# Analysis and estimation of rhythmic changes in climate

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The system-evolutionary approach to description, analysis, and estimation of climatic changes based on results of processing instrumental observations is discussed. Techniques for identification and technologies for analysis of rhythms in long-term changes of temperature regime are suggested. The techniques use a description of a sequence of states with seasonal (monthly) temperature extrema and the behavior of long-term changes in the length of cold and warm seasons. Examples and results of analysis of rhythmic temperature changes are given: the cyclic changes of winter temperature extrema with a period equal to the main solar cycle (179 years); features of the warming in Siberia with a stable tendency to formation of a regular rhythm. The interval estimation of regional warming rates based on the temperature increases in equitype phases of a cycle gives values between 0.6 and 1.4°C for the last 180 years.

## Introduction

Rhythms of multi-parameter processes reflect the ordered regular dynamics of complex systems. There are several types of rhythmic components of different scales in the hierarchy of the climate-forming processes: synoptic, seasonal, annual, multi-annual, multi-decade, centurial. A number of papers[1–3] are devoted to problems of non-stationarity in dynamics of climatic system, oscillations, and fluctuations of climate, analysis of periodicities in a series of observations. It follows from these papers that strict periodicity of climate-forming processes in the framework of a complex multi-level system of astro-geosphere climatic relations is not realized. However, we revealed intervals with characteristic rhythm of change of seasonal meteorological parameters (rhythm phases), regularly repeated in a certain time period. We succeeded in revealing this fact when studying the nature of rhythmic changes of the climate characteristics and biotic processes in biosphere from the unified meteorological standpoint of system-evolutionary approach to the analysis of structural changes, transformation of inter-system relations, and reorganization of the cycle of processes in the geosphere.

The investigations were carried out based on the concept of energy-transforming systems and the energy and mass transfer in geosphere.[4] The system intrinsic mechanisms of the energy transformation and weather forming within a regional climatic system (CS) were found. The oscillations of climate in northern latitudes on the decadal scale are found to be determined by the mechanism of the change of the cycle of the energy transformation and energy and mass exchange between energy transforming systems of the ocean and land at reorganization of relations in the ocean–cryosphere–atmosphere–land system[5,6] due to desalination of ocean water and change of ice amount in arctic seas, which cause long-term (several decades) changes of the climate and energy and mass transfer in mid-latitudes of Eurasia. Analysis of long series of net instrumental observations allowed finding regularities in the long-term behavior of extrema of meteorological parameter seasonal characteristics, in formation of arrhythmias and sequences of extrema characterizing the character of transformation of the energy and mass transfer.

Taking into account that variations in the atmospheric pressure and weather-climatic conditions are caused by changes in the gravity forces of planets acting on the Earth,[2] it was hypothesized that rhythmic changes in winter temperatures are connected with rhythmic variations of gravity forces (at the change of the distances between planets during their motion) and the Earth's position on the orbit around the Sun. V.V. Ivanov has shown the essential role of the solar energy flux modulation due to variations of the Earth's position on the orbit, as well as the predicting significance of astronomic factors.[2]

Development of methods of system-evolution analysis for multi-level systems, taking into account astrogeospheric relations, interaction of macroscale and regional processes requires qualitatively new tools for full and accurate description of peculiarities of the multi-level climatic system state, identification of the process of its transformation, and the technique for analysis of the variations.

The scientific-methodical principles of the information technique for analysis of rhythmic variations of the climate characteristics and estimation of climate changes taking into account the rhythmic component are presented in this paper.

