2.9. Characteristic of ice conditions in the Central Arctic Basin

2.9.1. Ice drift in the Arctic Basin

In many respects variability of sea ice cover characteristics in the Arctic Basin is determined by ice circulation. The Figure 2.9.1. presents patterns of mean resulting ice drift in the Arctic Basin for the winter and summer periods of the year calculated by means of the corresponding approximation formulas. These patterns agree with earlier published qualitative patterns of general ice drift. They show the presence of the Transpolar Drift Stream (often termed "Transarctic ice flow" in Russian studies) directed to the Greenland Sea between the near-pole area and the northern margins of the Eurasian shelf seas. A large quantity of ice exported from the Russian Arctic Seas joins this flow on the left, while the anticyclonic gyre area with the center approximately at 78ºN, 150º E adjoins it on the right.

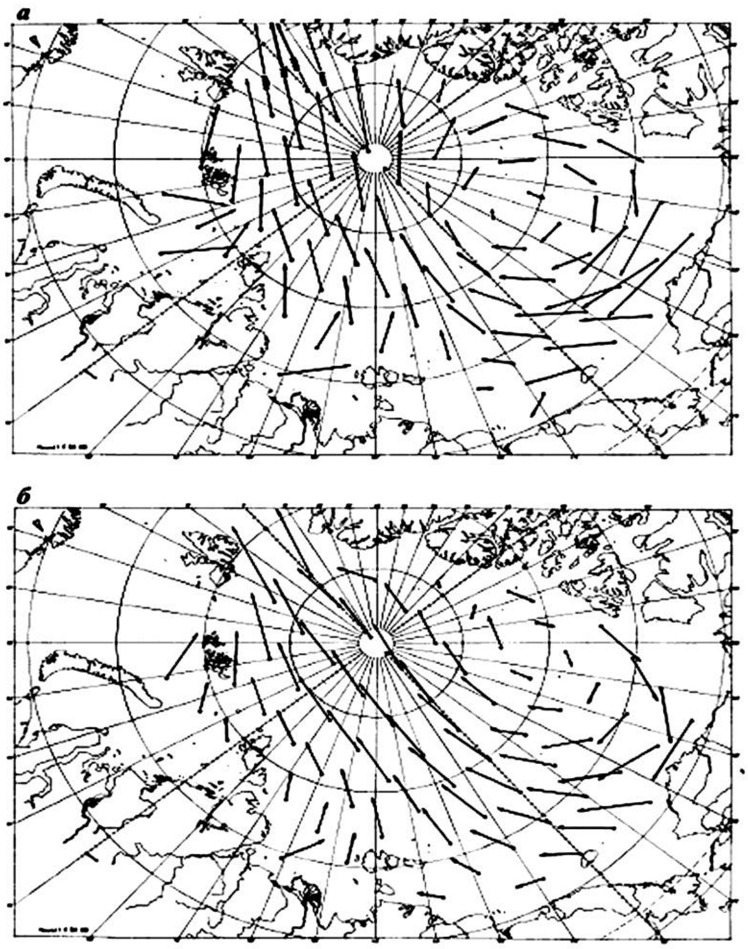

Fig. 2.9.1. Scheme of the average ice drift in October-March (a) and April-September (b)

Ice joining the Transpolar drift stream from the Kara Sea is exported to the Greenland Sea in 1-2 years, from the Laptev Sea – in 2-3 years, from the East Siberian – in 3-4 years and from the Chukchi Sea – in 4-5 years. The period of ice circulation within the anticyclonic gyre changes from 4 to 10-12 years. The lower bound refers to the quasi-circular ice drift area in the

Beaufort Sea and northwards, and the upper – to the trajectories passing across the stagnant region adjoining the north shores of Greenland and the Canadian Arctic archipelago.

In summer, ice from this area is partly transported to the straits of the Canadian Arctic archipelago and further to Baffin Bay. Observational data of ice drift allows determining of probability of drifting objects occurrence into the anticyclonic gyre. From observations data two boundaries were determined, one of them contours a part of the Arctic Basin, from which ice isn't strictly transported to the Greenland Sea. In summer this ice is partly exported to the straights of Canadian Arctic archipelago, but its bigger part remains within the gyre, or, when it is finished, joins the Transpolar Drift. The second boundary determines a region, where ice is transported to the Greenland Sea or melts within marginal seas boundaries, and never gets into anticyclonic gyre. There is a transition zone between listed boundaries, where ice in one case is transported to the Greenland Sea, and in other case – gets into the gyre region. Due to this the ice participating in the gyre can change from 2,5 to 3,5 million km^2 (approximately from 40 to 60% of the Arctic Basin area).

The variability of the general ice drift pattern is also manifested in a significant deviation of some branches of the Transpolar Drift Stream from their usual position. Due to this, closed cyclonic ice circulations occur in some years or seasons in the Laptev Sea and in the vicinity of Wrangel Island, whereas the usually existing export flow from the Kara Sea to the Arctic Basin changes its direction to reverse. Such changes are most frequent in the summertime.

A comparison of the ice drift patterns, presented in Figure 2.9 for winter and summer periods, reveals some specific differences between them. Most noticeable are the differences in the ice drift velocities at the approaches to the Fram Strait, where a velocity increase at approaching the strait is observed in winter. Another regular feature is a displacement of the Transpolar Drift Stream core from Eurasia to America and the corresponding decrease of the anticyclonic gyre area from winter to summer.

