ice massif, May 2013.

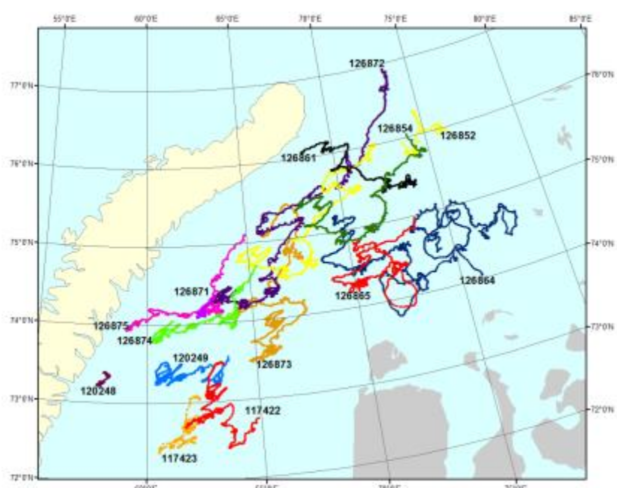


Fig. 7. Ice floes drift trajectories, May-August 2013.

It is also expected that as the ice cover melts and its concentration decreases, an increase in the average drift velocity of ice floes is noted. The findings for the Kara Sea are in good agreement and clarify existing information on the dynamics of water and ice in this water area.

Drift in the East Siberian Sea

The receipt of data on the drift of the ice of high concentration (9-10 points, 90-100%) in the water area of the East Siberian Sea was an important result for 2015 (Fig. 3). The small-scale map (Fig. 8) shows the drift trajectories of radio buoys installed on the ice cover in the area of Bennett, Zhokhov, Henrietta islands in May 2015. The drift of ice floes with buoys lasted from May to August 2015. The thickness of the ice floes north of De Long Island (Bennett Island, Henrietta and Jeanette Island) almost always exceeded 1.2 m, which corresponds to the "thick first year ice" (and older grades), concentration in the initial period of the drift was 9-10 points (90-100%). The distribution of ice cover for the first 10-day period of May 2015 is shown in Fig. 9 (green means "thick first year (FY) ice", brown means "old ice"), and the appearance of hummocks is shown in Fig. 10.

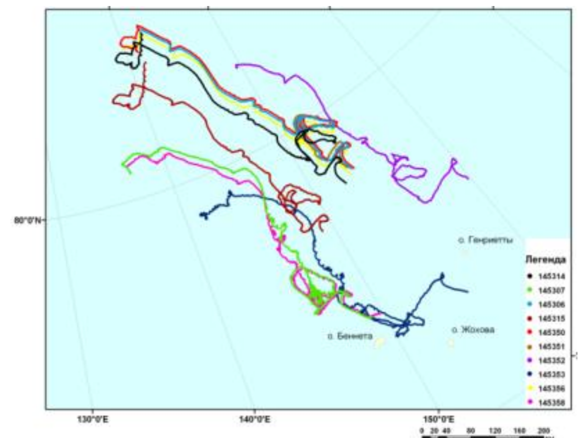


Fig. 8. Drift trajectories of ice floes in the East Siberian Sea, May-August 2015.

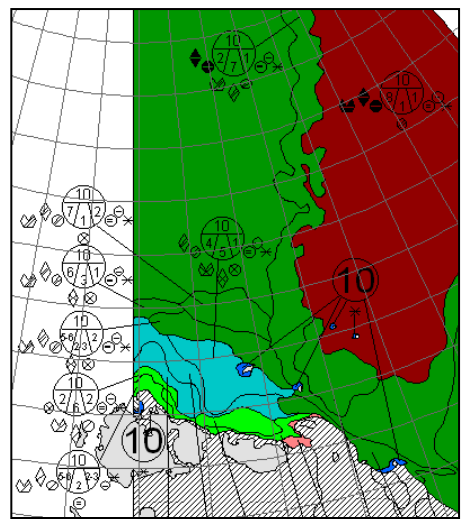


Fig. 9. Fragment of a generalized ice map for the region of the East Siberian Sea on May 05, 2015. (www.aari.ru).

