

INTERANNUAL AND SEASONAL VARIABILITY OF ARCTIC SEA ICE EXTENT ACCORDING TO SATELLITE OBSERVATIONS

A.V. Yulin¹, N.A. Vyazigina¹, E.S. Egorova¹

¹Arctic and Antarctic Research Institute, St. Petersburg

✉ icefor@aari.ru, naty_vyazik@mail.ru, egorova@aari.ru

The interannual and seasonal changes of Arctic sea ice extent according to satellite observations from 1978–2018 are analyzed. Steady reduction in the sea ice cover over the research period is reported. In addition, we denoted the especially pronounced during the summer months acceleration of the reduction of the sea ice extent in 2009–2018. The uneven reduction of the sea ice extent over the seasons is shown. In 2009–2018 the processes of the reduction of the sea ice are earlier and faster than in 1979–1988.

Keywords: Arctic Ocean, sea ice extent, interannual and seasonal variability, rate of the sea ice extent change.

Introduction

Ice cover of the Arctic Ocean and Arctic seas is the most available and informative indicator of the atmosphere–sea ice–ocean system and its changes. Ocean cooling during autumn–winter season results in increase of sea ice extent and thickness, while heating of ocean during spring–summer season results in sea ice melt and decline.

In this paper we analyze interannual and seasonal variability of the Arctic sea-ice extent for satellite record from 1978 to 2018. Sea-ice monitoring represents substantial interannual changes in ice extent both in winter and summer seasons.

It should be noted that sea ice extent variability has a long history of research. A number of studies show a consistent downward trend in sea-ice extent over the period of satellite observations, with even more intense decline during the last decade [1, 2, 3, 4]. This fact can be confirmed by comparison of Arctic sea ice extents in different periods: at the beginning of regular satellite observations in 1970–1980s sea ice covered approximately 12 000–12 300 thousand sq. km during winter season and 7 200–7 700 thousand sq. km during summer melting season; during the recent decade, sea ice extent has declined to 11 3000–17 000 thousand sq. km and 4 600–

5 500 thousand sq. km, respectively.

Sea ice extent in the Arctic has a well-defined seasonal cycle which has changed significantly over the past decade. During the period 2009–2018 the frequency of negative extent anomalies and the number of absolute minimum extents increased. At the end of winter season in 2016 Arctic sea ice extent was 11 365 thousand sq. km which was the record low maximum extent since 1978. In summer season 2012 the lowest Arctic minimum ice extent was observed (3 515 thousand sq. km). During the autumn period of 2018 the maximum rate of ice growth per month was indicated when sea ice extent increased for 3 477 thousand sq. km in November.

It is obvious that sea ice extent in the Arctic Ocean reveals significant interannual and seasonal changes in recent decade resulting in abnormal development of ice conditions. These changes in winter and summer ice extent require further detailed analysis.

Data sources

In this paper we use data sets from the World Data Center, based on daily passive microwave data for the north polar region. The time series are generated from SSMR-SSM/I-SSMIS data processed in the National Snow and Ice Data Center (NSIDC) using the

NASA Team algorithm, and copied to the World Data Center database from the NSIDC archive. The data cover the period from 26/10/1978 up to now [5,6]. Data set contains fields of ice concentration estimates as a percentage of ice cover in cells of a 25 km polar stereographic grid. It should be noted that these data have some limitations and inaccuracies, such as underestimating of the ice concentration during melting, gray wedges and speckles, as well as errors in areas of coastlines and in the zones of polar cyclones. However, this data set provides a unique opportunity to estimate probabilistic characteristics of ice concentration, ice edge position and ice extent.

We use time series of monthly average values of ice extent in the Arctic Ocean from the autumn season of 1978 to the end of 2018. Data archive is available online on the AARI website [<http://wdc.aari.ru>, 5].

Interannual variability of sea ice extent in the Arctic Ocean

Figure 1 demonstrates interannual variability of monthly average ice extents for the most representative two months

(April and September) together with annual average values of the satellite record 1978-2018. April is a period of maximum ice extent and indicates ice growth during the previous autumn-winter season. September is a period of minimum sea-ice extent due to spring-summer melting. Annual average ice extents represent total balance of sea ice extent in the Arctic as a result of winter growing and summer shrinking.

Ice extent changes in the Arctic Ocean have a consistent downward trend [2, 3, 4]. Range of interannual variability of sea ice extent in April is significantly less than one observed in September (Figure 1).

Table 1 contains statistical parameters of monthly average ice extents and their variability.

At the end of winter growing season (March-April) in different years the highest values of maximum ice extent can reach 12 539–12 608 thousand sq. km and the lowest values of maximum ice extents are 11 329–11 365 thousand sq. km. Interannual range of observed ice extent is 1 175–1 280 thousand sq. km and standard deviation is about 300 thousand sq. km.