Two winter seasons (October-December and January-March) have typical pattern, approximately corresponding to the described annual mean pattern of general drift. At that, location of the Transpolar Drift core, which is usually situated along the northern extremities of the Arctic Seas, can significantly change from year to year, affecting ice outflow from these seas.

In spring period (April-June) ice drift pattern gets simpler: in most regions of the Arctic basin and marginal seas, except of rather small stagnant region northwards of the Canadian Arctic archipelago, ice drifts in direction of the Greenland Sea.

In summer (July-September) deep stream of the Transpolar Drift shifts to the line, connecting Bering Straight and Fram Straight. However, interannual variability of ice drift in this period is clearly expressed. In some years ice drift is typical for winter period whereas cyclonic system with its center usually located northwards of the Laptev Sea, abnormally develops in other years. These changes significantly influence ice exchange of the marginal seas with the Arctic Basin.

2.9.2. Age (thickness) of drifting ice in the Arctic Basin

System of atmosphere and ocean circulation determines duration of ice cover existence, and therefore, prevailing age of the ice in different macrostructural regions. Due to this region with prevailing multiyear ice of increased thickness, specific mesostructure and other properties, is formed in the ocean (Fig. 2.9.2).

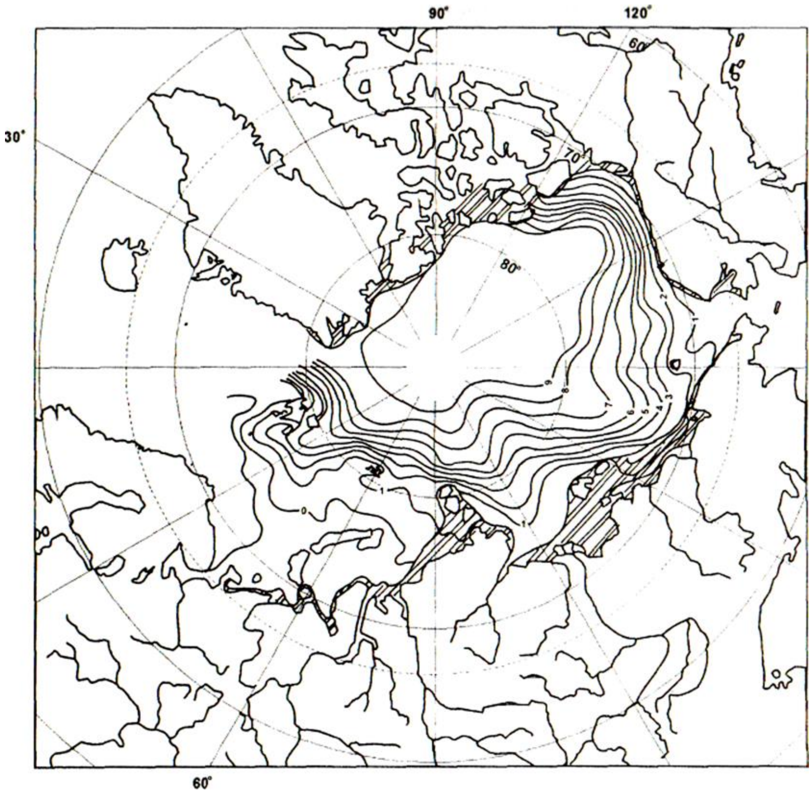

Fig. 2.9.2. Structure of the average field of old ice concentration (marks) and location of fast ice in February

Region, where amount of multiyear ice gradually decreases with increasing distance from the boundary of their relative predominance, is located in its periphery.

Macroscale distribution of multiyear ice corresponds to location of region with increased ice concentration, which forms the oceanic ice massif; its spurs are the major massifs of marginal seas: Svalbard, Kara, Taymyr, Ayon, Wrangel and Alaska.

Increased frequency of occurrence of offshore winds in many seas of the Eurasian shelf, on one hand, and onshore winds – northwards of Greenland and Canadian Arctic archipelago – on the other, contribute to formation of flaw polynyas and ice cover “rejuvenation” in the first region, and intensive ridging and ice accumulation in the second. Together with peculiar features of thermodynamic conditions it leads to large-scale spatial changes of average ice thickness – its increasing from Siberia coast to Canadian Arctic archipelago and Greenland. Maximum spatial gradients of ice thickness in the end of the winter, occurring due to ice cover "rejuvenation", are found in most marginal seas of the Siberian shelf.

Ice age in every region of the Arctic Basin is caused by local climate conditions, velocity and direction of general ice drift. Interannual variability of ice distribution by area and age depends on particular region of the Arctic.

The largest amount of multiyear ice is located near the coast of Canadian Arctic archipelago. From this coast it extents to Pole in the north, to Greenland – in the east, and to Alaska coast – in the south-west. Meridians180 - 0° are its western and eastern boundaries. Thickness of level multiyear ice in this region reaches maximum values of 420 cm. It is necessary to mention, that in places, where Arctic anticyclone is located, ice is covered with thin snow layer. Amount of snowfall is noticeably less here, than in other Arctic regions. Low air temperatures and thin snow-cover are the major factors, causing extreme thickness of level multiyear ice in this region. High ridging plays a significant role in formation of ice thickness.

