TRENDS OF THE CHANGES IN SEA ICE EXTENT IN THE NORTHERN HEMISPHERE AND THEIR CAUSES

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The solar radiation coming to the surface of the Earth's ellipsoid (without atmosphere) was calculated. The comparative analysis of the radiation and the surface temperature anomalies allowed enhancement in the inter-latitude heat transfer to be identified. This enhancement can be responsible for the present temperature increase in the atmosphere and the upper layer of the ocean in the North Polar Region. The increase in the greenhouse effect in the northern area of the heat outflow is also shown. The analysis showed close relationship between the sea ice extent in the Northern Hemisphere and the incoming solar radiation. The quantitative estimation of the sea ice extent in the Northern Hemisphere for the time interval of 2014–2050 is made based on the regression equation.

Sea ice, solar radiation, inter-latitude heat transfer, greenhouse effect

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INTRODUCTION

Changes in the Earth's cryosphere are primarily related to variations in the global temperature as one of the main parameters of the changing global climate. The climate is an important characteristic of the natural environment of the human society; therefore, investigation of changes in the global climate and their causes is one of the main issues of the modern nature science. The key point in the problem of studying and forecasting climatic changes is the issue of the causes of these changes [*Monin and Shishkov, 1979; Monin, 1982; Kondratyev, 1987; Monin and Shishkov, 2000*]. The 20th century saw the trend for the rise in the global near-surface temperature. However, the causes of this phenomenon have not been clearly identified. There is a widespread opinion that the greenhouse effect, mostly referred to the anthropogenic factor of impact, is the main cause of the global climate change [*Anthropogenic... Changes..., 1987; Ershov, 1997; Global Meteorological Organization..., 2014*]. At the same time, there is no doubt that the solar radiation providing light and heat to the Earth plays an important role in climate genesis [*Shuleikin, 1953; Lorentz, 1970; Budyko, 1974, 1980; Monin and Shishkov, 1979; Kondratyev, 1987; Monin and Shishkov, 2000*]. "The Sun is the only source of heat, which is powerful enough to exert significant impact on the surface temperature of the Earth and of the ambient air" [*Voyeykov, 1948, p. 166*].

Variations in the solar radiation coming to the Earth are determined by two major causes, which have different origin. The studies of variations in the solar radiation related to changes in the physical activity of the Sun have a long history (for example, studying the sunspots formation and the cycles of Schwabe–Wolf, Hale, and Gleisberg). The issue of there existing a relation between solar activity and

climate has been disputable for quite some time [*Eigenson et al., 1948; Eigenson, 1963; Kondratyev and Nikolsky, 1978; Vitinsky, 1983; Kondratyev, 1987; Abdusamatov, 2009; Dudok de Wit. and Watermann, 2010*]. This study presents the results of investigating variations in the solar climate of the Earth related to the processes of celestial mechanics. Changing the solar activity has been neglected.

Solar climate is understood as supply and distribution of solar radiation on the upper atmospheric boundary or on the earth surface in the absence of atmosphere which is theoretically calculated [*Milankovich, 1939; Monin and Shishkov, 1979; Drozdov et al., 1989; Khromov and Petrosyants, 2006*].

The solar constant, which is a flux of solar radiation (the other terms used are the solar radiation flux density and solar radiation intensity) on the outer atmospheric boundary is a measure of the solar climate [*Alisov and Poltaraus, 1974*].

Solar flux variations determined by the processes of celestial mechanics are traditionally (in the framework of the assumptions of the astronomic climate theory) examined within long time ranges. Orbital elements, like the perihelion longitude, eccentricity, and the Earth's tilt, subject to disturbances of secular perturbations, are taken into consideration. These perturbations have prolonged variation periods [*Milankovich, 1939; Brouwer and Van Woerkom, 1950; Sharaf and Budnikova, 1969; Vernekar, 1972; Berger, 1978, 1988; Monin, 1982; Berger and Loutre, 1991; Monin and Shishkov, 2000; Melnikov and Smulsky, 2004, 2009; Fedorov, 2014b, 1988*]. Calculations of the incoming solar radiation and studies of its spatial and temporal variations due to the process of celestial mechanics have been practically not made within the range of periodic perturbations of the Earth's orbit

elements and the Earth's tilt. Such studies were launched at the Voyeykov Chief Geophysical Observatory [*Borisenkov et al., 1983, 1985*]; however, they did not develop any further.

We made calculations of the incoming solar radiation to the upper atmospheric boundary (or onto the surface of the Earth's ellipsoid in the absence of atmosphere). Based on the astronomical ephemerides data (JPL Planetary and Lunar Ephemerides), DE-405/406 [*National... Administration, 2014*], the values of the incoming solar radiation (in the absence of atmosphere) were calculated for the tropical years, half years, and seasons of a tropical year in different latitudinal zones (extending to 5° latitude) of the Earth's ellipsoid within the range from 2950 BC to 2950 AD. The accuracy degree of the ephemerides evaluated by the distance between the Earth and the Sun is 10^{-9} a.e. (or 0.1496 km), and evaluated by the time it is 1 s (or 0.000 011 5 day). The Earth's surface was approximated by the ellipsoid (GRS80) with semi-axis lengths equal to 6,378,137 m (the major equatorial axis) and 6,356,752 m (the minor equatorial axis). The integration steps were 1° by longitude, 1° by latitude, and 1/360 tropical year length by time. In making the calculations, we considered changes in the distance between the Earth and the Sun and in the duration of the Earth's rotation period (a tropical year) due to periodic perturbations in the orbital rotation of the Earth [*Fedorov, 2012a,b, 2013a,b, 2014a, 2015b,c*]. Based on the results of calculations for the period within the range from 2950 BC to 2950 AD, a database was formed in a matrix format for the incoming solar radiation (granted no atmosphere) to the latitudinal zones (extending to 5° latitude) with a time step of 1/12 of the tropical year [*Fedorov, 2014b, 2015a*].