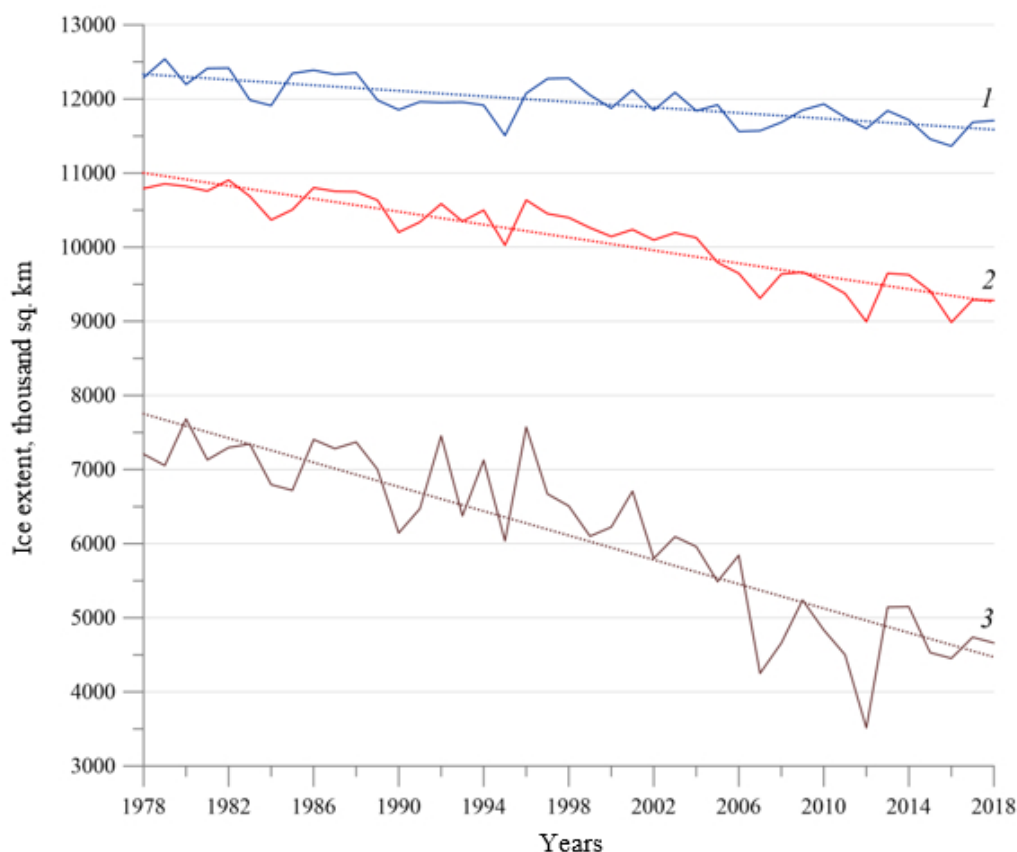


Figure 1 — Interannual variability of sea ice extent in the Arctic Ocean: 1 – sea ice extent for the season of maximum growing in April, 2 – annual average sea ice extent, 3 – sea ice extent for the season of maximum decline in September, dotted lines are linear trends.

Monthly average sea ice extent in the Arctic Ocean and main statistical characteristics of it changes for the period 1978-2018

Months	Parameters, thousand sq. km				
	Average	Minimum	Maximum	Amplitude	Standard deviation
I	11810	11095	12579	1484	377
II	11918	11207	12682	1475	361
III	11971	11329	12608	1280	294
IV	11962	11365	12539	1175	294
V	11684	10819	12407	1588	344
VI	10901	9834	11765	1930	524
VII	8961	7553	10116	2564	820
VIII	6859	4754	8081	3327	963
IX	6113	3515	7682	4168	1118
X	7927	5718	9312	3595	1048
XI	10093	8348	11150	2802	627
XII	11401	10303	12202	1899	454
Annual average	10132	8986	10906	1920	565

In the years of extreme sea ice cover reduction, annual minimum extent at the end of summer melting season (August-September) may decrease to 3 515–4 754 thousand sq. km, while the highest annual minimal ice extent may reach 7 682–8 081 thousand sq. km. Consequently, interannual range of seasonal minimum extent is 3 327–4 168 thousand sq.km and standard deviation is about 1 000 thousand sq.km.

To sum up, the range of interannual variations of sea ice extent may be up to several million kilometers and standard deviation may varies from 30 thousand sq. km in winter to 1 000 thousand sq. km in summer season.

The highest interannual variations of Arctic ice extent are observed in September at the end of summer melting. Ice extent may grow up to 7 600 thousand sq. km during the years of intense ice cover development. In this case there is a risk of occurrence of drifting ice which may block shipping routes and coastal areas. Arctic ice extent during the years of low development of sea ice cover is not more than 3 515 thousand sq. km. and results in ice-free Arctic seas and part of Central Arctic basin. The difference between minimum and maximum values of ice extent may reach

4 168 thousand sq. km which is almost equal to the area of European part of Russia (5 183 thousand sq. km).

