Evaluation of Exploration Drilling Scenarios in the Southwestern part of the Kara Sea

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Abstract

Ice-free period in the southwestern part of the Kara Sea is limited in average to 2-3 months and has significant interannual variability. A preliminary assessment of the ice-free period duration will allow advanced strategic and tactical planning of platforms operating and drilling activities and, thus, costs optimization of exploration drilling. Duration of ice-free period depends on the date of the sea clearing from the ice and on the date of the stable ice formation. Data analysis was based on historical ice maps and satellite information for a 30-year period from 1989 to 2018. Interannual variability of ice free periods, dates of sea clearing from ice and dates of ice formation are considered in the region of geological structures of the southwestern part of the Kara Sea. It is shown that combination of favorable hydrometeorological conditions that in the last decade increased the ice-free period duration by more than a month. Aanalysis of the main hydrometeorological factors determining ice-free period duration showed possibility to estimate the operational window for exploration drilling in the area of geological structures with a lead time of several months.

KEY WORDS: Kara sea, drilling, operational period, ice, forecast

Introduction

East Prinovozemelsky license blocks are located in the southwestern part of the Kara Sea between the Novaya Zemlya archipelago in the west, Yamal peninsula in the south and the Taimyr peninsula in the east. The northeastern border of the sea is an imaginary line between the Cape Zhelaniya and the Dickson Island. Several prospective geological structures have been identified within the boundaries of these license blocks (Fig. 1), and in 2014 the Pobeda field was discovered during exploration drilling at the Universitetskaya structure.

Usually exploration drilling in freezing seas is carried out in the ice-free period from floating drilling rigs of various ice classes. In the southwestern part of the Kara Sea the ice-free period is limited in average to 2-3 months (Atlas, 2014; Monograph, 2004) and has significant interannual variability.

Duration of the ice-free period depends on the time of clearance of ice and the dates of the beginning of stable ice formation. The timing of the ice phases depends on the features of ice regime in local areas of the Kara Sea, which are determined by hydrological and meteorological factors, river influx, bottom topography and coastline. Four local regions with homogeneous ice conditions were identified in the southwestern part of the Kara Sea: the Yamalo-Yugorsky, Ob-Yenisei, southern and northern Novaya Zemlya regions (Egorov, Spichkin, 1994; Monograph, 2004). Packed ice of the Novaya Zemlya ice massif near iceberg production zones (Tarasov et al, 2019) is usually thawed last of all in the Kara Sea.

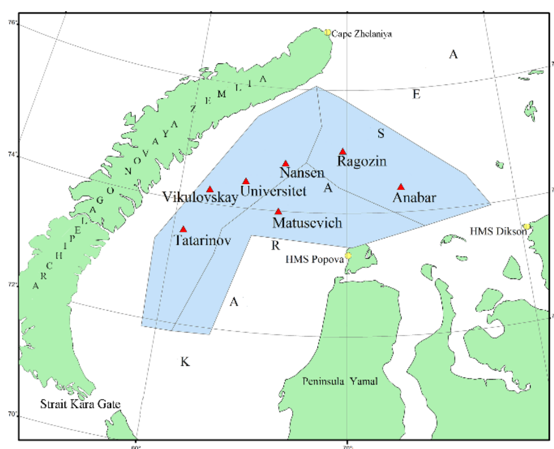

Fig. 1 Geological structures within the East Prinovozemelsky license blocks in the southwestern part of the Kara Sea

Six geological structures are located in the Novaya Zemlya ice region (northern and southern). The Anabar structure is located in the Ob-Yenisei region, the ice regime of which is strongly influenced by the flow of the Ob and Yenisei rivers, that results in earlier ice melt and water clearance, as well as in earlier freezing of desalinated waters in winter. Thus, taking into account the significant spatial heterogeneity of environmental conditions of the southwestern part of the Kara Sea, a detailed consideration of the ice clearance and freezing processes for each geological structure is necessary for effective planning of exploratory drilling.

Data and methods of calculation

Data of ice mapping for the water area of the Arctic Seas are used in the article. Ice charts are generated by the Data Center on Sea Ice (WDC-SI) of the Arctic and Antarctic Research Center (AARI) in the electronic format on the basis of geo-information technologies and are duplicated by paper copies. An ice chart is an information product for a complex depiction in space of ice cover characteristics. It is mainly created on the basis of an expert analysis of satellite observation data in accordance with the international and national standards of ice mapping.

For the data analysis there were used ice charts with a time interval of one week for the period 1989 to 2018 (http://wdc.aari.ru/ datasets/). One used a 30-year period, which is recommended by WMO for the analysis of climatic data. In the summer period (June–September) the charts are presented in the form of ice concentration distribution and in the wintertime (October–May) in the form of ice distribution of different age gradation (thickness).

