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EVALUATION OF THE EFFECT OF INSOLATION FACTOR ON SEA ICE EXTENT VARIABILITY IN THE RUSSIAN ARCTIC

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Application of the correlation and regression analysis which enabled evaluation of the role of insolation factor in seasonal, interannual, long-term variations (both region-specific and common for the Russian Arctic) of sea ice extent during the period of satellite observations (1979–2018) is discussed. The revealed correlation between multiyear variations of average annual and monthly values of sea ice area and multiyear variations of insolation contrast decreases with increasing spatial scale. The annual course is marked by a more stable and close relationship between seasonal variations in sea ice extent and in insolation (phase-shifted by three months to the past). The annual variations of the phase shifted insolation also have a close connection with the seasonal variability amplitude of interannual variation of sea ice extent, with distribution of the coefficient of determination in regression models, and with seasonal variations in sea ice extent decline. The seas in the central Russian Arctic (Kara Sea, Laptev Sea and East Siberian Sea) are interpreted as the most conservative in their response to the insolation factor, while the most pronounced response to variations of insolation and insolation contrast are reported from the marginal seas (Barents Sea and Chukchi Sea). The patterns of response to the insolation factor also differ considerably for these regions.

Russian Arctic seas, sea ice extent, annual, interannual and multiyear variations, insolation, insolation contrast, correlation and regression analysis

INTRODUCTION

Sea ice, as part of the Earth's cryosphere, is a critical component of the climate system. The role of sea ice in climate change is primarily determined by its involvement in the mechanisms of heat exchange between the ocean and the atmosphere. Sea ice parameters, such as its concentration and extent, are also of great practical importance both for navigation along the Northern sea route, and in equal measure for creating sea transport infrastructure and conditions for mining and transportation of minerals extracted from the Arctic seas shelf. This determines the pressing need for explaining the observed reduction in sea ice area, defining reasons underlying the trends, and predicting changes in sea ice extent in the Russian Arctic, and their implications. With this in mind, the authors have conducted a study of the sea ice area dynamics in the Arctic Ocean (AO), in the entire Russian Arctic (RA) and in individual seas in its territory. Seasonal (annual course), interannual (year-to-year) and multiyear variability in sea ice extent in the Russian Arctic waters, including the Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea and Chukchi Sea was studied in relation to changes in the Earth's insolation and insolation (irradiance) contrast (IC) in the Northern Hemisphere. This study sets out to analyze a relationship between insolation and IC in the Northern Hemisphere and sea ice extent in the Russian Arctic territory estimated from different spatial and temporal scales.

Ice covers about 6 % of the Earth's surface, which is ~30 mln km^2. A major part of ice mass is localized in the Arctic and Antarctic. In the Northern Hemisphere, land ice accounts for only 20 % of the total area of the Arctic glaciation, while the remaining 80 % are classified as sea ice [*Koryakin, 1988*]. In the Arctic, the area roughly totaling 10–17 mln km^2 is presently exposed to seasonal variations in onshore and offshore glaciation. In the RA seas, the area covered by sea ice grows and shrinks over the course of the year, which is illustrated by its area estimated to be 472,000 km^2 in March (sum total for the five seas), which is reduced by about half in summer, scaling down to 160,000 km^2 in September (Fig. 1).

The ice cover evolution is strongly influenced by thermal and dynamic, and variously scaled atmospheric and oceanic processes [*Zubov, 1938; Burke, 1940; Frolov, Gavrilo, 1997; Zubakin, 2006*]. Given that surface air temperature (SAT) and sea surface temperature (SST) are basically governed by incident solar radiation (insolation) over the course of the year, the multiyear variations in SAT and SST will be largely dictated by changes in IC [*Fedorov,*

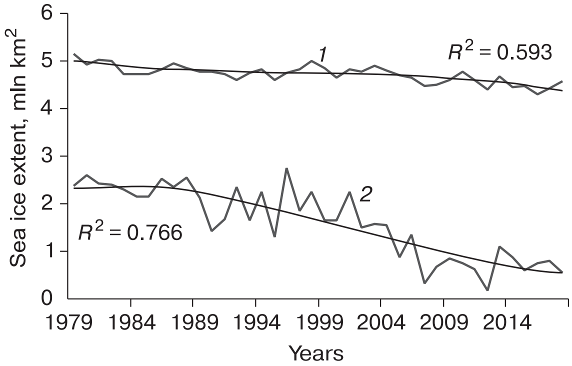

Fig. 1. Changes in the maximal (*1*) and minimal (*2*) estimates of the sea ice extent in the Russian Arctic during the period of satellite observations.

Trendlines are third-degree polynomial.

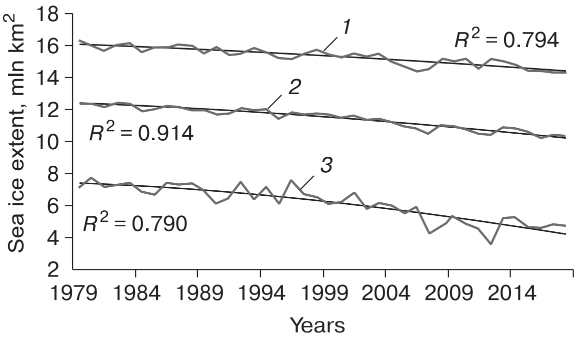

Fig. 2. Changes in sea ice extent in the Russian Arctic over the period of 1979–2018 according to the satellite-based data and their polynomial trends (second degree).

Extent: *1* – maximal, *2* – average annual, *3* – minimal.

2015, 2018; Fedorov, Grebennikov, 2018]. Insolation contrast is the difference between annual insolation of the heat source area (0–45° latitude) and heat sink area (45–90° latitude) in the two hemispheres. IC (for heat source and sink areas) generally reflects changes in the meridional gradient of insolation, which controls meridional heat transfer in the ocean–atmosphere system [*Fedorov, 2018, 2019a,b*].

An important parameter of the ice cover is its extent, or the area it occupies. Sea ice cover is subject to variations, of which the most common are seasonal, interannual and multi-year. Analysis of both the variations and their causes constitute one of the paramount tasks of cryolithology and sea ice science [*Zubov, 1938; Zakharov, 1981; Frolov, Gavrilo, 1997; Zakharov, Malinin, 2000; Alekseev et al., 2015; Shalina, Bobylev, 2017*].

In the Arctic Ocean, satellite observations of changes in the sea ice cover extent have been conducted since 1979 (Fig. 2) [*Fetterer et al., 2017*].

The value of the correlation coefficient for multiyear variations in IC is –0.920 for the estimated average annual sea ice cover area in the Arctic Ocean (–0.876 and –0.836 are the values for the area maximum and minimum, respectively). Based on the close relationship between multiyear variations in the sea ice cover and IC, the linear and polynomial regression equations describing the dependence of the sea ice area as function of IC are obtained. Comparison of actual and calculated values for sea ice coverage based on the ensemble of linear and polynomial solutions showed that multiyear variations in IC define the multiyear variability of the average annual (95.1 %), maximal (93.5 %) and minimal (89.2 %) sea ice extent in the Arctic Ocean. The resulting ensemble mean forecasts for the Arctic Ocean, the average annual sea ice area will be 8.43 mln km^2 in 2050 (maximum – 12.86 mln km^2, minimum – 1.87 mln km^2). As compared to 2018, the average annual area will shrink by 1.89 mln km^2 in 2050 (maximum: by 1.44 mln km^2, minimum: by 2.84 mln km^2). Thus, relative to 2018, the reduction in sea ice coverage will constitute 18.3 % for the average annual area, 10.1 % for the maximum area, 60.3 % for the minimum area of sea ice. The obtained values characterize multiyear variations in sea ice extent at the spatial scale of the Arctic Ocean.

