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OCEANOLOGY

Forecast of Natural Variations in Air Temperature and Sea Ice on the East Siberian Sea Shelf for the Coming Centuries

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Abstract—Based on the spectral analysis results obtained for air temperature and ice cover on the East Siberian Sea shelf reconstructed for the past five thousand years, empirical forecast models have been constructed to record the "natural trend scenario" of these climatic parameters in the coming centuries. Based on the forecast construction results, the duration of the ice-free period, as well as the near-surface air temperature, will tend to increase in the future. The studies conducted make it possible to suggest the anthropogenic influence on the temperature and ice conditions in the studied region in the industrial period. Taking into account this factor, it can be assumed that the studied natural phenomena will have a higher rate than is indicated by the models.

Keywords: paleoclimatology, forecast, sea ice, surface annual temperature anomalies, geochemistry, Arctic oscillation, solar radiation, East Siberian Sea

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INTRODUCTION

The climate is known to have a huge impact on human living conditions and to play a great role in its history. Numerous facts are indicative of the relationship between major political, social, and economic upheavals and climate events [1, 2]. Today, the causes of the current "global warming" and the possible negative consequences of this phenomenon for human civilization are actively being discussed. In this regard, the problem of constructing various forecast models of the future climate changes and the related natural phenomena seems very relevant.

The formation of the climate is based on the interaction between numerous different-scale natural phenomena and processes. Currently, two approaches to constructing the forecast climate models can be distinguished: physicomathematical and empirical. The physicomathematical modeling involves an a priori formulation of a range of natural and anthropogenic factors influencing the climate process under study or a natural phenomenon related to it, indicating their direct and reverse relations in a strictly formalized form. By setting different trend scenarios for the climate-forming parameters, it is possible to model the development of the future climate. Modeling results are regularly published by the Intergovernmental Panel on Climate Change (IPCC) in reviews of the actual state of the global climate system [3].

When building empirical models, no information on the natural factors affecting the system state and their relationships is required, because this modeling approach is based on the study of a certain relatively representative amount of data on the trends of the studied system over time. The final objective of empirical modeling is to identify trends of the phenomenon under study as formulas, equations, correlations, graphs, etc., to extrapolate the trends of the studied system outside the original time series. In this case, a substantial interpretation of the identified patterns is not necessary to obtain the final result.

The physicomathematical approach to modeling is definitely more rigorous and effective when focusing on well-studied processes. However, the relationships between numerous climate-forming parameters are so complicated, diverse, and hard to formalize that it is almost impossible to take them into account fully when constructing climate models. Empirical modeling is very efficient when studying phenomena that have not yet been thoroughly investigated. Due to the

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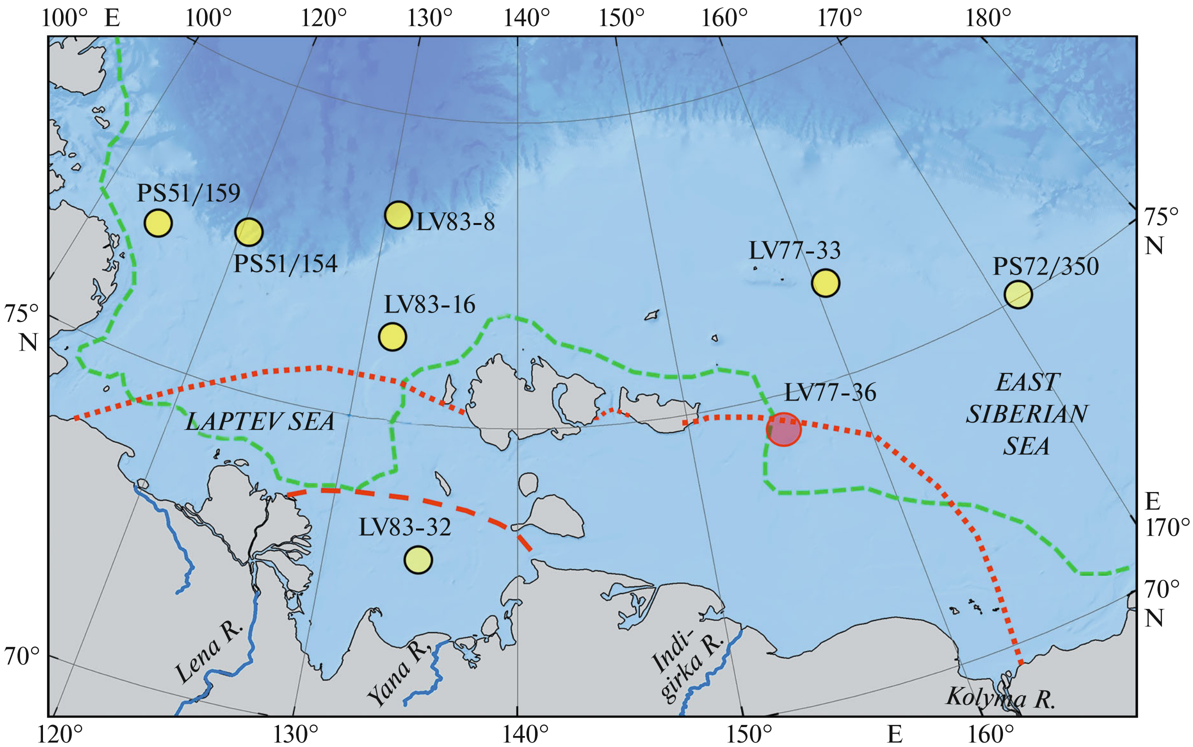

