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Research Article

The Impact of Warming in Greenland on the North-Atlantic, Arctic, And West Pacific Oscillations, As Well as on Fire Risk in Siberia Is Increasing

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KEYWORDS

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surface air temperatures
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ABSTRACT

One of the reasons for the increased fire danger due to weather conditions in any part of Siberia is the variations in average monthly surface air temperatures and average precipitation intensity. Significant factors in these processes include the North-Atlantic, Arctic, and West Pacific Oscillations. These oscillations are significantly influenced by the weakening of the Atlantic Meridional Overturning Circulation, caused by warming in Greenland, which accelerates the melting of its ice sheet. A hypothesis has been put forward: - the connections between the mentioned fluctuations and variations in the average monthly surface air temperatures for the summer months in the 21-st century have increased and have now become significant for the entire territory of Greenland; the correlation of these processes with variations in fire danger in some areas of Siberia, has also become significant. Testing this hypothesis confirmed its validity. It was shown that warming in Greenland leads to an increase in the components of all the aforementioned fluctuations, as well as fire danger in the identified areas of Siberia with annual periods. Therefore, in the 21-st century, the links between these processes have significantly strengthened and become significant between 2011 and 2025. The negative feedback limiting the rate of warming in Greenland has intensified and become significant. With further warming, the identified connections will strengthen, and the risk of landscape fires in the identified areas of Siberia will increase during the corresponding months.

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1. Introduction

One of the main factors of fire hazard due to weather conditions, as well as forest flammability in many regions of the world, are interannual changes in average monthly air temperatures and monthly precipitation amounts that fall during a certain month of the fire season in their territories (hereinafter referred to as MAT and MPT). These factors significantly influence changes in the safety of life of the population of each such region, the state of its water resources, agriculture, as well as the risks associated with the occurrence of landscape fires, droughts and floods. Therefore, improving the methods of long-term and ultra-long-term forecasting of their further variations is a pressing issue not only in meteorology and climatology, but also in emergency safety.

1.1. Relevance of the Topic

The solution to the problem under consideration is of greatest interest to regions in which the total area of forested areas burned by landscape fires (hereinafter referred to as TAF, he) has been increased in recent years. In Russia, these include many regions located in Siberia, which belong to the Federal Districts: the Ural (UFD), Siberian (SFD) and Far Eastern (FEFD). In the 21st century, the values of the PPO, as a rule, were elevated in such regions as the republics of Sakha (Yakutia) and Buryatia, Krasnoyarsk and Transbaikal Territories, as well as Irkutsk and Amur Regions.

As an example, Figure 1 shows the dependence of the TAF, he on time for the territory of the whole of Russia and Siberia, as well as separately for the UFD, SFD, FEFD and each of the mentioned regions, which are constructed according to data from [1].

As Figure 1a shows, from 2000 to 2023, the majority of forested areas damaged by fires in Russia each year were in Siberia. The time dependence of the corresponding fire risk indicators shows increasing trends.

Figure 1b shows that in Siberia, this trend was primarily driven by changes in the TAF values occurring in the FEFD. Meanwhile, for the SFD, TAF values decreased slightly, while for the UFD, they remained virtually unchanged.

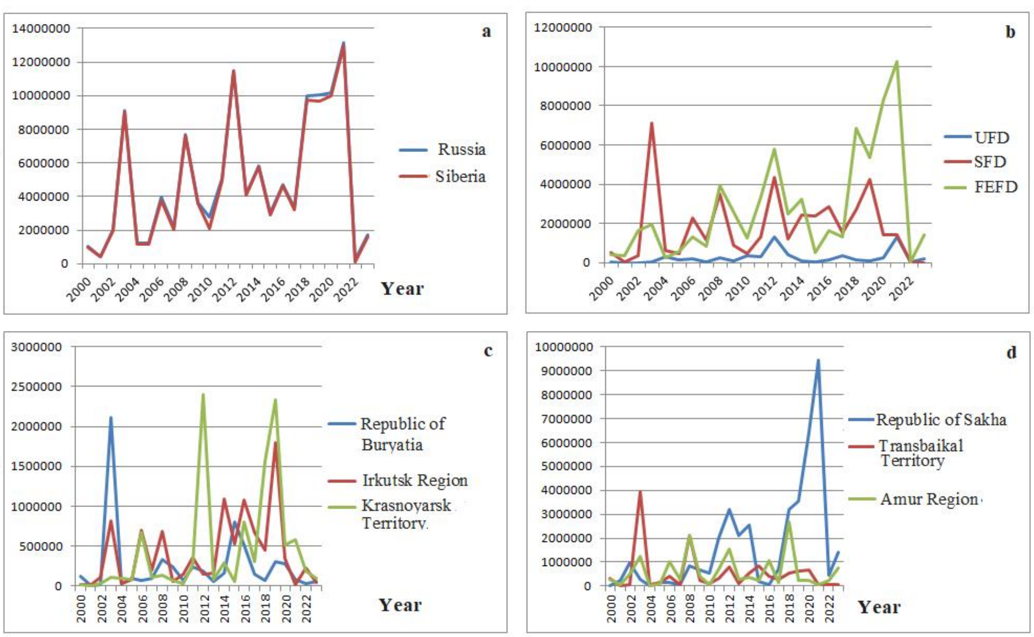


Figure1. Dependence of TAF, on time, in the territories (according to [1]).

a) all of Russia and Siberia; b) UFD, SFD and FEFD; c) Krasnoyarsk Territory, Irkutsk Region and the Republic of Buryatia; d) the Republic of Sakha (Yakutia), Transbaikal Territory and Amur Region.

Figure 1c shows that in the last decade, the highest peak values of TAF were in Krasnoyarsk Territory and Irkutsk Region.

Figure 1d shows that among the regions of the FEFD, the highest TAF values were in the Sakha Republic.

It's easy to see that all the TAF time dependences shown in Figure 1 represent complex fluctuations. The period of the main mode of these fluctuations for Yakutia was close to 11 years, while for other regions and Russia as a whole, it was 3-4 years.

The reasons for the mentioned fluctuations may not only be the cyclical nature of changes in the intensity of anthropogenic factors and processes of accumulation of combustible material [2]. Variations in the MAT and MPT in the corresponding territories may play a significant role in their formation [3-5].

1.2. Analysis of Existing Ideas About the Subject of Research

According to existing concepts regarding the causes of variability in the MAT and MPT [6-8], variations in atmospheric circulation are considered to be the most important of these. Over the northern part of Eurasia, the latter are caused by changes in the phases of the Arctic, North-Atlantic, and West Pacific Oscillations (hereinafter referred to as AO, NAO, and WP) [9-12].

AO is a macrocirculation process in the troposphere over the Northern Hemisphere, which characterizes the state of the circumpolar Polar Vortex existing here [9]. A quantitative indicator of its state is the climatic index (AO), which is defined as the anomaly in the difference in atmospheric pressure at sea level over the Arctic and at latitudes of 37-45° in the Northern Hemisphere. This indicator is calculated relative to the base period of 1981-2010.

During the positive phase of the AO, the Polar Vortex intensifies and becomes more compact, and intrusions of dry and cold Arctic air into the territory of Eurasia occur less frequently. As a result, atmospheric blocking [13] occurs less frequently over Siberia from April to October, while cyclones bringing cool air and precipitation are more prevalent. Therefore, during this phase of the Arctic Circle, the fire danger due to weather conditions in many areas decreases.

In the negative phase of the AO, inter-latitudinal air exchange over the northern part of the territory of Eurasia becomes more intense, atmospheric blockings occur more frequently, and the risks associated with the occurrence of landscape fires increase [10,11,14].

The relationship between AO changes and variations in meteorological conditions in the northern regions of Eurasia is most consistent and significant during the cold months of the year (November to March). The impact of Arctic climate warming on this relationship has been insufficiently studied. The influence of this process on the relationship between AK variability and variations in MAT and MPT in different parts of Siberia for the months of the fire-hazardous season (April-October) also requires further study [15].

The movement of Atlantic cyclones not only over Europe but also over Siberia is controlled by the NAO, which manifests itself in changes in the baric gradient over the North Atlantic. The quantitative characteristic (index) of the NAO is calculated as the difference in atmospheric pressure between the Azores High and the Icelandic Low [16,17].

In the positive phase of the NAO, the tracks of Atlantic cyclones over Eurasia are shifted to the north, and in its negative phase they pass over the southern regions of Siberia.

The movement of Pacific cyclones over Eurasia and its Far Eastern seas is regulated by the WP – a macrocirculation process in the troposphere over the Sea of Okhotsk and the northwestern part of the Pacific Ocean.

The WP is caused by variations in the difference in atmospheric pressure in the sections of the mentioned water area located in the Shelikhov Gulf (J (60°N, 155°E)) and in the subtropical zone of the Pacific Ocean (K (30°N and 155°E)) [12,18].

The J and K sections form a dipole in which atmospheric pressure fluctuations cause latitudinal shifts in the East Asian jet stream, as well as in the trajectories of Pacific cyclones that bring precipitation to Siberia. The JTC also controls the frequency of Rossby wave breaks (hereinafter RWB) [12].

The WP index is calculated as half the difference between the normalized values of the 500 mbar geopotential heights over sections J and K.

During the positive phases of the WP, the Aleutian Low weakens. At any time of year, the MAT is lower over Eastern Siberia, while the MPT is elevated at high latitudes and over the Pacific Ocean. During its negative phases, the opposite changes in meteorological conditions occur.

Changes in the states of the NAO and AO are caused by variations in the surface temperatures of the corresponding regions of the World Ocean [19]. A significant reason for these variations is changes in the characteristics of the Atlantic Meridional Overturning Circulation (AMOC) [20-23].

Along with changes in the state of the AMOC, other processes are also responsible for variations in the NAO indices, as well as the AO [24]. As a result, the correlation of time series formed from the values of the aforementioned indices was weaker in the past.

The more heat the waters of the corresponding North Atlantic Current jets in the aforementioned oceanic regions release to the atmosphere, the lower the atmospheric pressure above them. This increases the northward shift of Atlantic cyclone tracks over Eurasia. The greater the heat and moisture content of air masses entering its territory from the west, bringing with them atmospheric precipitation [25,26].

Changes in the state of the AO directly affect the characteristics of the Aleutian minimum, as well as the phase of the oscillation in the J-K baric dipole, known as the WP [12,27].

The relationship between AO variations and changes in the state of the fire zone is statistically most consistent during the winter season. It has been insufficiently studied during the fire-hazard months.

As we can see, climate warming in Greenland can influence the characteristics of the NAO, AO, and WP. Consequently, all of these aforementioned processes can, in one way or another, influence variations in the MAT and MPT, as well as fire danger in many regions of Siberia and neighboring countries [20,28].

Throughout virtually the entire Holocene, the AMOC remained in a positive phase, warming Europe, the North Atlantic, and the Arctic. Beginning in the mid-19th century, the AMOC began to weaken, a process that continues today. It is caused by global and regional climate warming, which is accelerating the melting of the Arctic ice sheet, including Greenland [20,21].

The process under consideration has the greatest influence on the dynamics of surface water temperature in the central part of the Irminger Sea, as well as the Norwegian and Greenland Seas, as well as areas of the Barents Sea located north of Spitsbergen [29].

As AMOC values decline rapidly in the 21st century, the heat flux delivered by the North Atlantic Current's central jet to the Arctic becomes significantly smaller. This phenomenon may lead to an increase in the frequency of negative phases of the NAO, AO and WP, as well as an increase in fire danger in Siberia.

Such an intense weakening of the AMOC had previously occurred only during the final phase of the Würm glaciation. It was caused by the eruption of fresh water from the enormous proglacial Lake Agassiz, formed during the melting of the Laurentide Ice Sheet, into the North Atlantic [30].

As a result of their breakthrough, a significant freshening of the surface layer of waters in the North Atlantic occurred. At the same time, the average density of the waters of this layer decreased so much that deep convection in the Irminger, Labrador and Greenland Seas ceased. The latter led to the collapse of the AMOC and the halt of the Global Ocean Heat Conveyor [31,34].

This resulted in the Heinrich Event—a cooling event in the high and temperate latitudes of the Northern Hemisphere that lasted for approximately 1,000 years (the so-called "Younger Dryas").

The desalination of surface waters in the North Atlantic and the weakening of the AMOC that is occurring in the modern period are caused by the warming of the climate of Greenland, which is manifested in an increase in average summer air temperatures over its entire territory (hereinafter MAT_G) [34].

According to [35-37], the process under consideration may lead not only to a weakening of the AMOC, but also to its repeated collapse, which may cause catastrophic climate changes in many regions of the Northern Hemisphere [3].