At regional scales, the connections between multiyear variations in sea ice area and IC increasingly weaken, while the observed responses in the sea ice area dynamics to multiyear variations in IC differ between regions. The weakening relationships observed across the regions in the AO are accentuated by local factors, as follows: ice motion (drift), local atmospheric processes (heat/cold advection, cloud cover), sea currents, geographical location, and geomorphological conditions. Regional estimates allow to reveal the role of variations in insolation and IC in the sea ice area dynamics in individual seas of the Russian Arctic. The authors used the satellite measurements available from the NOAA electronic resource (records of sea ice extent and concentration from satellite passive microwave brightness temperature data, sea ice index, etc.) [*Fetterer et al., 2017*] as input data on the sea ice coverage variations. The input IC and insolation data were the previously calculated databases on insolation [*Fedorov, Kostin, 2019*].

Methodology for calculating insolation and insolation contrast, and evaluating statistical significance of correlations

The annual and monthly insolation and annual IC calculated for the Northern Hemisphere are used as the insolation factor [*Fedorov, 2018, 2019b*]. Earth's insolation (solar radiation coming to the Earth's surface with the atmosphere not taken into account) was calculated by the authors earlier with a large spatial and temporal resolution [*Fedorov, 2018, 2019b; Fedorov, Frolov, 2019*]. The calculations of insolation were performed using the high-precision astronomical ephemerides data [*Giorgini et al., 1996*; http://ssd.jpl.nasa.gov] for the entire Earth's surface (no atmosphere) within the interval from 3000 BC to 2999 AD, the input astronomical data for calculating insolation were the declination and ecliptic longitude of the Sun, the distance from the Earth to the Sun, and difference between the course of uniformly running (coordinate time, CT) and the universal corrected time (universal time, UT). The surface of the Earth was approximated by ellipsoid (GRS80 – Geodetic Reference System 1980) with semi-axis lengths 6 378 137 m (big one) and 6 356 752 m (small one). The calculation algorithm can be generally represented by the expression

$$I_{nm}(\varphi_1,\varphi_2)=\int_{t_1}^{t_2}\left(\int_{\varphi_1}^{\varphi_2}\sigma(H,\varphi)\left(\int_{-\pi}^{\pi}\Lambda(H,t,\varphi,\alpha)\,d\alpha\right)d\varphi\right)dt,$$

where I is incoming solar radiation for elementary n-th fragment (period) of the m-th tropical year, J; σ is square multiplier (m^2), which enables calculation of the square differential $\sigma(H,\varphi)d\alpha d\varphi$, the square of infinitely small trapezoid ellipsoid cells; α is horary angle, rad unit; φ is geographical latitude, rad unit; H is height of ellipsoid surface relative to Earth surface, m; $\Lambda(H,t,\varphi,\alpha)$ is insolation at the stated moment at the stated ellipsoid surface point, W/m^2; t is time, s. The integration steps were: longitude 1°, latitude 1°, defined as one three hundred sixtieth (1/360) of the length of tropical year [*Fedorov, 2013*]. The value of solar constant (average multiyear TSI value (total solar irradiance)) was taken to be 1361 W/m^2 [*Kopp, Lean, 2011*]. Changes in the solar activity were not taken into consideration [*Fedorov, 2015, 2019a,b; Fedorov, Frolov, 2019; Fedorov, Kostin, 2019*].

The statistical significance of the linear correlation coefficient was evaluated from the correlation analysis according to the existing evaluation criteria and methods [*Tsymbalenko et al., 2007*]. The linear correlation coefficient was calculated for some sample (from the period of instrumental observations). Its estimate is therefore a random variable whose statistical significance needs to be tested. The input (digital) data used for the calculations represent a sample size using as many observations as possible, which constitute a normal population. Therefore, in this case the calculated error of a sample correlation coefficient was taken into account, when the interval estimation of the normal population correlation coefficient was determined.

The standard deviation of the correlation coefficient was calculated using the formula

$$m_r=\sqrt{\frac{1-r^2}{n-2}},$$

where r is the sample correlation coefficient; n is the sample size.

Testing the significance of the sample correlation coefficient requires that a certain assumption (the null hypothesis) is satisfied, i.e. the hypothesis that there is no linear correlation dependency between the studied series.

For determining the statistical significance of the linear correlation coefficient, the actual (designated as "fact") statistical value was adopted, using Student's original definition of the t-test, and found with the formula:

$$t_{\text{fact}}=\frac{|r|}{m_r}.$$

The inferences about the significance of r were made on the basis of comparison of t_{fact} and $t_{\text{corr}}(\delta,\ n-2)$ of the critical (tabulated) value of the t-distribution (where δ is the level of significance; $(n-2)$ is the number of degrees of freedom). The correlation coefficient was considered statistically significant if the condition $t_{\text{fact}} > t_{\text{corr}}$ was fulfilled. Otherwise, it was considered statistically insignificant.

Annual dynamics of sea ice extent

The annual dynamics of the sea ice cover displays a pronounced maximum (in March) and minimum (in September) (Fig. 3). The maxima and minima in sea ice cover are phase-shifted by three months to the past relative to the minimum and maximum in the annual course of insolation, accordingly. It stands to reason that the annual course of the Earth's insolation is interpreted as a major factor affecting the annual dynamics of the sea ice extent (Table 1).

However, responses to the annual course of insolation in individual seas will differ. These differences are estimated from the correlation coefficients (R) on the basis of the sea ice extent dynamics and annual course of insolation and have different values for the Russian Arctic seas, as follows: –0.931 (Barents Sea), –0.817 (Kara Sea), –0.681 (Laptev Sea), –0.712 (East Siberian Sea), and –0.862 (Chukchi Sea). The values of R are statistically significant with a probability (p-value) of 0.99 for all seas except the Laptev Sea, for which the p-value is 0.98. The most pronounced response to the annual course of insolation is thus observed in the marginal seas of the Russian Arctic (Barents Sea and Chukchi Sea), while the central Russian Arctic (Laptev Sea) responds the most conservatively to the annual course of the Earth's insolation.

