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IMPLICATIONS OF CHANGES IN INSOLATION CHARACTERISTICS FOR LONG-TERM SEA ICE EXTENT DYNAMICS IN THE NORTHERN HEMISPHERE

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A correlation analysis of long-term dynamics of sea-ice extent in the Northern Hemisphere involving calculations of insolation characteristics with high spatial resolution was performed. The revealed close negative relationships between multi-year variations in sea ice extent, winter insolation and irradiance contrast were calculated in model cells with resolution of 1° × 1° for the period 1901–2018. The linkage density maps have been constructed to analyze relationships between multi-year change in sea ice extent and insolation characteristics based on annual, semi-annual and monthly (March, September) means of sea ice extent. It is revealed that the correlation between multi-year variations in sea ice spatial distribution in the Northern Hemisphere and insolation contrast is interpreted as cause and effect relationship, while insolation contrast can be used as a predictor in statistical models for the sea-ice extent dynamics. A close relationship between spatial distribution of sea ice and insolation contrast throughout the entire Northern Sea Route has been determined. This gives a perspective for long-term forecasting of the sea-ice extent for the Northern Sea Route based on calculations of the intensity of insolation contrast for the Northern Hemisphere.

Key words: *sea ice area, seasonal, interannual and multi-year variability, insolation, insolation contrast, correlation analysis, Northern Sea Route, solar climate theory.*

INTRODUCTION

The distribution of sea ice depends on many factors determined by geophysical processes. Those are, first of all, the air temperature and humidity, ocean surface temperature, cloudiness, river runoff, albedo, etc. However, the energy basis of those factors, as well as of the circulation processes in the atmosphere and ocean, is the solar radiation coming to the Earth – the main source of energy for hydrometeorological processes. Heat exchange mechanisms ('heat engine of the first and second kind') are the consequence of the irregularity of the irradiation time and the uneven distribution of solar radiation in space. Due to the heterogeneity of the components of the natural environment, heat exchange mechanisms are formed between the atmosphere, the ocean and the sea ice. That implies the importance of the radiation factor in the dynamics of the spread of sea ice and the need to determine the relationship between those variables. That is also relevant for improving the methods of predicting the spread of sea ice in the changing climate. Forecasting the spread of sea ice is important for long-term planning the strategy of using the Northern Sea Route and the socio-economic development of the Arctic regions [*Fedorov, 2015; Fedorov, Grebennikov, 2018*].

The spread of the area of sea ice (drift) is influenced by sea currents and tides associated with the gravitational interaction of the Earth with the Moon and the Sun. That influence is not considered in this work.

The aim of this work is to determine the correlation and cause-and-effect relationships of long-term changes in the area of sea ice with the characteristics of insolation in the Northern Hemisphere with a high spatial resolution. That block of studies is one of the constituent parts of the statistical model of the distribution of sea ice in the Northern Hemisphere developing by the authors. The other two blocks of the statistical model will include relationships between the seasonal and interannual variability in sea ice area and insolation characteristics. As a result, an assessment of the influence of the insolation factor on the dynamics of the sea ice area and the possibility of modeling and forecasting the spread of sea ice, taking into account the seasonal, the interannual and the long-term changes in insolation characteristics, calculated with high spatial and temporal resolution in the future, will be carried out. In addition to insolation factors, it is assumed that air humidity and other factors will be taken into account on the basis of a multi-factorial multiple regression equation. The elaboration of a specialized statistical model for the distribution of sea ice is relevant and justified taking into account the problems noted for physical and mathematical models, in which sea ice is one of the fragments of climate modeling [*Fedorov, 2019a,b*].

INPUT DATA AND RESEARCH METHODOLOGY

The database of the Hadley Meteorological Center (Hadley Center for Climate Prediction and Research, Met Office, UK) HadISST1 (Hadley Center Sea Ice and Sea Surface Temperature data set) has been used as an input data (http: //www.metoffice.gov.uk/...html).

The information presented in the HadISST1 database on the mean-monthly temperature of the ocean surface (TOS) and the area of sea ice in the Northern and Southern Hemispheres has been obtained as a result of the consolidation of the reanalysis's data (ERA40) into a single data set. The reanalysis has been carried out using empirical orthogonal functions (EOF) and instrumental data (primarily the shipboard and satellite data) of observations. Reconstruction of the sea ice area in the massif on a 1° × 1° grid has been carried out on the basis of the approximation and extrapolation algorithms for available data (digitized sea ice area maps, ship and satellite observation data) taking into account the TOS [*Rayner et al., 2003*]. Since the insolation characteristics are calculated by the authors for the future, the determination of close correlations and cause-and-effect relationships seems to be a possible basis for statistical and probabilistic forecasts of changes in the area of sea ice.