For the analysis of thermal conditions one used daily data of air temperature measurements at Popov (Bely Island) and Dikson Island hydrometeorological stations (HMS) from the archives of Gosfond (http://meteo.ru), as the most representative for the southwestern Kara Sea. Sums of degree-days of frost (FDD) were calculated on the basis of these data.

The criterion of the date of ice achieving the thickness of 50 cm after the start of ice formation was used in the work. The ice thickness was calculated at each point of geological structures from the actual moment of ice appearance based on the empirical expression connecting the ice thickness with the air temperature which follows from the Stefan's theoretical formula, showing that the ice thickness is proportional to the square root of the sum of degree-days of frost. The calculated data were compared with the actual ice charts of ice age distribution.

Construction of regression dependencies, assessment of correlation coefficients, trend significance (for the confidence probability of not less than 0.95) and selection of the type of approximation of the time series was made on the basis of standard software packages.

Trends of the time series of ice-free period duration

The time interval from the date of water area clearance until the beginning of freeze up comprises the ice-free period duration. In the work such period was determined for each of 7 geological structures. Fig. 2 shows the variability of ice-free period duration in the southwestern area of the Kara Sea for the last 30 years. For construction of the plot the average values of the ice-free period duration for seven geological structures were used. The variability is characterized by short-period random fluctuations, which are determined by the influence of different factors, and the long-period quasi-cyclicity, determined by climatic changes for the periods of more than 10 years (Monin, 1969). By cyclicity in this case one understands the repeated return of the ice-free period duration to the initial value. In monograph (Frolov et al., 2007), an analysis of spectral density of fluctuations of multiyear ice area values was performed and it is shown that the cycles with duration of about 20 and 60 years play a significant role in the Arctic Seas. A similar conclusion was also obtained for some other ice cover characteristics (ice thickness, ice exchange, etc.). In (Diansky et al., 2018) it is shown that the ice-free period duration has a significant cycle of about 60 years which is necessary to take into account for climatic estimates.

In addition to short-period fluctuations one can identify visually in Fig. 2 three time intervals (1989-1999, 1999-2009 and 2009-2018). The first two time periods comprise a 20-year quasi-cycle, at which there was a decrease of the ice-free period (1989-1999) to the minimum value in 1999 and its increase (1999-2009). The third time interval (2009-2018) is characterized by the large amplitude of values of the ice-free period compared with the previous periods. Checking of three identified time intervals for the trend significance by the Student's criterion showed the linear trend to be significant only for the period 1999-2009 at the confidence probability of 0.99. In the case of the other two periods, the trend is not pronounced. Slowing of the increase of the ice-free period duration in the southwestern Kara Sea beginning from 2009 occurs in the framework of global climatic changes. There are a number of publications which note slowing of warming from the 2000s (Boykoff, 2010, Chen, Tung, 2014, England et al. 2014, Fife et al. 2013, Karl et al., 2015).

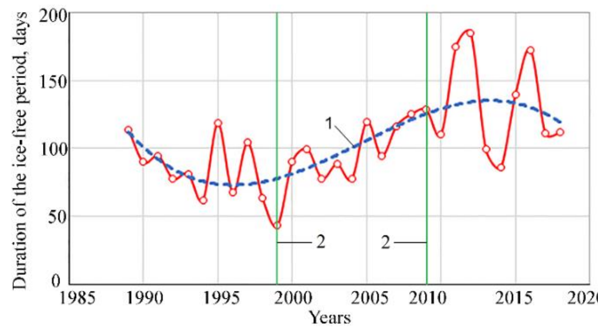

Fig. 2. Interannual variability of ice-free period duration from 1989 to 2018 in the area of the East Prinovozemelsky license blocks in the southwestern Kara Sea.
1 — line of the trend of ice-free period duration, 2 — line of division of interannual changes into three periods

Absence of the trend for the last time period at a large standard deviation does not allow us to forecast the ice-free period duration for the forthcoming years. Besides even in the case of a well-pronounced trend, the use of the regression equation is not sufficiently reliable. The trends can change depending on the time while the methods of forecasting of the critical moment, meeting the practical needs, are absent. In this case for an assessment of duration of the forthcoming ice-free period one can use its dependence on the hydrometeorological factors, which determine its duration.

The ice-free period duration changes not only in time but also depending on the geographical location. Table 1 presents the average and extreme values of the ice-free period duration and its standard deviations (RMSD) for 7 geological structures for the last decade. It is shown in the same table how much the ice-free period duration increased for the last decade compared with the previous 20-year period.