RESULTS AND DISCUSSION

The secular trends in the global temperature changes. The values obtained for the incoming solar radiation coming to the Earth's ellipsoid in the absence of atmosphere were compared to the temperature anomaly data for the period from 1850 to 2013 [*University..., 2014*]. The calculation results show that, given the general trend of reduction of the incoming solar radiation (without considering atmosphere), the trend for essential reduction in the incoming solar radiation is observed for the polar regions of the Earth, while in the equatorial regions a trend for certain increase in the incoming radiation has been noted (Fig. 1). Thus, the latitudinal contrasts are increasing in the solar climate of the Earth. This effect may result in the increase of the meridional heat transfer in the atmosphere from the equatorial region to the polar regions (known as "the first-order heat engine" [*Shuleikin, 1953*]) and in the respective changes in the temperature characteristics of the global climate.
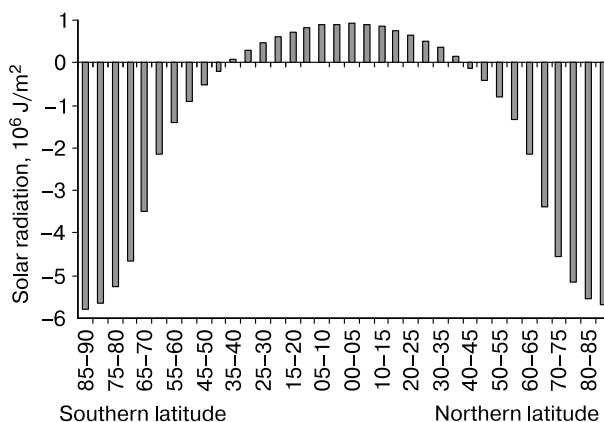
Fig. 1. Distribution of the differences on the amount of solar radiation coming (without atmosphere) to the corresponding latitudinal regions of the Earth in 2050 and in 1850.

Reduction in the amount of solar radiation coming to the polar regions in the period from 1850 to 2050 is determined by the value of $5.79 \cdot 10^6$ J/m², which constitutes 0.11 % of the mean value of the incoming solar radiation for latitudinal zones (85–90° geographic latitude). The increase in the equatorial region is much lower: in the equator area (0–5° latitude), it is $9.15 \cdot 10^5$ J/m² (0.007 %). The increased difference between the amounts of radiation coming to these regions in 2050 will be $6.70 \cdot 10^6$ J/m², which is 0.09 % more than in 1850. At the same time, it is taken into account that the area of the heat source regions is approximately 2.7 times greater (due to the spherical shape of the Earth) than the area of the heat sink regions.

Investigation of the temperature data and of solar radiation was conducted based on correlation and regression analysis. The correlations were studied by series with a time step of 100 years (secular periods) with their consecutive shifting (with a 1 year step) from the observation start (1850) to the end of the array of physical data referred to the temperature anomaly. The calculated solar radiation coming to the Earth during the tropical year (without considering atmosphere) [*Fedorov, 2013a*] and to the Earth's hemispheres was compared to the data on temperature anomalies presented in four archives of the University of East Anglia and of the Hadley Centre [*University..., 2014*]. The HadCRUT3 and HadCRUT4 archives contain information about the globally averaged near-surface temperature of the Earth (obtained by combining the air temperature data for land and the near-surface water temperature of the ocean). The CRUTEM4 archive contains values of the air temperature above land (at the height of 2 m). The HadSST3 archive contains data on the temperature anomalies in the near-surface ocean layer. The tem-
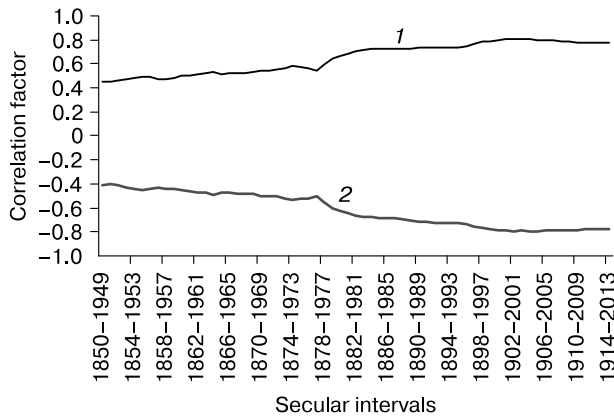
Fig. 2. Distribution of the correlation factor values between the difference in the solar radiation coming to the equatorial and polar regions and the near-surface water anomaly (HadCRUT3 data) (curve *1*) and between the incoming solar radiation and the near-surface water anomaly (curve *2*) by secular intervals.

perature anomalies were compared also with the differences in solar radiation coming to the latitudinal zone ranging from 45° N to 45° S and radiation coming to the regions ranging from 45° to 90° of the latitude in each hemisphere of the Earth. This difference was determined for the hemispheres between solar radiation of the latitudinal zones of 0–45° and 45–90° for each hemisphere. The values of the series shown in Fig. 2 (the HadCRUT3 array data are referred to the near-surface temperature) have close negative correlation (−0.996). A similar relationship between the incoming radiation and the differences in the amounts of radiation coming to equatorial and polar regions are characteristic for each hemisphere.

Table 1. **The average values of the correlation factor for the near-surface water temperature anomaly and solar radiation by certain secular intervals (the probability rate is 0.99)**

| Database	Earth		Northern hemisphere		Southern hemisphere	
	R_1	R_2	R_1	R_2	R_1	R_2
HadCRUT3	−0.786	0.790	−0.734	0.728	−0.783	0.805
HadSST3	−0.777	0.779	−0.702	0.687	−0.810	0.831
CRUTEM4	−0.717	0.717	−0.687	0.687	−0.714	0.715
HadCRUT4	−0.776	0.780	−0.714	0.711	−0.793	0.809
Average value	−0.764	0.767	−0.709	0.703	−0.775	0.790

N o t e. R_1 is the correlation factor with incoming solar radiation; R_2 is the correlation factor with difference in solar radiation coming to the equatorial and polar regions of the Northern Hemisphere.

The correlation factors (R) calculated for secular intervals (Fig. 2) are characterized by a high degree of correlation with the average secular interval values of the weather record data (−0.961 – with incoming radiation, 0.931 – with the difference). The meteorological data consisted in the percentage of the Earth's surface covered by 5° meteorological data cells relating to the entire Earth's surface. Based on the correlation analysis results, secular intervals were identified from 1900–1999 up to 1914–2013 (Fig. 2), in which the values of R become rather high (Table 1) and close to each other (the difference less than 1.5 %). These secular intervals agree with the most reliable data from the HadCRUT3 database (http://www.cru.uea.ac.uk/cru/data/temperature); so we used them as a basis for developing linear regression equations for the incoming solar radiation and the temperature anomalies.

Based on the regression equations for the entire Earth and for the hemispheres, the values of the temperature anomalies were calculated for the period from 1850 to 2050, and detailed comparison was made between the calculated temperature anomalies and the basic data for the period of reliable meteorological data covering 1900–2013 (Fig. 3, 4). The correlation factor for the physical values of the temperature anomaly was 0.826 for the Earth, 0.775 for the Northern Hemisphere and 0.840 for the Southern Hemisphere.

