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ACCESS

Arctic Climate Change, Economy and Society

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PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

ACCESS Consortium’s statement:

The deliverable D2.13 has been provided by the partner responsible (AARI) and has been reviewed by the ACCESS Project Management Board and ACCESS WP leaders. The question of the method and its interpretation applied to D2.13 has been discussed but no consensus was found between the partner responsible (AARI) and reviewers. The consensus view of ACCESS climate scientists is that solar variations have a minor impact on ongoing Arctic climate change in general and near future Arctic sea-ice retreat in particular. The ACCESS consortium does not consider it likely that a hitherto-unrecognized 180-200 years solar cycle should be responsible for a major re-growth in Arctic sea-ice extent over the forthcoming years and decades as stated in D2.13. This is in contradiction with AARI scientists involved in ACCESS. As a consequence, the views on future Arctic Climate evolution in deliverable D2.13 cannot be endorsed by the ACCESS consortium. However in order to respect our contractual commitment toward the EU Commission, we submit D2.13 as it is even if it does not reflect the point of view of the ACCESS consortium. This deliverable is confidential (CO). The content of this report has no direct impact on other ACCESS deliverables and reports.

Contents

1. Recent ice conditions in the Arctic: climate changes in the Arctic Seas during XX – beginning of the XXI centuries

Continuing decrease of summer ice extent and area in the Arctic is caused by ongoing climate change. The most important parameter is the air temperature. Results of the AARI's investigations show that long-term changes of the annual average surface air temperature in the Arctic, sea ice extent and other hydrometeorological parameters in XX – beginning of XXI centuries are characterized by long-term cyclical fluctuations with period about 60, 20, 10 and less years [Frolov et all, 2007; Frolov et al., 2009]. These fluctuations were observed simultaneously with the linear warming trend that is possibly a part of the 200-years cycle.

The mostly energy-intensive fluctuation is the of 60-year cycle. This cycle reflects all climate phenomena in the Arctic that happened during the XX century: air temperature decreasing in the beginning of the century; Arctic warming in 1920-1940; cooling in the end of 1950th – middle of 1980th, following warming from the middle of 1980th with the maximum in the beginning of XXI century. During the last years air temperature in the northern hemisphere stabilized, but the warming period is still continuing in present [Sherstyukov et all, 2010; Hansen J., Ruedy R., Sato M., Lo K., 2010, Humlum O., 2011] .

1.1 Change of sea ice extent in the Arctic Seas

Changes of the sea ice extent in the Arctic Seas in XX-XXI centuries characterized by negative linear trend. The changes with 60, 20 and 10 years fluctuations demonstrate spatial peculiarities. The more intensive negative trend of ice extent (15% ice concentration) was observed in the western Arctic seas (Barents Sea and Kara Sea). This trend is characterized by long-term fluctuations with main period about 60 years. Linear trends in the eastern seas (Laptev Sea, East-Siberian Sea, Chukchi Sea) are weaker, ice extent fluctuations are characterized by stronger interannual variability and 60-year cycle is weaker as well. Sea ice extent fluctuations in the western and the eastern seas and their linear trends can be compared on the Fig. 1.

The coldest period in the XX century was observed in 1965-1975, while the warmest period was observed in the XXI century during 2001-2012. Major sea ice parameters for summer and fall-winter periods were analyzed and compared. Comparison of sea ice extent in the Arctic seas during different climate periods is presented in Table 1. As follows from this table, changes in sea ice extent from cold to warm period were e mostly significant in the Kara Sea and the East-Siberian Sea. Average ice area in these seas decreased from 37% to 31% correspondingly. During the warm period sea ice cover in these two seas almost completely or completely melted during summer more often than in other Arctic seas. On the average, the area of the ice cover in the Arctic seas decreased by 20%, which is equal to 786 x 10^3 km^2 and is comparable to the total area of the East-Siberian Sea (770 x 10^3 km^2).

Table 1.

Sea ice area in the Arctic seas in August during the cold 1965-1975 and warm 2001-2012 periods, x 10^3 km^2

Period	Barents Sea	Kara Sea	Laptev Sea	East-Siberian Sea	Chukchi Sea	Total
1965-1975	180	521	269	630	127	1727
2001-2012	46	215	221	389	69	941
Difference	134	306	47	241	58	786
Difference in % from the sea area	10	37	9	31	16	20

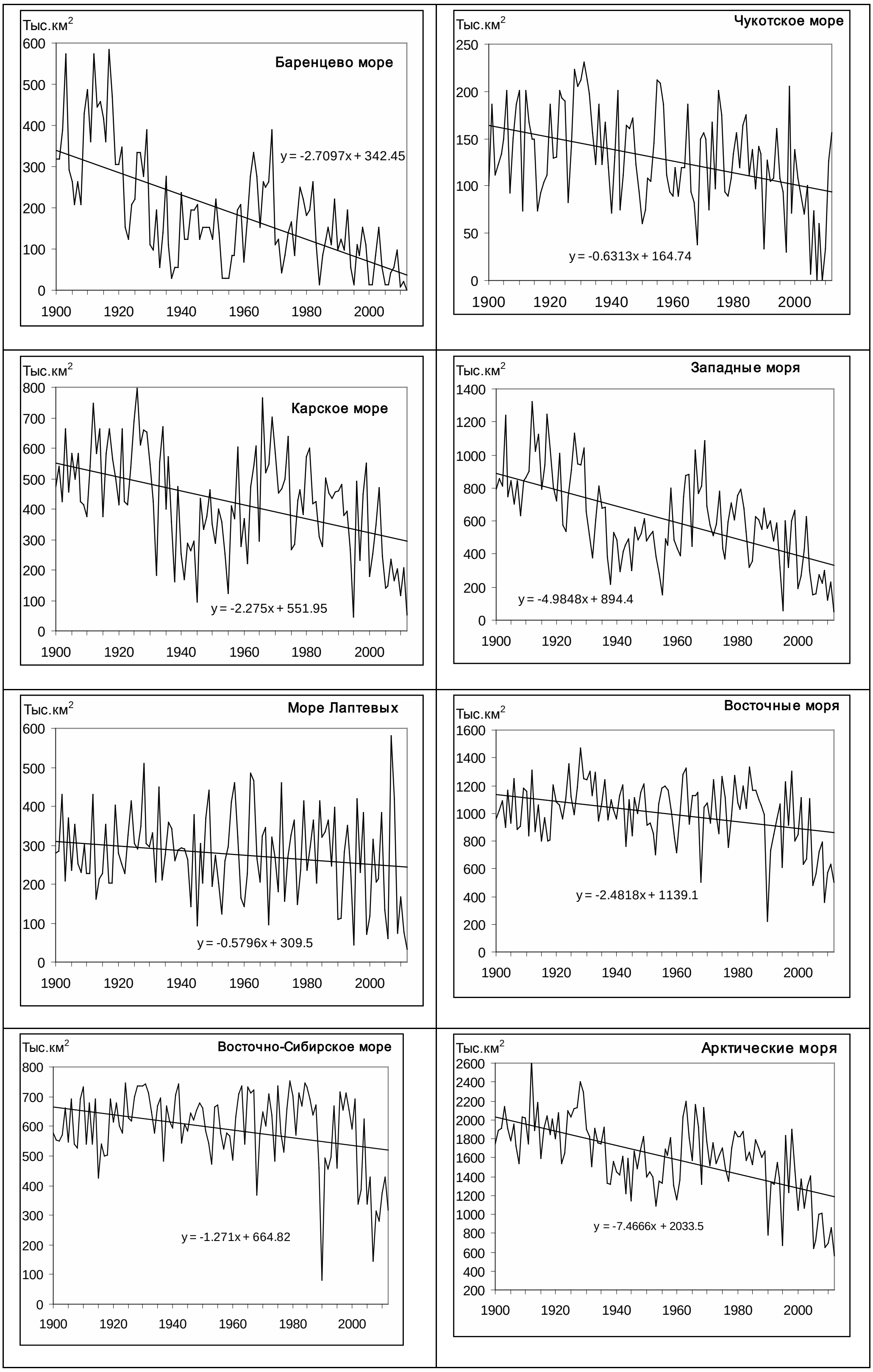

Fig.1. Changes of ice area in the Arctic Seas in August during the period 1900-2012

Left column from top to the bottom: Barents Sea, Kara Sea, Laptev Sea, East-Siberian Sea.

