Application of wavelet analysis methods to study the climate of the Arctic region

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Abstract. This paper provides an assessment of the possibilities and advantages of using wavelet analysis methods in the study of regional mechanisms of climate formation in the Arctic region by analyzing the relationship between the values of the air temperature anomalies at the Earth's surface and the North Atlantic Oscillation index. It is shown that the methods of wavelet analysis of climatic indices have certain advantages for identifying cyclical changes in climatic characteristics on local time scales and allow an in-depth spectral assessment. The conducted wavelet analysis of the NAO and SAT index (1950-2020) made it possible to estimate the previously known natural quasi-cyclic oscillations with a typical period of 7-15 years and other dominant components of their spectrum.

1. Introduction
Climatic variability in the Arctic is primarily determined by regional and local mechanisms, many of which can play a decisive role. Such tools are associated with a considerable number of feedback regulating climatic processes in the Arctic [1]. Climate changes in the Arctic are amplified by feedbacks, among which the degradation of sea ice in the Arctic Ocean, which is acutely responsive to climate change, attracts particular attention. The removal of freshwater from the Arctic Ocean affects the distribution of sea ice, thermohaline circulation in the adjacent water area of the North Atlantic and through them on the regional and global climate. Several variable heat sources and feedback between them make the Arctic the region of the most significant climate change and fluctuations. Many features of interrelated processes remain insufficiently studied at present [2]. The intensity and direction of the influence of feedback caused by the methods of energy exchange at the ocean-atmosphere interface can be investigated by analyzing the time series of data characterizing climatic fluctuations in the Northern Hemisphere, including the Arctic region. The most significant changes that have a direct impact on the climate of the Arctic region include the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Atlantic Multi-Decade Oscillation (AMO) [3-6]. In most cases, the climatic data of these fluctuations are presented in the form of time series set at a finite time interval with a constant time step (day, month, year, etc.). This makes it possible to use spectral and wavelet analysis methods to study the characteristics and assess the potential effects of climatic fluctuations on the climate. It is important to note that it is precisely the role of these fluctuations and their regional impacts that little attention was paid to when predicting climate changes in the Arctic.

At its core, climatic fluctuations are a combination of various details into a full generalized description of the atmosphere or ocean, which can be further used to characterize the factors that affect the global climate system of the Arctic region.

This paper evaluates the possibilities and advantages of using wavelet analysis methods in studying the climate of the Arctic region using the example of the analysis of the North Atlantic Oscillation (NAO)
index and its relationship with the interannual variation of the mean annual air temperature anomaly in the Arctic region (SAT) (see Figure 1).

![Figure 1. Interannual variation of the Surface Air Temperature anomaly (SAT) (°C) averaged for the latitudinal zone 60–90 °N. for the period 15.01.1950—15.07.2020. (a) and the interannual variation of the standardized index NAO for the period 01/15/1950—07/15/2020. According to the BEST archive [7].](image)

We used the air temperature at the Earth's surface (SAT) synthesized at the NASA Goddard Institute of Space Science (NASA GISS) as part of the Berkeley Earth Surface Temperature (BEST) project as the initial information for assessing the interannual variation of the average annual air temperature in the Arctic region (for the latitudinal zone 60-90 ° N) [7]. The period 1951-1980 was used as the base averaging period for assessing air temperature anomalies; the methodology and algorithms for data processing and quality control at all stages are described [8]. In Fig. 1 (a) on the graph for the latitudinal zone 60-90 ° N. for the period 15.01.1950 - 07.15.2020 two pronounced warmings are visible. The first falls on the period 1950 - 1962, the second, more prolonged, - starting from the 1980s of the 20th century. In July 2020, the value of the average annual air temperature anomaly in the Arctic region reached its maximum for the entire history of observations - 2.45 ° C, which confirms the factual data on the unprecedented acceleration of the Arctic climate warming in recent years [9]. It is important to note that warming in the Arctic occurs against the background of a predominantly positive phase of fluctuations in the index NAO (warm Arctic) [10].

The North Atlantic Oscillation (NAO) is associated with North America, Greenland, and Europe's prevailing weather patterns, the difference in the surface height of 500 hPa between points in Iceland (64 ° N, 24 ° W) and near the Azores (39 ° N, 24 ° W) during the winter-spring season is considered as the index NAO. Data source NAO: National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center. The index values are publicly available on the official website of the organization [11].

