FIRST PUBLISHED: **October 2014**

THE COMPLEX SYSTEMS

Interdisciplinary Scientific Journal

April - June **№ 2 (8), 2020**

Publishing company: LlC «AGROMASHPRO», 2018
Federal Service for Supervision in the Sphere of Communications, Information Technology and Mass Communications (Roskomnadzor)
Certificate of registration of mass communication media ПИ No. ФС77-**55834** as of October **30, 2013**
Registration number of changes ПИ No. ФС77-**74236** as of November **02, 2018**
ISSN No. 2409-0379

Sent for the press 05.09.2020. Format 60×88 1/8. Circulation 50. Publishing company:
LlC «AGROMASHPRO» Address of Editorial office: 5/2, alleya Zhemchugovoy, office 109/7, Moscow, 111402, Russia. Postal address: Maria A. Vinnik, p/b 41, Moscow, 105318, Russia Tel./Fax: +7(495) 941 62 72
http://thecomplexsystems.com/; e-mail: *mail@systemology.ru*
Frequency: Quarterly

Typography: LlC «Agromashpro», 5/2, alleya Zhemchugovoy, office 109/7, Moscow, 111402, Russia, https://www.технопарк.рф **технопарк ®,** order **190**

BASIC RESEARCHES

UDC 551.583: 551.467

ARCTIC ICE COVER AND MERIDIONAL COMPONENTS OF THE ATMOSPHERIC CIRCULATION IN THE NORTHERN HEMISPHERE

A.V. Kholoptsev [1, 2] (Dr. Sci. (Geogfaphy), prof.)**,**
S.A. Podporin [2] (Cand. Sci. (Engineering), associate professor),
N.K. Kononova[3, 4] (Cand. Sci. (Geography)

[1] *Zubov N.N. Sevastopol Branch of State Oceanographic Institute, Sevastopol, Russia;**kholoptsev@mail.ru***
[2] *Sevastopol State University, Sevastopol, Russia; **SAPodporin@sevsu.ru***
[3] *Institute of Geography RAS, Moscow, Russia; **NinaKononova@yandex.ru***
[4] *Federal Research Center "Institute of Biology of the South Seas named after A.O. Kovalevsky RAS",Sevastopol, Russia*

Abstract. The paper considers the features of the mutual influence caused by the ice cover of the Arctic waters and the meridional components of the atmospheric circulation in the Northern Hemisphere of Earth, which are manifested in the modern period. The identification of such features is an urgent problem of climatology, meteorology, oceanography, as well as the maritime transport industry.

The subject of this research is the statistical relationship between interannual changes in a number of characteristics of the Arctic ice cover and components of the atmospheric circulation. The features of the impact of external factors on them are also investigated.

The paper checks the adequacy of the hypothesis put forward that the significant factors of the interannual variability of the characteristics belonging to Arctic air invasions that occur in the summer season in a number of regions of the Arctic include variations in the state of their ice cover caused by the combined effect of global warming and the decline of the average level of solar activity taking place in the current period.

To achieve this goal, there are considered the results of a retrospective analysis of changes in 1993–2019 concerning average daily values of the average thickness of the ice cover, its concentration, average temperature and salinity of the surface layer of the Arctic water areas, as well as air temperatures and meridional components of wind speed in various layers of the troposphere. The specified information has been obtained from the GLORYS, V12, NCEP / NCAR, and ERA - Interim electronic databases. The method of correlation analysis and statistical goodness-of-fit tests were used to assess the adequacy of the hypothesis under consideration.

Using the example of the Arctic waters located in the European, Siberian, Far Eastern and Pacific sectors of the Northern Hemisphere, the features of the mutual influence of changes in the state of their ice cover and meridional components of the atmospheric circulation in the summer season are revealed. The results obtained make it possible to confirm the adequacy of the concept on the significance of the impact on the ice cover of the Arctic waters of the southern cyclones entering high latitudes. The existence of a significant influence of the state of their ice cover on the characteristics of arctic air intrusions formed in the same sectors was also established.

It is shown that in the modern period, and in the coming decades of the twenty-first century changes in the state of the ice cover in the Arctic will be determined by competing factors of global warming and cooling factors caused by a decrease in the average level of solar activity. The latter will entail a decrease in the average intensity of insolation in the Arctic waters. The result of the confrontation of these factors is currently unpredictable, since it depends on the average level to which solar activity will decrease at the next minimum of the Suess cycle, as well as on the concentrations of greenhouse gases in the Earth's atmosphere reached by that time. It is not ruled out that ice conditions in the Northern Sea Route will become more difficult in the summer-autumn navigation period, which confirms the relevance and timeliness of the implementation of the Russian Icebreaker Fleet Development Program.

Key words: Arctic, ice cover, invasions, Arctic air, southern cyclones, statistical relationships, solar activity, reanalysis.

INTRODUCTION

Changes in the characteristics of the ice cover of the Arctic waters caused by various processes in the climatic system of our planet have a significant impact on both the safety of navigation on the waterways passing through them, and on the environmental conditions in the Arctic zones, as well as the life of the population there. Therefore, the identification of the factors causing such changes and their consequences are an urgent problem of oceanography, meteorology, climatology, and operation of transport systems and complexes.

The identification of factors influencing the state of the ice cover in all regions of the Arctic is of the greatest interest. One of them is the interannual variability of the characteristics of the meridional components comprising the atmospheric circulation in the Northern Hemisphere of the Earth, which provide the incoming of warm temperate air in the Arctic and accelerating the processes of ice melting [3, 8, 16, 26].