Fig. 10. Installation of a GPS buoy on a hummock ridge at a thick FY ice floe by Igor Buzin, 12.06.2015 (photo by K. Kochi).

The high concentration of the ice cover led to a very close character of the drift of all floes in this region (i.e., the ice cover was displaced as a single massif). A similar picture was also observed here for the drift of two ice floes in 2014. The average drift velocity is 0.14 m/s in the north-western direction (to the Arctic Basin), the maximum velocity reaches 0.65 m/s.

When analyzing trajectories that have a similar shape and parameters, we can conclude that the movement of the entire array occurs simultaneously and synchronously. The movement of ice floes in the region coincides with the general scheme of ice movement, obtained on the basis of satellite and field data gathered in different years, and is called the “Transpolar Drift” (Gudkovich et al., 2005; Mironov et al., 2007).

Ice cover drift variability

The following information on the **velocity and variability of ice drift** in the waters of the southwestern part of the Kara, Laptev and East Siberian Seas under the conditions of compact ice cover (April-May) and during its decay (June-August) throughout the sample (2013-2017) can be used for specialized engineering calculations (see clause “Analyzed parameters…”).

Fig. 11 shows RMS tensors and average drift vectors for individual points of the considered water areas. When calculating these parameters, for each point in a radius of 30 km, one nearest drift vector was selected for each particular moment of time, as a result of which a time series was formed, according to which the considered parameters were estimated. As can be seen from fig. 11, ice drift in the considered water areas has significant spatial variability. Ice drift variability is anisotropic ($\sqrt{X} = 0.4 \div 0.6$) in the N and NE parts of the East Siberian Sea and the SW part of the Kara Sea. In the Laptev Sea, the variability of ice drift in directions is closer to homogeneous. Such differences are primarily determined by the nature of the tidal drift.

In areas with high anisotropy of variability, tidal ice drift is close to reversible, which is characterized by an increase in velocities in the directions of maximum variability. The tidal drift in time changes in speed, and at half the tidal cycle, the direction of the tidal drift changes to the opposite. In areas with low anisotropy, tidal ice drift is either weak or has close tidal drift velocities in all directions, i.e. tidal ice drift changes in time in direction with relatively small changes in speed.

The absolute value of the variability of ice drift in the Kara Sea is in the range from 0.09 to 0.32 m/s, in the Laptev Sea - from 0.13 to 0.27 m/s (moreover, the variability is mainly determined by the variability of the directions of ice drift), in the East Siberian Sea - from 0.006 to 0.07 m/s. The low value of variability of ice drift in the East Siberian Sea is associated with the period when observations were made there. The main data set for this region was obtained in July-August, i.e. during the decay of the ice cover.

The duration of the observations does not allow us to draw reasonable conclusions about the average drift in the considered water areas.

It can be noted that in most areas of the southwestern part of the Kara Sea and in the Laptev Sea, the average transport is not large in absolute value, as well as in comparison with the RMS. This indicates that here, over most of the water area, the ice melts in place, not being carried to neighboring areas. A different situation is observed in the northern part of the East Siberian Sea, where within the limits of the considered water area, ice transport to the Arctic Ocean was distinctly traced.

Fig. 12 shows the repeatability of ice drift velocities. It can be noted that the ice cover in the SW part of the Kara Sea is more dynamic than in the waters of the Laptev and East Siberian Seas. Repeatability of the ice drift velocities more than 0.2 m/s is greater in the Kara Sea than in Laptev and E.-Siberian Seas, both in compact ice and during the period of ice cover decay.