Figure 2 provides an illustration of high interannual variability of ice cover comparing high and low minimal ice extent in September in different years. During the years of high ice extent Russian Arctic seas are covered by ice up until the season of the next ice formation in autumn. In the years of low ice extent, Arctic seas completely lose sea ice, the passage zone along the Northern Sea Route is ice-free and the edge of drifting ice is occurred near 80–85° N.

The analysis of frequency distribution of ice extent in the Arctic for the period 1978–2018 (Figure3) shows the bimodal distribution characterized by 2 specific groups of values. First of them ties high ice extents (with values within 10 000–11 000 thousand sq. km) and characterizes the period 1978–1998. Another group ties low ice extents (values within 8 800–9 900 thousand sq. km) and describes the recent two decades.

The main features of interannual variability of the 42-year record of ice extent are consistent downward trends, which are well approximated by linear functions [2, 3, 4]. Linear trends are statistically significant

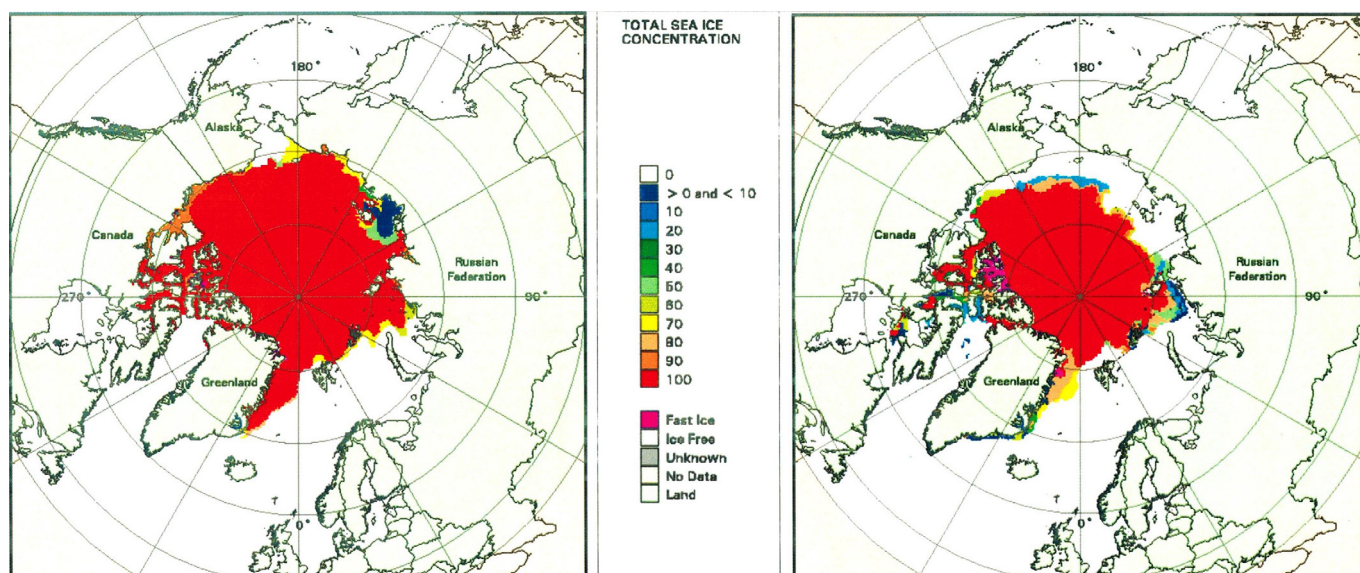


Figure 2. Charts of sea ice distribution during the years of high (the left one) and low (the right one) ice extent in September [5].

at the 95% level and have determination factor R^2 about 0.7-0.8, indicating high contribution of trend to the total variance of Arctic sea ice extent.

Linear retreat (by linear trend) of ice extent for the total 42-year record is rated at -18 000 sq. km per year in April, -80 000 sq.km per year in September and total rate is -40 000 sq.km per year (see Figure 1).

However, according to some authors [1, 2, 3, 4] the decline of Arctic sea ice extent

is non-uniform. Recent two decades show accelerated decrease of sea ice extent which is especially distinct during summer seasons. The analysis of linear trends individually for decades of 1978–1998 and 1999–2018 demonstrates definitely higher ice decline in the Arctic Ocean both in summer and winter seasons for the past two decades (Figure 4). Summer seasons show the most distinctive decline of sea ice extent (see Fig. 4b).

