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Original Theoretical Research

Relationship between Changes in the Frequency of Thunderstorms, the Number of Forest Fires in the Territory of Yugra, and Air Temperature and Solar Activity during Climate Warming

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Abstract

Introduction. Improving methods for modeling and forecasting changes in the number of forest fires, as well as the frequency of thunderstorms that cause them, is a significant challenge for environmental safety, emergency preparedness, and climatology. This is particularly relevant for regions with a forest landscape, such as the Khanty-Mansi Autonomous Okrug (Yugra). Domestic and foreign researchers have found that variations in seasonal average air temperatures and solar activity are effective predictors for modeling these processes in many regions. However, the connections between these processes and these factors in Yugra remain understudied, hindering our ability to determine the usefulness of including them in predictive models. The aim of the study is to test the hypothesis that there are significant statistical relationships between changes in the frequency of thunderstorms, the number of forest fires in the territory of Yugra, and variations in average air temperatures near the surface of the atmosphere during the thunderstorm season. The study aims to investigate whether these relationships are significant and increasing during periods of climate warming, as well as to assess the impact of solar activity on these relationships. To achieve this goal, we have analyzed the significance of correlation between the changes in the frequency of thunderstorms over the territory of Ugra and synchronous variations in the number of forest fires occurring here, as well as synchronous and ahead of time variations in the average seasonal air temperatures and solar activity in the period of climate warming.

Materials and Methods. The study used observational data on average daily air temperatures, dates of thunderstorms over representative hydrometeorological stations of the studied area, information on changes in average annual solar radiation with a wavelength of 10.7 cm, and information on forest fires and related emergencies in Yugra. The data were obtained from international and Russian climate data banks and systems, as well as official reports from relevant ministries and agencies. The method of assessing the strength of links between processes was multiple correlation analysis. The statistical significance of identified links was assessed using the Student's t-test.

Results. As a result of the study, it was established that the hypothesis put forward was valid. There was the correlation between the changes in the frequency of thunderstorms and the number of forest fires in the territory of Yugra with variations in average air temperatures and solar activity during the thunderstorm season. This trend was significant and increasing. We proved that the correlation of interannual changes in the number of forest fires that occurred in the XXI century in the territory of Yugra per year with synchronous variations in the frequency of thunderstorms over it was significant and intensified. The conditions were identified under which statistical relationships between changes in the frequency of thunderstorms here, as well as variations in average monthly air temperatures and solar activity, were significant and are increasing now. Therefore, when these conditions were met, it was advisable to take into account the factors under consideration during modeling and forecasting of the process under study.

Discussion and Conclusion. The results obtained fully confirm the existing ideas about the impact of climate change and solar activity on the frequency of thunderstorms in the atmosphere, as well as the features of current climate change in Western Siberia. These connections can be used to predict changes in thunderstorm frequency and forest fire risk, and these predictions should be taken into account when planning activities within the unified state emergency management system.

Keywords: Khanty-Mansi Autonomous Okrug, forest fires, thunderstorms, solar activity, mean air temperatures, correlation, modern period

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Оригинальное теоретическое исследование

Связь изменений повторяемости гроз и количества лесных пожаров на территории Югры с температурой воздуха и солнечной активностью при потеплении климата

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Аннотация

Введение. Совершенствование методик моделирования и прогнозирования изменений количества лесных пожаров, а также повторяемости гроз, их вызывающих, является актуальной проблемой экологической безопасности, безопасности при чрезвычайных ситуациях, а также климатологии. Наибольший интерес ее решение представляет для регионов лесной ландшафтной зоны, одним из которых в России является Ханты-Мансийский автономный округ (Югра). Отечественными и зарубежными учеными установлено, что во многих регионах к числу эффективных предикторов моделей изучаемых процессов относятся вариации среднесезонных температур воздуха над исследуемыми территориями, а также солнечная активность. Вместе с тем связи таких процессов с названными факторами в Югре изучены недостаточно, что не позволяет оценить целесообразность их учета. Целью данной работы является проверка гипотезы о том, что статистические связи изменений повторяемости гроз и количества лесных пожаров на территории Югры с синхронными или опережающими их по времени вариациями средних за грозоопасный сезон температур воздуха в приземном слое атмосферы и солнечной активностью являются значимыми и усиливаются. Задачи, которые были решены для достижения поставленной цели, состоят в оценке значимости корреляции между изменениями повторяемости гроз над территорией Югры и синхронными вариациями количества возникающих здесь лесных пожаров, а также синхронными и опережающими по времени вариациями среднесезонных температур воздуха и солнечной активности в период потепления климата.