The entry of southern cyclones into the Arctic plays a significant role in the delivery of this air to the Arctic. With their arrival, not only the air temperature rises in the Arctic, but also storms intensify there with causing the destruction of ice cover, which accelerates ice melting [26].

Arctic air invasions (AAI) into the temperate latitude regions, which lead to the formation of blockings in them, are also significant meridional components of atmospheric circulation in the Northern Hemisphere [10, 14, 15, 18]. Nevertheless, the relationship between these processes and the ongoing changes in the state of the Arctic ice cover has been insufficiently studied.

According to modern ideas about the reasons for the variability of atmospheric circulation characteristics [21, 25], significant changes include those in the properties of the underlying surface, as well as the absorbed solar radiation, which penetrates into waters in the Arctic mainly in the summer season (from June to September).

This allows us to assume that among the significant factors of interannual variability of the characteristics concerning AAI invaded in the regions of temperate latitudes in the summer season, there may be changes in the state of the ice cover in some Arctic regions; in the modern period, those changes are caused by the combined influence of climate warming factors [19, 21] and average level of solar activity.

The hypothesis put forward is not trivial, since the characteristics of the ice cover of the Arctic, and possibly the AAI, can also be influenced by other factors (a decrease in the average salinity of the surface layer of its waters (ASSL), changes in the characteristics of its surface currents, etc.) [11, 16].

Despite the fact that the factors of variability of the Arctic ice cover have been studied by domestic and foreign scientists for many decades [3, 16, 19], their role in the ongoing changes in the characteristics of AAI has been insufficiently studied.

Confirmation of the adequacy of the hypothesis put forward would have the greatest practical importance for the Arctic regions, along which its most important transport route (the Northern Sea Route) passes, the development of which is one of the strategic priorities of Russia [5]. Such regions can include all the waters of the Arctic Ocean and the Arctic seas (from the pole to the corresponding sections of the continental coast), which are located in the following sectors of the Northern Hemisphere: European (0-60°E), Siberian (60°–120°E), The Far East (120°–170°E) and the Pacific (170°E – 120°W).

Despite the fact that during the period of modern climate warming, the average ocean surface temperatures (OST) of all Arctic regions have increased, and the total ice cover area (TIA) and its volume (TIV) have significantly decreased [16, 19], the trends of these indicators have changed in some of its regions over the past years. Confirmation of the adequacy of the hypothesis put forward for the indicated regions of the Arctic would allow not only to take into account the ongoing changes in the state of their ice cover when forecasting the AAI, but also to clarify the existing ideas about the trends of its further changes and the development of sea transport here. Consequently, testing this hypothesis is of significant theoretical and practical interest.

In view of the above, the purpose of this paper is to test the adequacy of the hypothesis put forward.

METHODS AND MATERIALS

To achieve this goal, a technique was applied that involves the two-stage testing of the adequacy of the hypothesis put forward. The first stage consists in checking the presence of significant statistical relationships between the time series of the TIA and the TIV for the specified regions of the Arctic, as well as a number of AAI characteristics and invasions of southern cyclones. The second stage involves testing the validity of the assumption that the features of modern changes in the TIA and TIV in the indicated regions of the Arctic are due to the combined effect of climate warming factors and a decrease in the average level of solar activity.

At the first stage, the following characteristics of macrocirculation processes were taken into account:

- Total duration of southern cyclones invading in the Arctic in a particular sector (TDSC);
- Total duration of blockings occurring in the same sectors (TDB);

- The average values of the speed of movement in the lower tropospheric layer of air, which enters the Arctic (V_s) and leaves it (V_N) within a given sector, as well as their difference V_S - V_N.

The values of TIA and TIV were calculated for each month (from June to September), and also on the average for the summer season for all Arctic waters, which belong to each sector considered. The specified indicators for each sector were calculated as:

$$TIA = \sum_{i=1}^{N} S_i l_i;$$

$$TIV = \sum_{i-1}^{N} S_i l_i h_i,$$

where h_i is the average ice thickness of the i- th area, which has the shape of a trapezoid with bases located along one or another parallel; l_i - its average ice coverage; S_i - the area of the same region, which was calculated taking into account the latitudes at which its northern and southern boundaries (trapezoid bases) are located, as well as the distance between them; N is the total number of districts that belong to the considered sector.

The OST and ASSL values for all Arctic waters belonging to the same sector were calculated as the weighted sum of the corresponding indicators:

$$OST = \frac{\sum_{i=1}^{N} t_i S_i}{\sum_{i=1}^{N} S_i};$$

$$ASSL - \frac{\sum_{i=1}^{N} l_i s_i}{\sum_{i=1}^{N} s_i},$$

Where t_i is the average surface temperature of the i-th region; s_i - average salinity on the surface of the i -th region.

The values of t_i, s_i, h_i, l_i for each region were determined as the arithmetic mean of the values of the corresponding indicators set at its vertices. At the same time, the GLORYS 12 v.1 reanalysis [20] was used as factual material about the values of these indicators in all points of the considered regions of the Arctic.

The source specified presents estimates for every day in the interval of 1.01.1993–31.12.2019 concerning average daily values of these indicators, which correspond to nodes of a uniform coordinate grid with the increment of 0.08333°. The estimates mentioned were obtained using the NEMO ocean model.

When verifying the model, we used the satellite monitoring results of the variability of t_i, s_i, h_i, and l_i for the same period. To reduce the variance of errors of such estimates, the Kalman filter is applied.