The input data containing information on the area of sea ice (HadISST1) are presented in several text files, which have been combined by the authors into a single array in Excel format. The array is consisted of data on the area of sea ice in the Northern Hemisphere in a 1° × 1° spatial cell as a percentage of the cell area. In total, the array, collected in that way, has covered about 7400 cells, each of which provides information on the sea ice area with monthly values

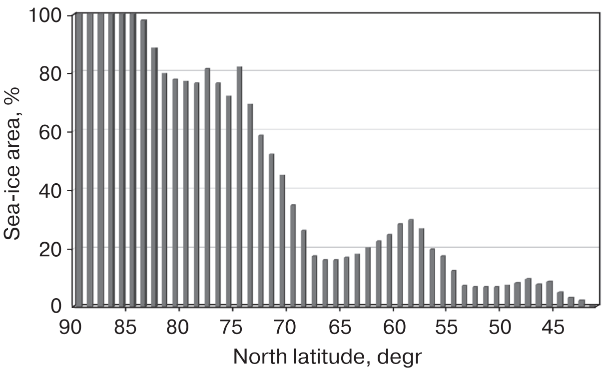

Fig. 1. Distribution by latitudes of the average perennial values of the area of sea ice for the period from 1901 to 2018 in a 1° × 1° cell.

for the period from 1901 to 2018. The array is completely filled with monthly values (no gaps). The monthly values were used to calculate the mean-annual (as averages for all months of the year) and semiannual (as averages for the months from April to September for the summer half of the year and from October to March for the winter half of the year) values of the sea ice area.

The analysis of the values of the sea ice area within the latitudinal range of 90° N up to 42° N have been accomplished. We have adopted the lower boundary conditions on the basis of the typical 0.5 % mean-multi-year value of the annual sea ice area in the cell at latitude of 42° N. At lower latitudes, the long-term average value does not exceed 0.5 % of the cell area. For latitude of 42° N the mean long-term value of the cell area occupied by sea ice exceeds 0.5 % (0.556 %). For latitude 41° N the ice area on average for the period from 1901 to 2018 is 0.278 % (Fig. 1). The pattern of the distribution remains the same throughout half-years and months, but the latitudinal range with cells, in which the average ice area exceeds 0.5 %, changes. In the winter half of the year, the parameters of the lower values of the sea ice area are identical to the annual ones. In the summer half of the year at latitude of 43° N the average cell area occupied by ice is 1.389 % of the cell area. Sea ice does not spread further southward during that period. In March, the range (at the boundary value of 0.5 %) of the analyzed values is 90–42° N, for September it is 90–54° N (in September, the peak noted in Fig. 1 in the region of 55–65° N disappears). Thus, we have excluded the cells that occurred in seas not covered by ice in the period from 1901 to 2018. The analysis of the results has been carried out and the Table 1 has been compiled.

The previously calculated values have been used as the initial characteristics of insolation in the Northern Hemisphere: 1) the incoming solar radiation per year, summer and winter semesters (J/m^2, W/m^2), 2) the seasonality, i.e. the difference between the incoming solar radiation in the summer and winter semesters (J/m^2, W/m^2), 3) the annual insolation contrast (IC) [*Fedorov, Kostin, 2019*]. The IC (W/m^2) has been determined as the difference between the insolation of the heat source region (0–45° N) and the heat sink area (45–90° N). The IC reflects the change in the meridional gradient of insolation, which regulates the transfer of heat from the equatorial and tropical regions to the polar regions, in a generalized manner (for the regions of the heat source and heat sink) – the operation of the 'heat engine of the first kind' [*Shuleikin, 1953; Fedorov, 2018*].

Correlation analysis of long-term series (118 years long) of average annual, semiannual and monthly (March, September) values of the sea ice area in each 1° × 1° cell with the characteristics of insolation of the Northern Hemisphere has been carried

Table 1. **Distribution of the values of the correlation coefficient of long-term changes in the area of sea ice and the characteristics of insolation in the Northern Hemisphere (%)**