Annual mean values of ice thickness in the end of winter are the most interesting. Ice of Canadian origin occupies Alaskan, Canadian and western part of Greenland regions. Ice is located in the Transpolar Drift.

Multiyear ice of Canadian origin occupies the entire Arctic Basin, the northern Chukchi Sea and the western East-Siberian Sea. Ice zone of Siberian origin directly borders with Severnaya Zemlya, Franz-Josef Land and Svalbard.

Summarizing direct measurements of ice thickness at drifting stations and calculation results, where age composition of the ice and its ridging are accounted, and also data of sonar observations from submarines, allowed obtaining average ice thickness distribution in the Arctic Basin in the end of winter (Fig. 2.9.3). As it is seen, maximum ice thickness, exceeding 7 m, is observed near the northern coast of Canadian Arctic archipelago, gradually decreasing to 2 m in the Siberian shelf seas.

If ice cover had been immovable, ice thickness distribution in the end of winter would have been determined only by conditions of ice growth, i.e. would have depend on air temperature, water heat content, conditions of heat exchange in air and water. Ice motion noticeably changes ice thickness distribution and its entire meso- and macrostructure. As a result of ice exchange with the Arctic Basin "rejuvenation" of the Siberian Seas ice cover occurs.

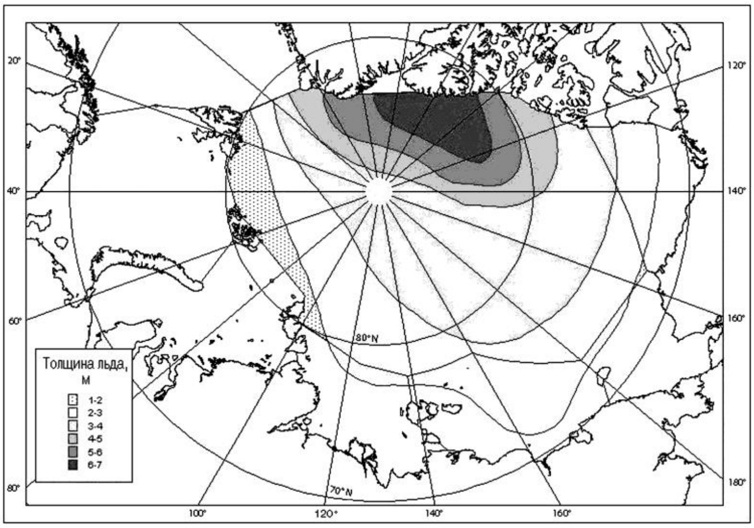

Fig. 2.9.3. Average ice thickness in the Arctic Basin

2.9.3. Distribution of level ice thickness along the navigation route in summer period.

Large amount of in-situ data, contained in the database, allows to estimate distribution of sea ice characteristics and changes of navigation ice conditions in summer period (July-September), and to consider regularities of the main sea ice characteristics distribution and operational indicators of ice breaker motion in three sectors of the Arctic Basin:

1) sector between 10° E and 100° E;

2) sector between 100° E and 150° E;

3) sector between 150° E and 165 W.

The southern boundary of these sectors follows the multiyear ice boundary, located in 81-82° N in the first sector, 79-80° N in the second sector and 73-75° N in the third sector.

Hereinafter in the text these sectors referred to as the “Western”, “Central” and “Eastern”.

Figures 2.9.4-2.9.6 show the thickness distribution of ice, directly broken by vessel during its sailing in the Arctic Basin. It is necessary to mention, that only level ice thickness was estimated in observations (outside the hummocks).

As a result of summer melting processes ice thickness distribution from July to September shifts to larger values. Thus, in the Western sector (Fig. 2.9.4) the ice with thicknesses of 120-200 cm, 140-260 cm, and 180-300 cm has the maximum frequencies of occurrence in July (58 %), in August (61 %), and in September (68 %), respectively.

In the Central sector (Fig. 2.9.5) ice with thicknesses of 120-240 cm and 180-260 cm prevail in August (61 %) and in September (60 %), respectively.

Distribution of level ice thickness, recorded by special ice observations in the Eastern sector, is characterized by lower values of prevailing ice thickness (Fig. 2.9.6). In this sector the predominant ice thickness is within the range of 80-180 cm. The relative length of navigation route in this ice is: 55 % in July, 59 % in August and 63 % in September.

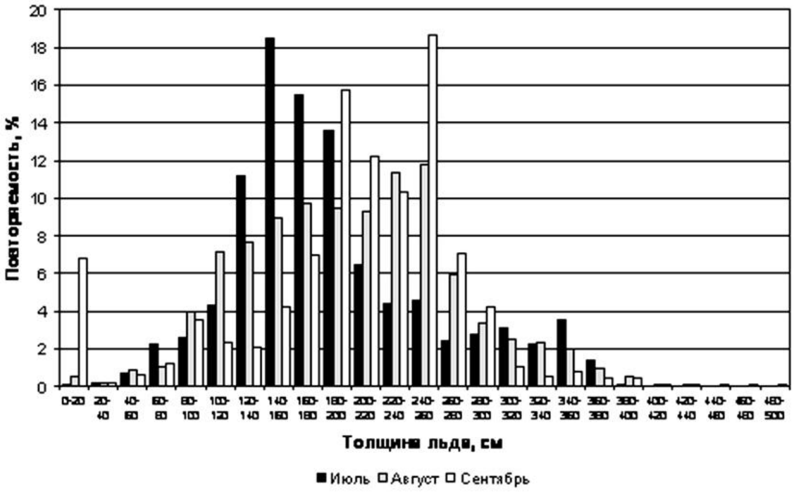

Fig. 2.9.4. Distribution of level ice thickness along the navigation route in the Western sector in the period July-September