Материалы и методы. Фактический материал исследования составили данные наблюдений о среднесуточных температурах воздуха и датах, в которые происходили грозы над репрезентативными гидрометеорологическими станциями изучаемого района, информация об изменениях среднегодового потока солнечного радиоизлучения с длиной волны 10,7 см, сведения о количестве зарегистрированных лесных пожаров и чрезвычайных ситуаций, ими обусловленных, на территории Югры, представленные в международных и российских климатических банках данных и информационных системах, а также в официальных докладах профильных министерств и ведомств. Методом оценки силы связей между рассматриваемыми процессами явился множественный корреляционный анализ, а оценка статистической значимости выявленных связей выполнена с использования критерия Стьюдента.

Результаты исследования. В результате исследования впервые установлено, что выдвинутая гипотеза о том, что связи изменений повторяемости гроз и количества лесных пожаров на территории Югры с вариациями средних за грозоопасный сезон температур воздуха и солнечной активностью являются значимыми и усиливаются, является справедливой. Доказано, что корреляция межгодовых изменений количества лесных пожаров, возникавших в XXI веке на территории Югры за год, с синхронными вариациями повторяемости над ней гроз была значимой и усиливалась. Выявлены условия, при которых статистические связи между изменениями здесь повторяемости гроз, а также вариациями среднемесячных температур воздуха и солнечной активностью значимы и в настоящее время усиливаются. Следовательно, при выполнении этих условий учет рассматриваемых факторов в ходе моделирования и прогнозирования изучаемого процесса целесообразен.

Обсуждение и заключение. Полученные результаты в полной мере соответствуют существующим представлениям о влиянии потепления климата и солнечной активности на изменения повторяемости гроз в земной атмосфере, а также об особенностях современных изменений климата Западной Сибири. Выявленные связи могут быть использованы при прогнозировании изменений повторяемостей гроз и лесных пожаров, результаты которого целесообразно учитывать при планировании деятельности соответствующих функциональных подсистем единой государственной системы предупреждения и ликвидации чрезвычайных ситуаций.

Ключевые слова: Ханты-Мансийский автономный округ, лесные пожары, грозы, солнечная активность, средние температуры воздуха, корреляция, современный период

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Для цитирования. Холощев А.В. Связь изменений повторяемости гроз и количества лесных пожаров на территории Югры с температурой воздуха и солнечной активностью при потеплении климата. *Безопасность техногенных и природных систем*. 2024;8(3):9–18. https://doi.org/10.23947/2541-9129-2024-8-3-9-18

Introduction. According to Russian [1] and foreign researchers [2], thunderstorms that pass over certain areas are a cause of landscape fires in various parts of the world, causing significant damage to ecosystems. Therefore, the improvement of methods for modeling and forecasting changes in the frequency of thunderstorms is an urgent problem of environmental safety. The regions with significant forest resources are the most interested in solving this problem, as landscape fires, which occur predominantly in forests, cause the most damage to the environment, population and economy.

In Russia, one of these regions is the Khanty-Mansi Autonomous Okrug (Yugra). Its territory is located on the West Siberian lowland and is characterized by almost monotonous taiga landscapes[1], as a result of which the Khanty-Mansi hydrometeorological station (HMS) (61.01ºN, 69.06ºE) can be considered representative for it

52% of the Yugra's area is covered by forests, and the fires that occur there annually cause significant damage to the region's forest resources [3]. A notable feature of this territory is that approximately 30% of all forest fires are caused by thunderstorms[2].

Figure 1 shows the territories of Yugra that belong to the control zone. These territories are relatively small, and most of them are occupied by the area of forest aviation activities. Therefore, the data from the Information System for Remote Monitoring of the Federal Forestry Agency (ISDM-Rosleskhoz)[3] is quite reliable regarding the number of forest fires (NFF) that occurred on this territory in a given year.

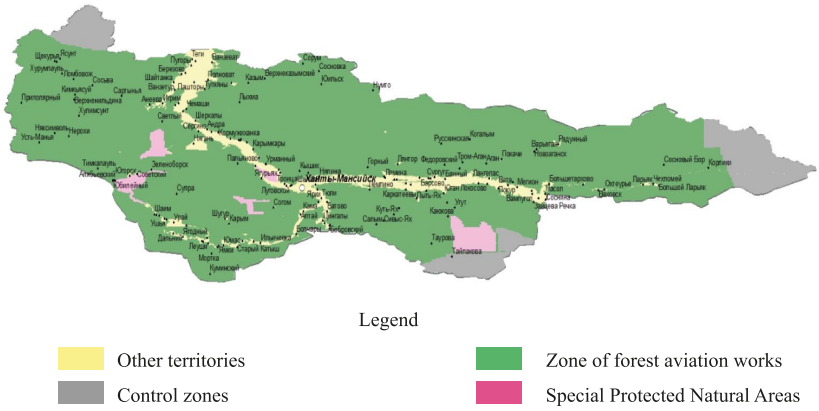

Fig. 1. Sections of control zones on the territory of Yugra [4]

In the territory of Yugra, the risk of forest fires is increased due to its status as the major oil-producing region of Russia. Oil production takes place at 406 oil fields, including the Samotlor, Priobskoye, Fyodorovskoye, and Mamontovskoye fields, which have unique reserves [4].