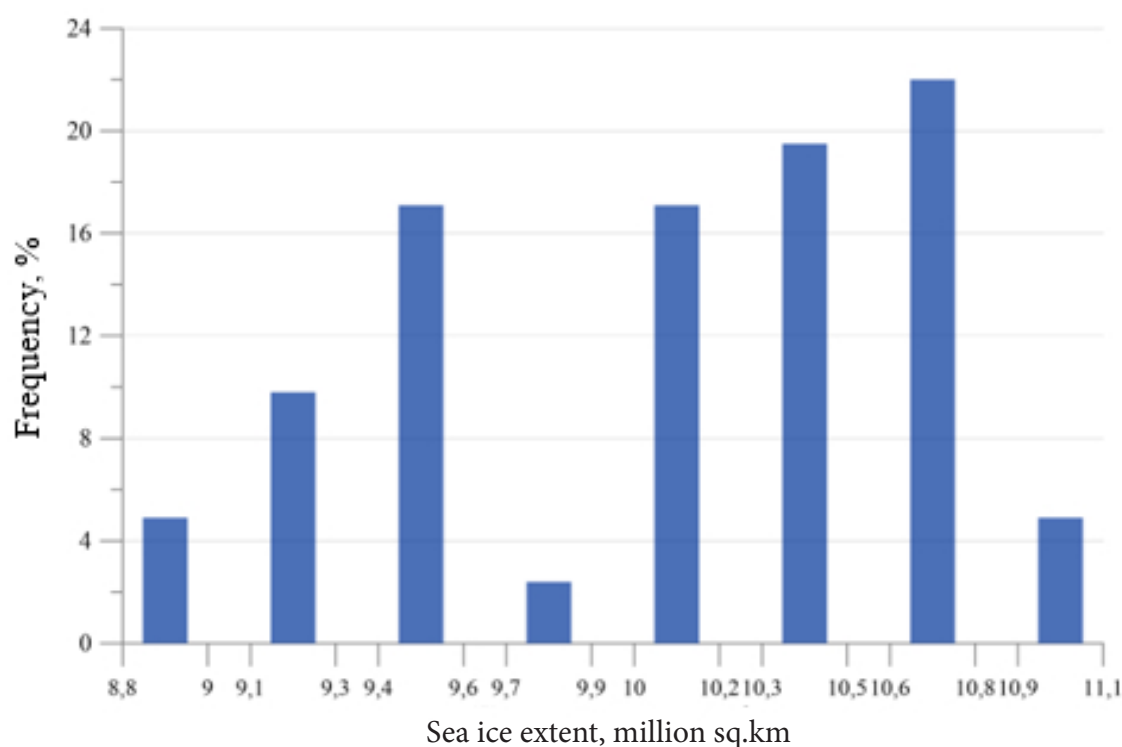


Figure 3. Frequency distribution of annual average sea ice extent in the Arctic Ocean for total record of 1978–2018.