Correlation coefficient	Insolation, J/m^2		Seasonality of insolation, J/m^2	Insolation contrast, W/m^2
	Summer	Winter		
Summer semester				
<–0.9	0.00	0.00	0.00	0.00
<–0.8	0.00	0.38	0.00	0.64
<–0.7	0.04	6.42	0.07	7.63
<–0.6	0.23	21.23	0.22	23.68
<–0.5	0.49	41.58	0.52	43.68
> 0.5	42.41	0.48	43.19	0.53
> 0.6	23.23	0.22	23.70	0.22
> 0.7	6.77	0.03	7.25	0.07
> 0.8	0.53	0.00	0.67	0.00
> 0.9	0.00	0.00	0.00	0.00
Winter semester				
<–0.9	0.00	0.00	0.00	0.00
<–0.8	0.00	0.00	0.00	0.00
<–0.7	0.45	0.94	0.46	1.44
<–0.6	0.73	6.80	0.78	8.28
<–0.5	1.16	21.12	1.13	23.55
> 0.5	22.04	1.12	23.12	1.14
> 0.6	7.86	0.75	8.10	0.78
> 0.7	1.16	0.42	1.32	0.48
> 0.8	0.00	0.00	0.00	0.00
> 0.9	0.00	0.00	0.00	0.00
March				
<–0.9	0.00	0.00	0.00	0.00
<–0.8	0.00	0.00	0.00	0.00
<–0.7	0.38	0.22	0.39	0.41
<–0.6	1.20	2.84	1.30	3.46
<–0.5	3.41	9.47	3.50	10.38
> 0.5	9.90	3.25	10.11	3.39
> 0.6	3.34	1.20	3.40	1.30
> 0.7	0.34	0.34	0.41	0.41
> 0.8	0.00	0.00	0.00	0.00
> 0.9	0.00	0.00	0.00	0.00
September				
<–0.9	0.00	0.00	0.00	0.00
<–0.8	0.00	0.00	0.00	0.02
<–0.7	0.00	0.92	0.00	2.45
<–0.6	0.00	14.33	0.00	16.45
<–0.5	0.07	30.81	0.07	32.11
> 0.5	32.41	0.07	32.49	0.07
> 0.6	16.52	0.00	16.84	0.00
> 0.7	2.11	0.00	2.20	0.00
> 0.8	0.02	0.00	0.02	0.00
> 0.9	0.00	0.00	0.00	0.00

out. Using geoinformation technologies, maps of the correlation coefficient values have been built. The maps reflect the coefficient of correlation between the area of sea ice distribution and the characteristics of insolation. Possible errors in the correlation analysis are associated with the chronological discrepancy between the calendar year, semesters, and months for which there are sea ice area values with the tropical year, semesters, and months for which the insolation characteristics have been calculated. A tropical year is a period of time between the passages of the successive points of the vernal equinox by Earth. The assessment and significance of the linear correlation coefficient when performing the correlation analysis have been carried out in accordance with the existing methods [*Tsymbalenko et al., 2007*].

RESULTS AND DISCUSSION

Close correlations have been found between long-term changes in the sea ice area (annual, semiannual, and monthly) and summer and winter insolation of the Northern Hemisphere (J/m^2), seasonality of insolation (J/m^2), and annual insolation contrast (W/m^2).

The correlation of long-term changes in annual (average for the winter and summer half-year) values of the sea ice area with long-term changes in summer insolation is characterized mainly by positive values (Fig. 2). All values of the correlation coefficient are statistically significant with a probability of 0.99. Out of 7416 values of the correlation coefficient (R) of long-term changes in the annual area of sea ice with summer insolation in the Northern Hemisphere, 541 of them (7.30 %) have negative values and 6875 ones (92.70 %) have positive values (Fig. 2). 70.16 % of them have positive values over 0.5; 42.98 % of them exceed the values of $R = 0.6$, 19.82 % of them exceed the values of $R = 0.7$ and 2.27 % of them have the values of $R > 0.8$ (Table 1).

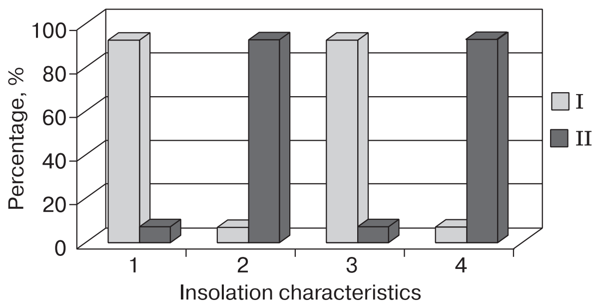

Fig. 2. Ratio of positive (I) and negative (II) values of the correlation coefficient of the annual area of sea ice:

1 – with summer insolation, 2 – with winter insolation, 3 – with seasonality of insolation, 4 – with insolation contrast of the Northern Hemisphere.

The correlation of long-term changes in the annual sea ice area with long-term changes in winter insolation is characterized mainly by negative values. 6895 values of the correlation coefficient (92.97 %) are negative and 521 (7.03 %) are positive. 68.46 % have negative values of $R < -0.5$; 40.17 % have the R values < -0.6; 18.18 % have the R values < -0.7 and 1.35 % have the R values < -0.8.

The correlation of long-term changes in the annual sea ice area with the seasonality of insolation is mainly characterized by positive values (Fig. 2). Out of the 7416 values of R, 6884 ones (92.83 %) have positive values and 531 ones (7.17 %) have negative values. 70.73 % have positive values exceeding 0.5; 44.27 % exceed the values of $R = 0.6$; 20.60 % of the values have $R > 0.7$ and 2.36 % have $R > 0.8$.