1.3. The Hypothesis Put Forward

The presented facts allow us to hypothesize:

- the relationships between interannual changes in the NAO, AO, and WP indices and variations in the MAT_G have strengthened in the 21-st century and have now become significant. As a result, in some areas of Siberia, the correlation of these processes with variations in the MAT and MPT for the corresponding months of the fire season has also become significant.

The proposed hypothesis is not trivial, since the connections between the processes being studied may not be significant, and their strengthening has not been previously established. Confirmation of its validity would allow us to take into account the connections between the processes under consideration, which possess the indicated properties, when developing long-term and ultra-long-term fire hazard forecasts in the territories of the corresponding regions of Siberia.

Such predictions may be consistent with a scenario in which Greenland's climate continues to warm in the future and its ice cover is preserved [5,38].

The implementation of this scenario in the coming decades is highly probable [39]. Consequently, testing the proposed hypothesis is not only of theoretical interest to climatologists, but also of significant practical interest to specialists in the field of planning the activities of fire departments and many economic facilities in Siberia, as well as its management.

1.4. The Purpose of the Work and the Tasks to Be Solved to Achieve It

The purpose of this work is to carry out such a check and identify areas of Russian territory related to Siberia for which statistical relationships between the processes under consideration had the required properties.

To achieve this, the following tasks were solved:

- determining the time shifts between changes in the MATG and variations in the monthly average values of the WP, AO, and NAO indices, in which the corresponding relationships have steadily strengthened in the 21-st century and have now become significant;
- detection of areas of Siberian territory for which the connections between changes in the corresponding MPT and MAT for the months of the fire-hazardous season and synchronous variations in the indices of the processes being studied were significant and increased over the same period;
- development of a high-quality forecast of changes in fire hazard based on weather conditions in the identified areas of Siberia, which are likely to occur under a scenario in which warming of the thermal regime of Greenland for the summer months continues in the future, and its ice cover is at least partially preserved.

2. Factual Material and Research Methodology

2.1. The Factual Material

In solving the first and second problems, information on changes in the climatic indices AO, NAO, and WP from [40] was used as factual material. This source presents data for the period 1950–2025. Also used were data on variations in hourly precipitation amounts and average hourly surface air temperatures at a height of 2 m above all points on our planet, which are presented in the ERA-5 reanalysis [41,42]. The information provided is presented for all nodes of the Mercator coordinate grid, with a step of 0.25o x 0.25o, as well as for each hour in the period from 00:00 on 01.01.1940 to 10.31.2025.

The period from 1971 to 2025 was considered as the period of modern climate warming [3,4].

Therefore, using the mentioned information from the ERA-5 reanalysis relating to the specified period, for each node of the coordinate grid of this reanalysis located within the territory of Greenland, the values of the MATG were calculated for each summer month. The obtained results were used to generate time series of the MATG corresponding to each month of the year.

As an example, Figure 2 shows the time dependence of the calculated MATG values corresponding to different summer months.

From Figure 2 it follows, that for all summer months the time dependences of the calculated values of the MATG represent complex fluctuations superimposed on certain increasing trends, which for the period 1991-2024 can be approximately considered as linear.

The highest values of the MATG for all years correspond to July, which allows us to accept the assumption that it was for this month that the melting of the Greenland ice sheet during the specified period was the most intense every year. Moreover, in the period 2010-2024, the rate of increase in the MATG for June and July decreased slightly. For August, its value was the highest: +0.084 oK/year (for July, +0.042 oK/year, and for June, -0.054 oK/year).

For other months of the year, as expected, the MATG values are similar, but significantly lower. Therefore, the studies reviewed only considered MATG changes for June, July, and August.

When solving the second problem, time series of MPT and MAT for the months from April to October were considered. Each member of these series is calculated using the corresponding ERA-5 reanalysis data on average hourly precipitation amounts and average hourly temperatures for each day of the month under consideration, for a point in the region bounded by the meridians of 60°N and 180°N, as well as the parallels of 35°N and 80°N.

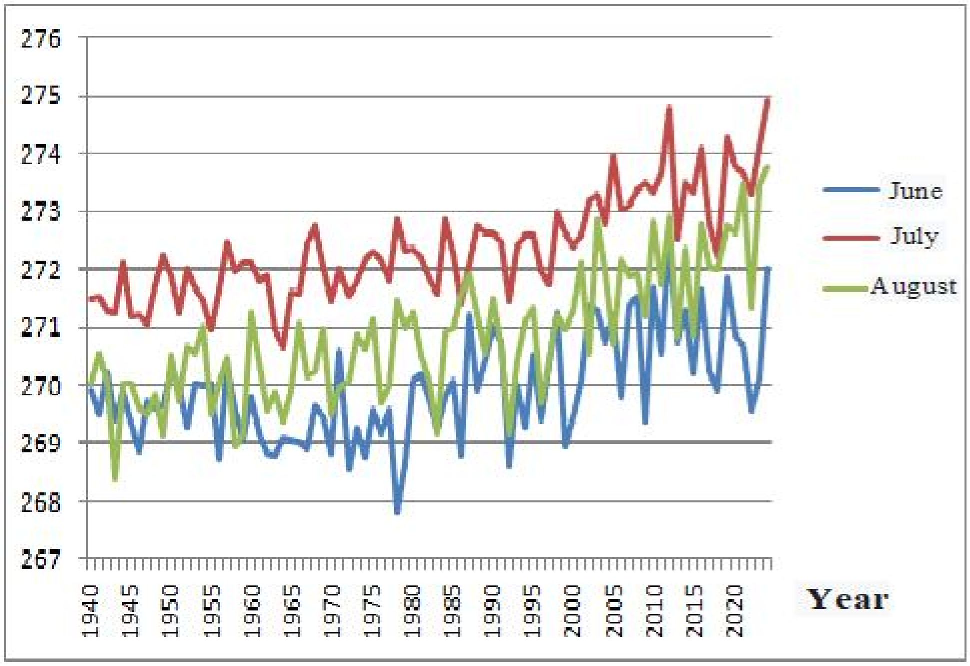


Figure 2. Interannual changes in the calculated values of the MAT_G for the summer months in the period 1940-2025.

It is easy to see that the territory of the specified region includes the entire territory of Siberia and the Asian countries bordering it, as well as the waters of the adjacent Arctic and Pacific seas.

From the calculated values of the MPT and MAT, the studied time series were formed, corresponding to each point and month, reflecting the interannual changes in these indicators for 1971-2025.

2.2. Research Methodology

When developing the research methodology, it was taken into account that the processes under study may not be stationary. Therefore, the relationships between time series segments corresponding to different 15-year time intervals were studied, and changes in these relationships were analyzed depending on the year the intervals began.

The pairwise correlation coefficient (hereinafter K) was used to characterize the strength of the relationship between the segments of the time series under study. Therefore, correlation analysis and the Student's t-test were used to solve problems 1 and 2.

A decision on the significance of the relationship under consideration was made if the reliability of such a statistical conclusion according to the specified criterion was at least 0.95.

Before calculating the correlation coefficient between certain segments of the time series under study, the corresponding linear trend was compensated for in each of them.

Based on the autocorrelation functions of the compared time series segments, it was established that the corresponding number of degrees of freedom was equal to 15. Therefore, a decision on the significance of the studied relationships was made if the value of the modulus K exceeded 0.52. The reliability of the same conclusion, not lower than 0.9, corresponds to a threshold level of 0.41, and its reliability of 0.99 corresponds to a level of 0.62.

For changes in the MATG, the time interval 2010–2024 was considered as the modern period, which made it possible, when solving the first problem, to take into account the connections of this process with variations in the AO, NAO, and WP indices for 2011–2025, lagging in relation to them by up to 16 months.

The relationships between the segment of the MATG time series for a certain summer month corresponding to the specified time interval, as well as the segments of the studied time series of the AO, NAO and WP indices lagging in relation to it, were studied. To do this, we calculated the cross-correlation functions of the corresponding processes for the specified delay values. We determined the time shifts between the studied intervals at which the relationships between them for the specified time intervals were considered significant with a reliability of at least 0.95.

When identifying areas for which the connections between the processes under study were strengthened, similar cross-correlation functions were calculated for segments of the MATG time series starting in previous years from the 1971-2009 interval.

From the values of K thus established, corresponding to different years of their beginning, time series containing 40 members each were formed.

For each time series K, corresponding to a particular time shift between the series of the MATG and the series of the index under consideration (AO, WP or NAO), the value of the angular coefficient of its linear trend (hereinafter UCLT) is determined.

An assumption was made that the deviations of the terms of each series K from the corresponding linear trend are random numbers with a normal probability distribution.

The validity of this assumption was confirmed using Pearson's α-test.

A decision on the significance of the UKLT, with a confidence level no lower than a certain level, was made if:

$$40*ABS(UKLT) > 1.65*RMS, \quad (1)$$

Where: ABS is the operator for calculating the absolute value of its argument;

RMS is the standard deviation of the terms of the studied series from the corresponding linear trend;

Assuming a normal probability distribution for the deviations K, the reliability of such a conclusion is at least 0.95.

If K*UKLT>0, a decision was made to strengthen the relationship between the processes under consideration. Otherwise, a conclusion was drawn that it was weakened.

The trend of changes in the values of K in the 21st century was recognized as stable if the signs of the UKLT, which were calculated for the segments of the time series of values of this indicator corresponding to members with numbers 31-35 and 36-40, coincided.

Similar studies have been carried out with respect to the relationships between the synchronous segments of the time series of the NAO, AO and WP, as well as the leading segments of the MATG series with the MPT and MAT series for each point under consideration in the territory of Siberia, corresponding to all months of the fire-hazard season (April-September), as well as various 15-year time intervals. The time interval 2011–2025 was considered as the current period for the MPT and MAT series.

When solving the third problem, it was assumed that the trends in changes in K, identified from the histories of the processes being studied, will not change in the future.

The results of solving previous problems were taken into account, and literary sources [20-57] were analyzed, which present modern ideas about the influence of climate warming in Greenland on the weakening of the AMOC.

As follows from the above, the trends present in the compared segments of the studied time series can be considered as linear only approximately.

As a result, compensation in such segments of linear trends only weakens (but does not eliminate) the influence of the quasi-deterministic components present in them on the results of the correlation analysis. This introduces some errors into the assessment of the reliability of the conclusions.

The length of the time series K is also short, making the Pearson normality test unreliable. Due to these characteristics of the described method, the results obtained using it should be considered qualitative.

3. Results and Analysis

3.1. Teleconnections Between Changes in Matg, and ao, Nao and Wp

Using the described methodology, we studied the correlation coefficients between various segments of the AO, NAO, and WP time series, spanning 15 years, as well as the preceding segments of the MATG time series for June, July, and August.

As an example, Figure 3 shows the dependences of the correlation coefficient of the segments of the AO, NAO and WP time series for 2000-2014, 2008-2022, 2011-2025, as well as the segments of the MATG series that precede them in time, corresponding to the summer months, on the time shifts between their beginnings.