## 1. Methodical and physical foundations for analysis of rhythmic changes in climate

Methods for system-evolution analysis of changes in the environment and climate,[4,5]

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information techniques for estimation and interpretation of the observed changes[6] are realized using the algorithms and techniques for processing different data of net and special observations; means of integrated representation of the ensemble of CS states, and constructing models. The climatic system is considered as organized multilevel formation of energy-transforming systems (ETS) connected by the cycles of the energy and mass transfer (EMT), energy and mass exchange (EME), and water circulation in particular geographical regions. The cycle of energy transformation and energy exchange in the ETS realizes certain regime of weather formation in a particular regional CS with corresponding organization of the processes in the near-ground atmospheric layer. In terms of the system-evolution approach,[3] the dynamics of states of the regional CS is described by models of non-stationary multi-step processes. The process of transformation of the state $X$ at a change of combination of factors $\Phi_1$, $\Phi_2$, $\Phi_j$, $\Phi_k$ is described by the relationship

$$X^{(p+1)} = X^{(p)} + L^{(p+1)}(\Phi_1, \Phi_2, \Phi_j, \Phi_k, X^{(p)}),$$

where $X^{(p)}$ is the matrix of the system characteristics at the stage $p$, $p = 0, 1, 2, 3, \ldots$; $L^{(p+1)}$ is the transformation operator of the weather formation regime and characteristics $X$ at the stage $(p + 1)$.

When analyzing the dynamics of the multi-stage approach, the integral estimating function $Z$ of a meteorological parameter is used (the discrete analogue $Z(k, n)$):

$$Z(t_1, t) = \int_{t_1}^{t} X(t)\mathrm{d}t, \quad Z(k, n) = \sum_{p=k}^{k+n} X(p), \quad n = 1, 2, 3, \ldots,$$

the properties of which make it possible to analyze the oscillation variability of sign-alternating parameters, characterizing the process.

We stated a set of estimating parameters for climate, which are significant for biosphere: the length of the vegetation period $\tau_v$, the length of the heat-deficient period $\tau_d$ (daily mean temperature $t_c < 10°C$), the sum of (active) temperatures of the vegetation period $Z_v$, the sum of heat-deficient temperatures $Z_d$ for the period $\tau_d$, the amplitude of annual behavior $A$, the extrema of monthly temperatures, rhythms of intra-seasonal temperature variations, the annual rhythm of seasonal (monthly) temperature variations, the rhythm of many-year changes of the estimating characteristics ($Z_v$, $\tau_v$, $Z_d$, $\tau_d$, $T_y$).

The information model of the weather-formation process contains a sequence of operators of climatic regimes and conjugated information elements of the multilevel database. The information model of an actual climatic process describes the ensemble of CS states for a long-term period and changes of climate in a geographic region.

The detailed analysis of dynamics of multi-regime weather-formation processes and the rhythm of the change of meteorological parameters has shown that transformations of the regimes of weather formation lead to formation of an ensemble of CS physical states, annual behavior of which is reflected in the rhythm of monthly temperatures.

The rhythms of monthly mean and seasonal temperatures in De Bilt city are shown in Fig. 1 for different climatic periods: the small glacial period (1810–1811), the period of the warming with a regular rhythm (1871–1872), and the modern period 1990–1991.

