Monitoring and modeling of climatic changes in Siberia

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We present a review of empirical regularities recently revealed based on statistical processing of the instrumental data compiled. Among these regularities there are: trends and trajectories of the warming observed in Siberia, interseasonal variations of surface temperature, and temporal periodicities of the warming in different Siberian cities. The possibility of applying modern mathematical climate models to description of regional climatic changes are also discussed. Among the results of mathematical modeling that encourage there are the following: retrievals of regional surface temperature using joint model of general atmospheric and ocean circulation, assessments of the regional consequences of the global warming, the account for regional hydrological processes. Combination of these two methodological approaches (the empirical and mathematical modeling ones) is recognized to be promising; also, some unresolved problems arising at such a combination are shown to be necessarily addressed.

Introduction

In 1972 Academician M.I. Budyko was the first to express the view, at an international conference, based on his calculations, that, instead of the anticipated trend toward cooling, the global warming should occur soon,[1] what strongly embarrassed specialists. The observed changes in nature and climate under the effect of natural and anthropogenic factors were considered at the UN conference in 1992 as threatening to the civilization.[2] The decisions made at this UN conference and signed by many heads of the states and their governments present significantly stimulated research into the environment and climate on the Earth within the frameworks of the international, national, and regional programs developed.

The results of further scientific investigations of the global and regional changes in nature and climate lead to the conclusions that more detailed account of the regional peculiarities is necessary,[3] and correlated changes in the different components of the Earth system can not be explained based on only simple paradigm of "the cause and effect" (Amsterdam declaration 2001).[4] The most concise and comprehensive formulation taking into account new methodological principles of the research uses the wording "integrated regional investigation," which, in the frameworks of International Geosphere–Biosphere Program, was announced in 2002 as a strategic goal for the further multidisciplinary investigations.[5] New methodological principles found a well-paved way for use in further investigations in Siberian region. The matter is that, already in 1993, multidisciplinary investigations were organized in the frameworks of the regional project "Climate and ecological monitoring of Siberia" (the coordinator was M.V. Kabanov, the Corresponding Member of RAS) by the initiative of Academician V.A. Koptyug (at that time president of Siberian Branch of the Russian Academy of Sciences) who took part in the preparations and work of the UN Conference in Rio-de-Janeiro. The idea of the comprehensive regional monitoring formulated at that time, as well as the grouped instrumentation basis for field measurements and some results of investigations were described in a series of monographs under general title "Regional monitoring of the atmosphere."[6]

Further development of research and technological basis for monitoring, modeling, and forecasting climate and ecosystem changes under impact of natural and anthropogenic factors became the major task of the Institute of Monitoring of Climatic and Ecological Systems of Siberian Branch of the Russian Academy of Sciences. Actually, statement of this problem already takes into account main methodological principles of "integrated regional investigations," and already the first results of investigations have demonstrated the necessity of their comparison with the available mathematical models of climate, which with sufficient accuracy take into account and describe the global climate-forming processes.

In their turn, modern mathematical models of climate (see, for example, Ref. 7), in difference of a number of previous models (in particular, Ref. 8), consider, according to definition of World Meteorological Organization, the climate system of the Earth as a global system formed by such interacting components as atmosphere, ocean, land, cryosphere, and biota.[9] Mathematically, climate is defined as a statistical ensemble of states the climate

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system takes during sufficiently long time interval (~ 30 years), and which are characterized by great but finite set of parameters. From the first sight, comparison of such global mathematical models of climate with the results of instrumental monitoring within limited time intervals seems to be problematic. However, some promises have appeared here in recent years.

The mathematical model of climate was developed at the Institute of Numerical Mathematics RAS[7] based on the global models of the general circulation of the atmosphere and ocean and on the precise description of all physical processes taking part in the formation of climate. This model was tested while reconstructing modern climate and confirmed its competitive ability compared to other models (about 30) developed in different countries and incorporated into the international programs on comparing the climate models. As the computation techniques and the climate models themselves were improved, their possibilities of studying most urgent regional problems of climate change have expanded, including those based on use of empirical data obtained in some regions, including Siberia.