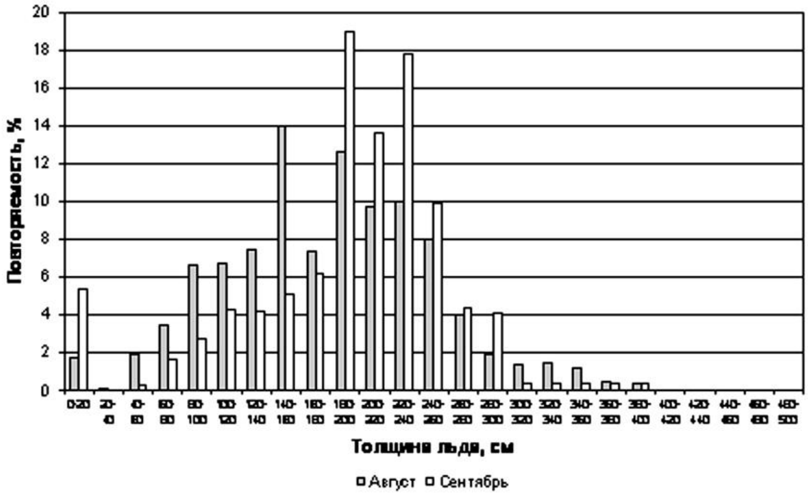

Fig. 2.9.5. Distribution of level ice thickness along the navigation route in the Central sector in the period August – September

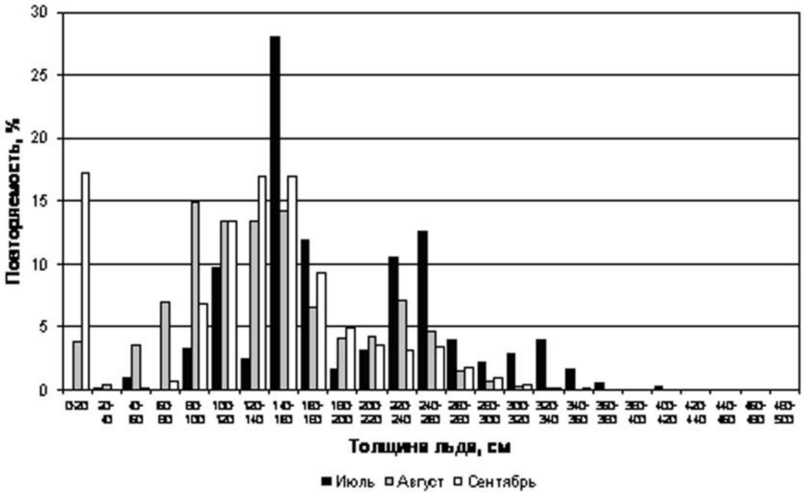

Fig. 2.9.6. Distribution of level ice thickness along the navigation route in the Eastern sector in the period July-September

Selective icebreaker route, when it mostly moves in easier ice conditions and also in thinner ice, affects the ice thickness distribution along the sailing route. Due to this it is reasonable to analyze ice thickness distribution for first-year and old ice separately.

In the western sector prevailing thickness of the first-year ice in July is 140-200 cm (70 %), in August – 100-180 cm (69,5 %), in September – 140-200 cm (61 %) (Fig. 2.9.7). In the western sector prevailing thickness of the old ice in July is 200-260 cm (68 %), in August – 180-260 cm (69 %), in September – 180-240 cm (73 %) (Fig. 2.9.8).

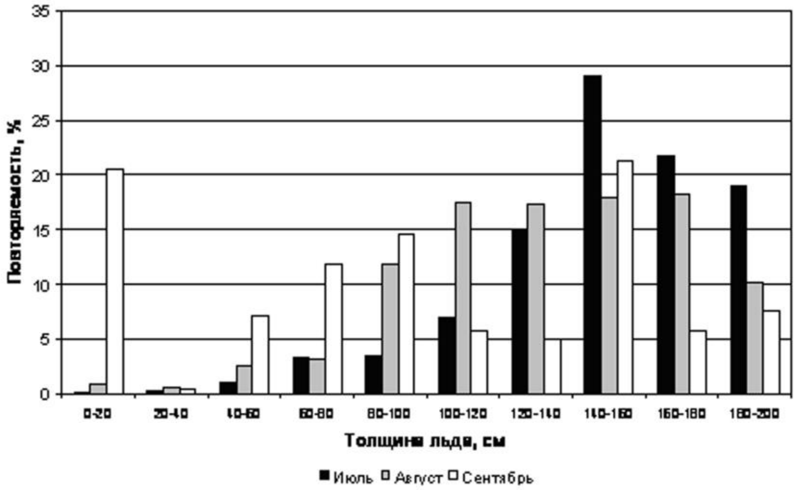

Fig. 2.9.7. Distribution of level first-year ice thickness along the navigation route in the Western sector in the period July-September