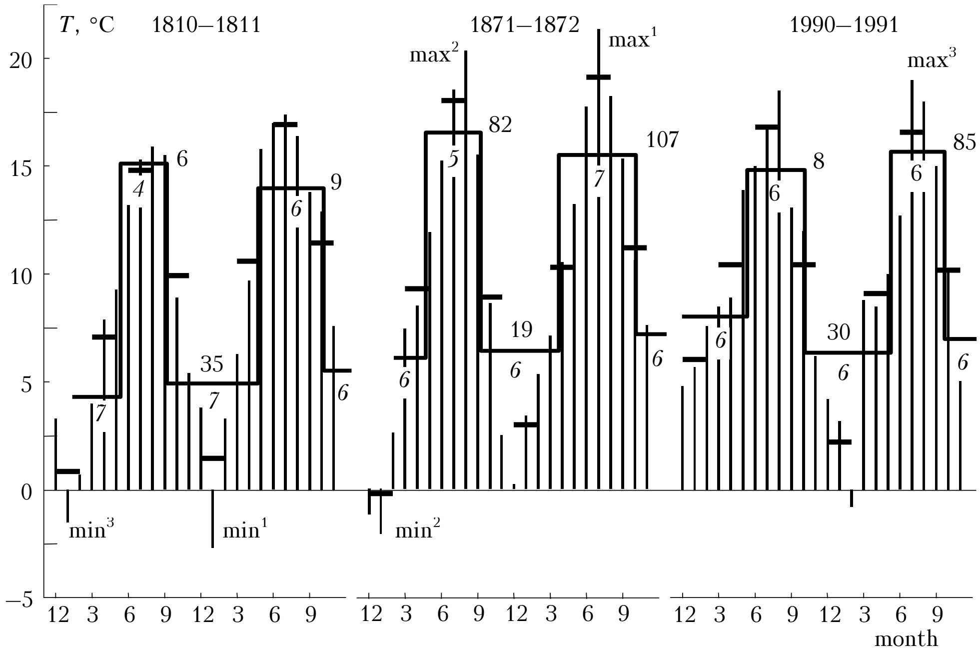


**Fig. 1.** Rhythms of monthly, seasonal, and estimating characteristics of the annual cycle. Lengths of cold and warm seasons (in months) are shown inside the columns, the values of the estimating characteristics (sums of monthly temperatures) are shown above the columns.

Annual rhythms differ in the amplitude, the repetition frequency of extrema of the first ($\max^1$, $\min^1$), second ($\max^2$, $\min^2$) and third ($\max^3$, $\min^3$) ranks in seasons, as well as in the amplitude of seasonal temperatures. Climatological estimation of variability of the repetition frequency of monthly summer and winter temperatures has shown that the repetition frequencies of maxima of the 2nd and 3rd ranks increase at warming, while those of minima decrease. Rhythms of interannual variations of the estimating characteristics (in months) ($\tau_v \to \tau_d \to \to \tau_v \to \tau_d$) change in the first ($5 \to 7 \to 6 \to 5$), second ($6 \to 6 \to 7 \to 5$), and the third periods ($6 \to 7 \to 5 \to 6$). The rhythm of the period 1842–1847 is characterized by the regularity, a higher long-term temperature, and small amplitude of interannual and long-term variations of the estimating temperature characteristics. Thus, it follows from empirical data that alternation of warm phases with regular rhythm and colder phases with irregular rhythm is the characteristic regularity of climate changes. It is observed throughout the warming and glacial periods. The observed empirical facts and the revealed regularity served the basis for working out of the methods, algorithmic and information techniques for analysis of rhythmic changes of the climate.

## 2. Description of rhythmic variations of regional climate characteristics

Rhythms of seasonal climatic characteristics at different phases of centurial cycle of climatic changes of pressure and temperature are described by a set of models. Their description is proposed in the form of a sequence of seasonal (monthly) temperature extrema. Extrema of seasonal temperatures are ranked by the amplitude. All states are numbered (within 180-year cycle) depending on the rank of the seasonal temperature extremum by corresponding signs: $N^*$ is the state $N$ with centurial extremum of the seasonal (monthly) temperature, $K'$ is the state $K$ with temperature extremum of the 1st rank, $M''$ is the state $M$ with temperature extremum of the 2nd rank. The sequence of states $N$, $K$, $M$, $P$ with extrema of high rank describes the rhythm $N^* \to K' \to M'' \to P'$.

The description of the ensemble of winter states (using the extremal characteristics of seasonal and monthly temperatures) for Saint Petersburg is presented in Table 1.

According to the information model, the rhythm of temperature variations of 1810–1829 in the beginning of a new cycle can be described by the rhythm model of the type $A1$: $03^* \to 04^* \to 10^* \to \to 13' \to 19'$, the rhythm of seasonal temperature variations between 1786 and 1799 in $N-1$ cycle can be described by the model of the type $C4$: $156'' \to 159' \to 162' \to 169^*$, the rhythm of the last phase of seasonal temperature variations at the 4th stage in $N-1$ cycle can be described by the rhythm of the type $D4$:

$$170'' \to 175'' \to 177'' \to 179^*.$$

More complete models are used to analyze the variability peculiarities in more detail. They describe the behavior of interannual changes of the CS states, the length of the cold $\tau_d$ and warm $\tau_v$ seasons, the amplitude of the temperature annual behavior, and the peculiarities of states (spring extrema ($B^*$) of temperatures, continentality ($C$), aridicity ($A$)). In general, the behaviors of state changes and the length of cold and warm seasons are described in the form:

$$N-1^* \quad \to \quad N^* \quad \to \quad N+1''$$
$$\tau_d(N-1)-\tau_v(N-1)\bullet\tau_d(N)-\tau_v(N)\bullet\tau_d(N+1)-\tau_v(N+1).$$