Right column from top to the bottom: Chukchi Sea, western seas, eastern seas, all seas

1.2 Estimation of the compact ice area in the Arctic seas

The most important characteristic of ice conditions in summer period is the area of ice massifs – zones covered by compact ice with concentration of 70-100%. There are 9 ice massifs in the Siberian Arctic Seas. These massifs are distinguished by their geographical position (Fig. 2).

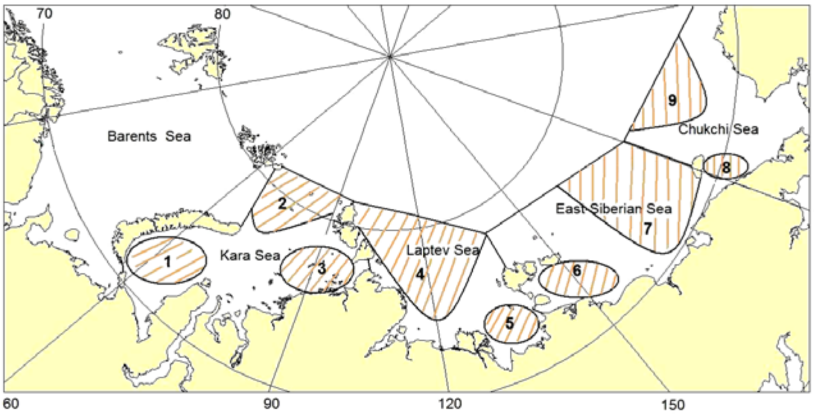

Fig.2. Scheme of sea ice massifs in the Siberian Arctic seas.

1-Novozemelskiy 2-North Kara 3-Severnaya Zemlya 4- Taymyr 5-Yanskiy, 6-New Siberian 7-Ayonskiy 8-Vrangel 9- North Chukchi

Table 2 shows the difference between averaged monthly areas of compact ice in the Arctic seas during cold and warm periods, and the impact of these differences on difference between sea ice areas during the same climate periods (%). Areas of compact ice in each sea were calculated by summation of specific ice massifs areas shown in Fig.2..

Table 2.

Average monthly areas of compact ice in the Arctic seas in June-September during the cold (1965-1975) and warm (2001-2012) periods, x 10^3 km^2.

Ice massifs	June	July	August	September	Average
Kara Sea	77	230	310	214	208
Laptev Sea	68	73	200	113	113
East-Siberian Sea	8	28	106	212	88
Chukchi Sea	74	71	60	60	66
Total Area	227	402	675	599	476
Impact to the total change of sea ice area, %	89	86	66	58	75

The strongest decrease of the compact ice area is observed in the Kara Sea, 208 x 10^3 km^2. On the average, the area of compact ice had decreased by 476 x 10^3 km^2 during the summer season with maximum decrease in August, by 675 x 10^3 km^2.

1.3 Change of starting date of stable ice growth in the Arctic Seas

Observational data at polar stations in the Arctic seas (2 stations per sea) were used to evaluate starting dates of stable ice growth. Sea ice formation in all Arctic seas in 2001-2011 was starting later than in 1965-1975: with 12 days delay on the average. The largest delays of ice formation were observed in south-western parts of the Kara and Chukchi Seas – 22 and 21 days (stations Amderma and Vrangel correspondingly). In close bays, like Dikson and Tiksi the positive shift in the date of stable ice growth start is 3-7 days. In the open sea areas the start of ice formation was observed 9-13 days later.

Table 3.

Starting date of stable ice growth at polar stations during the cold (1965-1975) and warm (2001-2012) periods

Periods	Kara Sea		Laptev Sea		East-Siberian Sea		Chukchi Sea	
	Amderma	Dikson	Tiksi	Kigilyakh	Ayon	Valkarkai	Vrangel	Vankarem
1965-1975	27.X	6.X	4.X	2.X	3.X	8.X	3.X	11.X
2001-2011	18.XI	13.X	7.X	11.X	12.X	20.X	23.X	24.X
Difference	22	7	3	9	9	13	21	13

1.4 Change of fast ice area in the Arctic Seas

Fast ice in the Arctic seas covers from 7% to 53% of their area. Total fast ice area during the period of its maximal development (April-May) is about 30% of the total area of Arctic seas. The minimal area of fast ice is forming in the south-west Chukchi Sea, the maximal – in the east Laptev Sea, the west East-Siberian Sea and the north-east Kara Sea. Table 3 shows results of fast ice areas comparison during the cold and warm climate periods. On the average, total fast ice area in 2001-2012 decreased by 29 x 10^3 km^2 (about 4% of the average fast ice area) comparatively with 1965-1975 period. The maximal changes were observed in the Kara Sea, mostly influenced by warm Atlantic cyclones. In the eastern seas the difference between cold and warm periods was insignificant.

Table 4.

Fast ice areas in the Arctic Seas during the cold (1965-1975) and warm (2001-2012) periods, x 10^3 km^2

Climate periods	Kara Sea	Laptev Sea	East-Siberian Sea	Chukchi Sea	Total area
1965-1975	158	215	271	10	653
2001-2012	137	214	263	10	624
Difference	21	0	8	0	29
Relation to the average area %	15	0	3	0	4

1.5 Fast ice thickness in the Arctic Seas

On the average, thickness of the fast ice during the cold climate periods is more than the mean annual one. Table 5 shows that the most significant change were observed in the Kara Sea. The fast ice thickness near the polar stations in the Kara Sea during the last period decreased by 18 cm in comparison with the cold period. The maximum decrease was observed near the polar station Dikson (24 cm).

Table 5.

Fast ice thickness in the Arctic Seas during the cold (1965-1975) and warm (2001-2012) periods, cm

Periods	Kara Sea		Laptev Sea		East-Siberian Sea		Chukchi Sea	
	Amderma	Dikson	Tiksi	Kigilyakh	Ayon	Valkarkai	Vrangel	Vankarem
1965-1975	129	176	228	215	191	191	180	181
2001-2011	116	152	224	214	178	190	172	185
Difference	13	24	4	1	13	1	8	-4

In the eastern seas the difference between average fast ice thickness in two periods is insignificant and does not exceed 2% from the mean annual value. In the Kara Sea such changes are in the range of 10% from the mean value.

1.6 Change of the ice-cover duration in the Arctic Seas

Data from the polar stations in the Arctic seas were used to estimate the ice-cover duration. Table 6 shows that duration of icy period in all Siberian Arctic seas in 2001-2011 was 284 days. The decrease in comparison with 1965-1975 period is 40 days. Decrease of the ice-cover duration is mostly pronounced in the south-western Chukchi Sea. It is 59 days.

Table 6.

Ice-cover duration during the cold (1965-1975) and warm (2001-2012) periods in the Arctic seas, days

Periods	Kara Sea		Laptev Sea		East-Siberian Sea		Chukchi Sea		Average
	Amderma	Dikson	Tiksi	Kigilyakh	Ayon	Valkarai	Vrangel	Vankarem	
1965-1975	287	316	298	330	341	338	345	335	324
2001-2011	247	280	291	294	294	300	276	286	284
Difference	40	36	7	36	47	38	69	49	40

Consequently, significant improvement of sea ice conditions in the Arctic Seas during all seasons was observed.

2. Sea ice conditions during the IPY 2007-2009 and later

The time interval 2007-2013, includes IPY years, which were characterized by large-scale changes of atmospheric processes and significant anomalies of Arctic sea ice cover parameters.

2.1 Arctic Basin

Between 2006-2007 and 2012-2013 the frequency of the Arctic anticyclone had increased and its center moved to the west, as shown in Fig. 3. Intensification of the Arctic anticyclone and its westward shift led to blocking of Atlantic cyclones, accompanied by intensive heat transport to the western Arctic seas and the Atlantic sector of the Arctic Basin.