The correlation of long-term changes in the annual sea ice area with long-term changes in insolation contrast is characterized mainly by negative values. Among 7416 values of the correlation coefficient, 6901 ones are negative (93.06 %) and 515 ones (6.94 %) are positive. The negative $R < -0.5$ have been obtained for 71.79 % of the values; 44.70 % have the R values <-0.6; 21.14 % have $R < -0.7$ and 2.37 % have $R < -0.8$.

Correlation indicators of the semiannual, the March and the September values of the sea ice area are presented in Table 1. The values of the correlation coefficient in the summer half of the year, in the winter half of the year, in March and in September have been obtained, correspondingly, for 7324, 7354, 7149 and 6079 cells.

In the long-term changes in the annual values of the sea ice area, a close correlation with the insolation characteristics is noted in the vast Arctic region, including the Baffin Sea, Hudson Strait, Fox Basin, the northern part of Hudson Bay, many straits of the Canadian Arctic Archipelago (Lancaster, Barrow, etc.),

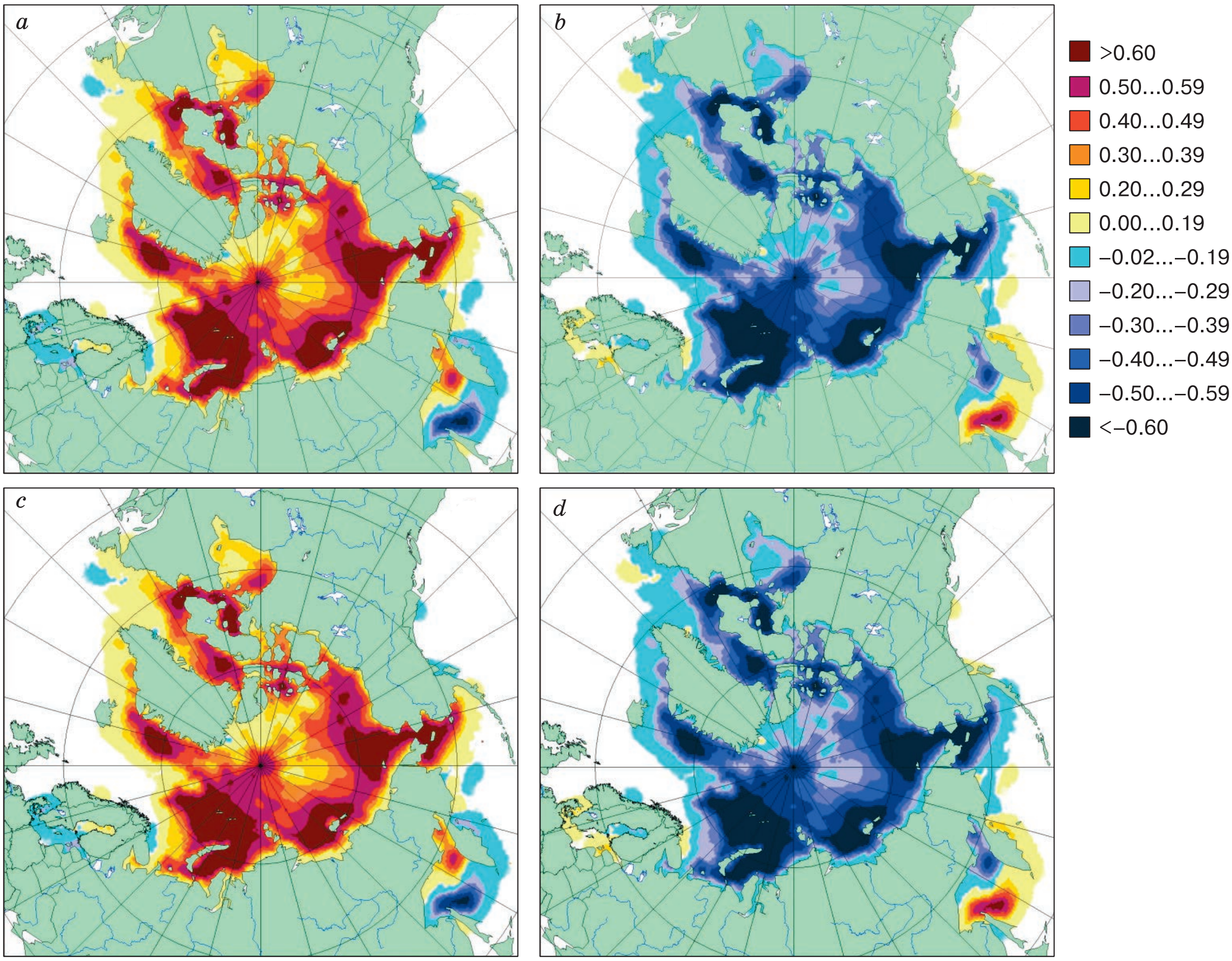

Fig. 3. Distribution of the correlation coefficient of long-term changes in the annual area of sea ice and insolation characteristics:

a – with summer insolation; *b* – with winter insolation; *c* – with seasonality of insolation; *d* – with insolation contrast of the Northern Hemisphere.

