Arctic sea ice extent in changing climate

GENRIKH ALEKSEEV, NATALIA GLOK, ALEXANDER SMIRNOV
Arctic and Antarctic Research Institute
Bering str. 38, St.-Petersburg
RUSSIA
alexgv@aari.ru http://www.aari.nw.ru/

Abstract: - An increase in surface air temperature (SAT) and reduced sea ice extent (SIE) in the Arctic develop with high degree of agreement in the summer season. On this basis it is proposed index for measuring SIE change which is the summer SAT in the marine Arctic that is defined as the maximal Arctic water area covered with ice in winter. Correlation between summer SAT and September SIE based on data from 1980 to 2013 is -0.93. On this basis the anomalies of Arctic September SIE was restored started from 1900. Restored SIE showed a significant decrease in 1930-40s with minimum in 1936 which, however, accounted for a half of the minimum in 2012. Impact of the inflow of warm and salty Atlantic water on distribution in winter SIE in the Barents Sea is considered. It is established increased air temperature trend in late autumn and early winter, when the atmosphere gain the heat from the ice-free areas, which grow with the development of warming. The close relationship between the increase in summer air temperatures and reduced ice are in September used to assess the onset of summer Arctic ice disappearing.

Key-Words: - Arctic, climate, sea ice, surface air temperature, Barents Sea, Atlantic water, ice disappearance

1 Introduction

The earliest systematic information about arctic sea ice is available for the Atlantic region of the Arctic Ocean since the twentieth century [6, 18, 27, 30]. The first sea ice charts have been prepared in the Danish Meteorological Institute based on ship observations in the Greenland and Barents Seas mostly collected in spring and summer months (i.e., from April to August). Growth of shipping along the coast of Siberia occurred in the 1930s results in extension of sea ice observations toward the Siberian Arctic seas. Since then aircraft-based surveys become the primary source of ice observations typically presented in form of ice charts. The ice charts produced for the period since 1933 are an important part of the historical archive, which was collected in Arctic and Antarctic Research Institute [3, 11], and successfully used to prepare historical ice series for the Arctic seas [19]. The earliest historical data about the sea ice in the Barents and Siberian Arctic seas were collected since 1924 [7-9, 31] from various sources.

The longest dataset starts in 1870 [21] and covers the oceans with a resolution of 1 ° x 1 ° [10]. Historical Arctic sea ice data in this dataset were taken from [4], and cover the period since 1901 [13]. Another long-term sea ice dataset can be found at [11].

Analysis of historical sea ice data had been carried out many times using continuously growing available observations. Data showed significant long-term changes in ice distributions. Zakharov [31] reported four stages in the development of the Arctic sea ice cover occurred in the twentieth century: two stages of expansion (1900-1918 and 1938-1968), and two stages of ice cover reduction (1918-1938 and 1968-1999), expressed on background of the secular decline of sea ice extent. According to Vinje [27] the sea ice extent in the Greenland and Barents Seas in April steadily declined since 1864, and in 1998 was reduced by 33%.

Comparison of historical ice series from various sources shows significant differences between them and rapid disappearance after transition to satellite observations [1] - the main tool for sea ice monitoring since 1978. Assessments of sea ice observations from satellites show reduction of the sea ice extent, which was accelerated over the past two decades [2, 5, 7, 15-17, 23, 25, 26].

Presence or absence of the significant Arctic sea ice reduction during the first warming of the Arctic in the 1930s is a subject for discussion [22]. The authors conducted experiments with a global atmospheric circulation model with prescribed sea ice boundaries and concentration taken from HadSST dataset. The results did not show the warming in the Arctic in the 1930s, while the warming was developed when the sea ice in the model is reduced. In this connection it is interesting to estimate the state of sea ice in the Arctic in the 1930s, when the warming in the Arctic has been observed. Some indications of the reduced ice extent in the 1930s are discussed in papers [28, 29], written

ISBN: 978-1-61804-270-5

directly in the period of the development of the first Arctic warming. Our paper presents an evaluation of the past and future changes in sea ice in the twenty and twenty-first centuries and their interrelation with other components of the Arctic climate system on basis of sea ice, air and water temperature observations in the Arctic and the Northern Hemisphere.

