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Research Article

Greenland Warming Drives Weakening of the Atlantic Meridional Overturning Circulation and Amplified Fire Hazard in Northern Europe

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KEYWORDS

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warming of thermal regime
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ABSTRACT

One of the reasons for the change in fire danger associated with weather conditions in any part of Europe is the corresponding variations in average monthly surface air temperatures, as well as monthly precipitation. The factors, causing these variations, include changes in the state of the Atlantic Meridional Overturning Circulation, which has tended to weaken since the mid-19th century. This trend is driven by Greenland's warming climate, which is increasing the volume of cold freshwater flowing from its glaciers into the North Atlantic. A hypothesis has been put forward about the existence of areas in Europe for which the links between the aforementioned fire hazard factors and changes in average summer temperatures across the entire surface of Greenland have increased during the period of modern climate warming and are now significant. Testing this hypothesis showed, that such areas exist in the territories of some regions of Europe that belong to the Forest and Arctic zones. It has been established that with further warming of the climate in Greenland, the fire danger in such regions will continue to increase during the spring months. The proposed forecast corresponds to a scenario in which the ice cover on the territory of Greenland remains, and the current “soft” stage of weakening of the circulation in question does not turn into a “catastrophic” one. Therefore, it is advisable to take it into account when planning the further development of fire services and agriculture in Europe.

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1. Introduction

Interannual changes in average monthly surface air temperatures (MAT) over a given region of the world, as well as monthly precipitation totals (MPT) for that region, corresponding to the months of the fire season, are among the main factors determining fire risk in terms of weather conditions and forest combustibility in the region [1-3]. These factors also significantly affect changes in the safety of the population's livelihoods, the sustainability of economic development, and the risks posed by certain dangerous natural phenomena. Therefore, improving methods for long-term and ultra-long-term forecasting of the processes under consideration is a pressing issue not only for meteorology and climatology, but also for emergency safety.

1.1. Relevance of the Topic

The solution to this problem is of greatest interest to regions where the total number of landscape fires occurring per year (hereinafter referred to as NLF) has been increasing at the fastest rate in recent years. These include many regions of Europe, including the European Territory of Russia (hereinafter ETR), belonging to the Forest and Arctic zones. As an example, Figure 1 shows the time dependencies of the NLF for the entire territory of Russia, for its European and Asian parts, the territories of the Central (CFD), North-Western (NWFDO), Volga (VFD) Federal Districts belonging to the aforementioned ETR zones, its Southern (SFD) Federal District, as well as some regions of the NWFD, CFD, and PFD, which are constructed based on data from [4]).

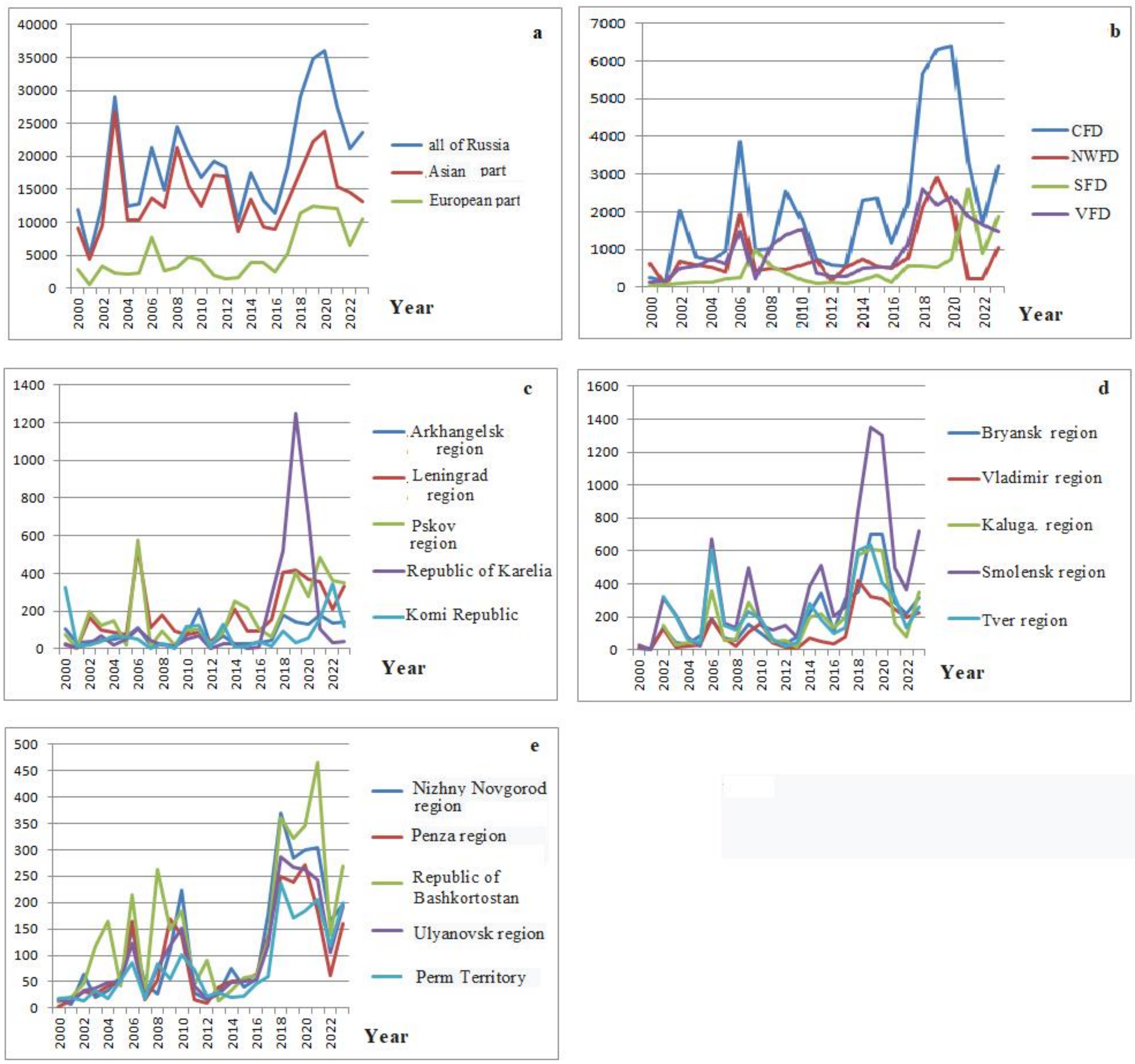

Figure 1. Changes in the 21-st century in the NLF in the following parts of Russia:

a) all of Russia, as well as the Asian and European parts of its territory; b) Federal districts of the ETR; c) regions of the NWFD; d) regions of the CFD; e) regions of the PFD.

