2.8. Characteristics of ice conditions in the Beaufort Sea

2.8.1. General aspects

The Beaufort Sea is distinguished by the most severe ice conditions in entire Arctic. Sea is characterized by rather narrow shelf region. Sharp damp of depth occurs immediately after 100–meter isobath, which is located in 20-40 miles from coasts of Cape Barrow - Herschel Island and increases eastwards up to 60–65 miles north-eastwards from Cape Bathurst. Spur of oceanic multiyear ice massif (from Arctic pack ice) is located in the northern sea. This massif can be dangerous for navigation during most part of the year and in severe years doesn't move from coast. Sea ice drifts clockwise, being saved in this rotation for several years, and only part of it is transported to the west. The most favorable time for navigation is on average period from middle of August to middle of September. Earlier and later navigation can take high risks.

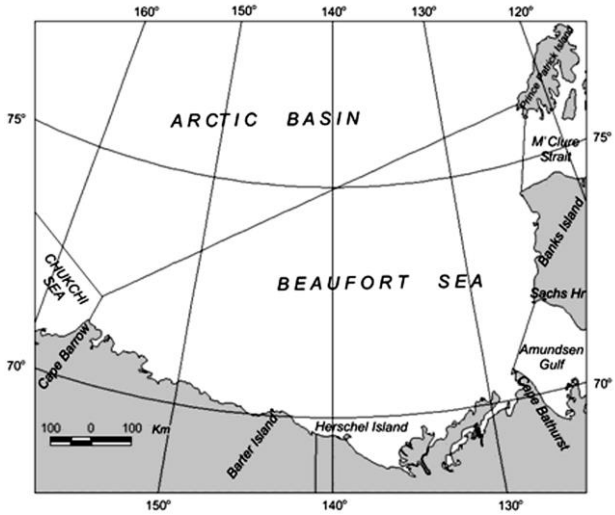

Fig. 2.8.1. The Beaufort Sea borders.

The Beaufort Sea has an open boundary with the Arctic basin in the north and with the Chukchi Sea in the west. In the east its boundary comes by capes and islands Prince Patrick and Banks coast and adjoins continent near Cape Bathurst. Southwards sea coast extends from Cape Bathurst in the east to Cape Barrow in the west (Fig. 2.8.1). Sea area is 480 000 км^2 in accepted sea boundaries.

2.8.2. Period of ice cover growth

2.8.2.1 Ice formation and young ice formation

The Beaufort Sea is covered with ice at least nine months a year. Sea freeze-up depends on propagation and location of southern multiyear ice boundary (polar pack ice) in late summer, because new ice formation occurs earlier in ice channels and fractures among multiyear ice of Arctic basin, and then propagates southwards.

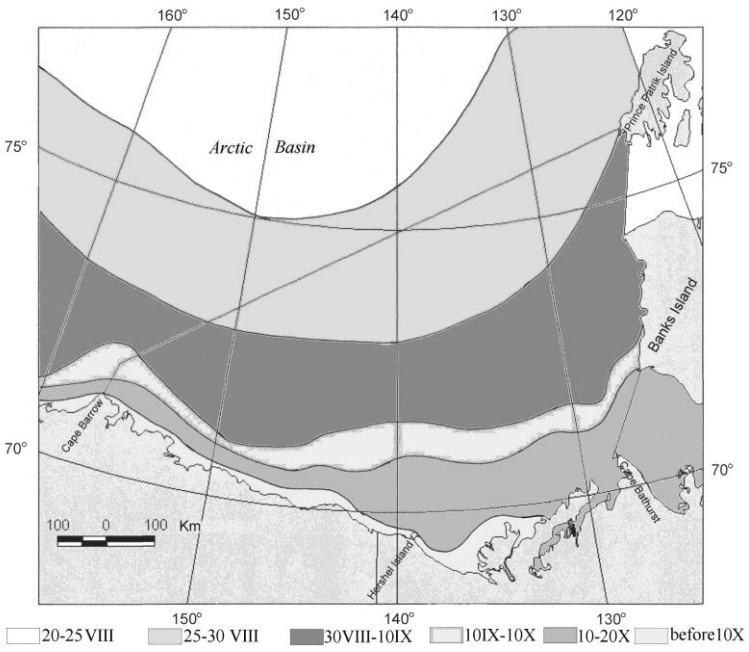

Fig. 2.8.2. Average terms of stable ice formation in the Beaufort Sea regions.

From data of Canadian ice atlas, processes of ice formation starts simultaneously in large zones, located in latitudinal direction (Fig. 2.8.2). In period of August, 20-25th initial ice appears in Arctic near northern sea boundary. During next five days ice formation propagates to the northern sea regions. By 10th of September young ice is formed in central sea region (Fig. 2.8.2). Then processes of ice formation are getting slower, and rather narrow zone with width about 30-40 miles freezes approximately by 10th of October. At the same time, coastal zone of the southern Beaufort Sea between Cape Barrow and Tuktoyaktyk Peninsula freezes up by 10th of October (Fig. 2.8.2).

Deep water area between multiyear (pack) ice massif and coastal zone freezes later – on 10–20th of October (Fig.2.8.2). Obviously, it can be explained by some heat storage in deep water sea region. In summer warm Bering waters are located along western and northern Alaska coasts, at the same time warmed up waters of Mackenzie river are propagated to the sea north-westwards and north-eastwards by two branches. Water heat storage is formed in deep water region under effect of advection and summer warming up, making slower processes of autumn water cooling in this region. In some years (1958) surface temperature of water in this region reached 5–9°.

In coastal shallow zones near Tuktoyaktyk Peninsula and further eastwards to Gulf of Amundsen ice formation normally starts in the second week of October.

Terms of stable freeze up change from year to year in coastal zones and in zones of drift ice, depending on amount of ice, survived summer melting, its location, water heat storage and terms of autumn cooling. From data before 1974, terms variability of stable freeze up changed within the

range of two months along coast between Capes Barrow and Bathurst (Table 2.8.1).