Table 1 – Ice-free period duration in the area of the East Prinovozemelsky license blocks of the Kara Sea

Structures	Ice-free period duration for the last 10 years (2009–2018), days			RMSD	Increase of ice-free period duration for the last 10 years as compared with the previous 20-year period, days		
	Minimum	Average	Maximum		Minimum	Average	Maximum
Ragozin	75	123	180	37	33	39	54
Nansen	82	126	186	34	54	42	62
Universitetskaya	89	134	192	36	30	46	65
Vikulovskaya	88	140	202	42	72	54	72
Tatarinov	90	146	210	42	46	49	61
Matusevich	86	135	199	38	38	38	44
Anabar	82	122	152	26	17	24	11

On average, the ice-free period duration for the last 10 years increased by more than one month. The RMS deviation of this characteristic has also increased. A large dispersion of the open water period duration in the last decade requires a detailed consideration of the influencing factors and identification of several scenario conditions principal for exploration drilling. In addition to the ice-free period duration, it is important to assess the date of its start in the area of each geological structure.

Variability of ice clearance and ice formation dates

The ice clearance of the water area usually begins in the first part of June and ends depending on the intensity of melting during July or August. It is shown in (Danilov et al. 2004) that the interannual dates of sea clearance are so large that when at the extremely easy ice conditions the clearance ends, at the extremely heavy conditions it just starts. Nevertheless, the sea ice clearance duration comprises about six 10-day periods both at the extremely easy and extremely heavy ice conditions.

Analysis of data for 30 years has shown that the interannual variability of the dates of ice clearance and onset of freeze up in the water area where the geological structures are located is similar to the ice-free period variability, which is quite expected (Fig. 3). For plot construction, the average dates of clearance and onset of freeze up for seven geological structures were used.

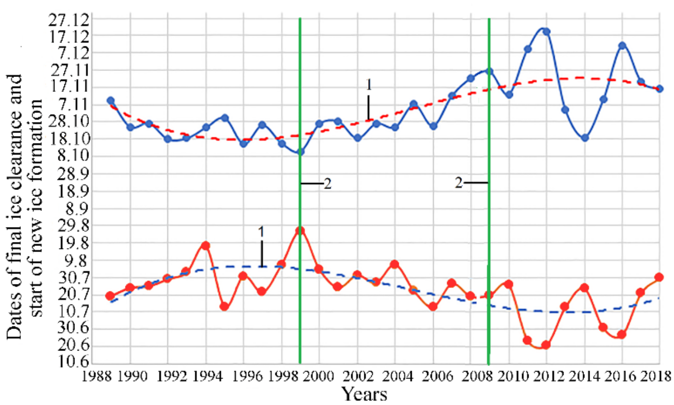

Fig. 3. Interannual variability of the dates of ice clearance of the water area and start of ice formation in the geological structures of the East-Prinovozemelsky license blocks
1 — lines of the trend of dates of final clearance and start of freeze up, 2 — lines of division of the interannual changes into three periods

As can be seen from Fig. 3, the year 1999 is critical both for the ice-free period duration and the time of ice clearance and start of freeze up, when the latest ice clearance and the earliest onset of ice formation were noted. During the last decade there was a significant shift of the dates of ice clearance in the area to the earlier dates and of the dates of onset of ice formation to the later dates. The dates of ice phases in the last decade are characterized by the increased amplitude of interannual fluctuations.

The interannual variability of the dates of ice clearance and start of freeze up are approximated by functions of the third power polynomial. Analysis of Fig. 3 shows that the plots themselves and the approximation lines are close to a mirror reflection of each other. This indicates that changes of in ice phases occur with a synchronous component determined by one cause. During the period 1989 to 2008, the average dates of ice clearance were in the end of July or beginning of August. Only in the Anabar structure the average date of ice clearance was relatively early (13 July). For the last decade (2009–2018) the average dates of ice clearance were noted in the first part of July. In the Anabar structure the average date of ice clearance similar to the previous period is the earliest for the last decade as compared with the dates at the other structures and is recorded on 3 July.
The shift of the dates of ice clearance to the earlier dates depending on the structure comprised 10 to 25 days with the least change recorded in Anabar structure comprising 10 days. The analysis of data of multiyear variability of the dates of ice formation for 30 years (Fig. 3) showed that there are also significant differences of the beginning of the freeze up dates for the period of 20 years (1989–2008) and 10 years (2009–2018). During the last decade there was a significant shift of the dates of ice formation to the later dates, comprising 15 to 30 days depending on the structure.