2 Data

Sea ice data are presented by the sea ice index (the average of sea ice extent in the Arctic since 1978, in millions sq. km) taken from the NSIDC site [13]. The average sea ice extent data have been collected since 1924, and can be found at the AARI website [11]. The average monthly air temperatures for the Arctic meteorological stations are derived from data archive surface meteorology in the North Polar Region, which was prepared in AARI, and from the NCEP/NCAR reanalysis [12]. The sea surface temperature (SST) is taken from the HadSST dataset [10]. The average Atlantic water temperatures in the 0-200 m layer at the Kola section (33°30’ E) in the Barents Sea are taken from the PINRO website [14].

3 Discussion

3.1 An empirical assessment of external influences and feedbacks on reduction of the Arctic SIE

There are many reasons responsible for the amplification of the warming and decline of sea ice extent (SIE) in the Arctic. The primary reason, in our opinion, is an increase of heat and moisture transports into the northern polar region, which triggers feedbacks in the Arctic climate system and accelerates the warming and degradation of the SIE. The Arctic warming was evident as an increase of surface air temperature (SAT). Air temperature changes in the marine Arctic, which is defined as the Arctic water area with presence of sea ice in winter [2], primarily affect the growth of ice cover in winter and its melting in summer. To estimate the average air temperature in this area we used records of 41 stations with observations started not later than in 1951. These stations were located on islands and at the coast of the Arctic Ocean (Fig. 1), from which the summer Arctic sea ice retreat begins.

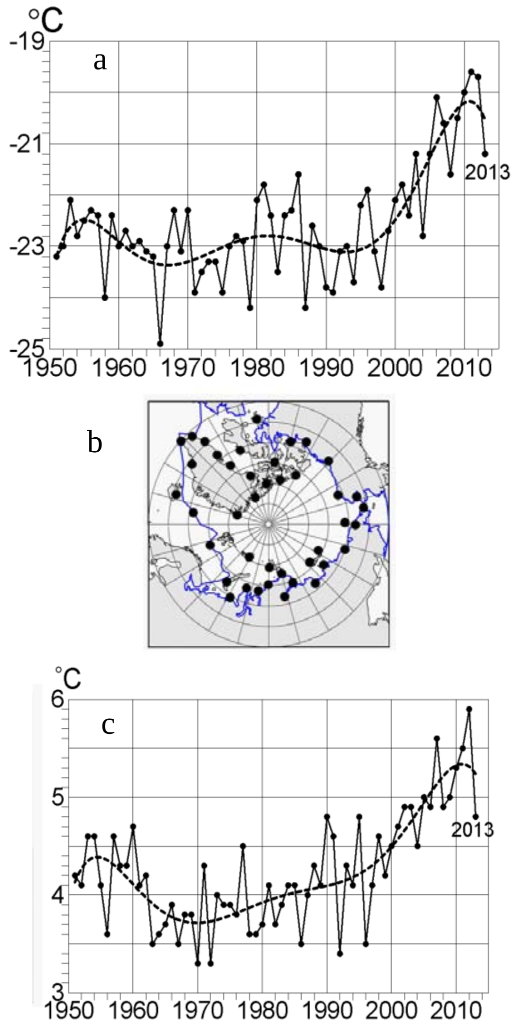

Fig. 1. Average surface air temperature in winter (a), in summer (c) at meteorological stations in the marine Arctic (b) during 1951-2013. Dotted line shows a 6^{th} order polynomial approximation.

Fig. 1 shows rapid growth of summer SAT since 1996 with an absolute maximum in 2012. The winter temperatures before 1991 and the summer temperatures before 1996 had weak negative trends, which changed to significant positive trends for the period after these years. In full accordance with rapid growth of summer air temperatures, the shrinking of the sea ice extent in the end of summer was accelerated (Fig. 2), and reached its absolute minimum in 2012. The correlation coefficient between the changes of summer air temperature in the marine Arctic and September sea ice extent equals to -0.93, suggesting that the summer SAT can be considered as an integral indicator (or index) of external influences on the SIE.