Table 2.8.1 – Terms of stable ice formation in coastal regions of the Beaufort Sea

Region	Terms of stable ice formation		
	Average	Early	Late
Cape Barrow	20 IX	3 IX	28 X
Barter Island	20 IX	3 IX	28 X
Mackenzie delta	1 X	3 IX	28 X
Cape Bathurst	1 X	3 IX	28 X

2.8.2.2 Propagation and formation of fast ice

Terms of formation and area of fast ice are determined by ice charts of National Ice Centre of the USA (USA NIC) for 1972–2004. Charts are located in Global Digital Sea Ice Data Bank (GDSIDB) by Navy project. According to this data fast ice formation in the Beaufort Sea most often occurs in October. In October 82%of all cases are observed, but at that 44% of cases are observed in the second ten-day period of October. However, there are some cases of early – in September, and late – in early November fast ice formation (Fig. 2.8.3). Early and late terms of fast ice formation are observed after heavy or soft ice conditions previous summer, respectively.

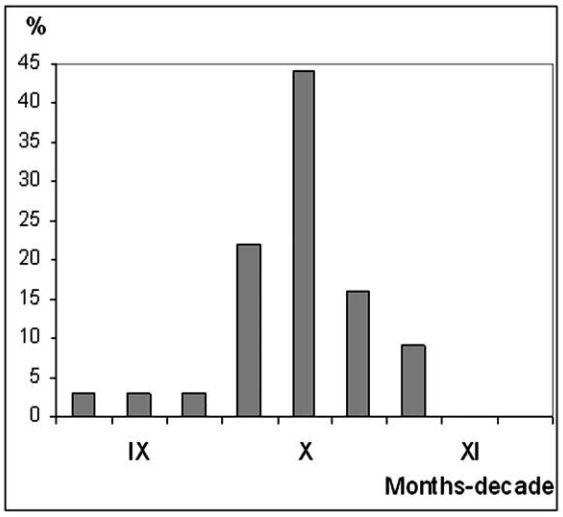

Fig. 2.8.3. Probability of terms of fast ice formation in the Beaufort Sea, %.

Fast ice is normally formed, at first, in zone of Cape Barrow – is. Barter, that occurs in middle of September, then it propagates to the western sea regions (Table 2.8.2).

Table 2.8.2 – Terms of fast ice development at stations of the Beaufort Sea

Station	Fast ice development		
	Average	Early	Late
Cape Barrow	14 X	27 IX	10 XI
m. Barter	16 X	27 IX	3 XI
Mackenzie delta	19 X	3 X	3 XI
Cape Bathurst	31 X	10 X	16 XI

As a result of data processing by USA NIC, data about fast ice area for every decade of its growth and melting for 1972–2004 was received. As it is seen from analyze, fast ice growth on average occurs before April, in severe winters – before May (Fig. 2.8.4). In moderate winters fast ice occupies about 15% of sea area, in severe winters – 25%. In mild winters fast ice area is less than 8% of sea area.

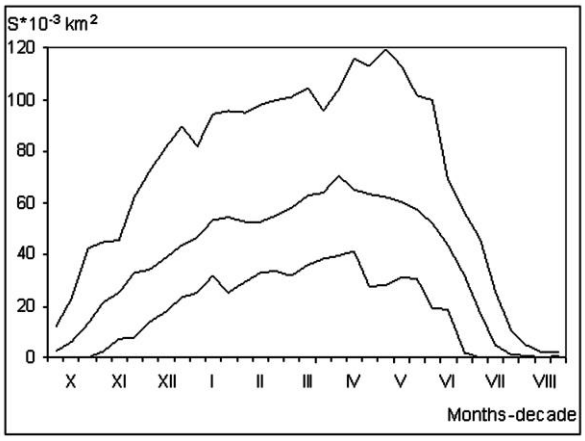

Fig. 2.8.4. Annual mean (curve in centre), maximum (upper curve) and minimum (lower curve) fast ice area (S) in the Beaufort Sea for 1972–2005.

Fast ice is rather level near coast, but it normally includes hummocks. Its amount increases closer to outer boundary.

Fast ice zone usually propagates to 50-60 km from coast within limits of 20-meter isobath. However, as it is seen from data of USA NIC, in 1972–2004 some years were marked, when fast ice width exceeded average value almost two times. It can be seen from Fig. 2.8.5, where probability of fast ice propagation in April is presented. As listed, in this month fast ice normally reaches its seasonal distribution maximum.

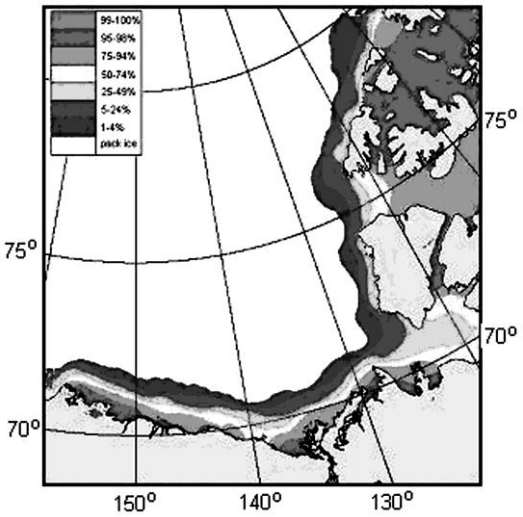

Fig. 2.8.5. Probability of fast ice propagation in the Beaufort Sea, %

Fast ice in the Beaufort Sea significantly differs from fast ice in other Arctic Seas. Its large part includes hummocks ridges, because anticyclonic ice rotation in the eastern Arctic basin and in the Beaufort Sea is mostly accompanied by northern winds, which press drift ice to fast ice zone between Capes Barrow and Parry. Offshore ice drift facilitates fast ice growth along coast line.

In coastal zone on depth up to 2 m fast ice freezes up to bottom. The other part is floating. Propagating from coast, fast ice is held by hummock ridges, settled on the ground on depth of 8–15 m. In late winter hummocks reach bottom on depth further than 20–meter isobath.