It follows from the obtained results that the average annual modular value of the near-surface temperature in the Southern Hemisphere (0.259 °C) for the period from 1900 to 2013 exceeded the respective value in the Northern Hemisphere (0.237 °C). Considering slight differences between the actual and estimated values for the Southern Hemisphere (0.120 °C in the Southern Hemisphere and 0.159 °C in the Northern Hemisphere) and the high values of R between the temperature anomaly and solar radiation (Table 1), one can state that the temperature rise is higher here than in the Northern Hemisphere and that it is related to the mechanism of inter-latitude heat exchange (determined by the inter-latitude gradient of the incoming solar radiation).

The variation shown in Fig. 4 demonstrates that there exist groups of actual temperature anomaly (28–29 years long) located either above the estimated values or below them. The complete variation cycle is approximately 56–58 years. On average for the Earth, in each group 84.1 % of the actual values are either above the calculated values or below them. Depending on this, we determined them as either "warm" or "cold", respectively. Four such groups (epochs) are identified for the Earth in the interval from 1900 to 2013: 1900–1925 – "cold", 1926–1953 – "warm", 1954–1985 – "cold", 1986–2013 – "warm". These groups are aligned with the circulation epochs identified for classifying the atmospheric processes in
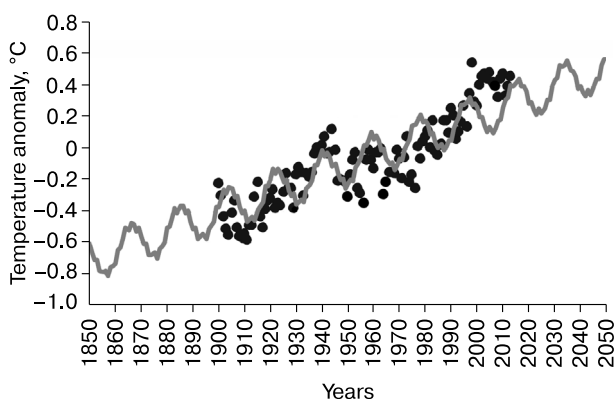
Fig. 3. Distribution of the near-surface water anomaly values calculated for the interval from 1850 to 2050 (the curve) and of the actual data for the interval from 1900 to 2013 (HadCRUT3 data) near-surface water anomaly values (the dots) (versus the average annual temperature in the interval of 1961–1990).
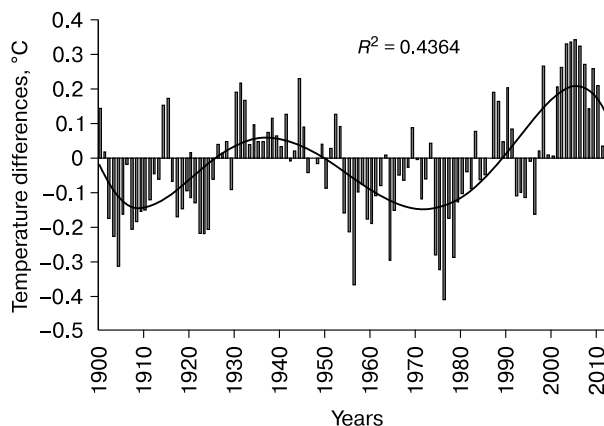
Fig. 4. Distribution of the differences between the actual values of the near-surface water temperature and the values calculated by the regression equation.

Approximation is a 5th-degree polynomial; R^2 is the certainty of approximation.

the Northern Hemisphere [*Kononova, 2009*] and similarity to the intervals of different phases of the modern climate, reflecting the interaction stages in the "ocean–atmosphere" system [*Anisimov et al., 2012*].

Considering the fact that the mean (in modulus) difference between the actual and calculated values of the near-surface temperature in the Northern Hemisphere is greater than in the Southern Hemisphere, as well as better homogeneity of the values (whether above or below the calculated values) in the groups (88.1 % in the Northern Hemisphere and 75.3 % in the Southern Hemisphere), we can regard the variance between the calculated and actual anomaly values to be determined by the disturbance of the inter-latitude heat transfer due to the mechanism of heat transfer in the "ocean–land" system, known as the "second-order heat engine" [*Shuleikin, 1953*]. This mechanism is related to the seasonal reverse change of the heat source and sink in the regions. Its action weakens the correlation between the temperature anomaly and solar radiation and increases the variance between the calculated values of the temperature anomaly and the respective actual values.

Considering the mean difference values obtained for the epochs taken as corrections, the variance between the calculated and actual temperature values becomes reduced on average by modulus for the Earth to 0.101 °C, which is 11.6 % less than that without the correction. In the Northern Hemisphere, the respective value, considering corrections, is 0.114 °C (18.9 % less than without corrections), in the Southern Hemisphere it is 0.105 °C (5.9 % less). The values of R between the calculated and actual temperature increase grow for the entire Earth whole

to 0.901, for the Northern Hemisphere to 0.885 and for the Southern Hemisphere to 0.890. It is known that the mechanism of inter-latitude heat transfer is most expressed in the hemisphere during winter half-years [*Shuleikin, 1953*]. On the contrary, analysis of the latitudinal radiation distribution made by half-years demonstrates that the intensification of the inter-latitude heat transfer mechanism is more expressed in the summer half-years (March–August) and less expressed in the winter half-years (September–February).

The author has also investigated the correlation between the accumulated incoming solar radiation and near-surface temperature anomaly from 1850 to 2050 [*Fedorov, 2014b*].The obtained results demonstrate the increase in the correlation factor and decrease in the variance between the calculated and actual near-surface temperature anomaly values. For example, the correlation factors between the incoming solar radiation and the near-surface temperature have negative values of –0.775 for the Earth, –0.733 for the Northern Hemisphere, and –0.776 for the Southern Hemisphere (in the series from 1850 to 2013). In the case of accumulated solar radiation, R is characterized by positive values equal to 0.805, 0.762 and 0.809, respectively. That is, the values of R in correlation between the temperature anomalies calculated considering the incoming solar radiation and the actual values increase (by modulus) by 3.9 % for the Earth. They raise by 4.0 % for the Northern Hemisphere, and the rise is equal to 4.3 % for the Southern Hemisphere.

The difference between the actual and calculated values of the temperature anomaly (by the linear re-

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gression equation with incoming solar radiation) is 52.3 % of the modulus of the mean annual value of the actual temperature anomaly for the Earth (without considering the correction for the quasi-sexagenarian variance), 63.2 % for the Northern Hemisphere and 45.8 % for the Southern Hemisphere. In calculating the near-surface temperature anomaly considering the incoming solar radiation accumulation, the variance values get reduced to 48.8, 60.3 and 43.6 %, respectively. Thus, the variance between the actual and calculated values gets reduced by 6.7 % for the Earth, 4.6 % for the Northern Hemisphere and by 4.8 % for the Southern Hemisphere. The rise in the *R* values and reduction of the variance indicate accumulation of heat related to the incoming solar radiation and the impact of this accumulation (the greenhouse effect) on the near-surface temperature regime of the Earth.