Figure 1a shows, that during the period 2000-2023, both across Russia as a whole and in its Asian and European parts, changes in the NLF represented complex fluctuations, the amplitude and average of which increased over time. At the same time, the average values of the NLF for the period 2018-2023 exceeded the corresponding indicator for 2000-2017 for the whole of Russia by 1.78 times, for its Asian part by 1.37 times, and for the European part by 3.44 times.

The reasons for the fluctuating nature of the dependencies under consideration may be the cyclical nature not only of changes in the intensity of anthropogenic factors in the relevant territories and the accumulation of combustible material in them [5], but also of corresponding variations in fire hazard depending on weather conditions (including MAT and MPT [6,7]).

Figure 1b shows that changes in the NLF are also fluctuating in the territories of the Federal Districts of the ETR under consideration. As can be seen from Figure 1b, the average value of the NLF in the ETR in 2018-2023 significantly exceeded the level of this indicator for 2000-2017, mainly due to an increase in its value for the Central Federal District.

For the Central Federal District, whose territory is mainly located in the Forest Zone, the value of the indicator under consideration increased 3.2 times. The peak of the NLF for the Central Federal District corresponded to 2020. By 2023, the value of the NLF for the Central Federal District had decreased, but still exceeded the levels of this indicator corresponding to the Northwestern Federal District and the Volga Federal District, which belong to the Arctic and Forest zones, as well as the Southern Federal District, where the values of the indicator in question also increased in 2018-2023.

Figure 1c shows that among the various regions of Russia belonging to the Northwestern Federal District, the most significant increase in the average NLF value for the same years, compared to the specified period, was found for the Republic of Karelia (9.44 times). This indicator value for Karelia is higher than for any other region of Russia! The values of this indicator increased significantly for the Leningrad, Pskov, and Arkhangelsk regions, as well as the Komi Republic.

As can be seen from Figure 1d, the largest increase in the average NLF for the years under review was observed in the Smolensk region of the Central Federal District (6.34 times). The values of this indicator also increased significantly for the Bryansk, Vladimir, Kaluga, and Tver regions.

Figure 1e shows that the average values of the NLF for 2018-2023 relative to the same indicator for 2000-2017 increased most significantly for the Republic of Bashkortostan in the Volga Federal District (by 4.12 times).

Figure 1 shows that in 2018-2023, the NLF values increased most significantly in the ETR. This was mainly due to the intensification of the process under consideration in the ETR regions belonging to the Forest and Arctic zones. The increase in forest combustibility in these territories occurred despite the fact that the relevant firefighting units fought the emerging fires with all available forces and means, and the Russian Ministry of Emergency Situations did everything possible to support them and accelerate their development.

Increased fire risks are also occurring in the forests of many other European countries.

1.2. Analysis of Existing Ideas About the Subject of Research

The phenomenon under consideration was caused by both anthropogenic and natural factors, including an increase in fire hazard due to weather conditions caused by an increase in MAT or a decrease in MPT [3,8].

According to existing ideas about the causes of changes in the characteristics under consideration [9-11], the most important changes are considered to be those in atmospheric circulation over the entire European macroregion, as well as in the heat and moisture content of the air entering it, which depend on variations in the state of the Atlantic Meridional Overturning Circulation (AMOC) [6,12]. The latter is the most important component of the global ocean heat conveyor [13,14], ensuring the exchange of heat and salt between the tropical and subarctic zones of the North Atlantic.

The surface link of the AMOC is the Gulf Stream, the North Atlantic Current, and the Irminger Current, while its deep link is the current that carries cold, dense water formed by deep convection, which develops as a result of the cooling of their surface layers, southward from these areas.

An important role is played by the reduction during the fire season of the total duration of cyclones over the studied territories, which bring cloudiness and atmospheric precipitation to the ETR.

Cyclones passing over the ETR regions belonging to the Forest and Arctic zones are mainly formed over the North Atlantic [9,10], and their tracks are determined by the state of the North Atlantic Oscillation (hereinafter referred to as NAO) [15,16].

In the positive phase of the NAO, the tracks of such cyclones are shifted northward. During the fire season, this leads to a decrease in MAT and an increase in MPT in the north of the ETR, which causes a decrease in fire hazard in the Forest and Arctic zones due to weather conditions.

During the winter months, when the NAO is in its positive phase, the intensity of atmospheric precipitation increases in Crimea and Kuban, as the tracks of Mediterranean cyclones, which bring most of the atmospheric precipitation to these territories, shift northward. At the same time, in the Caucasus Mountains and on its Black Sea coast, precipitation is less frequent in winter.

During the negative phase of the NAO, Atlantic and Mediterranean cyclones shift southward. As a result, from April to October, the fire hazard increases in the Arctic and Forest zones of Russia due to weather conditions. In winter, there is less precipitation in southern Russia and more in the Caucasus, resulting in an increased risk of avalanches in the mountains and more frequent landslides on the Black Sea coast.

One of the reasons for changes in the state of the Arctic Ocean is variations in surface temperatures in the North Atlantic regions, over which the Icelandic Low forms [17]. These variations are caused by changes in the average temperatures of the waters brought to these regions by the corresponding currents of the North Atlantic Drift [18].

The more heat is released into the atmosphere by water delivered by the surface link of the AMOC, the lower the pressure in the Icelandic low and the more significant the northward shift of Atlantic cyclone tracks over Europe, the greater the heat and moisture content of the air masses entering the ETR.

Therefore, changes in the state of the AMOC and the NAO are a significant factors in weather conditions and fire hazard in many regions of Europe, as well as the ETR [12,19-21].

From the mid-19th century to the present day, changes in the state of the AMOC have been dominated by a trend towards its weakening, caused by global and regional climate warming [6,12].

The weakening of the AMOC led to a decrease in the average temperature of the surface layer of water over most of the North Atlantic and the Norwegian Sea, and to an increase in this indicator for many areas of the Greenland Sea, as well as areas of the Barents Sea north of Spitsbergen. It had the greatest impact on the dynamics of surface water temperature in the central part of the Irminger Sea, where the amplitude of the fluctuations caused by them in the 21st century reached 1.5–2°C [22].

Since the AMOC is an ocean current, its main quantitative characteristics include the flow rate and heat content of the water it transports. These characteristics are calculated annually based on the results of monitoring the variability of the speeds of the water transported by the AMOC and its temperatures.

The question of where exactly these characteristics should be measured is currently under debate.

According to [23], the intensity of the AMOC is determined by the variability of deep convection intensity in the Greenland Sea, while the authors [24-26] believe that a similar process in the Irminger Sea plays a major role here.

In [25,27,28], it is suggested that deep convection in the Labrador Sea plays a significant role in AMOC variability, but in [29, 30], it is claimed that this process has virtually no effect on the AMOC.

To assess the intensity of the AMOC in this way, the characteristics of currents in the North Atlantic region at 50–60° N are monitored, and the results form the OSNAP array.