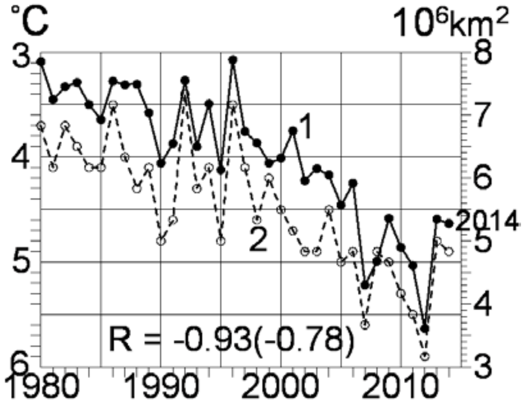

Fig. 2. (1) The average Arctic sea ice extent in September taken from NSIDC site [13]. (2) The average surface air temperature in summer (JJA) in the marine Arctic (temperature scale is inverted). R is a correlation coefficient between (1) and (2) for 1980-2014. Value in brackets is a correlation coefficient between the residuals of (1) and (2) with quadratic polynomial approximations.

Dependence of the September SIE from the summer SAT decreased in the Siberian Arctic seas under influence of sea ice dynamics. The correlation between the summer SAT and September SIE in those seas is characterized by the coefficient of -0.75 for 1951-2013. This correlation is responsible for ~60% of the variability of the September SIE. The rest of SIE variability is accounted by ice dynamics induced by impact of winds and currents, which form ice massifs – areas of compact ice spreading out of the Arctic Basin.

3.2 Reconstruction of the past Arctic SIE based on the temperature index

Taking into account strong relationship between the summer SAT and the Arctic SIE, the state of September SIE in previous year can be estimated. Unfortunately, most of the weather stations in the marine Arctic began their work after 1950, and just seven of them were operated until the beginning of the 20th century (Fig. 3).

The correlation between the summer temperatures at these stations and the Arctic SIE in September over 1980-2013 equals to -0.81. The reconstruction of the September SIE for the past years based on the regression model between the SAT and SIE shows (Fig. 3) significant SIE decrease in 1930-40, which is close to the Viese's estimate [28], who found decrease about 1 million km^2. However, the strongest reconstructed SIE reduction for 1930-40s, occurred in 1936, equals to only a half of the ice reduction in 2012.

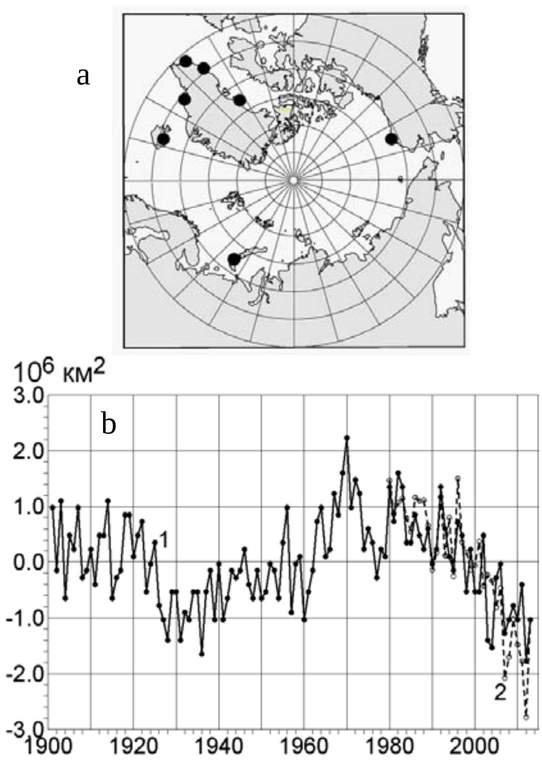

Fig. 3. (a) Positions of seven meteorological stations in the marine Arctic with collected observations since 1900; (b) 1 – reconstructed September SIE in the Arctic from 1900 to 2013. 2 – observed SIE for 1980-2013.