During the period 1989–2008 the average dates of the onset of ice formation were recorded in the second part of October. The exception was the date in the Tatarinov structure, where the average date of the onset of ice formation was recorded later and was on 7 November. The range between the late and early dates of the onset of ice formation at this time was 37–54 dates. The average dates of ice formation in the last decade (2009–2018) moved to November and in Tatarinov structure to the 2nd of December.

The dates of freeze up in the southwestern Kara Sea are characterized by a large spatial non-uniformity and duration of freeze up spreading over the water area comprises more than a month. The early freeze up occurs in the northern areas of the sea and also in the Ob'-Yenisey region where freshening of the sea occurs due to the inflow of river water. The influence on the dates of the onset of freeze up can be also produced by the southeast flows of the cold air masses from the territory of Siberia and the northeastern regions of the |Kara Sea. A comparatively late freeze up is typical of the southwestern area, which is determined by the inflow of warm water from the Barents Sea via the Kara Gate Strait.

Main factors affecting ice clearance and ice formation

A combined analysis of interannual variations of air temperatures, dates of ice clearance and the onset of freeze up showed the main factor determining the dates of ice phases in the area of most geological structures to be the degree of severity of the preceding cold season, which is quantitatively expressed by the sum of degree-days of frost during the period of below zero temperatures.

The influence on the dates of the onset of melting and freeze up in the Arctic Seas is also produced by the other factors, described in (Spichkin, 1987). After a stable transition of the heat budget of the upper snow-ice surface to the above zero values the process of ice melting begins. With the increased incoming solar radiation flux and spreading of puddles, the intensity of melting increases. The air masses from the North Atlantic and from the side of the heated mainland also contribute to sea clearance (Danilov et al. 2004). The summer air transports from the Arctic Basin bring cold air masses which significantly decreases the intensity of melting. In connection with non-uniformity of the age composition (thickness) of the ice cover, thinner ice of late winter formation melts out first and then ice of autumn formation. The main factor determining the dates of ice clearance is the ice cover area and thickness, formed over the entire preceding cold season. The process of melting over the water area will be the longer the larger is the ice thickness, and a large area will be occupied by thick first-year ice. An assessment of the maximum ice thickness can be performed by the sum of degree-days of frost for the preceding cold season.

For each of the structures the linear regression dependence can be constructed between the sum of degree-days of frost (FDD) in the preceding period at the hydrometeorological station located on Bely Island or on Dikson Island and the forthcoming duration of the ice-free period. The correlation coefficients between these hydrometeorological characteristics were calculated by a 20-year series for 1999- 2018. For the Nansen, Pobeda, Vikulovskaya and Tatarinov structures, where the dependence is well pronounced (*R*=0.82–0.88), one can develop a methodology for determining the ice-free period mainly based on taking into account the air temperature data for the past cold season. For an assessment of the ice-free period parameters in the area of the Ragozin, Matusevich and Anabar geological structures where the relation is characterized by a slightly smaller correlation coefficient (*R*=0.65–0.77), it is also necessary to take into account the other factors, influencing the ice-free period duration.

Fig. 4 shows a dependence of the ice-free period duration on the sum of degree-days of frost in the southwestern part of the Kara Sea for the geological Vikulovskaya structure

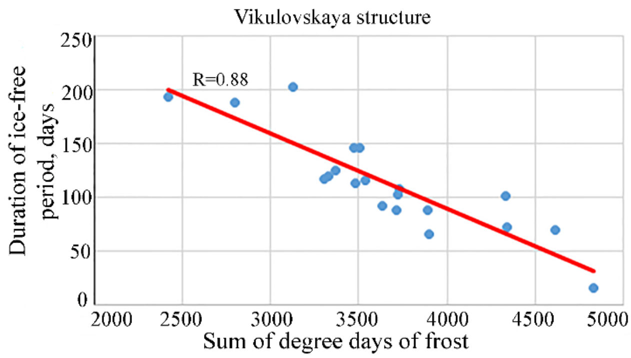

Fig.4 – Dependence of the ice-free period duration on the sum of degree-days of frost for the preceding cold season in the area of the Vikulovskaya geological structure

In addition to the ice-free period duration it is important to assess the dates of its onset. For the water are of the geological structures except for Ragozin and Anabar, the linear function describes quite efficiently the tendency of the change of the dates of clearance depending on the sum of degree-days of frost at a confidence probability of 0.99. For the Ragozin geological structure the correlation coefficient is significant at a confidence probability of 0.98, and for the Anabar structure it is not significant. The dates of ice clearance derived by averaging over the seven geological structures have a significant correlation coefficient with the sum of degree-days of frost equal to 0.82, which corresponds to the Student's criterion at a confidence probability of 0.99.