OSNAP is an international program designed to continuously record transbasin heat, mass, and freshwater fluxes in the water column in the subpolar North Atlantic. The OSNAP observation system consists of two sections: one extends from southern Labrador to the southwestern tip of Greenland via the Labrador Sea entrance (OSNAP West), and the other from the southeastern tip of Greenland to Scotland (OSNAP East).

The observation system also includes underwater buoys (OSNAP floats) to track water transport pathways in the basin and assess the connectivity of currents crossing the OSNAP line.

Another method for estimating the intensity of the AMOC is used in [20,31]. It takes into account that the main reason for changes in the heat content of water carried northward from the tropical Atlantic zone is variations in the surface flow of this current. Therefore, the intensity of the AMOC is defined as the integral flow rate of currents carrying water from the tropical Atlantic zone to the north.

The flow rates of these currents are measured in the upper 1000 m layer of Atlantic waters passing through a zonal section corresponding to the 26.5° N parallel. The intensity of the AMOC is calculated based on the results of its monitoring, which has been carried out daily since 2004.

The obtained estimates of the integral AMOC flow form the RAPID array and are presented in [https://www.rapid.ac.uk/ rapidmoc/overview.php].

To estimate the AMOC conditions in earlier periods, various reconstructions of this process are used, one of which is described in [19].

As an example, Figure 2 shows changes in the AMOC anomaly relative to the period 1981-2010, which occurred between 400 and 2024, based on reconstructions by Caeser et al. (2018) [19]. It also shows the results of reconstructions of the process under study obtained by Thornally et al. (2018), Rahmstof et al. (2015), Sherwood et al. (2011), Smeed et al. (2018), Thibodeau et al. (2018), and Zanna et al. (2019).

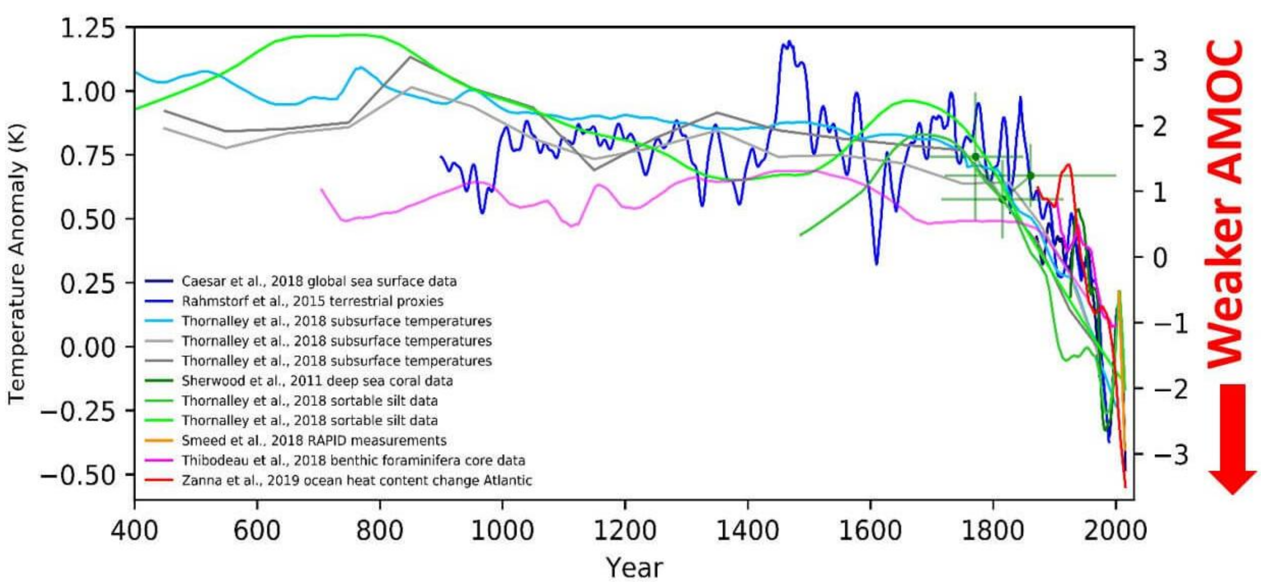

Figure 2. Changes in the state of AMOC during the period 400-2019, according to various authors, displayed in accordance with [33].

Figure 2 shows that between 400 and 2000 years, AMOS values exceeded the level corresponding to the period 1981-2010, resulting in the heat it delivered warming the northern regions of Europe. In the 20th and 21st centuries, AMOS has been weakening.

According to [6,19], immediately after the end of the Würm glaciation, AMOS was suspended for some time. At this time, the Heinrich event occurred, which led to a wave of cooling in the middle and high latitudes of the Northern Hemisphere lasting about 1,000 years (the so-called “Late Dryas”).

This event was caused by a decrease in the salinity of surface waters in the North Atlantic as a result of the influx of significant amounts of fresh water formed by the melting of the Laurentian Ice Sheet [32].

This led to the density of the water brought to the area of the Grand Newfoundland Bank by the Labrador Current becoming lower than the density of the water brought there by the Gulf Stream. As a result, the surface temperatures of the waters carried by the North Atlantic Current dropped significantly, causing the aforementioned cold spell in Europe and throughout the Northern Hemisphere.

Desalination of surface waters in the North Atlantic is also occurring in the modern period. It is caused by the warming of Greenland's thermal regime, which leads to an increase in the volume of meltwater formed in the summer months when its ice cover melts. This phenomenon weakens the AMOC and may have some influence on interannual changes in surface temperature (SST) and surface salinity SSO in the North Atlantic [6].

According to many authors [34-36], the process under consideration may lead not only to a weakening of the AMOC, but also to a sharp, nonlinear collapse of this current, which will occur after the onset of a “tipping point.”

This phenomenon could have catastrophic consequences for Europe. One of them could be a significant cooling in the ETR.

As can be seen in Figure 2, the process of AMOC weakening began as early as the 19th century, and in the 20th and especially in the 21st century, it has significantly intensified. The weakening of the AMOC continues today, which may contribute to a further increase in fire risk due to weather conditions in some regions of the ETR. Consequently, it could be one of the reasons for the increase in NLF in some regions of the ETR, as shown in Figure 1c-e.

1.3. The Hypothesis Put Forward

The facts presented allow us to put forward the following hypothesis:

- in the territories of the ETR regions belonging to its Forest and Arctic zones, there are areas for which interannual changes in MAT and MPT for any month of the fire season are significantly associated with variations in STP over Greenland, which precede them by several months; at the same time, the links between these processes have strengthened during the period of modern climate warming in Greenland.

The hypothesis put forward is not trivial, since the links between the processes under study may not be significant, and the question of their substantial strengthening during the period of modern climate warming in Greenland has not been studied before.

Confirmation of the validity of the proposed hypothesis would allow the identified links between the processes under consideration, which have the specified properties, to be taken into account when developing long-term and ultra-long-term fire hazard forecasts based on weather conditions in the relevant regions of Europe, for a scenario in which the warming of Greenland's thermal regime continues [8,37].