Fig. 1. Location of the core LV77-36 and other cores used in this work (according to [5–7]). A green dashed line shows the southern boundary of drifting ice; red dashed and dotted lines show the salinity isolines in July–September: 17 and 23‰, respectively (according to [7]).

fact that climate formation does not currently have an unambiguous, strict mathematical description, the use of this approach in this study seems completely justified.

Recent years have been marked by a considerable activation of the economic activity in the East Arctic offshore area. This activity is due to comprehensive prospecting and mining of mineral deposits, laying of pipelines and communication cables, and construction of a transport and logistics system along the Northern Sea Route. In this regard, the study of climate changes and related phenomena in the basins of the East Arctic Sea considerably affecting the success of these economic projects is becoming increasingly important.

Our objective was to study the East Siberian Sea waters by analyzing the data on past surface air temperature values and the duration of the ice-free period in this region over a relatively long-term interval, to reveal certain variation trends, and to build an empirical model of the phenomena trend scenario by extrapolation to the near future.

MATERIALS AND METHODS

The initial data of this paper included the reconstructed duration of the ice-free period and anomalies of the average annual surface air temperature for the last eight thousand years obtained using the core LV77-36 from the western part of the East Siberian Sea [4]. The core was obtained during the Russian–Chinese expedition, voyage 77 of R/V *Akademik M.A. Lavrentiev,* in 2016 at the point with the coordinates of 155.66° E, 74.10° N at a sea depth of 36.0 m (Fig. 1).

The age model of the core was substantiated by twelve AMS^{14}C dates of bivalve shells corrected by seven quartz dates by the optically stimulated luminescence [7].

The analysis of the chemical composition of the core material made it possible to reveal a correlation between the material composition of bottom sediments and the temperature and ice conditions in the region under study [6, 8]. The data obtained were used to make paleoreconstructions of these parameters for the entire depth of this core based on multidimensional regression analysis [4]. The reconstruction data over the last 5000 years (Fig. 2), when the sea level position corresponded to the current one, served as the source material for constructing the predictive scenarios of changes in the regional surface air temperature and ice cover for the coming centuries in the East Siberian Sea. Accordingly, we used the average annual surface air temperature (T, °C) reconstructed with decadal averaging [8] (hereinafter referred to as

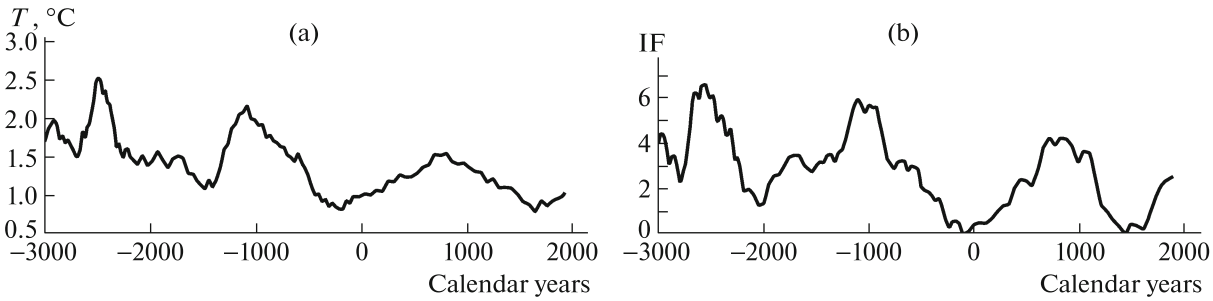

Fig. 2. Paleoreconstructions of anomalies of (a) the average decadal surface air temperature and (b) the duration of the ice-free period over the last 5000 years at the station LV77-36 (according to [4]). Calendar years here and further: 0-2000 AD; 0-(-3000) BC.