For example, the rhythm of long-term changes of the Saint-Petersburg climate states (by the temperature regime), taking into account the length of seasons within 1813–1818 is described in the form:

$$03^* \to 04^* \to 05 \to 06'' \to 07' \to 08$$
$$8\text{–}4 \bullet 8\text{–}4 \bullet 8\text{–}4 \bullet 8\text{–}4 \bullet 7\text{–}4 \bullet 9\text{–}4.$$

**Table 1. Information model of the ensemble of extremal winter states for Saint Petersburg**

| Year | 1754 | 1758 | 1760 | 1762 | 1768 | 1772 | 1776 | 1780 | 1783 | 1786 | 1787 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| State | 124″ | 128* | 130* | 132′ | 138′ | 142′ | 146* | 150″ | 153′ | 156″ | 157″ |
| $T_I$ | –12.9 | –15.9 | –17.8 | –13.0 | –14.4 | –15.9 | –19.6 | –12.7 | –19 | –10.2 | –9.4 |
| $T_w$ | –11.5 | –12.3 | –13.3 | –7.0 | –11.3 | –11.0 | –16.8 | –10.3 | –12.5 | –10.2 | –9.4 |
| Peculiarities | 12′ | | $B'$12* | 12′ | | | | | | | |
| Year | 1788 | 1789 | 1792 | 1799 | 1800 | 1805 | 1807 | 1809 | 1810 | 1813 | 1814 |
| State | 158″ | 159′ | 162′ | 169* | 170″ | 175″ | 177″ | 179* | 180″ | 03* | 04* |
| $T_I$ | –10.8 | –12.4 | –15.5 | –19.7 | –13.5 | –12 | –10.8 | –18.8 | –10.9 | –16.1 | –21.6 |
| $T_w$ | –10.1 | –13.9 | –10.6 | –13.4 | –11.7 | –9.8 | – | –15.1 | –8.3 | –13.8 | –8.2 |
| Peculiarities | | | | $B''$ | $B'$ | | $B'$ | $B^*$ | $B^*$ | 12′ | |
| Year | 1816 | 1817 | 1820 | 1821 | 1823 | 1826 | 1828 | 1829 | 1834 | | |
| State | 06″ | 07′ | 10* | 11″ | 13′ | 16″ | 18″ | 19′ | 24′ | | |
| $T_I$ | –14.4 | –17.6 | –17.4 | –10.8 | –13 | –11.5 | –12.6 | –13.6 | –14.4 | | |
| $T_w$ | – | –9.6 | –15.2 | –9 | –8.6 | –8.0 | –9.7 | –12.1 | –10 | | |
| Peculiarities | | 12* | 12* | | | | | | | | |

# 3. Techniques for identification and analysis of rhythmic climate changes

Taking into account the obtained results, we carried out the classification of the winter temperature rhythms, as well as their description for the regions, covered with data of long-term (more than 180 years) observations. Identification of the rhythmic variations of actual processes is carried out using the obtained models and the results of monitoring. Identification of rhythm types for regions of Western Siberia is carried out with 120–160 year long series in hand (with some misses), using procedures of estimation of similarity on the basis of comparison of the ensemble of extremal states for a certain period with the known (typical) descriptions of rhythms of seasonal temperature variations. When some peculiarities are present in description of the temperature variation rhythm, a modification sign is assigned to the new rhythm, for example, rhythm $B1(K)$ is the modified rhythm $B1$ for Kazan'. When the observation series length is less than two stages of the cycle (less than 120 years), the identification is carried out stage-by-stage by the method of successive approximations. At the first stage, the similarity of extremal temperatures for the region under study and neighbor regions is estimated; than the analogue is selected with the observation series longer than 120 years, and the identification is carried out on the basis of descriptions of the ensembles of states for the region-analogue. Further, based on peculiarities of the region-analogue, the modification of the rhythm type is performed for the region under study through a more complete analysis of characteristics of its entire ensemble of states compared with those for the region-analogue.