The works of Baranovskii N.V. [5], Ivanov V.A. and others [6] are basis for the existing ideas about modeling changes in the frequency of thunderstorms (FT), as well as NFF over Siberia. They show that the processes under consideration may depend on numerous factors, some of them are not observable, therefore it is advisable to consider them as random processes, in modeling which the multiple regression method is effective [7].

The mentioned method is also applicable in forecasting. The latter is possible if the factors of the studied processes, which were significant in the past, will remain significant in the future, for which the forecast is being developed. The future is not predetermined, however, the feasibility of this condition is more likely if the statistical relationships under consideration have been strengthened in the past [8].

[1] Makunina GS. *The West Siberian Plain.* The Great Russian Encyclopedia (2004–2017). URL: https://old.bigenc.ru/geography/text/4138680 (accessed: 19.03.2024). (In Russ.)
[2] *Information System of Remote Monitoring of the Federal Forestry Agency.* URL: https://pushkino.aviales.ru/main_pages/index.shtml (accessed: 19.03.2024). (In Russ.)
[3] *Information System of Remote Monitoring of the Federal Forestry Agency.* URL: https://pushkino.aviales.ru/main_pages/index.shtml (accessed: 19.03.2024). (In Russ.)
[4] *The Layout of the Control Zone on the Territory of the Khanty-Mansi Autonomous Okrug.*URL: https://aviales.ru/default.aspx?textpage=229 (accessed: 06.05.2024). (In Russ.)

It is obvious that the forecast of the studied process, built taking into account such a factor, may correspond to a scenario in which the main patterns that determine their dynamics will not change in the future.

In the studies of many authors, for example, Baranovskii N.V. [5], Ivanova G.A. et al. [9], Kopeikin M.A. et al. [10], it was found that the number of significant factors of FT and NFF in certain territories of Siberia may include synchronous variations in the average seasonal temperatures of the air above them and solar activity.

The relationship between changes in FT and average air temperatures (AAT) at the Earth's surface during the thunderstorm season is causal, since thunderstorms are formed during thermal convection in Cb thunderstorms [11], and the intensity of the latter is higher the higher the average air temperature in the cloud layer [12].

The relationship between changes in FT and solar activity is also causal, since due to the Forbush effect [13], the latter significantly affects variations in the flow of galactic and extragalactic cosmic rays entering the Earth's atmosphere and participating in the ionization of air in thunderclouds. The higher the solar activity, the lower the intensity of air ionization in thunderclouds, and the frequency of thunderstorms is decreased [14].

The connections of solar activity and changes in AAT with variations in NFF have been revealed only statistically. Nevertheless, in the twentieth century they were significant for several decades [15]. Since both of these factors of the studied processes were significant in the twentieth century, they are usually taken into account in modeling. The question of whether it is advisable to take these factors into account when forecasting the studied processes has not been adequately addressed. It has been found that quasi-biennial modes are present in the variability spectra of FT and AAT, which leads to a statistical relationship between their fluctuations with time lags of 2–3 years. The main mode of solar activity is the 11–year cycle, which also suggests a possible correlation between changes in solar activity over time that are shifted by years [16].

Consequently, the connections of changes in NFF and FT with the factors under consideration, which are ahead of them for such a time, are possible because these connections are inherent in these factors themselves. However, the significance of such connections is far from obvious.

The ideas about the importance of the factors under consideration are based on the results of monitoring conducted in the twentieth century. However, climate changes that have occurred on the territory of Yugra in the twenty-first century, as well as various anthropogenic impacts on forest ecosystems in this region, have the potential to disrupt the links between the studied processes and some of their factors [17]. As a result, taking these factors into account when predicting the studied processes may not improve, but, on the contrary, worsen the justifiability of its results.

In the 21st century, monitoring of the studied processes and their factors in the region continues. Nevertheless, the existence of properties between its results that determine the expediency of taking them into account in modeling and forecasting these processes has not been previously verified. As a result, the expediency of their accounting needs to be confirmed. Assessing the correlation between the studied processes and their coincident and overlapping factors, as well as identifying trends in their changes, is not only of theoretical interest, but also of practical significance.