Since such forecasts are necessary for planning the activities of firefighting units, agricultural and forestry enterprises, testing the proposed hypothesis is of considerable theoretical and practical interest.

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

The aim of this work is to carry out such a verification and identify areas of Europe for which the statistical relationships between the processes under consideration possessed the required properties.

To achieve this goal, the following tasks were solved:

- to identify areas of Europe for which the relationships between interannual changes in the average summer season MAT over Greenland and variations in MAT and MPT for these areas and for any month of the fire season, lagging behind them by a few months, are significant.
- assessment of trends in the variability of the strength of the connection between the processes studied for the identified areas of the ETR during the period of modern climate warming in Greenland;
- development of qualitative forecasts of changes in fire hazard based on weather conditions in the Arctic and Forest zones of Russia for a scenario in which the warming of Greenland's thermal regime for the summer months will continue in the future, while its ice cover will remain intact.

2. Factual Material and Research Methodology

2.1. The Factual Material

In solving the first and second tasks, ERA 5 reanalysis data [38,39] was used as factual material, describing changes in average hourly air temperatures at a height of 2 m above the Earth's surface and hourly atmospheric precipitation totals for all points on our planet corresponding to the nodes of the Mercator coordinate grid, with a step of 0.25° x 0.25°, as well as for each hour in the period from 00:00 on January 1, 1940, to December 31, 2024.

Using this information, for each point relating to the area of the Earth's surface bounded by the meridians 0°W and 60°W, as well as the parallels 40°N and 80°N, including the entire ETR and the territories of many European countries, the STV and MSO values were calculated for each month of the fire season from 1950 to 2024. These values were used to form the time series under study.

Also, using information on average hourly air temperatures at a height of 2 m above all points in Greenland corresponding to the same coordinate grid, time series of average MAT values across the entire surface of the island (hereinafter referred to as MATG) were formed for the summer seasons of 1951-2024.

The resulting time dependence of MATG for the summer seasons, calculated using ERA 5 reanalysis data, is shown in Figure 3.

Figure 3 shows that a steady trend toward an increase in MATG ,o K for the summer seasons is observed in the period 1979-2024. Therefore, this period was further considered as the period of modern climate warming in Greenland.

2.2. Research Methodology

The value of the coefficient of their pairwise correlation (hereinafter referred to as K) was considered as a characteristic of the strength of the connection between the segments of the studied time series.

The decision on the significance of the identified connection was made if the reliability of such a statistical conclusion exceeded 0.9. Therefore, when solving the first problem, the correlation analysis method and Student's criterion were applied.

The relationships between segments of the MATG time series for the summer seasons of 2009-2023 were studied, as well as segments of the MAT and MPT time series for the months from March to August that lag behind them. The linear trend was compensated for in all compared segments. Based on the autocorrelation functions of the compared segments of the time series, it was established that the corresponding degrees of freedom are equal to 15.

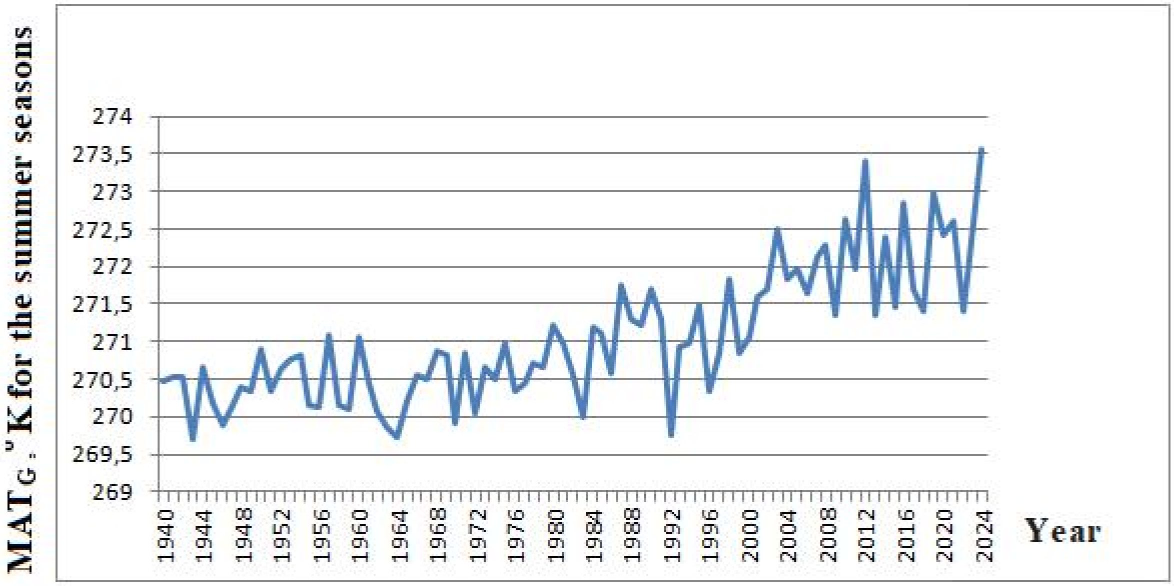

Figure 3. Changes in MAT_G, °K for the summer seasons of 1951–2024, calculated based on ERA 5 reanalysis data [39].

Therefore, the decision on the significance of the studied relationships was made if the value of the K module exceeded 0.4. The reliability of the same conclusion, not less than 0.95, corresponds to a threshold level of 0.52, and its reliability of 0.99 corresponds to a level of 0.62.

In solving the second problem, a method was used that involved calculating the values of K corresponding to segments of similar duration in the MAT and MPT time series for points in Europe and MATG that began in other years of the study period. These calculations were performed for each point on the Earth's surface in the European region and for each month from March to August.

From the K values established in this way, time series with a length of 32 members were formed, corresponding to the year of the beginning of the MAT or MPT series segment used in its calculation.

For each time series K, the value of the angular coefficient of its linear trend (hereinafter referred to as KLT) is determined.

It is assumed that the deviations of the members of each series K from the corresponding linear trend are random numbers with a Gaussian probability distribution.

The validity of this assumption was confirmed using Pearson's criterion.

The decision on the significance of KLT, with a confidence level of at least 0.95, was made if:

$$15*ABS(KLT) > 1.65*CKO$$

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

CKO is the standard deviation of the members of the series under study from the corresponding linear trend.

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

If K*KLT>0, a decision was made to strengthen the connection between the processes under consideration. Otherwise, a conclusion was made about the weakening of this connection.

The scenario for the development of the process under study and its factors was considered close to conservative [37,40] if the signs of KLT, which are calculated for segments of time series K, including their members with numbers 1-16 and 17-32 (corresponding to 1979-1994 and 1995-2024) coincided.