The intensity of the melting process is also influenced by the frequency of occurrence of advection of warm air masses at the air temperature transition to the above zero values. Indirectly, these processes characterize the mean monthly values of air temperature in the summertime. Taking into account such factors is preferably to perform on the basis of the method of local-genetic typification of ice conditions (Egorov, Spichkin, 1994).

The dates of the onset of ice formation are also significantly connected with the sum of degree-days of frost. The correlation coefficient according to the Student's criterion is significant for all geological structures at a confidence probability of 0.99, being in the range of 0.66-0.85. Fig. 5 shows the plot of dependence of the dates of the onset of ice formation on the sum of degree-days of frost for the preceding cold season for the area of the Vikulovskaya structure.

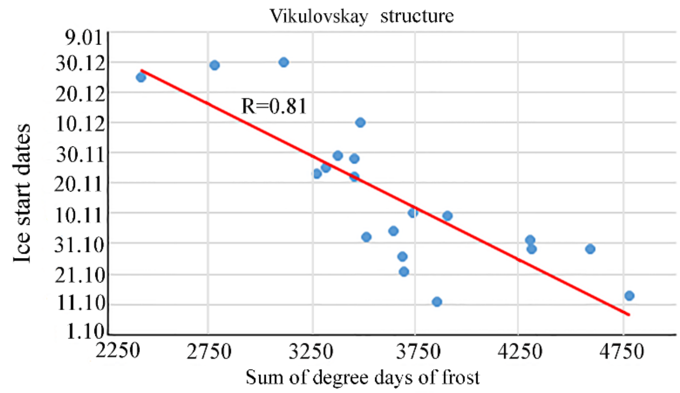

Fig. 5. Dependence of the dates of onset of ice formation on the degree days of frost for the preceding cold season

For the area of seven geological structures of the East-Prinovozemelsky license blocks the water heat content is the main factor influencing the dates of freeze up. Accumulation of the heat content of the water masses occurs during the ice-free period which is determined by the dates of ice clearance. The earlier the ice cover melting occurs, which depends on the sum of degree-days of frost in the preceding cold season, the larger is the period of time for formation of the heat content. The dependence of the dates of the onset of freeze up on the sum of degree-days of frost for the preceding cold period is large for the structures under consideration, and is characterized on average by the correlation coefficient of 0.77. Thus, the dates of ice clearance and the onset of ice formation are determined in many aspects by one and the same factor — severity of the preceding cold season, which is assessed by the sum of degree-days of frost.

The analysis of data suggests that forecasting of the dates of ice clearance and onset of ice formation will be efficient for the cases of anomalously large or anomalously small sum of degree-days of frost for the preceding cold season. The average values of the sum of degree-days of frost indicate a sufficiently large range of the dates of ice clearance and the onset of ice formation (Fig. 5), which decreases the possibility of the accurate assessment of the expected date of final melting and requires taking into account the other factors influencing the processes of ice clearance.

The ranges of complete ice clearance dates for geological structures are divided into three groups - "Early", "Mean" and "Late" in accordance with the features of their 10-year distribution. The FDD value for Dixon is less than 3700 ("warm winter season") at the end of the winter season was observed in 2011, 2012, 2016. This fact unambiguously indicates early ice clearance for all of the structures, which allows recommending this indicator for forecasting the time of ice clearance.

For all geological structures with FDD sum less than 3990 correlations were constructed between the start of clearance and FDD at Dixon. For Nansen, Universitet and Matusevich structures the regression turned out to be significant, which make it possible to predict with sufficient accuracy the time of ice clearance for these structures in the case of warm winters (Table 2). Due to the significant features of ice clearance and formation caused by active influence of the Yenisei and the Ob rivers influx in the eastern part of the Kara Sea, we will divide the structures into two groups.The first group of structures: Ragozin, Nansen, Universitetskaya, Vikulovskaya, Tatarinov and Matusevich. The second one is Anabar structure.

Table 2.Typification of the ice clearance dates for geological structures in the groups of "Early", "Mean" and "Late". In parentheses is the number of observed cases for the period 2007-2017.

Structure	Late	Mean	Early
First group	1 August - 15 August (4)	25 July - 1 August (3)	1-10 July (4)
Ragozin	25 July - 5 August (4)	20-25 July (3)	1-10 July (4)
Nansen	25 July - 10 August (4)	10-20 July (3)	1-10 July (4)
Universitet	26 July - 10 August (3)	10-20 July (4)	1-10 July (4)
Vikulovskaya	1 August - 10 August (3)	15-25 July (4)	1-5 July (4)
Tatarinov	2 August - 10 August (3)	15-25 July (4)	1-5 July (4)
Matusevich	25 July - 5 August (2)	10-20 July (4)	1-10 July (5)
Second group	15 July - 25 July (5)	1-10 July (2)	10-20 June (4)
Anabar	15 July - 25 July (5)	1-10 July (2)	10-20 June (4)

Time of ice formation is determined by the ratio of variable active components of the thermal budget, which ensure heat input and loss on the water surface. The main factors that cause heat loss from the sea surface are effective infrared radiation and turbulent heat transfer.

