2.4. Characteristics of the Kara Sea ice conditions

2.4.1. Physic-geographical sea characteristics

Borders, depths. The Kara Sea is a marginal sea of the Arctic Ocean, which has borders with the Arctic basin in the north, in the west – with the Barents Sea, in the east – with the Laptev Sea. Coast line is indented, with large gulfs (Baidaratskaya, Obskaya, Gidanskaya Bays, Gulf of Enisey), deeply run into continent shore (Fig. 2.4.1).

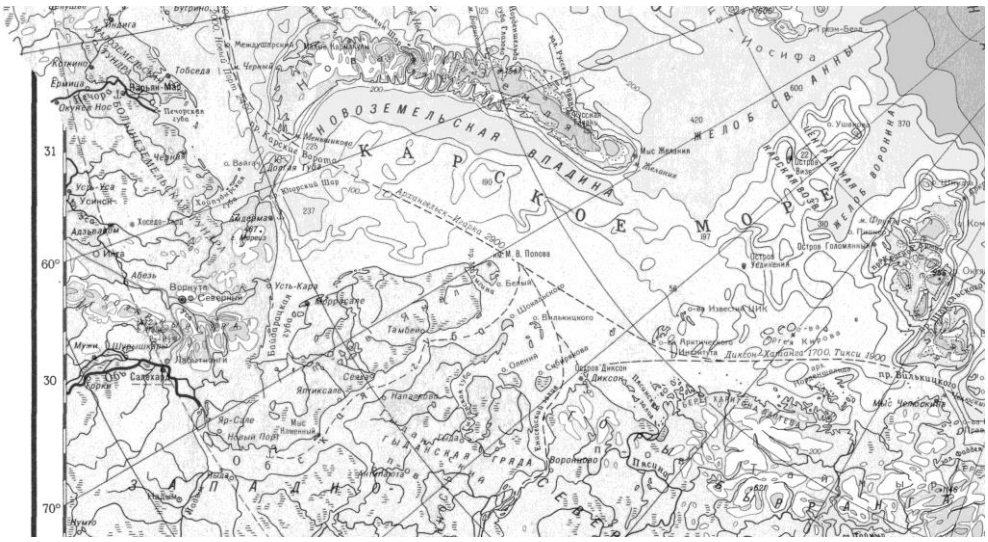

Fig. 2.4.1 – Geographical location of the Kara Sea

The Kara Sea is divided into two parts: south-western and north-eastern. Conventional border between them is on the line of Cape Zhelaniya – Dixon Island (Fig. 2.4.2). Such division into zones is provided taking into account geographical location, hydro meteorological and ice conditions, which are more severe in north-eastern area.

Main morphometric characteristics of the Kara Sea:

- Total area – 830 000 km^2
- North-eastern part area – 495 000 km^2;
- South-western part area – 335 000 km^2
- Average depth: 111 m; the largest depth - 600 m.

Deep water parts of the Kara Sea (with depth more that 500 m) occupy more than 1% of the total ground.

Climate. The Kara Sea is located northwards of the Polar circle and is situated under influence of the Arctic basin and Asian continent from the south.

From September-October the Kara Sea is under influence of narrow of Icelandic depression and Asian anticyclone. During this period southern winds dominate over the sea.

In April reconstruction of baric field occurs. The narrow of Icelandic depression decreases,

above Asian continent extensive depression is established. In summer period northern winds dominate over the sea.

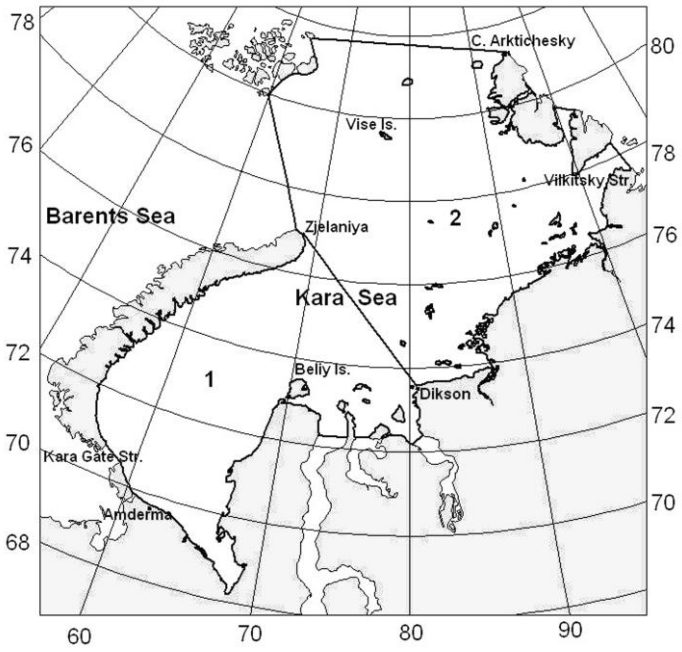

Fig. 2.4.2 – The Kara Sea division into zones: 1 – south-western and 2 – north-eastern regions

Significant sea length and peculiarities of atmosphere circulation cause differences in thermal regime. Average annual temperature above the south-western sea part is 6-7° higher, than above the north-eastern. In January air temperature in the south-western part of the sea changes from -17 to–20°C, and in the north-eastern – from –28 to –30°C.

From April to March air temperature starts to increase. In July air temperature above sea is positive everywhere: above south-western part it is 4–6°C, above north-eastern - 0–2°C. At the same time in the Ob'-Yenisey district it can reach 6–12°C.

Warm period duration lasts from 50 days in northern sea parts to 120 days near southern coast.

Wind currents with unstable directions and changeable velocity dominate in shallow areas of the Kara Sea. Gradient and tidal currents in general are weak.

More or less stable water flows are typical for summer period. In the south-western part they form cyclonic circulation from relatively warm Yamal current, moving from Kara Gate Straight to the north-east, and relatively to cool Eastern-Novozemelsky current, moving to the south along the eastern coast of Novaya Zemlya (Fig. 2.4.3).