Ice rafting and ice piles on coast for distance from 20 to 50 m and sometimes to 100 m are observed during motion of fast ice. Hummocks are formed between fast ice zone and drift ice, settled on the ground on depth of 15–40 m.

Almost in all districts inclusions of multiyear ice are observed in fast ice, and in some years – pieces of small ice islands. During winter fast ice is quasistationary, but under activity of stormy winds, tidal phenomena and air temperature changes sporadic fast ice motion occurs. Near coast fast ice moves within limits of meters, but far from coast fast ice move off can approach tens of meters.

2.8.2.3. Fast ice growth

Thickness of first-year fast ice during winter period increases up to 2 m. On Fig. 2.8.6 seasonal course of fast ice growth in stations of the Beaufort Sea, located in the west (Cape Barrow), in centre of northern Alaska coast (Barter Island) and in the eastern region (Sachs Harbor). Data is referred to 1955–1967, when relatively cold climate was observed in Arctic.

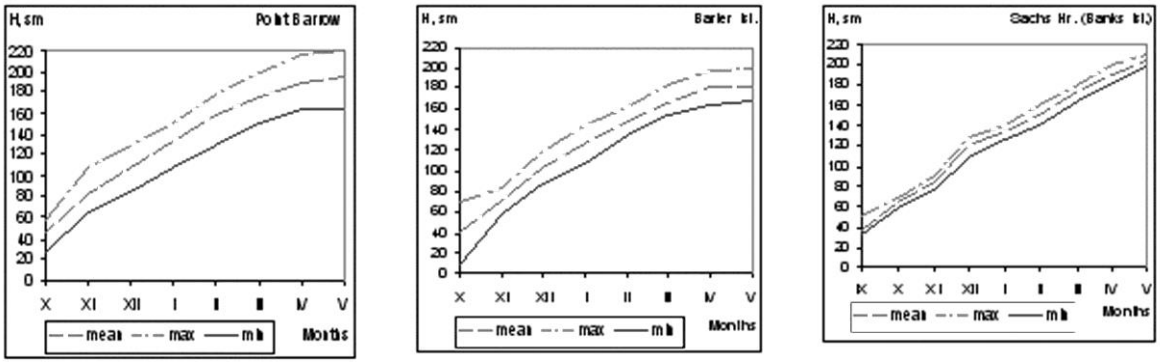

Fig. 2.8.6. Seasonal changes of average, maximum and minimum ice thickness at stations in the Beaufort Sea

As it is seen from Fig. 2.8.6, in coastal region level fast ice reaches age of thin first-year (30–70 cm) in October – early November, in December – medium first-year (70–120 см), and during January – March ice thickness increases to its maximum values - age of thick first-year ice (more than 120 cm). Multiyear range of fast ice thickness in end of its growth period near

Cape Barrow is 30 cm, then it decreases to 12 cm eastwards from Barter Island, and near Banks Island coast – up to 10 cm.

2.8.2.4. Flaw polynyas

In winter one constant polynya is formed in the Beaufort Sea - Cape Bathurst polynya. It is located between southern extremity of Banks Island and Cape Bathurst along western boundary of fast ice, blocking Gulf of Amundsen (Fig. 2.8.7).

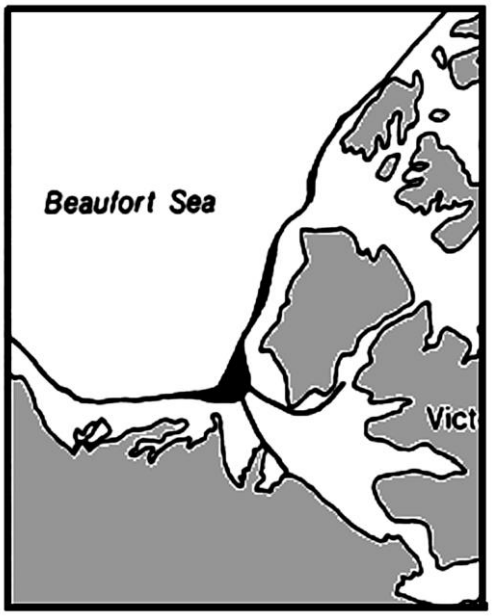

Fig. 2.8.7. Location of Cape Bathurst polynya

Polynya is supplied by eastern and north-eastern winds. When wind transits to western - it closes, but when western winds weaken, it opens again. Like other Arctic polynyas in spring it is a place of heat accumulation and sea clearing from ice. In spring (usually in May), when temperature increases and winds transit to southern, polynya gets wider northwards along Banks Island and further to Prince Patrick Island, and also westwards.

Polynya on bar of river Mackenzie is developed in June, when ice starts melting. In some years its development coincides with Cape Bathurst polynya development. The largest development is observed during their confluence, which is often observed in late June – early July. During intensive confluence, polynyas are finally connected with Chukchi lead polynya in July – August, which propagates from Bering Straight along western coast of Alaska and can move further to Cape Barrow.

In winter and spring local flaw polynyas and open zones episodically occur along entire fast ice boundary. Terms of occurrence of these polynyas are 5-7 days.

2.8.2.5. Drift ice

Typical macroscale propagation of ice cover is established after fast ice formation in the Beaufort Sea. Rather dynamic zone is located behind fast ice with prevailing first-year ice. It is "transition" zone, adjoining to region of less movable multiyear ice, which is called Arctic Pack in some Canadian sources (Arctic Pack). Average multiyear location of these zones is shown on Fig. 2.8.8.