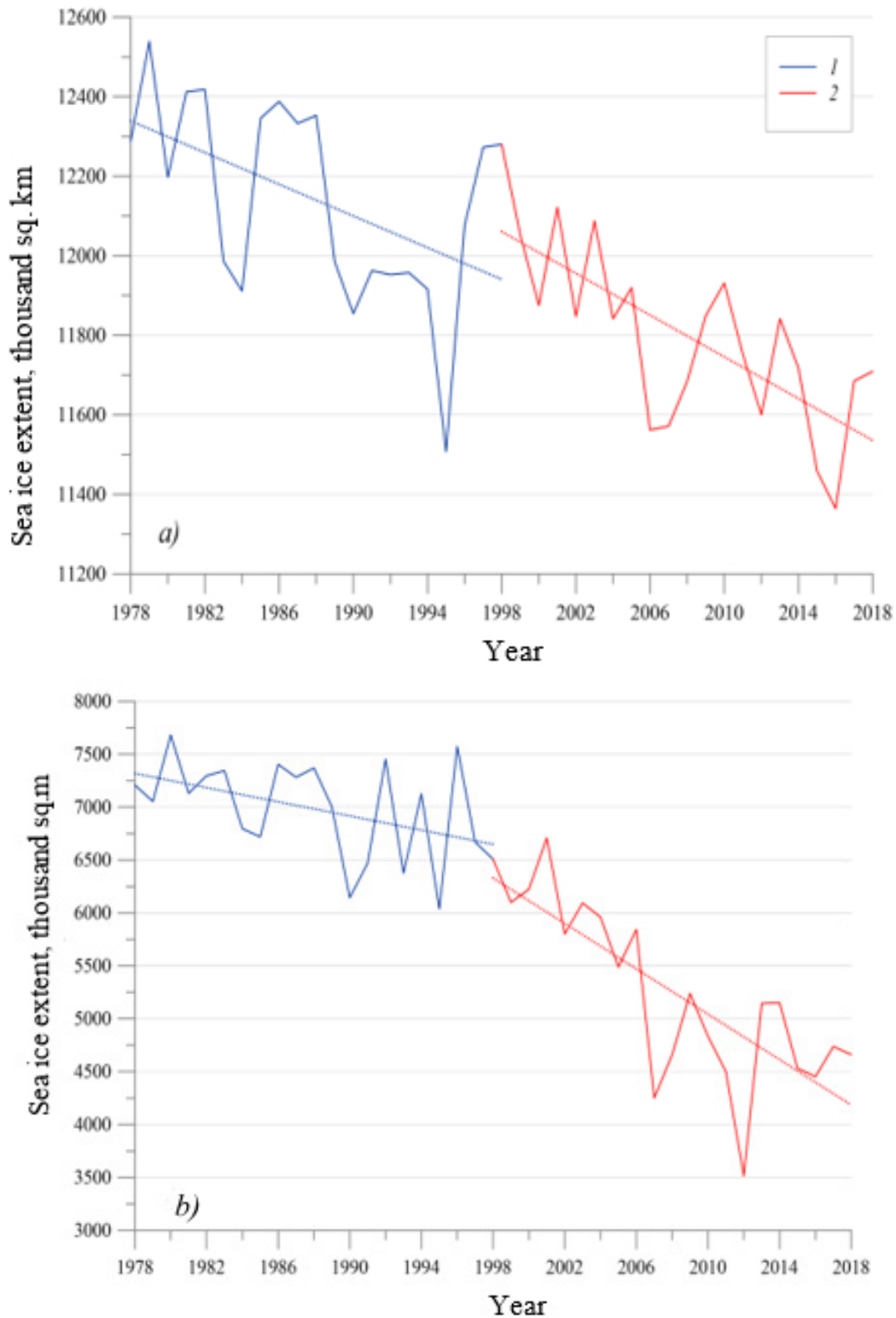


Figure 4. Approximation of interannual variability of Arctic sea ice extent in the periods of maximum ice extent in April (a) and minimum ice extent in September (b) for two twenty-years periods (1 – 1978–1998, 2 – 1999–2018) and their linear trends (dotted lines).

Table 2 represent monthly average ice extent in the Arctic Ocean for the periods of high (1978–1998) and low (2009–2018) sea ice extent, as well as the difference between them.

Data (see Table 2) represent general decline of Arctic sea ice extent for the 42-year record which is different over the

seasons. Wintertime extent has declined by 600–700 thousand sq. km, thus ice-free area in the western Arctic Seas (Greenland See and Barents Sea) has increased by the same value. Summertime extent loss appears to be more significant amounting 2 200–2 500 thousand sq. km. Consequently, the same is the increase of ice-free area within the

Monthly average ice extent in the Arctic Ocean for the periods of high and low ice extent, thousand sq.km

Months	Periods of record		
	1979–1988	2009–2018	Difference between periods
I	12151	11395	756
II	12253	11520	733
III	12268	11650	617
IV	12288	11691	597
V	12043	11312	730
VI	11457	10210	1247
VII	9806	7852	1954
VIII	7792	5583	2208
IX	7208	4676	2532
X	8889	6538	2351
XI	10664	9292	1372
XII	11827	10854	973
Annual average	10720	9380	13400

marginals Arctic seas. Therefore about half of the Arctic Ocean was free of ice during the summer seasons of 1979–1988, while in the last decade 2009–2018 almost 2/3 (68%) of the overall Arctic Ocean was ice-free.

Seasonal variability of ice extent in the Arctic Ocean

Arctic sea ice extent variability has a well-defined seasonal cycle [3, 4, 5], with dividing into three periods:

- spring-summer period of ice extent retreat from May to September (5 months),
- autumn-winter period of ice extent active growth from October to December (3 months),
- wintertime slight growth of ice extent from January to April (4 months).

Characteristics of seasonal fluctuation are affected by Arctic conditions.

Sea ice formation in the Arctic begins at the end of August to the north of 80°N in areas with presence of old ice and lasts until the end of September inside these areas and in narrow near-edge zone. During this period no substantial gain of young ice is observed. From the end of September, the edge of ice formation extends to ice-free

areas. This results in rapid growth of Arctic sea ice cover.

Sea ice extent increases continuously from October to April. The most active sea ice growth occurs in the period from October to December and amounts 1 500–2 000 thousand sq. km per month up to January. Magnitude of ice extent growth diminishes in January and later on doesn't exceed 20–10 thousand sq.km per month until April, which is less than 1% of Arctic ice extent in that period, despite severe conditions of these months.

In April Arctic ice cover reaches its maximum extent with usual values approximately 12 000 thousand sq.km (see Table 1). Ice extent decline starts in May due to breaking and melting processes as well as sea ice export mainly through the Fram Strait. Ice cover stops its decline in September. Average ice extent in September is about 6 000 thousand sq. km (see Table 1). Ice cover which has survived summer melt consists mainly of old multi- and second-year ice.

However, considering year-to-year variability of sea ice extent and frequency distribution of its annual average amount (see Fig. 1, 3), it is insufficient to analyze only

annual average seasonal variability of ice extent for understanding the changes in the Arctic Ocean. The increasing ice cover in the 1970–1980s, as well as amplified decrease of sea ice extent revealed in recent decade make it necessary to consider these periods separately.