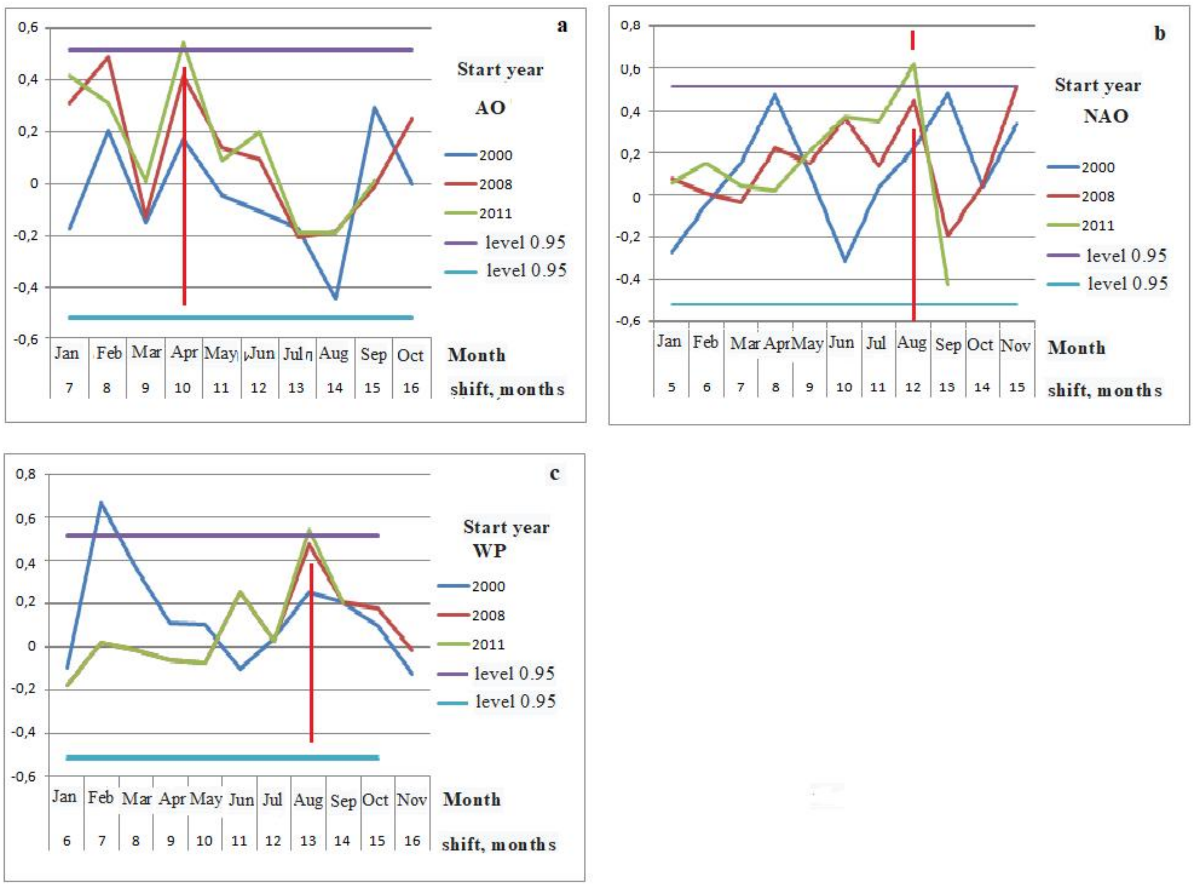


Figure 3. Dependences of the correlation coefficient of the 15-year segments of the AO, NAO, and WP time series, as well as the segments of the MAT_G series leading them in time, on the time shift between them, for the months to which the MAT_G G series correspond

a) June; b) September; c) July;

In Figure 3, the red line indicates the significant maximum corresponding to the time interval 2011–2025. Figure 3 shows that all the relationships under consideration are oscillatory. The corresponding maximum values of K exceed the selected significance level (0.52).

From Figure 3a it is evident that the correlation coefficient of the segment of the AO index series for 2011-2025 with the segment of the MAT_G series for 2010-2024 is significant if the first one corresponds to April, and the second one, which is 10 months ahead of it, corresponds to June. For segments starting earlier or later, the same shifts also correspond to maxima of the correlation coefficient, but they do not exceed the selected significance level.

Figure 3b shows that the reliability of the conclusion about the significance of the correlation coefficient between the NAO index series for 2011–2025 and the MAT_G series exceeds 0.95 if both series correspond to August, but the second series is 12 months ahead of the first.

As follows from Figure 3c, the relationship between the WP index series for 2011-2025 and the MAT_G series with a reliability of at least 0.95 is significant if the former falls in July, and the latter lags behind by 13 months and corresponds to August.

This shows that, over the 2011-2025 period, the components of changes in the NAO, AO, and WP indices, which are caused by variations in the MAT_G for one of the summer months and are characterized by a one-year period, significantly influence these processes. For earlier time periods, the relationships between the processes in question and the corresponding factors were not significant. Therefore, it is reasonable to assume that the relationships between the processes in question have strengthened.

The validity of this assumption is confirmed by Figure 4, which shows the dependence of the values of K, corresponding to the connections of these same processes with the preceding variations of the MAT_G for the identified and adjacent months, calculated for different time periods lasting 15 years, on the year of their onset.

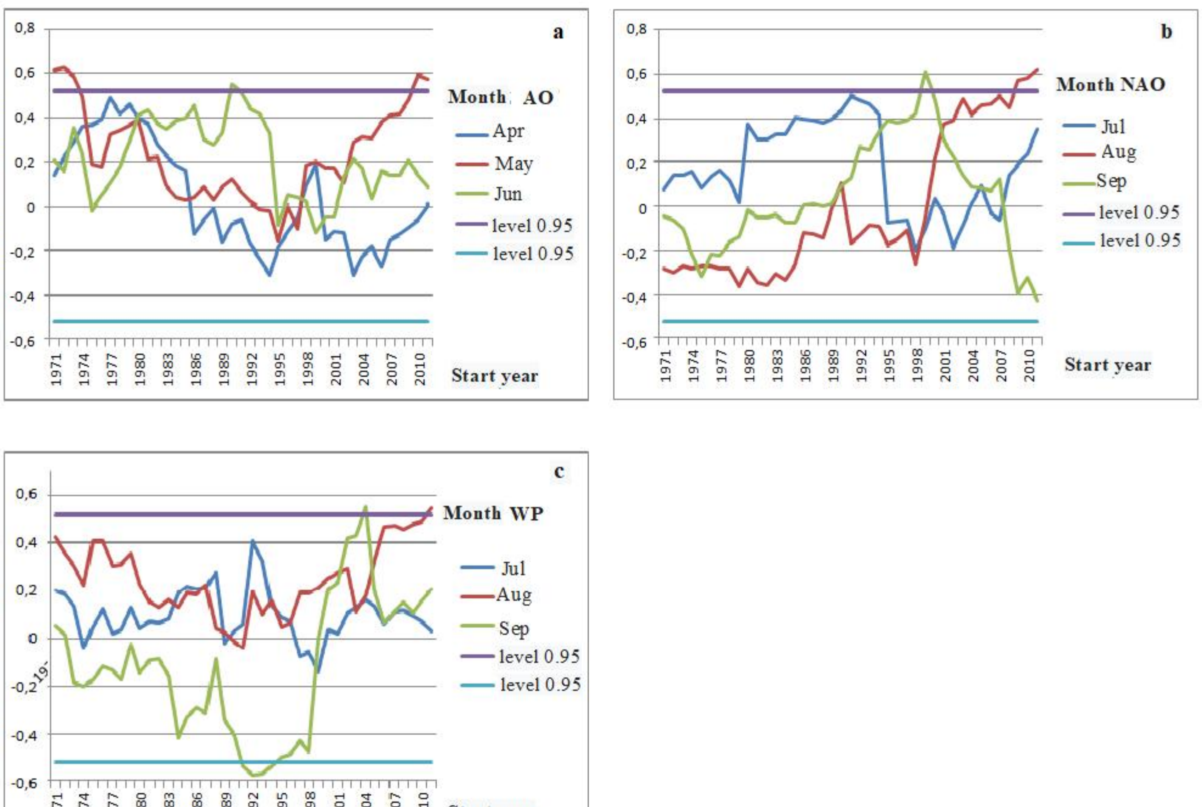


Figure 4. Dependences of the correlation coefficient of the studied processes on time intervals of 15 years on the year of the beginning of these intervals

a) MAT_G (June) and AO; b) MAT_G (August) and NAO; c) MAT_G (July) and WP;

As follows from Figure 4a, the relationships between changes in the AO index for May, as well as the preceding variations in the MATG for June (shift of 11 months) over 15-year time periods starting from 1993–2011, changed in general in the same direction. Moreover, in the period 2011-2025, the correlation of these processes is positive and significant (with a reliability of at least 0.95).

As can be seen from Figure 4b, a similar conclusion regarding the relationships between changes in the NAO index for August, as well as the preceding variations in the MATG for August (12-month shift) over 15-year time periods starting from 1998–2011, is also valid.

Figure 4c shows that the same conclusion is also true for the relationships between changes in the WP index for August, as well as the preceding variations in the MATG for July (a 13-month shift) over 15-year time periods starting from 1989–2011.

The significant correlation between the WP series for 2011-2025 and the MATG is also positive.

From Figure 4 it is clear that for the period 2000-2025 the identified trends in changes in the studied relationships can be approximately considered as stable.

Similar properties are inherent in the relationships between each of the studied processes and variations in the MATG for any summer months; however, the relationships under consideration are significant only for the specified months.

Consequently, Figure 4 allows us to conclude that, at least in the 21-st century, the connections between interannual changes in the MATG for July–August with lagging variations in the AO, NAO, and WP indices have steadily strengthened. The latter means that in the period under consideration the amplitudes of the components of variability of each of these processes increased with periods of 1 year.

The reason for the strengthening of the MATG -AO and MATG -NAO links is the increase in the amplitude of the signal generated by changes in the MATG. This signal is the intra-annual variability of the average water temperatures delivered by the North Atlantic Current to the corresponding ocean regions.

This phenomenon also led to an increase in the amplitudes of the components of the variability of the AO and NAO with a period of 1 year, which caused an increase in the impact of the AO on the WP, and also strengthened the response of this process, which is characterized by the same period.

With further warming of the climate in Greenland, not only the amplitude of this signal will increase, but also its duration, since the time interval in which the Labrador Current brings highly freshened water to the Grand Banks of Newfoundland, as noted above, will also expand.

From a comparison of Figure 3a and 4a it follows that as a result of an increase in the MATG that occurred in the summer of a certain year, an increase in the AO occurs more frequently in the summer of the following year in 2011–2025, which is a consequence of cooling in the Arctic. Consequently, due to the existence of the AMOC, changes in the MATG are regulated by negative feedback, which restrains further increase in the growth rate of this indicator.

The presented results indicate that modern climate warming has already led to changes in the characteristics of the relationships between interannual changes in the MATG for the summer months, with variations in the AO, NAO, and WP indices lagging behind them by 10–13 months.

In the initial stages of these processes, corresponding to the 1990s, stable and significant connections between them existed only in isolated cases, but now they exist and are strengthening. This can be easily verified by examining Figure 5, which shows the dependence of the correlation coefficient of synchronous segments of 15 members in length in the time series of the NAO and AK for the months of May–July in the year of their beginning.

Figure 5 shows that for June, the relationships between the synchronous 15-term intervals of the NAO and AO time series were significant throughout the entire period under consideration. Moreover, for intervals beginning in 2003–2011, the correlation between them increases.

For May, the relationships between the series under consideration are significant and gradually strengthen over the periods beginning in 1993–2011. For July, they exhibit the same properties over the periods beginning in 2000.

With further warming of the climate in Greenland, which, as a result of the identified negative feedback, will apparently also occur gradually, the duration of the period of intensive melting of its ice cover (and the intensity of this process) will increase. This will cause an increase in the amplitude of the annual components of the intra-annual variability in the average water temperature delivered by the North Atlantic Current to the oceanic regions involved in the formation of the NAO and AO. The time periods during which the phases of these oscillations are close will likely decrease.

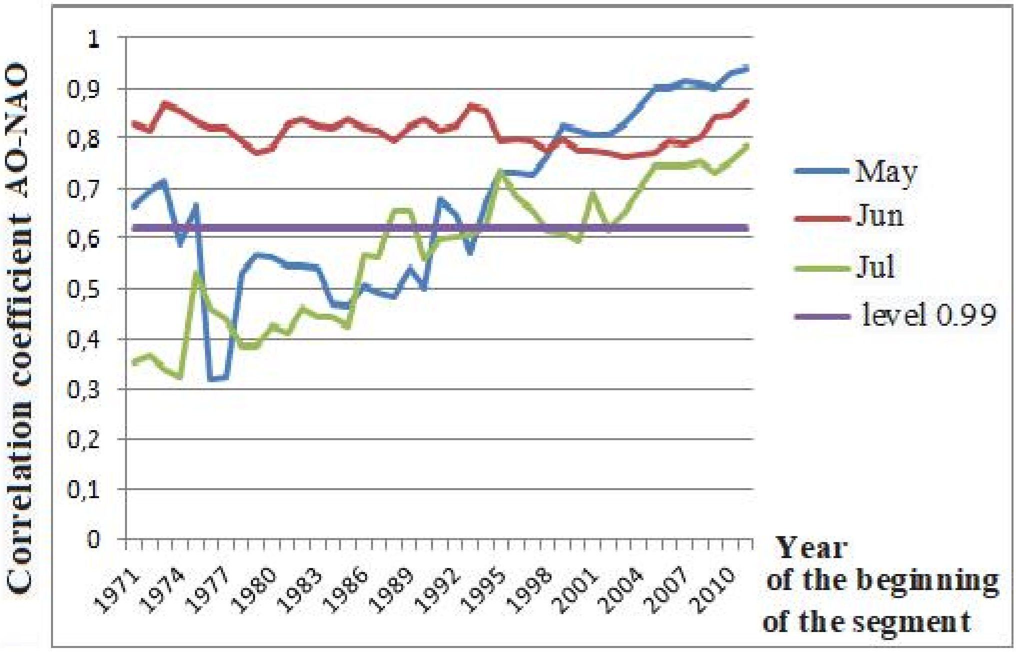


Figure 5. Dependencies of the correlation coefficient of synchronous segments of 15 members in length of the time series of the NAO and AO, for the months of May–July in the year of their beginning.