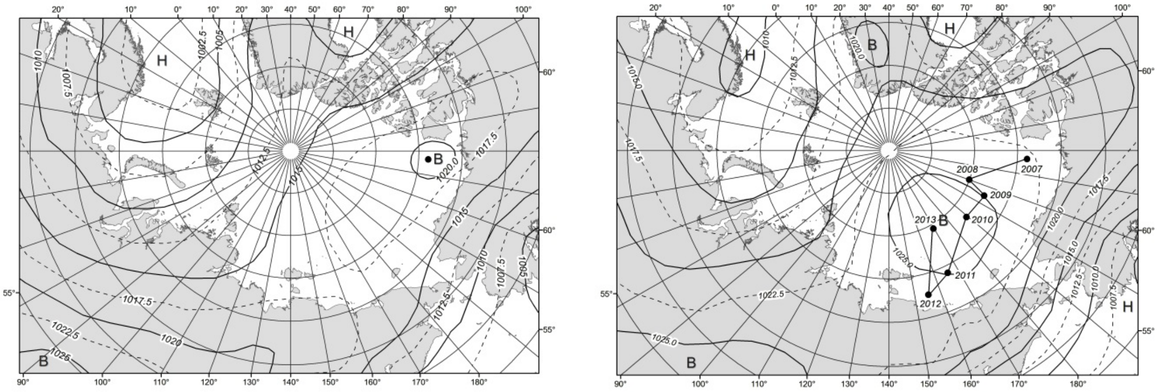

Fig.3. Average fields of the atmospheric pressure in winter (October-March) in 2006-2007 (left picture) and in 2012-2013 (right picture). Black dots indicate location of centers of the Arctic anticyclone in 2007-2013

Increasing frequency of the Arctic anticyclone favors anticyclonic ice drift during the winter period. The center of this circulation has moved westwards as well (Fig. 4).

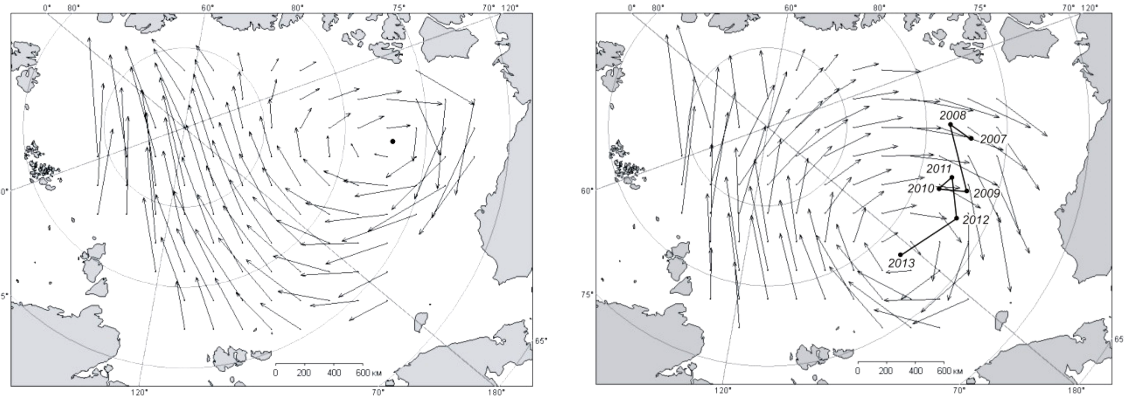

Fig. 4. Resulting sea ice transportation during the winter periods (October-March) in 2006-2007 (left picture) and in 2012-2013 (right picture). Zigzag line denotes the trajectory of the anticyclone sea ice circulation center shift in 2007-2013

The scheme of resulting ice motion was created on the basis of observations from drifting buoys, with respect to isobars. As a result of continuing warming, sea ice area in the Arctic Ocean decreased to its minimum in summer 2007. Negative anomaly exceeded 2 x 10^6 km^2. During the following 4 years sea ice area was more than in 2007. Since 2010 sea ice area became to decrease again and in 2012 reached the new record minimum. Sea ice area in 2012 was less by 750 x 10^3 km^2 than in 2007, as shown in Table 7.

Increase of the sea ice cover in the Eastern Arctic Ocean was observed in the Beaufort and East-Siberian Seas in summer 2013 as result of maintaining the anticyclonic type of the atmospheric circulation, which settled since fall 2012. In September 2013 sea ice area was by 1.7 x 10^6 km^2 more than it was in September 2012 (about the size of September 2009 (Table 7).

Table 7.

Average ice cover area in the Arctic in September based on SSMR-SSM/I – SSMIS data, NASATEAM algorithm (calculated by the AARI)

Years	S, million sq.km	Anomalies, million sq.km	
		From mean value	from 2007
1979-2013	6,360	-	-
2007	4,328	-2,032	-
2008	4,729	-1,631	+0,401
2009	5,307	-1,053	+0,979
2010	4,910	-1,450	+0,582
2011	4,565	-1,795	+0,237
2012	3,581	-2,779	-0,746
2013	5,213	-1,147	+0,885

Fig. 5 illustrates that position of the first-year ice edge in the Western Arctic were very close in 2012 and 2013. This is the area, which is influenced by Atlantic cyclones. The maximal decrease of ice cover area in 2013 as well as in 2012 was observed in the Western Arctic. The most part of sea ice edges in this area were located as far to the north as 84ºN and slowly descended to72 ºN in the central part of the East-Siberian Sea (Fig 5).

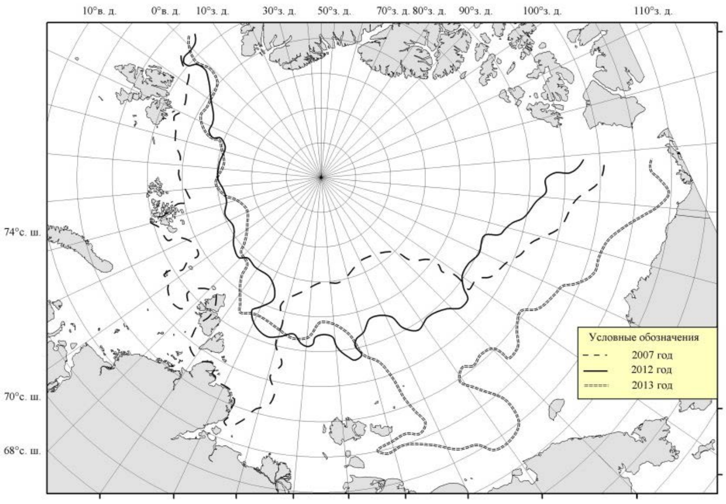

Fig. 5. Positions of the first-year ice edges in September 2007, 2012, and 2013

2.2 Siberian Arctic Seas

Sea ice parameters in the Siberian Arctic Seas changed during the period 2007-2013 as a result of alterations of large-scale atmospheric processes in the Arctic. These changes may be an indication of termination of the prolonged warm period. Signs of such alteration are mostly noticeable in the Eastern Arctic Seas. Stable ice growth in the Siberian Arctic Seas started 12-15 days later in 2007-2012 than on the average (Table 8). However, positive anomalies of ice formation terms in the Kara and Chukchi Seas decreased by 4 and 8 days correspondingly in the second part of 2007-2012 period in comparison with its first part.

Table 8.

Average anomalies of starting date of stable ice growth in the Arctic seas in 2007-2012, days

Sea	Periods		
	2007-2012	2007-2009	2010-2012
Kara	15	17	13
Laptev	12	12	12
East-Siberian	13	13	12
Chukchi	15	19	11

Earlier dates (than in the previous years) of ice formation in the Chukchi Sea are caused by anticyclonic type of weather conditions during the fall, that favors faster cooling at the sea surface.

Faster motion of young ice edge to the south and complete freezing of the Eastern Arctic Seas are related to intensified influence of the Arctic anticyclone (Table 9).

Table 9.

Average dates of complete freezing of the Arctic Seas and its anomalies in 2007-2012

Sea	Average terms	Anomalies, days		
		2007-2012	2007-2009	2010-2012
Kara	20.XI	50	42	57
Laptev	5.X	18	19	18
East-Siberian	5.X	34	41	31
Chukchi	15.X	16	21	6

Multi-year observations in the Laptev and East-Siberian seas show that these seas are covered by young ice in 35-40 days after the beginning of ice formation. Kara and Chukchi Seas become totally ice covered in 80-85 days. Table 4 shows that freezing of the East-Siberian and Chukchi Seas in 2010-2012 was earlier by 10 and 15 days correspondingly to 2007-2009. In fall 2012 sea ice in the Chukchi Sea started to form close to the average date, about November 15, for the first time during the last 10 years.