When assessing the TDSC and TDB values, the typification of macrocirculation processes in the Northern Hemisphere proposed in [6] was used, as well as the elementary circulation mechanisms (ECM) described in the same place. Upon them, southern cyclones invade the Arctic or blockings occur in the sectors under consideration [7]. The mentioned ECMs are given in table 1.

Table 1. The *ECMs at which southern cyclones invade the Arctic in the indicated sectors of the Northern Hemisphere or where blockings are formed.*

Invasion of southern cyclones			
No.	**Sector**	**Longitudes**	**ECM**
1	European	0 - 60°E	2a, 2b, 3, 8a, 8bk, 8ck, 8dk, 9a, 9b, 12a, 12bk, 12ck, 13k
2	Siberian	60 - 120°E	2a, 2b, 2c, 3, 4b, 4c, 6, 7bk, 13k
3	Far Eastern	120 - 170°E	1a, 2b, 3, 8bl, 8dk, 12bk, 13k, 13j
4	Pacific	170°E – 120 W	9b, 13k
Blocking formation			
No.	**Sector**	**Longitude**	**ECM**
1	European	0 - 60°E	4b, 4c, 10a, 10b
2	Siberian	60 - 120°E	8bk, 8cl, 8dk, 12a, 12bk, 12ck
3	Far Eastern	120 - 170°E	6, 8cl, 12a, 12cl
4	Pacific	170°E - 120°W.	6, 7bl, 8cl, 9a, 9b, 10b, 12a, 12bl

Total duration of the effect in a given month of the period 1993–2018 of each ECM mentioned in table 1 is presented in the source [13]. The values of TDSC or TDB for a certain month in any sector were calculated as the sum of the total duration of the effect in the month of all ECMs mentioned in the corresponding line of the table 1. If an effect of a certain ECM began in one month and ended in another, its effect period duration was taken into account in the month to which most of this period belongs.

Indicators V_S and V_N were estimated at the southern Arctic border, for which the parallel of 70°N is conventionally taken, in the atmospheric layer corresponding to the geopotential of 1000 hPa. Thereby, the information from the ERA - Interim reanalysis [23] was used. The source specified presents data for the period starting from 01.01.1979 on changes in the average daily values of meridional components of wind speeds in various layers of the atmosphere above the points of the Earth's surface, which correspond to the nodes of the coordinate grid with a step of 0.7°× 0.7°.

Positive (negative) values of this indicator correspond to the winds of the southern (northern) points of the compass. Therefore, when assessing the V_S and V_N we calculate the sums of its positive and negative values in all points located on the parallel 70°N between the meridians that limit this or that sector. The results obtained were normalized with regard to 122 (the total number of days in the summer season) and to the total number of such points (85 for the European and Siberian sectors, 70 for the Far Eastern sector, and 100 for the Pacific sector).

The study of statistical relationships between the TIA and TIV series, as well as between the considered characteristics of the atmospheric circulation was carried out using the correlation analysis method [2] and Student's test [9]. Links were assessed for three time periods: 1993–2019, 2000–2019, and 2012–2019. Linear trends were compensated for in all compared series before conducting the analysis.

It was assumed that the hypothesis is adequate if the reliability of the statistical conclusion about the significance of the correlation between changes in the ice cover characteristics and the considered atmospheric circulation indicators is at least 0.95.

When performing the second stage of the study, the presence of the conditions was checked; they are necessary for a certain mechanism of changes in the TIA and TIV in the sectors under consideration to have a significant impact on these processes.

A decrease in the intensity of insolation in high-latitude regions of our planet is possible with a decrease in the values of the solar constant and / or the transparency coefficient of Earth's atmosphere. The latter is possible with a decrease in the average level of solar activity over an 11-year cycle [1, 17]. Therefore, a prerequisite for the significance of this mechanism for decreasing the TIA and TIV in the Arctic waters is a decrease in the average level of solar activity over the 11-year cycle.

It follows from [1, 24], that in the modern period, the average level of solar activity actually decreases as approaching to the next least value of its 189-year cycle (Suess cycle), which is expected in the middle of the twenty-first century. Consequently, a decrease in the average intensity of insolation in high-latitude regions of our planet will most likely occur in the coming decades. If this level at the minimum of the mentioned cycle turns out to be low enough, climate cooling would develop not only in the Arctic, but also in some regions of temperate latitudes. It is quite possible that an increase in TIA and TIV which is happening in the period of 2012–2019 is the first manifestation of such a cooling.

If this is true, then an increase in TIA and TIV should be observed to some extent not in certain regions of the Arctic, but in all its regions under consideration. It should also be accompanied by a halt in the OST increase in their water areas, as well as in average air temperatures in different layers of the troposphere.

The check for the availability of these effects was carried out by identification, depending on the time of the TIA, TIV and TPO, which is calculated for each sector considered. The tendencies of changes in mean air temperatures in the tropospheric layers above each sector corresponding to the geopotential values of 300, 500, 700, and 1000 hPa were also estimated. The NCEP/NCAR reanalysis was used as factual material about the changes in the average daily air temperatures that occurred in the period 1979–2019 in the indicated tropospheric layers [22].

The angular coefficient value for the linear trend of the corresponding time series calculated for the time intervals of 1979–1999, 2000–2019, or 2012–2019 by the least squares method [2] was considered as a quantitative measure for the estimated tendency of each process under study. The results of such calculations were considered significant if the reliability of such a statistical conclusion assessed by Fisher's test exceeded 95% [9, 12].