Thus, experimental investigations of the real climatic system (monitoring) and theoretical investigations of the global climate system (mathematical modeling) came to a new turning point of combined investigations. To develop such investigations, it is necessary to construct the relevant hierarchy of interacting subsystems in the comprising the global climate system and to improve the description of the physical processes occurring in them. Technogenic systems, the role of which, on the quantitative level, has not yet reliably been revealed, occupy special place among similar subsystems with different scales of spatiotemporal variations. The purpose of this paper is to illustrate, using, as an example some specific results, the starting promises of two approaches to solving the general problem related with the global and regional climate changes under the effect of natural and anthropogenic factors.

Empirical regularities of warming

Changes in nature and climate in Siberia are of special interest in view of the global change in the Earth system. This special interest has been initiated by some facts.

First, the vast continental territory of Siberia (about 10 million km^2) is undoubtedly a ponderable natural territorial region of Eurasian continent, which is characterized by the various combinations of climate-forming factors.

Second, forests, water, and wetland areas are situated on a significant part of Siberia, which play planetary important climate regulating role due to the processes of emission and accumulation of the main greenhouse gases (CO_2, CH_4, etc.).

Third, the variety of climatic zones in Siberia and the presence of mesoscale regions with extremely high or absolutely absent technogenic load create globally unprecedented conditions for scientific investigations of the changes in nature and climate, as well as for revealing the weights of natural and anthropogenic factors in the observed changes.

The aforementioned and some other regional peculiarities of Siberia are undoubtedly important reason for integrated regional investigations in this region of the planet. But more important reasons for such investigations are the facts that evidence of the enhanced rates of the warming observed in the region and the consequences of such warming for natural environment. Analysis of the scales and the regularities of these changes revealed in Siberia are discussed below. The attempt has been undertaken in the review of the results obtained in recent years to discuss not only the empirical regularities revealed, but also the methodological problems of investigations, which follow from the results obtained.

Linear trends and trajectories of warming

Let us discuss analysis of the rate of warming in Siberia that follows from calculated results on the linear trends of annual mean temperatures in the period since 1965 until 2000. The annual mean temperatures were calculated using the data on the near-ground temperature taken from the NCDC site (Ashvill, USA, http://www.ncdc.noaa.gov) (the series of monthly mean temperatures at the height of 2 m at 223 meteorological stations in Siberia). The detailed description of the technique and some results of calculations are presented in Ref. 10.

The map of the spatial distribution of the value of the linear trend of the annual mean near-ground temperature over the territory of Siberia is shown in Fig. 1 taken from Ref. 10. Isolines on this map show the regions with different value of the trend (different gray scales) in 0.1°C step of warming during 10 years. The isolines are drawn with the error of the interpolation procedures.

As is seen from Fig. 1, the rates of warming on the entire territory of Siberia in the second half of XXth century were quite high (more than 0.2°C per 10 years), and in some regions they reached the value of the linear trend of 0.5°C/10 years. These mesoscale regions, which can be called the centers of accelerated warming, are concentrated first of all in East Siberia. If one compares the map of warming shown in Fig. 1 with climatic maps of previous decades,[11] the tendency is observed to recovering the latitudinal zonality of climate on the territory of Siberia, which was absent in those decades. The isolines of January mean temperatures for the period 1881–1935 in Fig. 1 (dotted lines) are evidence of this fact. They separate the regions of Siberia for colder (to the north from the isolines) and warmer (to the south from the isolines) and essentially deviate from latitudinal zonality in this period.