Conditions of ice formation during the cold period (October-May) in 2007-2013 significantly differ in western and eastern Arctic Seas. Prevailed anticyclone weather conditions resulted in increasingly thick first-year ice, with thickness more than 120 cm during the second part of 2007-2013 period (Table 10). Amount of thick first-year ice in the Chukchi Sea reached its maximum in March 2013 – 45%.

Table 10.

Area of thick first-year ice (with thickness more than 120 cm) at the end of March as percentage from the total ice cover in the Arctic Seas in 2007, %

Sea	Periods		
	2007-2013	2007-2009	2010-2013
Kara	21	25	18
Laptev	57	56	58
East-Siberian	69	64	73
Chukchi	11	5	16

Different conditions of ice formation influenced fast ice area and frequency of flaw polynyas opening. As shown in Table 11, fast ice area in the Eastern and Western Seas decreased by 60 x 10^3 km^2 in 2010-2013 (13%).

Table 11.

Fast ice area in the Western and Eastern Arctic Seas in 2007-2013, x 10^3 km^2.

Seas	Periods		
	2007-2013	2007-2009	2010-2013
Western Seas (Kara and Laptev)	325	351	305
Eastern Seas (East-Siberian and Chukchi)	499	464	525

Warm period 2007-2012 was favorable for flaw polynyas formation. Repeatability of flaw polynyas significantly increased in comparison with average annual as follows from Table 12. However, intensification of the Arctic anticyclone between 2007 and 2012 in the eastern part of the Arctic resulted in higher frequency of the northern and east-northern winds. This fact in its turn resulted in less frequency of flaw polynyas in the Eastern Arctic Seas during the second part of the 2007-2012 period. At the same time, the frequency of flaw polynyas opening in the Western Arctic Seas did not change (Table 12).

Table 12.

Average frequency of flaw polynyas opening in the Western and Eastern Arctic seas during 2007-2012, %

Seas	Average	Periods	
		2007-2009	2010-2012
Western Seas (Kara and Laptev)	71	86	86
Eastern Seas (East-Siberian and Chukchi)	40	66	51

Table 13 shows that melting processes slowed down and amount of first-year ice increased in the Eastern Arctic Seas in 2010-2012. This was caused by episodic change of cyclonic circulation to anticyclonic in spring-summer period, when sea ice is melting. 40% of the East-Siberian Sea and 10% of the Kara Sea were covered by the first-year ice by the start of the new sea ice formation season in 2013 (Table 13).

Table 13.

Mean areas of the first-year ice in the Arctic seas by the end of September 2007-2013, %

Sea	Average	2007-2012	2007-2009	2010-2012	2013
Kara	29	4	4	4	10
Laptev	33	10	16	5	0
East-Siberian	57	10	5	15	40
Chukchi	15	2	0	3	0

Therefore conditions of ice formation such as ice edge position, variability of sea ice parameters in the Western Arctic Seas during 2007-2013 were significantly various as a result of atmospheric processes change. Change of cyclonic circulation to anticyclonic is typical during the transition time between warm and cold climate periods.

3. Scenario of the most probable ice conditions before and after 2020

3.1. Climate oscillations in the Arctic and change of sea ice conditions in the Arctic seas

Research results, obtained in the AARI [Frolov et all, 2007; Frolov I.E. et all, 2009] have demonstrated that long-term changes of annual surface air temperature in the Arctic (and other areas), ice extent and other hydrometeorological parameters in XX – beginning XXI centuries were characterized by cyclic oscillations of 60, 20, 10 and less years. These oscillations were observed during the time of quasi-linear warming trend that is possibly part of the 180-200-year cycle and are caused by natural factors (mainly by change of solar fluxes) but are not connected with human activity.

The Arctic climate is characterized by variability of natural processes registered during the entire XX century. Air temperature in the Arctic zone (70-85N) was characterized by long-term natural oscillations with pronounced l cycle about 60 years (Fig. 6). This cycle represents all natural phenomena in the Arctic that happened in the XX century: air temperature decrease in the beginning of XX century, Arctic warming in 1920-40th, cooling in 1960-80th, the following warming, which started in the middle of 1980th and reached its peak in the beginning of XXI century.

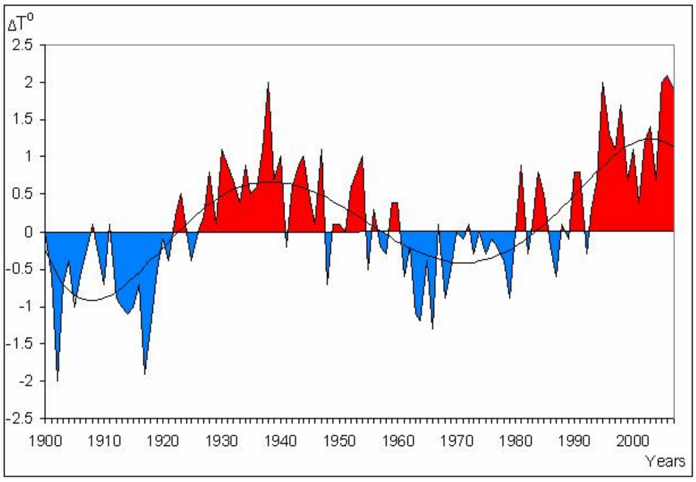

Fig. 6. Changes of anomalies of mean annual temperature (ºC) in the area between latitudes 70-85ºN in XX – beginning XXI centuries

Ice cover changes in the Arctic Ocean during the XX century were characterized by negative linear trend with simultaneous cyclic oscillations about 60, 20 and 10 years. Negative linear trend with simultaneous long-term oscillations with the main 60-year cycle was observed in the Western Arctic seas (Greenland, Barents and Kara) (Fig. 7). Oscillations of sea ice area in the Eastern Arctic seas (Laptev, East-Siberian and Chukchi) were mainly about average annual (excluding last years). Ice area oscillations in this region are characterized by strong interannual variability and 60-year cycle is less pronounced than in the Western Arctic Seas.

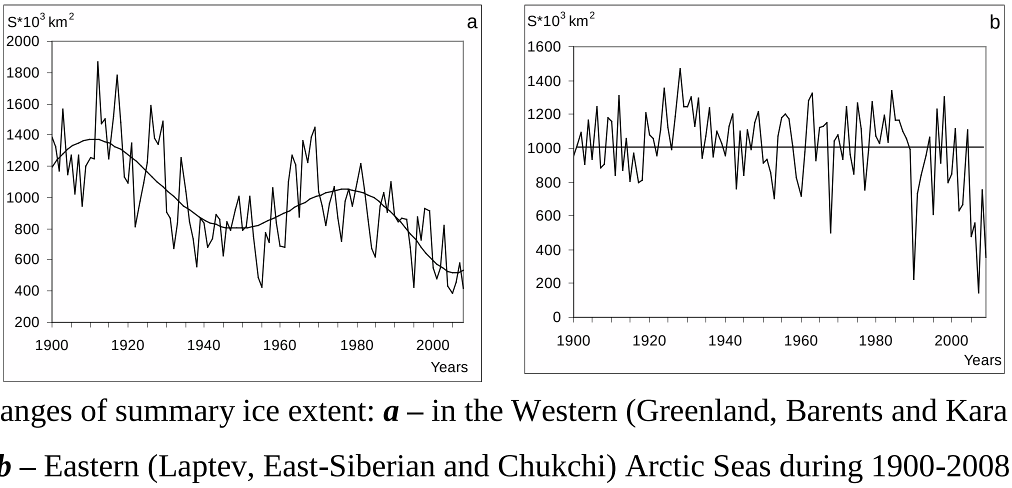

Fig. 7. Changes of summary ice extent: ***a*** – in the Western (Greenland, Barents and Kara seas) and ***b*** – Eastern (Laptev, East-Siberian and Chukchi) Arctic Seas during 1900-2008

3.2. Scenarios of climate and sea ice cover changes in the Arctic in the XXI century

Stable character of natural 60-year air temperature cycle in the XX century in the Arctic provides grounds for long-term scenario-forecast for the future decades of the XXI century (Fig. 8). Using physical-statistics methodology, AARI's specialists developed evaluative background forecast of the average annual air temperature in the area between latitudes 70ºN and 80ºN and ice extent in the Arctic Seas for the future decades of the XXI century [Frolov I.E. et all, 2007; Frolov I.E. et al, 2009]. According to this forecast, development of hydrometeorological and ice conditions in the Arctic during the future 5-10 years will happen under the influence of anomalously high air temperature, which starts to decrease sometime within 2015-2020. This decrease of air temperature is going to be prolonged and to continue till the middle of 2030-2040th , while the next warming phase is expected by about the mid-2060th.