"decadal average") and an ice-free period duration (IF) in decades (ten days).

The climate changes on our planet are clearly oscillatory in nature, and the periods of observed cyclic rhythms range from a few years to millennia ([9–15], etc.). Different periods of cyclic changes in the climate trends and related natural phenomena during the Holocene were also found for the Arctic seas [4, 8, 15, 16]. The identification of such multifrequency periodicities when analyzing the climate chronologies by harmonic analysis makes it possible to solve various extensive problems [11, 12, 14, 17–19], in particular, to make short- and long-term climate forecasts [15, 20].

In this case, the correlogram additive decomposition method (CADM) was used to analyze the abovementioned paleoreconstructions [20]. This method makes it possible to decompose any complex time series of data into several component functions as linear trends and a set of different-frequency quasi-periodic oscillations. In comparison with the better-known methods, such as the Fourier transform or wavelet analysis, this method is relatively simple and does not require specifying an a priori functional basis (component functions are derived adaptively directly from the analyzed series); furthermore, it is fairly suitable for the analysis of complicated nonlinear and nonstationary processes.

CADM solves this problem according to the following algorithm. The first step is identification of the linear trend of the analyzed time series subtracted from the original chronology. Then, the detrended time series is subjected to multiple exponential smoothing by the moving average method with a stepwise reduction in the smoothing window. If the smoothed function reaches a metastable state during processing, in particular, it maintains an almost unchanged shape over several iterations, then this signal is taken as the first quasi-periodicity, subtracted from the original function, and the processing process is continued. The components are revealed automatically by identifying characteristic points on the correlogram, which displays the smoothing process. As a result, the original time series is decomposed into a linear trend and a number of quasi-periodic components, from low-frequency to high-frequency, and an excess, which in total give the original function: $X(t) = Tr(t) + \Sigma C_k(t) + R(t)$, where $X(t)$ is the initial time series; $Tr(t)$ is a trend; $C_k(t)$ are quasi-periodic components, $k = 1, 2, ..., n$; n is the number of identified terms; and $R(t)$ is the last remaining function.

RESULTS

The described method was used to carry out a spectral analysis of the reconstructed temperature and ice conditions on the East Siberian Sea shelf over the past five thousand years. To exclude the possible influence of the anthropogenic factor on the analysis results, the time series of up to 1850 AD usually taken to mark the beginning of the industrial period was processed. The analysis results are demonstrated in Figs. 3 and 4.

As can be seen from the figures, the analyzed reconstructions were decomposed into trends and a set of quasi-periodic components the total of which exactly coincided with the original time series. In other words, it can be stated as follows: if the selected components are extrapolated to a certain time interval and then summed up, it is possible to build an empirical forecast model to display the "natural" development scenario of the analyzed natural processes in the future. However, due to the fact that the components identified by spectral analysis are quasi-periodic in nature, the implementation of this procedure faces some uncertainties and carries an element of subjectivity. To give the extrapolation procedure the maximum accuracy and unambiguity, an approximating sinusoid was selected for each quasi-periodicity (Figs. 3b–3d, 4b–4d). The optimizing criteria included maximizing the correlation coefficient between quasi-periodicity and sinusoid (optimizing periodicity) and minimizing the value of $S = \Sigma|Xi - Yi|$, where Xi and Yi were the quasi-periodicity and sinusoid values for the ith year (amplitude optimization).

The error arising when replacing quasi-periodicities by sinusoids was estimated by comparing the original reconstructions with time series obtained by summing trends and approximating sinusoids: for temperature reconstruction, the error estimated by the