Greenland and the Barents Sea, the western part of the Kara Sea, the Laptev Sea and the western part of the East Siberian Sea, the Chukchi Sea and the northern part of the Bering Sea, the western part of the Beaufort Sea (Fig. 3).

The search for cause-and-effect relationships in the pool of found close correlations has been carried out. As noted, the positive relationship between the long-term changes in the area of sea ice (annual, semi-annual, and monthly) with the summer insolation and the seasonality of insolation has been found. A negative relationship with winter insolation and insolation contrast has been marked. However, all those characteristics of insolation are closely related, and, therefore, are not independent variables. Thus, the correlation coefficient of IC with summer insolation within the interval of 1901 to 2018 is –0.950, the same with winter insolation is 0.994, with seasonality it is –0.985. All those characteristics are linearly related to a decrease in the inclination of the Earth's axis of rotation [*Fedorov, 2018*].

Let us consider the possible climatic effects associated with the found connections.

An increase in insolation (winter or summer) should also result in a decrease in the area of sea ice in that season (due to inertia, that effect can manifest itself in both seasons with some delay in time). In the case of a reduction in the incoming radiation, the opposite effect should be expected. During the study period, a decrease in both annual and summer insolation has been registered, yet, a decrease in the annual and summer area of sea ice has been observed. Consequently, the positive relationships (noted for summer insolation) with changes in the sea ice area are correlative, since, based on physical concepts, an increase in summer insolation should correspond to a decrease in the sea ice area. And, conversely, a decrease in summer insolation should correspond to an increase in the area of sea ice distribution. Winter insolation increases during the specified period and, therefore, can be the factor of the long-term changes in the area of sea ice.

A positive relationship between the long-term changes in the area of sea ice and the seasonality of insolation has been found. For the seasonality of insolation in the period under study, there is also a tendency to decrease [*Fedorov, Frolov, 2020*]. That trend is determined by the reduction in summer insolation. It is known that summer insolation is important in the genesis of climate and its changes, which are closely related to the formation and evolution of sea ice. That is determined, firstly, by the fact that the evaporation and the content of water vapor in atmosphere increase with the increasing of summer insolation, which leads to an increase in the greenhouse effect. Secondly, the release of heat is associated with an increase in atmospheric precipitation (transition of water vapor into water and snow). Third, because of decrease in albedo due to a reduction in the area of sea ice and glaciers, the heating of the surface (of continents and oceans) and, hence, the atmosphere increases. With a decrease in summer insolation, the opposite effects obviously occur. As a result, based on the above-mentioned physical concepts, the positive relationship between the long-term changes in the area of sea ice and the seasonality of insolation, characteristic of the period under study, should also be considered a correlative one. A close negative relationship between the long-term changes in the area of sea ice (for annual, semi-annual, and monthly values) and the insolation contrast has been obtained (Fig. 2, 4). In the summer half-year, close correlations between the long-term area of sea ice and the insolation contrast are observed over the vast territory of the Northern Hemisphere. In the winter half of the year, the area of close interrelations is noticeably reduced. There are no responses to long-term changes in IC in the central part of the Arctic Ocean, where the minimal changes in the area of sea ice are observed during the study period. However, a close relation is manifested in the individual marginal and coastal areas (Greenland Sea, northern Barents and Kara Seas, Chukchi Sea, western Beaufort Sea, northern Bering Sea, Hudson Strait, Shelikhov Bay in the Sea of Okhotsk). In March, close relations are noted only in the Greenland Sea, in the north of the Barents and Bering Seas. That time is characterized by the maximum distribution of sea ice in the Northern Hemisphere along with a low (for this month) long-term variability of the ice cover area. In September, a close relation is fixed for all seas of the Russian Arctic, the Beaufort Sea and the Fox Basin. The distribution of ice cover in those areas during that period is subject to the greatest long-term changes [*Frolov, Gavrilo, 1997; Zubakin, 2006*]. The close correlations obtained for September between the long-term changes in the area of sea ice for the seas of the Russian Arctic and the IC provide the basis for long-term forecasting of changes in the distribution of the area of sea ice along the entire length of the Northern Sea Route in summer (Fig. 4, *d*).