One of the alternative mechanisms that can lead to a decrease in the TIA and TIV in the considered regions of the Arctic could be a decrease in the volume of warm air entering them from temperate latitudes. The latter is possible with a decrease in TDSC and/ r $V_{S.}$

Another mechanism could be a decrease in the ASSL. In this case, other things being equal, in the regions where the decrease in ASSL took place, the increase in OST and air temperature in certain layers of the troposphere over the oceans under the influence of climate warming factors should have continued.

Migration of drifting ice from other regions of the Arctic could also lead to an increase in TIA and TIV in its certain regions (the values of these indicators decreased accordingly there). Therefore, if the observed increase in TIA and TIV is a result of such migration, then this effect should be reduced to zero with the expansion of the boundaries of the region within which the values of these indicators are estimated.

These features were taken into account at the second stage of the study upon determining the cause that could lead to an actual increase in TIA and TIV.

RESEARCH RESULTS AND THEIR DISCUSSION

At the first stage of the study, the values of TIA, TIV, OST, and ASSL were calculated for each month and each considered sector of the Northern Hemisphere in accordance with the described methodology. As an example, Fig. 1 shows the change over time in the TIA, TIV indicators for the Siberian sector.

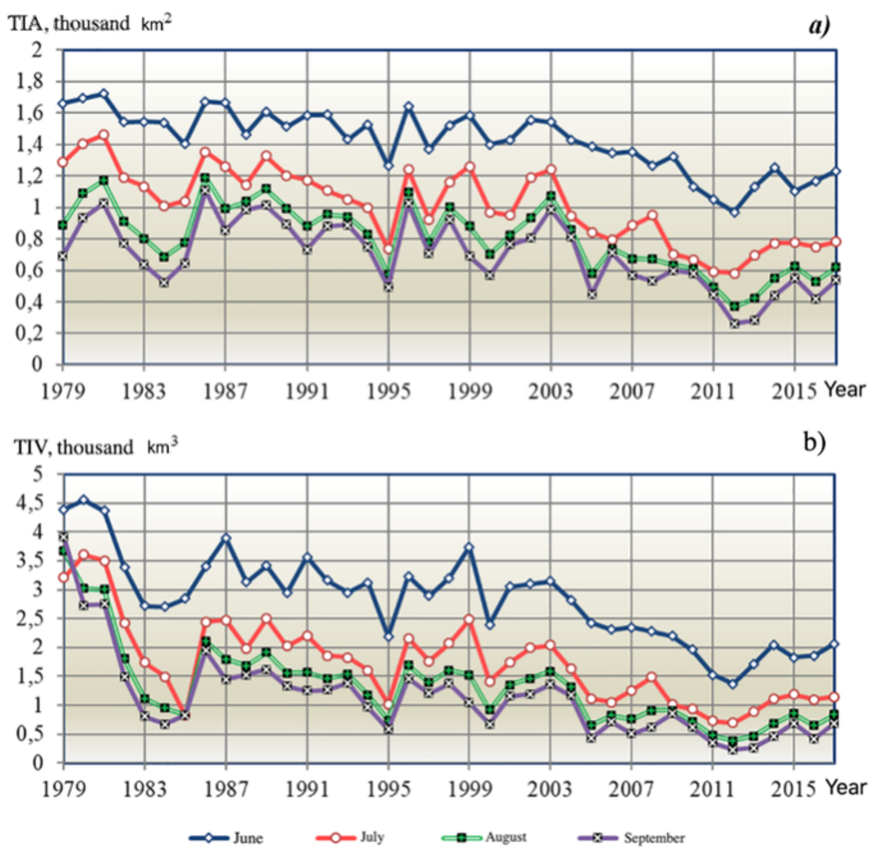

Fig. 1. *Change in the Siberian sector of monthly average values: a) TIA; b) TIV*

As seen from Fig. 1, for the period of 1993–2018 the monthly average values of TIA and TIV for the Siberian sector in the summer months decreased significantly; however, in the period of 2012–2018 there were increasing trends in the changes in these indicators. It follows from this that the phenomenon under consideration is not local in nature, but manifests itself on the scale of the entire Siberian sector. An increase in TIA and TIV in the same years was also recorded for other sectors of the Arctic, which corresponds to the ideas about the phenomena that are possible, if the hypothesis put forward is valid. Hence it follows that the phenomenon under consideration cannot be caused by the migration of drifting ice.

The changes in the parameters TDSC and TDB for the summer season, as well as the values of V_S and V_N were further calculated for each sector. As an example, Fig. 2 shows such calculations for the Siberian sector (60–120°E).