2.4.2. Characteristic of sea ice cover in period of its growth

The most part of year the Kara Sea is covered with compact ice. In the south-western sea part ice is observed during 7-8 months, from November to June-July. The north-eastern sea part in summer period isn't absolutely ice-free.

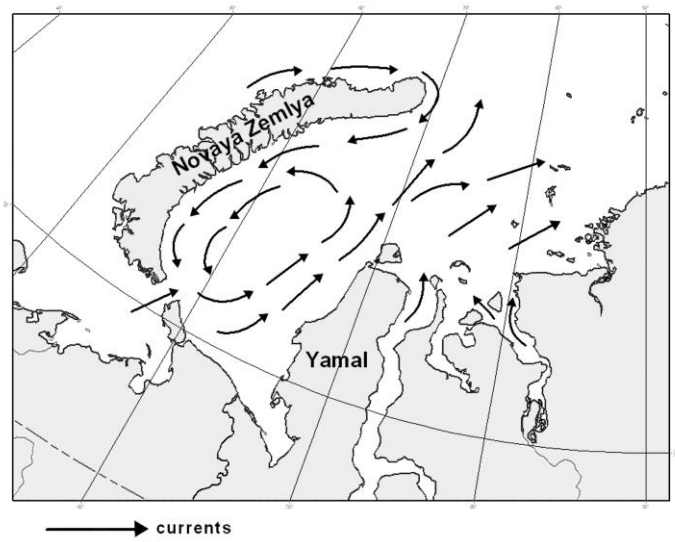

Fig. 2.4.3 – Scheme of quasi constant currents in the south-western Kara Sea

Ice formation. Ice formation in the Kara Sea starts in late August – early September on northern sea boundary, often among ice, survived after summer melting. In late September ice formation propagates to the most areas of the north-eastern sea part. Ice formation processes at the same time occupy large water areas, and in first decade of October new ice is observed in the whole north-eastern sea part (Fig. 2.4.4).

During October and first half of November "wave" of ice formation propagates to most part of coastal and open regions of the south-western sea part (Yamal and Novozemelskiy coasts, Baidaratskaya Bay), and on 20^{th} -25^{th} of November new ice appear in Kara Gate Straight (Fig. 2.4.4).

Thus on average, sea completely freezes up during two months and 20 days. At that, half of this period falls on the south-western sea part which area is 1,5 times less. It can be a result of summer warming of water in this area, and inflow of warmer water from the Barents Sea through Kara Gate Straight. In accordance with this isochrones of average terms of stable ice formation form arches, stretching to the north (Fig. 2.4.4).

Ice growth. Ice thickness increase takes place at the same time as ice formation processes develops in the sea. In the middle of September only 17% of the north-eastern sea region is free from ice, 60% of its area is covered with young (to 30 cm), 15% – with thin first-year ice (30-70 cm). Medium first-year ice (70-120 cm) forms in its northern part. At the same time young ice appears only on 40% of the south-western sea region, on the rest part ice formation hasn't started yet (Table 2.4.1). In the end of ice growth period, in May, most part of the Sea is covered with thick first-year ice (thickness more than 120 cm). 80% of this ice is located in north-eastern sea region and 60% – in northern parts of south-western region. Medium first-year ice (70-120 cm) covers southern parts of the south-western sea region (Fig.2. 4.5).

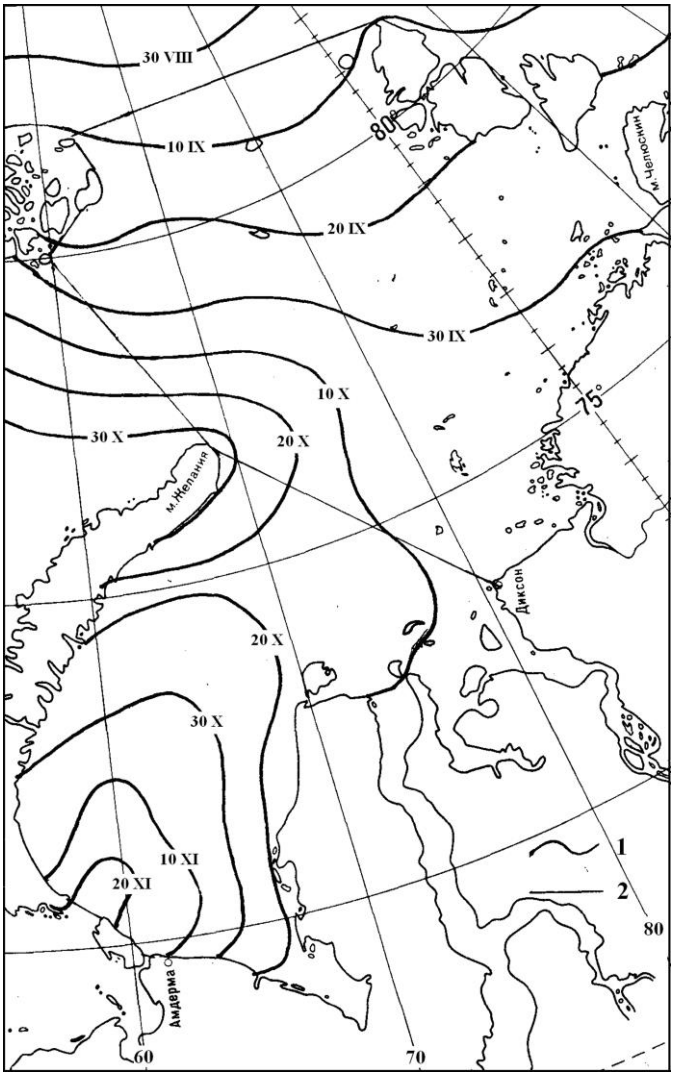

Fig. 2.4.4 – Isochrones of average terms of stable ice formation in the Kara Sea

Table 2.4.1 – Composition of ice age in the Kara Sea regions in autumn-winter period, %

Sea regions	Ice age																	
	No ice			Young			Thin first-year			Medium first-year			Thick first-year			Second-year, multiyear		
	Months																	
	X	II	V	X	II	V	X	II	V	X	II	V	X	II	V	X	II	V
South-western	60	0	0	40	12	15	0	35	3	0	53	20	0	0	62	0	0	0
North-eastern	17	0	0	60	2	6	15	10	5	8	20	5	0	65	81	6	3	3

Drifting ice is presented by ice objects of different linear sizes from ice cake to floes. In straights and coastal zones behind fast ice, ice is presented by small forms, medium floes and broken ice. In sea zones floes and medium floes prevail. Ice thickness in zones of thick first-year

ice is 1.4-1.8 m (Table 2.4.2). In the half of the sea area (as a result of drift) ice is hummocked, and hummocking increases to the end of ice cover growth period (April-May).