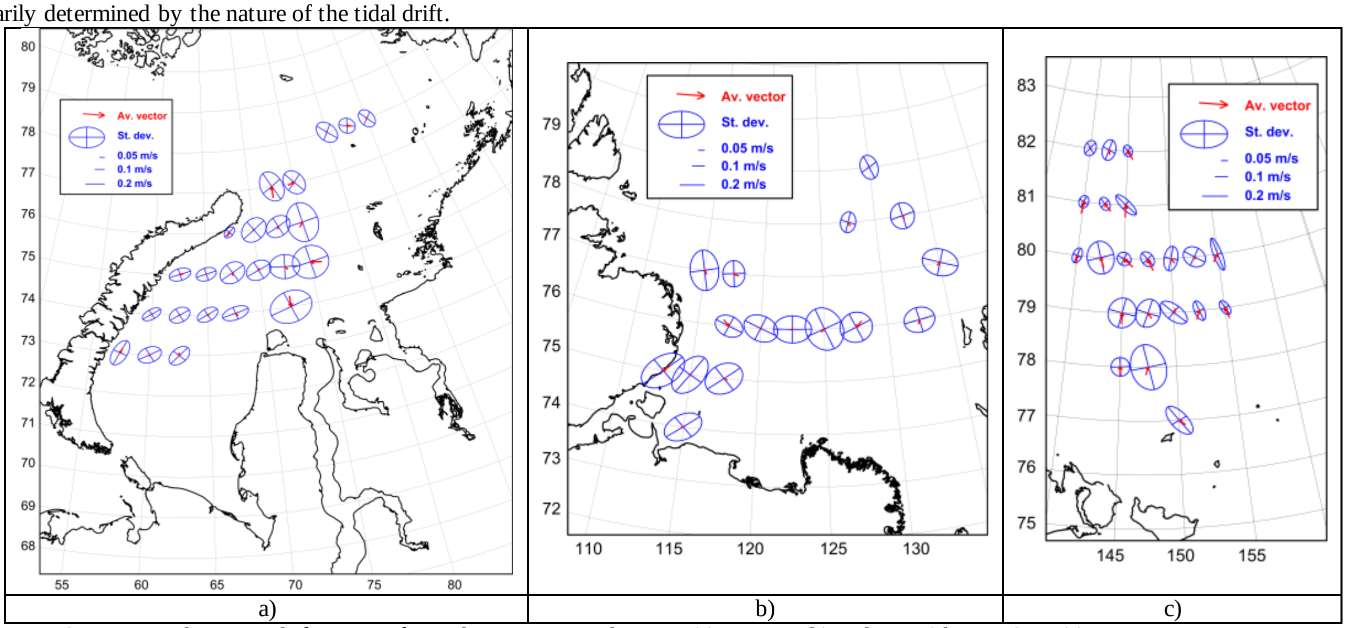
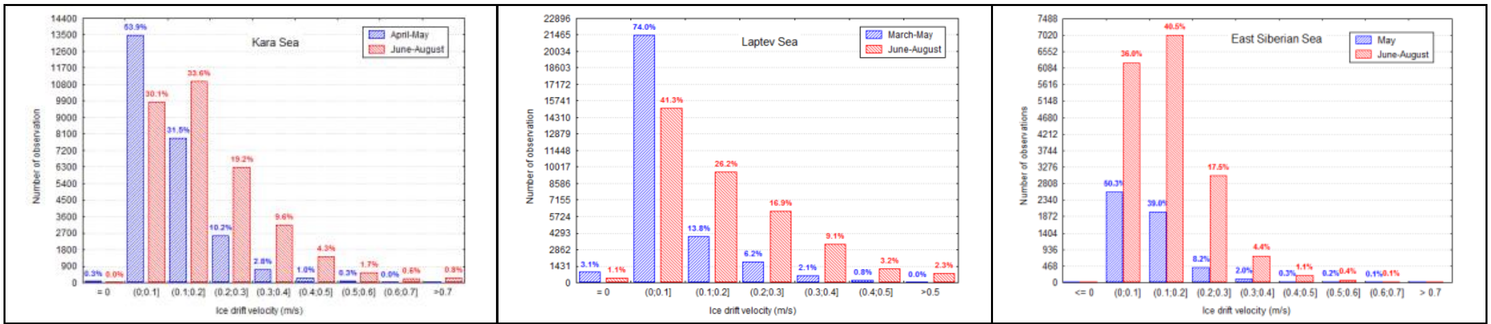


Fig.11. RMS tensors and average drift vectors from observations in the Kara (a), Laptev (b) and East Siberian Seas (c).