Based on the above, the aim of this study is to verify the hypothesis that there is a significant and increasing statistical relationship between changes in NFF and FT for the territory of Yugra with synchronous or time-ahead variations of AAT in the atmosphere and solar activity during the modern period.

To achieve this goal, an assessment was conducted of the significance of the correlation between FT over the territory of Yugra and synchronous changes in NFF, synchronous variations in AAT and solar activity. Additionally, time-ahead variations in AAT and solar activity were considered for the period of modern climate warming.

Materials and Methods. The information provided in the database on weather changes in various parts of the world[5] from 1961 to 2023 was used as factual material for the average daily temperatures above the reference HMS and the dates of thunderstorms occurred here.

The FT value was determined as the ratio of the number of days belonging to the thunderstorm season (May–September) of the studied year, in which thunderstorms occurred above the representative HMS, to its total duration (15 days).

The AAT value was calculated as the average value of the average daily temperatures of the surface layer of the atmosphere above the same HMS for the period from May 1 to September 30 of each year.

Information about the NFF in the territory of Yugra for the period from 2000 to 2023, which was also considered as factual material, was obtained from ISDM-Rosleskhoz[6].

[5] *Global Climate Data.* URL: https://en.tutiempo.net/climate (accessed: 13.05.2024).

[6] *Information System of Remote Monitoring of the Federal Forestry Agency.* URL: https://pushkino.aviales.ru/main_pages/index.shtml (accessed: 12.10.2023). (In Russ.)

As an actual material on solar activity, information from the database of changes in global climate indices[7], on changes in the average annual flux of solar radio emission with a wavelength of 10.7 cm (SA index), measurements of which were possible under any weather conditions and were most accurate, was used.

The value of their correlation coefficient was considered as a characteristic of the strength of the connection between the studied processes.

Taking into account the length of the considered NFF time series, the values of their correlation coefficient with synchronous FT series and the SA index were estimated in a sliding window of 11 years in solving the first problem.

The method of solving the second problem involved calculating the values of the correlation coefficient of the FT and AAT series, as well as the FT and the SA index in a sliding window of 11, 22 and 44 years for the period from 1961 to 2023.

When solving the third problem, the values of the correlation coefficient of the FT series, as well as the AAT series and the SA index series, which are 1–3 years ahead of it in time, were calculated.

When calculating the correlation coefficient values, the linear trends present in the compared segments of the time series corresponding to each sliding window have been previously compensated for.

The correlation coefficient value was considered significant if the reliability of such a statistical conclusion, estimated by the Student's t-test (taking into account the number of degrees of freedom of the series), was at least 0.95.

As a characteristic of the trend in the changes of the correlation coefficient in the studied series, we calculated the angular coefficient of the linear trend (ACLT) for the time series formed by the values of this coefficient within a sliding window of certain duration.

The revealed trend with a confidence of 0.95 was considered significant if:

$$N \cdot |A| > 1{,}65 \cdot CKO,$$

where $|A|$ — modulus of the angular coefficient of the linear trend in the time series being considered, which is determined from a series with length N; CKO — standard deviation of the members of this series from the corresponding trend.

The latter was true if the deviations of the members of the studied series from the corresponding trend followed the normal distribution. However, due to the small length of the series, it was not possible to verify the validity of this assumption using the Pearson's criterion. Therefore, the results should be considered to be of a qualitative nature.

Results. In accordance with the described methodology, when solving the first task, time series of the number of thunderstorms that occurred during the thunderstorm season (and actually over the year) over the representative GMS and NFF in the territory of Yugra were formed.

The corresponding time dependencies of these indicators are presented in Figure 2.