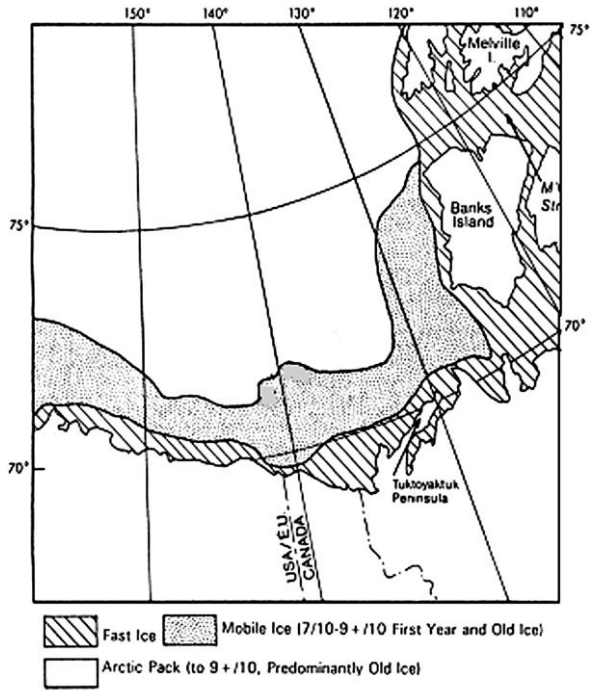

Fig. 2.8.8. Average ice propagation in winter in the Beaufort Sea

Multiyear ice in zone of Arctic pack reaches thickness of 450 cm, constantly moves with currents and winds in Arctic (mostly clockwise) and exists during the whole year (Fig. 2.8.9). Degree of its occurrence in the Beaufort Sea depends on wind regime during the year. On average Arctic pack boundary is located near Cape Prince Alfred (Banks Island), goes down to south-east, comes in 200 km from Hershel Island, then comes westwards in 200 km from northern coast of Alaska. Non-deformed multiyear ice with diameter about 500 m compose about 60% of this zone, some floes reach 10 km in diameter.

During winter sea ice drift is directed from east to west, according to Beaufort Gyre. However, when drift ice comes through eastern Arctic of cyclones and anticyclones, inclinations from general drift are observed. Interannual ice drift velocity is 1,4–4,8 km/day, diurnal speed changes within limits of 2,2–7,4 km/day, the highest speed, ever observed, was 32 km/day.

Ice in "transition" zone constantly moves. General drift direction in this part is - from east to west, similar to Arctic pack zone. Ice motion in zone is accompanied by ridging, channel formation and zones of open water, as a result of drift irregularity and short-term inclinations

from general direction of tidal phenomena.

The largest amount of ice in “transition” zone is observed in February – March. Ice thickness during its normal formation reaches its maximum in April – May, which is 0,9–2,0 m.

Multiyear ice can be observed among first-year ice. It is well defined by size and level hummock ridges. Multiyear ice exists in fast ice and in “transition’ zones. Probability of multiyear ice occurrence in fast ice can exceed 15% in middle of winter (January), in drift ice behind fast ice amount of multiyear ice sequentially increases northwards, to boundary of multiyear Arctic pack. Probability of occurrence increases up to 50% (Fig. 2.8.10).

Topography research and research of drift ice depth immersion were made using sonar along section with length 1135 km northwards from the Beaufort Sea coast during middle of May – middle of July in 1991. Immersion depth of drift ice on the cut was 3–6 m. Height of first-year ice above the water level was within 1,5–2 m, multiyear – 2,5–4,5 m. The largest depth of hummocks keel reached 30 m. Several keels approached 32 m.

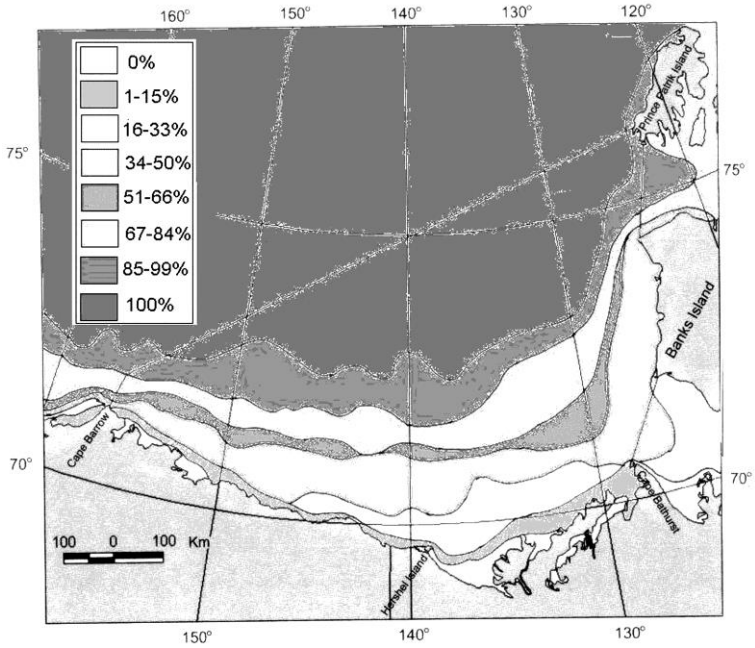

Fig. 2.8.10. Probability of multiyear ice occurrence in January from data for 1971–2000

2.8.3. Ice cover in melting period

2.8.3.1 Ice melting and sea clearing from ice

Ice melting in the Beaufort Sea starts in late May – early June. Formation of puddles on ice is the first feature of melting beginning. Puddles are formed under activity of radiation heat in day time before stable air temperature transition through 0º to positive values. According to Table 2.8.3, composed from data and taking into account average ice thickness at Barrow station, ice

melting pattern can be made (Fig. 2.8.6).

Table 2.8.3 – Changes of ice thickness at Cape Barrow in melting period

Time period	Melting value, cm	Ice thickness, cm
1st half of May	–	196
2nd half of May	2	194
1st half of June	3	191
2nd half of June	13	178
1st half of July	18	160
2nd half of July	21	139
1st half of August	24	115
2nd half of August	27	88

As it is seen from Table 2.8.3, intensity of ice melting increases from June to August. In August ice thickness decreases on value, which is total for both June and July, and approaches 51 cm. Just by early September ice thickness decreases on more than 100 cm. Consequently, by this time all young ice disappears in the southern sea part (up to 30 cm), thin first-year ice (30–70 cm) and medium first-year ice (70–120 cm), that has reached thickness of 100 cm.