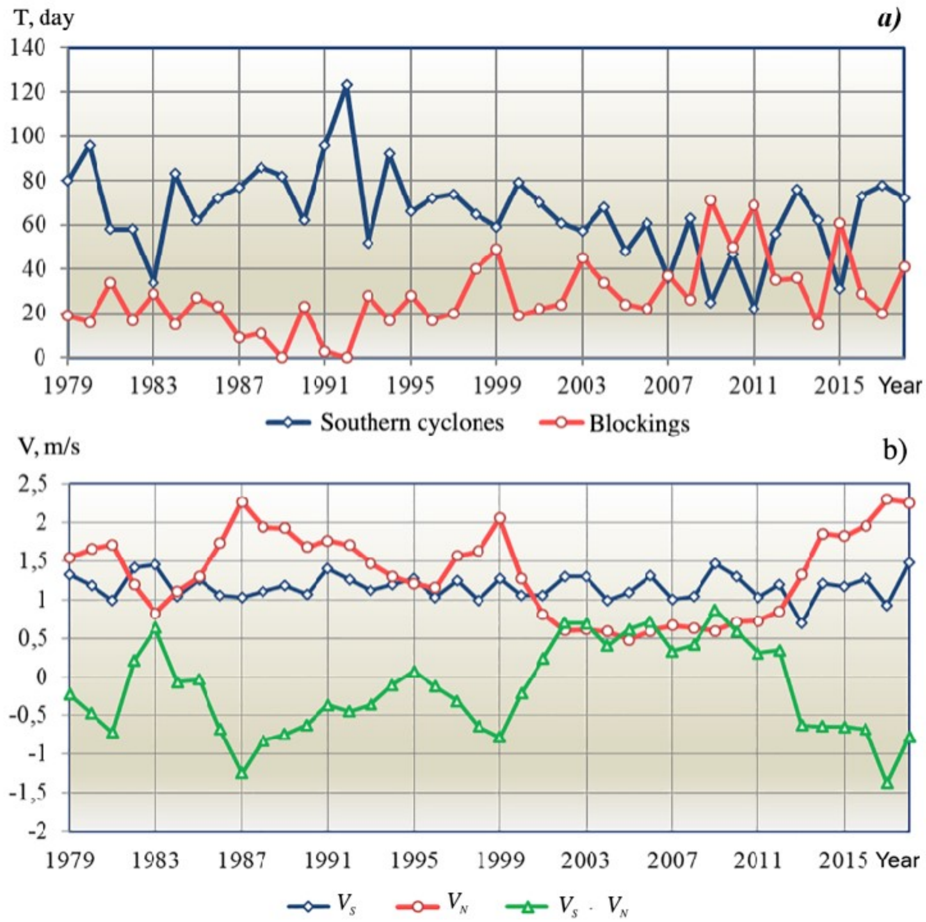

Fig. 2. *Time dependence of the meridional component characteristics of atmospheric circulation in the Siberian sector averaged over the period of June - September:*
a) Average duration (T) of southern cyclones and blockings;
b) Average speeds of these components V_N, V_S and the difference $V_S - V_N$

As seen in Fig. 2*a,* in the period of up to 2008 the TDSC values for the Siberian sector significantly exceeded the TDB values. Subsequently, they became equal on average (TDSCs were higher than TDBs in 2013–2015 and 2017–2018, and TDBs exceeded them in 2009–2012 and 2016). Moreover, in 2012–2018 TDSCs for this sector increased, which makes it possible to admit the possibility of an increase in the flow of warm air entering the Arctic region under consideration from temperate latitudes in the summer months.

Figure 2*b* shows that for a summer season, the time dependences of V_S, V_N and $V_S - V_N$ are complex oscillations. The main mode period of V_S variations is 2.66 years. The period of the main oscillation modes V_N and $V_S - V_N$ is close to 13 years. The phases of these oscillations are shifted by 180°.

In the summer months of 1982-1983 and 2001-2012 in the Siberian sector, air transport across a parallel of 70°N in the direction from south to north prevailed. All other things being equal, this should have caused a warming of the climate in this Arctic region and a decrease in TIA and TIV there. In other periods of time, including in the period of 2013 - 2018, air transport across the same parallel in summer was carried out in the southern direction, on average. At the same time, dry and cold Arctic air entered the temperate latitudes, which gave rise to blockings causing an abnormal heat in Europe, and increasing the fire hazard in Siberia.

There were not found significant alterations in the nature of V_S changes in 2012-2019. Consequently, the inflow of temperate air into the Arctic in the summer periods of the indicated years did not decrease, and therefore, there cannot be a reason for the increase in TIA and TIV.

A similar conclusion is valid not only for the Siberian, but also for other studied regions of the Arctic.

The results of the correlation analysis of the relationships between the time series of the TIA and the TIV for the period of June - September, as well as the considered characteristics of the atmospheric circulation for the Siberian sector are presented in Table 2.

As follows from Table 2, interannual changes in average TIA and TIV values for the summer period in the Siberian sector positively correlated with variations in V_S on all the studied time intervals. At the same time, the reliability of the conclusion about their significance exceeds 0.95 only in the period of 2012-2018. For other periods of time under consideration, its values exceed the level of 0.85.

Table 2. *Correlation analysis results*

	V_S	V_N	$V_S - V_N$	**TDSC**	**TDB**
1993-2018, 95% threshold = 0.39					
TIA	-0.092	0.317	-0.331	-0.174	0.097
TIV	-0.036	0.339	-0.372	-0.175	0.026
2000-2018, 95% threshold = 0.46					
TIA	-0.211	-0.338	-0.361	-0.406	0.068
TIV	-0.220	0.384	-0.391	–0.358	0.026
2012–2018, 95% threshold = 0.76					
TIA	0.934	0.966	-0.954	–0.853	0.355
TIV	0.916	0.954	-0.944	–0.844	0.258

Interannual changes in the TIV are negatively correlated with variations in V_S - V_N at any time intervals studied. The links between these processes are significant with a reliability of at least 0.95 only in 2012-2018.

The considered relationships of the interannual variations in the TIA and TIV, as well as the TDSC values with changes in V_S are also significant only for the period of 2012-2018.

Consequently, in 2012-2018 the factor that generates the correlation between the processes under consideration intensified. Similar features of the relationship between the processes under consideration were revealed for other studied sectors.

Since the air from the Arctic largely enters the temperate latitudes during the invasions of the Arctic air, it follows from the results obtained that the intensity of these macrocirculation processes in a certain sector is significantly and stably statistically related to both the TIA and the TIV values of the same sector.