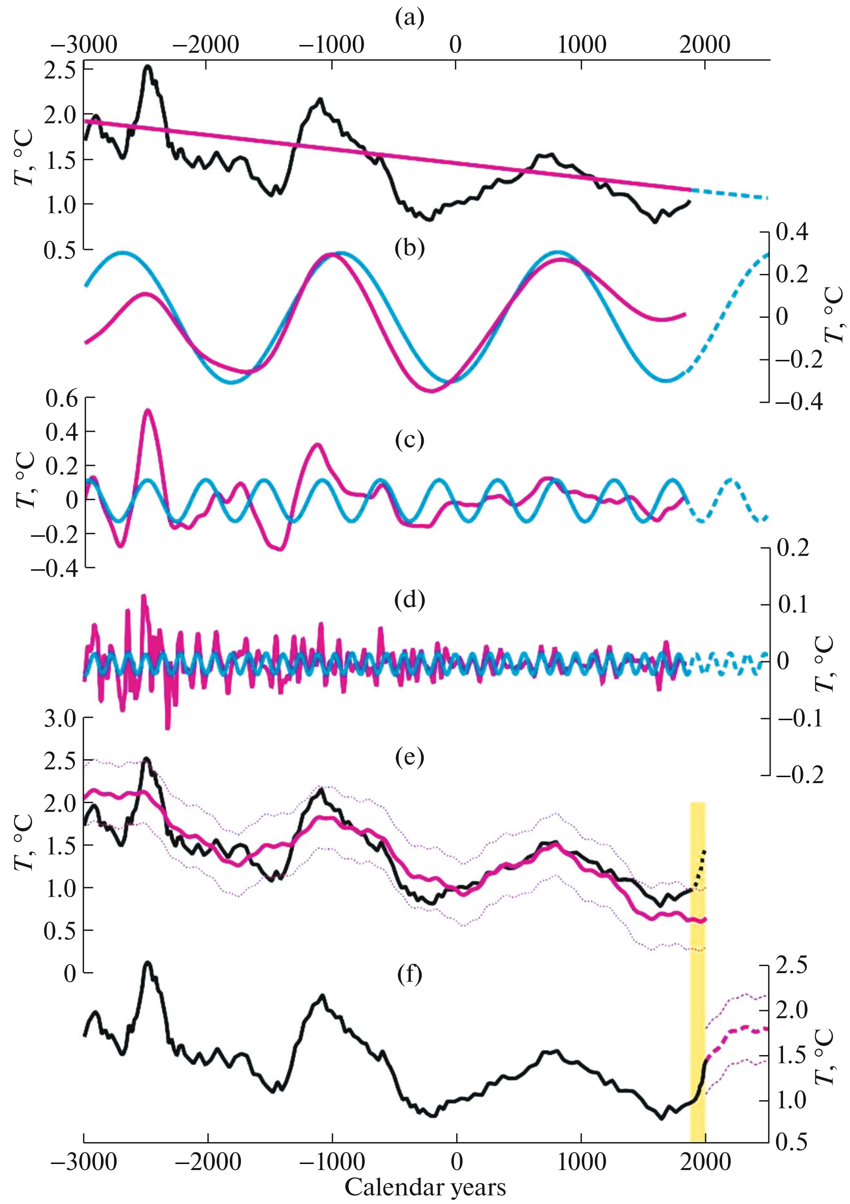

Fig. 3. Spectral analysis of variations in the average decadal air temperature for the past 5000 years reconstructed from the core LV77-36 and forecast for the next 500 years. (a) Initial temperature reconstruction (black line), linear trend (red line), and its extrapolation for the next 500 years (blue dotted line); (b, c, d) identified 1740-, 470-, and 140-year quasi-periodicities (red lines), sinusoids approximating them (solid blue lines), and their extrapolation to the next 500 years (blue dotted lines); (e) comparison of the temperature reconstruction (black line, dotted line shows instrumental measurements) with the time series obtained by summing up the trend and approximating sinusoids (red line, dotted line shows the 95% confidence interval); (f) forecasted temperature conditions indicating the 95% confidence interval. The temperature values in diagrams b, c, and d are indicated as anomalies relative to the previous component. The yellow shading shows the industrial period.

95% confidence interval was ±0.36°C (with $r = 0.86$ and $r^2 = 0.74$), and for the reconstructed ice-free period, ±1.32 (at $r = 0.87$ and $r^2 = 0.75$) (Figs. 3e, 4f).

The extrapolation of the trend and sinusoid total from the current state of the studied natural phenomena for the next 500 years made it possible to obtain the scenarios for the temperature conditions and the ice-free period duration within the East Siberian Sea shelf for a given time interval related to the external natural influences without taking into account the anthropogenic factor (Figs. 3f, 4g).