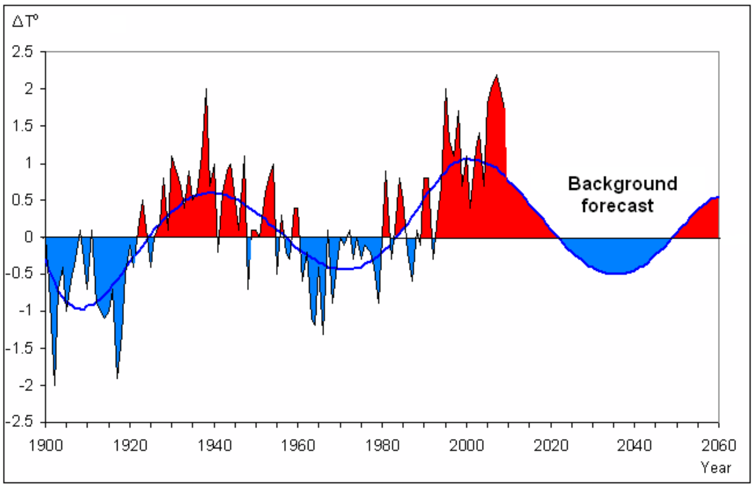

Fig. 8. Anomalies of average annual air temperature in the area between 70-80ºN in XX – beginning XXI century and its scenario-forecast

The forecast of possible ice extent changes in the Arctic Ocean in XXI century is based on natural "sinusoidal" oscillations, as shown on Fig. 9. This forecast takes into account 60-year and 20-year cycles in the Western Arctic Seas (Greenland, Barents and Kara) and 60-year cycle in the Eastern Arctic Seas (Laptev, East-Siberian and Chukchi).

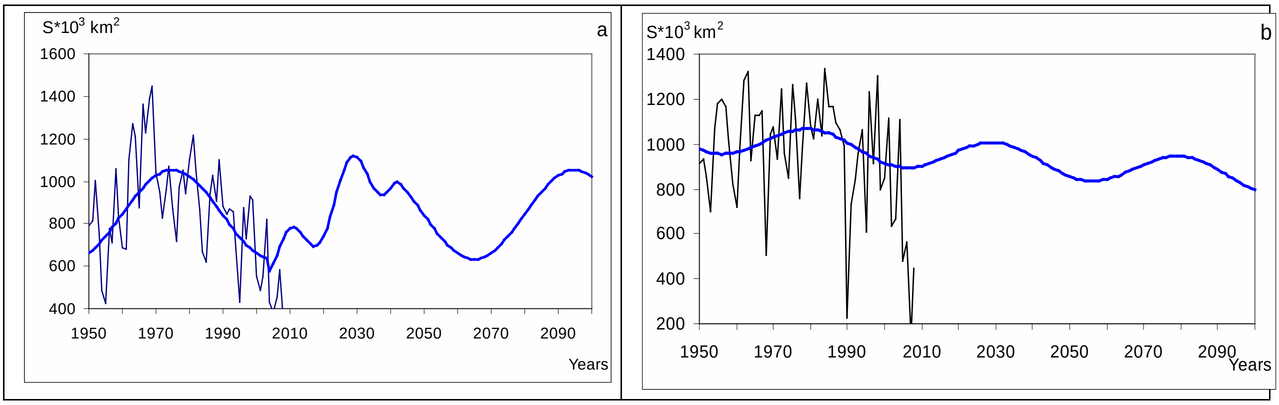

Fig. 9. Forecast of the total ice area in the western (a) and eastern (b) Arctic seas in the XXI century in August

Fig. 9 shows that in 2020-2040th years of the XXI century sea ice area in summer will increase with culmination in 2030-2035 in the Eastern Arctic seas and in 2035 in the Western Arctic seas. The second maximum is expected approximately in 2090-2095. Period of low ice extent is foreseen in 2050-2070th and at the end of the XXI century. The AARI's forecasts, based on main natural climate cycles and real trends, show that climate changes in the Arctic have cyclic oscillations but not a clear positive or negative trend. These conclusions are in contradiction to widespread assumption about significant decrease or even full disappearance of ice cover in the Arctic in the middle of XXI century.

4. Recommended navigational routes (economical and safety) in present climate conditions

4.1. The Northern Sea Route

Multiyear experience of navigation in the Arctic Seas determined main position of routes with favorable conditions for ice navigation. These routes have modern hydrographic support and are recommended (as standard ones) routes in the present time. Their position depends on season, hydrographic conditions, type of the vessel. However, the main factor defining the route of navigation is the sea ice cover.Huge spatial and temporal variability of sea ice conditions leads to significant difference in actual and standard routes of navigation. Navigational route, mapped through the most favorable ice conditions is optimal (or the easiest) option. In the most cases optimal route is a combination of fragments of recommended routes or coincides with one of recommended routes.

Barents Sea – Dikson Island (distance through open water is 495 nm). Optimal navigational route in June-October is determined by position of the Novozemelskiy ice massif. Three options of navigational routes are possible in the area between Kara Gate and Yugorskiy Shar Gate to the Beliy Island (Fig. 10, routes 1-3). If the Novozemelskiy ice massif is shifted to the west (the most frequent position during the first part of period), vessels are moving along the western coast of the Yamal Peninsula through the Yamal polynya. If the Novozemelskiy ice massif is in the center or shifted to the east, vessels are moving through the open ice along the eastern coast of the Novaya Zemlya Islands to the latitude 75ºN and further to the area near the Beliy Island. In favorable years when south part of the Novozemelskiy ice massif is weakly developed the navigation is possible from southern straits of Novaya Zemlya islands toward the north-east (the Beliy Island). During unfavorable years, when the area of the Novozemelskiy ice massif is more than the average one and it is transported to the south under the influence of winds and blocks the above mentioned routes, the best route for navigation is around north point of the Novaya Zemlya islands and further to the Dikson Island or to the Beliy Island (Fig. 10, route 4). The easiest option of navigation through the ice is typically the combination of traditional routes or the specific route, which is very close to one of them. Navigation from the Beliy Island towards the Dikson Island is generally along latitude and along the Ob'-Enisey polynya (Fig. 10, route 5). Navigation in this area in February-May is along the same routes as in June-October. Hogh concentrated ice is prevailing this time in this area. Navigational conditions are determined by the relation between the length of navigation in young and first-year ice of different ages, and by the presence of flaw polynyas. Favorable wind regime contributes to formation of the Yamal and Ob'-Enisey flaw polynyas with frequency of 70-100% in February (Fig. 11, routes 1-6). Navigation to the Ob' Bay is usually through the open water in summer period. Research of ice conditions in the Ob' Bay showed that icebreaker assistance in the winter period can be as beneficial as in the estuarial area of the Yenisei River.

Dikson Island – Chelyuskin Cape (distance through open water is 463 nm). Navigation to the harbors of the Laptev Sea and further to the east during June-October generally goes through the Vilkitskiy Strait. Traditional routes of navigation lie through the Matisen Strait or north from the Russkiy Island (Fig. 10, routes 7-9). The main barrier on this part of the NSR is fast ice near the western Vilkitskiy Strait and inside the strait. After fast ice fracturing the barrier is the drifting ice composing Severozemelsiy ice massif. Powerful nuclear icebreakers routinely use the method of channel breaking in fast ice for caravan escorting. Such approach is normally recommended until the commencement of the fast ice fracturing.