The maximum changes in the annual course are typical of the western the Russian Arctic, with the range of fluctuations in the annual course being particularly large for the Barents Sea. This is associated with the effect (besides the Earth's insolation) of other regional controls: atmospheric circulation (the

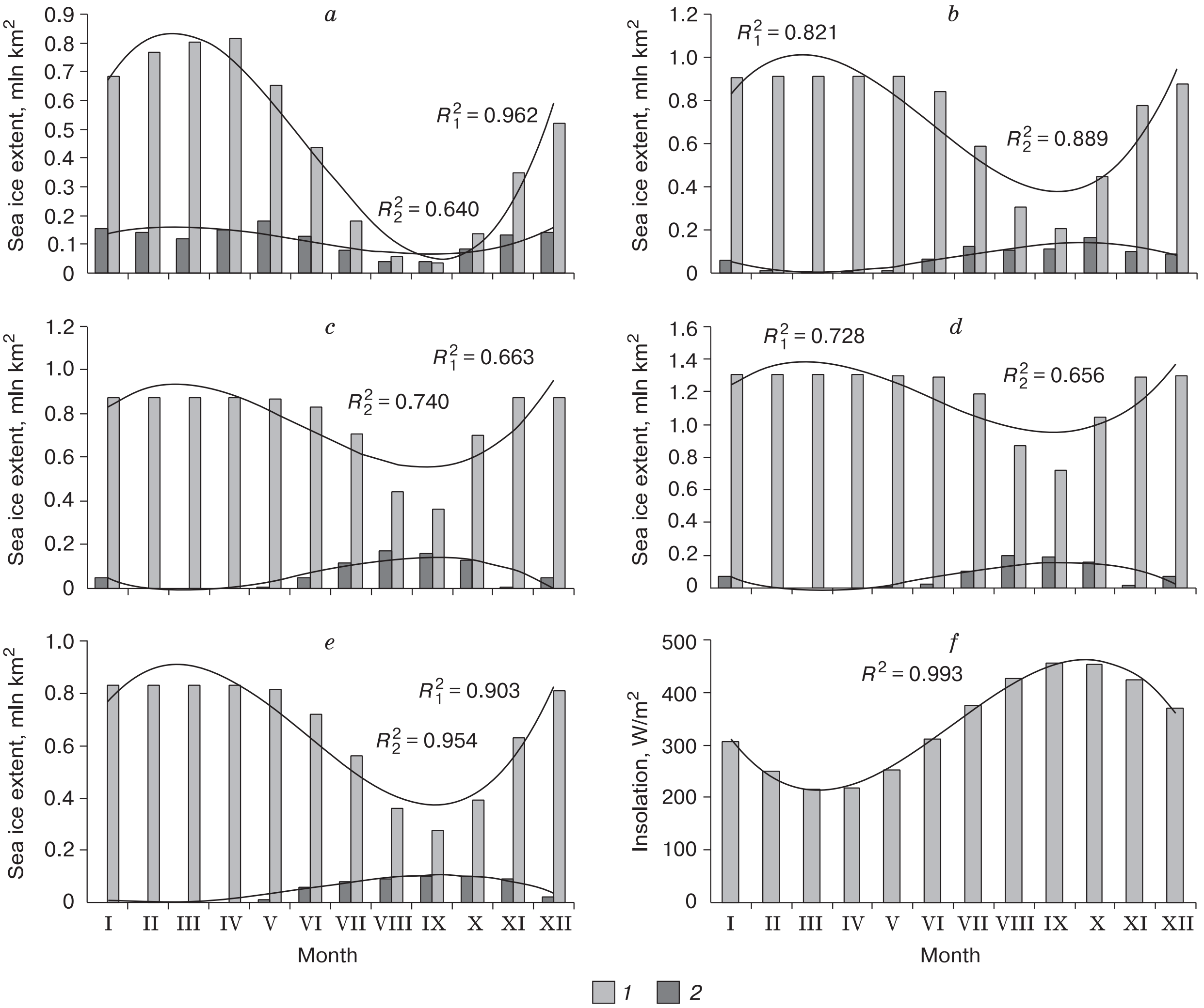

Fig. 3. Annual dynamics of the sea ice extent (*1*) and interannual variation amplitude (*2*) of the sea ice extent in the Russian Arctic.

Seas: *a* – Barents, *b* – Kara, *c* – Laptev, *d* – East Siberian, *e* – Chukchi. *f* – annual course of the Earth's insolation (phase-shifted by three months back in the course of a year) in the Northern Hemisphere.

so called the Iceland-Kara trough of low pressure, which redirects the paths taken by surface cyclones away from the Iceland area into the Barents Sea); and the warm ocean current of the Gulf Stream.

Interannual variability of sea ice area

The area of sea ice cover changes not only throughout the year (seasonal variability), but also from year to year (interannual variability). The max-

Table 1. **Variations in monthly values of sea ice cover (thou. km^2) in the Russian Arctic seas and insolation of the Northern Hemisphere**

Value	Barents Sea	Kara Sea	Laptev Sea	East Siberian Sea	Chukchi Sea	Insolation, W/m^2
Mean	453.6	716.6	762.5	1184.6	657.2	338.0
Maximum	814.9	914.2	872.4	1303.7	830.3	456.2
Minimum	36.4	207.5	361.6	715.9	276.8	216.8
Δ/mean	1.716	0.986	0.670	0.496	0.842	0.708
Δ/minimum	21.402	3.405	1.413	0.821	1.999	1.104

Note. Δ is the difference between maximal and minimal values.

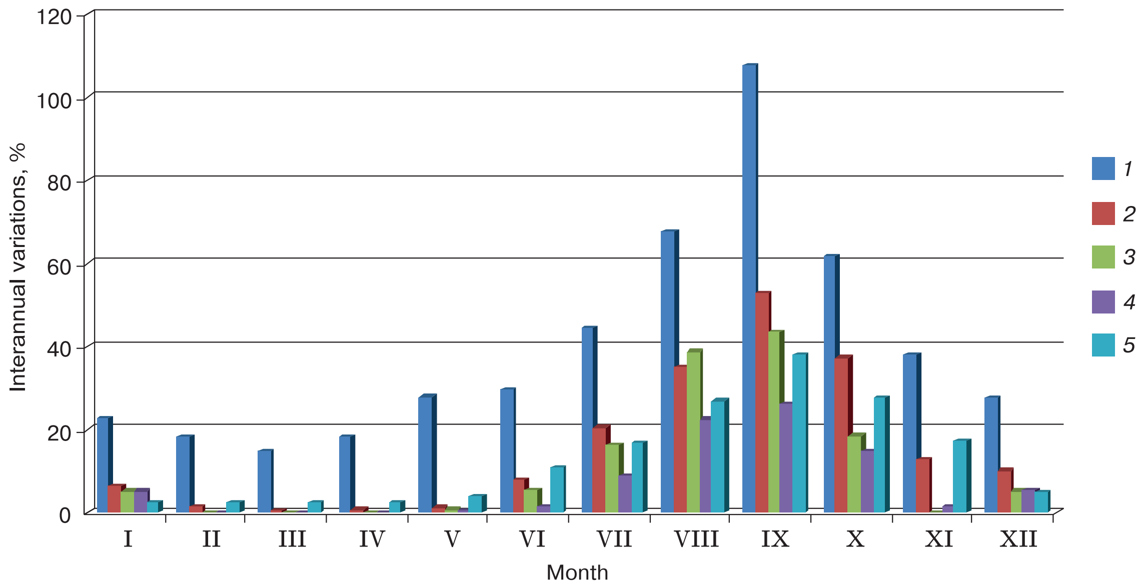

Fig. 4. Interannual variability calculated as percentage of the multiyear mean of sea ice extent.
Seas: *1* – Barents, *2* – Kara, *3* – Laptev, *4* – East Siberian, *5* – Chukchi.

imum values of amplitude of interannual variability fall on the summer season, which is responsible for the minimum in the sea ice coverage (Fig. 3, 4, Table 2). The authors understand the amplitude as the average multiyear value of the difference modulus for the interannual sea ice area values.