According to the radio buoys in the southwestern part of the Kara Sea, the average drift velocity was 0.11 m/s in April-May and 0.19 m/s in June-August. In the Laptev Sea, these values are 0.09 m/s and 0.17 m/s, respectively, in the East Siberian - 0.11 m/s in May and 0.14 m/s in June-August. In this case, the maximum drift using radio buoys was recorded in the Laptev Sea, where it amounted to 1.30 m/s in the direction of 359° (June-August period). In the Kara Sea in June-August, the maximum drift velocity reached 1.13 m/s (direction of 291°), in the East Siberian Sea, the drift velocity did not exceed 0.65 m/s.

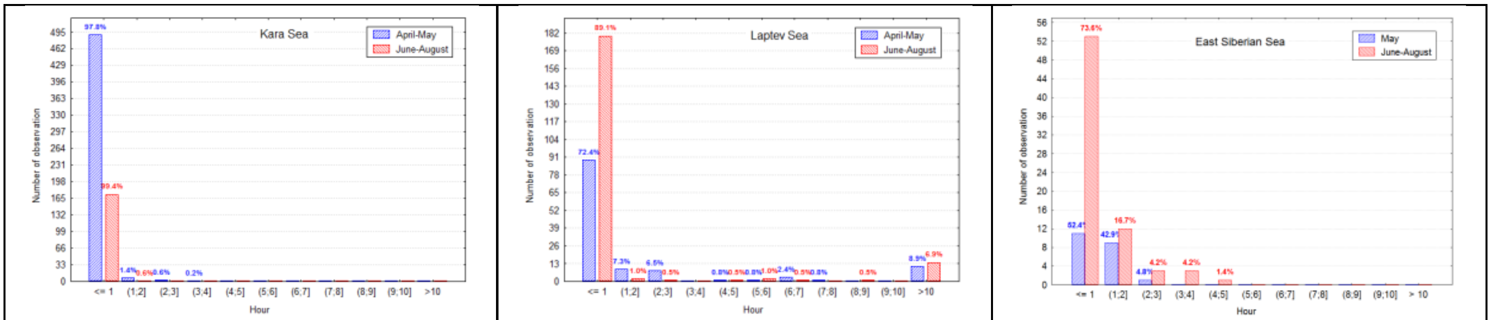
The repeatability of 0 m/s drift velocities in the Laptev Sea in March-May was 3.1%, in June-August - 1.1%. In the Kara Sea, zero drift velocities are observed only in April-May (0.3% of observations). During the observation period in the East Siberian Sea, the stationary state of ice was not recorded.

To characterize low drift velocities Fig.13 shows the drift duration repeatability at speeds of less than 0.01 m/s.



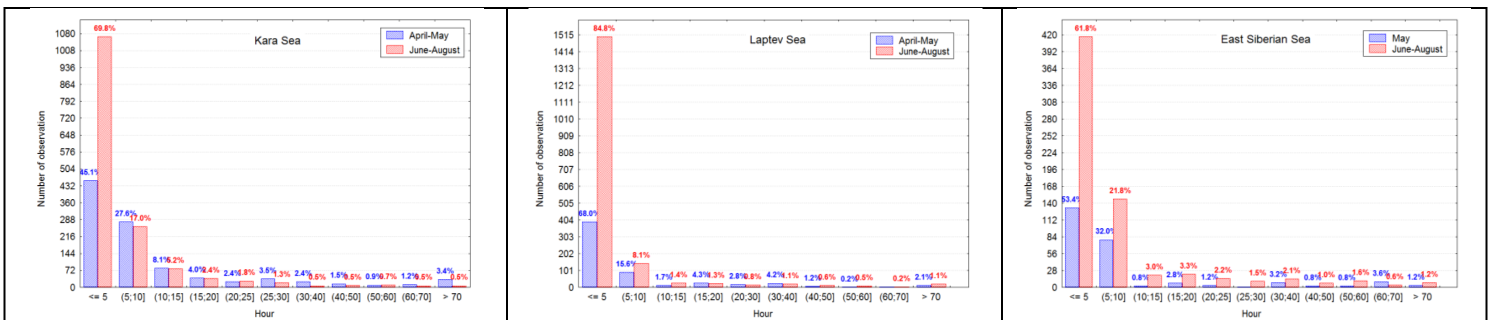
a) b) c)