Thus, the enhancing effect of the inter-latitude heat transfer has been found for the modern epoch ("the first-order heat engine"). This effect is related to reduction in the incoming solar radiation coming to the polar regions (the heat sink) and to increased inflow of solar radiation to the equatorial (the heat source) regions of the Earth (i.e. to the growth of the inter-latitude solar radiation gradient). The effect of the increase in the inter-latitude heat exchange is marked both in the Earth's atmosphere (the HadCRUT3 and HadCRUT4 archives) and in the near-surface ocean layer (the HadSST3 archive). It is determined by the secular change in the Earth's tilt [*Milankovich, 1939*]. Higher values of *R* and lower variances in the original temperature anomaly values, calculated considering accumulation of the incoming solar radiation, testify to the increase in the greenhouse effect in the area of the heat sink. The intensification of the greenhouse effect seems to be caused by condensation and increase in the condensation and the content of steam in the atmosphere, related to the growth in evaporation as the temperature increases in the areas of heat sink due to the increase in the inter-latitude heat transfer.

The increase in the inter-latitude heat transfer and in the greenhouse effect correlates with the secular variations of the near-surface Earth's temperature in the modern epoch [*Fedorov, 2014b*]. This brings about the modern trend of the cryospheric processes on the Earth – reduction of the sea ice cover and degradation of land glaciation and permafrost.

The trend of sea ice extent changing in the Northern Hemisphere. The ice covered area occupies about 6 % of the Earth's surface, or approximately 30 million km². The major mass of ice is located in the Arctic and Antarctic. In the Northern Hemisphere, the land ice accounts only for 20 % of the total ice area of the Arctic, while the remaining 80 % are occupied by the sea ice [*Koryakin, 1988*]. Seasonal changes in the land and sea ice extent in the Arctic are currently occurring on the area of 10–17 milli-

on km². In summer, the extent of the sea ice decreases by approximately two times, just as the amount of the incoming solar radiation decreases twice in the winter half-year, compared to the summer half-year [*Fedorov, 2015a*].

The obtained values of the solar radiation coming to the Earth ellipsoid without considering the Earth's atmosphere were compared to the data of the changes in the extent of sea ice (from 1870 to 2007) in the Northern Hemisphere [*Walsh and Chapman, 2001; Rayner et al., 2003; Illinois... University..., 2014; UK Met Office..., 2014*]. The ice cover is the result of interaction between the ocean and the atmosphere under certain temperature conditions [*Zubov, 1938; Burke, 1940; Sea Ice, 1997; Ice Formations..., 2006*]. The area of the ice cover is its important characteristic. As time goes, it experiences certain changes, the most significant of which are seasonal, annual, and perennial fluctuations. Investigating the changes and their causes is one of the most topical issues of cryolithology and sea ice studies [*Zubov, 1938; Sea Ice, 1997; Zakharov, 1981; Zakharov and Malinin, 2000*].

The author analyzed three characteristics of the sea ice extent in the Northern Hemisphere: the average annual values of the sea ice area, the summer (minimum), and seasonal variations (the difference between the maximum winter and minimum summer area of the sea ice) obtained on a perennial basis. The summer minimum of the sea ice extent is chronologically clearly localized in the annual cycle, and it is in September. September is the month of the autumn equinox and the end of the summer half-year in the Northern Hemisphere. The maximum is more extended in time and recorded from February to April (the period near the spring equinox, the end of the winter and the beginning of the summer half-year in the Northern Hemisphere) [*Sea Ice, 1997*]. Thus, the extreme values of the sea ice extent are characterized by a phase shift in the annual cycle of the extreme values of the incoming solar radiation by approximately 90°. The figures characterizing the extent of the sea ice were compared to the values of the incoming solar radiation without atmosphere in the Northern Hemisphere (the annual figure, the winter and summer figures) (Fig. 5). Comparison was made also with the difference between the solar radiation coming to the latitudinal region of 0–45° N, which is the source of heat, and solar radiation coming to the latitudinal area of 45–90° N (the area of the heat sink).

Based on the correlation analysis, the following relationships were studied in more detail: 1) the relationship between the values of the sea ice extent [*Walsh and Chapman, 2001; Rayner et al., 2003; Illinois... University..., 2014*] and solar radiation coming to the upper limit of the atmosphere in the Northern Hemisphere during the summer half-year; 2) the relationship between the sea ice extent and the difference between solar radiation coming to the equatorial and
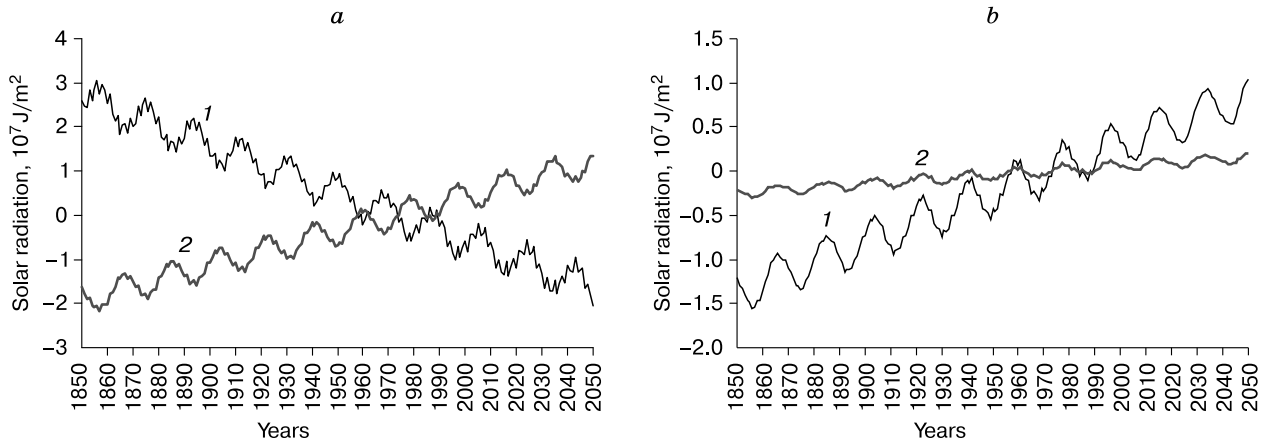
Fig. 5. Distribution of the values of solar radiation (versus the average amount of radiation in 1961–1990) coming to the Northern Hemisphere (curve *1*) and the differences of the solar radiation coming to the equatorial and polar regions of the Northern Hemisphere (curve *2*).

a – summer half year, *b* – winter half year.