For the Barents Sea, the amplitude of interannual variability in September exceeds the average value of sea ice area for this month. The annual course of the amplitude of interannual variations in sea ice extent is therefore closely related with the annual dynamics of sea ice extent. The calculated correlation coefficient for the studied seas constitutes 0.812 (Barents Sea), 0.868 (Kara Sea), 0.723 (Laptev Sea), 0.781 (East Siberian Sea), 0.878 (Chukchi Sea). The statistical significance of R with a p-value of 0.99 is typical of all these seas. At this, both the interannual variations in the RA seas as well as their own variabilities are closely interconnected. The values of the paired samples correlation coefficient range from 0.811 to 0.986 with a probability (p-value) of 0.99. Also, the annual course of the amplitude of interannual variability is closely related to the annual course of phase-shifted (by three months to the past) insolation. The values of the coefficient of correlation among the RA seas are: –0.876 (Barents Sea), –0.977 (Kara Sea), –0.991 (Laptev Sea), –0.974 (East Siberian Sea), and –0.990 (Chukchi Sea); the statistical significance of R with a p-value of 0.99 is also observed for all the seas.

Thus, both the annual amplitude of interannual variability of the average monthly values and the annual dynamics of sea ice area are governed by the annual course of insolation. Despite the well-known

Table 2. **Annual course of the amplitude of interannual variability calculated on a monthly basis as percentage of the value of multiyear average sea ice extent**

Month	Barents Sea	Kara Sea	Laptev Sea	East Siberian Sea	Chukchi Sea
January	22.7	6.4	5.1	5.1	2.6
February	18.47	1.6	0.0	0.0	2.6
March	14.9	0.6	0.0	0.0	2.6
April	18.3	0.8	0.0	0.0	2.6
May	27.9	1.3	0.7	0.4	3.8
June	29.7	7.7	5.3	1.6	10.8
July	44.4	20.5	16.3	8.7	16.6
August	67.8	35.0	38.7	22.5	26.9
September	107.8	53.0	43.5	26.1	38.0
October	61.8	37.3	18.5	14.9	27.8
November	38.1	13.0	0.1	1.4	17.1
December	27.5	10.1	5.1	5.3	5.1
Average	39.9	15.6	11.1	7.2	13.0

Table 3. **Values of the amplitude of interannual variations of average annual sea ice extent in the Russian Arctic seas (km^2)**

Value	Barents Sea	Kara Sea	Laptev Sea	East Siberian Sea	Chukchi Sea
Mean	116 412.3	71 274.8	59 504.8	68 381.4	46 130.4
Maximum	182 676.0	166 078.2	171 950.8	194 946.3	102 110.4
Minimum	38 401.6	5640.8	5.3	3.3	6.1
Δ/mean	1.239	2.251	2.890	2.851	2.213

relationship between the annual courses of the meteorological characteristics and insolation, these are found to be largely region-specific. Table 3 shows that the interannual variability in the Laptev Sea is close to zero from February through May (conservative response). In the East Siberian Sea, a similar situation is observed from February through April. The central Russian Arctic displays the most conservative response to the insolation factor in the seasonal and interannual variations, which is corroborated by the poorly expressed multiyear variations in the annual dynamics and interannual variability of sea ice area in the Laptev Sea and the East Siberian. On the contrary, during the specified periods sea ice extent in these seas practically does not change in February–May. The largest (on average) interannual variability of the average monthly sea ice area values is characteristic of the marginal seas (Barents Sea and Chukchi Sea), as well as the Kara Sea.

Multiyear variations in the sea ice area

Multiyear variations in the average annual and monthly values for the sea ice area were analyzed both for individual seas and the entire Russian Arctic (Fig. 5, 6). The mean annual value was calculated as the average of all the values for all months of the year.

The correlation of multi year variability of the average annual sea ice area in the Russian Arctic with the annual IC of the Northern hemisphere is −0.831 (p-value of statistical significance is 0.99). The IC-based regression model (second-degree polynomial) explains 69.8 % of multiyear variations in the average annual sea ice extent in the Russian Arctic.

Although the incoming solar radiation tend to decrease in the zone where the heat flux is absorbed, a reduction in average annual sea ice extent is noted for all the RA seas [*Fedorov, 2018*]. As such, this reduction is explained by the IC tendency for increase and enhancement of meridional heat transfer. It was shown earlier that in the modern era, an increase in IC variations is associated with a decrease in the angle of the Earth's axial tilt. Evaluation of the influence of this factor at a regional scale in the RA seas is of undoubted scientific and practical interest. The values of R for the time series of multiyear variations in average annual sea ice area and IC constitute: −0.782 (Barents Sea), −0.721 (Kara Sea), −0.625 (Laptev Sea), −0.661 (East Siberian Sea), −0.819 (Chukchi Sea). All the R values are statistically significant with a p-value of 0.99.

Reductions in the average annual sea ice coverage in regions were estimated from the difference between the averages for the first five years (1979–1983) S_0 and the last five years (2014–2018) S_T of the average annual sea ice extent in the satellite earth observation data. Accordingly, the reduced sea ice extent (thou. km^2) was estimated to be: 384.1 for the Barents Sea, 178.4 for the Kara Sea, 101.4 for the Laptev Sea, 173.8 for the East Siberian Sea, and 150.2 for the Chukchi Sea; while relative reduction in the sea ice coverage was calculated as a percentage of the average for the first five-year period (1979–1983) S_0.

A decrease in the average annual sea ice area reported for the Russian Arctic over the period of satellite observations accounted for 27.4 %. The distribution of monthly-mean values of sea ice area reduction in the Russian Arctic shows a strong relationship with the insolation (solar radiation) pattern. The coefficient of correlation between the annual rate of average annual sea ice extent reduction and annual phase shift (i.e. three-month phase shift to the past in the annual course) in the insolation equals 0.836 (p-value: 0.99) (Fig. 7, Table 4).

The calculated correlation coefficient for the phase-shifted insolation was found to be equal 0.888 (compared with its Δ annual course (Table. 4)), 0.836 (compared with the annual course of Δ/S_0), 0.869 (compared with annual dynamics of the coefficient of determination (R^2)); the p-value is 0.99 for all values

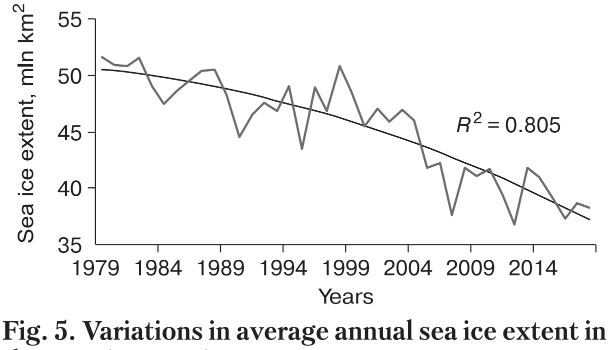

Fig. 5. Variations in average annual sea ice extent in the Russian Arctic.

The second-degree polynomial approximation.