Fig. 12. Repeatability of ice drift velocity from observations in the Kara (a), Laptev (b) and East Siberian Seas (c)



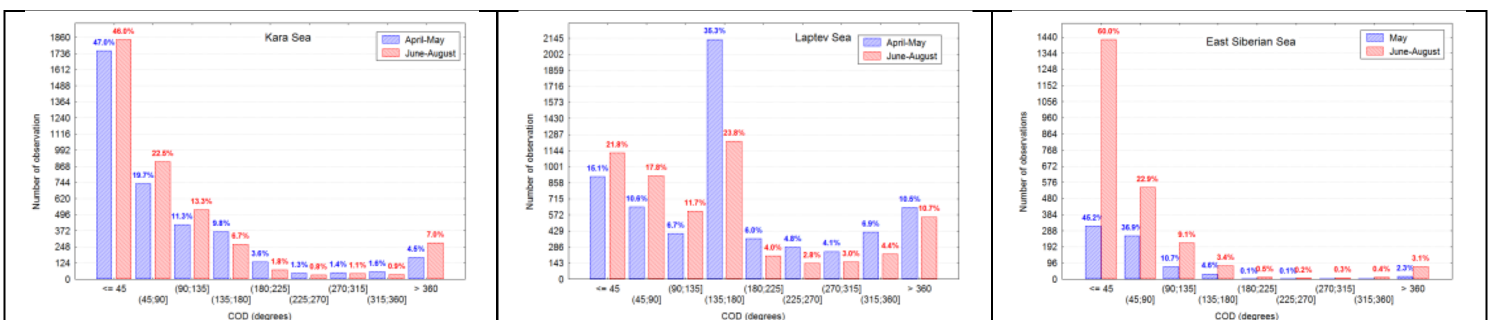
a) b) c)

Fig. 13. Repeatability of the continuous duration of ice drift at a speed of less than 0.01 m/s according to observations in the Kara (a), Laptev (b) and East Siberian Seas (c)



a) b) c)

Fig. 14. Repeatability of the continuous duration of ice drift at velocity of less than 0.1 m/s according to observations in the Kara (a), Laptev (b) and East Siberian Seas (c)



a) b) c)

Fig. 15. Repeatability of unidirectional changes in the direction of ice drift according to observations in the Kara (a), Laptev (b) and East Siberian Seas (c)

In the Kara Sea, the continuous duration of such a drift was no more than 4 hours. In the Laptev Sea, the maximum exceeded 10 hours near the edge of the fast ice of the Khatanga Bay. In the East Siberian Sea, the continuous duration of ice drift at a speed of up to 0.01 m/s did not exceed 5 hours.

In the Kara Sea, the duration of continuous ice drift with critical velocities of up to 0.1 m/s in April-May, on average, was 13.3 hours, while it could reach 222 hours. In June-August, the average duration of such a drift in the Kara Sea decreased to 6.6 hours, with a maximum of 141 hours. In 72.7% of cases in April-May and in 86.8% of cases in June-August, the duration of the drift at speeds of up to 0.1 m/s did not exceed 10 hours (see Fig. 14).

In April-May, in the Laptev Sea, the average drift duration at speeds of up to 0.1 m/s was 12.8 hours, with a maximum of 338 hours. In June-August, drift at a speed of up to 0.1 m/s on average continued for 17.2 hours, with a maximum duration of 493 hours. In 83.6% of cases in April-May and 92.9% in June-August, the duration of such a drift was not more than 10 hours.

From the point of view of this parameter (the effect of ice at speeds of up to 0.1 m/s, at which ice fracture is not yet brittle, at which the coefficient of static friction is great for an inclined surface), the most difficult conditions are observed in the Laptev Sea, where fast ice and drifts are quite developed occur in compacted conditions. The duration of the drift of firm and thick ice with a speed of up to 0.1 m/s here is on average 12.8 hours.