Ice intensively melts in zones, where polynyas are formed, which in spring accumulate heat from solar radiation. It is polynya of Cape Bathurst - in the eastern sea region, formed behind fast ice northwards the delta of the river Mackenzie. In western part development of large polynya along western coast of Alaska (Chukchi lead) facilitates ice melting and sea clearing from ice in May – early June. Chukchi lead often approaches Cape Barrow and comes further eastwards. On the early stage of ice melting, in June, about 10% of sea area is free from ice.

2.8.3.2. Absolute melting of fast ice

Fast ice break up and decreasing of area partly occur in sea, when ice thickness and its strength decrease during melting. As it is seen from Fig. 2.8.4 (section 2.8.1.2), having reached its seasonal development maximum in April – early May, fast ice starts melting and on average in July disappears. If fast ice sequentially grew in sea during seven months, it would absolutely melt away – during 2,5 months.

According to results of data processing by USA NIC, the earliest terms of absolute fast ice break up occur in the first 10-day period of June, the latest – in the third 10-day period of July. About 80% of cases of absolute fast ice break up occur in July. At that, in the first 10-day period of July fast ice isn’t observed in 40% of cases, in the second – 30% and in the third – 10%. In 20% of cases fast ice disappears in June (Fig. 2.8.11).

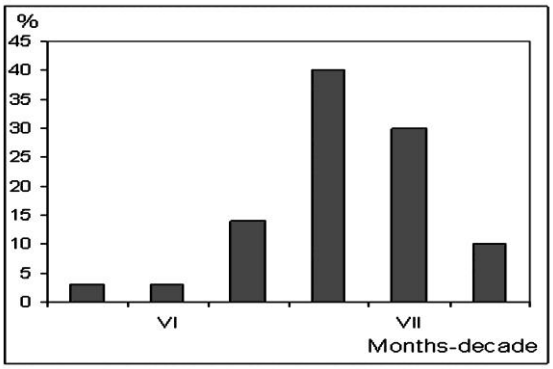

Fig. 2.8.11. Probability of terms of fast ice break up in the Beaufort Sea from data for 1972–2004

Long-term variability of terms of fast ice absolute melting is close to two months (Table 2.8.4).

Table 2.8.4 – Terms of fast ice break up in coastal regions of the Beaufort Sea

Regions	Date		
	Average	Early	Late
Point Barrow – Barter Island	7 VII	10 VI	27 VII
Barter Island – Cape Bathurst	8 VII	17 VI	22 VII

2.8.3.3 Sea ice in clearing period

Area of sea ice decreases on about 2% in late May, which is obviously connected with development of polynyas, where young ice hasn't already formed by this time. During June and July sea ice sequentially decreases on about 10% every month. Velocity of ice area reducing insignificantly increases in August – up to 14% and decreases in September to 7,5%. Sea ice area decreases for just about 40% during spring-summer period (Fig. 2.8.12). Ice, survived summer melting, can be observed in 60% of sea water area. Compact ice (7–10-th) composes its most part. This part occupies 40% of sea area, covered with ice, before autumn ice formation (Fig. 2.8.13).

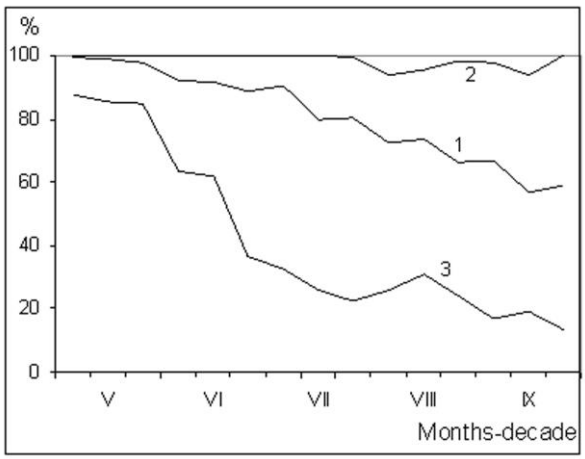

Fig. 2.8.12. Changes of average (1), maximum (2) and minimum (3) ice cover in the Beaufort Sea in spring-summer period, %

In years, unfavorable by hydro meteorological conditions, sea ice propagates to mostly entire sea water area, only about 6% is ice-free from late June to mid-September (Fig. 2.8.13). In contrary, in favorable years sea intensively clears from ice, and ice area reaches about 20% of sea area to late July. Ice melting slows down in August and September, and in late September it decreases up to 13% (Fig. 2.8.13).

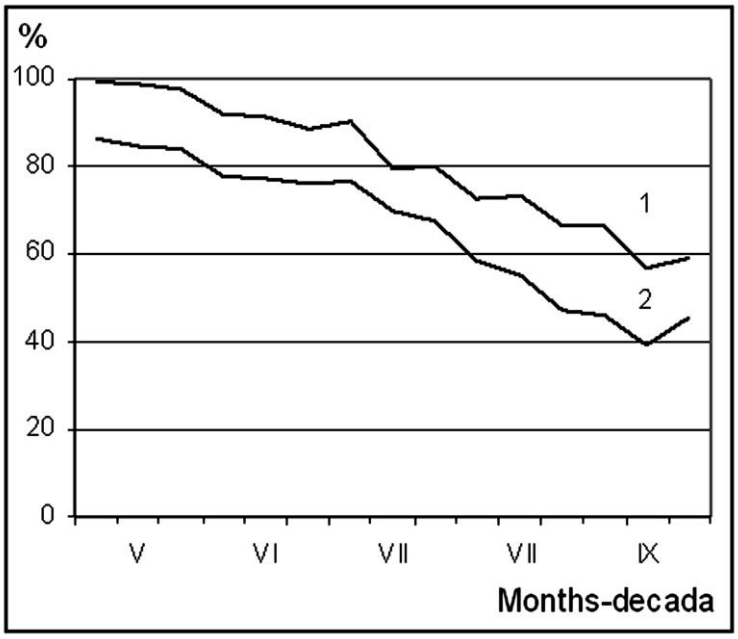

Fig. 2.8.13. Average seasonal changes of ice cover (1) and area of compact (2) ice in the Beaufort Sea

2.8.3.4 Compact ice

During the entire year compact ice dominates in the Beaufort Sea. In Russian (Soviet) science researches ice accumulation with large concentration and thickness within sea boundaries was called ice massif. Massifs have their own names, connected with their location. Ice massifs include ice with compactness 7–10-th. They are the main barrier for navigation in ice. Weather forecasts and location of ice massifs are the most essential data in navigation supplement on the NSR. In Canadian and American studies there isn't any concept of ice massifs, and massif of compact ice in the Beaufort Sea, being mostly a spur oceanic ice massif, doesn't have any name. However, in some Russian sources compact ice of the Beaufort Sea is called Alaska ice massif.