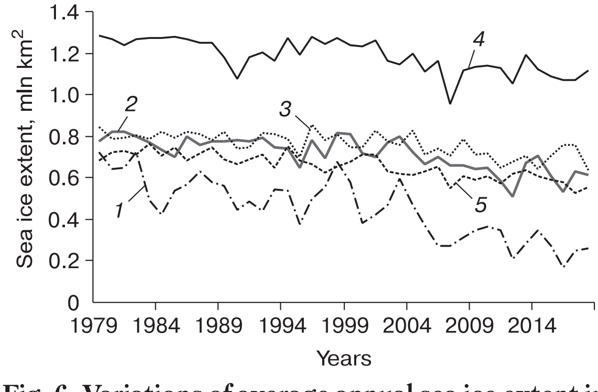

Fig. 6. Variations of average annual sea ice extent in the Russian Arctic according to the satellite-based data.

Seas: *1* – Barents, *2* – Kara, *3* – Laptev, *4* – East Siberian, *5* – Chukchi.

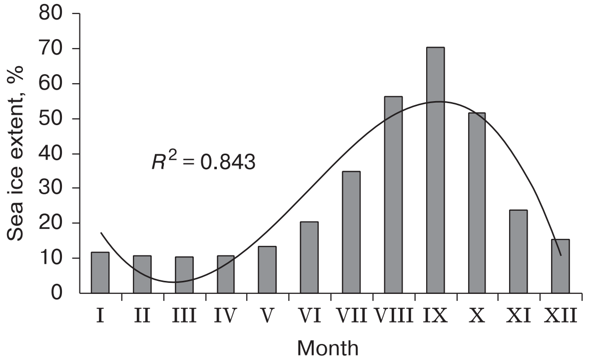

Fig. 7. Annual dynamics of the sea ice extent reduction in the Russian Arctic during the period of satellite observations calculated as percentage of the average for the first five-year period (1979–1983).

The third-degree polynomial approximation.

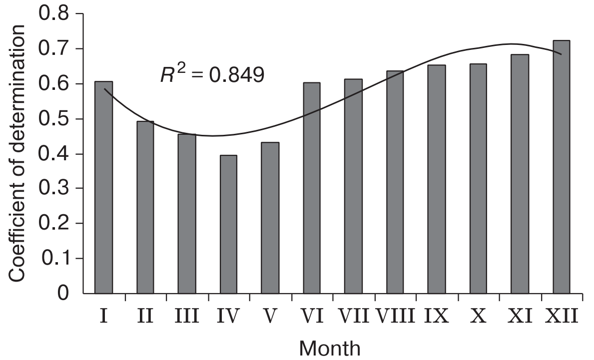

Fig. 8. Annual pattern of the coefficient of determination (second-degree polynomial) of multiyear variations of the sea ice extent in the Russian Arctic and total annual insolation contrast (third-degree polynomial).

This rate of change is characterized by a close correlation with the annual course, phase-shifted by three months, of incident solar radiation (R^2 = 0.869) and annual course of mean annual values of sea ice extent (R^2 = 0.994).

of R. The coefficient of determination shows a fraction of long-term changes in the average monthly sea ice coverage in the Russian Arctic determined by the multiyear variations in total annual IC for the Northern Hemisphere (Fig. 4). The average annual value of R^2 is 0.579. Thus, the long-term variability of the average monthly sea ice area in the Russian Arctic is by 57.9 % determined by the multiyear variability of the annual IC in the Northern Hemisphere. However, its annual course demonstrates an uneven monthly distribution of the coefficient of determination (Fig. 8, Table 5).

Results of the analysis of multiyear variability of the average monthly values of sea ice extent in the RA seas are listed in Table 6.

Table 4. **Reduction in average annual sea ice extent in the Russian Arctic, calculated on a monthly basis**

Month	Δ	Δ/S_0	R^2	Shifted insolation, W/m^2
January	575.6	11.78966	0.606	305.7
February	531.5	10.76759	0.493	249.6
March	509.7	10.26879	0.454	216.8
April	528.4	10.59843	0.396	217.6
May	650.8	13.32560	0.432	252.2
June	932.3	20.36982	0.602	310.1
July	1355.6	34.89303	0.612	374.3
August	1582.2	56.27730	0.636	427.4
September	1704.7	70.41270	0.654	456.2
October	1770.1	51.42638	0.657	454.5
November	1017.9	23.63600	0.684	422.9
December	725.1	15.46563	0.722	369.0

Note. Δ is the difference between the monthly means during the first five years (1979–1983) S_0 and last five years (2014–2018) S_T of annual average values for sea ice area in the Earth observation satellite database; R^2 is the coefficient of determination.

The annual dynamics of the sea ice reduction is closely linked with the annual course of insolation phase-shifted by three months to the past (the bottom line in Table 6). The correlation coefficient for the annual dynamics of average monthly reduction of sea ice area and the annual course of insolation is characterized by a negative value for the Barents Sea. This disproves the insolation factor to be a major factor controlling the sea ice extent declines in this part of the Russian Arctic. Here, the annual dynamics of decline is probably to a greater extent determined by the atmospheric circulation (the Iceland-Kara through) and the ocean current of the Gulf Stream (Fig. 9, 10).

The maximal multiyear variations in the average monthly sea ice area are chronologically recorded within the time interval bracketing also the observed maximal amplitude of interannual variability (Fig. 4) and minimal average monthly sea ice extent (Fig. 11). The range of changes was calculated as the ratio of the difference between the maxima and minima to the average value of monthly averages of sea ice area (for the period of satellite observations).

The correlation analysis allowed to investigate responses of multiyear average monthly values of sea

Table 5. **Reduction in average annual sea ice extent in the Russian Arctic seas over the first five-year period (1979–1983)**

Value	Barents Sea	Kara Sea	Laptev Sea	East Siberian Sea	Chukchi Sea
S_0	7752.5	9556.9	9618.5	15 180.4	8673.8
S_T	3113.5	7416.4	8402.0	13 094.7	6871.8
Δ, 10^3 km^2	4639.0	2140.5	1216.5	2085.7	1802.0
Δ/S_0, %	59.8	22.4	12.7	13.7	20.8

Table 6. **Reduction in average monthly sea ice cover in the Russian Arctic over the period of satellite observations, on a monthly basis**

Month	Barents Sea		Kara Sea		Laptev Sea		East Siberian Sea		Chukchi Sea	
	10^3 km^2	%	10^3 km^2	%	10^3 km^2	%	10^3 km^2	%	10^3 km^2	%
January	534.0	55.7	40.3	4.4	0.0	0.0	0.0	0.0	1.3	0.2
February	512.8	50.7	18.1	2.0	0.0	0.0	0.0	0.0	0.6	0.1
March	494.9	47.6	14.8	1.6	0.0	0.0	0.0	0.0	0.0	0.0
April	521.3	49.1	5.4	0.6	0.0	0.0	0.0	0.0	1.6	0.2
May	574.1	59.5	16.5	1.8	1.4	0.2	3.5	0.3	55.4	6.7
June	567.6	76.0	168.4	18.5	51.5	6.0	18.2	1.4	126.6	16.6
July	299.9	84.3	466.9	56.8	195.7	24.7	209.5	16.4	183.6	28.9
August	81.3	73.7	385.1	77.8	290.9	52.0	532.1	46.2	292.8	59.1
September	37.9	64.5	261.6	78.9	345.1	69.0	681.8	64.0	378.2	81.3
October	134.7	70.4	397.8	64.5	329.4	40.8	558.9	44.3	349.3	61.8
November	347.3	71.0	257.3	29.5	2.5	0.3	79.1	6.1	331.7	43.2
December	533.2	69.6	108.2	11.8	0.0	0.0	2.8	0.2	80.8	9.7
R	–0.826	0.716	0.833	0.869	0.766	0.741	0.792	0.776	0.930	0.901

Note. R is the correlation coefficient of the sea ice cover decline with a shift in annual course of insolation (the values of R are statistically significant with a p-value of 0.99).

ice extent in different regions of the Russian Arctic to multiyear variations in the annual IC in the Northern Hemisphere (Table 1). With increasing spatial (individual seas) and temporal (monthly) resolution, correlations between changes in sea ice area and IC have become weaker; while the contribution of local factors (geographical location, ocean currents, atmospheric circulation, etc.) tend to increase (Table 7).