3.3 Influence of the ocean on winter sea ice distribution

In spite of the fact that the winter SAT increases faster than the summer SAT, the reduction of winter SIE in the Arctic is much slower in comparison with summer shrinking. One of the reasons is that the Arctic seas in winter are completely covered with ice. Therefore, changes in the Arctic winter SIE are associated with a shift in the sea ice edge in the Nordic Seas and the Northwestern Atlantic that is determined by the boundary between the Arctic water and the salt and warm Atlantic water [32, 33]. Variations of winter SIE include the component determined by changes of the Atlantic Water (AW) inflow and by the shift of AW distribution in the Nordic Seas and the Northwestern Atlantic.

An influence of this component on the winter SIE is clearly evident in the Barents Sea from long-term historical datasets of SIE, AW temperatures at the Kola section, and sea surface temperature (SST). For example, Table 1 contains correlation coefficients between the SIE, AW temperature, and SST in the Barents Sea derived for 1928-2013.

Table 1.Correlation coefficients between the mean annual AW temperature in 0-200 m layer along the Kola section, HadSST in the Barents Sea, and the monthly SIE in the Barents Sea for1928-2013. (95% level of significance of the coefficients is 0.21)

	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
T_{AW}	-0,54	-0,64	-0,59	-0,66	-0,79	-0,75	-0,67	-0,56	-0,47	-0,37	-0,34	-0,51
SST	-0,52	-0,62	-0,65	-0,75	-0,80	-0,79	-0,74	-0,67	-0,57	-0,48	-0,33	-0,47

The correlation of the monthly mean AW temperature at the Kola section and SIE for 1951-2009 reaches its maximal value of 0.86 in May (Table 2).

Shift of the correlation maximum to May can be explained by significant impact of AW inflow occurred in southern part of the Barents Sea that prevents the southward spreading of sea ice edge. A correspondence between distributions of the AW and the sea ice in the Barents Sea can be seen from fig. 4, showing similar spatial pattern of surface salinity distribution and sea ice edge in June of 1969 and 1987. In June 1969 the salty AW occupies a smaller area, and sea ice goes further to south in comparison with June 1987.

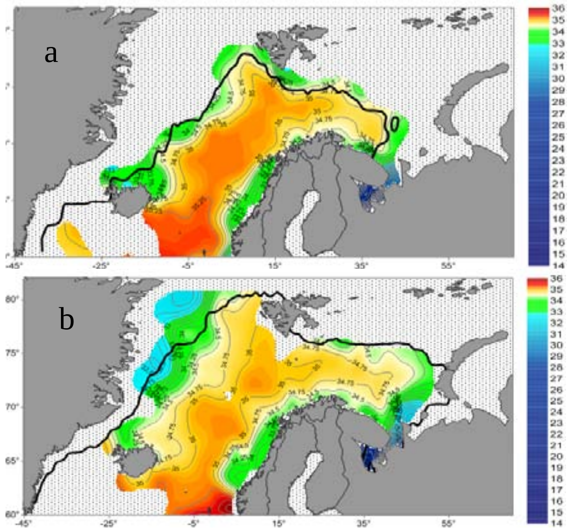

Fig. 4. Sea surface salinity and the sea ice edge in the Barents Sea in June 1969 (a) and 1987 (b).Sea surface salinity is taken from the digital “Climatological Atlas of the Nordic Seas and Northern North Atlantic” issued by NOAA in the International Ocean Atlas and Information Series in 2014. Ice edge position (black curve) is taken from HadSST dataset.

Table 2. Correlation coefficients between the monthly mean AW temperature in 0-200 m layer along the Kola section and the monthly SIE in the Barents Sea for 1951-2009. (95% level of significance of the coefficients is 0.26)

	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
T_{AW}	-0,68	-0,70	-0,68	-0,77	-0,86	-0,77	-0,59	-0,47	-0,41	-0,30	-0,40	-0,54

3.4 Effect of summer SIE reduction on winter air temperature in the Arctic

One of feedbacks that amplify the warming in the Arctic is the result of summer SIE reduction, which increases the air temperature in late autumn and early winter (Fig. 5). In the period with negative air temperatures, the heat accumulated in ice-free areas releases to the atmosphere. An additional contribution to the warming is due to increase of the water vapor content in the air surface layer, accompanied by increased downward long-wave radiation.