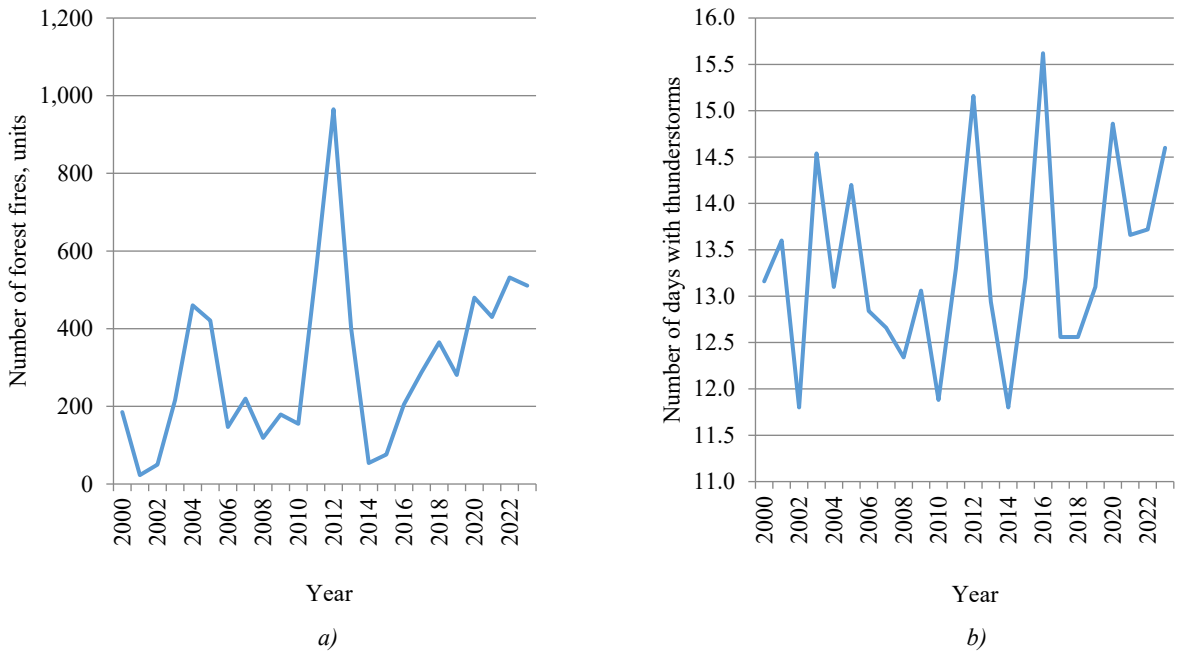

Fig. 2. Dependencies on the time of the number of events that occurred during the year over the Khanty-Mansi hydrometeorological station: *a* — number of forest fires; *b* — number of days with thunderstorms

[7] *Correlation of the Average Monthly Values of Climatic Time Series.* URL: https://psl.noaa.gov/data/correlation/solar.data (accessed: 13.05.2024). (In Russ.)

In Figure 2 it can be seen that both dependencies represented complex oscillations in which the periods of the most powerful short-period modes practically coincided. At the same time, in the period up to 2011, the maxima of the dependence of the number of thunderstorms on the time did not coincide with similar extremes of the same dependence of the NFF.

Since 2012, almost all the extremes of the same name of the dependencies under consideration coincided. Therefore, their correlation has clearly increased. The latter was confirmed by calculations.

The correlation coefficient of the series under consideration for the period from 2000 to 2023 was 0.484, which (with the number of degrees of freedom of the series 23) exceeded the threshold level of 0.44, corresponding to the reliability of the conclusion of 0.95. Consequently, the correlation of the time series of FT and NFF for the territory of Yugra was significant in the 21st century (the latter was quite expected, since, as noted above, about 30% of forest fires here caused thunderstorms). The correlation between the NFF and AAT series over the same period was also significant, which confirmed the validity of the conclusion [9] about the significance of the influence of Russian climate warming on forest fire.

Similarly, it was found that in the period from 2000 to 2023, the correlation of the time series of the NFF, as well as the series of the SA index, was not significant. The latter was quite understandable, since the periods of the most powerful modes of the spectra of interannual changes in the NFF and the SA index differed by 3–4 times.

An analysis of the relationships between the time series of the NFF in the territory of Yugra with the time-ahead series of the SA, AAT and FT indexes above the representative point showed that the correlation between them, estimated in a sliding window of 11 years, was not significant and became weaker over time. Therefore, when modeling changes in NFF over the territory of Yugra, it was advisable to take into account variations in the SA, AAT and FT indexes. However, it was ineffective to forecast these changes using the same predictors that are 1–3 years ahead of the studied process.

As a result of solving the second problem, the values of the correlation coefficient of synchronous segments of the FT and AAT series, as well as the FT and the SA indexes were calculated corresponding to sliding windows of 11, 22 and 44 years.

Taking into account these values, the dependencies of the coefficient of these series on the year of the beginning of the corresponding sliding window were constructed (Fig. 3).