Thermal content of water is the main factor affecting the ice freezing time in the southwestern part of the Kara Sea. In its turn, thermal content of water masses accumulate during the ice-free period, which is determined by the time of ice clearance. The earlier the ice cover melts, the longer the period of thermal content accumulation is. As indicated above, the time of ice clearance depends on severity of the previous cold season.

For the studied geological structures the dependence of ice freezing dates on the FDD sum for the previous cold period is characterized on average by a correlation coefficient of 0.82. Thus, the timing of ice clearance and ice formation is largely determined by the same factor - the severity of the previous cold season, which is estimated by the FDD sum.

Scenarios of operational period for non-ice resistant platform

Exploration drilling from conventional non-ice-resistant platform in freezing seas is limited by the ice-free period. The determining factors for choosing an operation scenario are the dates of ice-free period beginning and end. The ice-free period start date is understood as the mean date of the final ice clearance on a specific geological structure, and the end date – the mean date of ice freezing. Due to the different nature of ice clearance and ice formation the geological structures of the first and second groups are considered separately.

The operation period duration can be divided into three groups: “Long OP”, “Medium OP”, “Short OP”. For the structures of the first group, an intermediate group, “Medium-Long- OP” (observed in 2015) can be identified. For the structure of the second group (Anabar) such event was not observed. Frequency of occurrence of different operational periods for geological structures is shown in table 3.

For the structures of the first group, “Long-term OP” is uniquely determined by the FDD sum less than 3700; for some geological structures of the first group (Nansen, Universitet, Tatarinov) with the FDD sum at Dixon less than 3700, a linear regression relationship between the FDD sum and the duration of the operating period can be divided (Table 4). For the Anabar structure, the warm winter season (FDD sum at Dixon less than 3700) is also a predictor of a long operation period, although this connection is less strong.The groups “Short OP” and “Average OP” can be combined into one range with determined average duration and standard deviation (Table 5).

Table 3.Typification of the operation period duration for the groups “Long OP”, “Average OP”, “Medium-Long OP” and “Short OP”.

Structure	**Short OP**	**% ofcases**	**Average OP**	**% ofcases**	**Medium-Long OP**	**% ofcases**	**Long OP**	**% ofcases**
	days	-	*days*	-	*days*	-	*days*	-
Ragozin	75-100	45	101-125	27	126-150	0	151-175	27
Nansen	80-100	45	101-125	18	126-140	9	140-175	27
Universiter	80-100	36	101-125	27	126-150	9	151-175	27
Vikulov	80-100	27	101-125	36	126-150	9	151-180	36
Tatarinov	80-100	27	101-125	36	126-150	0	151-180	36
Matusevich	80-100	36	101-125	27	126-150	9	151-180	27
Anabar	80-100	27	100-120	27	121-135	0	136-160	45

Table 4. Duration of the operation period for the group "Long OP". Coefficients of linear regression between the FDD sum at Dixon and duration of operation period are indicated.

Structure	**Range**	**Min.**	**Max.**	**FDD sum at Dixon less 3700**	**Coefficient a**	**Coefficient b**
	days	***days***	***days***	***days* degree***	***Degree (-1)***	***day***
Ragozin	151-175	153	175	Light	-	-
Nansen	140-175	139	163	Light	-0,0521	328
Universiter	151-175	155	176	Light	-0,029	259
Vikulovskaya	151-180	159	174	Light	-	-
Tatarinov	151-180	153	178	Light	-0,0407	301
Matusevich	151-180	162	180	Light	-	-
Anabar	136-160	136	157	Light (partly)	-	-

Table 5. Duration of the operation period for the group “Average OP“ and“Short OP“. Mean values and standard deviations are indicated.

Structure	**Range**	**Min.**	**Max.**	**Mean**	**Standarddeviation**
	days	*days*	*days*	*days*	*days*
Ragozin	75-115	75	113	93	12
Nansen	80-115	80	113	93	12
Universiter	80-115	83	115	98	11
Vikulovskaya	80-125	83	123	101	13
Tatarinov	80-	85	125	108	14

	125				
Matusevich	80-125	80	122	99	15
Anabar	80-120	82	116	101	14

As seen from above, for geological structures of the first and second groups during 2007-2017duration of operation period and ice clearance dates for non-ice-resistant platform can be divided into two main scenarios (Table 6): "Light conditions" (30% for the period 2007-2017) and "Average conditions" (70% for the period 2007-2017).