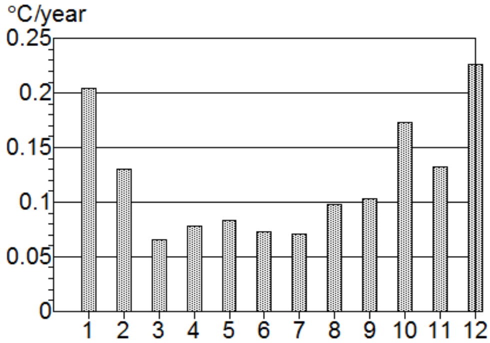

Fig. 5. Trend of the monthly mean SAT in the marine Arctic for 1993-2012. Period of 1993-2013 was chosen as a period of rapid SAT increase.

The largest values of SAT trends occur from October through February, exceeding background value (average for March-September), and contribute up to 75% to amplification of the trend caused by this feedback.

3.5 Summer sea ice disappearance

The close relationship between the summer air temperature and reduced ice area in September (Fig. 3) allows predicting the evolution of September SIE using statistical modeling. According to the elaborated statistical model the arctic summer sea ice can disappears in the middle of the 2030s. The date of disappearance of the summer ice cover can be estimated using simple extrapolation of the September SIE record, suggesting robustness of the estimates in case of

ISBN: 978-1-61804-270-5

coincidence of the results in both predictions. Fig. 6 shows the result of applying both methods for prediction of the time of the summer SIE disappearance.

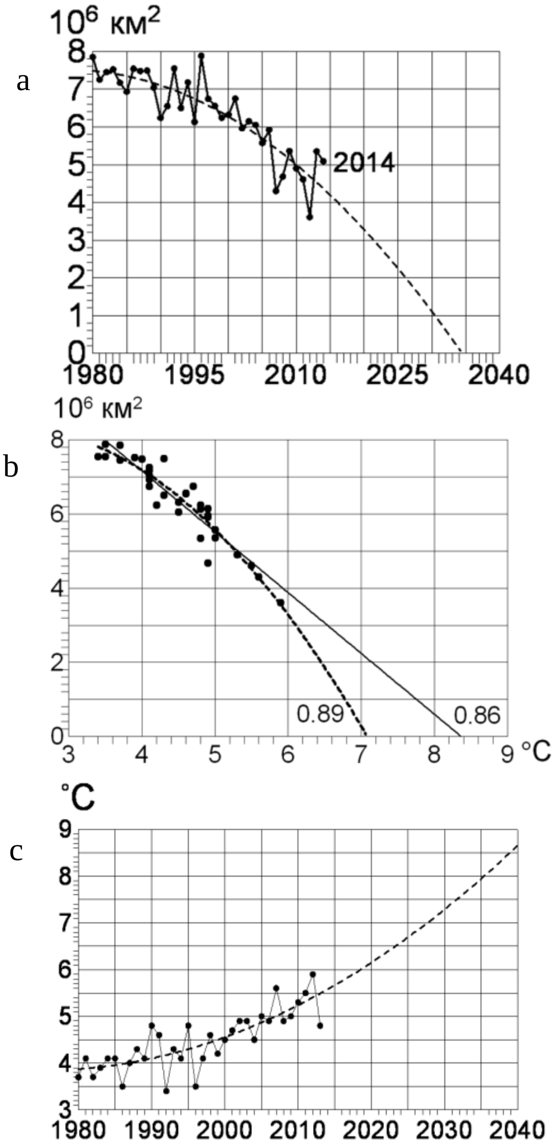

Fig. 6: (a) 2-nd degree polynomial extrapolation of the SIE in September (coeff. determination is 0.78); (b) extrapolation of relationships between the summer temperatures and SIE in September (coeff. determination for linear model is 0.85; for quadratic model is 0.89); (c) quadratic extrapolation of the summer air temperature (coeff. determination is 0.65), indicating achievement of 7.1 and 8.4 ° C about 2027 and 2038, respectively.

Derived empirical estimates include influence of both anthropogenic and natural factors, affecting the rapid decline of summer ice in the Arctic. They show possible disappearance of the sea ice in September in the middle 2030s. This prediction is found in range of the earliest disappearance of September sea ice, estimated from global climate models [20].