It is necessary to mention, that on average compact ice (7-10-th) doesn't occupy the entire sea area even in winter, compared to other Siberian Arctic shelf seas, due to constant ice motion and formation of polynyas and zones of open water. As seen from Fig. 2.8.14, on average during the whole year only about 12% of ice cover area is open floating ice. Its maximum amount is observed in early September (about 20%), minimum – in middle of November (about 5%).

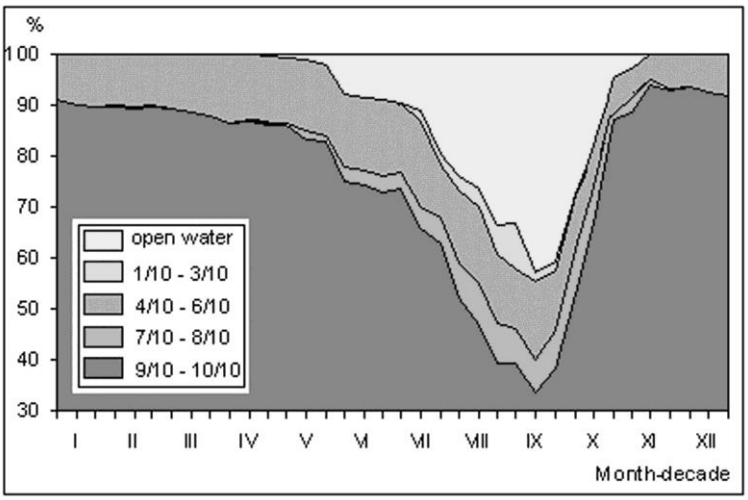

Fig. 2.8.14. Annual mean changes of area of different ice concentration in the Beaufort Sea, %

Before beginning of melting massif of compact ice in the Beaufort Sea includes ice of all age stages, from young ice (in polynyas and leads) to second-year and multiyear ice (Arctic pack in the northern sea regions), and ice on average occupies 86% of sea water area. During May – July its area decreases on 18%. Then velocity of compact ice melting increases, and in August its area decreases on 20% more. In September compact ice area is stable on the level of 40–45%. In late September new ice formation starts among compact ice, and its area sequentially increases (Fig. 2.8.15).

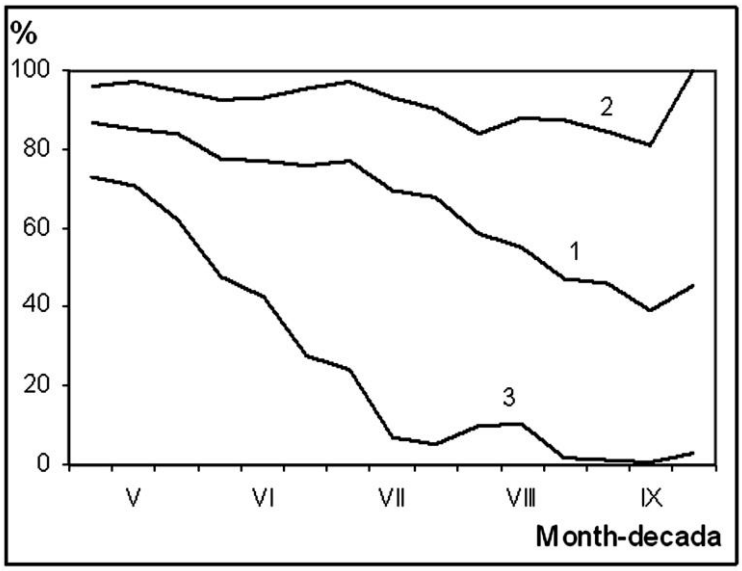

Fig. 2.8.156. Changes of average (1), maximum (2) and minimum (3) compact ice area in the Beaufort Sea (7/10–10/10) in spring-summer period, %

When compact ice melts and then transports out of sea limits, its boundary moves northwards. The most intensive sea clearing occurs in June in the south-eastern region, where Cape Bathurst polynya is developed in spring, which often joins with polynya on bar of the river Mackenzie (Fig.2.8.16). At the same time in zone of Cape Barrow – Barter Island boundary of compact ice locates in 10–15 miles from coast close to 20–meter isobath. In August velocity of

compact ice motion increases northwards. In zone of Cape Barrow – Hershel Island southern boundary is located far from coast (100–120 miles) (Fig. 2.8.16). In September compact ice insignificantly moves northwards, and in late month it moves down to coast.