Since the main process, where temperate latitude air penetrates the Arctic are invasions of southern cyclones, the presence of significant negative correlation between TIA and V_S corresponds to representations made in [26] that changes in repeatability of synoptic process data are an important factor in the destruction and melting of Arctic ice. The validity of this conclusion is also confirmed by the presence of a relatively strong (albeit insignificant) negative correlation between the series of TIA, TIV and TDSC values.

Absence of significant correlation between interannual changes in TIA, TIV and V_N values with TDB variations is explained by the fact that invasions of arctic air are the processes preceding to the formation of blockings, but not the blockings themselves, the duration of the existence of which are affected, among other things, by other factors [15].

Time dependences of the OST values averaged for the summer season in all studied regions of the Arctic was analysed in the second phase of the study. It was found that for the period of 1993–2018, the monthly average values of these indicators increased in June by 0.5°, and in July – September by 1°, which confirms the conclusions in [3, 16, 19]. Moreover, in the period of 2012–2018 their increase was not found anywhere (changes in OST in all regions have the nature of fluctuations with an amplitude from 0.3°C in June to 0.7°C in September). The same features of the OST variability were also revealed in other studied sectors of the Arctic.

Similar studies of the features of the ASSL interannual variability were carried out for the surface waters of the Siberian sector, and other Arctic sectors. It was established that for the periods of 1993–2019 and 2012–2019, there were areas in them where downward trends prevail in the summer months, but this is not the case everywhere. In the regions of the Arctic, where decreasing trends are revealed in the changes in the ASSL, they are not significant, as a rule. Significant differences in the variability of this indicator in 2012–2019 compared to 1993–2019 are not found. Consequently, decrease in TIA cannot be the main reason for the increase in TIA and TIV values in 2012–2019 in the water areas of the Arctic sectors under consideration.

We also estimated and compared the dependence of the values expressing the angular coefficient of the linear trend (ACLT) of the monthly average air temperatures over each studied sector in July estimated for the periods of 1979–1999, 2000–2019 and 2012–2019 on the latitude and the level of the geopotential corresponding to the considered tropospheric layer. Examples of such dependences for the Siberian sector in July are shown in Fig. 3.

Fig. 3*a* shows that in July, in the period of 1979-1999, there was an increase in monthly average air temperatures in all the considered layers of the troposphere and at all latitudes. On average, the rates of these processes increased as the latitude of the points for which their values were estimated, increased.

From Fig. 3*b* it follows that in the period of 2000–2019 in July the values of the average air warming rates significantly decreased in the same layers of the troposphere at all latitudes, and at an altitude of 300 hPa its cooling was revealed. The higher the latitude of the corresponding point, the more noticeable it is.

Figure 3*c* shows that in the period of 2012–2019, warming (albeit at a much lower rate) in the Siberian sector of the Arctic was noted only in the 1000 hPa layer. Cooling was revealed in the other considered layers of the troposphere. Similar results were obtained for the rest of the considered regions of the Arctic.

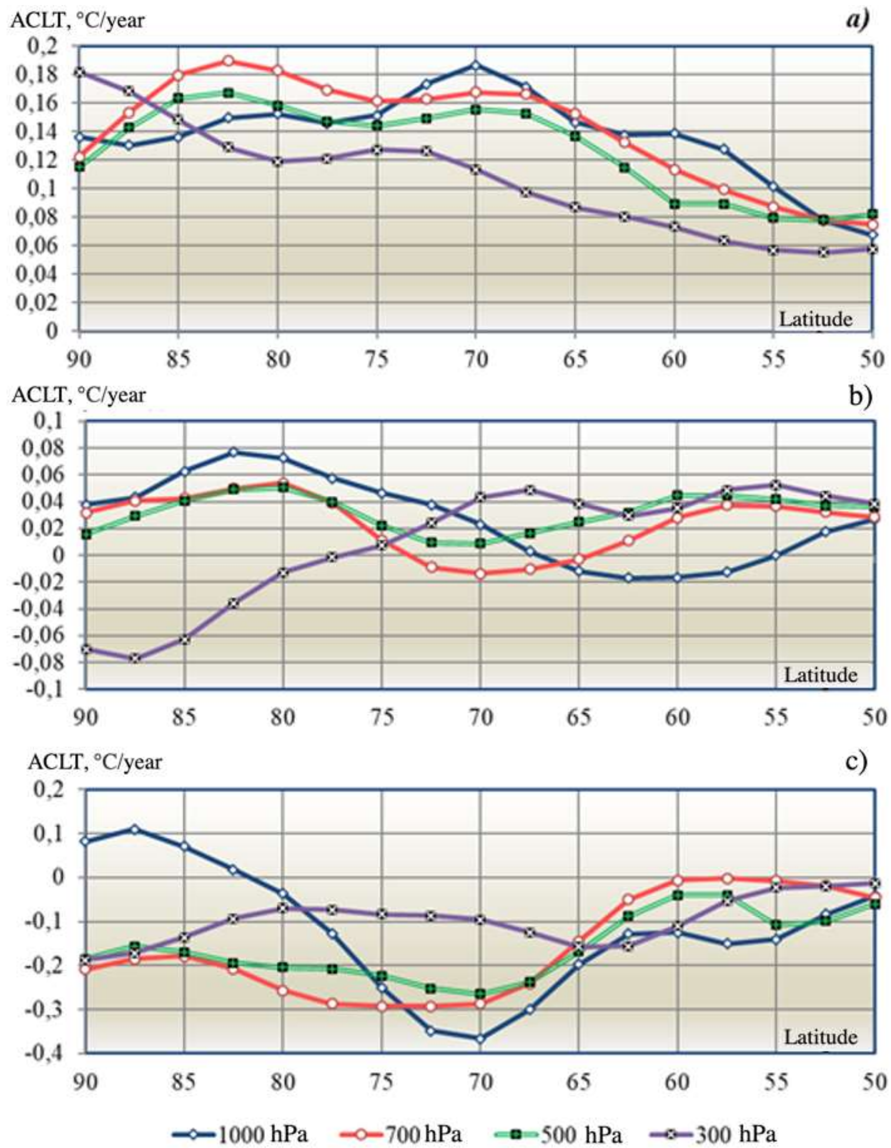

Fig. 3. *Dependence on the latitude of the values expressing the angular coefficient of the linear trend of monthly average air temperatures over the Siberian sector in July estimated for the following periods: a) 1979–1999, b) 2000–2019, c) 2012–2019.*