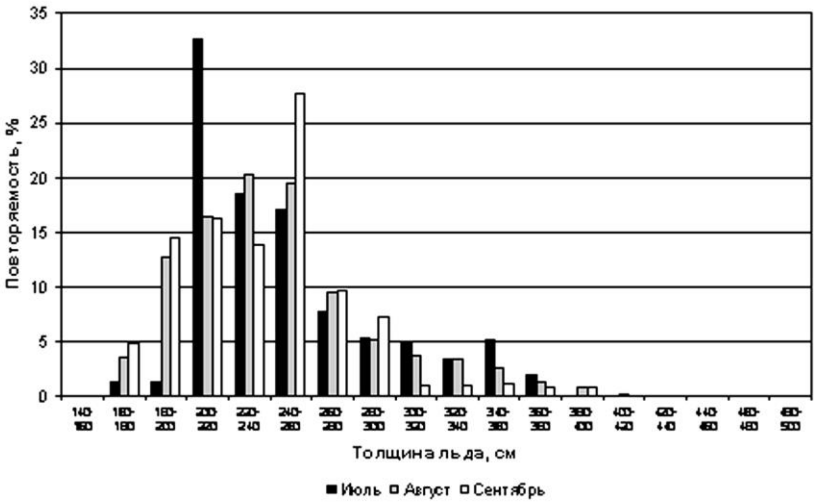

Fig. 2.9.8. Distribution of level thick ice thickness along the navigation route in the Western sector in the period July-September

In the central sector in summer period prevailing thicknesses of the first-year and old ice generally corresponds to their prevailing thicknesses in the western sector (Fig. 2.9.9, 2.9.10).

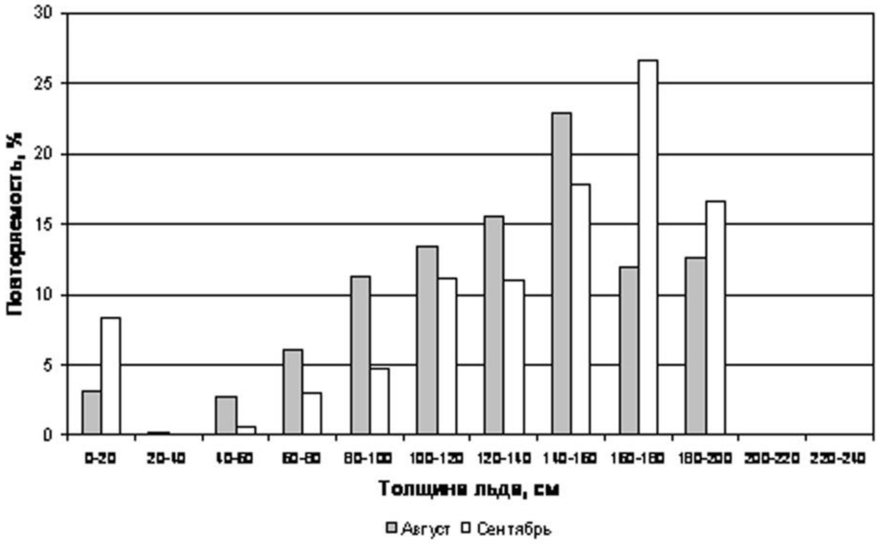

Fig. 2.9.9. Distribution of level first-year ice thickness along the navigation route in the Central sector in both August and September

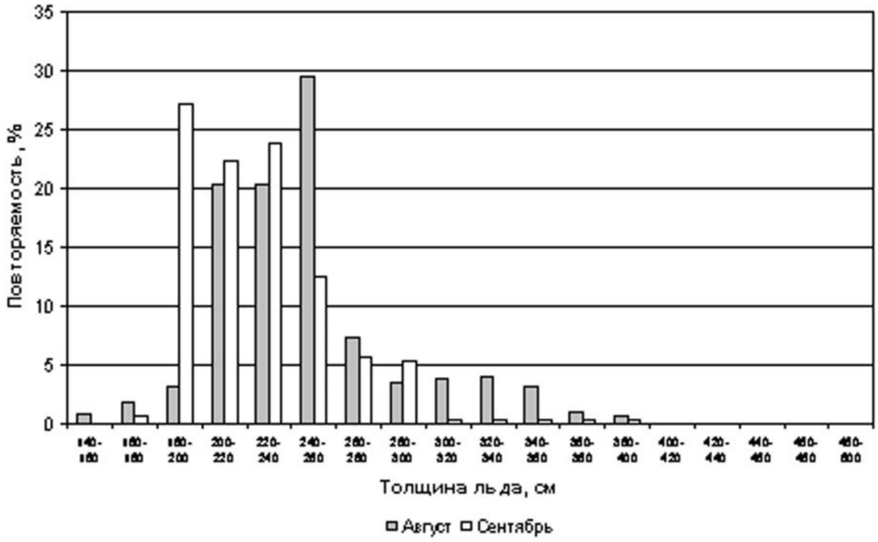

Fig. 2.9.10. Distribution of level thick ice thickness along the navigation route in the Central sector in both August and September

In the eastern sector prevailing thickness of the first-year ice in July is 140-180 cm (67 %), in August – 80-160 cm (77 %), in September – 100-180 cm (66 %) (Fig. 2.9.11). Prevailing thickness of the old ice in July is 220-280 cm (62 %), in August – 180-280 cm (75 %), in September – 180-260 cm (73 %) (Fig. 2.9.12).