The average duration of drift at speeds of up to 0.1 m/s in the East Siberian Sea in May was 10.3 hours (maximum 90 hours), in June-July - 9.2 hours (maximum 145 hours). In August, no such situations were observed. 85.4% of cases in May relate to a drift duration of less than 10 hours. Such a duration in June-July was observed in 83.6% cases.

The repeatability of high drift velocities (more than 0.5 m/s) in the Kara Sea was 0.3% in April-May and 3.1% in June-August. The duration of such a drift, on average, was 3.8 hours (maximum 7 hours) in April-May and 6.3 hours (maximum 125 hours) in June-August.

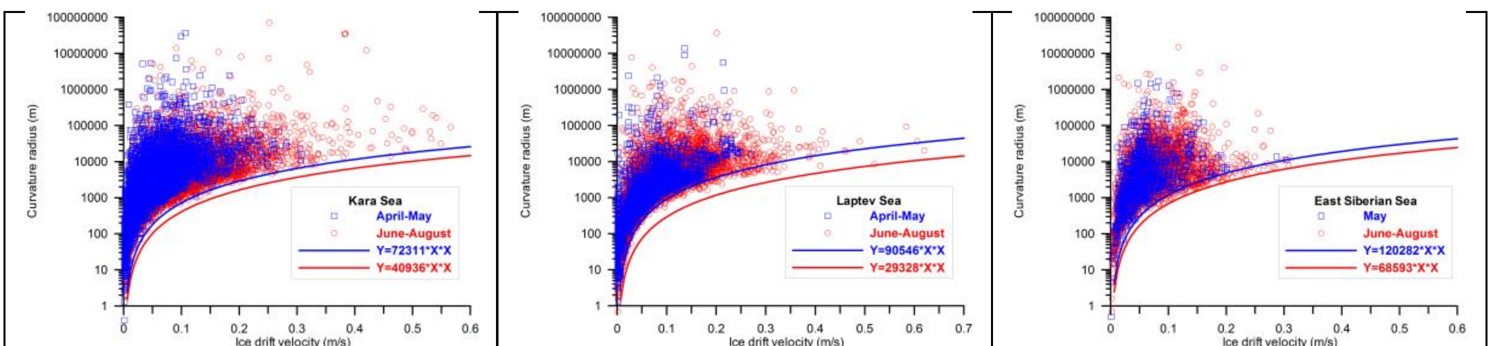
It should be borne in mind that in June-August, as a rule, ice is warmed up and weakened. Under such conditions, the viscosity of ice increases, which must be taken into account when evaluating the interaction of ice and an engineering structure.

The repeatability of high drift velocities in the Laptev Sea in May did not exceed 0.05%, in June-August it was 2.3%. In April, drift velocities of more than 0.5 m/s in the Laptev Sea were not observed during the period of work. The average duration of a strong drift in June-August was 4.3 hours, with a maximum of 24 hours.

The frequency of ice drifts with velocities of more than 0.5 m/s in the East Siberian Sea was 0.3% (average duration 4.3 hours) in May and 0.5% (average duration 3.8 hours) in June-August.

In more than 69% of cases, the continuous duration of ice drift with high speeds in the considered water areas did not exceed 5 hours. Based on the foregoing, it can be assumed that drifts with high velocities in the water areas covered by observations are not as critical as drifts with velocities less than 0.1 m/s.

The greatest repeatability in the Kara and East Siberian seas is shown by drifts with a unidirectional change of direction up to 45°, after which the ice drift direction begins to change in the opposite direction (Fig.15). In the Laptev Sea, drifts with the magnitude of unidirectional change of direction within 135-180° have the greatest repeatability. The rotation of the ice drift vector by more than 360° in the Kara Sea was recorded in 4.5% (April May) and 7.0% (June-August) cases, in the Laptev Sea - in 10.6% and 10.7%, respectively. This difference in the unidirectional change in ice drift between the seas is in good agreement with the differences in the anisotropy of the drift variability: in the Kara and East Siberian Seas there is a region with anisotropic drift variability (respectively, there is more variability in the drift velocity), in the Laptev Sea, the variability is uniform over most of the water area directions (respectively, more variability of drift directions).



a) b) c)