Dikson Island – Khatanga River estuary (distance through open water is 800 nm). Navigation routes in February-May from the Kara Sea to the Laptev Sea can lie through the Vilkitskiy, Shokalskiy, Krasnaya Armiya Straits and north of Arcticheskiy Cape. Ice conditions in Shokalskiy and Krasnaya Armiya Straits are not considered because of insufficient amount of observational data and impropriety of these straits for navigation during winter time. During the traditional navigation through the Vilkitskiy Strait the long band of fast ice should be passed (Fig. 11, route 7)

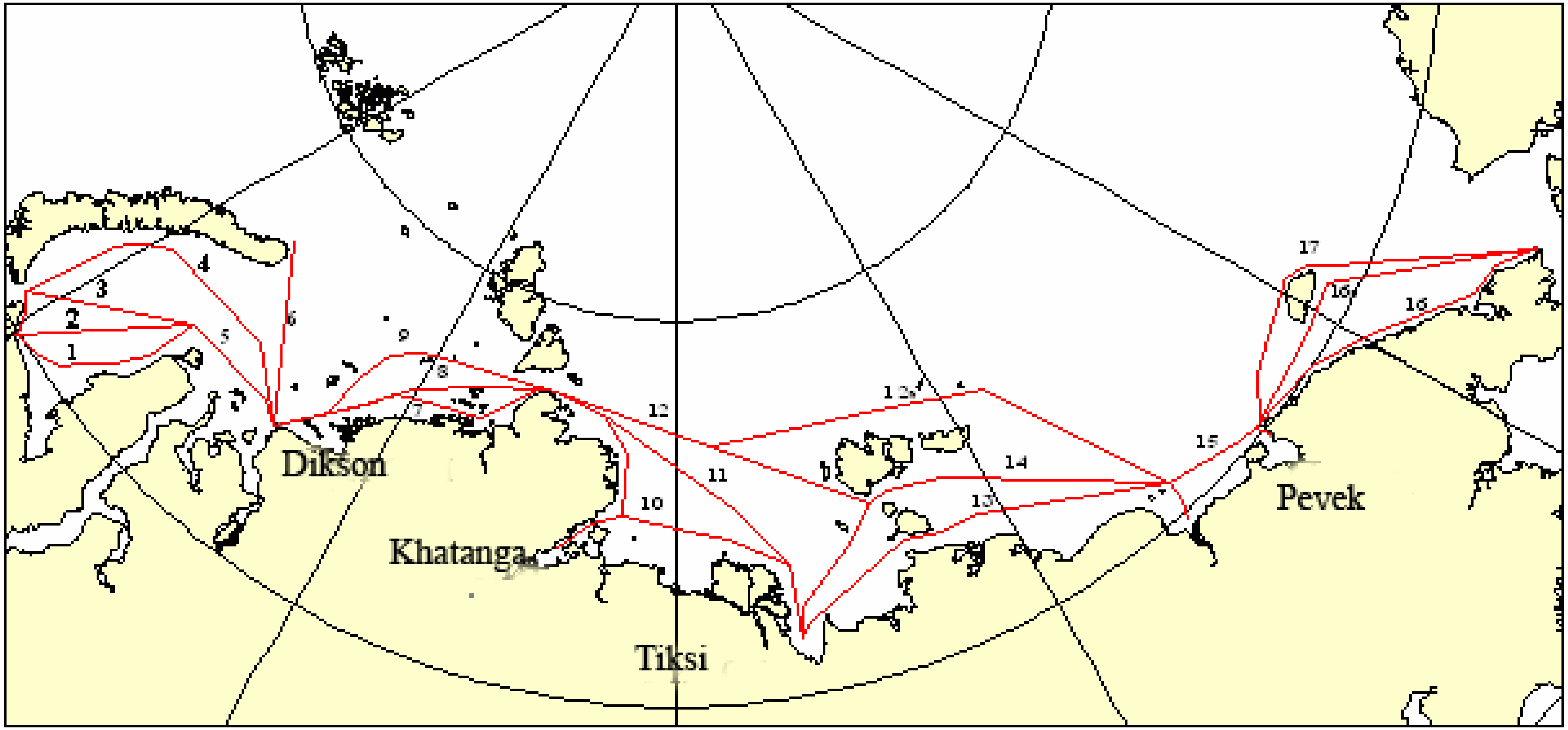

Fig.10. Optional navigation routes along the NSR in summer

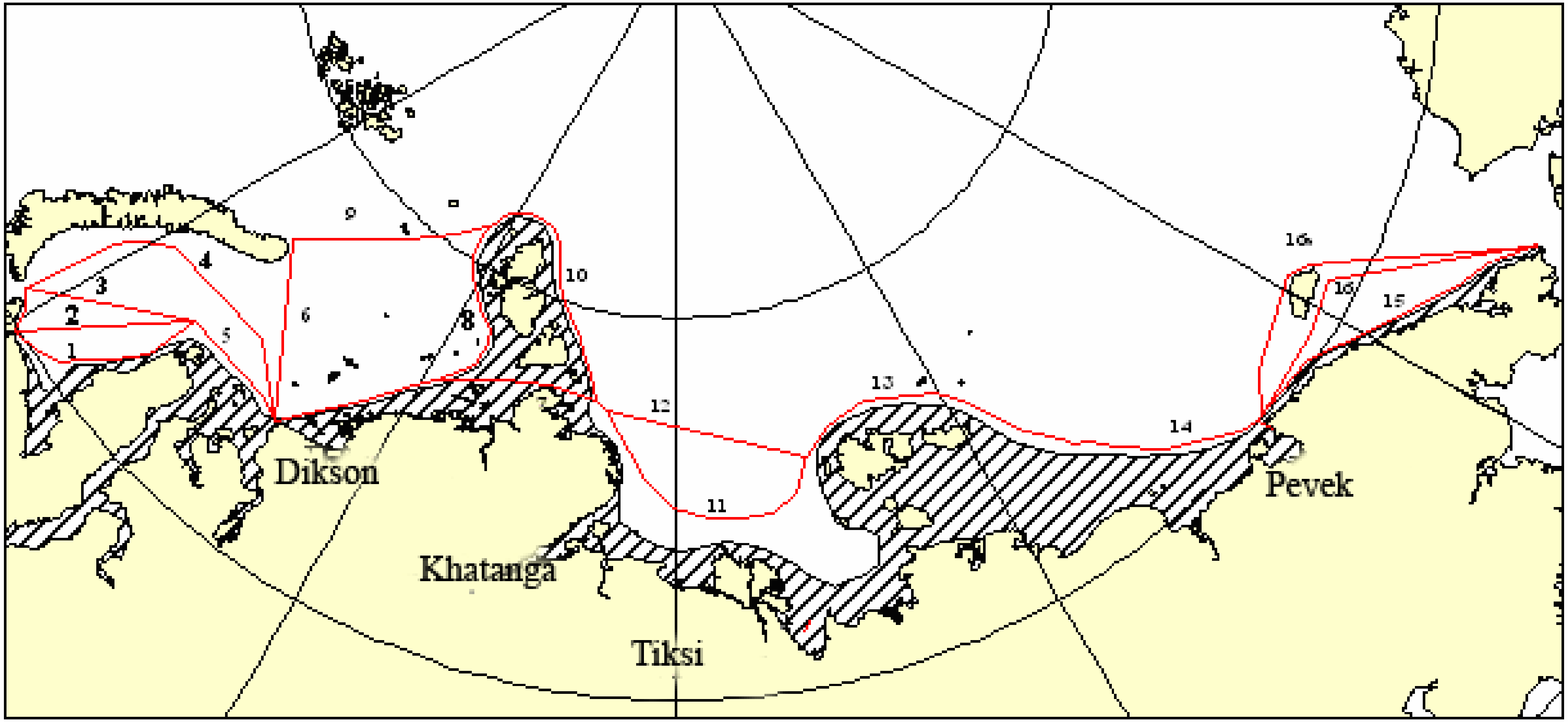

Fig. 11. Optional navigation routes along the NSR in winter

The route around the Cape Arkticheskiy is considered as one of the possible routes in favorable (easy) ice conditions (Fig 11, routes 8, 10). Stationary polynyas are developing in such years to the west of Severnaya Zemlya Archipelago. Feasibility of this route is significantly decreasing from February till May. Navigation through the Vilkitskiy Strait is the most appropriate during the years with average or heavy ice conditions.