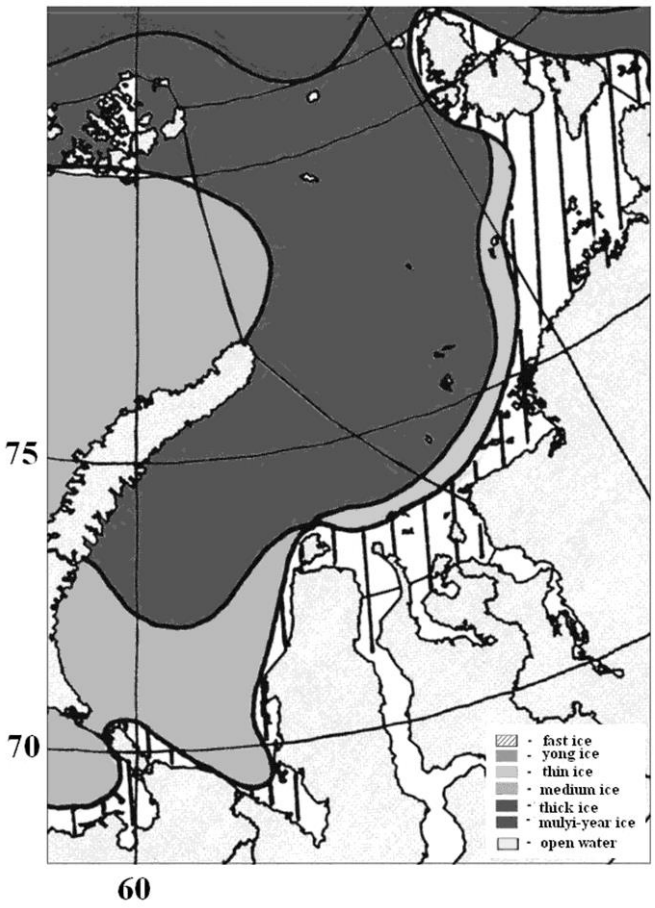

Fig 2.4.5 – Average distribution of different ice types in the Kara Sea in the end of sea ice growth period

Table 2.4.2 – Characteristics of drifting ice in the Kara Sea regions

Characteristic	Average values	
	South-western	North-eastern
Length of ice floes, m	3000-6000	4000-6000
Thickness of ice floes, m	1.4-1.6	1.6-1.8
Hummocking, marks	2-3	3
Month with the most hummocking	April-May	April-May
Average sail of hummocks, m	1.3-1.5	1.5-1.8
Maximum sail of hummocks, m	4.0-6.0	5.0-6.0

Drift and ice cover motion in autumn-winter period lead to interaction between ice floes and to occurrence of cracks and fractures in ice cover, or to ice compacting. Ice compacting leads to formation of hummocks and grounded hummocks (near fast ice zone).

In winter period ice outflow from the Kara Sea to the Arctic basin through its northern boundary and to the Barents Sea through Kara Gate Straight, prevails. During winter half-year (from October to March) more than 138 000 km^2 of ice cover is transported from the Kara Sea to

the north, and in summer half-year (from April to September) on average 24 000 km^2 of ice comes from the Arctic basin. Thus, about 115 000 km^2 of ice is transported to the north from the sea during the year, which is about 14% from total sea area or 23% from area of its north-eastern part.

Fast ice. When young ice reaches thickness of 10-30 cm fast ice is formed along continental and island coasts. In period of its maximum development boundary of fast ice is located along 10-20 m isobath.

Fast ice development in the Kara Sea can occur in the period from late September in its northern part to late January near Amderma Coast and Vaigach Island. According to satellite observation data variability of multiyear terms of fast ice development in the Kara Sea region varies is from 4 to 8 weeks. Average date of fast ice development in most sea part is less reliable (Table 2.4.3).

Estimation of probable terms of fast ice development is more reliable. With probability of about 70% fast ice development occurs in period of second-third decades of October in western approach to Vilkitsky Straight and along southern coast of north-eastern sea region (Table 2.4.3). Terms of fast ice development are less variable in desalinated waters of Ob'-Yenisey region. In more than 80% of cases fast ice is formed here in third decade of October – first decade of November

Table 2.4.3 – Probability of stable fast ice formation terms in the Kara Sea regions from the satellite data for the period 1980-2005, %

Regions	Months												
	IX	X			XI			XII			I		
	Decades												
	3	1	2	3	1	2	3	1	2	3	1	2	3
Severnaya Zemlya	33	17	12	28	11	–	–	–	–	–	–	–	–
Approaches to Vilkitskiy Straight	–	–	24	44	22	10	–	–	–	–	–	–	–
Piasinskiy gulf – Nordenskjold Islands	–	9	26	41	14	5	4	–	–	–	–	–	–
Ob-Enisey	–		8	53	31	4	4	–	–	–	–	–	–
Yamal coast	–		4	16	28	29	23	–	–	–	–	–	–
Amderma coast	–	–	–	–	–	4	26	10	8	20	16	10	6

The closer to Kara Gate, the more stretched is the period of probable fast ice formation. Thus, fast ice formation along Yamal coast is equiprobable in any decade of December. 80% of fast ice formation cases are in this month. (Table 2.4.3).

The largest variability in terms of fast ice formation is observed near Amderma coast and Vaigach Island, where it reaches 8 weeks: from the middle of November to late January. Fast ice here can be formed here in any of 8 weeks.