Taking into account the mechanism of the relationship between the AO and the WP, an increase in the amplitude of the components of intra-annual changes in the AO index with a period of 1 year will apparently lead to a further strengthening of similar components of the WP.

The question is whether these changes will have a significant impact on the changes in the MPT and MAT in various parts of Siberia and adjacent Asian countries?

To answer this question, the second problem was solved, which consisted of assessing the significance of the relationships between interannual variations in the MATG (for the summer months), as well as the AO, NAO and WP (for the identified months), with changes in the MPT and MAT for the months of April–October that occurred in certain areas of the territory of the megaregion under consideration.

Taking into account the identified patterns, such an assessment was carried out for various time periods of 15 years in length, relating to the 21-st century.

3.2. The Teleconnections Between Changes in Mpt, and Matg, ao, Nao and Wp

As a result of the study of the relationships between interannual variations in the MATG (for the summer months of the previous year) with changes in the MPT for the months of April–October, it was established that in the territories of Siberia and adjacent Asian countries there are numerous areas for which they were significant in 2011–2025, and have steadily increased over the 21st century.

The values of the ratios of the total area of the identified sites to the total area of the studied megaregion are given in Table 1.

	Manth MPT (next year)						
Manth MAT_G	April	May	June	July	August	September	October
June	0,109	0,159	0,146	0,229	0,105	0,092	0,071
July	0,134	0,196	0,142	0,172	0,108	0,0811	0,062
August	0,247	0,171	0,098	0,138	0,111	0, 087	0,067

From Table 1 it is clear that the areas for which the connections between interannual variations in the MATG with the changes in the MPT that precede them in time in 2011–2025 are significant, and have steadily increased over the 21st century, exist for all months of the fire-hazardous season. Moreover, their total area is maximum for April (with a delay of 8 months) and almost reaches 25% of the entire area of the mega-region (provided that changes in the MATG for August are taken into account).

The values of this indicator are also increased for May (almost 20% with a lag of 10 months) and July (23% with a lag of 13 months).

Table 2. presents the values of the ratios of the total area of the sites for which the relationships between the interannual variations of the AO and NAO, with changes in the MPT, coinciding with or lagging behind them in time, are significant in 2011–2025, and have steadily increased over the 21st century.

Table 2. Values of the ratios of the total area of sites for which the relationships between interannual variations in AO and NAO, with changes in MPT, coinciding with or lagging behind them in time, are significant in 2011–2025, and have steadily increased over the 21st century.

	AO						
Shift, month	April	May	June	July	August	September	October
0	0,170	0,232	0,169	0,125	0,260	0,153	0,086
1	0,134	0,143	0,135	0,140	0,207	0,147	0,111
2	0,150	0,178	0,239	0,129	0,144	0,093	0,067
	NAO						
0	0,082	0,239	0,136	0,131	0,161	0,129	0,085
1	0,104	0,173	0,125	0,136	0,219	0,134	0,096
2	0,101	0,132	0,150	0,141	0,130	0,095	0,063

As follows from Table 2, within the studied megaregion there are numerous areas of the earth's surface where the required properties are possessed by the relationships between the interannual variations of the AO and NAO for any month of the fire-hazardous season, with changes in the MPT that coincide with them in time or lag by 1-2 months. For AO coinciding with the MPT, such segments are most numerous for August and May. When the MPT series lags by one month, they are more numerous for August, and when it lags by two months, they are more numerous for June.

For NAO index changes synchronous with MPT variations, the target areas are larger for May. For a one-month shift between them, the target areas are larger for August, and for a two-month shift, the target areas are larger for June.

It is easy to see that for the studied mega-region, in terms of the number of areas in which the influence of the NAO and AO on changes in MPT is currently significant and is increasing in the 21-st century, these factors are almost equivalent.

For all months, which correspond to the considered changes in the MATG, AO and NAO, as well as the MPT, the locations of their sections for which the connections between these processes have the mentioned properties are determined.

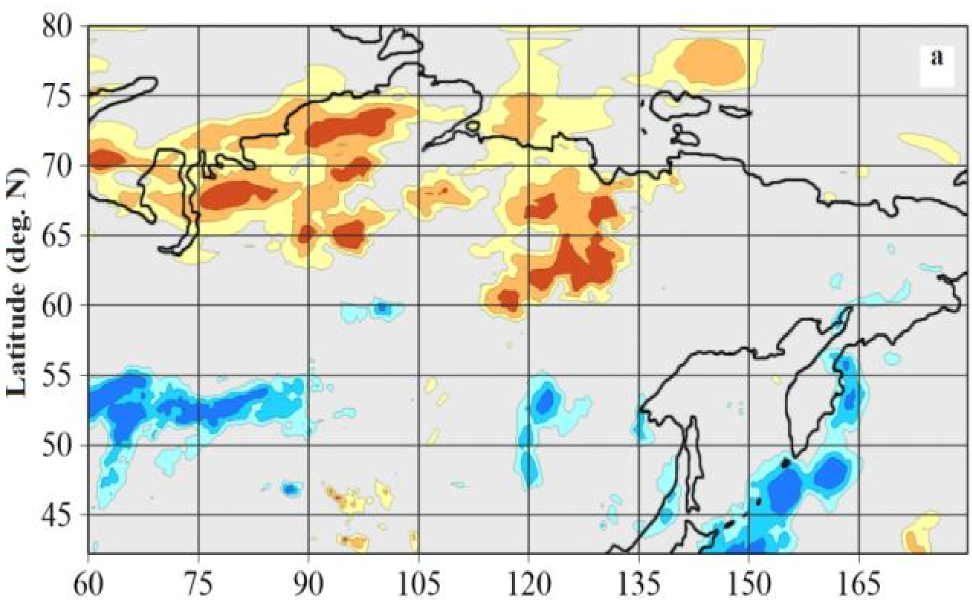
As an example, Figure 6 shows the identified areas of Siberia and the Asian countries bordering it, where the connections between the interannual variations of the MATG for August, with the lagging changes in the MPT for April and May in 2011-2025, are significant, and have steadily increased over the 21-st century.

From Figure 6a it follows that in the territory of the studied megaregion there are numerous areas where the correlation of interannual variations of the MATG for August, with lagging changes in the MPT for April in the 21st century, has steadily increased, and in 2011-2025 it is significant and positive. Such areas predominate in the Yamalo-Nenets Autonomous Okrug, the Taimyr, Turukhansk and Evenki districts of the Krasnoyarsk Territory, and many districts (uluses) of the Sakha Republic (Yakutia).

In the identified areas, with an increase in the MATG for August, the MPT values for April increase, which leads to an increase in the thickness of the snow cover formed on them.

The same process leads to a decrease in MPT and an increase in fire danger due to weather conditions in the territories of Chelyabinsk, Kurgan, Omsk, Novosibirsk, Irkutsk and Sakhalin regions, Krasnoyarsk, Kamchatka, Khabarovsk and Primorsky Territory, as well as in many areas of Kazakhstan, China, Mongolia and Japan.This is evidenced by the location of the areas shown in the same figure, where the significant correlation of the processes being studied is significant and negative.

From Figure 6b It is evident that in the territory of Siberia there are also areas where the correlation of interannual variations of the MATG for August, with lagging changes in the MPT for May in the 21st century, has steadily increased, and in 2011-2025 it is significant and positive.



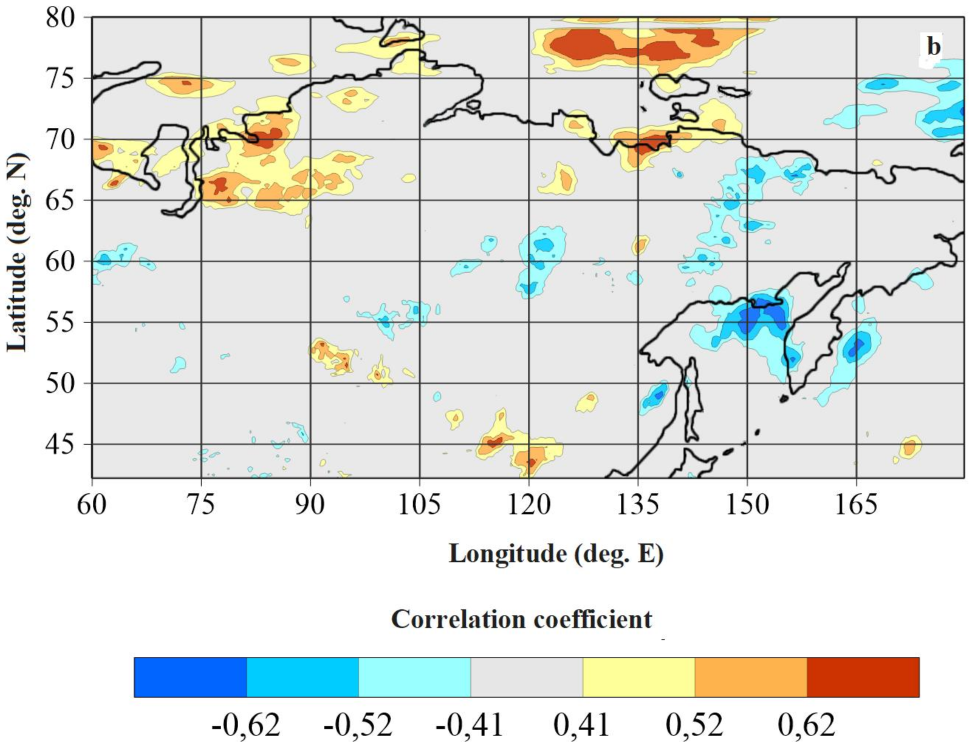


Figure 6. Areas of Siberia and neighboring Asian countries where the relationships between interannual variations in the MATG for August and lagged changes in the MPT in 2011–2025 are significant and have steadily strengthened over the 21st century.

a) April; b) May

Areas where the correlation between the processes under study in the modern period is significant and positive also predominate in northern Siberia. These areas include the Nenets and Yamalo-Nenets Autonomous Okrugs, the Yakutia and Komi Republics, and Krasnoyarsk Territory. Similar areas are also found in the People's Republic of China and Mongolia.

Areas where the correlation between the processes under study is both significant and negative were also identified. These areas are located in Yakutia.

Similarly, it was established that the relationships between interannual changes in the MATG for other summer months with lagging variations in the MPT for all months of the fire-hazardous season are characterized by the same patterns.

Areas, where MPT increases with increasing MATG, are clustered in northern Siberia, while areas where MNC decreases are clustered in the southern part of the region. The locations of these identified areas and their total area depend on the months corresponding to the MATG and MPT time series under consideration.

Figure 7 shows areas of Siberia and adjacent Asian countries where the relationships between interannual changes in the MPT index for August and variations in the AK index for August and July for the period 2000–2025 increased and were significant in 2011–2025.