Cape Cheluskin – Tiksi Bay (distance through open water is 615 nm). In June-October vessel caravans are generally moving from the Cheluskin Cape to the Tiksi Bay, harbors of the East-Siberian and Chukchi Seas and along the eastern coast of the Taymyr Peninsula toward the Preobrageniya Island (280 nm). Further to the east the go towards the Dunai Islands through the area of the low-concentrated ice and flaw polynya (Fig. 10, route 10). If the ice conditions are favorable, vessels are moving from the Andrey Island to the Tiksi Bay by the middle route, cross the Laptev Sea towards the Dunay Island and further go to the destination point (Fig. 10, route 11). During the years when south-western part of the Laptev Sea is occupied by consolidated ice, the northern fragment of the middle route is used: vessels cross the Taymyr ice massif from the Andrey Island towards the east-north-east up to the longitude 125°E and further move through the open water to the destination point (Fig. 10, route 12). The turning point from the transit route to the Tiksi Bay is located in the area of Lena flaw polynya at the longitude 125°E. Average length of the route from the turning point to the fast ice edge is 34 nm.

Tiksi Bay – estuary of the Kolyma River. Navigation from Tiksi to the estuary of Kolyma River is possible by three routes: north of the Novosibirskie Islands (Fig. 10, route 12-a), central – through the Sannikov Strait (Fig. 10, route 14) and coastal – through the Dmitriy Laptev Strait (Fig. 10, route 13). Selection of the route depends on draught of the icebreaker and escorted vessels, ice conditions (defined by position of ice edge) in the Novosibirskiy and Yanskiy ice massifs, and the destination point. The route around Novosibirskie Islands goes in shallow, about 15 m depths (distance along the open water is 1005 nm). This route is available for the modern icebreakers and high-capacity transport vessels. Navigation through the Sannikov Strait is limited by 13 m depth, which makes it difficult for navigation. However, Sannikov Strait can be passed in case of precise motion along the fairway (the distance through open water is 820 nm). The route through the Dmitriy Laptev Strait is the shallowest (the distance through open water is 765 nm). This route can be used by harbor icebreakers like "Vasiliy Pronchischev", transport vessels with draft less than 7 m and river vessels.

Estuary of the Kolyma River – Shelagskiy Cape (distance through open water is 175 nm). Vessels move along the coast in June-October depending on position of close ice usually after fast ice fracturing (early fracturing in June 24, the late one is June 29). Icebreaker assistance through the channel made by icebreaker in the fast ice is possible (Fig. 10, route 15).

Harbor Pevek – Bering Strait (distance through the open water is 550 nm). Traditional route is along the northern shore of the Chukchi Peninsula (Fig. 10, route 17). Navigation toward the Billings Cape depends on sea ice condition and is possible to the north of the Long Strait (Fig. 10, route 16a) or to the north of the Wrangel Island (Fig. 10, route 17). The route to the north of Long Strait depends on the position of the Wrangel ice massif and the ice age. If the Wrangel ice massif is located in its southern position (near the Chukchi coast), the route to the north of Long Strait – along the southern coast of the Wrangel Island is more favorable. In some years, when the Long Strait is completely covered by consolidated ice, large area of the low-concentrated ice and open water may form south-east and north of the Wrangel Island. In this case the most favorable route of navigation is to the north of the Wrangel Island. Leads are often forming between Wrangel and Ayonskiy ice massifs (in the area between the Billings Cape and Shelagskiy Cape) and are used as favorable routes. Table 14 illustrates the most important features of transit navigation: position of the most favorable routes, length of navigation in consolidated ice and in the fast ice.

Table 14.

Frequency (P, %) of the favorable navigation along specific segments of the NSR and total length of the NSR (nm) in the beginning, middle and at the end of standard navigational period

Navigational segment of NSR	Frequency (P,%)		
	June	August	October
Through the Kara Gate (or Yugorskiy Shar Gate)	85	55	20
Around Cape Gelaniya	15	45	80
Through the Vilkitskiy Strait	95	100	100

Around the Cape Arcticheskiy		5	0	0
Through the Sannikov Gate		0	80	75
Around the Novosibirskie Islands		100	20	25
South of Wrangel Island		15	20	25
Along the Chukchi coast		85	80	70
Total length of the transit route	Average	2800	2500	2300
	Minimum	2350	2200	2100
	Maximum	3400	2800	2650

4.2. High-latitudinal route

High –latitudinal route goes through the northern margins of the Arctic Seas and adjacent areas of the Arctic Basin. This route provides important reserve option for transit navigation, searching of new navigational routes, extension of the navigational period and increasing the speed of vessels escorting. Advantages of the high-latitudinal routes in comparison with NSR include: decreasing the length of navigation, hydrographical safety (depth), weak ice pressure. However, efficiency of transport navigation along the high-latitudinal routes completely depends on the ice class of transport vessels and the quality of hydrometeorological support. Modern remote sensing methods (artificial Earth satellites, aircraft radars) allow determining spatial position of appropriate areas for navigation. In combination with the knowledge on conditions of ice navigation this information allows to choose optimal route of navigation. In [Buzuev et al., 1988] two main variants of high-latitudinal transit routes were proposed (Fig. 12).

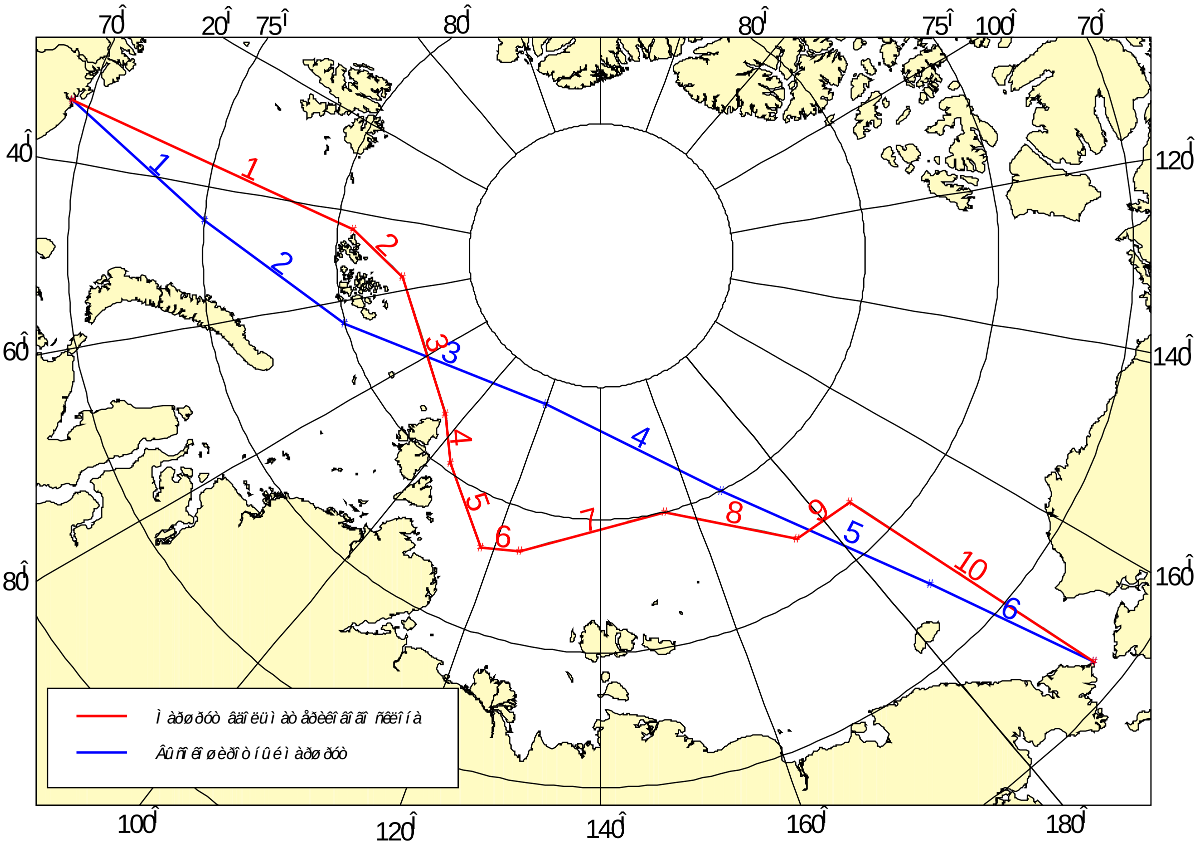

Fig. 12. Scheme of high-latitudinal transit routes. Red line – high-latitudinal route along the continental slope, blue line – the shortest high-latitudinal route

The shortest high-latitudinal route (Murmansk – Bering Strait) (total length 2677 nm) goes from Murmansk harbor to the south-eastern Franz-Josef Land archipelago and further by shortest way to the Bering Strait. The shortest route consists of 6 parts:

1) Murmansk – point 75°00´N, 45°00´E;
2) point 75°00´N, 45°00´E - point 80°00´N, 65°00´E;
3) point 80°00´N, 65°00´E - point 84°00´N, 120°00´E;
4) point 84°00´N, 120°00´E - point 80°00´N, 167°00´E;
5) point 80°00´N, 167°00´ E – point 72°30´N, 175°00´E;
6) point 72°30´N, 175°00´E – Bering Strait.