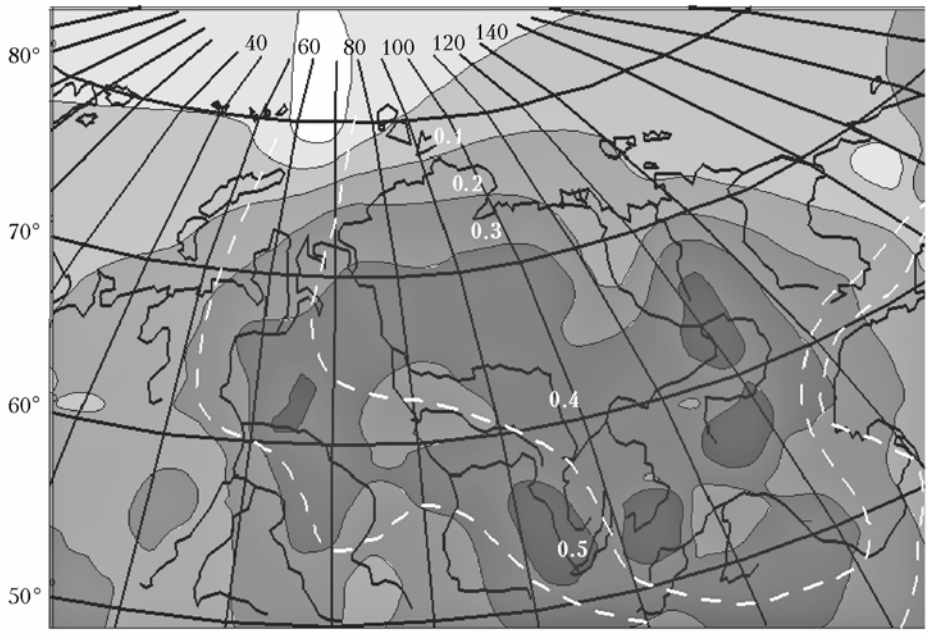

Fig. 1. Map of linear trends of annual mean near-ground temperature during the period from 1965 to 2000. Dotted lines show isolines of January monthly mean temperature during the period since 1881 until 1935 (the upper line for −28°C, the lower one for −20°C).

The map of warming in Siberia shown above gives a rough image of interannual changes of near-ground temperature, because different rates of warming in different years were not taken into account when calculating the linear trends. The most obvious and not distorted by smoothing averaging way of revealing different rates of warming in separate years lies in simple summing of the monthly mean temperatures. Then the temperature trajectories were obtained, which are shown in Fig. 2 taken from Ref. 12 for two cities of Siberia. The ordinate axis here is the sum of the monthly mean temperatures ΣT_{M}, where T_{M} is measured in degrees Centigrade, and the abscissa axis is years (and months). In such coordinate system, the slope of the trajectory shows the rate of warming, and the oscillation structure inside each year characterizes the scale of interseasonal variations of near-ground temperature.

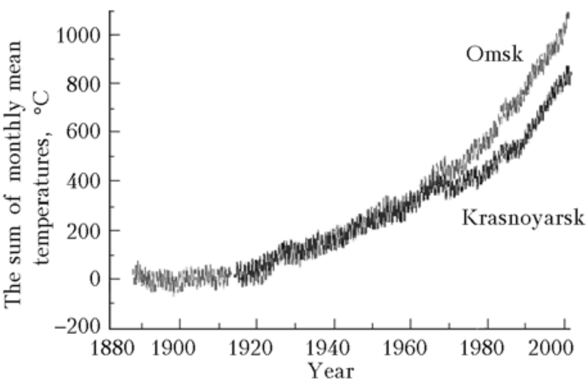

Fig. 2. Evolution trajectories of near-ground temperature.

Two principle facts follow from analysis of the temperature trajectories shown in Fig. 2 and many others (for different meteorological stations in Siberia). One of them is that the temperature trajectories for all considered meteorological stations are close to the parabolic shape corresponding to the linear trend of interannual variations, but are not smooth (monotonic). The non-monotonic behavior of the trajectories in Fig. 2 is the evidence of temporal inhomogeneity of the rates of warming during the past century.

Another fact follows from comparison of the trajectories for two cities shown in Fig. 2. These trajectories coincide before 70s of XXth century, while then these very rapidly diverged from each other, and then became parallel again. Taking into account the fact that filling the big Krasnoyarsk water reservoir (the area 2000 km^2, with the volume 73 km^3)[13] was finished just in 1970, one can draw a conclusion about sufficient sensitivity of the temperature trajectories to that large geographical events of anthropogenic origin. At the same time, it follows from similarity of the two trajectories before and after the aforementioned event that the observed long-term trends of warming are caused by factors common for Siberian region.