2.3. Previously Established Facts, That Were Taken into Account When Developing the Forecast

In addressing the third task, contemporary views on the impact of Greenland's warming climate on the weakening of the AMOC were analyzed. It was also assumed that the trends in K changes identified in the background of the processes under study would not change in the future.

It was taken into account that as Greenland's climate warms, the volume of meltwater flowing from its glaciers into the North Atlantic increases, and the density of the surface layer of water delivered by the Labrador Current to the Grand Newfoundland Bank area would decrease, approaching the density of a similar layer of water in the Gulf Stream [41,42].

Since the volume of meltwater formed on Greenland's ice sheets in summer is significantly greater than in other seasons, the salinity and density of Labrador waters flowing into the Grand Newfoundland Bank area are minimal in autumn, but in the winter months these indicators increase significantly [43,44].

At any time of the year in the specified area of the Atlantic, there are layers in which the density of the Gulf Stream waters is equal to the density of the surface waters of the Labrador Current [19]. In such layers, when the aforementioned waters merge, numerous thermohaline intrusions are formed [45-47].

Since the temperatures of the Labrador waters are significantly lower than those of the surrounding Gulf Stream waters, heat exchange occurs at the boundaries of the intrusions formed between them. At the same time, the desalinated Labrador waters gradually heat up, which leads to a decrease in their density. As a result, they rise to the surface, forming numerous thermals and submesoscale eddies [48,49].

After a while, these waters end up directly on the surface of the North Atlantic. As a result, an area of cooled and desalinated water forms in the surface layer of the North Atlantic, which is carried by the North Atlantic Current to the shores of Europe. Since there are numerous eddies in the structure of the North Atlantic Current [49], as this area moves northeast, its size increases and surface temperatures change. An anticyclone forms above this area (and moves with it), in which Arctic air enters temperate latitudes [50].

Since the upwelling waters are carried by the North Atlantic Current, the area of the North Atlantic where they first reach the surface is located northeast of the area where the waters of the aforementioned currents merge.

The waters of the Gulf Stream are saltier. As they cool, they become denser and therefore sink into the depths of the Labrador Sea, forming deep convection [51].

All other things being equal, the higher the salinity and density of the Labrador waters entering the area under consideration, the higher the temperature and salinity of the desalinated waters that rise to the surface, and the further northeast the area where these waters first reach the surface is located.

As a result of the warming of Greenland's thermal regime, the average annual salinity of the waters carried by the North Atlantic Current decreases, mainly due to the decrease in the average salinity and density of the waters of the Labrador Current [42,52].

This decrease is most pronounced in late summer and early autumn [43]. As a result of Arctic intensification, the melting of the Arctic Ocean ice cover is having an increasingly significant impact on the decline in these characteristics.

In the modern period, the density of the waters of the Labrador Current has almost equaled the density of the waters brought by the Gulf Stream [53,54]. The latter has led to a more significant decrease in the temperature and salinity of the surface waters of the area under consideration, which form in the corresponding months (to the levels of these indicators for the waters brought by the Labrador Current).

In autumn and winter, the average salinity and density of the waters of the Labrador Current increase as the melting of Greenland's glaciers becomes less intense. As a result, the salinity and density of the waters brought to the area in question by the Labrador Current also increase, and they reach the surface of the Labrador Sea in its eastern part. The temperature and salinity of the waters carried northeast by the North Atlantic Current increase.

As follows from the above, the solutions to the tasks set, which can be found using this methodology, are approximate. The main reason for this is the short length of the time series K, for which Pearson's criterion, as a test of normality, is not sufficiently reliable. Consequently, the results obtained are qualitative in nature.

3. Results of the Research and Their Analysis

3.1.The Areas of European Territory, That Have Been Identified

The first and second tasks were solved using the methodology described above. We figured out the parts of the ETR, as well as other European countries, where the statistical links between the year-on-year changes in MATG in 2009-2023 and the variations in MAT and MPT for March-August 2010-2024 were statistically significant with a confidence level of at least 0.9. Among them, areas were also identified for which the relationships under consideration significantly strengthened over the period 1979-2024.

As an example, Figure 4 shows areas of Europe where the statistical relationships between interannual changes in MATG in 2009-2023 and MAT variations for the months of March-June 2010-2024 were statistically significant, and for 1979-2024 they intensified.

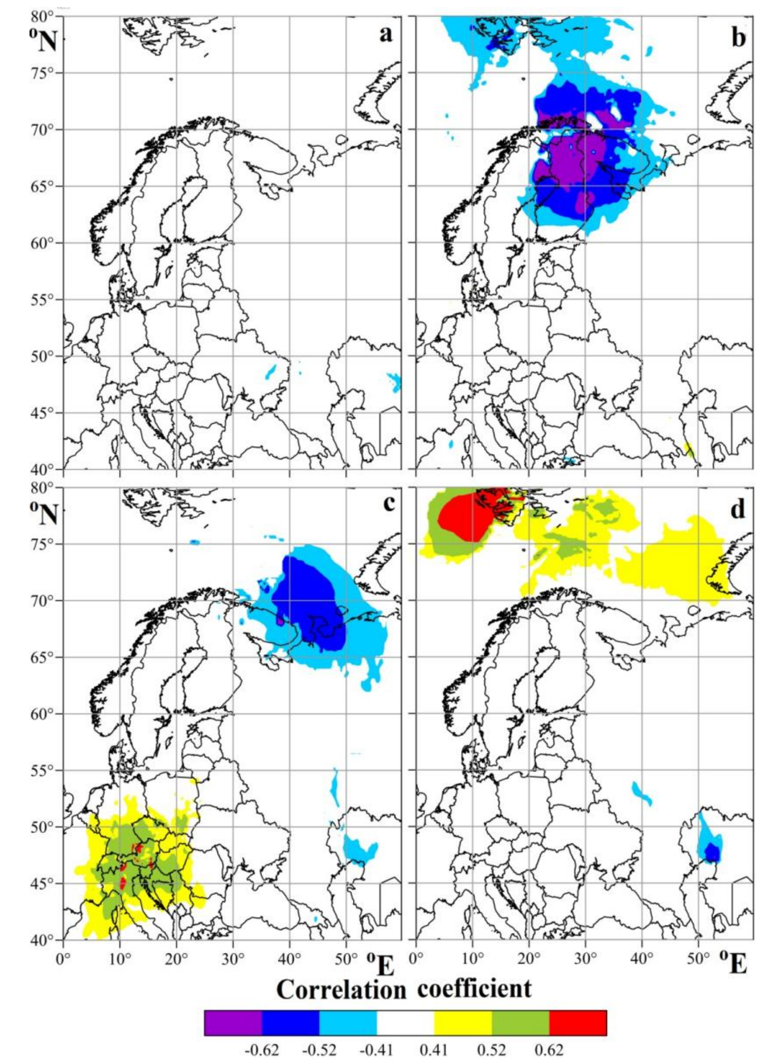

Figure 4. Areas of the ETR and territories of European countries where statistical correlations between interannual changes in MAT_G in 2009-2023 and variations in MAT for 2010-2024 were statistically significant, and where they intensified over the period 1979-2024.

a)March; b) April; c) May; d) June

Figure 4a shows that there are areas in Europe where the correlation between the corresponding interannual variations in MAT for March 2010-2024 and changes in MAT_G in 2009-2023 was significantly negative, and for 1979-2024 such areas are located in the Donetsk People's Republic and Kazakhstan. No areas were found where the correlation between the same processes was significantly positive and increased.