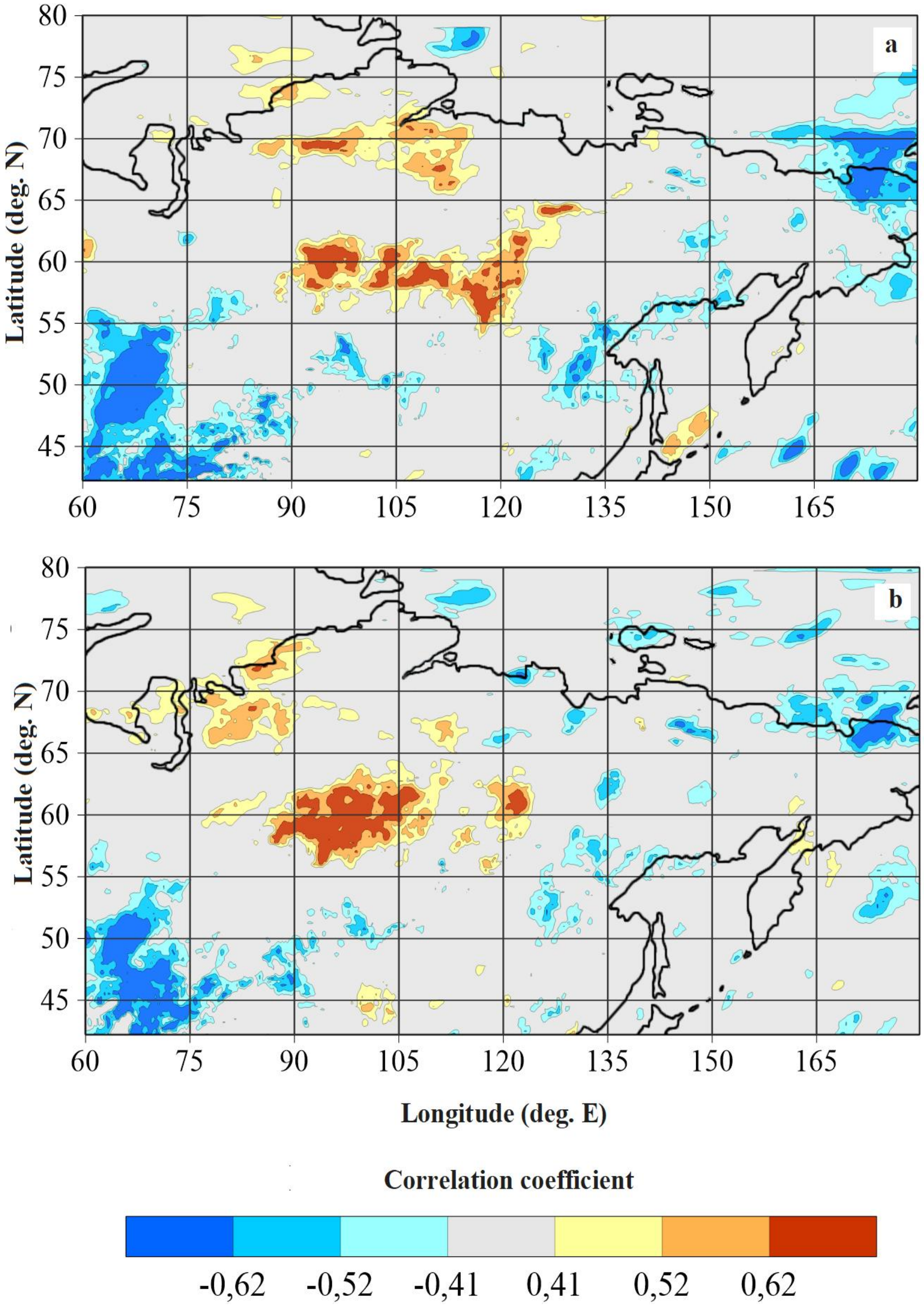


Figure 7. Surface areas of the studied megaregion where the relationships between interannual changes in the MPT for August and variations in the AO index for August and July increased over the period 2000–2025, and were significant in 2011–2025.

a) AO corresponds to August; b) AO corresponds to July.

From Figure 7a it is evident that the areas where the correlation of synchronous interannual changes in the MPT for August with variations in the AO for August for the period 2000–2025 increased, and in 2011–2025 was significant and positive, belong to the territory of Krasnoyarsk and Zabaikalsky Territory, Irkutsk Region and Yakutia.

Areas where the correlation of the same processes had similar properties, but was significant and negative, are located in the south of the megaregion under consideration. They cover the Chelyabinsk, Kurgan, Omsk, and

Novosibirsk Regions, Khabarovsk and Primorsky Territory, Kazakhstan, and China. Similar areas are also found in the north of Siberia - in the territory of Yakutia and the Chukotka Autonomous Okrug.

From Figure 7b it is clear that the areas where the correlation of interannual changes in the MPT for August with variations in the AO for July over the same period increased, and in 2011 – 2025 was significant and positive, belong to the territory of Krasnoyarsk Territory, Irkutsk and Tomsk Regions, Khanty-Mansi Autonomous Okrug and Yakutia.

From a comparison of Figure 6 and 7 it is clear that the general layout of the areas where the correlation of the processes being studied is positive or negative does not change in both examples.

Figure 8 shows the surface areas of the region under consideration, where the relationships between interannual changes in the NAO index for the months of June and July with variations in the MPT, lagging in relation to them by 1 month, have increased during the 21-st century and were significant in 2011–2025.

From Figure 8a it follows that the areas where the correlation of interannual changes in the MPT for July with variations in the NAO index for June for the period 2000–2025 increased, and in 2011–2025 was significant and positive, belong to the territory of Krasnoyarsk Territory and Yakutia. Areas for which a significant correlation of the same processes had the same properties, but was negative, were found in the Kamchatka, Khabarovsk and Altai Territory, the republics of Altai, Khakasia, Tyva, Yakutia, Novosibirsk, Kemerovo and Sakhalin Region.

Figure 8b shows that the areas where the correlation of interannual changes in the MPT index for August with variations in the NAO index for July for the period 2000–2025 increased, and in 2011–2025 was significant and positive, belong to the territories of Krasnoyarsk, Kamchatka, Zabaikalsky Krai and Yakutia, as well as the Yamalo-Nenets Autonomous Okrug and China.

Areas for which the significant correlation of the processes under consideration had similar properties, but was negative, were also found. They are located on the territory of the Republics of Altai, Khakassia, Tyva and Yakutia, and also belong to Khabarovsk Territory, Chukotka Autonomous Okrug, Chelyabinsk, Kurgan, Omsk, Magadan, Novosibirsk, Kemerovo and Amur Regions.

Figure 9 shows the locations of areas of Siberia for which the relationships between interannual changes in the WP for June and July 2010–2024, with synchronous variations in the MPT, were significant, and for the period 1971–2024 there was a steady increase in them.

From Figure 9a it follows that for June in the territory of Siberia and adjacent Asian countries there are numerous areas for which the connections between the studied processes for the period 2000-2025 were strengthened, and for the time interval 2011-2025 they were significant.

At the same time, there are areas where the significant correlation of the processes under consideration was positive and areas where it was negative.

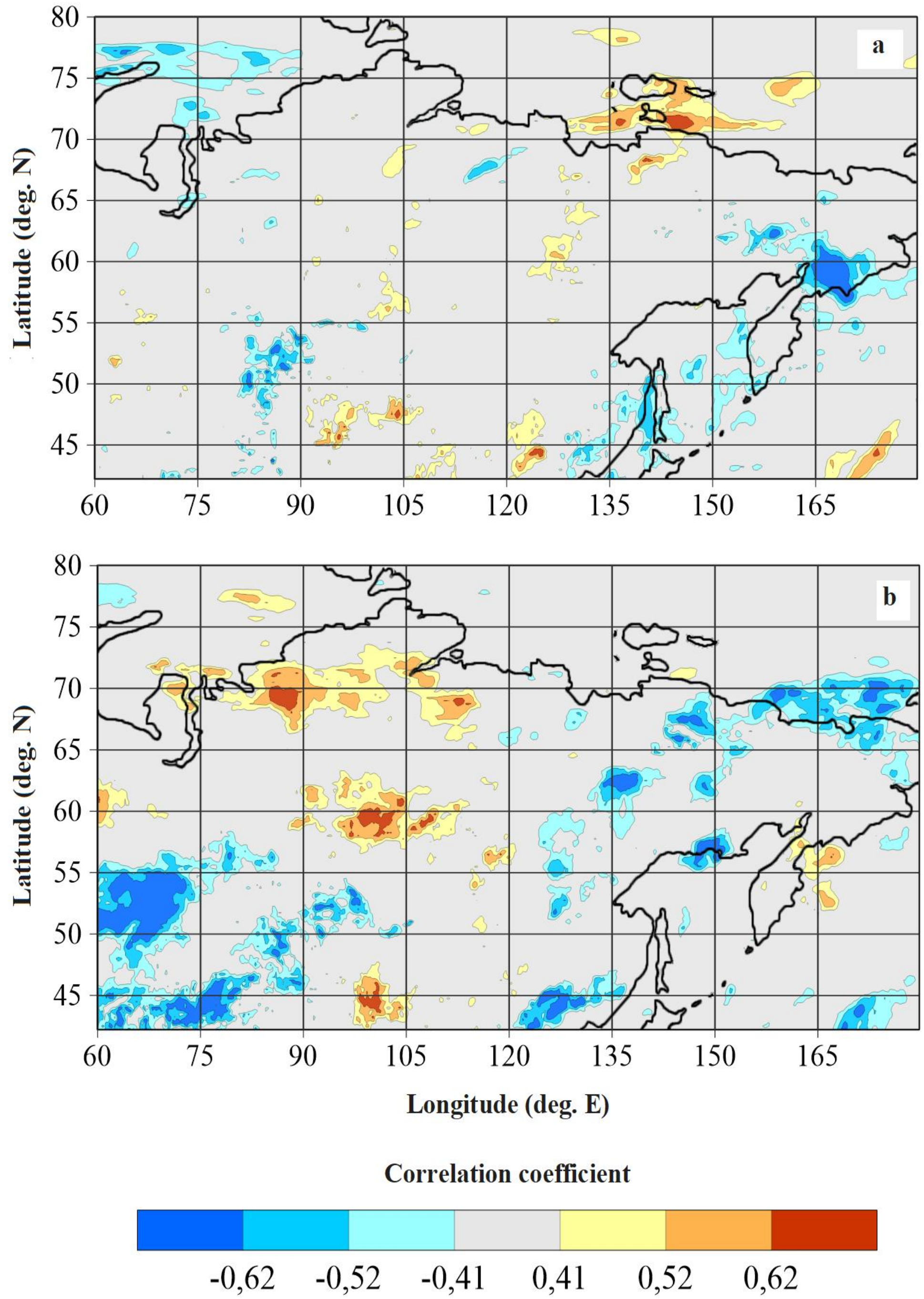


Figure 8. Surface areas of the studied megaregion where the relationships between interannual changes in the MPT index for June and July and variations in the AO index for August and July increased over the period 2000–2025, and were significant in 2011–2025.

a) AO corresponds to August; b) AO corresponds to July.

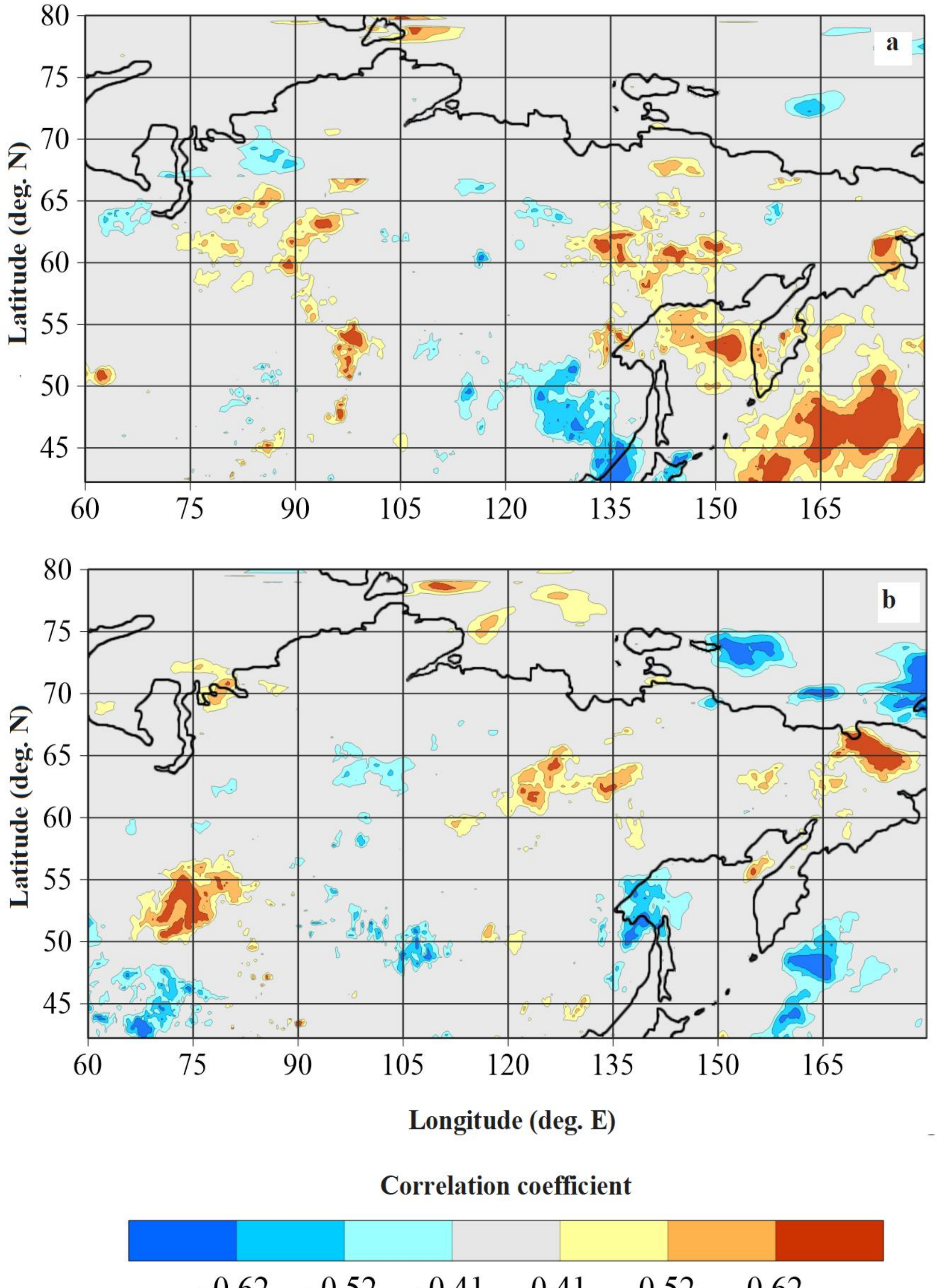


Figure 9. Areas of Siberia and adjacent Asian countries where the relationships between interannual changes in the MPT for 2011–2025 and synchronous variations in the WP were significant, and where they increased for the months of 1979–2024:

a) June; b) July

In the first, MPT changes in the identified months are close in phase to the WP variations (and therefore to the AO, NAO, and MAT_G variations), while in the second, they are practically out of phase with these variations. Opposite MPT changes are likely in the identified areas during the remaining months of the year.