Interseasonal variations of temperature

Analysis made using the temporal mean parameters discussed above (annual and monthly mean) relates only to one side of the observed regional changes in the temperature regime. The dynamics of interseasonal variations of temperature is not less important for characterization of these changes. The amplitude of such variations even for monthly mean temperatures in some regions of Siberia exceed 10% of the annual mean temperature (in K). So, in comparison with the observed interannual changes, which are of hundredth of percent of the annual mean temperature (in K), the observed interseasonal variations of temperature seem to be too large.

The correlation between the amplitude of interseasonal variations of near-ground temperature A_T and annual mean temperature was obtained from the results of processing the instrumental data of meteorological stations of the Northern hemisphere for several decades.[12] The value A_T was determined as annual mean half difference of the monthly mean temperatures between the warmest and coldest months for each meteorological station. The sufficiently high correlation coefficient (0.87) between the value A_T and annual mean temperature T made the basis for approximation of the correlation revealed, which, with acceptable accuracy, is close to linear and is described by the formula

$$A_T = \alpha(300 - T), \quad (1)$$

where T is in K, and the value α for the Northern hemisphere is equal to 0.56 ± 0.04. The value α in Siberian region varies in quite a wide range for different climatic zones, that is evidence of the higher, in comparison with interannual variations, sensitivity of interseasonal variations of the temperature regime to mesoscale peculiarities.

Another important parameter integrally describing the interseasonal variations of temperature is the ratio of the mean temperatures for warm and cold seasons. There is special interest in this parameter describing the half-year variations of climate as it is related to the fact that the warm season (May–October in the mid-latitudes) covers the vegetation period, during which the climatic and ecological systems interact most actively. Besides, the climatic characteristics during the vegetation period are usually reconstructed using many known methods in paleoinvestigations,[14] which have no alternative in studying the Earth climate history during the past thousands of years. So, analysis of the half-year characteristics and their changes during recent decades is necessary for justified comparison with the results of paleoinvestigations.

The dynamics of temperature regime in three different geographic regions of Siberia (Omsk, Khanty-Mansiisk, Turukhansk) is shown in Fig. 3 taken from Ref. 15 in the coordinates of the sums Z_s of daily mean temperatures during warm season (according to the period of stable transition of daily mean temperatures above 0°C) on the ordinate axis, and the sums Z_w during cold season on abscissa axis. For clarity, the arrows show the sequence of years. The period (1966–1974) was selected for illustration, when the regularity observed was common for the majority of meteorological stations analyzed.

As is seen from Fig. 3, the changes in the temperature regime in these years for the aforementioned meteorological stations occurred similarly: before 1969 the vector of changes in the selected coordinates circumscribes the triangle counterclockwise, and then the trajectory along the reverse direction. Such a behavior of the vector of changes can be interpreted as reverse oscillation of the regional climatic system during these years.

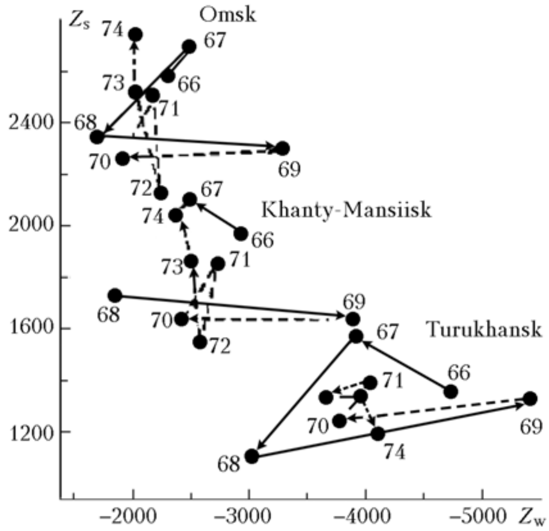

Fig. 3. Trajectories of the change of temperature regime in some cities of Siberia.