DISCUSSION

The identified general trend and subperiodicity of changes in the ice-free period and surface air temperature at the station LV77-36 can be explained based on

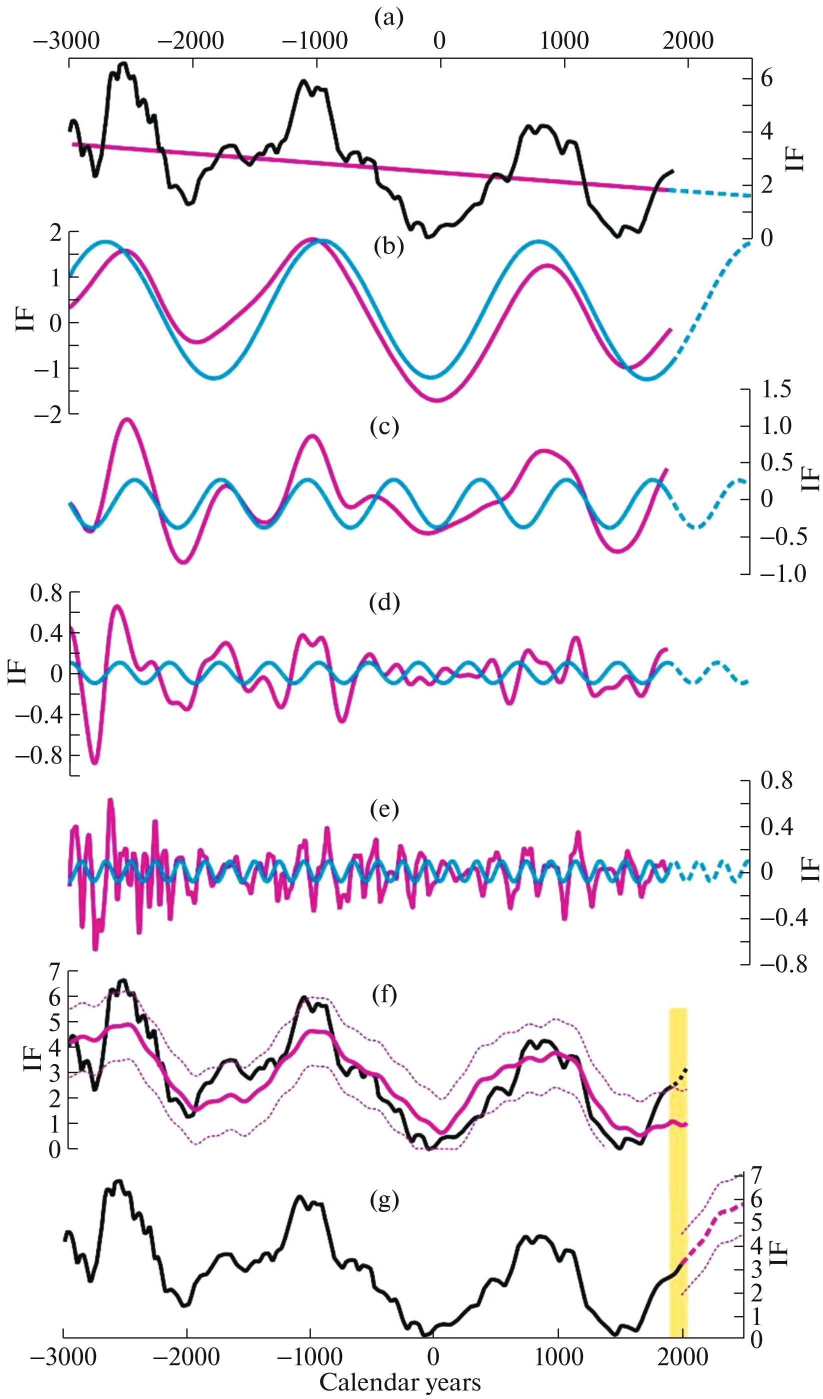

Fig. 4. The spectral analysis of the average decadal duration of the ice-free period (IF, decades) for the past 5000 years reconstructed from the core LV77-36 and a forecast for the next 500 years. The legend is similar to that in Fig. 3. The ice-free periods in diagrams b, c, d, and e (subperiodicities of 1750, 700, 400, and 200 years, respectively) are indicated in anomalies relative to the previous component.

the current ideas of the climate variability in the Arctic region. The trends of increasing ice cover (decreasing IF) and decreasing T (Figs. 3, 4) correspond to the orbitally determined change in the total solar radiation in summer at these latitudes [7].