Figure 5 demonstrates annual average seasonal cycle of ice extent in the Arctic Ocean over the satellite record, as well as for two specific decades. The decade 1979 to 1988 is characterized by higher ice extent (so further it is referred to as the decade of high ice coverage), the decade 2009 to 2018 is referred to as decade of low ice coverage and is specified by lower ice extent values.

Seasonal curve shape is the same over the whole period of record (see Fig. 5). Recent decade is characterized by the three main periods: spring-summer, autumn-winter and winter period. Compared to the decade of high ice coverage, the period 2009 to 2018 reveals a substantial decline in total ice extent both in winter and summer seasons, with non-uniform decrease in different seasons.

Average increase of maximum sea ice extent in April is up to 12 288 thousand sq. km in the decade of high ice coverage and up to 11 691 thousand sq. km in the decade of

low ice coverage. Decrease of total ice extent in wintertime is about 600 thousand sq. km or 5% of total ice amount.

Maximum decrease of sea ice extent in September reached 7 208 thousand sq. km during the decade of high ice coverage and 4 676 thousand sq. km during the decade of low ice coverage. Extent of old ice at the end of summer melting season was reduced by 2 500 thousand sq. km, or approximately 35% of total ice extent.

Significant changes have occurred in a rate of ice fluctuation within an annual cycle.

During the period 1979–1988 ice extent was decreased by 5 080 thousand sq. km from 12 288 thousand sq. km in April to 7 208 thousand sq. km in September. During the autumn-winter season sea ice extent was increased by approximately the same value.

During the period 2009–2018 the decline of ice extent was from 11 691 thousand sq. km in April to 4 676 thousand sq. km in September, which amounted 7 015 thousand sq.km. Sea ice grew approximately the same extent during the autumn-winter season.

Area of the Arctic Ocean which is free of ice in summertime and covered by ice in autumn-winter season has increased by 2 000 thousand sq. km (38%) for the recent decade.

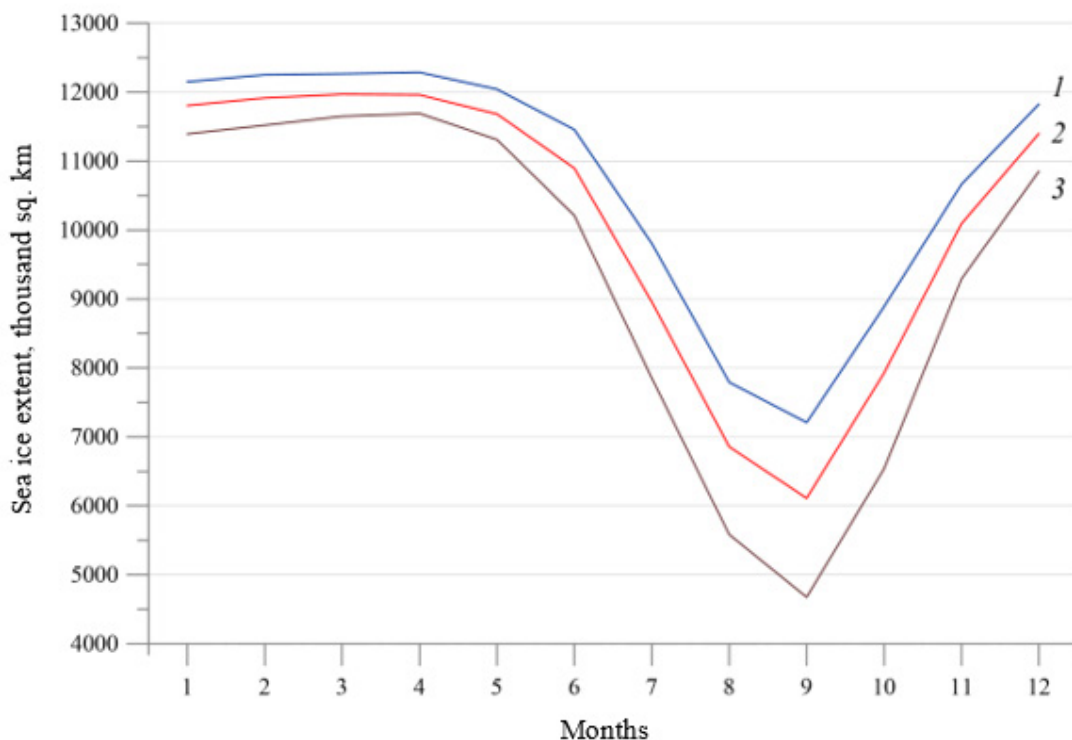


Figure 5. Seasonal cycle of ice extent in the Arctic Ocean: 1 – for total satellite record 1978–2018, 2 – for the decade of high ice coverage 1979–1988, 3 – for the decade of low ice coverage 2009–2018.