Let us consider a possible physical explanation of the found relationship between the long-term changes in sea ice area and the insolation contrast. Due to the uneven distribution of solar radiation on the Earth's surface, a meridional insolation gradient (MIG) occurs. Previously, the authors have obtained a latitudinal profile of changes in the annual MIG for the period from 3000 B.C. to 2999 A.D. [*Fedorov, 2018*]. The maxima of the increase in the MIG are localized near the polar circles (60–70° N, an annual 'turbulence zones'). The annual 'turbulence zones' coincide with the regions of maximum development of extratropical cyclones (cyclogenesis) in the hemispheres [*Pogosyan, 1976*]. The increase in the annual MIG occurs in the area of the Hadley and Ferrel cir-

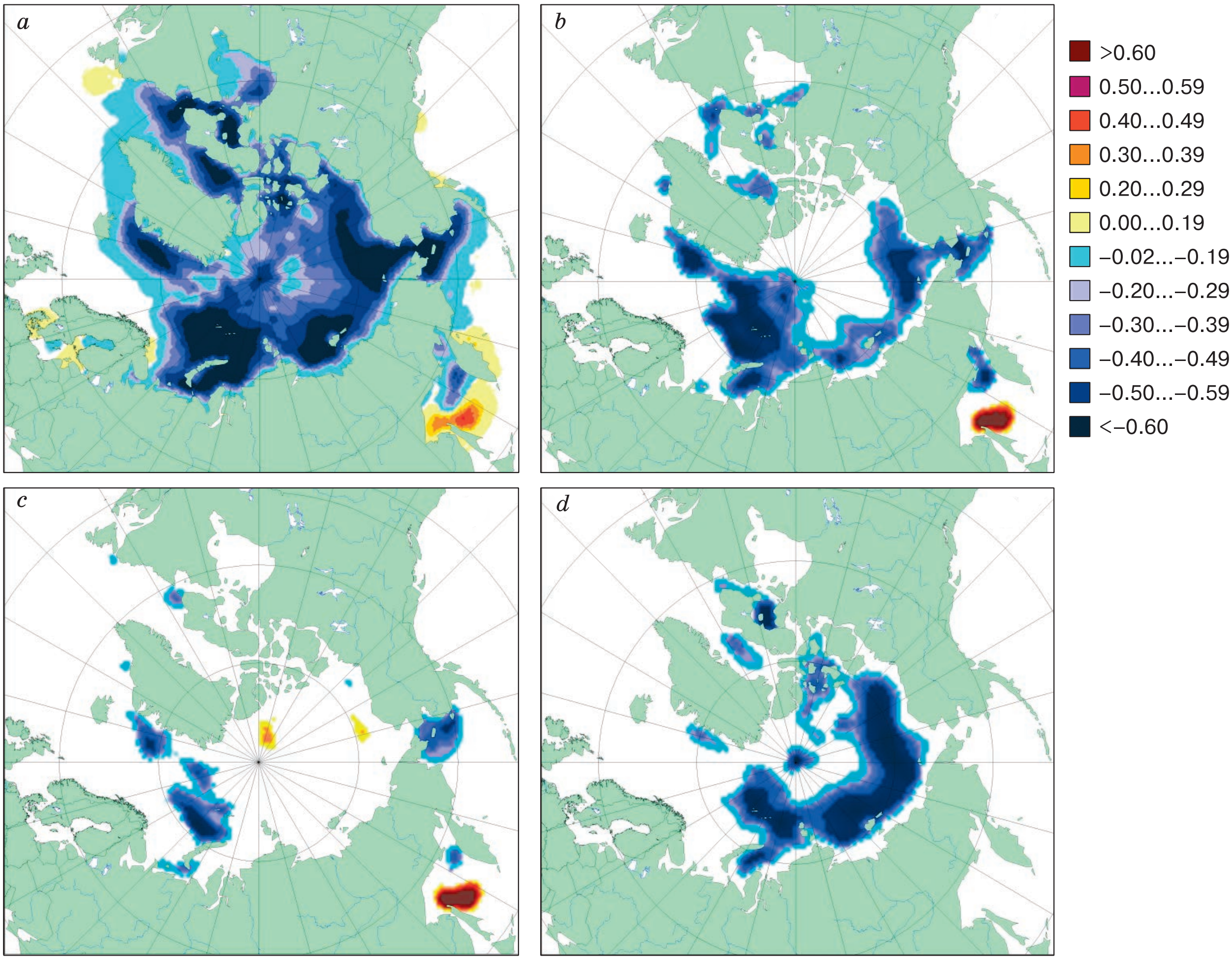

Fig. 4. Distribution of the correlation coefficient of long-term changes in the area of sea ice and insolation contrast in the Northern Hemisphere:

a – in the summer half of the year; *b* – in the winter half of the year; *c* – in March, *d* – in September.

culation cells in the atmosphere. The decrease in the annual MIG falls on the area of polar cells. Thus, the change in the MIG determines the features of both the circulation and vortex activity in the atmosphere. Also, long-term changes in the MIG for the winter and summer semesters have been determined. The MIG values maximally increase in the winter (for the Northern Hemisphere) six months in the latitudinal zone 15–20° S (11.8 %) and decrease maximally in the latitudal zone of 10–15° S (17.8 %). In the summer (for the Northern Hemisphere) six months, the maximum increase (11.8 %) is fixed in the latitudinal zone of 10–15° N, the maximum decrease (17.8 %) is noted in the latitudinal zone of 5–10° N [*Fedorov, 2018, 2019c*].