The revealed similarity of synchronous interannual variations of the temperature regime for different climatic zones of Siberia in the period of oscillation can be described by the model with separation of temporal t and spatial r variables.[16] Denoting the ratio of the sums of daily mean temperatures as $y(r, t) = Z_s/Z_w$, one can write for the interannual increase $\Delta y(r, t)$ as follows:

$$\Delta y(r, t) = a(r)\Delta b(t), \quad (2)$$

where $a(r)$ is the scale of the increase of $y(r, t)$ for the climatic zone situated at the distance r from the basis one, $\Delta b(t)$ are interannual increases of $y(r, t)$ for the basis climatic zone.

Thus, the half-year variations of the ratio $y(r, t)$ have high sensitivity to mesoscale peculiarities in the region as do the interseasonal variations of the temperature. At the same time, there are some regularities, common for different mesoscale climatic zones during the periods of several years. Other and more efficient methods of statistical analysis of time series of different parameters of climatic systems are necessary for more detailed study of such regularities.

Temporal periodicities of warming

The method based on wavelet transform[17–19] is among the efficient methods of statistical analysis in revealing possible periodicities in time series. In contrast to Fourier transform providing for obtaining the time frequency spectrum in the analyzed time series, wavelet transform, which uses soliton-like function (wavelet), provides for revealing statistically significant periodicities in the time series. The results obtained by applying wavelet transform to quantitative analysis of time series of annual mean near-ground temperature in order to reveal the periodicities, which are qualitatively observed in temporal inhomogeneities of the rates of warming (see Fig. 2) are discussed below.

Coefficients of the wavelet transform $W_k(s)$ for a discrete time series are determined by the formula[18]:

$$W_k(s) = \sum_{n}^{N-1} X_n \Psi^* \left[\frac{(k-n)\Delta t}{s} \right], \quad (3)$$

where X_n is the value of annual mean temperature in the nth year; $\Psi^* \left[\frac{(k-n)\Delta t}{s} \right]$ is the complex conjugate wavelet function (Morlet wavelet in our case); s is the scale of periodicity; k is the shift along the time axis; Δt is the time interval between the neighbor values X_n (1 year in our case). The restrictions of the method on the temporal periodicities that can be revealed are determined by the so-called triangle of reliability.[17] The maximum reliable scale of periodicities in the time series of the length t does not exceed $t/2\sqrt{2}$ (the maximum reliable scale at the time series length of 100 years is no more than 30 years). The minimum reliable scale of periodicities is 2 to 3 times longer than the discreteness of the time series Δt (the minimum scale at the discreteness of 1 year is more than 2 or 3 years).

Examples of the wavelet transforms of time series of the annual mean temperature for some cities of Siberia are shown in Fig. 4 taken from Ref. 19. The darker spots correspond to the higher absolute values of the coefficients $|W_k(s)|$, and the observed changes of the scales and brightness of these spots correspond to the changes of the scales of periodicities and the rates of warming. Analysis of the images of the distribution $|W_k(s)|$ for the presented and other cities of Siberia shows that, apart from the existing differences in the revealed temporal periodicities, the regularities are observed that are common for different cities. The main of them is that the scales of periodicities for all cities underwent gradual evolution in the past century. This fact revealed by means of the wavelet transform of the series of temperature has not yet been reliably interpreted, but it evidences of the increasing role of the general factor of warming for the entire region.