As a result, two substantial changes in seasonal fluctuation of Arctic sea ice are to be indicated during the past decade of low ice coverage:

- total annual ice extent has negative trend which is non-uniform over the seasons: the decrease is by 5% in autumn-winter and by 35% in spring-summer seasons;

- sea ice involved in ice balance, that is the area of the Arctic Ocean which becomes ice-free in summer and ice-covered in autumn-winter seasons, has increased by 2 000 thousand sq. km (38%) from 5 000 to 7 000 thousand sq. km.

For a more detailed understanding of changes, it is necessary to focus on the rate of ice extent changes within seasonal cycles, i.e. the difference between extent values in two consecutive months. Rate of ice extent changes is an informative indicator of ice growth and loss processes.

Figure 6 represents seasonal cycle of rate of monthly average extent changes from the previous month for the decades of high and low ice coverage, and the difference between them.

Rate of change of ice extent is remained almost the same from January to April during all periods under consideration. In 2009–2018, a slight increase in ice extent of about 100 thousand sq. km was observed

in the Arctic Ocean during this season, which was less than 1% of ice extent.

The substantial differences are revealed in ice extent changes during spring-summer melting season, which starts in April-May. In the past decade, ice retreat began earlier and at a higher rate, as compared to the decade of high ice coverage.

Absolute values of rates of extent change between June and July have increased substantially in the same period 2009–2018. The lowest sea ice extent has shifted to the period June-July and dropped to -2 355 thousand sq. km, compared to -2 015 thousand sq. km in July-August of 1979–1988 (see curve 2 on the Fig. 6). During spring-summer season the rate of ice extent change has increased by absolute value from -88 thousand sq. km in April-May to -300...-700 thousand sq. km in other months (see curve 3 on the Fig. 6). As a result, ice loss during spring-summer season was dramatically higher during the last years. Total average loss of ice extent has reached almost -7 000 thousand sq. km in the past decade of low ice coverage, compared to approximately -5 000 thousand sq. km in the decade of high ice coverage. Increase of melting ice extent and thus increase of ice-free area in the Arctic during summertime exceed 2 million sq. km. It should be mentioned that

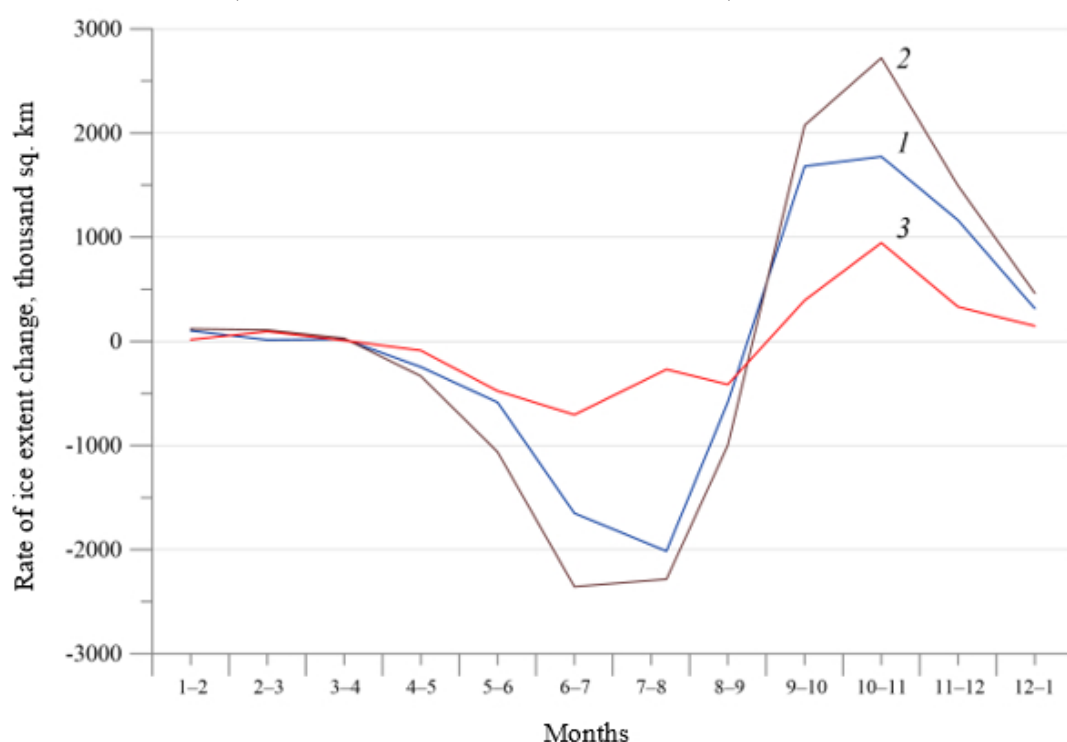


Figure 6. Average annual cycle of rates of ice extent changes in the Arctic Ocean: 1 – for the decade of high ice coverage 1979–1988, 2 – for the decade of low ice coverage 2009–2018, 3 – difference between two periods.

the additional loss of ice is due to melting of first-year thin and thick ice (100-150 cm thick) and old ice (more than 150 cm thick) [8].