The correlation coefficient value for a month averages 0.423 (Table 7). The monthly variations in the correlation coefficient are characterized by a close and negative correlation with the annual course of phase-shifted insolation (the bottom line in Table 7). The values R are statistically significant with a p-value of 0.99 for almost all the studied seas. The exception is the Barents Sea, for which a weak and statistically unreliable positive correlation was obtained (the value is statistically significant with a p-value of 0.75). This indicates a significant influence of the factors non-related to insolation on the multiyear variability in sea ice area in this part of the Russian Arctic.

Thus, all the Russian Arctic seas show a remarkable and close negative correlation between multiyear average annual variations in the sea ice area and long-term changes in the annual IC in the Northern Hemisphere [*Tsymbalenko et al., 2007*]. The values of R for the Russian Arctic seas average –0.719 (with a probability of 0.99). The most intense responses to long-term changes in IC (reflecting changes in the meridional heat transfer from low to high latitudes) are observed for the Chukchi Sea (–0.819) and Barents Sea (–0.782). The average annual values for sea ice extent in the RA seas were found based on the re-

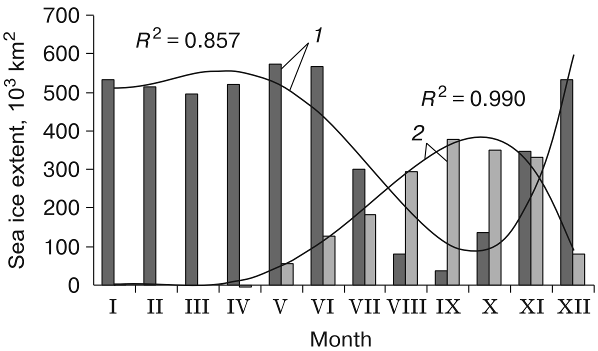

Fig. 9. Annual dynamics of the monthly average sea ice extent reduction in the Russian Arctic (thou. km^2) in the Barents Sea (*1*) and Chukchi Sea (*2*).

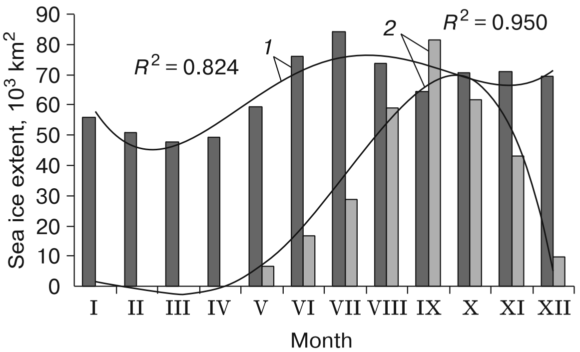

Fig. 10. Annual dynamics of the monthly average sea ice extent reduction in the Barents Sea (*1*) and Chukchi Sea (*2*) (as percentage of S_0, average for the period 1979–1983).

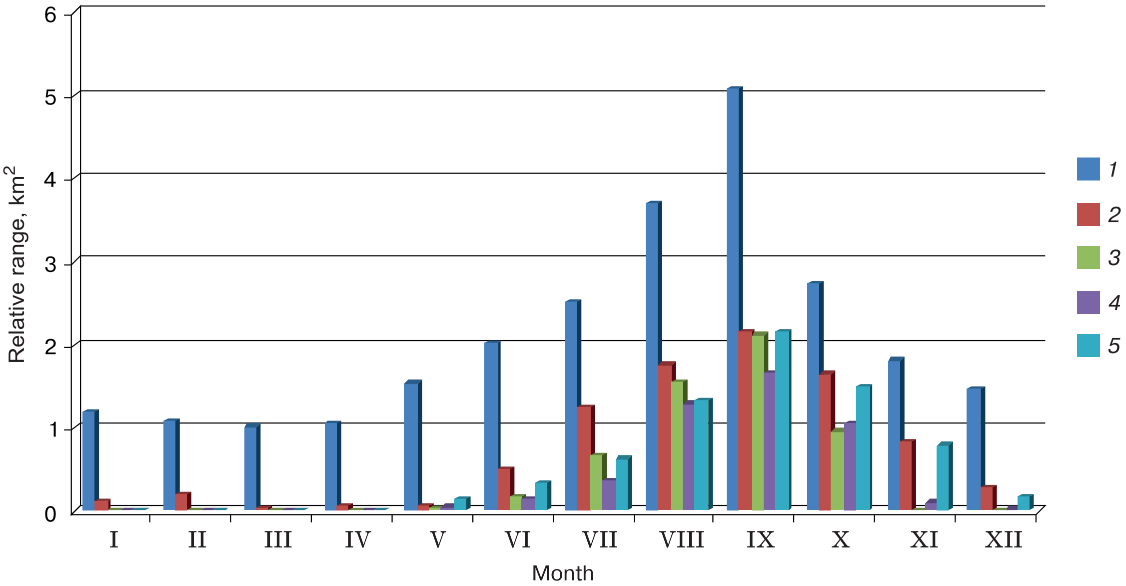

Fig. 11. Annual rate of the relative range of multiyear monthly variations of sea ice extent in the Russian Arctic.

Seas: *1* – Barents, *2* – Kara, *3* – Laptev, *4* – East Siberian, *5* – Chukchi.

lationships calculated using linear and polynomial (second-degree polynomial) regression equations. The forecast (until 2050) was carried out for the ensemble of the sea ice area values calculated using linear and polynomial regression equations (Fig. 12).

The dispersion analysis shows that multiyear variations in IC play a formative role in the multiyear variations in the average annual sea ice area in the Barents Sea (69.1 %), and in the Chukchi Sea (68.4 %), while in other seas these values are lower. Thus, multiyear variations (annual for the Northern hemisphere) in IC affecting the average annual variations in sea ice area in the Kara Sea account for 52.3 %, in the Laptev Sea for 39.1 %, and in the East Siberian sea for 44.5 %. The forecast estimates show that in the late 30s of this century the Barents sea may remain ice-free throughout the year (Fig. 12). The coefficient of determination averages 0.547 for all the RA seas.