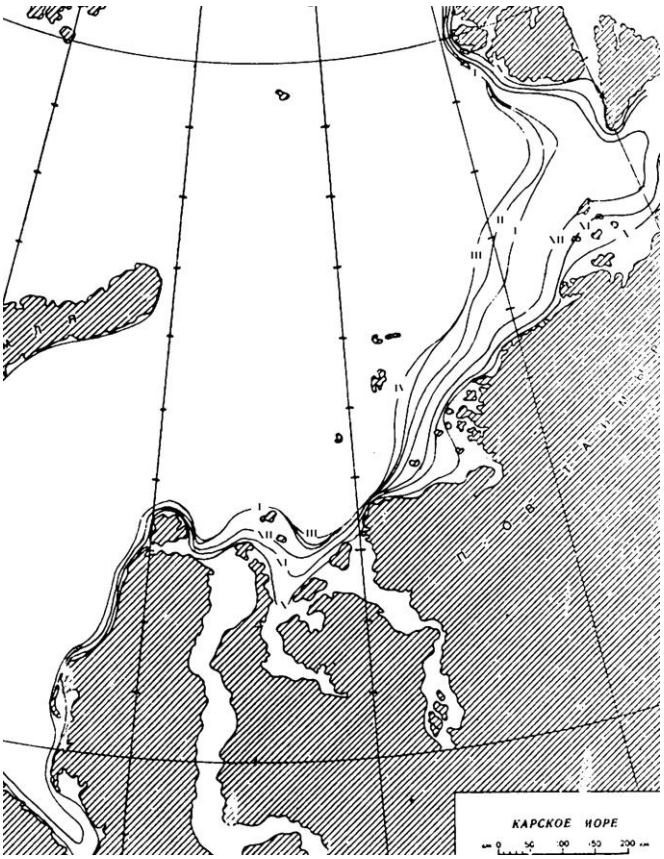

Fig. 2.4.6 – Average location of fast ice boundaries in the Kara Sea in period of ice growth from satellite data for the period 1980-2005

Development of fast ice intensively occurs till January, then its boundary slowly moves to open sea and is established in March - early April (Fig. 2.4.6).

As it can be seen from Fig. 2.4.6, the largest area of fast ice is in the north-eastern sea region. Fast ice develops in shallow southern and eastern parts, involves all groups of islands and comes along entire coast of Severnaya Zemlya archipelago. On average fast ice here occupies 26% of the area (with multiyear range 9-33%). Fast ice width to north-west from Taimyr coast can reach 250 km.

Fast ice area in the south-western sea part on average is 14% (with range10-26%). Its most development is in the Ob-Yenisey region and in Baidaratskaya Bay. Near coast of Yamal peninsula its width doesn't exceed 20 km, near Amderma coast – 5 км. Ice Thickness of fast ice in south-western part reaches 1,6 m, in north-eastern part – 1,8–2,0 m.

Increasing of fast ice area in the Kara Sea is during 7-8 months from October to late May – early April. During April-May fast ice area is getting stable, its gradual melting starts in May (Fig. 2.4.7).

Fast ice in the Kara Sea consists mostly of first-year ice of autumn formation. In fast ice near Severnaya Zemlya archipelago inserting of second-year or multiyear ice formed here from ice,

survived last summer melting, is possible.

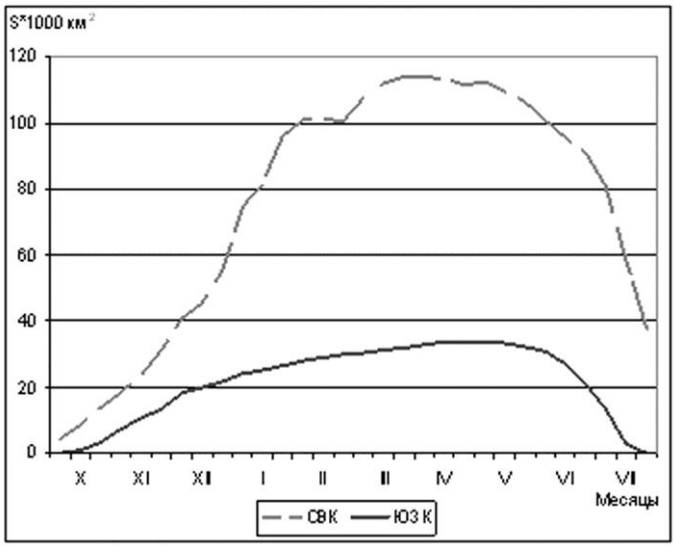

Fig. 2.4.7 – Seasonal changes of fast ice area in the north-eastern (NE) and south-western (SW) Kara Sea

Flaw polynyas. Flaw polynyas are formed behind fast ice during whole winter period. Flaw polynyas are areas with open water and young ice with thickness up to 30 cm. Their formation depends on direction of winds and their stability.

Frequency of occurrence of polynyas behind fast ice of Novaya Zemlya Islands is about 50%. Stable polynyas (with frequency of occurrence about 75%) are observed behind fast ice of Amderma and Yamal coasts, in Ob'-Enisey region and behind fast ice in the north-eastern sea region (Fig. 2.4.8).

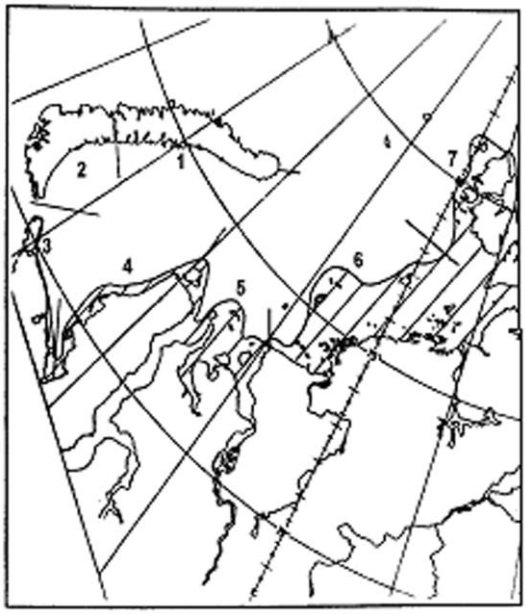

Fig. 2.4.8 – Areas of flaw polynya formation in the Kara Sea. 1-Northern Novozemelskaya; 2-Southern Novozemelskaya; 3-Amderminskaya; 4-Yamalskaya; 5-Ob'-Yeniseyskaya; 6-Central Kara;7-Western Severozemelskaya.