4 Conclusion

We propose to use summer SAT in the marine Arctic as a predictor for estimates of September SIE changes. The marine Arctic is defined as the area of the Arctic, which is covered with sea ice in winter. The correlation coefficient between the summer SAT and the Arctic SIE in September equals to -0.93 for 1980-2013. Based on this correlation, September SIE anomalies were reconstructed for 1900-2013. The reconstructed SIE dataset shows significant reduction in 1930-40s with minimum of ice extent registered in 1936. However, it was just a half of the reduction found in 2012.

The close relationship between the increase of summer air temperature and the reduction of September SIE is used to assess the onset of summer Arctic ice disappearance. Remaining the current rate of warming of air temperature we found that such an event can happen as early as the middle of 2030s. An impact of sea ice dynamics on September SIE variability is evident in the Siberian Arctic seas, where about 40% of the SIE variability is governed by winds and currents.

Changes of the Arctic winter SIE are associated with a shift in the sea ice edge in the Nordic Seas and in the Northwestern Atlantic, which is determined by the boundary between the Arctic water and the salt and warm Atlantic water. An impact of the inflow of the warm and saline Atlantic water and shift of AW distribution on the winter SIE is evident in the Barents Sea. The correlation coefficient between the monthly Atlantic water temperatures and SIE in the winter/spring months reaches to -0.86 in May. We argue the shift of highest negative correlation to May by significant influence of the AW inflow, which prevents the southward spreading of sea ice edge in the Barents Sea.

The largest positive trends were found in surface air temperature in the marine Arctic during the last decade are were observed in the late autumn and early winter, when the heat accumulated in ice free water areas releases to the atmosphere. This process is responsible for up to 75% of the trend in this period.

This research has been supported by the Ministry of Education and Science of the Russian Federation project 2014-14.610.21.0006 RFMEFI61014X0006 and the Russian Foundation for Basic Research grant 13-05-01006A.

References:

1. Alekseev G.V., Kuzmina S.I., Nagurny A.P., Ivanov N.E. Arctic sea ice data sets in the context of the climate change during the 20th century. Climate variability and extremes during the past 100 years // Series: Advances in Global Change Research, V.33, 2007, pp.47–63.
2. Alekseev, G.V., Danilov A.I., V.M. Kattsov, S.I. Kuzmina, and N.E. Ivanov: Changes in the climate and sea ice of the Northern hemisphere in the 20th and 21st centuries from data of observation and modeling // *Izvestia of Russian Academy of Sciences: Physics of Atmosphere and Ocean*, 45, 6, 2009, pp. 723–735.
3. Borodachev V.E., Shilnikov V.I. *History of aerial surveys in the Russian Arctic.* SPb.: Gidrometeoizdat, 2001
4. Chapman W.L. and Walsh J.E. Recent variations of sea ice and air temperature in high latitudes // *Bull. Amer. Meteorol. Soc*. 74, 1993, pp.33–47.
5. Comiso J.C., Parkinson C.L., Gersten R., Stock L. Accelerated decline in the Arctic sea ice cover // *Geophys. Res. Lett.* 35, L01703, 2008, doi:10.1029/2007GL031972.
6. Divine D.V., Dick C. Historical variability of sea ice edge position in the Nordic Seas // *J. Geophys. Res.,* 111, C01001, 2006, doi:10.1029/2004JC002851.
7. Frolov I.E. (ed.) *Oceanography and sea ice. Ser. "Russian contribution to the International Polar Year 2007-2008.* M. – SPb: Paulsen. 2011, P. 431
8. Frolov I.E., Gudkovich Z.M., Karklin V.P., Kovalev E.G., Smolyanitskiy V.M. *Climatic changes of the ice cover of the seas of the Eurasian continental shelf,* SPb: Nauka, 2007, P. 135
9. Frolov I.E., Gudkovich Z.M., Radionov V.F., Timohov L.A., Shirochkov A.V. *Scientific investigation in Arctic. V. 1: Research drifting station "North Pole",* SPb: Nauka, 2005, P. 267
10. http://hadobs.metoffice.com.hadsst/
11. http://www.aari.ru/projects/ECIMO/index.php
12. http://www.esrl.noaa.gov/psd/data/reanalysis
13. http://www.nsidc.colorado.edu
14. http://www/pinro.ru/n22/index/phpstructure/labs/labhidro
15. Ivanov V.V., Alekseev V.A., Alekseeva T.A., Koldunov N.V., Repina I.A., Smirnov A.V. Does Arctic ice cover become seasonal?// *Earth Res. from Space,* 4, 2013, pp. 50–65.
16. Johannessen O.M., Bengtsson L., Miles M.W., Kuzmina S.I., Semenov V.A., Alekseev G.V., Nagurnyi A.P., Zakharov V.F., Bobylev L.P., Pettersson L.H., Hasselmann K., Cattle H.P., Arctic climate change: observed and modelled temperature and sea ice variability // *Tellus,* 56A, 2004, pp. 328–341.
17. Kwok R., Rothrock D.A. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958 – 2008 // *Geophys. Res. Lett.,* 36, L15501, 2009, doi:10.1029/2009GL039035.
18. Løyning T., Dick C., Goodwin H., Pavlova O., Vinje T., Kjærnli G., Villinger T. *ACSYS historical ice chart archive (1553 – 2002).* International ACSYS/CliC Project Office. 2003.
19. Mahoney A.R., Barry R.G. , Smolyanitsky V., Fetterer F. Observed sea ice extent in the Russian Arctic, 1933–2006 // *J. Geophys. Res.*, 113(C11005), 2008, doi:10.1029/2008JC004830.
20. Overland J.E., Wang M. When will the summer Arctic be nearly sea ice free? // *Geophys. Res. Lett.,* 40, 2013, pp. 2097–2101, doi:10.1002/grl.50316.
21. Rayner N.A., Parker D.E., Horton E.B., Folland C.K., Alexander L.V., Rowell D.P., Kent E.C., Kaplan A. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century // *J. Geophys. Res.*, 108(D14), 4407, 2003, doi:10.1029/2002JD002670.
22. Semenov V.A., Latif M. The early twentieth century warming and winter Arctic sea ice // *The Cryosphere*, 6, 2012, pp. 1231–1237.doi:10.5194/tc-6-1231-2012.
23. Smolyanitskiy V.M. *Spatio-temporal variability of ice cover on the basis of the "Global Bank of digital data about sea ice"* // abstract of Ph.D. thesis, SPb: AARI, 2003, P. 24.
24. Stroeve J.C., Holland M.M., Meier W., Scambos T., Serreze M. Arctic sea ice decline: Faster than forecast // *Geophys. Res. Lett,* 34, L09501, 2007, doi:10.1029/2007GL029703.
25. Stroeve J.C., Markus T., Boisvert L., Miller J., Barrett A. Changes in Arctic melt season and implications for sea ice loss // *Geophys. Res. Lett,* 41, 2014, doi:10.1002/2013GL058951.
26. Stroeve J.C., Serreze M.C., Holland M.M., Kay J.E., Malanik J., Barrett A.P. The Arctic's rapidly shrinking sea icecover: a research synthesis // *Clim. Change*, 2011, doi:10.1007/s10584.
27. Vinje T. Anomalies and trends of sea ice extent and atmospheric circulation in the Nordic Seas during the period 1864–1998 // *Journal of Climate,* V.14, No.3, 2001, pp.255–267.
28. Vise V.Yu. *Bases of long-term ice forecasts for the Arctic Seas.* M. Glavsevmorput. 1944. P. 274
29. Vise V.Yu. The reason of the Arctic warming // *Sovetskaya Arktika*, 1, 1937, pp. 1–7.
30. Zakharov V.F. *Arctic cooling and Arctic Seas ice cover*. Proceedings of the AARI 1976. 337. P. 96

31. Zakharov V.F. *Interdecadal changes of Arctic sea ice distribution in twentieth century* // formation and dynamics of the modern Arctic climate. edited by Alekseev G.V. SPb: Gidrometeoizdat, 2004, pp.112–159.

32. Zakharov.V.F. *Ice of the Arctic and current natural processes*. L. Gidrometeoizdat. 1981. P. 136

33. Zakharov.V.F. *The World Ocean and glacial epochs of the Pleistocene.* L. Gidrometeoizdat, 1978, P. 64