The multiyear variations in the average monthly sea ice area were calculated for the seas of the Russian Arctic. The values of the coefficient of determination

Table 7. **A correlation relationship between multiyear mean monthly values of the sea ice extent and IC**

Month	Barents Sea	Kara Sea	Laptev Sea	East Siberian Sea	Chukchi Sea
January	–0.765	–0.608	0.158	0.205	–0.355
February	–0.705	–0.307	–0.035	–0.031	–0.299
March	–0.670	–0.462	0.262	0.141	0.174
April	–0.641	–0.078	–0.099	0.209	–0.326
May	–0.633	–0.251	–0.165	0.109	–0.642
June	–0.735	–0.525	–0.439	0.023	–0.595
July	–0.725	–0.736	–0.542	–0.381	–0.676
August	–0.590	–0.727	–0.584	–0.583	–0.769
September	–0.361	–0.589	–0.622	–0.699	–0.813
October	–0.581	–0.642	–0.645	–0.714	–0.774
November	–0.724	–0.613	–0.380	–0.554	–0.688
December	–0.831	–0.577	0.081	–0.198	–0.586
Average	–0.663	–0.510	–0.251	–0.206	–0.529
R	0.365	–0.783	–0.756	–0.941	–0.804

Note. *R* is the correlation coefficient of the monthly values of sea ice cover and annual course of insolation (phase shifted by 3 months).

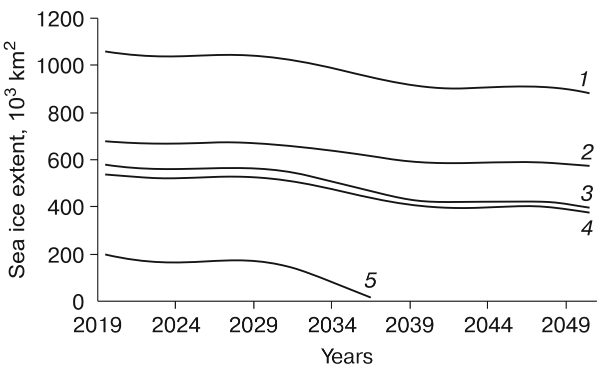

Fig. 12. Predicted estimates of the changes in average annual sea ice extent in the Russian Arctic seas.

Seas: *1* – Barents, *2* – Kara, *3* – Laptev, *4* – East Siberian, *5* – Chukchi.

were obtained based on the regression analysis of multiyear variations in monthly averages of sea ice area and in the total annual IC (for the Northern Hemisphere). The coefficient of determination shows the proportion of multiyear variations in the average monthly sea ice area which is determined by multiyear variations in IC in the regression model (Table 8).

The influence of the insolation factor exerted on multiyear variations in average monthly sea ice coverage has thus been estimated on the scale of individual seas for the Russian Arctic seas. All R values are statistically significant with a p-value of 0.99 (except the Barents Sea, for which they are not statistically significant).

In the Barents Sea, on average, 45.9 % of multiyear monthly variations are derived from multiyear variations in IC (the maximum value observed in December is 70.3 %). In the Chukchi Sea, the multiyear monthly variations determined by multiyear variations in IC average 47.6 %. The maximum values reported for multi-year variations in sea ice extent are observed in May (64.6 %) and in the period from August through November (i.e. encompassing the period of maximum variability, see Fig. 11). Whereas seas in the central Russian Arctic respond more conservatively to the IC factor. Thus, multiyear variations in the average monthly sea ice area determined by multiyear variations in IC in the context of the central parts account for, on average, 32 % in the Kara Sea, only for 18.5 % in the Laptev Sea, and 18 % in the East Siberian Sea. The coefficient of determination averages 0.324 for all the Russian Arctic seas.

Sea ice area in the Laptev and the East Siberian seas changes most synchronously with the annual course of insolation, while the Kara Sea and Chukchi Sea show far worse consistency (Table 8). At that, the Barents Sea is differentiated by a specific distribution pattern as compared to the rest of the Russian Arctic seas (Fig. 13, 14).

Table 8. **Values of the coefficient of determination (R^2) in the regression equation for the monthly average sea ice cover with IC**

Month	Barents Sea	Kara Sea	Laptev Sea	East Siberian Sea	Chukchi sea
January	0.588	0.497	0.008	0.060	0.341
February	0.505	0.094	0.028	0.008	0.335
March	0.451	0.279	0.074	0.024	0.034
April	0.412	0.011	0.022	0.045	0.366
May	0.401	0.064	0.028	0.023	0.646
June	0.541	0.281	0.201	0.025	0.438
July	0.530	0.542	0.294	0.181	0.539
August	0.357	0.530	0.341	0.341	0.606
September	0.131	0.348	0.387	0.488	0.661
October	0.344	0.429	0.452	0.533	0.635
November	0.548	0.402	0.356	0.391	0.638
December	0.703	0.360	0.024	0.040	0.470
Average	0.459	0.320	0.185	0.180	0.476
R	−0.290	0.719	0.863	0.882	0.739

The correlation coefficient in the annual distribution of the coefficient of determination (Table 8) and the annual course of the variations range is 0.650 for the Chukchi Sea (p-value of 0.95), for the Barents Sea −0.692 (p-value of 0.98). That is, in the Barents Sea, IC explains some of the multiyear variations, except those from the region of their maximum range. Probably, here, other factors are bigger players (which have the range of variations which is consistent with the association of the coefficient of determination). These are: atmospheric circulation (e.g. the extratropical cyclone trajectory coincides with the Iceland-Kara low-pressure trough) and the warm Gulf stream.

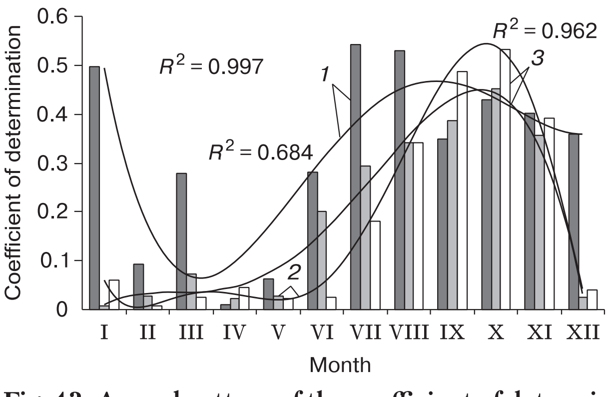

Fig. 13. Annual pattern of the coefficient of determination in the Kara Sea (*1*), Laptev Sea (*2*) and East Siberian Sea (*3*).

The fourth-degree polynomial approximation.

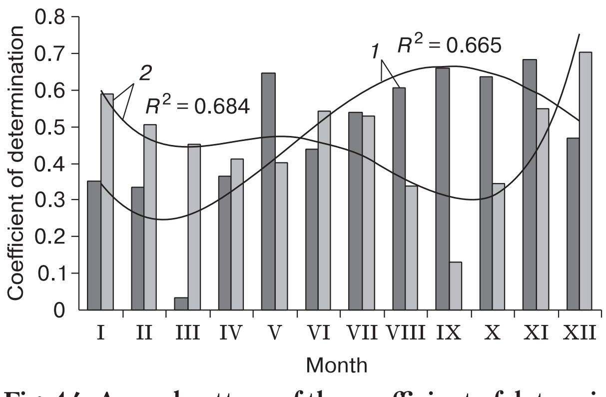

Fig. 14. Annual pattern of the coefficient of determination in the Chukchi Sea (*1*), and Barents Sea (*2*).