As can be seen from Figure 9a, the positive correlation between the studied processes for June in 2011-2025 is significant for many areas of the territory of the republics of Sakha (Yakutia) and Tyva, Krasnoyarsk, Khabarovsk and Kamchatka Territory, Kemerovo and Magadan Regions.

In the identified areas, the increase in MPT coincides with increases in MAT_G, AO, and NAO. A decrease in MPT in these areas occurs during periods when the values of the WP index and other indices under consideration become negative.

As noted above, this is precisely what is happening now with an increase in the MAT_G and a weakening of the AMOC, which causes a decrease in the MPT in the corresponding months and an increase in the fire danger in the specified territories.

The negative correlation between the processes under consideration in June from 2011 to 2025 is significant in several areas of the Sakha Republic (Yakutia), Khabarovsk and Primorsky Territory, and Sakhalin, Chelyabinsk, and Irkutsk Regions. In these areas, variations in the MSO are out of phase with changes in the MAT_G.

In these areas, during periods of time when fire risks increase in the areas mentioned above, there is an increase in risks associated with excessive precipitation (including high floods and inundations on rivers, and flooding of territories in low-lying areas).

From Figure 9b it is clear that for July, in the territory of Siberia and adjacent Asian countries, areas were also found for which the connections between interannual changes in the MPT with synchronous variations in the WP during the period of modern climate warming increased, and for the modern period 2010-2024 they were significant.

Moreover, the positive correlation between them is significant for many areas of the Sakha Republic (Yakutia), the Yamalo-Nenets Autonomous Okrug, and the Tyumen, Novosibirsk, Omsk, and Tomsk regions.

In the identified areas, the increase in MPT for June coincides with the increase in the MAT_G and the weakening of the AO. A decrease in MPT in these areas occurs during periods when the WP index values become negative and the AO index values become positive.

The negative correlation between the processes under consideration is significant in several areas of Krasnoyarsk and Khabarovsk Territory, and Sakhalin, Chelyabinsk, and Irkutsk Region. In these areas, changes in the MPT for June are out of phase with changes in the MAT_G.

Thus, from Figure 6-9 it follows that in the territory of Siberia and adjacent Asian countries there are areas in which the changes in the MPT for the identified summer months in 2011-2025 are significantly correlated with the variations in the MAT_G, AO, NAO and WP that precede them by the corresponding time. Moreover, the links between these processes have steadily strengthened in the 21st century.

In areas where significant correlation between the processes under consideration is currently positive or negative, changes in the MPT in the identified months occur in phase or antiphase with the variations under consideration. In other months, in such areas, the relationships between the phases of the same processes are opposite.

In earlier time periods of the same duration, the total areas of the areas of Siberian territory where the connections between the interannual changes in the MPT for the same months and the synchronous variations in the WP were significant and had increased in the past were significantly smaller, although many of them retained their location. It follows from this that with a further strengthening of the studied connections (which will occur with a further increase in the MAT_G for the corresponding month), an increase in the total area of its sections where these connections will be significant is likely. The location of such sites will likely remain close to their current location.

3.3. The Teleconnections Between Changes in Mat, and Matg, Ao, Nao and Wp

Studies of the relationships between interannual variations in the MATG (for the summer months of the previous year) with changes in the MAT for the months of April–October have established that in the territories of

Siberia and adjacent Asian countries there are numerous areas for which they were significant in 2011–2025, and have steadily increased over the 21-st century.

The ratios of the total area of the identified sites to the total area of the study region are presented in Table 3.

Table 3. Ratios of the total area of sites where the relationships between interannual variations in the MATG and changes in the MAT have steadily increased over the 21-st century and are significant in 2011–2025 to the total area of the study region.

Manth MAT_G	Manth MAT (next year) April	May	June	July	August	September	October
June	0,066	0,186	0,280	0,141	0,194	0,325	0,162
July	0,252	0,088	0,216	0,083	0,281	0,200	0,118
August	0,108	0,182	0,023	0,072	0,168	0,087	0,063

From Table 3 it follows that areas for which the connections between interannual variations in the MATG with the MAT changes that precede them in time in 2011–2025 are significant, and have steadily increased over the 21st century, exist for all months of the fire-hazardous season. Moreover, their total area is maximum for September (with a lag of 15 months) and almost reaches a third of the entire area of the mega-region (provided that changes in the MATG for June are taken into account). The values of this indicator were also increased for April (almost 25% with a 9-month delay), June (28% with a 12-month delay) and August (28% with a 13-month delay).

Table 4 contains the values of the ratios of the total area of the sites for which the connections of the interannual variations of the AO, NAO and WP with changes in the MAT, coinciding with or lagging behind them in time, are significant in 2011–2025, and have steadily increased over the 21-st century.

Table 4. Values of the ratios of the total area of sites for which the relationships between interannual variations in AO, NAO and WP with changes in MAT were significant in 2011–2025, and have steadily increased over the 21-st century.

Shift, month	April	May	June	July	August	September	October
AO							
0	0,169	0,157	0,027	0,088	0,095	0,428	0,073
1	0,290	0,256	0,098	0,055	0,066	0,051	0,007
2	0,279	0,254	0,049	0,058	0,044	0,006	0,004
NAO							
0	0,057	0,198	0,064	0,108	0,176	0,066	0,013
1	0,519	0,157	0,076	0,055	0,049	0,017	0,009
2	0,312	0,206	0,238	0,070	0,050	0,178	0,006
WP							
0	0,586	0,387	0,130	0,201	0,373	0,151	0,005
1	0,243	0,126	0,232	0,256	0,101	0,107	0,004
2	0,210	0,265	0,075	0,118	0,128	0,052	0,005

From Table 4 it is clear that the relationships between the factors under consideration and the variations in the MAT have the required properties for a significant number of areas in the studied megaregion.

Such plots account for at least 50% of the MAT connections for April and the NAO for March (the shift between series is 1 month), as well as for the MAT and WP connections for April (the shift between series is zero). For more than 40% of all plots, synchronous MAT and AO connections for September are significant.

The areas of Siberia, adjacent Asian countries and the waters of the seas adjacent to them, for which the connections between the MAT, as well as the MATG, AK, NAO and WP have the mentioned properties, were identified for all the months under consideration.

Fig 10 shows, as an example, the identified areas corresponding to the relationships between interannual changes in the MAT for June and September with variations in the MATG for June.

From Figure 10a it is clear that in the territory of Siberia and the waters of the seas adjacent to it, among the areas where the synchronous connections of the interannual changes in the MAT and MATG for June in 2011-2025 were significant, and have steadily increased over the 21-st century, those for which the correlation of these processes was negative predominate. Such sites are located in the territories of the Taimyr District of the Krasnoyarsk Territory, the Anabar, Olenek, Bulun, Ust-Yansky Alaikhovsky and Nizhnekolymsky uluses of the Republic of Sakha (Yakutia), the Chukotka Autonomous Okrug, the Transbaikal and Kamchatka Territories, the Amur Region, as well as Mongolia and China. For many of the identified areas, the conclusion about the significance of the relationships under consideration is characterized by a reliability of at least 0.99.

Figure 10b shows that numerous areas were found on the surface of the studied megaregion for which the relationships of interannual changes in the MATG for June, as well as variations in the MAT for September (lagging behind them by 15 months), have the same properties. Among them, areas where the significant correlation between these processes is negative predominate. Such areas include the republics of Khakassia, Tyva, and Buryatia, the Trans-Baikal and Krasnoyarsk Territory, the Amur and Irkutsk Regions, as well as Mongolia and China.

Figure 11 shows the identified regions corresponding to the relationships between interannual MAT variations for April and NAO variations for April and March.

Figure 11a shows that regions of Siberia where synchronous relationships between MAT and NAO time series exhibited the required properties were identified only in Yakutia, Kazakhstan, and China.

Figure 11b shows that the total area of the Siberian territory for which the correlation of interannual changes in the MAT for April with variations in the NAO index for March (1 month shift) has increased in the 21st century and is significant in 2011–2025 is significantly larger.

Such sites have been discovered in all regions of Russia belonging to the Siberian Federal District, as well as in many areas of the Yamalo-Nenets, Khanty-Mansi, Chukotka and Nenets Autonomous Okrugs, Sverdlovsk, Tyumen, Magadan and Amur Region, Transbaikal, Khabarovsk and Primorsky Territory, as well as Mongolia and China.

In all such areas, MAT increases during positive phases of the NAO for the specified months, which contributes to increased fire danger there.

No areas were found where a significant negative correlation for these same processes was observed in the entire studied megaregion.

The areas of Siberian territory for which the connections between interannual AO changes increased in 1979–2025, with the MAT variations lagging behind them by 1 month for the months of April and May, which were significant for 2011–2025, are shown in Figure 12.

As follows from Figure 12a, there are numerous areas in Siberia where the positive correlation of interannual changes in the MAT for April with variations in the NAO index for March (1 month shift) increased over 2000–2025, and was significant in 2011–2025.

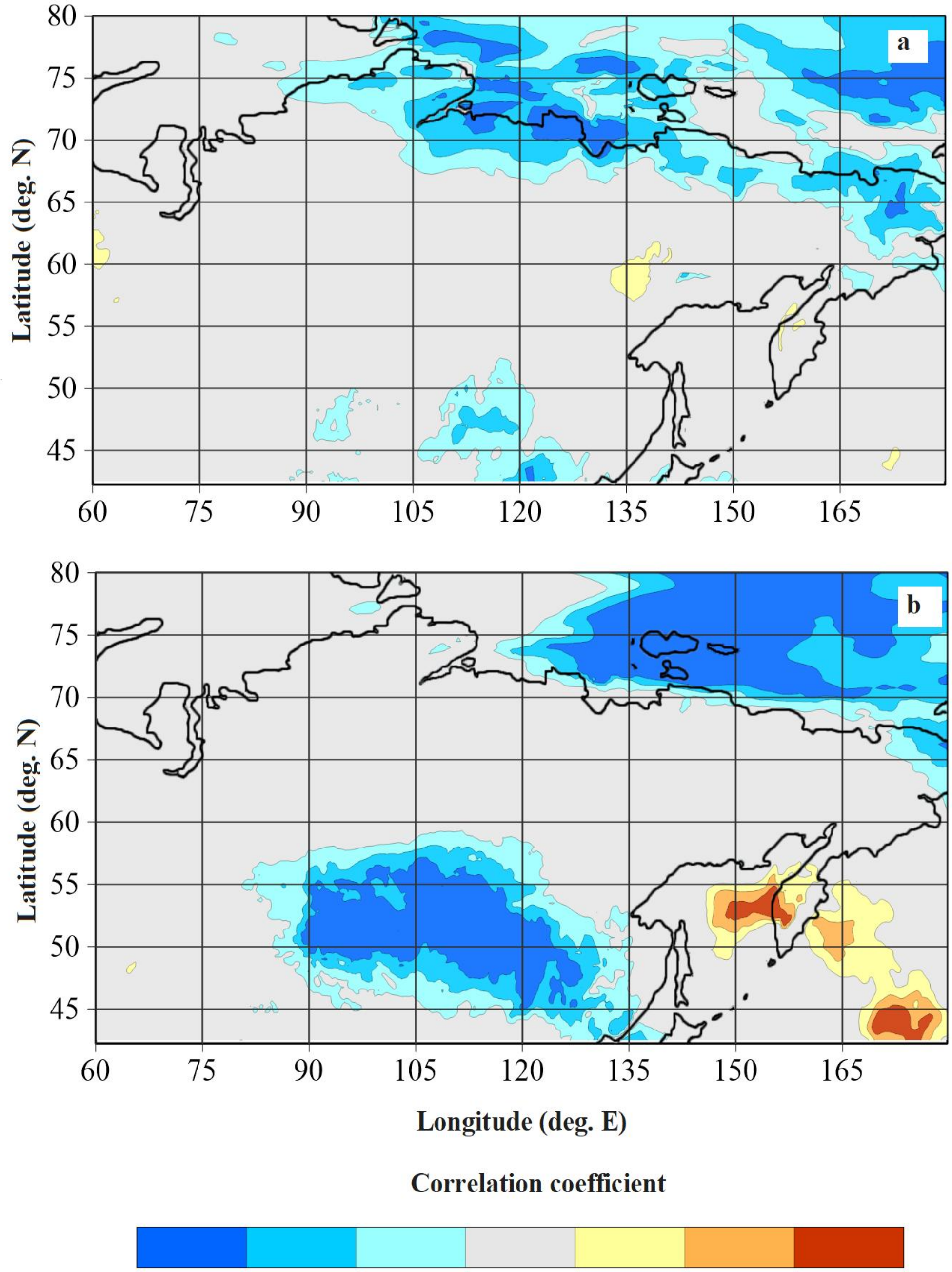


Figure 10. Surface areas of the studied megaregion where the relationships between interannual changes in the MAT_G for June for 1979–2024 increased and were significant for 2010–2024, with lagging MAT variations for the months:

a) June; b) September.