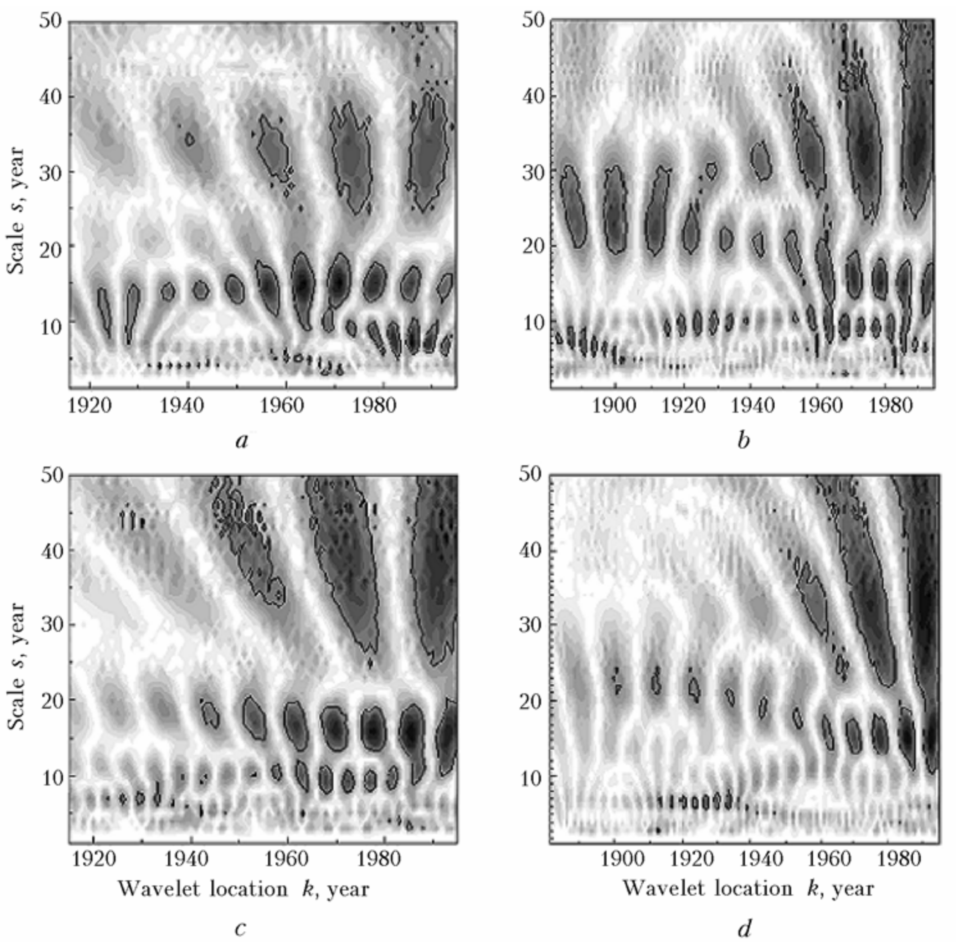

Fig. 4. Distribution of the coefficients of wavelet transform $|W_k(s)|$ for some cities of Siberia: Omsk (*a*), Tomsk (*b*), Krasnoyarsk (*c*), and Irkutsk (*d*).

Quantitative estimate based on the regularities of the revealed periodicities follows from correlation analysis of the rates of warming for different scales of temperature periodicities and their comparison with the corresponding quantities of the planetary significance. Such planetary factors can be the South Oscillation Index SOI (the difference of pressure at two sites, Darwin and Tahiti) and the North-Atlantic Oscillation (NAO) index (the difference of pressure at the Lisbon and Stikkihoulmur sites), as well as the Wolf numbers W characterizing the solar activity. The coefficients of correlation between temperature periodicities of different scales in some cities of Siberia (K_O – Omsk, K_T – Tomsk, K_K – Krasnoyarsk, K_I – Irkutsk) obtained using some selected data from Ref. 20 are shown in the Table, as well as that for periodicities of the planetary factors with the scale of 30 years.

Table. Correlation coefficients of temperature periodicities and planetary indices

Parameter	Periodicity	K_O	K_T	K_K	K_I
Annual mean temperature	5	1	0.85±0.38	0.61±0.49	0.30±0.57
	11	1	0.88±0.37	0.72±0.44	0.67±0.46
	22	1	0.89±0.36	0.70±0.45	0.59±0.49
	30	1	0.97±0.32	0.74±0.43	0.95±0.33
SOI	30	0.3±0.6	0.3±0.5	0.8±0.4	0.4±0.5
NAO	30	0.7±0.3	0.6±0.4	0.7±0.3	0.4±0.4
W	30	0.8±0.4	0.7±0.4	0.7±0.4	0.7±0.4

As is seen from the Table, the regular increase of the correlation coefficients for different cities of Siberia is observed with the increase of the scale of temperature periodicities. Another situation is for the indices of atmospheric circulation SOI and NAO, for which the correlation coefficients for all presented cities strongly vary. Moreover, analysis of similar correlation coefficients for neighbor observation sites shows[20] that they have significant variance up to the change of sign for some neighbor sites. Correlation of temperature periodicities with Wolf numbers is relatively stable, that is evidence of certain relation between the temperature regime and solar activity. But, even in this case it is early to say about significant correlation between these parameters, because the correlation coefficients for the scales of more regular periodicities of the Wolf numbers of 11 and 22 years with temperature periodicities of the same scales are noticeably less than for the scale of 30 years.