Table 6. Operational period for various scenarios.

Scenario / Group	Firstgroup (Ragozin, Nansen, Universitet, Vikulovskaya, Tatarinov, Matusevich)	Secondgroup (Anabar)
Light	150-175 days	135-160 days
Average	80-120 days	80-115 days

"Light Conditions" scenario for the geological structures of the first group is uniquely determined by the warm winter season, and in quantitative terms by the FDD sum at Dixon less than 3700 at the end of the freezing period. For the second group of structures (Anabar), the connection between the "Easy conditions" scenario and the warm winter season is less rigid.

Complete ice clearance and work commencement of non-iceresistant drilling platform takes place for the considered scenarios in the following terms (Table 7). For the structures of the second group, the beginning of operation period occurs on average 15 days earlier compared with the structures of the first group for both scenarios.

Table 7.Dates for ice clearance.

Scenario / Group	Firstgroup (Ragozin, Nansen, Universitet, Vikulovskaya, Tatarinov, Matusevich)	Secondgroup (Anabar)
Light	1-10 July	10-20 June
Average	25 July – 15 August	5-25 July

Thus monitoring of the FDD sum at Dixon during months characterized by a negative air temperature (starting from October) makes it possible to determine implementation of the warm winter season far in advance (in the spring of the current year). And in a result, to predict the operation season duration ahead of the game. On the graph of the FDD sum (Fig.6) at the Dixon HMS, points below the minimum curve of relatively cold winter periods (2007, 2008, 2009, 2010, 2013, 2014, 2015) indicates a warm winter season (2011, 2012, 2016). It's clearly seen that there is a possibility to predict it in March-April.

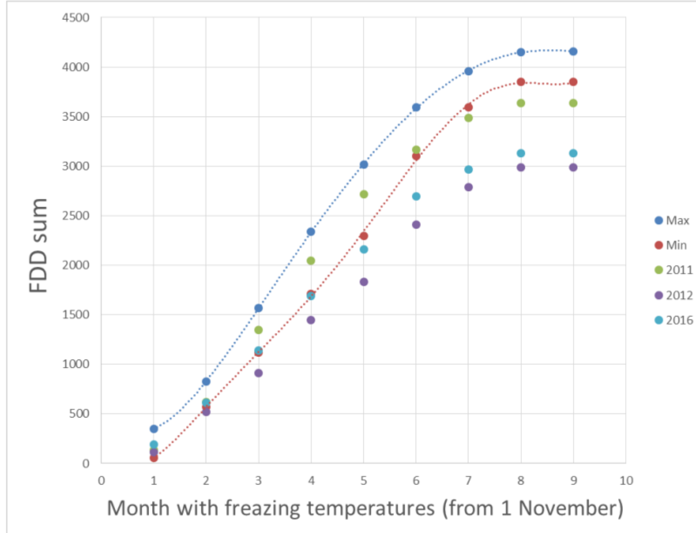

Fig. 6. FDD sum at Dixon by months for 2007-2017 period.

Critical question for planning of exploration drilling in the Kara sea is the date of the drilling rig mobilization to the Kara Gate and the operation period duration. Duration of drilling and primary well tests should be selected based on the lower limit (minimum curve) of the operating period range, and the upper limit should be used for planning of additional well tests.

The decision tree for exploration drilling on the geological structures of the first and second groups is shown in Figures 7 and 8.It should be noted that for the Nansen structure, the operational period is 140-165 days in the case of a warm winter season (early ice clearance) and for Ragozin structure the operational period is 75-115 days for a relatively cold winter (late ice clearance). For the structures of Nansen, Universitet and Tatarinov in the case of a warm winter season, it is possible to forecast the operation period duration based on the FDD sum at Dixon in June according to Table 8 that shows minimum operation season duration with a probability of not exceeding 90% for all geological structures.

Table 8. Duration of the operation period (days) for a non-ice-resistant platform.

Structure	**Operation period, days**
Ragozin	75
Nansen	80
Universitet	83
Vikulov	83
Tatarinov	85
Matusevich	80
Anabar	82

Under the "Light Conditions" scenario, it is possible to drill two wells per season taken that construction time of exploratory well is about 75 days (including mobilization, drilling, well cementing and minimum list of geophysical and hydrodynamic tests).In this case drilling should be started either from the structures of the second group (Anabar), or from the Nansen/Ragozinsky structures. This choice is due to the early ice clearance of the second group structures and the early closure of first group structures. For drilling the second well in one season, it is reasonable to choose a structure with a maximum period of open water - Matusevich or Tatarinov. Algorithms of exploratory drilling in the structures of the first and second groups are shown in Figures 7 and 8.