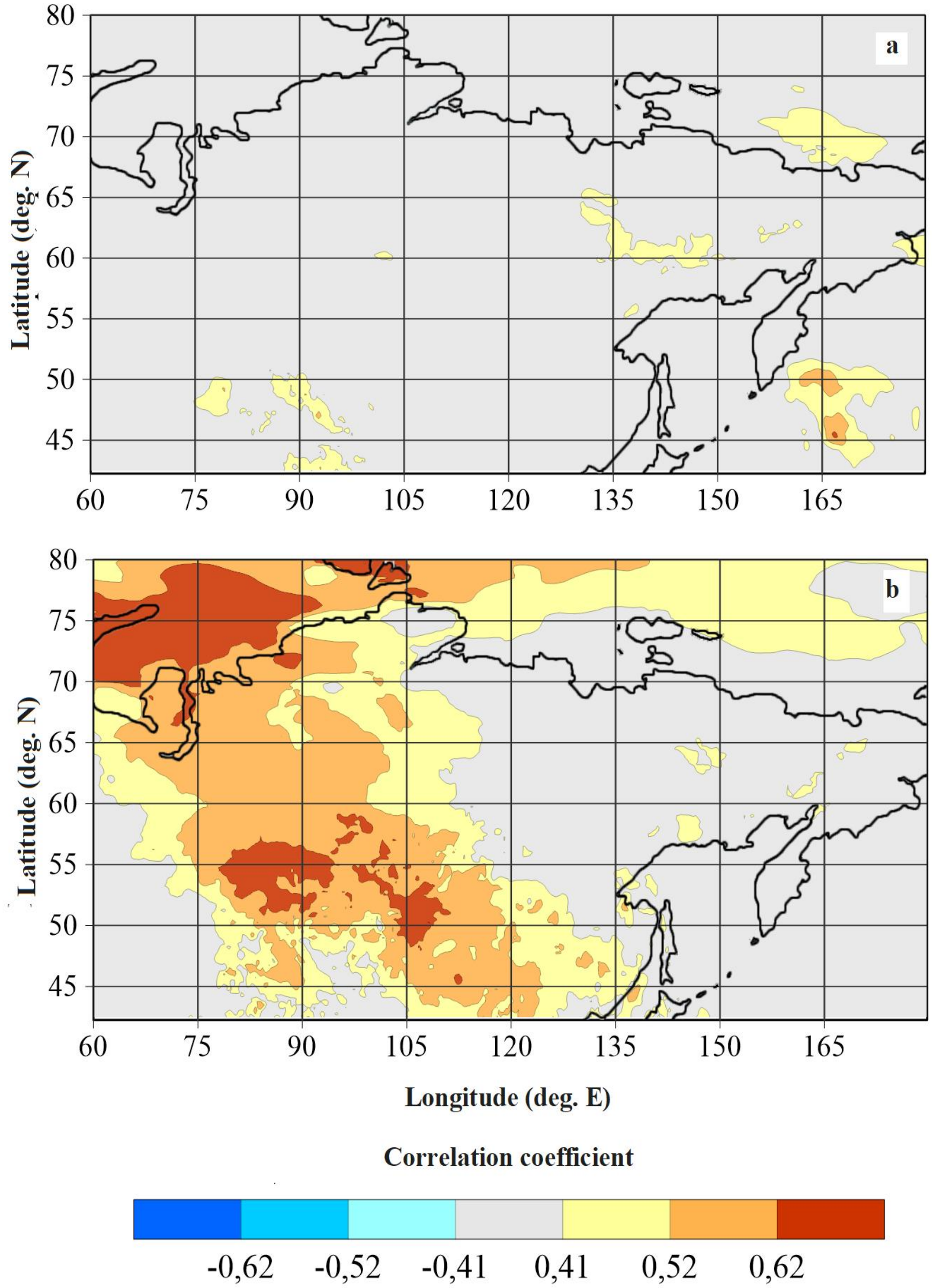


Figure 11. Areas of Siberia for which the relationships between interannual MAT variations for April for 1979–2025 increased and were significant for 2011–2025, with lagging NAO variations for the months: a) April; b) March.

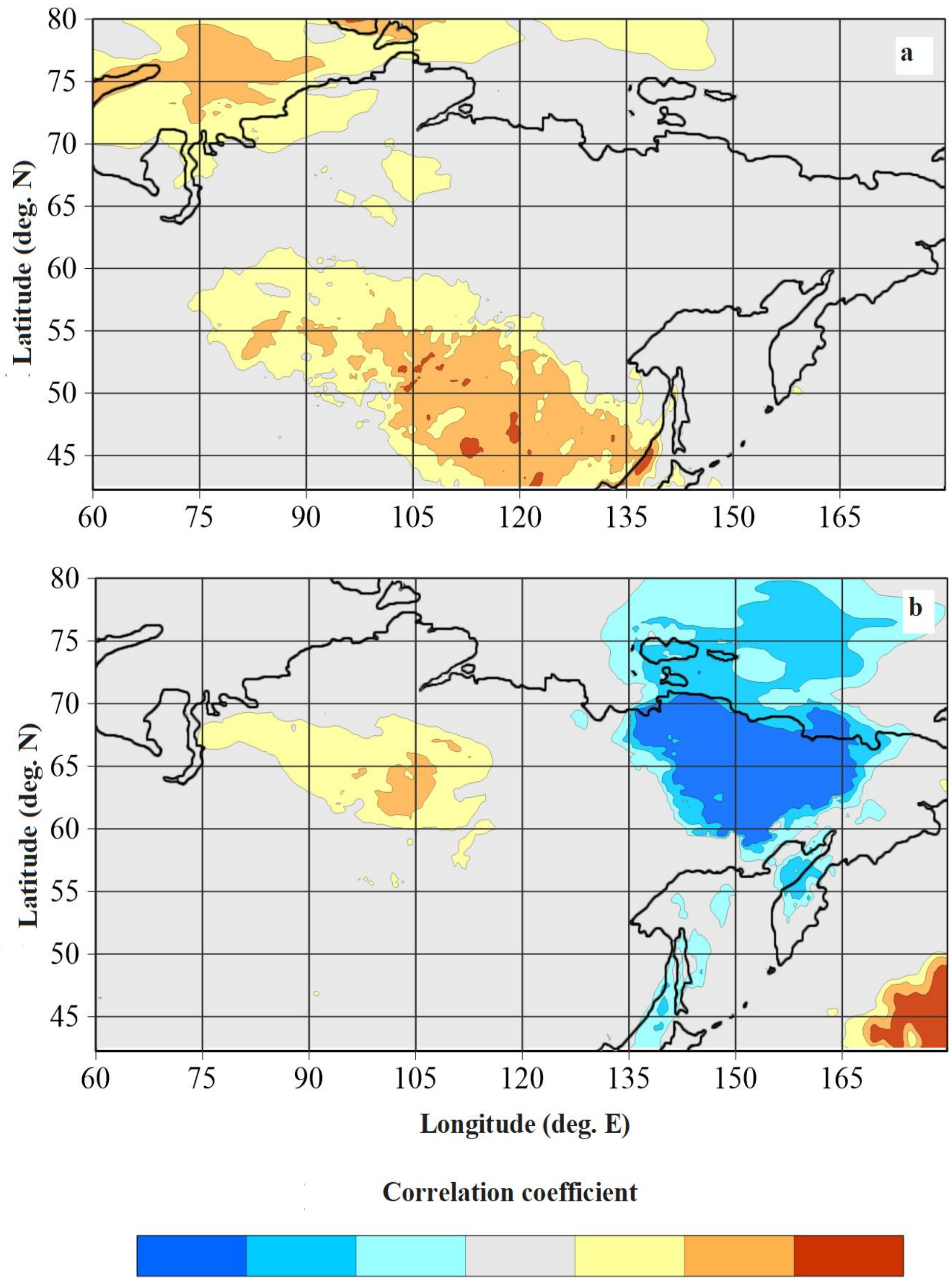


Figure 12. Areas of Siberia for which the relationships between interannual AO changes for April and March, lagging by one month with MAT variations that were significant for 2011–2025, have strengthened over 1979–2025:

a) April; b) March.

These areas belong to the territories of all regions of the SFD, the Yamalo-Nenets Autonomous Okrug, Yakutia, Primorsky and Khabarovsk Territory, as well as the territories of China and Mongolia.

Areas where the connections between the same processes had the properties in question, but their correlation was negative, were not found in the entire studied mega-region.

As we can see from Figure 12b, the areas of Siberian territory for which the correlation of interannual changes in AO for April with variations in MAT for May increased for 1979–2025, and was significant and positive for 2011–2025, were identified in the territory of the Yamalo-Nenets Autonomous Okrug, Krasnoyarsk Territory and the Sakha Republic (Yakutia).

Areas where the significant correlation of the same processes for 2011-2025 was negative are located in Yakutia, Kamchatka and Primorsky Territory, as well as Sakhalin region.

The areas of Siberian territory for which the synchronous connections between the interannual changes in the WP for the months of April and May increased in 1979–2025, with the variations in the MAT that were significant for 2011–2025, are shown in Figure 13.

As can be easily seen from Figure 13, for all areas presented in it, for which the correlation of the processes being studied had the indicated properties, it was negative.

Figure 13a shows that in April, such areas cover the entire territory of Eastern Siberia, and also include the Sakha Republic (Yakutia), the Chukotka Autonomous Okrug, and Kamchatka and Khabarovsk Territory. Similar areas have been found in Kazakhstan.

Figure 13b shows that for May the areas under consideration predominate in the territory of Yakutia, and are also identified within the Taimyr (Dolgano-Nenets) region of Krasnoyarsk Territory, Transbaikal Territory and Amur Region.

Areas were also identified where the same processes intensified in the 21-st century and showed a significant positive correlation between 2011 and 2025. These areas are located in the Khanty-Mansi Autonomous Okrug, Tyumen, Tomsk, Novosibirsk, Kemerovo, and Omsk Region, as well as Kazakhstan and Japan.

Therefore, when developing long-term and ultra-long-term forecasts of MPT and MAT for the identified areas of the surface of the studied mega-region, it is advisable to take into account the interannual changes of all the studied processes that correspond to the identified months.

3.4. The Forecast of Further Changes in Fire Danger in Siberia

In solving the third problem, the following was established.

As follows from [40,44], as a result of further warming of Greenland's climate, the volume of meltwater flowing from its glaciers into the North Atlantic will increase in summer.

This will lead to a decrease in the average salinity of the waters delivered by the Labrador Current to the Grand Banks of Newfoundland in early autumn. As a result, the period of time during which the density of these waters will be lower than that of the Gulf Stream will increase [39].

Since the melting of the Greenland ice sheet practically ceases in the fall, the salinity and density of Labrador waters entering the Grand Banks region in late fall, as well as in winter and spring, will continue to increase annually to levels close to modern ones [44,45].

At any time of the year in the specified region of the Atlantic there will be layers in which the density of the Gulf Stream waters is equal to the density of the surface waters of the Labrador Current [20]. In such layers, when the aforementioned waters merge, as now, thermohaline intrusions will form [46,48].