During the period when the index values are high, an increase in the subtropical pressure maximum and the deepening of the Icelandic minimum are observed, which leads to large gradients between these atmospheric formations and an increase in winds carrying warm and humid air from the Atlantic Ocean to northern Europe, while in Canada and Greenland is dominated by dry and cold weather. During the period of low values of the index, the intensity of atmospheric formations weakens. The power of winds decreases, and their direction shifts towards the Mediterranean, where warm, humid weather sets in. In northern Europe, in this case, on the contrary, dry and cold weather prevails.

There is reason to believe that the North Atlantic Oscillation affects the Atlantic Ocean and, being part of the global circulation, has a connection with the oscillations of the entire Northern Hemisphere. In particular, the mechanism of its impact on the Arctic region's climatic dynamics was studied using the INM-CM5 climate model with a period of about 15 years [10]. For this, a technique was used to calculate the contribution of various terms to the generation of oscillation energy and phase change. As a result, it was shown that during the positive phase of the oscillation (warm Arctic), the below zero temperature and salinity anomaly occur in the North Atlantic's temperate latitudes. A positive North Atlantic Oscillation Index accompanies these anomalies. A quarter of the period after the warming of the Arctic, warming and salinization occurs in the North Atlantic's temperate latitudes. In the Arctic Ocean, temperature anomalies arise due to increased advection of Atlantic water [12]. The oscillation phase's evolution occurs due to the transfer of heat from the Atlantic and the flow of heat on the surface. Anomalies in currents transferring heat from the Atlantic to the Arctic Ocean are generated mainly by wind friction.
The purpose of this work is to assess the possibilities and advantages of using wavelet analysis methods in the study of regional mechanisms of climate formation in the Arctic region by the example of analyzing the values of the interannual variation of the mean annual air temperature anomaly averaged in the Arctic region near the Earth's surface (SAT) and the North Atlantic Oscillation index (NAO).

2. An object of study and methods

2.1. The advantage of wavelet transforms over Fourier transforms

Wavelet analysis is used in problems related to the study of spatial fields with a complex multiscale structure (turbulent flow) or temporal signals with a spectral composition that changes over time (natural and economic cyclic processes). The wavelet transformation's main idea meets the specifics of many time series, demonstrating the evolution in time of their main characteristics - mean value, variance, periods, amplitudes, and phases of harmonic components. The overwhelming majority of processes studied in various fields of knowledge have the above features [13]. The advantage of the wavelet transform over the Fourier transform is that it allows you to trace the change in the signal's spectral properties with time and indicate which frequencies (scales) dominate the movement [36].

In several works, connection was found between various climatic indices, including the North Atlantic Oscillation (NAO) index (distinct periods of 7-11, 22-40 and 40-80 years, respectively) with the regime of precipitation and temperature, directly affecting the formation of the climatic control of the Arctic [14.15]. To recognize such nonstationary processes, the wavelet analysis method has been increasingly used recently [16]. In studies of this kind, the most interesting is the determination of the nature of a random process and the concept of causes that lead to fluctuations in atmospheric parameters that differ in characteristic periodicities or cycles.

2.2. Results of wavelet analysis of NAO and SAT and ways of their presentation

The one-dimensional Fourier transform also gives one-dimensional information about the relative contribution (amplitudes) of different time scales (frequencies) [16]. The result of the wavelet transform of the one-dimensional series \( f(t) \) is a two-dimensional array of wavelet transform amplitudes of the values of the coefficients \( \omega(a, b) \):

\[
\omega(a, b) = a^{\frac{1}{2}} \int_{-\infty}^{\infty} f(t) \psi' \left( \frac{t-b}{a} \right) dt, \quad \text{where} \quad \psi(t) \text{ is a real or complex function.}
\]

The distribution of these values in space \((a, b) = (\text{time scale, time localization})\) gives information about the evolution of the relative contribution of components of different scales in time and is called the spectrum of the wavelet transform coefficients (time - scale spectrum, or wavelet spectrum in contrast to the single spectrum Fourier transform).

The spectrum \( \omega(a, b) \) of a one-dimensional \( f(t) \) signal is a surface in three-dimensional space. The way this information is visualized can vary. Instead of images of characters, one often presents their projections onto the plane \((a, b)\) with isolines, which make it possible to trace the change in the intensity of the wavelet transform amplitudes at different scales and in time, as well as pictures of the lines of local extrema and these surfaces (Power spectrum), which reveal the structure of the analyzed process.