The easiest ice conditions for navigation in summer are observed on parts 1 and 2. Prevailing open water and compact ice-covered zones with concentration of 70-80% are observed there in July-September. Other parts of the route are covered by ice of various concentration.

The route along the continental slope is perspective as well. This route passes between isobaths 200 and 2000 m north of the Barents, Kara, Laptev, East-Siberian and Chukchi seas. Total length of the route from Murmansk to the Bering Strait is 3055 nm.

The route consists of 10 segments, which are characterized by homogeneous ice conditions (Fig. 12). Segment 1 starts in Murmansk and finishes at the south-western coast of Franz-Josef Land. In summer it is mostly ice free. Segments 2 and 3 are located to the north of Franz-Josef Land and Kara Sea (on the average along the latitude 82ºN). These segments are the northernmost ones within the entire route. In comparison with the eastern area, ice conditions at these segments are the most favorable for navigation. Average length of the route in consolidated ice reaches minimal value in the middle of September. Segments 4-7 go through the northern Laptev Sea and adjacent Arctic Basin (along the latitude 79°37´N). These route segments typically pass through the consolidated ice area. Segments 8-10 are characterized by strong interannual variability of sea ice cover. These segments go to the north of the East-Siberian and Chukchi Seas.

5. Estimation of sea ice influence on the navigation efficiency in the Arctic seas under the different scenarios of climate changes

The most important parameters of sea ice cover, which influence the efficiency and safety of ice navigation are the next:

- total ice concentration and ice age;
- ice thickness;
- ice pressure;
- size of ice floes;
- hummocks and ridges concentration;
- leads, fractures and cracks.

Ship velocity is an ultimate measure of difficulty of ice navigation. It reflects the influence of all noted above sea ice parameters.

Total ice concentration is the main affecting parameter in summer. It is used as criteria for icebreaker escorting requirement. Effect of total ice concentration and estimated ice thickness on ship velocity was obtained on the basis of shipborne observations (Buzuev, 1981). Increasing of the total ice concentration by 10% results in decreasing of the caravan speed (1 icebreaker and 1 transport vessel) by 10 %. Amount of young ice is the most important factor in winter and spring, because navigation through the first-year ice is easier than through the multiyear ice.

Ice thickness. In winter, when sea ice concentration is predominantly 90-100%, the distribution of ice thickness plays crucial role in effective navigation. In spring-summer season, ship speed is higher than in the fall-winter even for navigation in the ice of the same thickness. This is caused by seasonal changes in physical and mechanical properties of sea ice.

Snow depth is also important parameter for navigation during the cold season. Its effect on navigation is similar as additional ice layer would provide (Kashtelyan, 1968).

Hummocks and ridges significantly influence ice navigation. Increasing of hummocks and ridges concentration by 10% (20% of the total ice area) leads to increasing of the ice “capacity” by 25% (Gordienko, 1963; Sergeev, 1980).

Melting stage. Melt ponds reduce ice strength and simplify navigation through the ice.

Size of ice floes is important parameter in fall-winter and spring periods if total ice concentration is 90-100%. Field observations show that horizontal floe size significantly affects ship speed. Navigation through huge ice floes is slower than in brash ice.

Ice pressure is one of the most important parameters, which influences navigation, particularly in winter, when ice concentration is 90-100% and ice thickness is above 70 cm. Ice pressure is often the cause of ice-enforced vessels drift and damage.

Leads, fractures and cracks are typical for ice cover in winter and contribute to easier ice navigation. Leads, fractures and cracks appear in the fall and continue to develop throughout winter season till April-May. Re-frozen ice packs, fractures and leads normally disappear during the melt season. Winter navigations in the western Arctic confirm the efficiency of using leads, fractures and cracks while selecting the optimal navigational route in the ice-covered seas (Frolov, 1999). *Flaw polynyas* are succesfully used for navigation in the Arctic Seas in winter.

Total ice cover area in the Arctic seas also determines conditions of navigation along the NSR (Table 15).

Table 15.

Relation between total length of navigation in consolidated ice along the NSR (L_{7-10}, %) and total area of consolidated ice in the Arctic seas (S_{7-10}, %)

S_{7-10}	100	80	60	40	20
L_{7-10}	73	52	30	13	6
L_{7-10} / S_{7-10}	0,73	0,65	0,50	0,32	0,30

The data in Table 15 confirm that selective motion in consolidated ice has more important influence on reduction of length of navigation than decreasing of total area of consolidated ice. However, it is obvious that expected changes of ice extent in the Arctic seas will have influence on ice conditions along the NSR. Specialists from the Institute of Atmospheric Physics used results of numerical experiments with global climate model to estimate duration of navigational period (Mokhov, 2011). Based on data of this research duration of navigational period along the NSR will be 134 days (with standard deviation 38 days) till the end of XXI century. Total ice concentration of 15%, 30% and 50% was used as criteria.

According to the AARI scenario-forecast (see Section 3), sea ice parameters in the middle of XXI century will be close to parameters during the cold period of 1963-1980 with significant interannual variability. Increased ice extent in the Arctic Seas will lead to increased length of navigational route in consolidated ice and in fast ice and decreased period of non-icebreaker navigation. Maximal increase of ice extent during 2020-2030 is expected in the Barents and Kara Seas. At the same time, in these seas significant intensification of navigation is expected. Intensified navigation is related to shelf exploration, mineral resources extraction and transportation. Using the high-tonnage vessels in more difficult ice conditions will require reinforcement of the ship hull and increasing capacity of power engines. Decreasing the period of non-icebreaker navigation will require enhancing the icebreaker support and, as a consequence, increasing the tonnage and power of the icebreaker fleet. The following algorithm is recommended to estimate the influence of ice conditions on efficiency of navigation:

- analysis of the variability of sea ice conditions along the navigation route: selection of specific types of ice conditions, determination of frequency of distinguished types;
- defining regularities of ice parameters distribution, significantly influencing the efficiency of navigation in the ice during the year;
- estimating periods of possible non-icebreaker navigation of modern and perspective transport vessels with respect to criteria of definite kind of navigation depending on ice conditions type;
- estimating the period of navigation with icebreaker assistance and required icebreaker support with respect to capabilities of modern and perspective icebreaker fleet in accordance with criteria of navigation efficiency of the caravan in the ice covered area.

6. Conclusions

Intensification of using the NSR for transit navigation last year demonstrates profitability of regular cargo transportation from Europe to Asia and back. This is also supported by enhanced cargo tonnage, application of flexible tariff policy and significant improvement of sea ice conditions along the navigational routes in summer.

If the present tendency of sea ice cover decreasing in warm season will sustain during the next 10-15 years, possible non-icebreaker navigation will increase and duration of transit navigation along the NSR with icebreaker escorting will increase up to half-year. However, stochastic nature of environmental parameters makes long-term climate forecast questionable.

Ongoing climate change, intentions of increased cargo transportation along the NSR, extending periods of transit navigation, using the high-latitudinal routes predetermine necessity of maintaining present and building new icebreaker fleet. This will guarantee reliable and safe operations along the NSR.

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