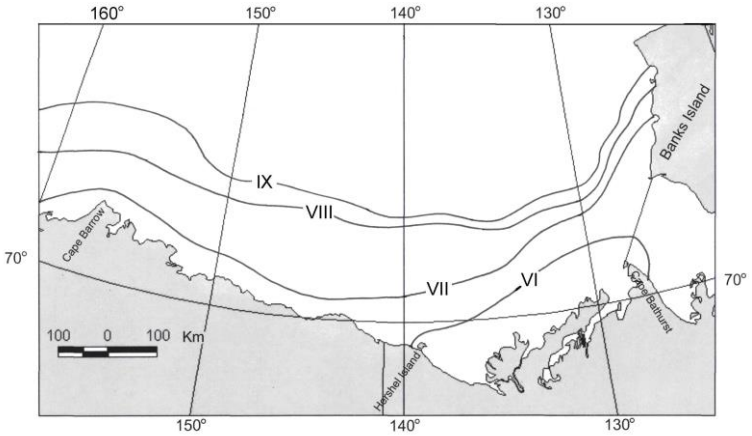

Fig. 2.8.16. Average location of compact ice boundaries (7/10–10/10) in the Beaufort Sea in June – in September from data for 1971–2000

In some years pack ice is transported into the Beaufort Sea water area in summer. Though summer boundary of pack ice normally locates 250 – 300 km from coast, strong winds (stormy) can bring it closer to coastal waters from a few days to a few weeks. Normally this ice includes thick first-year ice, second-year ice and multiyear ice. Concentration of transported ice usually increases during its transportation down to coast. Typical ice thickness of thick ice changes within 1–1,5 m, old ice floes – from 3 to 7 meters. These floes are covered with hummocks, which keels approach 10–20 m. Due to this circumstance, thick ice doesn't come to coast closer than 10-meter isobath.

2.8.3.5. Ice propagation and location of ice edge in June - September

The Beaufort Sea is partly free from ice, when flaw polynyas appear and develop (without ice formation in it), and zones of open water among drift ice also occur. Stable sea clearing starts, when fast ice breaks up and coastal zone clears from floes of broken fast ice. Location of ice edge in ice clearing period (June-September) is shown on Fig. 1.18. Sea clearing starts from delta of the river Mackenzie in the second 10-day period of June, when fast ice isn't absolutely broken, and propagates westwards to Hershel Island and eastwards to Cape Barhurst, then further (through Gulf of Amundsen) to Banks Island to late July (Fig. 2.8.17).

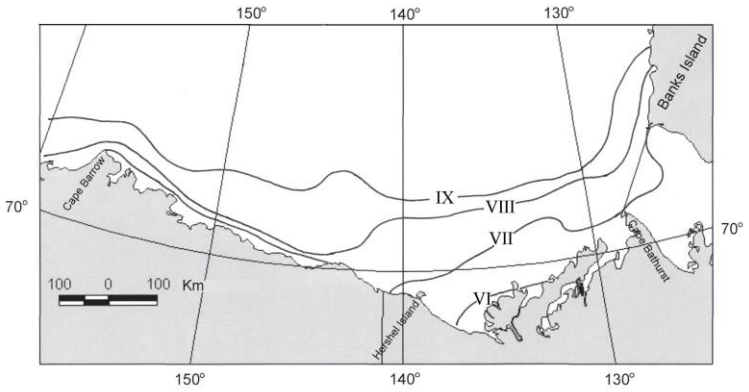

Fig.2.8.17. Average location of ice edge in the Beaufort Sea in June – September from data for 1971–2000

Sea clearing from ice occurs more intensive in August, especially in the south-western sea region. Along Alaska coast ice edge remains near coastal zone. Maximum sea clearing from ice is on average observed in September. At this time ice edge in central region goes up to 72° N, and it has maximum distance from Cape Barrow (35–40 miles).

Chart's fragments of average ice concentration in Canadian-American Arctic in late June – September are shown On Fig. 2.8.18.

According to chart compact ice prevails in sea during all summer months. It occupies 86% of area in June and about 70% in September. At that, area of open water in sea increases from 10% in June to 45% – in September (Fig. 2.8.19).

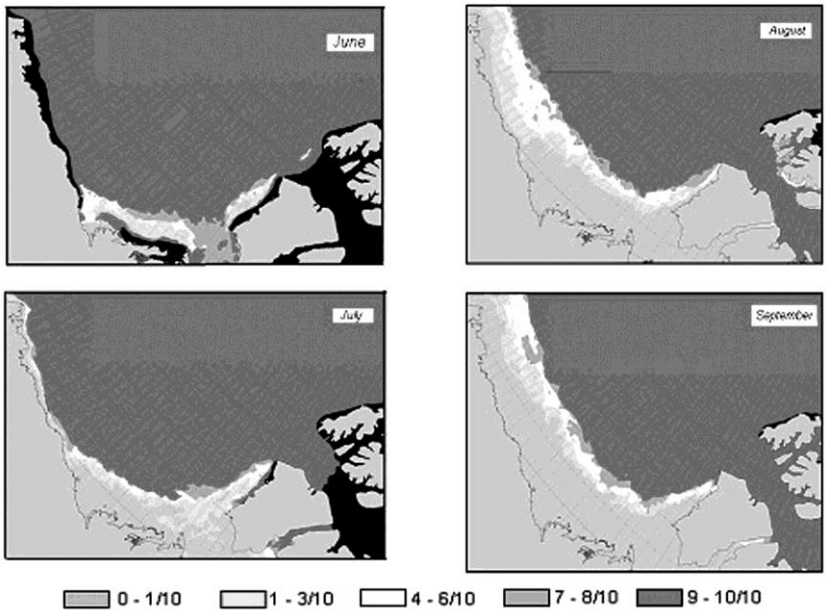

Fig. 2.8.18. Average ice propagation in the Beaufort Sea in late June – late September for 1971–2000

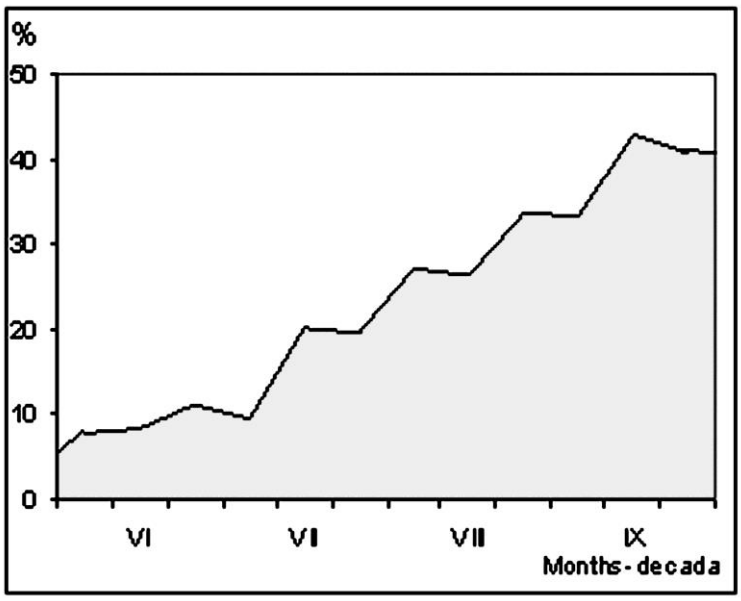

Fig. 2.8.19. Average multiyear changes of open water in the Beaufort Sea in June – September, %