Figure 4b shows that there are areas where the correlation between the corresponding interannual variations in MAT for April 2010-2024 and changes in MAT_G in 2009-2023 is significantly negative, and for 1979-2024 it intensified. They are located in the waters of the Norwegian Sea, the White Sea, and the western part of the Barents Sea, as well as in the territories of the Murmansk, Leningrad, and Arkhangelsk regions and the Republic of Karelia. The total area of such areas is significantly larger than in the previous month.

Areas where the correlation between the corresponding interannual variations in MAT for April 2010-2024 and changes in MAT_G in 2009-2023 is significantly positive, and where it has intensified over the period 1979-2024, have been identified in the Republic of Dagestan. The total area of these areas is significantly smaller than the areas for which the correlation of the same processes is negative.

Figure 4c allows us to conclude that for May, areas where the correlation between the corresponding interannual variations in MAT for 2010-2024 and changes in MAT_G for 2009-2023 is significantly negative, and for 1979-2024 it has intensified, have also been identified. Such areas are located in the Barents and White Seas, in the territories of the Murmansk and Arkhangelsk regions, the Komi Republic, the Nenets Autonomous Okrug, and Kazakhstan.

Areas where the correlation between interannual variations in MAT for May 2010-2024 and changes in MAT_G in 2009-2023 is significantly positive, and for 1979-2024 has intensified, have been identified over the Mediterranean and Adriatic Seas, as well as over the territories of many foreign countries in Central, Eastern, and Southern Europe.

As can be seen in **Figure 4d**, the ETR identified areas where the correlation between the corresponding interannual variations in MAT for June 2010-2024 and changes in MAT_G in 2009-2023 was significantly negative, and for 1979-2024 such areas are located in the Voronezh region and Kazakhstan.

There are also areas where, for 1979-2024, there was a strengthening of the positive correlation between interannual variations in MAT for June 2010-2024 and changes in MAT_G, which was significant for 2009-2023. They were identified in the waters of the Norwegian and Barents Seas, in the territories of the Svalbard and Novaya Zemlya archipelagos.

As can be seen from Figure 4, the ETR areas for which the studied relationships have properties that allow them to be effectively used in long-term forecasting tasks are mainly identified for April and May.

For the months preceding March and following June, no relevant areas were found. Among the identified ETR areas, those where the significant correlation of the studied processes was negative predominate.

Figure 5 shows the ETR areas where the statistical relationships between interannual changes in MPT for the months of March-June 2010-2024 and variations in MAT_G in 2009-2023 were statistically significant, and in the period 1979-2024 they intensified.

Figure 5a shows that in the Baltic, Northern Sea, and Barents Sea, there are areas where the correlation between the corresponding interannual variations in MPT for March 2010-2024 and changes in MAT_G in 2009-2023 was significantly negative, and for 1979-2024, it intensified.

Similar sites have been found throughout Europe in countries belonging to the Baltic region, as well as in the United Kingdom, France, Belgium, the Netherlands, the Czech Republic, and Luxembourg.

Such areas have also been identified in the Murmansk, Arkhangelsk, Dnepr, and Pskov regions, the republics of Karelia, Komi, and Bashkortostan, as well as the Stavropol Territory and Kazakhstan.

Areas where the correlation of the same processes was significantly positive and intensified were found in the waters of the Norwegian, Mediterranean, and Black Seas, as well as in the southern coast of Crimea, the Nizhny Novgorod region, Spain, France, Slovakia, Romania, Ukraine, and Hungary. The total area of regions where the correlation of the processes under consideration is significant and negative is significantly larger than that of regions where it is positive.