polar regions of the Northern Hemisphere during the summer half-year. This was determined by two facts. Firstly, higher correlation factor (Table 2) was obtained for the value of the sea ice extent in the summer half-year. Secondly, greater intensification of the inter-latitude heat transfer (resulting from many years of the observations) was observed in the summer half-year than in the winter half-year.
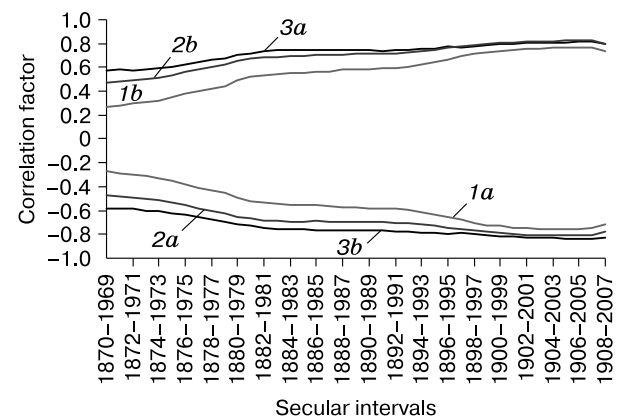
The correlation was investigated in series with constant duration of 100 years (secular intervals) with their consecutive shifting from the beginning of the array (1870) to the end (2007 – the last year in the archive) with a step of one year. Thus, the values of the correlation factor were determined for the secular intervals of 1870–1969, 1871–1970, etc. (altogether 39 secular intervals) (Fig. 6). The distributions of the correlation factors obtained for secular intervals reflect an inhomogeneous character (in terms of reliability) of the data distribution regarding

the sea ice extent in the original series [*Rayner et al., 2003; Illinois... University..., 2014*]. In the arrays, there are secular intervals (the last ones in the array) from 1900–1999 and further to 1908–2007 (altogether nine intervals), in which the correlation factor figures become high (Table 3) and rather close. Variations for the nine secular intervals are 1.10 % of the average annual data (incoming radiation) and 0.98 % (the difference) of the minimum values of the sea ice area (the summer half-year). They are 0.71 and 0.66 %, while for the seasonal sea ice area range they are 0.65 and 0.75 %, respectively.

Fig. 6. Distribution of the values of the correlation factor for the sea ice extent with the differences in the solar radiation coming to the northern hemisphere in the summer half year to the equatorial and polar regions (index *a*) and the solar radiation coming to the Earth by secular intervals (index *b*).

1 – average annual area, *2* – minimum area, *3* – seasonal variation.

Table 2. **Average values of the correlation factor of the sea ice extent for the Northern Hemisphere and solar radiation for the entire series of data (1870–2007), the probability rate is 0.99**

Sea ice extent (area)	Summer half year		Winter half year	
	R_1	R_2	R_1	R_2
Average annual area	0.689	−0.677	−0.671	−0.643
Minimum area	0.762	−0.749	−0.746	−0.719
Seasonal variation	−0.791	0.775	0.773	−0.747
Average value by modulus	0.747	0.734	0.730	0.703

N o t e . R_1 is the correlation factor with incoming solar radiation; R_2 is the correlation factor with the difference of solar radiation coming to the region of heat source and heat sink.

Ta b l e 3. **Values of the correlation factor of the sea ice extent (area) and solar by certain secular intervals, the probability rate is 0.99**

Secular interval	Average annual area		Minimum area		Seasonal variation	
	R_1	R_2	R_1	R_2	R_1	R_2
1900–1999	0.7385	−0.7308	0.8047	−0.7898	−0.8189	0.7964
1901–2000	0.7455	−0.7414	0.8082	−0.7958	−0.8214	0.8011
1902–2001	0.7539	−0.7483	0.8161	−0.8025	−0.8317	0.8091
1903–2002	0.7579	−0.7533	0.8176	−0.8055	−0.8298	0.8097
1904–2003	0.7635	−0.7590	0.8210	−0.8091	−0.8314	0.8116
1905–2004	0.7707	−0.7580	0.8267	−0.8088	−0.8372	0.8115
1906–2005	0.7648	−0.7565	0.8225	−0.8079	−0.8355	0.8124
1907–2006	0.7620	−0.7479	0.8229	−0.8050	−0.8374	0.8134
1908–2007	0.7346	−0.7137	0.8006	−0.7771	−0.8247	0.7957
Average value	0.7546	−0.7454	0.8156	−0.8002	−0.8298	0.8068

N o t e. R_1 is the correlation factor with incoming solar radiation; R_2 is the correlation factor with the difference of solar radiation coming to the equatorial and polar regions.

These secular intervals seem to agree with the most reliable original data [*Walsh and Chapman, 2001; Rayner et al., 2003*]. Based on the criteria of reliability of the ice extent data (Fig. 6), high (Table 3) and stable values of the correlation factor reflecting the actual and reliable relation between the values of the sea ice extent and solar radiation at the upper bound of the atmosphere (incoming radiation and the difference), we assumed these secular intervals to be the basis for developing regression equations.