Since the temperatures of the Labrador waters are significantly lower than those of the surrounding Gulf Stream waters, heat exchange occurs between the two waters at the boundaries of the intrusions. This gradually increases the temperature of the Labrador waters, leading to a decrease in their density.

As a result, such waters rise to the surface, forming numerous thermals, secondary intrusions and submesoscale eddies [49,50], and the cooled Gulf Stream waters sink, forming

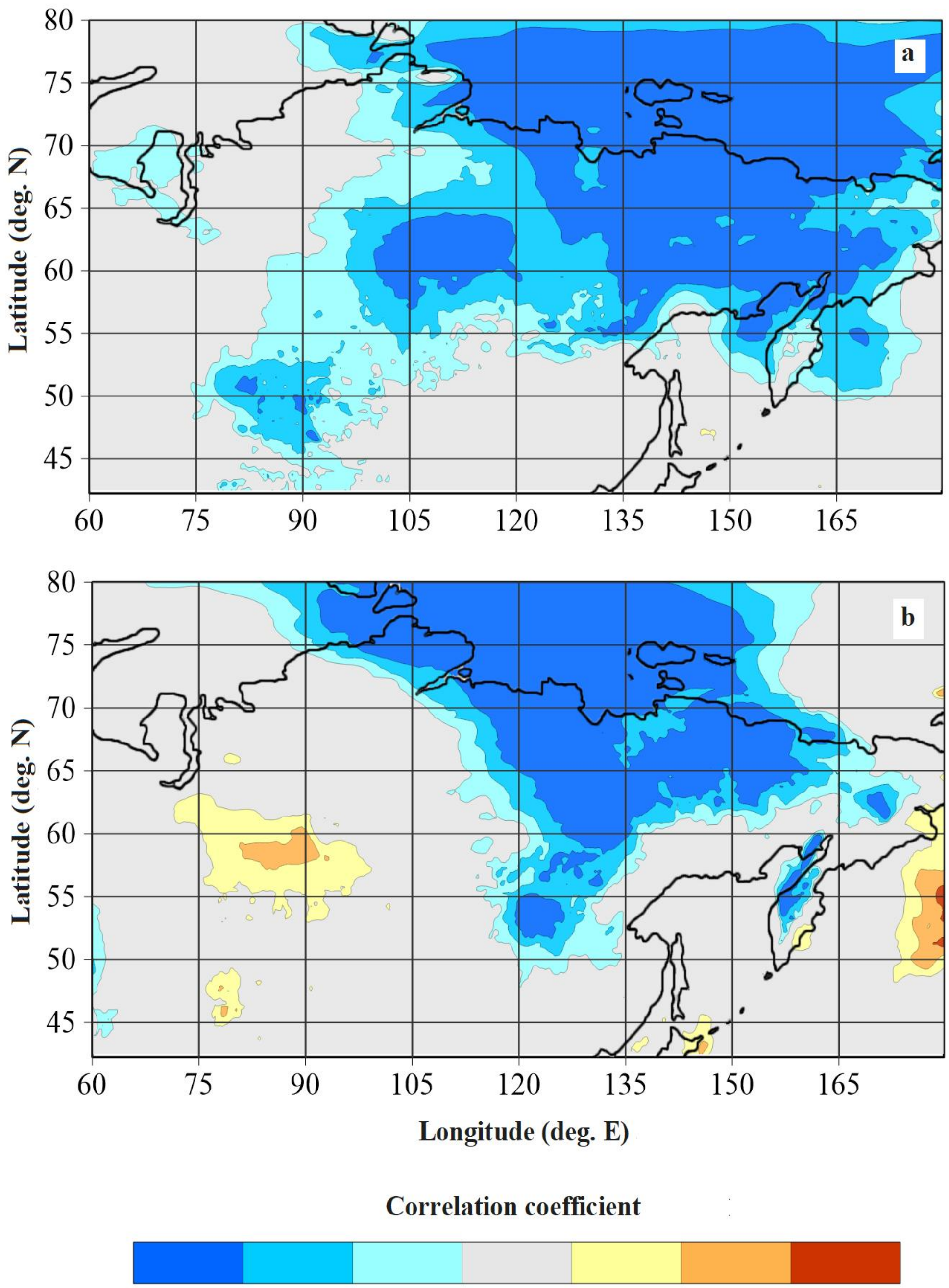


Figure 13. Areas of Siberian territory for which, over the period 2000–2025, synchronous relationships between interannual changes in the TCZ and variations in the STV that were significant for the period 2011–2025 increased for the following months:

a) April; b) May.

deep convection [51]. After some time, the warmed and less saline Labrador waters end up directly on the surface of the North Atlantic. They form a region in the surface layer of the oceanic region under consideration that is carried by the North Atlantic Current to the northeast.

At the same time, its waters are subject to turbulent mixing in the upper quasi-homogeneous layer of the North Atlantic and the influence of numerous eddies that form the North Atlantic Current [50].

As a result, as the region moves toward the shores of Europe, its size increases, and the surface temperatures of the waters that form it rise. An anticyclone forms over the region (and moves with it), bringing Arctic air into the temperate latitudes [52].

The same thing will happen in the future, but as Greenland's climate warms, the area will become larger and its average surface temperatures will be lower. The average annual salinity of the waters carried by the North Atlantic Current will decrease as the average salinity of the waters of the Labrador Current decreases [39,53].The salinity of the latter, as now, will become minimal at the beginning of autumn [44], but the time interval when Labrador waters with increased freshening enter the region of the Grand Banks of Newfoundland, as the Arctic climate warms, will end later and later (and its duration will increase) [54,55].

Consequently, one of the results of further warming of the Greenland climate for the summer months will be an increase in the amplitude of intra-annual fluctuations in the surface temperature of waters carried by the North Atlantic Current and entering the oceanic regions involved in the formation of the NAO and AO.

These oscillations are the signal that still drives these processes. Since this signal will be amplified by Greenland's warming climate, the responses to it from the NAO, AO, and WP will also become more intense.

These responses manifest themselves as increases in the amplitudes of the components of these processes with annual periods. Therefore, the links between interannual changes in the MAT_G and variations in the NAO, AO, and WP indices will strengthen with further warming of Greenland's climate.

As a result of the discovered negative feedback, the warming of the climate of Greenland, as well as the Arctic as a whole, with further warming of the global climate, will occur at an increasingly slower pace. However, it is likely that the volume of meltwater formed in the summer when its ice cover melts will, as it does now, increase.

The consequence of this process will be an increase in the amplitude and duration of the maxima of the specified signal, which annually affects the processes under study, causing an increase in their components with a period of 1 year, as well as a positive correlation between them.

The duration of pauses between its maxima will decrease with further warming of Greenland's climate.

The ratio between their durations will shift in favor of the maxima, but these changes will occur gradually. Similarly, further weakening of the AMOC will occur, and the periods of prevalence of negative phases of the NAO and AO, as well as the seasons of decrease and increase of MPT (or MAT) in the identified areas of Siberia will change. The dangers in such areas associated with these processes will be caused not only by a significant decrease (or increase) in MPT or MAT, but also by a sharp change from the dry season to a season characterized by excessive moisture.

As established when solving problems 1 and 2, in the past, no significant relationships were observed between changes in the MAT_G, as well as variations in the NAO, AK and WP.

As a result, the correlation between their responses to these changes in the MAT_G was weak, and the combined effect of these responses to changes in the MAT and MPT in Siberia, as well as in the neighboring Asian countries, did not lead to an increase in the amplitude of the latter.

With further warming of the climate in Greenland, the links between the processes under consideration will gradually strengthen, which will also increase the consequences of their combined action.

As a result, in the identified areas, intra-annual changes in meteorological conditions will likely become increasingly contrasting in different months, and hazardous meteorological phenomena may occur more frequently, which is extremely dangerous for the population, the economy, and wildlife.

As follows from the above, at the current stage of climate warming in Greenland, the weakening of the AMOC is occurring precisely according to this scenario, which can logically be called “mild”. Under this scenario, the volumes of meltwater generated in the summer are relatively small. Breakthroughs of Labrador waters to the surface of the North-Atlantic Current are short-lived and localized, and therefore do not lead to catastrophic consequences.

However, the amplitude of the components of temporal variability of surface temperatures of the corresponding regions of the Atlantic gradually increases with a period of 1 year.

The above allows us to predict that with further warming of the climate in Greenland, changes in fire danger due to weather conditions in the identified areas will continue according to the same scenario in the future.

The duration of time periods in which the connections between changes in the MAT_G and variations in the AO, NAO, and WP over time periods of the same duration will gradually increase, causing corresponding changes in the MPT and MAT in the identified territories, as well as the likelihood of landscape fires.

Due to the strengthening of the detected negative feedback with further warming of the Greenland climate, the transition from the "soft" scenario of development of the process under study to a catastrophic one (corresponding to the collapse of the AMOC [35-37]) seems unlikely.

Since, if the current scenario for the development of the processes under study is maintained in the future, changes in the MPT and MAT, as well as variations in the MAT_G, will likely occur gradually, the population of Siberia and neighboring countries, their economies, as well as fire departments, have the opportunity for early adaptation.

As follows from the above, the proposed forecast of further changes in the AMOC, NAO, AO, WP, as well as MAT, MPT and fire hazard in Siberia can only be realized under the condition that the warming of the climate in Greenland continues and the ice cover remains on its territory.

Thus, it has been established that the proposed hypothesis is valid and the stated objectives have been achieved. Consequently, the study's objective has been achieved.

4. Discussion of the Results

As follows from the obtained results, they are fully consistent with existing ideas about the influence of climate change in Greenland on the intensity of deep convection in the Labrador and Irminger Seas [29,30,53,56], as well as on variations in the state of the AMOC [3,20,39,43].

They also confirm the validity of the conclusions [10,57] about the connection between the AMOC and the NAO and AK, as well as the AK with the WP [12,18], with the dynamics of the MPT, MAT and fire hazard in the territories of Siberia [11,15,58].

At the same time, some of the established facts possess significant scientific novelty.

4.1. Facts That Have Been Established for the First Time

These include the following provisions:

4.1.1. The ongoing warming of Greenland's climate has not only weakened the AMOC but also strengthened the links between the MAT_G and changes in the NAO, AO, and WP states, as well as the MNC and STV during the identified months in some regions of Siberia and neighboring Asian countries. These links are already significant for the 2011–2025 period.

4.1.2. An increase in the MAT_G leads to an increase in the amplitude of the intra-annual variability of the temperatures of the near-surface layer of waters in the North Atlantic waters through which the North Atlantic Current and the Irminger Current pass, as well as the amplitudes of the annual components of the temporal variability of the NAO, AO and WP, which are almost synchronous.

4.1.3. As a result of the strengthening of the positive correlation between the interannual changes in the MAT_G and AO, in 2011–2025 the negative feedback acting due to the AMOC and regulating the rate of climate warming in Greenland and the Arctic became significant.

4.1.4. The scenario under which the processes under study are currently developing and the AMOC is weakening appears to be "soft." It allows for the possibility of timely adaptation of the populations of the identified regions, their economies, and firefighting units to the described process.

4.2. Recommendations

The results indicate that in the 21-st century, fire hazard in Siberia is increasingly determined by global climate processes in the North Atlantic and Arctic. This requires a revision of forecasting approaches and improvements to monitoring processes such as the MAT_G, AMOC, NAO, AO, and WP.

The results of such monitoring are necessary for the development of long-term and ultra-long-term forecasts of MPT, MAT, and fire hazard in Siberia, as well as in the territories of neighboring Asian countries.

The results indicate that the trend toward increasing fire hazard in the identified areas of Siberia and adjacent Asian countries could continue for decades, even if global warming is contained. To reduce the risks to the population and economy of the identified regions of Russia caused by this process, timely development of adaptation measures is necessary.

5. Conclusions

Thus, the obtained results confirm the validity of the proposed hypothesis.

5.1. The existence of numerous areas of Siberia has been established where warming in Greenland for the summer season in the period 2010-2024 had a significant impact on the interannual variability of monthly precipitation amounts for the months from April to August. Among the identified areas, there are those where, during this process, the fire danger in forests increased due to weather conditions, and areas where it decreased.

5.2. The connections between the processes under consideration have strengthened in the 21-st century. As a result, their combined impact on fire hazard in the identified regions may lead to a resonant increase in fire hazard.

5.3. The increase in fire danger caused by the process under consideration, based on weather conditions in the identified areas, will occur in the coming decades according to a "mild" scenario, which is already underway. The collapse of the Atlantic Meridional Overturning Circulation is extremely unlikely.

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Data Availability

Data supporting the findings of the published article can be obtained from [39] publicly available sources.

Conflicts of Interest

The author declares that he has no conflict of interest.

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