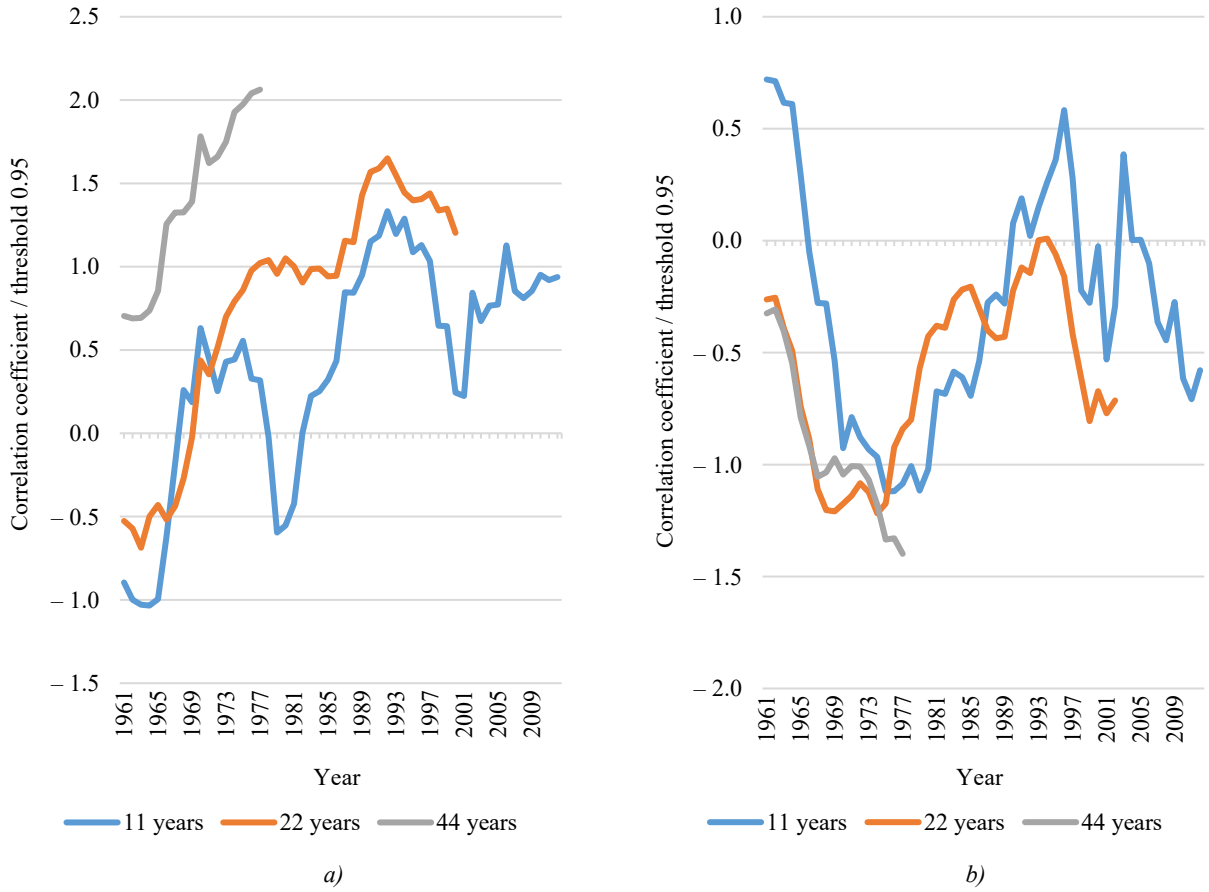

Fig. 3. Dependencies of sliding windows of 11, 22 and 44 years on the year of the beginning, their corresponding ratios to the threshold of significance of the coefficient of synchronous correlation of changes in FT over Khanty-Mansi HMS, as well as variations: *a* — AAT; *b* — SA index

The data in Figure 3 *a* demonstrate that the dependencies on the year of the start of the sliding windows with lengths of 22 and 44 years, as well as their corresponding ratios to the significance threshold of the correlation coefficient for changes in greenhouse gas emissions over the Khanty-Mansi region, and synchronous variations in AAT, were described by increasing functions on average. The values of these indicators for the windows corresponding to the modern period (2000–2023 and 1978–2023) were greater than 1 (indicating significance). Therefore, a scenario in which AAT remains a significant FT factor in the near future was more likely than an alternative scenario.

The dependence under consideration, which corresponded to a sliding window of 11 terms, was oscillatory in nature. For the window corresponding to the modern period (2012–2023), the value of the correlation coefficient of the FT and AAT series did not reach the level of significance. The reliability of the statistical conclusion about their significance was at least 0.94.

The obtained result confirmed the expediency of taking into account AAT variations when modeling FT changes over the territory of Yugra occurring in the 21st century.

Figure 3 *b* demonstrates that the dependencies of the ratio of the correlation coefficient of FT changes over the Khanty-Mansi HMS, as well as synchronous variations of the SA index to the threshold of significance for sliding windows of 11 and 22 years, also represented complex fluctuations. The values of this indicator for modern periods were significantly less than 1 (the correlation is not significant).

For a sliding window with a length of 44 years, the studied dependence was monotonous, and for the period 1978–2023, the correlation of the studied processes was negative and significant (the reliability of such a conclusion exceeds 0.95). Therefore, when modeling FT changes over such long periods of time, including the modern period, it was also advisable to take into account variations in the SA index.