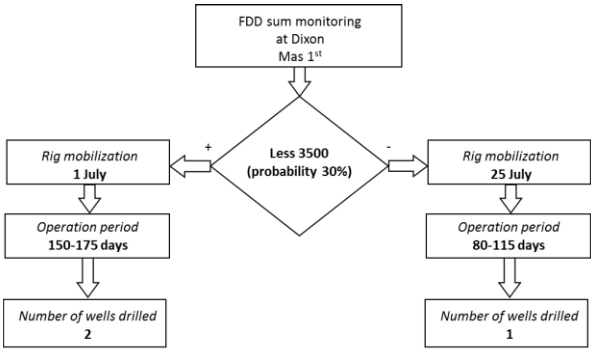

Fig. 7.Decision tree for exploration drilling with ice-nonresistant platform on the structures of the first group.

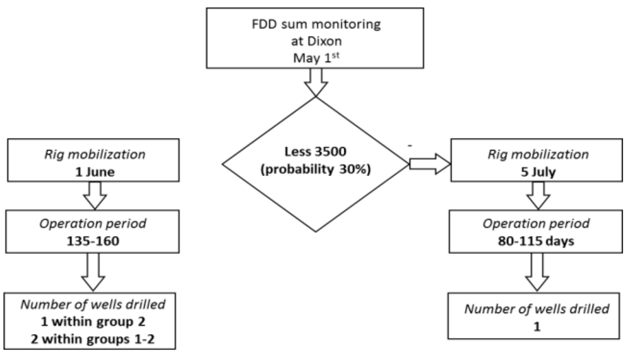

Fig. 8. Decision tree for exploration drilling with ice-nonresistant platform on the structures of the second group.

Increased duration of the operation period for the ice-resistant platform of exploration drilling

When using the ice-resistant platform it becomes possible to extend the operation period due to the start of drilling directly after the ice concentration decreases to a specific gradation during the period of melting and the end of drilling after the ice growth to a specific thickness, which were assumed to be the boundary conditions of safe operation of the ice-resistant platform. There are possible several variants of extending the operation period depending on the chosen boundary conditions. For the last decade 2009–2018, the dates of presence of the last close ice after the onset of the processes of melting were determined and the dates of ice achieving the thickness of 50 cm in the subsequent freeze up season were calculated. The interannual change of duration of such period at its comparison with the ice-free period is given in Table. 9.

During the last decade ice closure (70-80%) in the southwestern part of the Kara Sea disappears during the period middle of June to the first days of July. Then until complete melting one observes only open ice (40-60%) and very open ice (10-30%). After the onset of new ice formation, ice achieves the thickness of 30 cm on average in mid-December and the thickness of 50 cm on the first dates of January. As can be seen in Table 9, the duration of the operation period at the adopted boundary conditions comprises more than half a year and exceeds on average by 58 days the ice-free period duration. It should be also mentioned here that iceberg towing (Kornishin et al, 2019) can be carried out in ice conditions with maximum ice thickness of 30 cm (Efimov et al, 2019). Also ridges formation in early ice can create additional ice hazards for offshore structures (Guzenko et al, 2019).

Table 9. – Increase of the operation period using the ice-resistant platform

Years	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Ice-free period duration, days	129	111	175	185	100	86	140	173	111	112
Period from the last close ice in spring to the thickness growth up to 50 cm in autumn, days	165	189	242	224	161	155	205	208	178	173
Increase of the operation period duration, days	36	78	66	39	61	69	65	35	67	61

CONCLUSION

The dates of water area ice clearance and the onset of ice formation over a significant area of the Southwestern Kara Sea are determined in many aspects by one and the same factor – severity of the preceding cold season, which is assessed by the sum of degree-days of frost.

The ice-free period duration is determined by the hydrometeorological factors for the preceding winter period (indicator — integral below zero air temperature) and in the summertime (indicators – date of area clearance from ice, air temperature, sea heat content). For each of the structures, the linear regression dependence between the number of degree-days of frost and duration of the operation period can be constructed.

During planning of prospecting-exploration drilling by the ice-resistant platform the main parameters are the date of mobilization of the drilling rig to the Kara Gate Strait and the ice-free period duration in the area of the geological structures.

Drilling using the ice-resistant platform makes it possible to extend the operation period, as drilling can start after the disappearance of close ice and end after the ice thickness growth to 30 or 50 cm.

Application of the ice-resistant platform allows one to extend the drilling season in the area of the East-Prinovozemelsky license blocks and practically guarantee drilling of two wells over a season, and for about two months the work will be carried out under the ice conditions.

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