In the summer half of the year there are seasonal 'turbulence zones' in the hemispheres located within the latitudinal range of 5–20° N. Here, in the neighboring five-degree latitudinal zones, the maximum discrepancies in the trends of changes in the summer MIG are fixed. The seasonal 'turbulence zones' coincide with the areas of tropical cyclone generation (80 % of which are formed within the range of 10–20° N). The vortex transfer of energy is associated with the work of the 'heat engine of the first kind', the mechanism of meridional heat transfer from low latitudes to high ones [*Shuleikin, 1953*]. In the polar regions (polar circulation cells), an increase in the MIG is noted in the hemispheres in the winter semesters, and a decrease is fixed in the summer semesters.

The resulting average distribution of the annual MIG was compared with the meridional distribution of the average annual energy transfer in the ocean-atmosphere system given in [*Lorenz, 1970; Palman, Newton, 1973*]. The correlation coefficient between the mean values of the annual MIG (calculated from the mean long-term values of insolation in the five-degree latitudinal zones for the period from 1900 to

2018) and the values of energy transfer in the ocean-atmosphere system was 0.98 (linear relationship). At the same time, the numerical values of energy transfer in the ocean-atmosphere system in [*Lorenz, 1970; Palman, Newton, 1973*], on average, by 6–7 times exceed the MIG values, which may be due to the participation of water and air masses in the energy transfer in the ocean–atmosphere system. In later works, the values of energy transfer are approximately 3 times higher than the values of the annual MIG [*Peixoto, Oort, 1984*].

Since the energy transfer in the ocean-atmosphere system is determined by the MIG, the features obtained for it can also manifest themselves in the ocean–atmosphere system (an increase or decrease in the intensity of circulation in the cells of the general atmosphere circulation, an increase or decrease in the vortex energy transfer and climatic variability). The features of the Earth's solar climate noted for the modern era are associated with a decrease in the inclination of the Earth's axis of rotation as a result of precession [*Milankovich, 1939; Fedorov, 2018, 2019a,c*].

Earlier, as a result of the correlation analysis, we have determined the relationship between the long-term changes in the anomalies of the surface air temperature (SAT), the temperature of the ocean surface (TOS) of the Earth, the World Ocean and the hemispheres (http://www.cru.uea.ac.uk/cru/data/ temperature) and the long-term changes in the annual insolation contrast. The temperature regime, as noted earlier, is the main factor in the formation and dynamics of the distribution of sea ice. The IC generally (for the regions of the heat source and sink) reflects the change in the MIG. Long-term changes in the MIG and IC are determined by a change in the angle of inclination of the Earth's axis of rotation as a result of precession and nutation [*Fedorov, 2018, 2019c*].

Changes in the SAT and TOS of the Earth and hemispheres (data from the University of East Anglia and the Headley Weather Bureau) are mainly taken into account by trends [*Fedorov, 2018*]. The values of the determination coefficient range from 0.693 to 0.862 (trends are polynomials of the second degree). The coefficient of determination demonstrates the proportion of changes in the SAT and TOS determined by the trend. Consequently, in order to explain the tendencies of long-term changes in global temperature, it is necessary to find a factor that determines the trends of long-term changes in the SAT and TOS. The analysis reveals that long-term changes in the SAT and TOS of the Earth and hemispheres are characterized by close positive correlations with long-term changes in IC and negative correlations with long-term changes in the axis tilt angle. The calculations performed using the regression equation (based on an ensemble of linear and polynomial solutions) has demonstrated that long-term changes in the SAT and TOS are mainly associated with long-term changes in the annual insolation contrast, enhanced by positive feedbacks (Table 2), as shown below.

Table 2. **Long-term changes (%) in near-surface air temperature (SAT) and temperature of ocean surface (TOS), explained by the regression model**

Territory	SAT	TOS
Earth, World Ocean	80.7	79.7
Northern Hemisphere	73.4	69.3
Southern Hemisphere	83.1	84.1

The physical mechanism of the close correlation (found by the authors) of the long-term changes in the area of sea ice in the Northern Hemisphere with the insolation contrast in a generalized form can be reduced to the following. The increase in the IC associated with a decrease in the angle of inclination, which controls the meridional heat transfer or the intensity of the 'heat engine of the first kind', leads to an increase in heat transfer (due to circulation processes in the atmosphere and vortex formations) from the low to high latitudes. As a result, the ocean surface temperatures and near-surface air temperatures rise. That leads to an increase in evaporation and an increase in the content of water vapor in the atmosphere and an intensification of the greenhouse effect. That results in an additional rise in temperature, etc. That process, constantly repeating, increases the climate warming in the Northern Hemisphere and leads to a reduction in the area of sea ice. In addition, as a result of condensation due to the advection of warm air masses to high latitudes, heat is also released, making an additional contribution to the scheme of radiation heat exchange in the atmosphere (Fig. 5).