When solving the third problem, it was established that the same conclusion was valid for the problems of forecasting changes in FT, in which the series of the SA index were used as predictors of multiple regression models.

As confirmation of this, Figure 4 shows the dependence of the correlation coefficient of FT changes over the Khanty-Mansi HMS on the year of the beginning of the 44-year sliding window, as well as the variations of the SA and AAT indexes that were 1–3 years ahead of them in time.

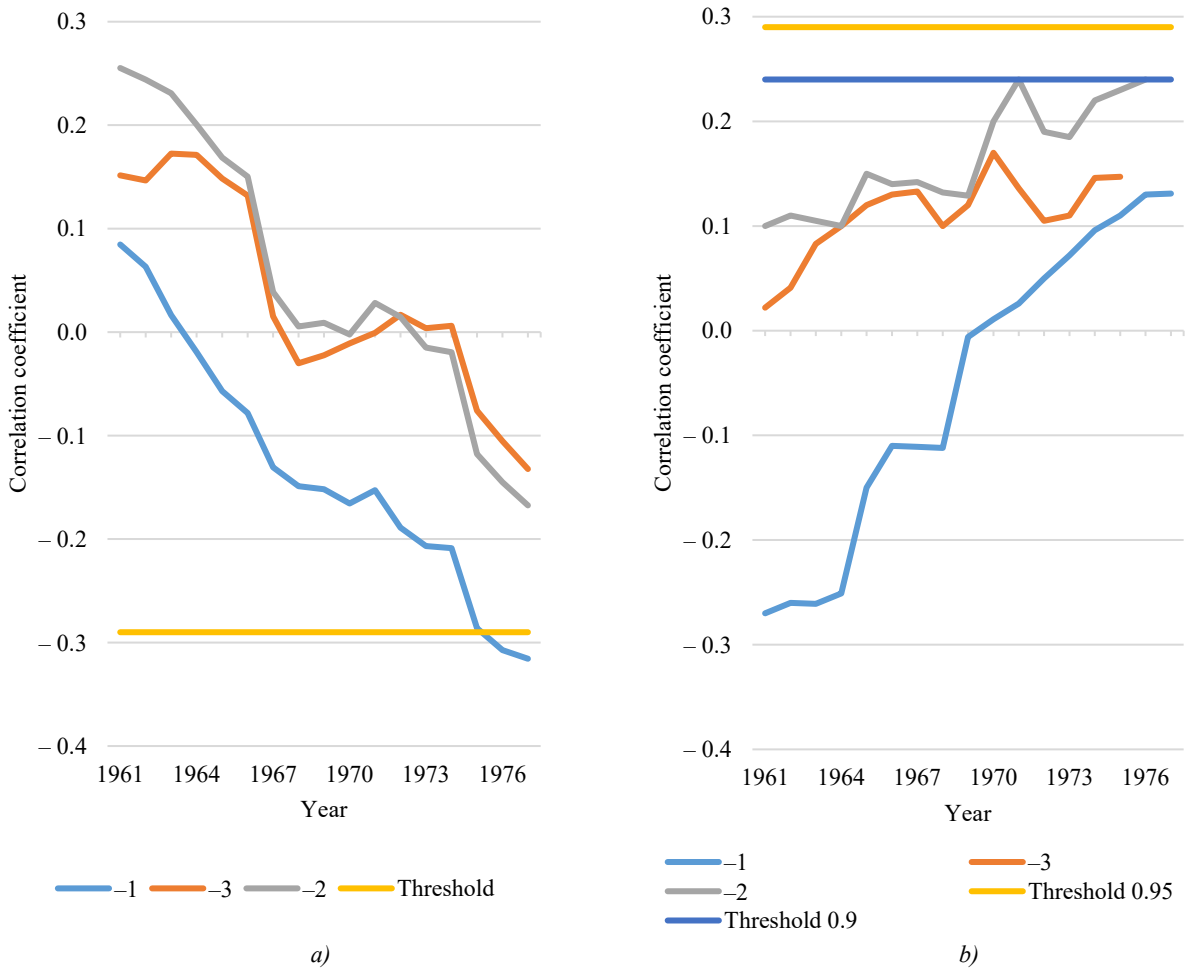

Fig. 4. Dependencies on the year of the beginning of the sliding window with a length of 44 years, the correlation coefficient of FT changes over the Khanty-Mansi HMS, as well as variations that are 1–3 years ahead of them in time: *a* — SA index; *b* — AAT

According to the data in Figure 4 *a*, it can be seen that during the period of modern climate warming, the correlation of 44-year-long segments of the FT time series over the representative HMS, as well as segments of the SA index series that were 1 year ahead of them in time, intensified and was significant in the period 1975–2023.