Total average length of polynyas is about 2000 km, maximum more than 4000 km (Table 4). If all polynyas of the Kara Sea occur at the same time, their average area will be about 9% of the

Kara Sea area.

Table 2.4.4 – Average frequency of occurrence (P, %) and size of the Kara Sea flaw polynyas in October-June from satellite data for the period 1980-2008.

№	Polynya name	P, %	Characteristic					
			Length, km		Width, km		Area, km^2	
			average	range	average	range	average	range
1	Northern Novozemelskaya	59	341	50-630	28	2-110	10,0	0,5-66
2	Southern Novozemelskaya	58	271	60-350	42	2-160	10,4	0,5-45
3	Amderminskaya	73	287	40-470	32	2-127	10,5	0,4-58
4	Yamalskaya	76	420	80-670	28	2-137	12,3	0,6-70
5	Ob'-Eniseyskaya	88	281	50-560	44	2-190	12,9	0,4-65
6	Central Kara	80	479	50-920	36	2-138	20,9	1,0-144
7	Western Severozemelskaya	66	259	50-620	29	2-170	8,0	0,4-56

Polynyas are formed under influence of offshore (from fast ice boundaries) winds. Under western or eastern air flows above the south-western sea region polynyas, formed behind fast ice of Yamal and Novaya Zemlya coasts, react opposite. Under western flows frequency of occurrence of Novozemelskaya polynyas increases and that of Yamal polynyas decreases. Change of directions of air flows to opposite seems to be favorable for Yamal polynya development and unfavorable for polynyas on the opposite coast. It can be observed rather well from comparing average monthly frequency of occurrence of Southern Novozemelskaya and Yamal polynyas in Fig. 2.4.9: with increasing of Yamal polynya frequency of occurrence –frequency of occurrence of Southern Novozemelskaya polynya decreases and vice versa.

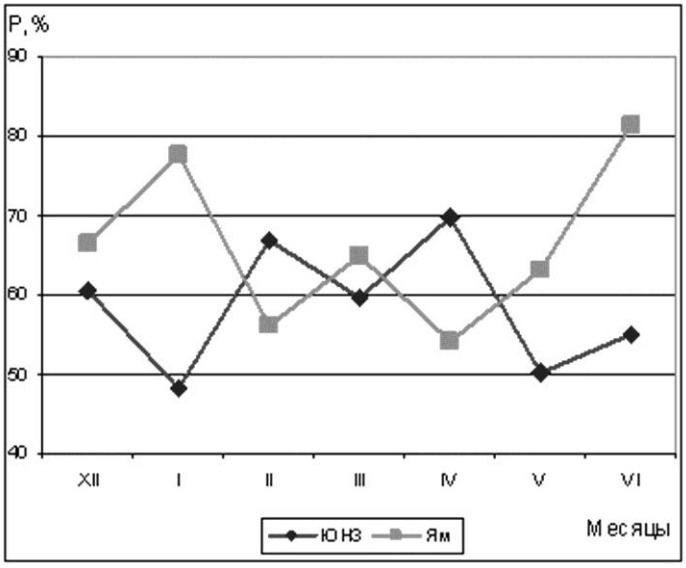

Fig. 2.4.9 – Average monthly frequency of occurrence of Southern Novozemelskaya and Yamalskaya polynyas

Finish of winter season, when ice cover becomes thicker, can be considered as time, when ice formation stops in polynyas, and from this moment polynyas become heat accumulators and areas of sea clearance from ice.

2.4.3. Characteristics of sea ice cover during its melting period

Melting and sea clearing from ice. Occurrence of puddles on ice is first feature of melting, which occurs normally when air temperature is –1,2º. Ice cover melting starts in the south-western Kara Sea in late May. As a result of thermal and dynamic effect in early June about 10% of the south-western region area is free from ice (Table 2.4.5).

Ice melting and clearing of the north-eastern sea part during whole summer season occurs slower, than in south-western sea part, and this area isn't absolutely clear from ice (Table 2.4.5).

Table 2.4.5 – Area of the Kara Sea ice-free regions in the melting period, %

Sea region	June			July			August			September		
	1	2	3	1	2	3	1	2	3	1	2	3
South-western	8	11	12	22	38	48	80	91	94	100	100	100
North-eastern	4	6	7	9	11	12	18	23	36	53	52	54

Velocity of cleaning from ice in south-western sea part increases in July. By this time ice cover is influenced by dynamic processes and melting, and as a result of this process - fast ice breaks up and changes into drift ice of different size.

Break up of fast ice. Fast ice starts melting the earliest in Amderma region, where in 80% of cases it completely melts during June. Mostly in the first half of July fast ice breaks up along Yamal coast and the Ob'-Enisey region (Table 2.4.6). Range of multiyear terms of absolute fast ice melting in Amderma and Yamal regions is about one month, in Ob'-Enisey region – two decades (Table 2.4.6).

Table 2.4.6 – Terms of ultimate fast ice melting in the south-western regions of the Kara Sea

Terms	Parts		
	Amderma	Yamal	Ob'-Enisey
Average	23.06	6.07	17.07
Early	8.06	18.06	8.07
Late	5.07	14.07	27.07

In the north-eastern sea part break up of fast ice starts on average in early June from the fast ice

edge side. Most area of fast ice breaks up during July and by end of month fast ice exists only in narrow coastal part between Minin skerry and southern part of Nordensheld archipelago and in straights of Severozemelskiy archipelago (Fig. 2.4.10).

Range of multiyear terms of absolute break up of fast ice is one month in north-eastern sea region (Table 2.4.7). Thus, if fast ice is formed during 7-8 months in sea, its complete melting will occur during 2 months.