Thus, main stages of the technique are the following: processing the data series,[8] identification of the peculiar states, determination of states' characteristics, calculation of the rhythm characteristics, estimation of rhythmic variations of the characteristics, selection of the periods with a certain rhythm, determination of the length of a cycle of characteristics rhythmic variations and the periodicity of the variations, determination of regularities in the rhythmic variations and their peculiarities depending on combination of conditions and factors. The requirements to the monitoring of rhythmic variations of characteristics of the system states, providing the solubility of the problem, have been determined, the most important of which is the monitoring length (no less than two periods of the cyclic process).

# 4. Results and discussion

The study of long-term series of meteorological observations has resulted in revealing cycles of seasonal temperature variations with periods of 60, 120, and 180 years. It is found that the rhythm forms a sequence of extremal states in the winter period. Characteristics of rhythms of the mean winter temperature and monthly temperature extrema for a number of meteorological stations are determined. The system-evolution analysis of conjugated long-term variations of characteristics of regional climate seasonal states for Siberia, baric-circulation conditions, and ice cover of northern seas has shown that the extremal winter and spring states are caused by anticyclonic circulation regime in the Arctic.

The processes of transformation of the components in the Arctic Ocean and formation of baric systems at transformations of atmospheric circulation in fall exert some effect on formation of these states. The spatial structure of the baric field is of essential significance. So, the location of anticyclonic vortex close to seas of the Siberian shelf, ice drift, and macrodeformations of the ice cover favor the conditions for formation of the stable ice cover in Kara Sea and development of anticyclonic circulation at the north of Siberia in winter[7] with invasion of cold air masses deep into the continent (up to 50°N).

On advection of cold air masses in mid-latitudes, the conditions appear for formation of long-term stable states with cooling transformation regime. The deep freezing of soils affects the heat balance in spring and leads to decrease of the warm season length. Regular repetitions of winter extremal states act predominantly on the behavior of climate centurial variations in the northern regions, the heat budget of the territory, and transformation of biocenosis.

It follows from results of analysis of long-term series of seasonal temperatures that the cycles of rhythmic variations of temperature repeat in the mid-latitudes of Europe and Western Siberia. The extrema of January monthly mean temperature in De Bilt (the Netherlands) were: −5.1°C in 1716, −5.3°C in 1776, −6.7°C in 1838, and −3.1°C in 1895; (−33.7°C in Turukhansk, and −22.1°C in Omsk). The period of repetition of extrema is 179 years (between 1716 and 1895), which exactly corresponds to the period of the main cycle of the solar system (triple cycle of motion of bodies around the center of inertia along the trefoil trajectory).[3] This reflects real manifestation of astrogeosphere–climate relations. The variety of types in the manifestations of rhythmic variations is revealed. Each cycle contains from 6- to 14-year phases repeating every 60 years with a certain rhythm in the consequence of extremal winter states and monthly states in spring.

Thus, a regular periodicity of centurial rhythmic variations of the extremal winter temperatures and repetition of the stages of characteristic rhythm with the period of 60 years is revealed.

Individual rhythm phases repeat every 60 years with small variations. The phase rhythm of long-term variations of temperature regime and lengths of cold and warm seasons in Kazan' is described by the model of the type $B$ for 1831–1838:

$$31'' \to 32 \to 33' \to 34^* \to 35'' \to 36^* \to 37'' \to 38^*$$

4–8 • 4–9 • 4–7 • 5–8 • 3–9 • 3–8 • 4–8 • 5;

by the model of the type $B1(K)$ for 1891–1897:

$$91^* \rightarrow 92' \rightarrow 93^* \rightarrow 94'' \rightarrow 95'' \rightarrow 96^* \rightarrow 37''$$

4–8 • 5–7 • 5–8 • 4–8 • 5–7 • 5–7 • 5;

by the model of the type $B2(K)$ for 1950–1957:

$$50^* \rightarrow 51' \rightarrow 52'' \rightarrow 53' \rightarrow 54^* \rightarrow 55 \rightarrow 56^* \rightarrow 57'$$

5–6 • 6–7 • 5–7 • 5–7 • 5–7 • 5–7 • 4–8 • 5.