The three lower blocks in the diagram reflect the mechanism of increasing the warming process in the Arctic and reducing the area of sea ice (Fig. 5). Also, one should take into account the positive feedbacks, a decrease in albedo due to a long-term reduction in the area of sea ice and an increase in the greenhouse effect due to the degassing of permafrost owing to climate warming [*IPCC, 2013*]. Thus, the natural causes of changes in the current global climate are confirmed. The main one is the change in the inclination of the Earth's rotation axis, which regulates the distribution of the solar radiation coming to the Earth by latitudes and seasons and the intensity of the meridional heat transfer (the work of a 'heat engine of the first kind') [*Shuleikin, 1953*].

Taking into account the above-mentioned physical explanation, the found close correlation between long-term changes in annual, semi-annual and monthly values of the sea ice area with the IC of the Northern Hemisphere can be considered the cause-and-effect relationship. The relationship of long-term changes in the area of sea ice with the winter insola-

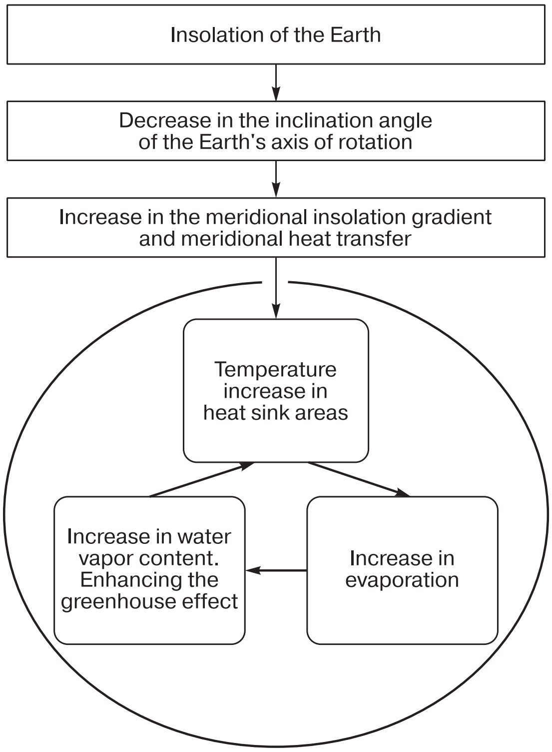

Fig. 5. Schematic diagram of radiation heat exchange in the atmosphere.

tion (its increase corresponds to a decrease in the area of sea ice) can also be considered the causal relationship. The winter insolation in the period of 1901 to 2018 increases by 0.020 %, while the IC increases by 0.048 %, that is, the contribution of the IC to long-term changes in the sea ice area is more significant than the effect associated with an increase in winter insolation. In addition, as follows from the description of the climatic effect of the IC, it manifests itself throughout the year (seasons, months). Wherein the winter insolation is a seasonal factor. At the same time, the variability of the sea ice area mainly falls on the summer half of the year. Therefore, in the statistical model (taking into account the close relationship between the IC and winter insolation and their linear dependence on the axis tilt angle), the IC should be used as a predictor when forecasting long-term changes in the area of sea ice. However, at the same time, it seems necessary to obtain quantitative characteristics of the ratio of the influence of those factors (IC and winter insolation) on the trend of changes in the area of sea ice in the Northern Hemisphere.

CONCLUSIONS

A causal relationship between long-term changes in annual, semi-annual and monthly values of the sea ice area with the characteristics of insolation – winter insolation and insolation contrast of the Northern Hemisphere – on a scale of high spatial resolution has been found. Insolation characteristics are linearly related to the inclination of the Earth's rotation axis and are closely related to each other, therefore, they are not independent parameters, which excludes the possibility of using a two-factor (the winter insolation and the IC) multiple regression model. Due to the large range of the IC changes, that characteristic, taking into account the associated physical mechanism of climate change, is taken as one of the predictors in the developed statistical model of the sea ice area. Thus, the model will take into account long-term changes in the sea ice area associated with changes in the meridional insolation gradient and meridional heat transfer. Long-term changes in the area of sea ice associated with variations in the income of solar radiation (including the winter half of the year) will be taken into account in the block of connections in the annual course of insolation with the annual course of changes in the area of sea ice in the cells. The third block assumes taking into account the relationships between the long-term interannual changes in the sea ice area and the long-term interannual changes in insolation characteristics. Separate blocks and algorithmic scheme (architecture) of the statistical model of sea ice will be presented in the subsequent works.

The close correlations obtained for September between the long-term changes in the area of sea ice for the seas of the Russian Arctic and the IC represent the basis for predicting of changes in the distribution of the area of sea ice along the entire length of the Northern Sea Route in summer.

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