To develop the regression equations of the sea ice extent and of solar radiation (incoming radiation and the difference), the second-degree equation was used. Altogether, 9 regression equations were developed for reliable secular intervals for three characteristics of the sea ice area. In addition to higher values of approximation of the relative linear regression, the use of a second-degree polynomial as a regression equation was also determined by the fact that sea ice is the result of interaction between the atmosphere and the ocean. It means that ice melts as a result of heat exchange both with atmospheric air and with ocean water. Increase in the inter-latitude heat exchange is recorded both for the atmosphere and the surface layer of the ocean. Hence, two simultaneous factors are responsible for intense reduction of the sea ice area, which are related to the Earth's atmosphere and to the ocean. The polynomial form of the regression equation reflects acceleration in the effect of the inter-latitude heat transfer in the atmosphere and in the surface layer of the ocean. Graphically, the regression equations (average for the reliable secular intervals) are shown in Fig. 7.
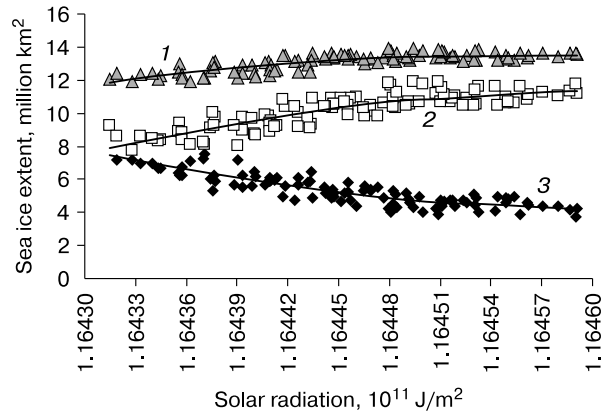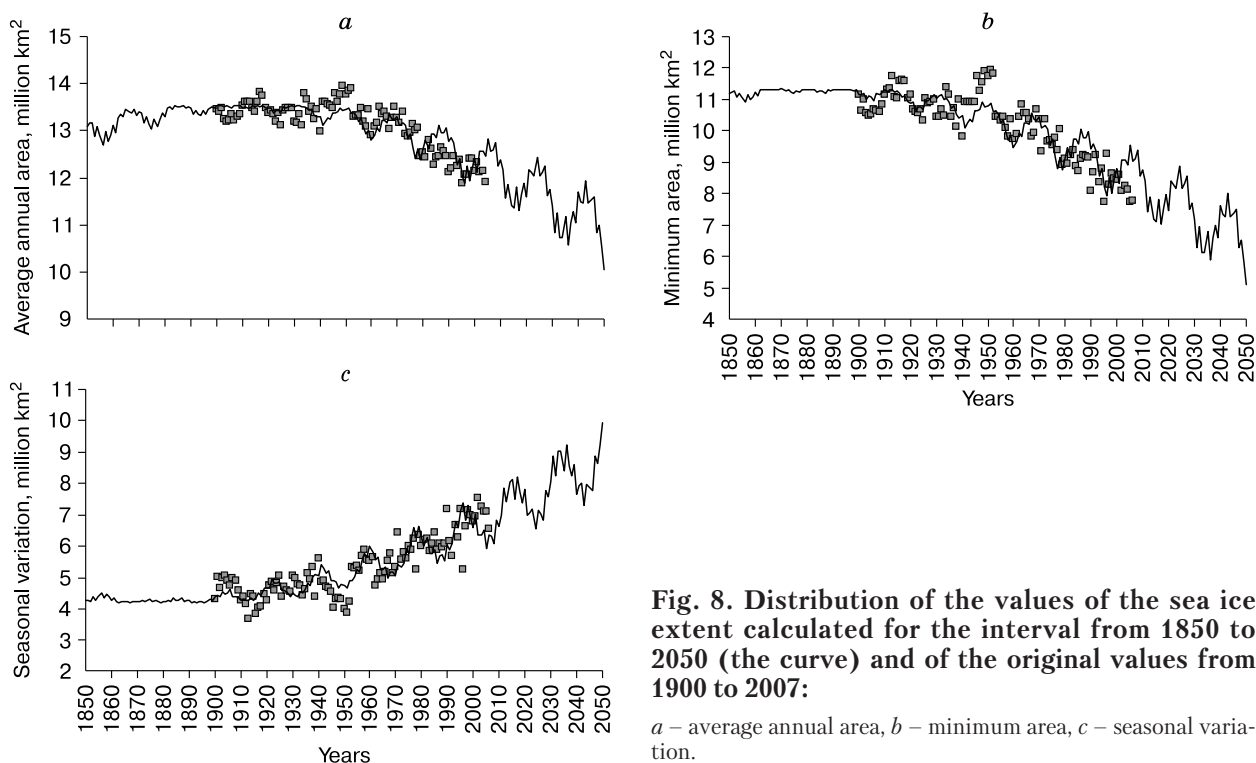

Fig. 7. Distribution of the average annual sea ice extent (*1*), minimum sea ice extent (*2*) and seasonal variation (*3*) depending on the incoming solar radiation and the plots of the corresponding regression equations (a second-degree polynomial).

Based on the regression equations and values of the incoming solar radiation, calculations of the area of sea ice were made for the time period of 1850–2050. The characteristic of the incoming solar radiation was chosen due to the higher values of the correlation factor and reliability of approximation compared to the radiation difference (the regions of the heat source and sink). It is likely that the incoming radiation more completely reflects the relation of the mechanism of inter-latitude heat exchange and the process of the impact of insolation on ice. Ice melting resulting from atmospheric heat exchange is known to be caused by two factors: absorption of heat coming from direct and dissipated sunrays onto the ice surface and a flow of heat from warmer air (advection). Ice melting as a result of heat exchange with the ocean occurs due to heat received by ice from water [*Burke, 1940*]. The results of the calculations of the sea ice area based on regression equations (the average secular intervals out of nine calculated reliable intervals) till 2050 are shown in Fig. 8.

The results testify to acceleration of reduction of the area (average annual and minimum area) of sea ice. At the same time, the seasonal variation increases, mainly due to accelerated reduction of the minimum summer values of ice extent. According to our estimates, the average annual area of the sea ice was 13.53 million km^2 in 1900, 13.45 in 1950, 12.41 in 2000, and it will be 10.05 million km^2 in 2050. In 2014, this value was close to 11.42 million km^2; hence, by 2050, reduction in the average annual ice extent will be 12.0 % versus the average annual area of sea ice in the Northern Hemisphere in 2014. The average annual reduction in the sea ice extent is related to its accelerated reduction in the summer period, as well

Fig. 8. Distribution of the values of the sea ice extent calculated for the interval from 1850 to 2050 (the curve) and of the original values from 1900 to 2007:

a – average annual area, *b* – minimum area, *c* – seasonal variation.

as to significant intensification of inter-latitude heat exchange exactly in the summer period. The calculated area of the sea ice was 11.16 million km^2 at the end of the summer half-year in 1900, 10.82 in the 1950, 8.81 in the 2000, and they will be approximately 5.09 million km^2 in the 2050. In 2014, the sea ice extent in the Northern Hemisphere was close to 7.20 million km^2, hence its reduction by 2050 will be 29.3 % versus 2014. The difference between the maximum (in the winter half-year) and minimum (in the summer half year) area of sea ice will increase by 1.90 million km^2 (by 23.6 %) in 2050 versus 2014. In the interval from 2014 to 2050, the ice melting rate caused by inter-latitude heat transfer will be –0.002 12 million km^2/year^2 in the average annual, –0.003 26 million km^2/year^2 for minimum values and 0.002 93 million km^2/year^2 for the seasonal variation. The ice melting rate is determined both by simultaneous increasing action of two factors: inter-latitude heat transfer and the greenhouse effect and the intensification of these factors in the atmosphere and in the surface layer of the ocean.

At the background of secular trends (Fig. 8), a cycle which is close to the 19 years' cycle is manifested, related to the change in the Earth's tilt as a result of nutation and determining variations in the distribution of the incoming solar radiation by latitudes [*Fedorov, 2013a, 2015a*] and the corresponding variations in the area of sea ice. For example, the average annual area of sea ice changes from the maximum of

12.74 million km^2 in 2008 to the minimum of 11.3 million km^2 in 2017. Then, till 2024 the increase in the average annual area of sea ice is expected to constitute 12.45 million km^2, to be followed by reduction to 10.72 million km^2 by 2036.