The presence of three main extremes in winter monthly temperatures is characteristic of each period. Two additional extremes of the 1st rank appeared in the last period. Main peculiarities of the modified rhythms lie in the change of lengths of cold and warm seasons. The warming is directly related to the decrease of the cold season length. Thus, the connection between the cold season length and the repetition frequency of the temperature rhythm extrema and corresponding direction of variations of mean seasonal and annual temperatures is found. This provides for basis for quantitative assessment of the direction of variations of the extremal climate characteristics and the tendencies of climate changes.

The cyclic structure of rhythmic variations of the regional climate and their similarity are closely related to the 180-year cycle of planet rotation around the common mass center. The greatest similarity of the cyclicity rhythm phases is observed in periodic rhythm variations of winter characteristics, the cold season length, the annual behavior amplitude, and the peculiarities of monthly (decade) temperature rhythm variations.

The behavior of mean winter temperatures in Saint Petersburg for 1770–2005 is shown in Fig. 2. In addition to the main cycle, the last phases of the previous cycle and the first phase of the new cycle are presented as well.

The rhythmicity of biospheric processes and climate is predetermined by the rhythmicity of regularly changed chorological relations between planets and other bodies in the solar system. Impacts of gravity forces, solar wind, radiation fluxes, and cosmic particles on the geosphere shell cause variations (splashes) in geophysical fields,[2,3] changes in the processes of energy transformation in the components of the geosphere, and energy exchange between their elements, that leads to reorganization of the cycles of energy and mass transfer in the atmosphere, ocean, and geosystems, as well as to the change in the circulation of water and chemical elements. Under the effect of the stimulating forces, changes in the character of the processes of interaction between fluxes and geophysical fields, the pressure field gradients are formed under conditions of changed intra-system relations.[2] This affects the energetics of the moving air and water masses.

It is known that the kinetic energy of the general circulation of the atmosphere and ocean depends on the pressure gradient,[1] and small pressure variations can change the energetics of the moving air masses and pressure systems due to spatial inhomogeneity of thermodynamic parameters. In high latitudes, especially in Arctic, a share of incoming radiation in the energy budget is low as compared to the kinetic energy of motion of air and water masses. This significantly determines the energy and mass transfer and invasion of cold air masses deep into continent. Besides, the mechanism of transformation of anthropogenically polluted media (for example, the influence of protons and neutrons on aerosols of anthropogenic origin) causes a change of physical properties of the atmospheric upper layers and thermodynamic characteristics of individual layers. Formation of spatial inhomogeneity in thermodynamic characteristics affects the direction of motion of air masses and the circulation character,[1] that causes disorganization in the cycle of climate-forming processes and destruction of the rhythm.

At significant long-term variations of energy and mass transfer conjugated with changes of ice cover of seas of North-west sector of Arctic, similar variations in the estimating characteristics of Siberia and Ural regional climates were observed in 60s of the XX century.[6] The rhythm of long-term variations of winter and summer (monthly) extremal temperatures of the cold phase 1844–1859, containing the main centurial extrema, repeated after 119 years in the period 1963–1979. The increase of ice amount in Arctic, Barents and Kara seas was observed in that period.

The warming occurs at restoration of the cycle and regular rhythm of the climate-forming processes (decrease of the cold season length, decrease of the repetition frequency of winter temperature extrema) after termination of the pulsed external impacts. The increase in seasonal and annual temperatures depends on the state of the ocean, spatial structure of water masses, area of ice cover, and zones of desalination, which determine the convection and heat and moisture exchange between the ocean and the atmosphere[6];