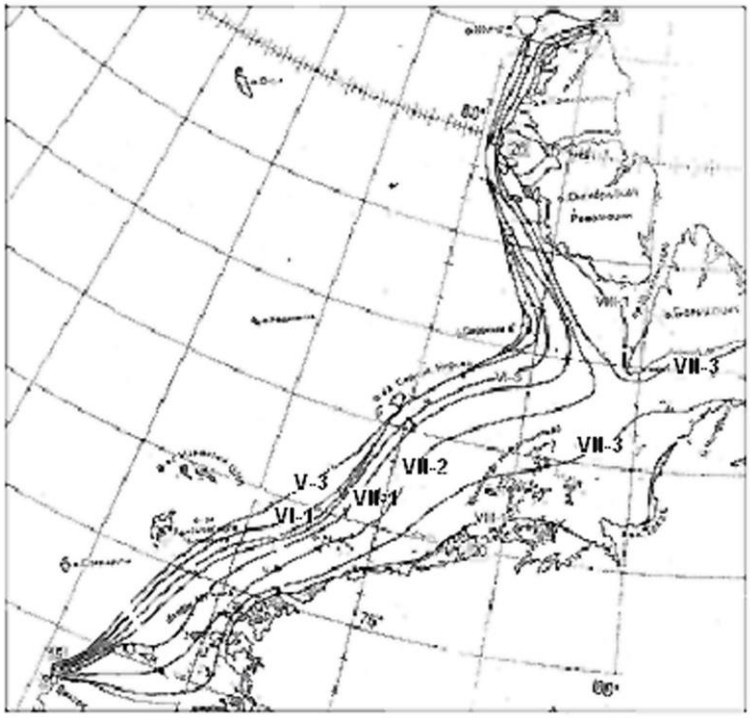

Fig. 2.4.10 – Isochrones of average terms of fast ice ultimate melting in the north-eastern Kara Sea

Table 2.4.7 –Terms of ultimate fast ice melting in the north-eastern regions of the Kara Sea

Terms	Date
Average	30.07
Early	15.07
Late	14.08

Ice distribution in melting period. In late July half of south-eastern sea part clears from ice under influence of thermal and dynamic process, and in this district only very open ice and open ice remain most often (Table 2.4.5). In late August – early September in 80% of cases this district is completely free from ice (Fig. 2.4.11).

Cleaning of south-western sea part starts from peninsula Yamal and distributes in western direction most often. Initial point of cleaning is Yamal flaw polynya.

Ice melting in north-eastern sea part occurs slower, and to the end of melting period (in September) about half of the region is still covered with ice, survived summer melting (Fig. 2.4.11).

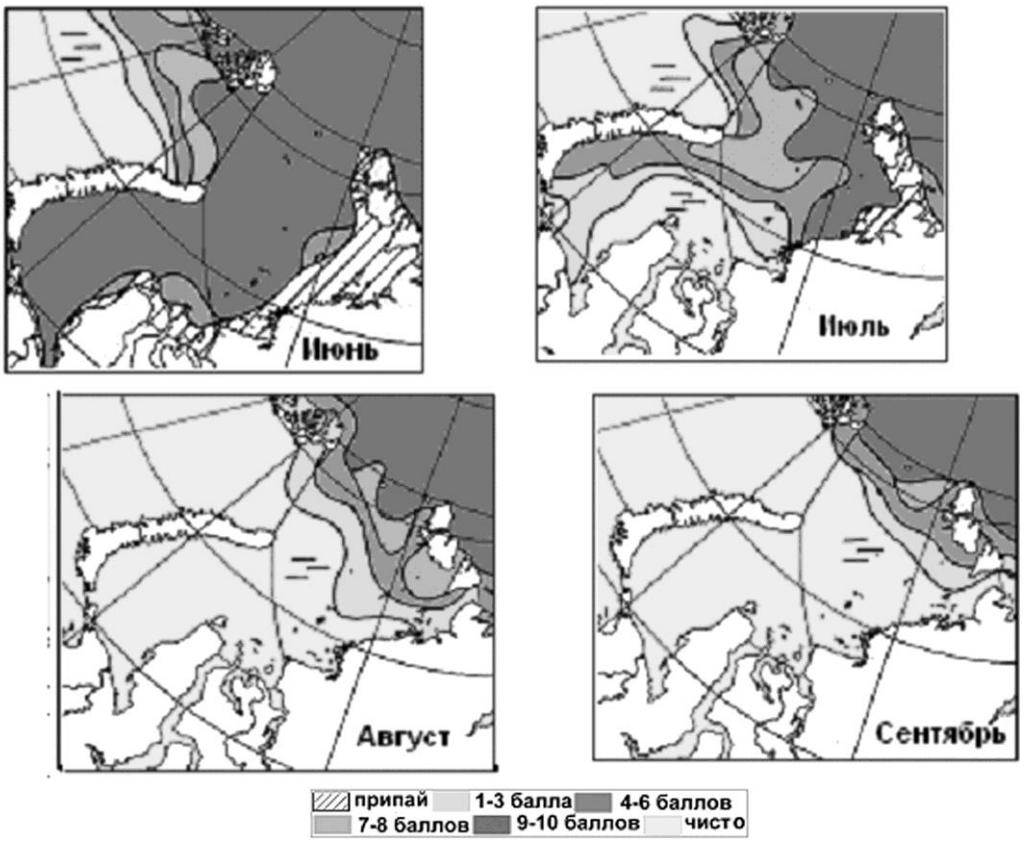

Fig. 2.4.11 – Ice distribution in the Kara Sea in June-September (with probability of 50%)

At the same time with melting of compact ice area of very open and open ice increases, and in late September their areas in north-eastern sea part are approximately equal (Fig. 2.4.12).