The calculated sea ice extent is characterized by a high correlation with the original data [*Rayner et al., 2003; Illinois... University..., 2014*]. For the year series from 1870 to 2007, the correlation was 0.773 for the average annual area of sea ice. It was 0.841 for the minimum and 0.827 for the seasonal variation. Divergence between the original data and the calculated figures for the average annual sea ice extent is 0.270 million km^2, or 2.067 % in relation to the average annual for the period of 1870–2007. For the summer minima, the divergence is equal to 0.467 million km^2 or 4.597 %, for the seasonal variation it is 0.400 million km^2, or 7.439 %. Variation of the divergence of the calculated values of the sea ice extent (seasonal variation) and of the original values is shown in Fig. 9.

It can be seen from Fig. 9 that, with the general trend for the increase in the seasonal variation, periodicity is manifested. It is related to the presence of groups in which the original values are lower or exceed the calculated ones. This indicates the existence of an additional periodic factor, which has been neglected or underestimated in the regression equation. The spectral analysis of variations shows that the fluctuation with a period of 20 years dominates in the

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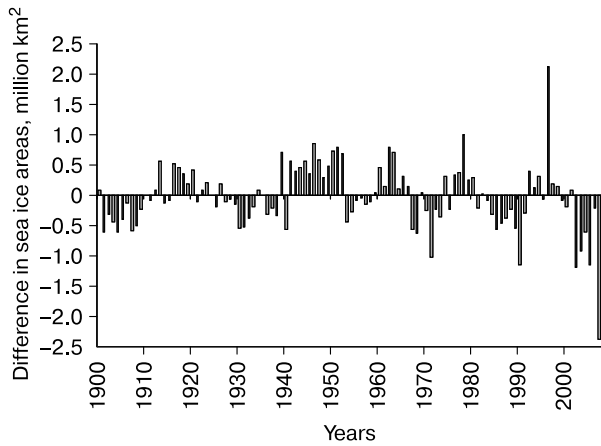
Fig. 9. Distribution of the difference between the original values of the sea ice extent (seasonal variation) and the values calculated according to the regression equation (a second-degree polynomial).

spectrum. In the periodogram, this maximum occurs in the period equal to 18 years. It seems that this periodicity is determined by the nutation cycle. Similar periodicity is noted, for example, in the isotope-oxygen composition of the ice in the southern polar region [*Vladimirova and Yekaikin, 2014*]. Considering

the averaged divergence values for positive and negative groups as correction (their average duration is 9–10 years, corresponding to the phase duration in the 19 years' cycle), the divergence for the seasonal variation decreases from 7.439 to 5.136 % (from the average annual value). The correlation factor grows from 0.827 to 0.908. In the other parameters of the sea ice extent, this periodicity is expressed to a lesser degree.

The calculated (without accumulation of the solar radiation) data for prognostic scenarios, based on the linear and quadratic formats of correlation between the solar radiation coming (without atmosphere) to the surface of the Earth's ellipsoid in the Northern Hemisphere and changes in the sea ice area are shown in Fig. 10. Two scenarios are shown, as, in case of strong correlation between solar radiation and the sea ice extent, the format of this correlation has not been unambiguously determined.

The author has investigated the correlations between the changes in the area of sea ice and the variations in the accumulated incoming solar radiation. The value of the incoming solar radiation in the summer half year of 1870 was taken to be the benchmark of calculations (the first year in the array of data for the area of sea ice) [*UK Met Office…, 2014*]. Accumulation of radiation was calculated by way of sequential addition of the summer half-year's values of the incoming solar radiation in calculations for the future
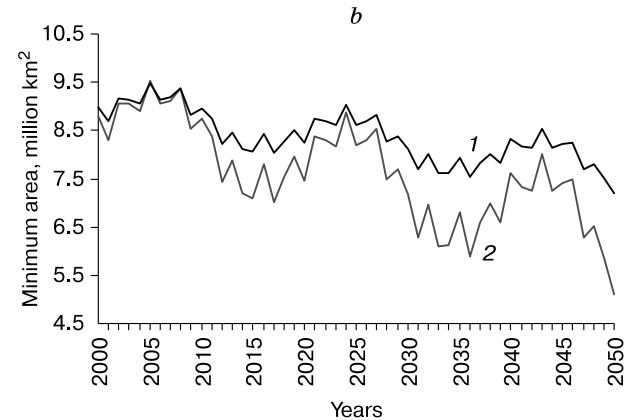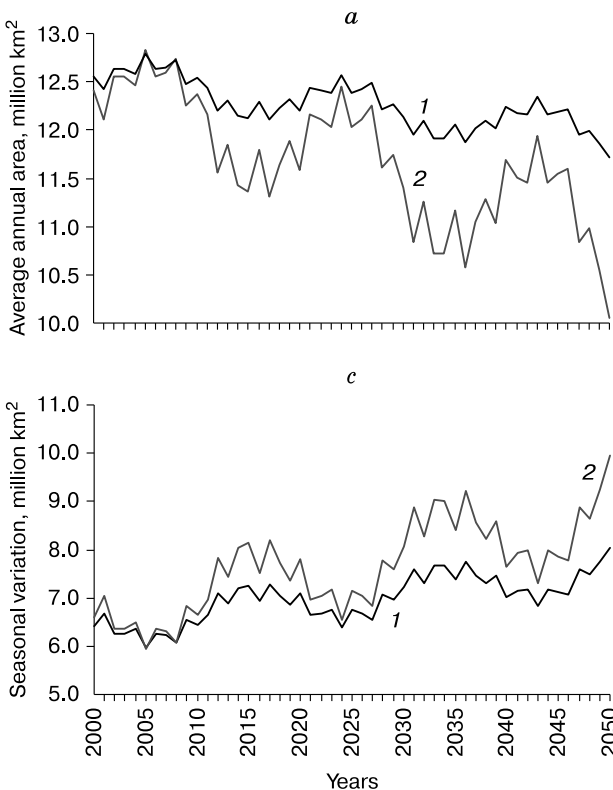
Fig. 10. Distribution of the values of the sea ice extent calculated for the interval from 2000 to 2050:

1 – by a linear regression equation, *2* – by a second-degree polynomial; *a* – average annual area, *b* – minimum area, *c* – seasonal variation (averaged by certain secular intervals).

Table 4.   **Divergence between the actual values of the sea ice extent and those calculated (a second-degree polynomial)**

Solar radiation (Northern Hemisphere, summer half year)	Area of sea ice*					
	Average annual area		Minimum area		Seasonal variation	
	%	million km²	%	million km²	%	million km²
Without accumulation	2.067	0.270	4.597	0.467	7.439	0.398
With accumulation	1.438	0.189	3.160	0.327	5.966	0.306

_____

* In percentage from the average annual value (1870–2007) and million km².

and by sequential subtraction in calculations for the past.