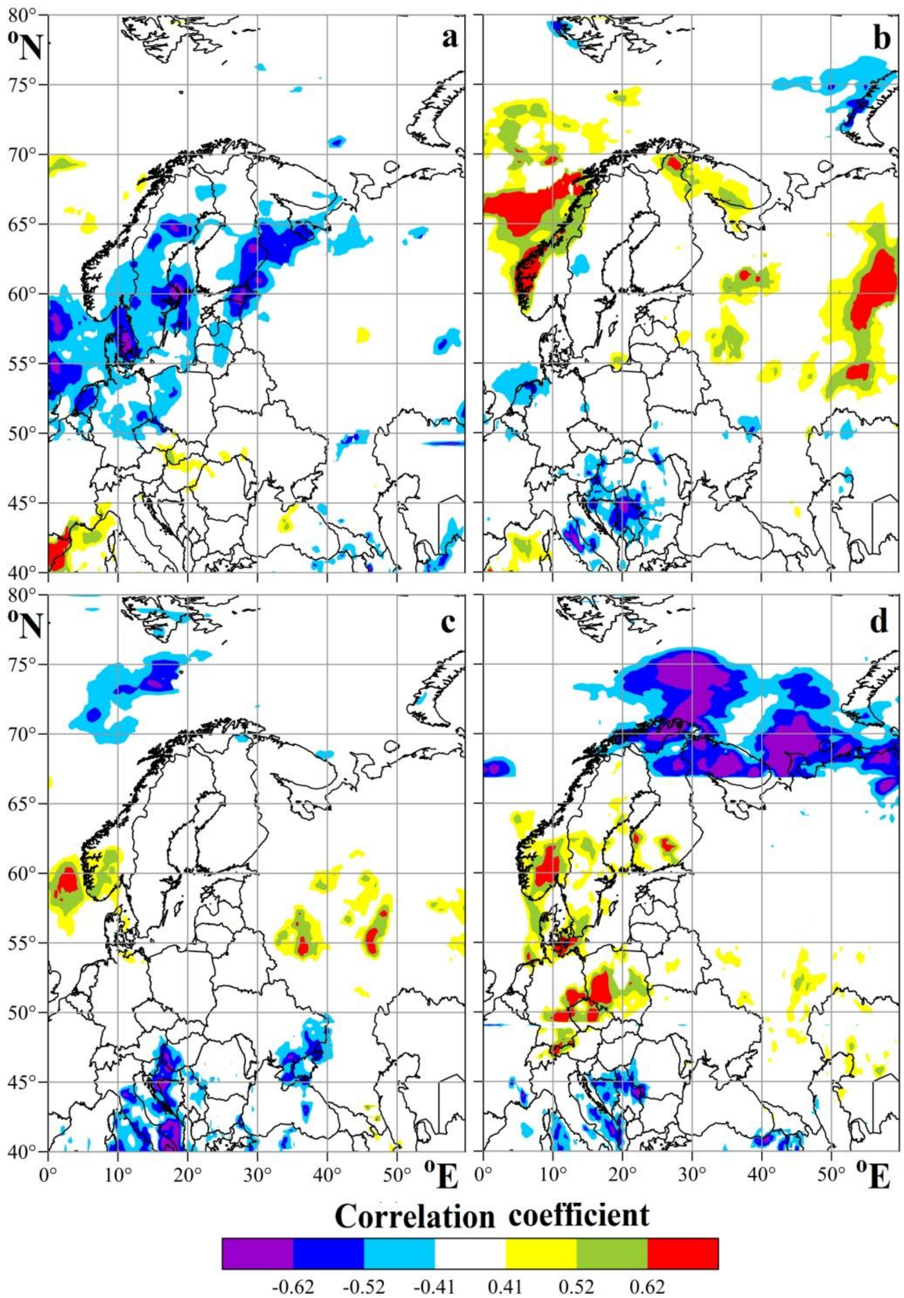

Figure 5. Areas of the ETR and European countries where statistical correlations between interannual changes in MAT_G in 2009-2023 and variations in the MPT for 2010-2024 were statistically significant, and where they intensified between 1979 and 2024.

a) March; b) April; c) May; d) June

As can be seen from **Figure 5b**, areas where the correlation between the corresponding interannual variations in MPT for April 2010-2024 and changes in MAT_G for the summer seasons of 2009-2023 is significantly negative, and for 1979-2024 they have intensified. The areas mentioned are located in the eastern part of the Barents, Northern, and Caspian Seas, as well as in the territories of the Belgorod and Voronezh regions, Sweden, Germany, the Netherlands, Austria, Southern European countries, and Kazakhstan.

Areas where the correlation between interannual variations in the MPT for April 2010-2024 and changes in the MAT_G in 2009-2023 is significantly positive, and for 1979-2024 has intensified, have been identified in the waters of the Norwegian, Mediterranean, Baltic, and the White Sea. They have also been found in the Murmansk, Arkhangelsk, Vologda, Moscow, Smolensk, Sverdlovsk , Orenburg, Vladimir, and Kirov regions, as well as in the republics of Karelia, Komi, and Udmurtia, and the Perm Territory. The total area of sites where the correlation between the processes under consideration is significant and positive is considerably larger than that of sites where it is negative.

Figure 5c shows that for May, areas where the correlation between the corresponding interannual variations in MPT for 2010-2024 and changes in MAT_G in 2009-2023 is significantly negative, and for 1979-2024 it has intensified, have also been identified. Such areas are located in the waters of the Norwegian, Mediterranean, Black, and Adriatic Seas, as well as in the territories of the Voronezh and Rostov regions, the Krasnodar Territory, the Republic of Crimea, Turkey, and many countries of Southern Europe.

Areas where the correlation between interannual variations in MPT for May 2010-2024 and changes in MAT_G in 2009-2023 is significantly positive, and for 1979-2024 it intensified, were identified in the North Sea, as well as in the Novgorod, Pskov, Vologda, Kirov, and Sverdlovsk regions, the republics of Udmurtia, Dagestan, Perm Krai, and Sweden.

As can be seen from **Figure 5d**, the areas where the correlation between the corresponding interannual variations in MPT for June 2010-2024 and changes in MAT_G in 2009-2023 was significantly negative, and for 1979-2024 they intensified. They were also identified in the Barents, Kara, Norwegian, and Mediterranean Seas. They were also identified in the ETR, where they occupy almost the entire Arctic zone, as well as in Norway, Turkey, and some countries in Southern Europe.

There are also areas where, between 1979 and 2024, there was a strengthening of the positive correlation between interannual variations in the MPT for June and changes in the MAT_G, which was significant between 2010 and 2024. They have been identified in the Belgorod, Voronezh, Penza, Saratov, and Volgograd regions, as well as in many countries in Central Europe, the Baltic region, Kazakhstan, and Scandinavia.

As can be seen in Figure 5, ETR areas for which the studied relationships have properties that allow them to be effectively used in long-term forecasting tasks have been identified for all months from March to June. For the months preceding March and following June, no such areas have been found. Among the identified ETR areas, those prevail where, for 2010-2024, the significant correlation between interannual changes in MAT_G and variations in MPT for March and June was negative, and for April and May, it was positive.

The results of the study presented indicate the existence in the past of significant teleconnections between variations in the MAT_G and changes in the MAT and MPT in many parts of Europe, which have increased over time. The latter indicates the advisability of taking into account the identified patterns when developing a forecast for the further development of the process under study.

3.2. The Forecast of Further Development of the Process Under Study

An analysis of existing ideas about the impact of Greenland's warming climate on the state of the AMOC, carried out as part of the third task, revealed the following.

As Greenland's climate continues to warm, the volume of meltwater formed there in summer will increase. As a result, the average salinity and density of the water brought by the Labrador Current to the Grand Newfoundland Bank in the fall will decrease for a while. Sooner or later, there will come a time when the density of the Labrador waters will be lower than that of the Gulf Stream. At the same time, due to global warming, the average temperature of the Gulf Stream waters will also increase. However, the average density of these waters will decrease at a slower rate, since the warming of these waters increases the rate of their evaporation, which leads to an increase in their salinity. Since the density of Labrador waters decreases faster than that of the Gulf Stream, sooner or later there will come a point when the density of Labrador waters will be lower than that of the Gulf Stream.

According to data [42], this moment has long since arrived. At this moment, Labrador waters entered the surface layer of the area where the North Atlantic Current is formed for the first time, causing its temperature to drop to the level of the Labrador Current. This did not have a significant impact on the weather in Europe, as the duration of the phenomenon in question was initially short (the salinity and density of the waters of the Labrador Current soon increased again, as the summer peak in the intensity of meltwater discharge from Greenland into the surrounding seas is not prolonged) .

With further warming of Greenland's thermal regime, the duration of the period during which the density of the waters of the Labrador Current will become less than the density of the waters of the Gulf Stream will increase. The size of the area of extremely cold water forming in the autumn in the general flow of the North Atlantic Current will also increase, and the influence of the associated anticyclone on the weather in Europe (after this area approaches its shores) will intensify.

As these waters approach the shores of Europe, the flow of Arctic air drawn into its territory by this anticyclone will increase, causing a further decrease in MAT and MPT for the spring months in the identified areas of the ETR.

In summer, the cold and desalinated waters of the North Atlantic Current will, as is currently the case, be carried by its corresponding currents to the Norwegian Sea, the Greenland Sea, and the Irminger Sea, as well as being carried south to the shores of North Africa. As a result, the anticyclone associated with these waters will be partially destroyed, and its influence on the weather in the ETR during the specified season will weaken.