DISCUSSION

As it follows from the results obtained, the changes in the state of the Arctic ice cover occurring in the current period suggest that the ratio between the intensity of factors causing climate warming and cooling has changed in favour of the latter. The consequences of this change are manifested in different ways at different latitudes. They are most noticeable in the Arctic, where changes in solar activity most noticeably affect the intensity of insolation in its water areas.

The distributions of the average rates of interannual changes in air temperatures similar to those shown in Fig. 3 correspond to the ideas about possible changes in these indicators. Those changes would take place if in the period of 2000–2019 the energy flow absorbed during the melting of drifting ice to the surface of the water areas of the considered Arctic region decreased (most rapidly in 2012–2019).

The fact that this condition is actually fulfilled is evidenced by the conclusions [1], from which it follows that the average levels of solar constant and solar activity in the period under consideration decreased and will continue to decrease for approximately 25–35 years. Therefore, the hypothesis put forward is adequate.

CONCLUSION

Thus, using the example of the Arctic waters located in the European, Siberian, Far Eastern and Pacific sectors, it was found that changes in the state of their ice cover in the summer season not only depend on variations in the TDSC, but they also have significant effect on the characteristics of Arctic air invasions into temperate latitude regions of the Northern hemisphere of our planet.

Necessary conditions for the significance of the impact on changes in the TIA and TIV values of the Arctic waters can lead to an increase in their values. They were performed in the summer seasons of 2012–2019 only for such a mechanism as a decrease in the average intensity of their insolation caused by a decrease in the average level of solar activity.

Since a new minimum of Suess cycle may occur in the middle of the twenty-first century, it is possible that ice conditions in the summer-autumn navigation period in the Arctic, including the Northern Sea Route, will continue to be complicated (if the cooling factor will be stronger than warming factors). As a result, the implementation of the State program approved by the Russian government for the development of Russian icebreaker fleet is urgent.

This work was carried out within the framework of the Basic Research Program implemented by the Institute of Geography at the Russian Academy of Sciences, project no. 0148-2019-0009, and R&D of FRC IBSS (registration number: AAAA-A19-119061-190081-9).

REFERENCES

1. Abdusamatov Kh. I. Dvuhvekovoe umen'shenie solnechnoj postoyannoj privodit k nesbalansirovannomu teplovomu byudzhetu Zemli i glubokomu poholodaniyu klimata [A two-century decrease in the solar constant leads to an unbalanced thermal budget of the Earth and a deep cooling of the climate]. *Kinematika i fizika nebesnyh tel* [*Kinematics and physics of celestial bodies*]. 2012. Vol. 28, No. 2. P. 22-33.

2. Ajvazyan S.A., Mhitaryan V. S. *Prikladnaya statistika i osnovy ekonometriki* [Applied Statistics and Basics of Econometrics]. Moscow, 1998. 1022 p.

3. Alekseev G.V. Proyavlenie i usilenie global'nogo potepleniya v Arktike [The manifestation and intensification of global warming in the Arctic]. *Fundamental'naya i prikladnaya klimatologiya* [*Fundamental and applied climatology*]. 2015. Vol. 1. P. 11-26.

4. Veretenenko S.V., Raspopov O.M. Solnechnaya aktivnost' i kosmicheskie luchi: vliyanie na oblachnost' i processy v nizhnej atmosfere (pamyati i k 75-letiyu M.I. Pudovkina) [Solar activity and cosmic rays: the effect on cloudiness and processes in the lower atmosphere (devoted to the 75th anniversary of M.I. Pudovkin)]. *Geomagnetizm i aeronomiy*a [*Geomagnetism and Aeronomy*]. 2009. Vol. 49, No. 2. P. 147-155.

5. Gosudarstvennaya programma «Social'no-ekonomicheskoe razvitie Arkticheskoj zony Rossijskoj Federacii». Utverzhdena postanovleniem Pravitel'stva Rossijskoj Federacii ot 21 aprelya 2014 g. [State program "Socio-economic development of the Arctic zone of the Russian Federation." 2014. Approved by the Government of the Russian Federation on April 21, 2014. No. 366] 140 p.

6. Dzerdzeevskii B.L., Kurganskaya V.M., Vitvickaya Z.M. Tipizaciya cirkulyacionnyh mekhanizmov v severnom polusharii i harakteristika sinopticheskih sezonov [Typification of circulation mechanisms in the northern hemisphere and characteristic of synoptic seasons]. *Tr. n.-i. uchrezhdenij Gl. upr. gidrometeorol. sluzhby pri Sovete Ministrov SSSR. Ser. 2. Sinopticheskaya meteorologiya,* 1946. No. 21. 80 p.

7. Dzerdzeevskii B.L. Cirkulyacionnye mekhanizmy v atmosfere Severnogo polushariya v XX stoletii .Materialy meteorologicheskih issledovanij [Circulation mechanisms in the atmosphere of the Northern Hemisphere in the twentieth century. Materials of meteorological research]. Moscow, 1968. 240 p.