Fig. 16. Radius of curvature of ice drift according to observations in the Kara (a), Laptev (b) and East Siberian Seas (c)

The radius of curvature of the ice drift during the period of its decay is smaller than in the winter period with high ice concentration (Fig. 16). At the same time, an interesting feature is noted that the minimum radius of curvature of the drift in April-May is smaller in the Kara Sea compared with the Laptev Sea, and in June - August the opposite picture is observed. At a drift velocity of 0.1 m/s, the minimum radius of curvature of ice drift in June-August is 409 m for the Kara Sea, 293 m for the Laptev Sea and 686 m for the East Siberian Sea. We repeat that this applies to time scales of 1 hour and above.

CONCLUSIONS

The use of buoys to measure ice drift in the seas of the Russian Arctic shelf in the period 2013-2017 allowed us to collect a unique array of direct measurement data in remote and inaccessible areas where such observations were practically never made or were not available before. The collected data allows us to clarify our ideas on the dynamics of ice in the marginal seas of the Arctic Ocean, as well as to obtain estimates of the drift parameters of ice formations necessary for engineering calculations. The analysis performed in the work shows that:

1) The drift of "large areas of compacted ice" occurs in the SW part of the Kara Sea ("the Novaya Zemlya ice massif") mainly along the SW-NE axis, which is apparently caused by the semi-closed form of the water area of this part of the sea. The average modulus of the drift velocity here lay in the range 0.11-0.14 m/s. The ice of high concentration in the East Siberian Sea moved in accordance with the well-known drift pattern (transport of ice into the "Transpolar Drift" system), the average velocity modulus was 0.11 m/s. In both cases, the trajectories of individual ice floes show their predominantly synchronous movement.
2) Ice variability is anisotropic in the N and NE parts of the East Siberian Sea and the SW part of the Kara Sea. In the Laptev Sea, the variability of ice drift in directions is closer to homogeneous. In most areas of the SW part of the Kara Sea and in the Laptev Sea, the average transport is not large in absolute value, as well as

in comparison with the RMS. This indicates that here, over most of the water area, the ice melts in place, not being carried to neighboring areas. A different situation is observed in the northern part of the East Siberian Sea, where within the water area under consideration, the outflow of ice to the Arctic Ocean was clearly observed during the measurement period.

3) The ice cover in the SW part of the Kara Sea is, on the whole, more dynamic than in the waters of the Laptev and East Siberian Seas. The average drift velocity in the SW part of the Kara Sea was 0.11 m/s in April-May and 0.19 m/s in June-August. In the Laptev Sea, these values are 0.09 m/s and 0.17 m/s, in the East Siberian Sea - 0.11 m/s in May and 0.14 m/s in June-August, respectively. At the same time, the maximum drift using buoys was recorded in the Laptev Sea, where it amounted to 1.30 m/s.
4) When considering ice drift with velocities of up to 0.1 m/s (when ice destruction is not as brittle), the most difficult conditions are observed in the Laptev Sea, where landfast ice is quite well developed and ice cover drift occurs in compacted conditions. The duration of the drift of firm and thick ice with a speed of up to 0.1 m/s here, on average, is 12.8 hours. In general, this parameter should be recognized as critical for the considered water areas.
5) Drifts with unidirectional change of direction up to 45° have the greatest repeatability in the Kara and East Siberian Seas, after which the ice drift direction begins to change in the opposite direction. In the Laptev Sea, drifts with the magnitude of unidirectional change of direction within 135-180° have the greatest repeatability.
6) The radius of curvature of the ice drift during the period of its decay is less than in winter with high ice concentration. At a drift velocity of 0.1 m/s, the minimum radius of curvature of ice drift in June-August is 409 m for the Kara Sea, 293 m for the Laptev Sea and 686 m for the East Siberian Sea.

It should be noted that the above results refer to the average drift velocities over 1 hour and, accordingly, to time scales from 1 hour and above. Currently, the practice of ice research has included the use of drifting buoys with a positioning resolution of 10 minutes, which significantly improves the quality of the materials collected. Higher time resolution allows more objective estimates of drift variability, operating with speeds with a shorter averaging period.

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