2.9.4. Ice melting

With increasing of solar radiation and air temperature in spring snow and then ice start to melt. The mean terms for the onset melting falls on the last 10-day period of May in the Arctic Seas, located to the south of 72° N; in the first 10-day period of June it usually propagates to 75° N, and by the end of the second 10-day period of June it reaches the northern boundaries of the marginal seas, and by late June approaches the near Pole region (Fig. 2.9.13). Standard deviation, which characterizes the interannual variability of ice melting terms, is 10 days.

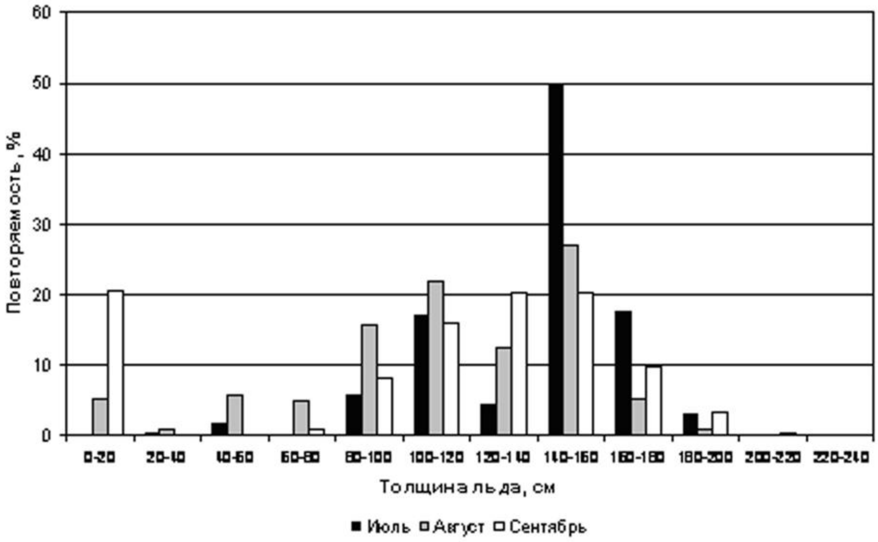

Fig. 2.9.11. Distribution of level first-year ice thickness along the navigation route in both August and September

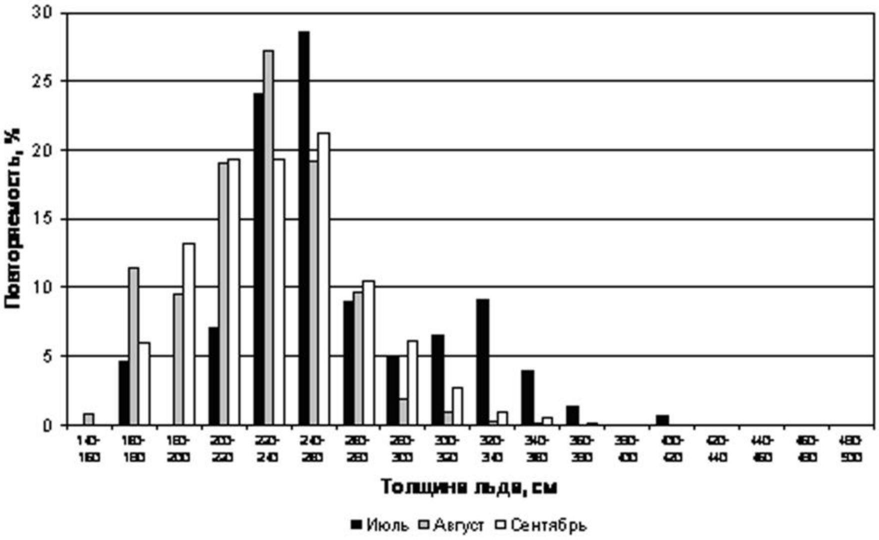

Fig. 2.9.12. Distribution of level thick ice thickness along the navigation route in the Eastern sector in both August and September

Velocity of ice thickness decreasing significantly changes as a result of melting in the Arctic Seas. In the Arctic Basin the mean value of ice thickness decreasing changes during season from 75—100 cm near the northern boundaries of the seas, and to 0—20 cm in the near Pole region (Fig. 2.9.14).

In the period of ice melting essential feature of ice state is estimation of ice decay. Estimation of ice decay is based on accounting external features, which are typical for ice surface changes as a result of its melting: appearance of puddles and their development stage, presence of snow cover etc.