The evidences of substantial changes in rates of sea ice melting in recent decade are the two record-lowest ice extents in 2007 and 2012 when ice dropped respectively for 2 780 thousand sq. km per month (in June-July of 2007) and 2 799 thousand sq. km per month (in July-August 2012).

These changes are an expected result of global warming, which is also affirmed by seasonal and interannual trend of rate of Arctic ice decline.

In autumn-winter season from September to December, ice extent increases due to ice formation. In recent decade, ice growth accelerated and expands compared to the decade of high ice coverage.

In 2009–2018 a significant increase in rate of extent change was observed in every month of autumn-winter period (see curve 2 on the Fig. 6). The peak of rate values occurred in the period of October-November and reached 2 721 thousand sq. km. Peak of rate of extent growth in 1979–1988 occurred in the same months but was only 1 775 thousand sq. km. Thus, increase of rate of ice extent growth between October-November totaled almost 1 million sq. km (947 thousand sq. km).

Rate of ice extent growth from the previous month has increased for all months during the past decade at a range of 148–947 thousand sq. km, resulted in significant gain of arctic ice extent of almost 2 million sq. km (see curve 3 on the Fig. 6). This newly-formed ice cover consists of predominantly new and young ice.

Nevertheless, this increase of ice extent growth during the autumn-winter season over the past decade indicates a rapid consumption of heat in the upper active layer of the ocean in autumn. This increase of rate of ice growth is evidenced by the highest rate of ice expansion in 2018 when ice grew rapidly at a rate of 3 477 thousand sq. km per month from October to November.

Derived estimates of ice melt and growth in the decades of high and low ice coverage enable to evaluate roughly changes of ice age distribution in the Arctic Ocean. Sea ice

which has survived summer melt, consists of old and second-year ice. Young ice appeared during the autumn-winter season from December until January, transforms into predominantly medium and thick first-year ice to the end of the season. Small part of ice, which has developed during spring months (up to 1% of total ice cover), remains young ice or thin first-year ice.

During the decade of high ice coverage, Arctic sea ice at the peak of its growth in April was composed of approximately 4 676 thousand sq. km of old and second-year ice and about 5 080 sq. km of first-year ice (see Table 2), which is 59% and 41% respectively.

In the past decade of low ice coverage old and second-year ice in April averaged 4 676 thousand sq. km and first-year ice averaged 7 015 thousand sq. km (see Table 2), which is 40% and 60% respectively. According to our estimates, the shift to the predominance of first-year ice in the Arctic sea ice cover occurred in 2002–2004. Some other authors report that contribution of multi-year and first-year ice in the Arctic Ocean at the end of winter season has dramatically changed since 2004 and is 33.3% and 66.7% respectively [9], though until 2000s this ratio was inverse. The estimates are close enough to confirm their reliability.

To sum up, Arctic ice age distribution has substantially changed over the past decades. Predominance of multi- and second-year ice during the decade 1979–1988 has changed to the predominance of first-year ice developed in autumn-winter season in 2009–2018.

Conclusion

The study reveals substantial interannual variability of Arctic sea ice extent in the 1978–2018 record. Long-term ice extent variability represents strong downward trend, which is well defined by linear negative trend of 40 thousand sq. km per year.

Besides, ice extent decline appears to have accelerated, which is especially evident for summer season. Area of the Arctic Ocean, where ice completely disappears during summer melting season, has extended up to 68% (2/3 of total area of the Arctic Ocean). Seasonal cycle of Arctic sea ice extent has

changed significantly. Total annual ice extent tends to decrease with varying over the seasons. Ice extent decline in autumn-winter season has been 600–700 thousand sq. km, which is 5% of record average annual value. Spring-summer loss has been greater totaled in 2 200–2 500 thousand sq. km (35% of record average annual extent).

To sum up, we can indicate the main features of changes in sea-ice seasonal cycle:

- summer sea ice retreat is more intense and starts earlier in the past decade compared with the decade of high ice coverage (1979–1988);

- sea ice growth in autumn-winter has accelerated with substantial increase of ice extent in the past decade (2009–2018), as compared to the decade of high ice coverage.

Sea ice extent involved into ice balance, which is the difference between autumn-winter and summer ice extents, has increased from 5 000 to 7 000 thousand sq. km. Sea ice age distribution has changed significantly over the Arctic Ocean. Old ice and second-year ice prevailed during the decade of high ice coverage (1979–1988), though first-year ice has become predominant over the recent years (2009–2018).

In general, sea-ice extent in the Arctic Ocean reveals substantial interannual and seasonal variations resulting in abnormal development and occurrence of ice conditions.

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