Fig. 2 and Fig. 3. show the results of the Wavelet analysis of time fluctuations in NAO and the interannual variation of the mean annual air temperature (SAT) anomaly averaged in the Arctic region. In Fig. 2, the lighter areas correspond to positive, and the dark ones, to negative values of \( \omega(a, b) \); the ranges of values are highlighted in shades of colour in each of the areas \( \omega(a, b) \). It is clear that the value of the wavelet transform amplitude at the point \((a_0, b_0)\) is the more significant (in absolute value), the stronger the correlation between the wavelet of a given scale and the behaviour of the signal \( f(t) \) in the vicinity of \( t = t_0 \). The coefficients' picture demonstrates that the process consists of different scales: the extrema \( \omega(a, b) \) are observed at different scales, their intensity changes both with time and with the plate.
Figure 2. Spectral characteristics of the interannual variation of the smoothed values of the index (NAO) - (a) and its wavelet spectrum for the NAO index - (b and c) for the period 01.1950 - 07.2020. The wavelet transform decomposes the analyzed process into its constituent waves, components of different scales, and gives information about the process localized in time. Having wavelet spectra, one can calculate valuable characteristics of the process under study and analyze many of its properties. Let us describe the possibilities of exploring the features of the signal and its energy characteristics in more detail.

Figure 3. Spectral characteristics of the interannual variation of the mean annual air temperature (SAT) (°C), averaged for the latitudinal zone 60-90 N. - (a) and its wavelet spectrum for SAT - (b and c) for the period 01.1950 - 07.2020. Source: authors’ calculations.

The horizontal section of the picture shown in Fig. 2 (c) and 3 (c) (Power spectrum), at a given scale, and demonstrates the change in the component of the selected scale over time. Power spectrum allows you to highlight the distinct periods for the analyzed signal (time series of oscillation data). For NAO and SAT, there are six line maxima each, labelled with digital signatures next to the Power curve. However, in contrast to the Fourier spectrum, we see that both the periods and the amplitudes of these lines change over time. The position of such maxima (peaks) of the Fourier spectrum is usually associated with the frequencies and the corresponding characteristic modes of the analyzed signal, which carry the primary energy of the process. The Power spectrum maxima are interpreted in a similar way - they determine the scale of the process that makes the main contribution to the total energy.

3. Results and discussion

To interpret the obtained results of the wavelet analysis of the NAO time fluctuations and the SAT interannual variation, it is necessary first to consider in detail the mechanisms of the possible NAO impact on climatic variability Arctic region. Since at least the 18th century, it has been known that if Denmark has a harsh winter, then Greenland’s winter is milder than usual, and vice versa. This behaviour is part of a climate behaviour pattern known as the North Atlantic Oscillation. The North Atlantic Oscillation is the fluctuation in atmospheric pressure at sea level between the Arctic and the subtropical Atlantic that is most noticeable during the Arctic cold season (November-April) is associated with changes in mean wind speed and direction. Westerly winds blowing across the Atlantic bring warm, humid air to Europe. When westerly
winds are strong, summer is cool, winter is moderate, and precipitation is more frequent. If the westerly winds weaken, the temperature in summer and winter reaches its critical levels, leading to the transfer of warm air masses, severe frosts and less precipitation. The constant low-pressure area over Greenland and the Azores’ constant high-pressure area govern the westerly winds’ direction and strength into Europe. Changes in the North Atlantic Oscillation alter the regular seasonal transport of heat and precipitation between the Atlantic and neighboring continents. The number of storms, their strength and direction of movement also change.

Changes in the North Atlantic Oscillation cause significant changes in ocean surface temperatures, ocean currents, and associated heat transfers. Changes in ice cover in arctic and subarctic regions are also associated with the North Atlantic Oscillation. These climatic changes can impact agricultural yields, water supplies, energy supplies, fish catches, etc. An extensive NAO index is called a positive phase - a small index, respectively, a negative phase. In a positive phase during winter, westerly winds intensify along the North Atlantic, moving relatively warm and moist sea air along much of Europe and further through Asia. In contrast, stronger northerly winds carry cold air along Greenland and northeastern Canada to the south. At the same time, the air temperature and the temperature of the ocean surface in the northeast Atlantic decrease.

Wavelet analysis of the NAO and SAT index (1950 - 2020) revealed the characteristic dominant (11 - 13-year period) harmonic components and smaller ones (0.97 - 6.5 years). The maximum power of the global wavelet spectrum for the NAO is at the 13 - year harmonic, for the SAT - the harmonic at 6.5 years. Simultaneously, there is a statistically significant relationship between the characteristics of the global wavelet spectrum NAO and SAT in the low-frequency region of oscillations (Table 1.).