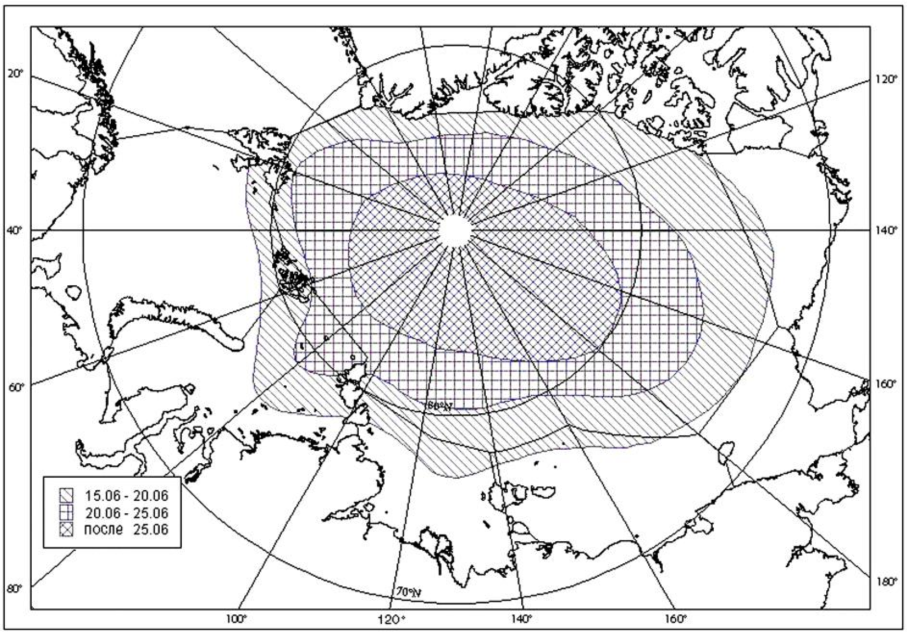

Fig. 2.9.13. Average terms of the beginning of thawing of an ice in the Arctic sector

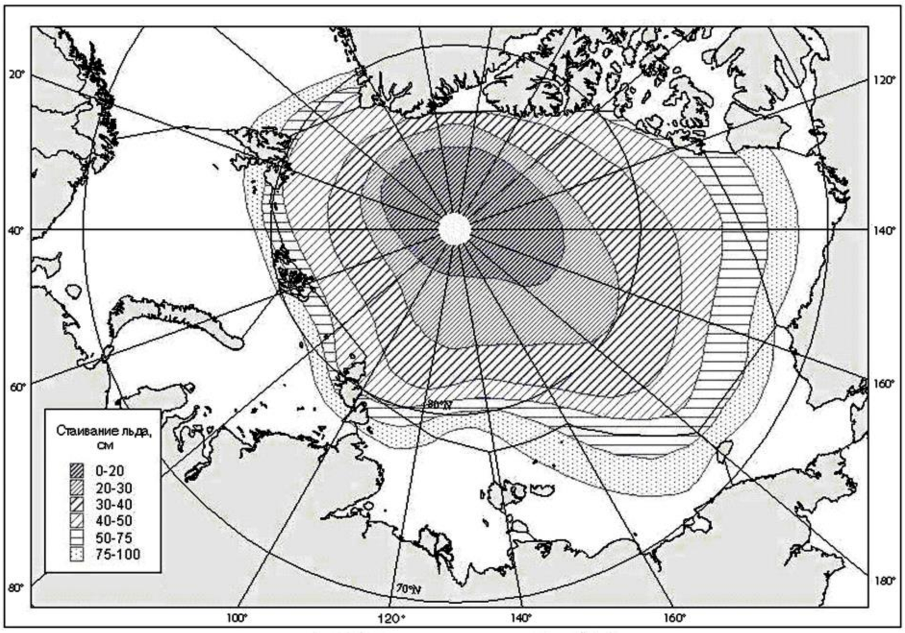

Fig. 2.9.14. Average size of thawing of an ice for a summer in the Arctic sector

It is necessary to mention, that ice decay is characterized with significant interannual and spatial variability. Obviously, ice decay depends on atmospheric processes (air temperature), proportion of different ice types (first-year ice melts more intensive, than old one). Thus, in August 1996 ice with a degree of decay (2-3 marks) typical for these months was observed southwards of 86º, at the same time, northwards of this latitude features of ice melting were absolutely absent, and snow depth amounted to 20-25 cm. This case was observed in all three sectors.

In the western sector the maximum ice decay degree is observed in July – about 50 % of the ice has a decay degree of 3 marks (Table 2.9.1). In high latitudes in the second half of August freezing of puddles can begin, at this moment a degree of decay conventionally considered to be 0 marks. The Relative length of the route in this ice is less than 7 %. Ice, with a degree of decay of 2 marks has the highest frequency of occurrence in this month. In September in the Western sector ice melting wasn't observed.

Table 2.9.1. Relative length of navigation route in ice of different degree of decay in the Western sector for July-September, %

Month	Ice decay degree, marks					
	0	1	2	3	4	5
July	1,3	13,9	34,9	49,9	0,0	0,0
August	6,7	7,4	63,7	22,2	0,0	0,0
September	100,0	0,0	0,0	0,0	0,0	0,0

In August the most probable value of ice decay degree in the Central sector is 2-3 marks (43 %), however, decay degree of 0 marks was recorded in 37 % of the route (usually it is connected with the end of ice melting). In September melting is observed in 43 % of the route in this sector, and prevalent degree of ice decay is 1 mark (Table 2.9.2).

Table 2.9.2. Relative length of navigation route in ice of different degree of decay in the Central sector in August and September, %

Month	Ice decay degree, marks					
	0	1	2	3	4	5
August	37,2	18,0	18,7	24,0	1,9	0,2
September	56,6	30,1	1,9	11,4	0,0	0,0

Ice of the Eastern sector in July is characterized with a small degree of decay; its values are less than 1 mark (observation data for 1996). In August prevailing degree of ice decay amounts to 1-2 marks (78 %), and in September melting is observed only on 50 % of the route (Table 2.9.3).