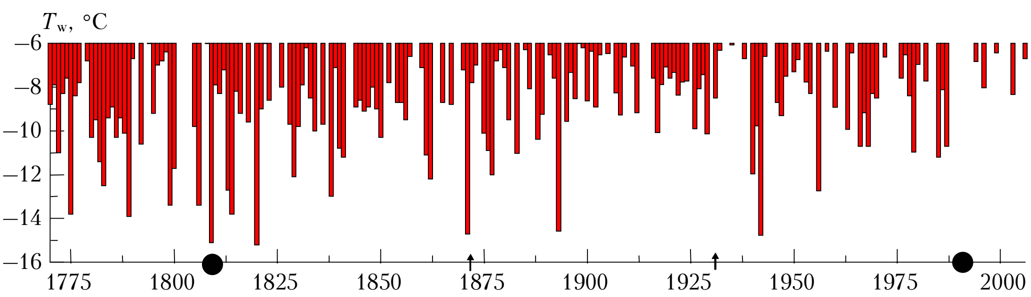


**Fig. 2.** Rhythms of mean winter temperatures in Saint Petersburg; (●) – beginning of the main solar cycle.

on the zonal circulation intensity and efficiency of energy and mass transfer between the ocean and the continent. The decrease in the repetition frequency of extremal winter temperatures and the warming in the 90s of XX century are connected with the peculiarities of the rhythm of the phase *A*, which is characterized by alternation of the intervals with regular rhythm and intervals with frequent repetition of the main extrema in winter seasonal (monthly) temperatures. This fact is confirmed by extremal winter temperatures in 2001, 2003, and 2006. Main centurial extrema of the mean monthly temperature in January 2006 were observed in Turukhansk (−37.6°C), in Salekhard (−30.1°C), in Tarko-Sale (−37.3°C), in Kolpashevo (−33.8°C), and in Enisejsk (−31.0°C).

Thus, the observed variations of the mean long-term temperature at the modern stage of the warming contain the rhythmic component, which is superimposed on the centurial trend. The recent warming in Siberia is characterized by the tendency of formation of a regular rhythm (since 1994 in southern regions lower 56°N), resistant to extremal winter states; and the increase of the vegetation period, that is meaningful for biosphere and has important social consequences. The characteristic of the warming is the increase of May temperatures (higher than +10°C) since 1987. Such state of the regional climates of Siberia is first observed for the last 120 years, and perhaps, for the last millennium.

The rhythmic variations of seasonal characteristics are main components of short-period and centurial climate changes. They have to be taken into account both in estimation of the observed climate changes (trends) and in the forecast of future states. The results of preliminary comparative analysis, identification, and estimation have shown that mean increase of temperatures in the period 1978–1990 (Phase E of the cycle) as compared to the period 1798–1810 is 0.6°C in Vrotzlav (Poland) and 1.08°C in De Bilt (the Netherlands) for 180 years. The mean long-term increases of annual temperatures in the modern period 1991–2005 (phase A) as compared to 1811–1825 are 0.2°C in Vrotzlav, 1.1°C in De Bilt, and 1.4°C in Kazan'.

## Conclusions

1. The revealed rhythmic character of the temperature variations in the near-ground atmosphere with the cycle period of 179 years, equal to the period of the main solar cycle, is the evidence of Astrogeosphere–climate relations and of essential effect of astronomic factors on the long-term variability of seasonal air temperatures and the short-period oscillations of climate in the framework of the cycle and 60-year periods.

2. In periods of non-stationary dynamics of the weakly coordinated motion of bodies of the solar system, their disturbing effect changes the organization of the cycle of the energy and mass transfer and disturb the regularity of the rhythm of climate-forming processes, which causes the cooling (increase of the cold season length and increase of the repetition frequency of the states with negative extremal temperatures in winter months) at the prevalence of the role of the Arctic in climate-forming factors. Variations of seasonal meteorological parameters depend on the ocean state, spatial structure of water masses, the area of ice cover, and zones of desalination.

3. The peculiarities of the modern warming in Siberia, i.e., the tendency to formation of a regular rhythm (since 1994 in southern regions lower 56°N) resistant to the extremal winter states, and increase of the vegetation period are important for biosphere and have significant social consequences.

4. Interval assessment of the temperature increases in the equitype phases of the cycle is the evidence of moderate rates of the warming in Europe: 0.6–1.4°C for 180 years.

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