The fourth-degree polynomial approximation.

CONCLUSION

A statistical relationship between multiyear variations in sea ice area and IC variations was determined. In multiyear variations in sea ice extent, the connection with IC tends to decline, as the spatial domain of the study increases. Thus, for the entire Arctic Ocean, the coefficient of correlation between multiyear variations in the IC and average annual sea ice area equals –0.920. In the regression model, 95.1 % of multiyear changes in the average annual sea ice area are determined by multiyear variations in IC. In the context of the Russian Arctic, the correlation coefficient decreases to –0.831, whereas in the regression model, 69.8 % of multiyear variations in the average annual values are accounted for multiyear variations in IC. On the scale of the Russian Arctic seas, the average correlation coefficient is –0.719, and multiyear variations in IC are liable for as much as 54.7 % of multiyear variations in the average annual sea ice area.

Multiyear variations in the IC explain 57.9 % variations in monthly averages of sea ice area in the Russian Arctic and, on average, 32.4 % average monthly variations in sea ice area in the RA seas.

The annual dynamics of sea ice area and insolation display a closer and more persistent correlation between them, which increasingly weakens, however, still remaining very close, with enlargement of the spatial scale. Thus, the calculated coefficient of the correlation between the annual course of insolation (phase-shifted by three months) and the annual dynamics of the sea ice area equals –0.906 for the Arctic Ocean; –0.892 for the entire Russian Arctic; and, on average, –0.801 for the seas of the Russian Arctic. In addition, the annual course of insolation is closely associated with: the annual course of the interannual variability of sea ice area; distribution of the coefficient of determination in regression models with IC; the annual dynamics of sea ice area reduction. This demonstrates an important role of annual insolation oscillations in the Earth's cryosphere and climate system.

The most conservative response received by the insolation is from the seas in the central Russian Arctic (Kara Sea, Laptev Sea and East Siberian Sea), while the most active response recorded in the sea ice area dynamics is observed in the marginal seas of the Russian Arctic. At this, the nature of the responses in the Barents and Chukchi seas differ essentially. This is associated with significant involvement of the circulation factor in the variations in sea ice area (in the annual course and multiyear changes) and the influence of the Gulf Stream ocean current on the Barents Sea. The influence of warm water masses of the Bering Sea on the variations in sea ice area in the Chukchi Sea is less remarkable, which is probably dictated by the narrowness of the Bering Strait.

The experience of such assessment of the role of insolation factor in the changing sea ice area may be of both theoretical (e.g. construction of regional climate models) and practical significance (e.g. strategic planning for a new stage of developing the Russian Arctic).

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References

Alekseev, G.V., Aleksandrov, E.I., Glok, N.I., et al., 2015. Arctic sea ice cover in connection with climate change. Issledovanie Zemli iz Kosmosa (Earth Observation and Remote Sensing), No. 2, 5–19, DOI: 10.7868/S0205961415020025.

Burke, A., 1940. Sea Ice. Glavsevmorput', Leningrad; Moscow, 96 pp. (in Russian).

Fedorov, V.M., 2013. Interannual variations in the duration of the tropical year. Doklady Earth Sciences 451 (1), 750–753, DOI: 10.1134/S1028334X13070015.

Fedorov, V.M., 2015. Trends of the changes in sea ice extent in the Northern Hemisphere and their causes. Earth's Cryosphere XIX (3), 46–57.

Fedorov, V.M., 2018. The Earth's Insolation and Recent Climate Changes. Fizmatlit, Moscow, 232 pp. (in Russian).

Fedorov, V.M., 2019a. Earth's insolation variation and its incorporation into physical and mathematical climate models. Physics-Uspekhi 62 (1), 32–45, DOI: 10.3367/UFNe.2017.12.038267.

Fedorov, V.M., 2019b. The problem of meridional heat transport into the astronomical climate theory. Geofizicheskie Protsessy i Biosfera (Geophysical Processes and Biosphere), 18 (3), 117–128, DOI: 10.21455/gpb2019.3-8.

Fedorov, V.M., Grebennikov, P.B., 2018. Insolation contrast of the Earth and changes in the sea ice extent in the Northern Hemisphere. Arktika: Ekologiya i Ekonomika (The Arctic: Ecology and Economy), No. 4 (32), 86–94, DOI: 10.25283/2223-4594-2018-4-86-94.

Fedorov, V.M., Frolov, D.M., 2019. Spatial and temporal variability of solar radiation arriving at the top the atmosphere. In: Cosmic Research (English translation of Kosimicheskie Issledovaniya), Maik Nauka/Interperiodica Publishing (Russian Federation), 57 (3), 156–162, DOI: 10.1134/S0010952519030043.

Fedorov, V.M., Kostin, A.A., 2019. The Earth's insolation calculations for the period from 3000 BC to 2999 AD. Protsessy v Geosredakh (Processes in Geosciences), No. 2, 254–262 (in Russian).

Fetterer, F., Knowles, K., Meier, W., et al., 2017. Updated daily sea ice index, version 3. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center, DOI: 10.7265/N5K072F8.

Frolov, I.E., Gavrilo, V.P. (Eds.), 1997. Sea Ice. Gidrometeoizdat, St. Petersburg, 402 pp. (in Russian).

Giorgini, J.D., Yeomans, D.K., Chamberlin, A.B., et al., 1996. JPL's on-line solar system data service. Bulletin of the American Astronomical Society 28 (3), p. 1158.

Kopp, G., Lean, J., 2011. A new lower value of total solar irradiance: Evidence and climate significance. Geophysical Research Letters, vol. 37, L01706, DOI: 10.1029/2010GL045777.

Koryakin, V.S., 1988. Arctic Glaciers. Nauka, Moscow, 160 pp. (in Russian).

Shalina, E.V., Bobylev, L.P., 2017. Sea ice transformations in the Arctic from satellite observations. Issledovanie Zemli iz Kosmosa (Earth Observation and Remote sensing), 14 (6), 28–41, DOI: 10.21046/2070-7401-2017-14-6-28-41.

Tsymbalenko, T.T., Baydakov, A.N., Tsimbalenko, O.S., Gladilin, A.V., 2007. Mathematical Statistics Methods in the Processing of Economic Information. Finansy i Statistika, Moscow, 200 pp. (in Russian).

Zakharov, V.F., 1981. Ice of the Arctic and Modern Natural Processes. Gidrometeoizdat, Leningrad, 136 pp. (in Russian).

Zakharov, V.F., Malinin, V.N., 2000. Sea Ice and Climate. Gidrometeoizdat, St. Petersburg, 92 pp. (in Russian).

Zubakin, G.K. (Ed.), 2006. Ice Formations in the Western Arctic Seas. AANII, St. Petersburg, 272 pp. (in Russian).

Zubov, N.N., 1938. Seawater and Ice. Moscow, Gidrometeoizdat, 454 pp. (in Russian).

URL: http://ssd.jpl.nasa.gov/ – NASA, Jet Propulsion Laboratory California Institute of Technology (JPL Solar System Dynamics) (last visited: 25.08.2019).

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