Table 2.9.3 - Relative length of navigation route in ice of different degree of decay in the Eastern sector in July-September, %

Month	Ice decay degree, marks					
	0	1	2	3	4	5

July	8,6	91,4	0,0	0,0	0,0	0,0
August	0,1	39,3	38,5	22,0	0,1	0,0
September	49,8	36,6	12,9	0,7	0,0	0,0

Distribution of snow depth along the navigation route in summer period

Snow depth on ice of the Arctic Basin depends on many factors: amount of precipitation, fallen during previous winter (which in its turn depends on cyclonic activity), wind conditions, air temperature in the melting period and etc. Snow observations from a ship consist of estimating its depth on level ice (outside of hummocks).

In July snow depth on 60 % of the route in the Western sector is less than 10 cm (Table 2.9.4). Nevertheless, in some parts its depth can amount to 55 см. These snow depth values were recorded in July 1992 in the near Pole region. Obviously, in August snow depth generally decreases due to melting. In this month about half of the sailing route in the Western sector is in the ice without snow. The process of snow accumulation starts in September, after finishing of melting, (see Table 2.9.4). Prevailing snow depth in this month is within the range of 1-20 cm (89 %).

Table 2.9.4 –Distribution of snow depth on ice in the Western sector in July-September, %

Month	Snow depth, cm						
	0	1-10	11-20	21-30	31-40	41-50	51-60
July	15,1	44,5	10,6	16,1	9,6	2,1	1,8
August	49,4	35,2	14,0	1,4	0,0	0,0	0,0
September	2,2	58,3	30,8	7,4	1,0	0,3	0,0

The snow distribution pattern in the Central sector is similar (Table 2.9.5). It is necessary to mention, that ice cover of the Central sector is distinguished by rather larger values of snow depth comparing to ice of the Western sector. This peculiar feature is recorded both in August and in September.

Table 2.9.5. Distribution of snow depth on ice in the Central sector in August and September, %

Month	Snow depth, cm						
	0	1-10	11-20	21-30	31-40	41-50	51-60
August	35,4	33,9	23,9	6,3	0,6	0,0	0,0
September	4,5	30,0	44,3	18,8	2,0	0,3	0,0

In July the prevailing snow depth in the Eastern sector amounts to 20-40 cm (61 %) (Table

2.9.6). In August snow cover is absolutely absent in 57 % of navigation route, though in some areas its depth amounts to 25 cm. In September, after the end melting, newly fallen snow prevails with its depth mostly less than 10 cm (76 %).

Table 2.9.6 - Distribution of snow depth on ice in the Eastern sector in July-September, %

Month	Snow depth, cm						
	0	1-10	11-20	21-30	31-40	41-50	51-60
July	2,7	20,8	10,0	31,1	30,1	5,2	0,0
August	57,2	11,4	24,6	6,8	0,0	0,0	0,0
September	11,5	76,2	12,2	0,1	0,0	0,0	0,0

2.9.6. Distribution of compacting along the navigation route in summer period

Compacting of ice cover is the essential feature of its dynamic processes. An estimation of compacting is qualitative pattern based on external features of changes of some sea ice characteristics – increasing of concentration, formation of new ridges, young ice rafting and etc. One of the most essential features of ice compacting is sharp decrease of ship speed.

In the Western sector compacting is absent along the significant part of the sailing route - 65 % in July, and 75-76 % - in August and September. Weak compacting has the largest frequency of occurrence in summer period, with intensity of 0-1, 1 mark. Relative length of navigation route under strong compacting (1-2, 2 marks) changes from 4 % in July to 2.5 % in September. Very strong compacting (2-3, 3 marks) was not recorded in summer period in the Western sector (Table 2.9.7).

Table 2.9.7 - Relative length of navigation route under compacting of different intensity in the Western sector in July-September, %

Month	Ice compacting intensity, marks			
	0	0-1, 1	1-2, 2	2-3, 3
July	65,2	30,9	3,9	0,0
August	75,8	21,1	3,1	0,0
September	74,8	22,7	2,5	0,0

In the Central sector length of the route without compacting is much higher (by 5 % in August and 15 % in September) comparing to the Western sector – (Table 2.9.8).

In the Central sector compacting frequency of occurrence both in August and September is practically the same. Increasing of navigation route length under compacting with intensity of 1-

2, 2 marks, from 1 % in August to 2 % in September is the main distinction.

Table 2.9.8 - Relative length of navigation route under compacting of different intensity in the Central sector in August and September, %

Month	Ice compacting intensity, marks			
	0	0-1, 1	1-2, 2	2-3, 3
August	80,2	18,9	0,9	0,0
September	80,0	18,1	1,9	0,0

In the Eastern sector during summer relative length of navigation route without compacting gradually increases: from 75 % in July to 86 % in September. Along ships route mostly weak compacting with intensity of 1 mark was recorded during ice observations from ships (Table 2.9.9).

Table 2.9.9 - Relative length of navigation route under compacting of different intensity in the Eastern sector in July-September, %

Month	Ice compacting intensity, marks			
	0	0-1, 1	1-2, 2	2-3, 3
July	74,9	23,8	0,0	0,0
August	79,7	19,3	1,0	0,0
September	85,7	13,7	0,6	0,0