Thus, the wavelet analysis of the series of annual mean temperatures enabled us to reveal the statistically significant temperature periodicities and their evolution during the past century. However, weak correlation between these periodicities and the periodicities of some planetary factors of the same scales (see Table) does not allow unambiguous conclusions to be drawn. Evidently, it is necessary to seek the statistically significant correlations using not only the global circulation of the atmosphere and the ocean, but also the regional regimes of atmospheric circulation. Such methodological conclusion does not contradict the analysis made using the dynamics of the annual sum of precipitation on the territory of Russia and neighbor countries in XXth century[21] and using the closely related dynamics of thunderstorm activity on the territory of Siberia and on the neighbor territories.[22]

Regionalization of the mathematical models of climate

In modeling global climate, it is necessary to reconstruct the latitudinal spectrum of its characteristics: seasonal and monthly mean values, seasonal variability (monsoon cycle, parameters of storm-tracks, etc.), climatic variability (its dominating modes, such as El Niño or Arctic Oscillation), etc. At the same time, it is quite urgent now to use modern mathematical models in studying regional climate and ecological peculiarities, in particular, that of Siberia. It is related with the fact that, according to modern ideas, natural environment in mid- and high latitudes of the Northern hemisphere is most sensitive to the observed global climate changes. One should consider such tasks of modeling regional climate as detailed reconstruction of its characteristics, investigation of the peculiarities of hydrological cycle, estimation of the possibility of extreme phenomena to occur, and investigation of the consequences of the regional climate changes for the environment and socio-economic relations as its basic tasks.

Joint use of experimental data and the results obtained by mathematical modeling seems to be the most expedient both for estimation of the current state of the climate system and for forecasting its further evolution using the verified climate models. At the same time, there is an essential circumstance related to the spatial scales of the system under study. The problem arises, in mathematically modeling the global climate system, on the parameterization of the processes of subgrid scales that assumes the necessity of studying its regional (most likely, the mesoscale) peculiarities. On the other hand, the results of empirical modeling based on instrumental data obtained on a limited territory are often overburdened with its microscale peculiarities and do not reveal the macroscale regularities. The approach seems to be a compromise, which uses the results obtained using global climate models of sufficient spatial resolution (along with the data of the network of meteorological, aerological, and remote observations) as characteristics of the external climate-forming factors, while the empirical and local (mesoscale) mathematical models are used for climate-ecological estimation of the regional consequences of the global processes, especially in the boundary layer of the atmosphere as human natural habitat.

Modeling of climate and its changes

Comparison of more than 30 models of the general circulation of the atmosphere carried out in the frameworks of the AMIP II international project showed that the best of them are now capable of reconstructing the main features of the observed atmospheric circulation with good accuracy. The models were integrated for the 17-year period, with the temporal behavior of ocean surface temperature and boundaries of sea ice observed in 1979–1995 used as boundary conditions. The error in reconstructing many climatic parameters by such models only slightly exceeds now the uncertainty, with which this parameters are obtained from observations. At the same time, there are systematic errors in reconstructing the climate inherent to practically all models. The most complete analysis of reconstructing the climate by different models involved in AMIP II can be found at the www-pcmdi.llnl.gov/amip web site.

The regional (within the limits from 55° to 155°E and from 50° to 90°N) field of systematic errors in reconstructing air temperature at the level of 2 m with the model of the general circulation of the atmosphere[7,23] developed at the Institute of Numerical Mathematics RAS (longitudinal resolution of 5°, latitudinal resolution of 4°, and 21 height levels were used) is shown in Fig. 5 as an illustration. The systematic error here is the difference between the calculated results and data of Reanalysis NCEP[24] averaged over the period of integration (17 years). As is seen from Fig. 5, the distribution of systematic errors over the territory of Siberia has well-pronounced localizations of the nidal type.