8. Dumanskaya I.O., Fedorenko A.V. Analiz svyazi ledovyh harakteristik morej evropejskoj chasti Rossii s makrocirkulyacionnymi atmosfernymi processami [Analysis of the relationship of the ice characteristics of the seas of the European part of Russia with macrocirculation atmospheric processes]. *Meteorologiya i gidrologiya* [*Meteorology and Hydrology*]. 2008. No. 12. P. 82-94.

9. Zaks Sh. Teoriya statisticheskih vyvodov [Statistical Inference Theory]. Per. s angl. E. V. Chepurina; pod red. Yu. K. Belyaeva. Moscow, 1985. 776 p.

10. Zolotokrylin A.N., Titkova T.B., Cherenkova E.A., Vinogradova V.V. Sravnitel'nye issledovaniya zasuh 2010 i 2012 g. na Evropejskoj territorii Rossii po meteorologicheskim i MODIS dannym [Comparative studies of droughts of 2010 and 2012 in the European territory of Russia according to meteorological and MODIS data]. *Sovremennye problemy distancionnogo zondirovaniya Zemli iz kosmosa* [*Modern problems of remote sensing of the Earth from space*]. 2013. Vol.10, No. 1. P. 246-253.

11. Kasimov N.S., Klige R.K. Glavnye faktory sovremennyh global'nyh klimaticheskih izmenenij prirodnoj sredy [The main factors of modern global climatic changes in the environment]. *Sovremennye global'nye izmeneniya prirodnoj sredy* [*Modern global changes in the natural environment*]. 2012. Vol. 3. P. 11-40.

12. Kiktev D.B., Kryzhov V.N. O sravnenii razlichnyh metodov ocenki statisticheskoj znachimosti linejnyh trendov [On the comparison of different methods for assessing the statistical significance of linear trends]. *Meteorologiya i gidrologiya* [*Meteorology and Hydrology*]. 2004. No. 11. P. 27-38.

13. Kolebaniya cirkulyacii atmosfery Severnogo polushariya v XX – nachale XXI veka [Fluctuations in the circulation of the atmosphere of the Northern Hemisphere in the XX - beginning of the XXI century]. URL: http://www.atmospheric-circulation.ru (appeal date 11.02.2020)

14. Kononova N.K. Izmeneniya global'noj cirkulyacii atmosfery v period 1899-2018 gg. [Variations of global atmospheric circulation in the period 1899-2018]. *Fundamental'naya i prikladnaya klimatologiya* [*Fundamental and applied climatology*]. 2019. Vol. 4. P. 120-138.

15. Mokhov I.I., Akperov M.G., Prokof'eva M.A. Blokingi v Severnom polusharii i Evro-Atlanticheskom regione: ocenki izmenenij po dannym reanaliza i model'nym raschetam [Blockings in the Northern Hemisphere and Euro-Atlantic Region: Assessment of Changes Based on Reanalysis and

Model Calculations]. *Doklady Akademii nauk* [*Academy of Sciences reports*]. 2013. Vol. 449, No. 5. P. 1-5.

16. Frolov I.E., Gudkovich Z.M., Karklin V.P., Smolyanickij V.M. Izmeneniya klimata Arktiki i Antarktiki – rezul'tat dejstviya estestvennyh prichin [Climate change in the Arctic and Antarctic is the result of natural causes]. *Problemy Arktiki i Antarktiki* [*Problems of the Arctic and Antarctic*]. 2007. No. 2 (85). P. 52-61.
17. Kholoptsev A.V., Nikiforova M.P. *Solnechnaya aktivnost' i prognozy fiziko-geograficheskih processov* [Solar activity and forecasts of physical and geographical processes]. Saarbrucken, Deutschland, 2013. 333 p.
18. Cherenkova E.A., Semenova I.G., Kononova N.K., Titkova T.B. Droughts and dynamics of synoptic processes in the south of the East European Plain at the beginning of the twenty-first century. *Arid Ecosystems.* 2015. Vol. 5 (2). P. 45-56.
19. Climate Change 2013: The Physical Science Basis. URL: https://www.ipcc.ch/report/ar5/wg1/ (appeal date 11.12.2019).
20. Global Ocean Physics Reanalysis. URL: http://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_PHY_001_030 (appeal date 11.12.2019).
21. Mankin M. 2011. Atmospheric dynamics. London: Cambridge Univ. press. 512 p.
22. NCEP/NCAR reanalysis database. URL: ftp://ftp.cdc.noaa.gov/Datasets/ncep.reanalysis.dailyavgs/pressure/ (appeal date 11.02.2020).
23. The Climate Data Guide: ERA-Interim. URL: https://climatedataguide.ucar.edu/climate-data/era-interim (appeal date 11.02.2020).
24. Trenberth K. E., Fasullo J. T., Kiehl J. Earth's global energy budget. *Bull. Amer. Meteor. Soc.* 2009. Vol. 90, No. 3. P. 311-324.
25. Wiedenmann J.M., Lupo A.R., Mokhov I.I., Tikhonova E.A. The climatology of blocking anticyclones for the Northern and Southern Hemispheres: Block intensity as a diagnostic. *J. of Climate.* 2002. Vol. 15. P. 3459-3473.
26. Zakharov V. G., Kononova N. K. Relationship of dynamics of fields of ice drift in the arctic basin and atmospheric circulation in northern hemisphere (summer season). *The complex systems.* 2015. No. 1 (2). P.45-57.