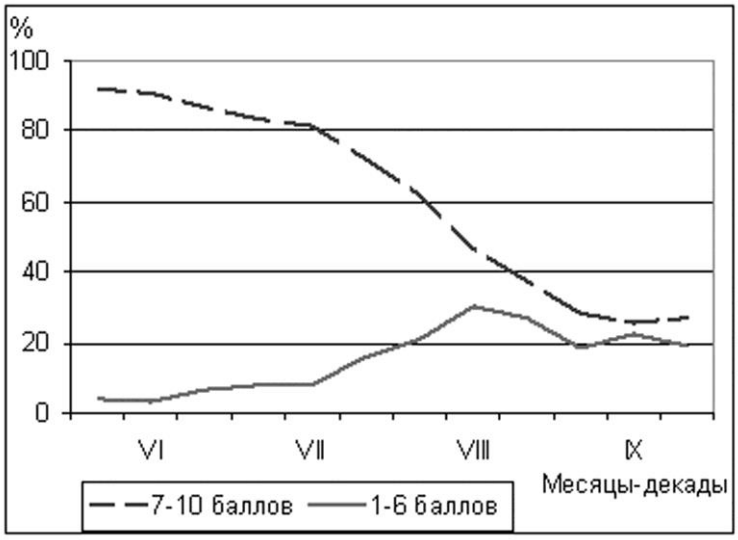

Fig. 2.4.12 – Changes of close (7-10/10-th), very open, and open (1-6/10-th) ice areas in the north-eastern Kara Sea in melting period, %

As it is seen from ice edge location in Fig. 2.4.13, sea cleaning is the most intensive in July and

August. In late August only about 60% of sea water area is ice-free, mainly due to south-western sea region. In September melting processes continue. During September 10-15% of sea is clear from ice as a result of melting and ice drift (Table 2.4.8). In northern sea regions ice formation starts at the same time.

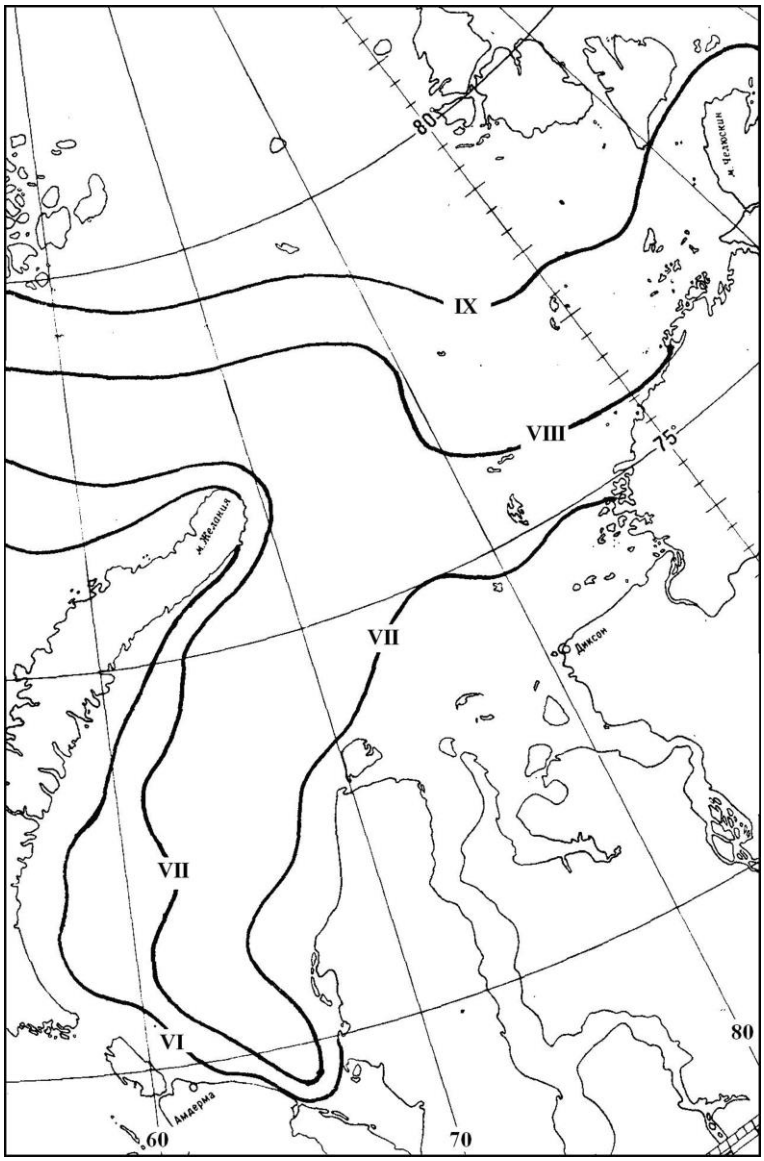

Fig. 2.4.13 – Location of ice edge in the Kara Sea in late June-September

Under average melting conditions by the end of summer melting period all age types of ice, except of thick first-year ice are melted. Its thickness can decrease to 20-40 cm. Ice melting in very compact ice cover (9-10/10) occurs slower, and in late September their thickness in north-eastern sea part is about 100 cm.

Table 2.4.8 –The Kara Sea ice-free areas in melting period, %

June			July			August			September		
1	2	3	1	2	3	1	2	3	1	2	3
6	8	9	14	22	26	43	50	59	72	71	73

Ice massifs. Compact sea ice (7-10/10) is localized into ice massifs in melting period:

Novozemelsky massif in the south-western sea part, and Severozemelsky and Northern Kara - in the north-eastern sea part (Fig. 2.4.14).