### Table 1.

Characteristics of the global wavelet spectrum (Power spectrum) for NAO - (a) and for SAT - (b) for the period 01.1950 - 07.2020 for the latitudinal zone 60-90° N. according to the BEST archive

|       | Power NAO (max) | Periods (y.) | Power SAT (max) | Periods (y.) |
|-------|----------------|--------------|----------------|--------------|
| (a)   | 1.1461         | 0.24         | 2.7553         | 1.60         |
|       | 1.7155         | 5.50         | 3.0113         | 11.0         |
|       | 1.8125         | 0.49         | 3.5444         | 2.80         |
|       | 2.7019         | 2.30         | 4.4167         | 0.97         |
|       | 2.8252         | 0.97         | 4.6527         | 4.60         |
|       | 3.3877         | 13.0         | 5.1350         | 6.50         |

The graphs of the NAO and SAT index changes are a series of peaks, each of which covers a certain period (Fig. 2 (a) and Fig. 3 (a)). It can be seen from the figures that the amplitude of their oscillation cycles is continuously changing. Analysis of the characteristics of the global wavelet spectrum (Power spectrum) for the NAO and SAT index (1950-2020), shown in Table 1, made it possible to estimate not only the previously known natural quasi-cyclic oscillations with a typical period of 7-15 years but also other dominant components of the spectrum. The interannual variability of the NAO index during the warming of the Arctic is complex. The positive phase (growth of the NAO index) means an increase in the western geostrophic transport of air masses in temperate latitudes, an increase in southerly winds in the eastern part of the North Atlantic, an increase in northerly winds in the Labrador Sea, a mixing of cyclone trajectories to the north, which ultimately causes the formation of negative water temperature anomalies in temperate and subpolar latitudes. For the negative phase of NAO, the opposite situation is characteristic: favourable conditions are created for an increase in the SAT temperature anomaly due to the prevailing southwestern winds over the area of the North Atlantic Current. This leads to a rise in the inflow of warm water into the North European Basin and into the Barents Sea, which manifests itself in a decrease in efficiency and an increase in water temperature in the Kola section meridian.

### 4. Conclusion

Using the methods of wavelet analysis, the contribution of various terms to the generation of the oscillation energy of the NAO index and the interannual variation of the mean annual air temperature (SAT) for the latitudinal zone of 60-90° N was estimated. Warming in the Arctic occurs against the background of the positive phase of fluctuations in the NAO index (warm Arctic). This suggests that the generation of temperature anomalies in the Arctic Ocean occurs due to increased advection of Atlantic water. Wavelet analysis data showed that NAO and SAT have characteristic dominant oscillation harmonics close in their
values, which confirms a specific contribution of NAO to the regional mechanisms of the currently observed warming of the Arctic. NAO influences ocean currents and associated heat transfer processes. In the positive phase of NAO, westerly winds intensify along the North Atlantic, moving relatively warm and moist sea air along much of Europe and further through Asia. In contrast, stronger northerly winds carry cold air along Greenland and northeastern Canada southward. At the same time, the air temperature decreases in the northeast of the Atlantic.

The performed estimates of the global wavelet spectrum (Power spectrum) for the NAO and the SAT showed a statistically significant relationship between them in the low-frequency region of oscillations. Therefore, climatic changes caused by cyclical fluctuations of the NAO index can be of considerable importance in the formation of the climate of the Arctic region, which is comparable to the current long-term trend of warming of the Earth's atmosphere, in turn, caused by external, mainly anthropogenic factors [17].

The relevance of the use of wavelet analysis methods in the study of the climatic characteristics of the Arctic region is determined by the fact that monitoring, diagnostics and physical description of the leading regional mechanisms of climatic variability (climatic cycles) in high latitudes of the Northern Hemisphere will minimize technological and environmental risks, increase the efficiency and safety of production processes.

Modern global climatic changes will contribute to the fact that the number of permanent residents of the Arctic latitudes will grow steadily. This will be possible due to the ongoing warming, which is most pronounced in the Arctic [18]. Due to the rapid melting of sea ice and permafrost, it will become easier to access the deposits in the coming years. Tourists will be able to access the Arctic. In a warmer climate, it will become easier to conduct economic activities, which will ultimately cause an influx of the region's resident population. This determines the importance of monitoring, diagnosing and physically describing the main regional mechanisms of climate variability (climatic cycles) in the Arctic region.

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