Comparison of ice conditions in August 1998 and 1969 shows long-term variability of ice conditions in the Beaufort Sea (Fig. 2.8.20). In August 1998 the most favorable hydro meteorological conditions were observed in the sea during 1968–2007, and sea ice occupied only about 25% of area. In contrary, in summer 1969 solid compact ice occupied most part of the water area, and only rather narrow coastal part with very open floating ice and open water was ice-free.

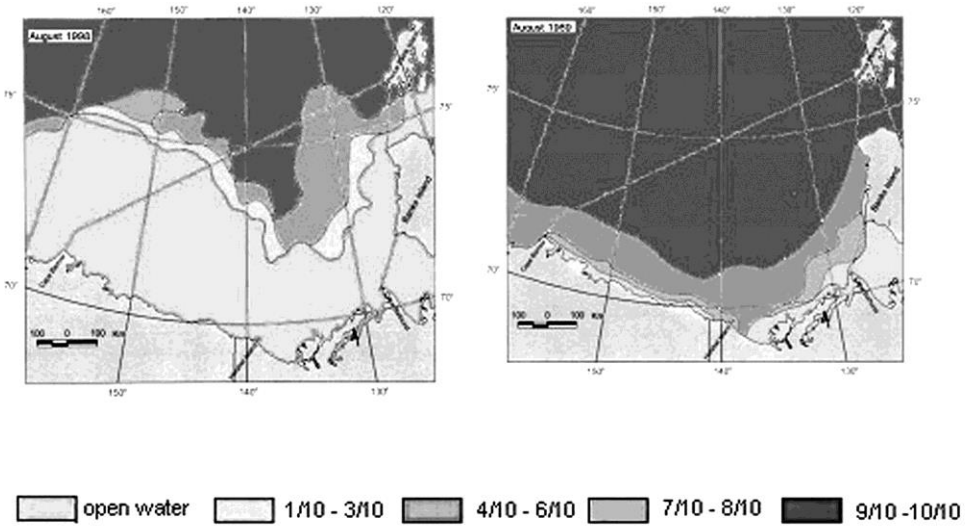

Fig. 2.8.20. Ice conditions in the Beaufort Sea in August 1998 and 1969

Charts on Fig. 2.8.20 are compiled according to archive data of weekly ice charts for navigation months of Canadian Ice service for 1967–2007.

2.8.3.6 Hummocks and grounded hummocks

Zones of grounded hummocks and ridging are located further in the Beaufort Sea. This is area of dynamic interaction between rather stable fast ice and drift ice zone. Ice rafting and formation of hummock ridges are observed along outer boundary of fast ice under activity of offshore wind. These ridges reach depth of 8-15 m, and sometimes 25 m, and plays role of sea anchors for fast ice, propagating to 20–meter isobath. Many fractures, polynyas and leads are formed in grounded hummocks area. Grounded hummocks are mostly settled on depth of 15-45 m, some of them remain during entire ice season.

Typical height of hummock ridges of drift ice in winter is 1,5–1,7 m, but sometimes ridges up to 6 m are observed. In case of ice rafting hummocks more than 30 m can be formed. Hummocks keels of multiyear ice floes with thickness 3–7 m, reach 20–25 m. Relation of above water hummock height to their keels is 1:4,5 for first-year ice and 1:3,3 for multiyear ice, respectively.

In 70s of last century study of hummocks was provided in the eastern Beaufort Sea using airplane profilometer. Obtained data (about 7000 of measurements) are summarized by squares of net region (Fig. 2.8.21).

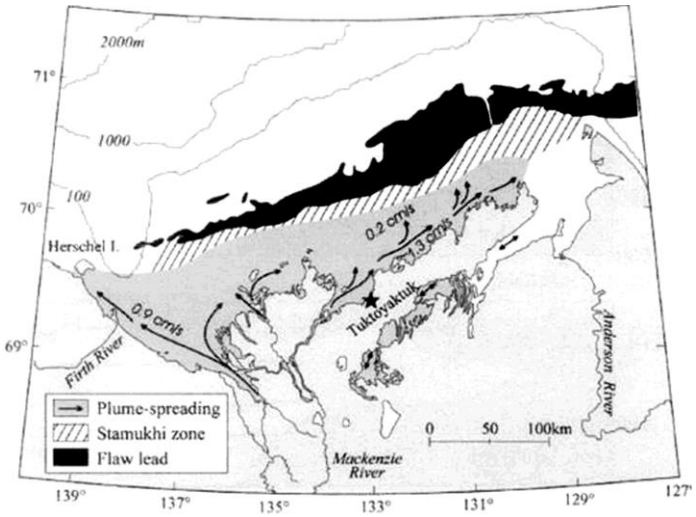

Fig. 2.8.21. Zone of hummocks height measurements in the eastern Beaufort Sea

This data, approximated for all regions, is presented in Table 2.8.5.

Table 2.8.5 – Frequency of occurrence of hummock height intervals in the eastern Beaufort Sea

Interval, m	1,0-1,5	1,6-2,0	2,1-2,5	2,6-3,0	3,1-3,5	3,6-4,0	4,1-5,0	5,1-6,0	6,1-7,0
Frequency of occurrence, %	67,5	20,1	6,6	2,5	1,7	0,9	0,4	0,2	0,1

As seen from Table 2.8.5, 70% of hummocks are mostly less than 1,5 m. In a few cases hummock height approaches 5–7 m.