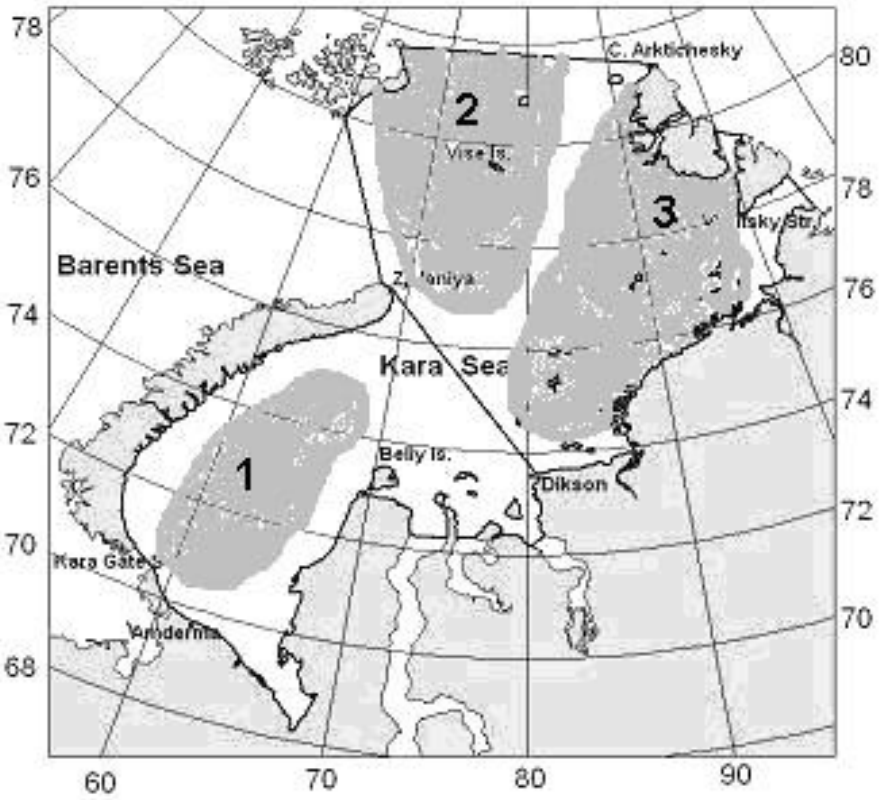

Fig. 2.4.14 – Scheme of ice massif location in the Kara Sea. 1 – Novozemelsky, 2 – Northern Kara, and 3 – Severozemelsky

Novozemelsky ice massif consists of first-year and young ice (in places of polynyas formation). In sea clearing period it can take central, western and eastern location. Western location is observed most often, when the massif is pressed to Novaya Zemlya and blocks Kara Gate Straight. In the middle of July massif occupies about 50% of the south-western Kara Sea area, and in August ice massif intensively melts and in the end of month in 80% of cases it disappears (Fig. 2.4.15).

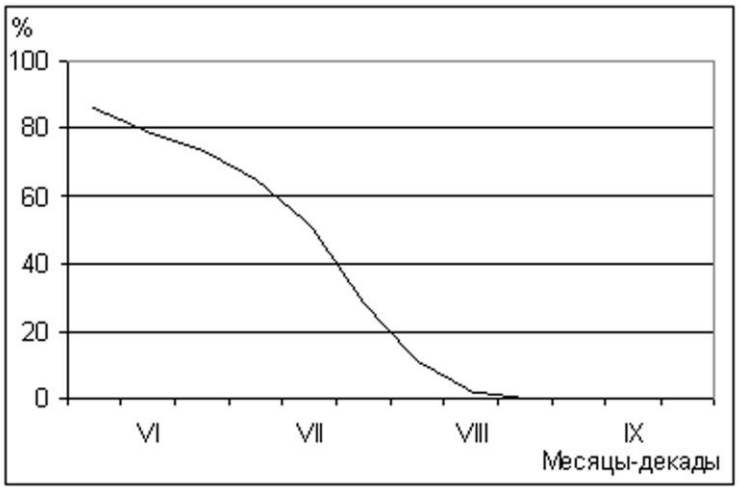

Fig. 2.4.15 – Change of the Novozemelsky ice massif area in melting period.

Severozemelsky ice massif is formed from local fast ice and is situated on navigable route between Dixon Island and Vilkitsky Straight.

Northern Kara ice massif is a branch of oceanic ice massif and occupies north-western sea parts. Mainly it consists from first-year ice, and only in northern part second-year and multiyear ice can be observed.

Division of compact ice of north-eastern sea part into two massifs occurs in the middle of August in most years. Northern Kara massif melts slower than other ice massifs, and up to 40% if its area don't melt in summer period. Severozemelsky ice massif blocks western approaches to Severnaya Zemlya archipelago and to Vilkitsky Straight most part of summer period, and on average up to 20-25% of massif is preserved in the beginning of ice formation (Fig. 2.4.16).

Fig. 2.4.16

Grounded hummocks. As a result of onshore ice drift in zone of fast ice, and its loading to fast ice in the depth up to 20 m grounded hummocks are formed (Fig. 2.4.17). Observed maximum values of geometry of grounded hummocks are – sail height 10-15 m, keel depth 20-25 m.

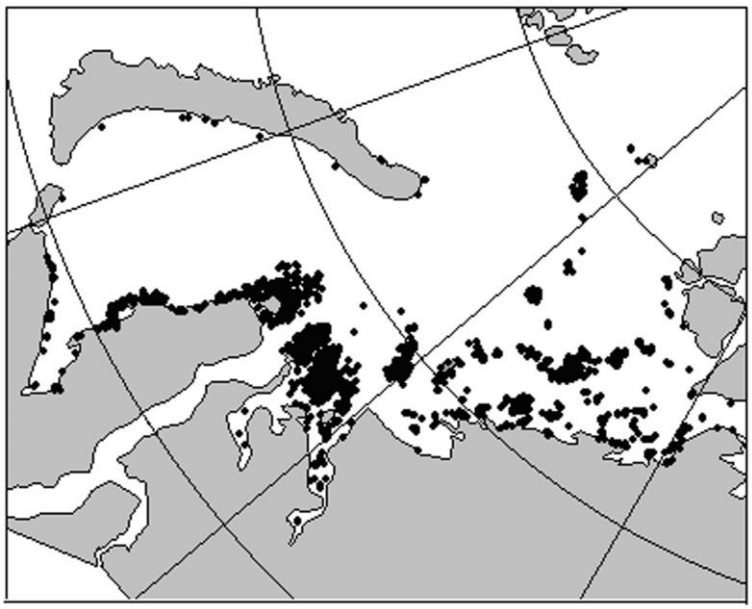

Fig. 2.4.17 – Zone of grounded hummocks formation in the Kara Sea according to data for 1962-1991

Icebergs. Icebergs are observed near north-eastern coast of Novaya Zemlya and western coast of Severnaya Zemlya archipelagos. In southern coastal parts icebergs are not observed.