The correlation factors (R) of the solar radiation coming to the Northern Hemisphere and accumulated during the summer half-year with the data on the area of sea ice (1870–2007) are characterized by the following: for the average annual area –0.715, for the minimum area –0.776, and for the seasonal variation 0.802. These values exceed those obtained by correlation analysis of the area of sea ice with incoming solar radiation without accumulation (0.689, 0.762 and –0.791, respectively). Thus, the values of R increase by 3.6 % for the average annual area, by 1.8 % for the minimum (summer) area of sea ice, and by 1.4 % for the seasonal variation.

The correlation factors for the actual values of the sea ice extent calculated on the basis of a regression equation (a second-degree polynomial), considering accumulated solar radiation (1870–2007) are 0.882 for the average annual area, for the minimum area 0.900, and for the seasonal variation it is 0.895. These values also exceed the values of R for the period of 1870–2007, obtained by correlation analysis of the calculated values of the area of sea ice by a regression equation (a second-degree polynomial) without accumulated solar radiation (0.778, 0.841 and 0.827, respectively). In this case, the increase of R is 13.4 % for the average annual values of sea ice area, for the minimum area it is 7.0 %, and for the seasonal variation it is 8.2 %.

Comparison of the divergence of the calculated values of the area of sea ice with the actual values without accumulation of the incoming solar radiation and with this accumulation is shown in Table 4.

Divergence of the actual values and those calculated (considering accumulated solar radiation) for the sea ice extent decreases. For the average annual area of sea ice the reduction is 30.5 %, for the minimum it is 31.3 %, and 19.8 % for the seasonal variation. The increase in the correlation and reduction of divergence indicate accumulation of heat related to the incoming solar radiation in the atmosphere and in the near-surface layer of the ocean. Higher evalua-

tions obtained for assessing the correlation between the change in the area of sea ice and the accumulated solar radiation prove the impact of the increase in the greenhouse effect on the trend for changing the area of the sea ice.

The calculations considering accumulated solar radiation made by Walsh and Chapman on the basis of the linear regression equation by the long data series [*Walsh and Chapman, 2001*] demonstrate that the value of the average annual area of sea ice will be 12.02 million km² in 2050. The minimum area of the sea ice is 7.95 million km², and the seasonal variation 7.24 million km². Reduction of the average annual area is about 3 % against 2014, and 8.8 % of the minimum area. The seasonal variation increases by 10.4 %. The calculations made on the basis of a polynomial show that the average annual area of sea ice is 9.78 million km² for 2050, the minimum area is 4.16 million km², while the value for the seasonal variation increases to 10.05 million km² (Fig. 11). This, reduction of the average annual area versus 2014 is 15.3 %, and that of the minimum area is 42.9 %. The seasonal variation grows by 31.7 %.
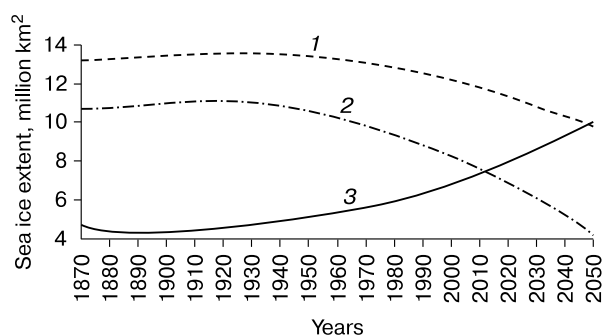

Fig. 11. Distribution of the values of the sea ice extent calculated considering solar radiation accumulation by a regression equation (a second-degree polynomial):

1 – average annual area, *2* – minimum area, *3* – seasonal variation.

CONCLUSION

The close correlation between the perennial variation in the sea ice extent and the difference in the amounts of solar radiation coming to the equatorial and polar regions of the Northern Hemisphere proves the contribution of the increase in the inter-latitude heat transfer recorded for the modern epoch to the reduction of the area of sea ice. The effect of the increase in the inter-latitude heat exchange is determined by increase in the amount of the incoming solar radiation to the equatorial region and by reduction in the amount of solar radiation coming to the polar region of the Earth [*Fedorov, 2015a,b*]. Reduction of the amount of the solar radiation coming to the polar regions in the period of 1850 to 2050 is determined by the value of $5.79 \cdot 10^6$ J/m^2, which is 0.11 % of the average value of the incoming solar radiation for the period in question. The increase in the amount of the solar radiation coming to the equatorial regions is $9.15 \cdot 10^5$ J/m^2 (or 0.07 %). The value of the difference between the amount of solar radiation coming to these regions in 2050 increases by $6.70 \cdot 10^6$ J/m^2, which is by 0.09 % greater than in 1850. The increase in the meridional gradient of the solar radiation (and of the heat gradient related to it) is determined by the secular change in the Earth's tilt.

Higher estimates of the correlation between the incoming solar radiation and the change in the sea ice extent are recorded for the case of its accumulation. The correlation factors of the calculated values (with a regression equation – a second-degree polynomial) of the area of sea ice and of the original values increase by 13.4 % for the average annual area, by 7.0 % for the minimum area, and by 8.2 % for the seasonal variation. Divergence between the original values and those calculated considering accumulated solar radiation decreases for the average annual area of sea ice by 30.5 %, for the minimum area by 31.3 %, and for the seasonal variation by 19.8 %. This is a proof of heat accumulation (intensification of the greenhouse effect) related to the amount of solar radiation coming to the ocean and in the atmosphere.

Thus, two factors have been revealed in the behavior of the area of sea ice: the inter-latitude heat exchange and the greenhouse effect. The author attributes intensification of the greenhouse effect to condensation and increase in the water vapor in the atmosphere due to increased evaporation caused by the rise in temperature in the northern polar region due to increased inter-latitude heat exchange. That is, the intensification of the greenhouse effect is a natural effect of the increase in the inter-latitude heat transfer, which is determined by the secular variations in the Earth's tilt. These two factors result in the trend for reducing the area of sea ice in the Northern Hemisphere.

Such studies may be of important practical value in exploration and production of mineral resources, for oil and gas production in the Arctic offshore regions, for development of the fishing industry, shipping and construction of hydro-engineering and other structures and buildings on frozen ground. The fundamental study of the cryospheric processes seems to be obligatory in developing strategic plans of the new phase of Russian Arctic exploration.

In accordance with the obtained results, the effect of the anthropogenic factor (due to the increase in the CO_2 concentration in the atmosphere caused by burning of the organic fuel, heat pollution, increase in the concentration of aerosols in the atmosphere, and hence the greenhouse effect) on the formation of the trend for a change in the global temperature and the area of sea ice in the Northern Hemisphere seems to be insignificant.

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