If the SA index series were ahead of the FT series for a longer time, their correlation also increased over the same period, but did not reach the selected significance level.

As follows from the data in Figure 4 *a*, the probability that the correlation of the FT series and the SA index would remain significant over time periods that also included the near future. It was higher than the probability of an alternative scenario. Therefore, taking into account changes in this factor when forecasting FT over the territory of Yugra for the coming year would help to increase the justifiability of its results.

The data in Figure 4 *b* indicate that the values of the correlation coefficient of FT changes over the same HMS over a time interval of 44 years, as well as AAT variations that were 1–3 years ahead of them, have increased over the period of modern climate warming. It follows that a scenario in which they would become larger in the future was more likely than an alternative scenario. At the same time, the reliability of the conclusion about the significance of the considered links in the period 1978–2023 reached only 0.9 (assuming that a number of AAT is 2 years ahead of a number of FT).

Similar studies performed for comparable shorter time periods showed that the time dependence of the correlation coefficient of changes in FT over the same HMS, as well as 1–3 years ahead of them, variations in the SA and AAT indexes were oscillatory (the trends of these processes were alternating). For the segments of the FT series, including 2023, the values of their correlation coefficient with the time-leading series of the factors under consideration were significantly less (modulo) than the threshold of significant correlation. Consequently, there were no grounds to believe that taking into account such short time series of the factors under consideration when predicting FT changes over the Khanty-Mansi HMS, which were 1–3 years late in relation to them, would lead to positive results.

Thus, it has been established that the hypothesis put forward regarding the synchronous connections of changes in NFF for the territory of Yugra with variations in FT and AAT was valid. It was also valid for synchronous connections of changes in FT with variations in AAT and the SA index. The hypothesis under consideration was also valid in relation to the relationships of FT changes, as well as variations in the SA index that were 1 year ahead of them.

In addition, it is shown that at present, the relationship of changes in the time intervals of 44 years of FT over the territory of Yugra, as well as the variations of the SA and AAT indexes ahead of them, are increasing, as a result of which such relationships may become significant in the future with other values of these advances.

The results obtained fully correspond to existing ideas about the influence of climate warming and solar activity on changes in the frequency of thunderstorms in the Earth's atmosphere [1], including those published by Rosgidromet[8], as well as about the features of modern climate changes in Western Siberia [3].

Discussion and Conclusion. The statistical links between changes in NFF and FT, as well as NFF and AAT in the territory of Yugra in the 21st century are not only significant, but also significantly enhanced. Therefore, it is advisable to take into account the results of monitoring of AAT and FT when modeling forest fires in the territories belonging to the control zone, as well as when managing the activities of its fire-fighting units (according to Federal Laws 69–FZ and 123–FZ).

The correlation of FT changes over the territory of Yugra, as well as time-matching variations of AAT over time periods ending in 2023 is significant and increases provided that their length is at least 11 years. For such a factor as variations in the SA index, it is significant and increases only if the length of the corresponding segments is at least 44 years.

The correlation of FT changes over the territory of Yugra with variations of the SA index that are 1 year ahead of them in time is significant and increases, provided that it is estimated for time periods of at least 44 years. With large values of such advances, the relationship between these processes also increases, but it has not reached the level of significance by 2023.

Thus, it has been established that the revealed features of statistical relationships between changes in the period of modern climate warming, the number of forest fires and the frequency of thunderstorms over the territory of the Khanty-Mansi Autonomous Okrug (Yugra), as well as with variations in seasonal average air temperatures and solar activity, correspond to existing ideas about the reasons for the existence of these relationships.

In the 21st century, synchronous relationships between changes in the number of forest fires that occurred per year in the territory of the studied region and variations in the frequency of thunderstorms over it are significant and increasing. This suggests that part of the total number of forest fires formed here due to the action of lightning discharges will increase in the future.

[8] *The Third Assessment Report on Climate Change and Its Consequences on the Territory of the Russian Federation. General Summary.* Saint-Petersburg: Naukoemkie tekhnologii; 2022. 124 p. URL: https://www.meteorf.gov.ru/upload/pdf_download/compressed.pdf (accessed: 14.05.2024). (In Russ.)

It is advisable to take into account the relationship of changes in the average seasonal air temperatures in the studied region during the thunderstorm period with synchronous variations in the frequency of thunderstorms during the same season and the number of forest fires when modeling these processes, since it has been established that with climate warming they intensified and are significant for the modern period.

It is advisable to take into account the relationship of changes in solar activity with synchronous, as well as 1–year delayed variations in the frequency of thunderstorms over the territory under consideration when forecasting the latter, since they increased over the same period and for the modern period the reliability of the conclusion about their significance exceeds 0.95.

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