Earlier [4], the longest subperiodicity identified from variations in IF and T (1740–1750) in the core LV77-36 was compared with the Bond cycles (1470 ± 500 years) identified in the North Atlantic region from a changing direction of iceberg rafting in the Holocene

[16]. The nature of these cycles and the related Dansgaard–Oeschger cycles characteristic of the ice ages is debated. In the Laptev Sea, these cycles are compared with the periodicity of changes in the 1500 ± 500-year ice conditions identified from biomarkers [5]. In the eastern Arctic seas, these cycles were determined from the changing direction of ice transport from the Kara (1560) or Laptev (1700) seas [16] and compared with variations in the Arctic Oscillation (AO). The latter records the pressure conditions over the Arctic Ocean, which, first of all, affects the wind direction and, accordingly, the ice and surface water movement.

The connection with solar cycles is more pronounced for short-period subperiodicities. In relation to *T*, the used subperiodicities of 470 and 140 years (Figs. 3c, 3d) have analogues in the total solar radiation cycles of 500 and 140 years [16]. Meanwhile, they can also be traced in the AO cycles determined from the ice removal from the Laptev Sea (480 and 131 years, respectively [16], supplementary data).

As for the identified IF subperiodicities with a duration of 1740, 700, 400, and 200 years (Figs. 4b–4e), analogues in the AO cycles are available for long-term periods (1700, 690 years) and, probably, for 400 (380) years ([16], supplementary data). The subperiodicity of 200 years corresponds to one of the main Suess–deVries solar activity cycles (200 years) [20] and has an analogue in variations of the total solar irradiation as clearly defined cycles of 210 years [16]. The water and thermal runoff of Siberian rivers, considerably dependent on variations in the solar irradiation, due to a number of factors, affects the ice conditions of the Arctic shelf, in particular, at station LV77-36 [7] located on the East Siberian Sea shelf, in the area where sea waters are desalinated by river outflows (Fig. 1). Hence, it can be assumed that, in addition to atmospheric oscillations (AO), the variability of ice and temperature conditions at a given station and, accordingly, their forecast, are influenced by various climate-forming processes, including those characteristic for the mainland.

The forecast for *T* and IF variations in the coming centuries (Figs. 3f, 4g) is based on the identified natural regularities (trends and cyclicities) in these parameters over the past five thousand years, without taking into account the industrial period, when the anthropogenic factor could influence the natural phenomena under study. In other words, the presented options for changes in temperature and ice conditions in the region under study record the "natural" scenario without taking into account the possible man-made impacts on the environment in the future. However, a comparison of the instrumental measurements of *T* and IF values in the period after 1850 with the model of their "natural" behavior is indicative of their trend of being outside the upper limit of the 95% confidence interval. Hence, the influence of the anthropogenic factor on the temperature and duration of the ice-free period toward their increase can be suggested (Figs. 3e, 4f). It should be noted that a decrease in ice cover in the last century was also noted from the reconstructed ice conditions based on materials from other stations in the Laptev and East Siberian seas (Fig. 1) [5, 6]. The impact of industrialization is especially clear in relation to the temperature curve, where the excess of instrumentally measured parameters over "model" indicators is about 0.5°C (Fig. 3e). Considering that the forecast continues from the current state of the parameters, it takes into account changes caused by the anthropogenic influence during the industrial period. The following can be assumed: if the anthropogenic impact on climate events continues in the very near future, *T* and IF will increase at a higher rate than recorded in the forecast constructions.

CONCLUSIONS

The retrospective spectral analysis of paleoreconstructions of the temperature and ice conditions in the East Siberian Sea over the past five thousand years made it possible, bypassing the complicated physical and mathematical simulation modeling, to construct the empirical forecast models recording the "natural trend scenario" of these climatic phenomena in the coming centuries without taking into account the anthropogenic factor.

The comparison of variations in the surface air temperature and the duration of the ice-free period in the East Siberian Sea makes it possible to reveal their synchronous behavior over the previous 5000 years most obviously manifested in ~1750-year quasi-periodicity. The correlation of these parameters, judging from the forecast constructions, will be observed in the future. The ice-free period will be characterized by a continuous trend to increase in the coming centuries, reaching the maximum values already observed in the last five thousand years. The temperature will also presumably increase in the studied region with the following leveling off at about 1.8°C.

Based on our study results, we can conclude that the anthropogenic factor exerted some influence on temperature and ice conditions in the studied region in the industrial period. Due to the fact that the forecast constructions record the development of these natural phenomena in the future according to the "natural scenario," it is possible that the duration of the ice-free period and, to a greater extent, the air temperature will increase at a faster rate due to the anthropogenic impact.

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SUPPLEMENTARY INFORMATION

Supplementary materials, digital data, and forecast results can be requested from the authors.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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