With the arrival of the waters in question in the area above which the Icelandic Low forms, the average temperature and salinity of the surface layer of its waters will, as in the present period, decrease, causing an increase in atmospheric pressure above it. Therefore, with further warming of Greenland's thermal regime in the previous year, the recurrence of negative phases of the Arctic Oscillation will increase in the summer months of the current year, and the tracks of Atlantic cyclones over Europe will shift southward more often.

Consequently, as this process continues to develop, the frequency of Atlantic cyclones over the Arctic and forest zones of the European part of Russia during the summer months will decrease, while the fire hazard due to weather conditions in the relevant regions of Russia will increase.

As noted above, after the end of the summer season, the melting of Greenland's ice cover now practically ceases. The salinity and density of the waters brought by the Labrador Current to the Grand Newfoundland Bank in October-November increase again. The waters carried away from this area by the North Atlantic Current are also becoming warmer. Their salinity also increases. Consequently, the effects of the warming of Greenland's thermal regime, which are felt in Europe as these waters approach, will be offset, although the weakening of the AMOC and the increase in the amplitude of intra-annual changes in the surface temperature of the North Atlantic Current will continue.

As follows from the above, at the current stage of AMOC weakening, there have been no sudden and catastrophic changes in weather conditions in the ETR (although the amplitude of their variability has increased, leading to natural disasters that are occurring with increasing frequency). At the same time, the fire hazard in the identified regions of the ETR has been gradually increasing from year to year, in line with the changes in the MATG of the previous year.

This allows us to predict that with further warming of Greenland's thermal regime, changes in fire hazard due to weather conditions in such regions will occur according to the specified “mild” scenario.

The transition from the “mild” scenario to the catastrophic one (corresponding to the collapse of the AMOC [34, 36]) is possible if the duration of the period during which the density of Labrador waters entering the Grand Newfoundland Bank exceeds the density of the surface layer of the Gulf Stream is reduced to zero. This will not happen soon (if it ever happens at all).

The aforementioned change in the AMOC weakening scenario is only possible if the volume of meltwater forming in the Arctic Ocean increases to a level where the maximum annual density of water delivered by the Labrador Current to the Grand Newfoundland Bank area remains lower than the density of the corresponding Gulf Stream waters. The question of whether this is possible given the current state of the ice cover in the Arctic Ocean requires further study (there may not be enough fresh water).

With a further increase in MATG, changes in MAT and MPT on the ETR will be most noticeable in the months from April to August, but in the autumn and winter months, significant variations in these indicators caused by the process under consideration are unlikely.

Short-term breakthroughs of Labrador waters into the North Atlantic Current are already occurring. They are likely to cause a significant decrease in MAT and MPT in many parts of the ETR and some European countries.

The links between changes in MATG and variations in MAT and MPT for the identified areas of the ETR during the period of modern climate warming in Greenland (1979-2024) have steadily strengthened. Therefore, if the scenario for the development of the processes under study does not change, the relationships between them will continue to strengthen, and the total area of the forest and Arctic zones of the ETR for which they will be significant will increase as long as the ice cover remains in Greenland.

Since, if the current scenario for the development of the processes under study continues in the future, changes in MAT and MPT, as well as variations in MATG, will occur gradually, the population of Europe, its firefighting units, and agricultural enterprises have the opportunity to adapt to them in advance. So let's not miss this opportunity!

4. Discussion of the Results

As can be seen from the results obtained, they fully correspond to existing ideas about the influence of climate change in Greenland on the intensity of deep convection in the Labrador and Irminger Seas [52,55], as well as on variations in the state of the AMOC [6,19,42,56]. They also confirm the validity of the conclusions [47] about the connection between the latter and other processes causing Arctic amplification with the dynamics of MAT and MPT in the forest and Arctic zones of the European part of Russia and Siberia. At the same time, some of the established facts are of significant scientific novelty.

4.1. Facts That Have Been Established for the First Time

These include the following statements:

1. The weakening of the AMOC during the period 2010-2024 has already had a significant impact on the evaporation and moistening regimes of combustible material, as well as increasing the fire hazard due to weather conditions in some regions of the Forest and Arctic zones of the Europ. This impact has steadily increased between 1979 and 2024. The significant connection between these processes is no longer a hypothesis in the modern period, but an observable reality (a fait accompli).

2. The scenario currently leading to the weakening of the AMOC appears to be a “soft” one, not implying a sharp and nonlinear collapse of this current (in contrast to the ideas presented in [48,59]). It allows for the possibility of timely adaptation of the activities of firefighting units in the identified regions and reduction of the damage that may be caused by this process. Such a scenario probably corresponds to the early, initial stage of the AMOC phase change.

It should be noted that the results obtained do not exclude the possibility of this process transitioning to an acute, critical stage in the future, at which point threats may arise not only on a regional scale, but also on a national and global scale, although the probability of such an event is not high.

Greenland is part of the Arctic. Therefore, the warming of its climate is one of the components of a larger process in our planet's climate system – the warming of the entire Arctic (Arctic amplification), which can cause an almost synchronous increase in fire danger due to weather conditions not only in the European part of Russia, but also in Siberia (as shown in Figure 1). Consequently, similar processes may also develop in Siberia.

5. Conclusions

Thus, the results obtained confirm the validity of the hypothesis put forward.

5.1. It has been established that there are numerous areas in the European part of Russia that belong to its forest and Arctic zones, where the warming of Greenland's temperature regime for the summer season in the period 2010-2024 has had a significant impact on the interannual variability of fire risk due to weather conditions for the months of March to June.

5.2. The links between the processes under consideration during the period of modern climate warming in Greenland (1979-2024) have strengthened. This is because the warming of Greenland's temperature regime caused a corresponding weakening of the Atlantic Meridional Overturning Circulation. As a result, the connection between this process and variations in monthly precipitation totals, as well as average monthly air temperatures, which lag behind it by several months, has strengthened.

5.3. With further warming of Greenland's thermal regime, monthly precipitation amounts falling in the months from March to June in the territories of the aforementioned zones will decrease. In some of them, the process under study will also cause significant changes in the thermal regime (in some, it will warm up, and in others, it will cool down). All this will cause an increase in fire hazard due to weather conditions in the identified areas of Europe, which should be taken into account when developing fire prevention measures and planning the activities of relevant firefighting units and agricultural enterprises.

5.4. The increase in fire hazard 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 has actually been in effect since 1979 and assumes no sharp or nonlinear changes. At the same time, the spatial and temporal variability of surface temperatures in the North Atlantic Current zone will increase, which will cause a further increase in the recurrence of dangerous meteorological phenomena over European territories.

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Data Availability

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

Conflict of Interest

The author declares that he has no conflict of interest.

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