The modern tendency of the development of the climate models is based on the joint use of the models of general circulation of the atmosphere and ocean and lies in more and more detailed account of all physical mechanisms affecting climate. At present, tens of such models are available, more than 20 of them have been incorporated in the international project CMIP (http://www-pcmdi.llnl. gov/cmip) on their comparison,[25] the climate model of INM RAS[7] is among them. The resolution in the atmospheric block of this model is 5° in longitude, 4° in latitude and it uses 21 height levels. In the ocean block the resolution of 2.5 × 2° (longitude and latitude) is used with 33 depth levels. Ocean surface temperature is not set, but calculated (as well as land temperature) by means of the heat budget equation. Following the modern tendencies in the development of the joint models, correction of the ocean surface fluxes is not used when combining the atmospheric and ocean parts.

The long-term (integration over 130 years) numerical experiment on modeling the modern climate was carried out with the joint model of INM RAS.[26] Concentrations of all gases active in radiative processes were fixed and equal to those observed in the end of the XXth century. Establishment of the model climate occurred during 50 years, and the results calculated for the subsequent 80 years were used in analysis. The distribution of systematic errors of the joint climatic model (averaging over 80 years of calculations) analogous to that Fig. 5 is shown in Fig. 6. Comparison of Figs. 5 and 6 shows that, in general, the distribution of systematic errors is the same, however, the additional source of errors in Arctic region appeared in the experiment with the joint model.

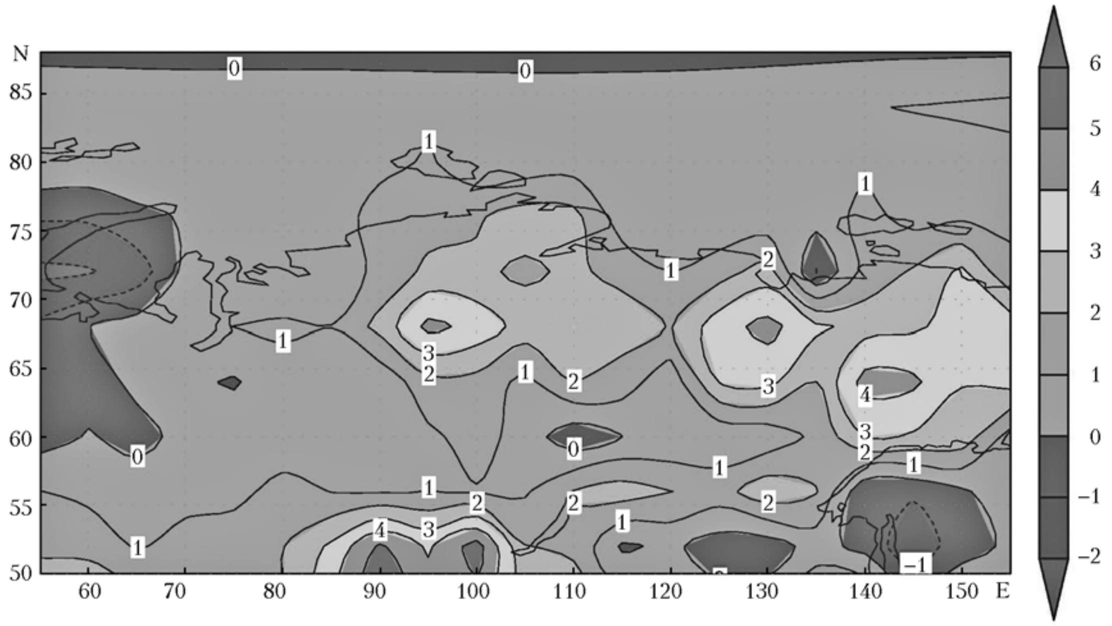

Fig. 5. Field of systematic errors of reconstruction of air temperature at the level of 2 m (in Kelvins) with the model of general circulation of the atmosphere.

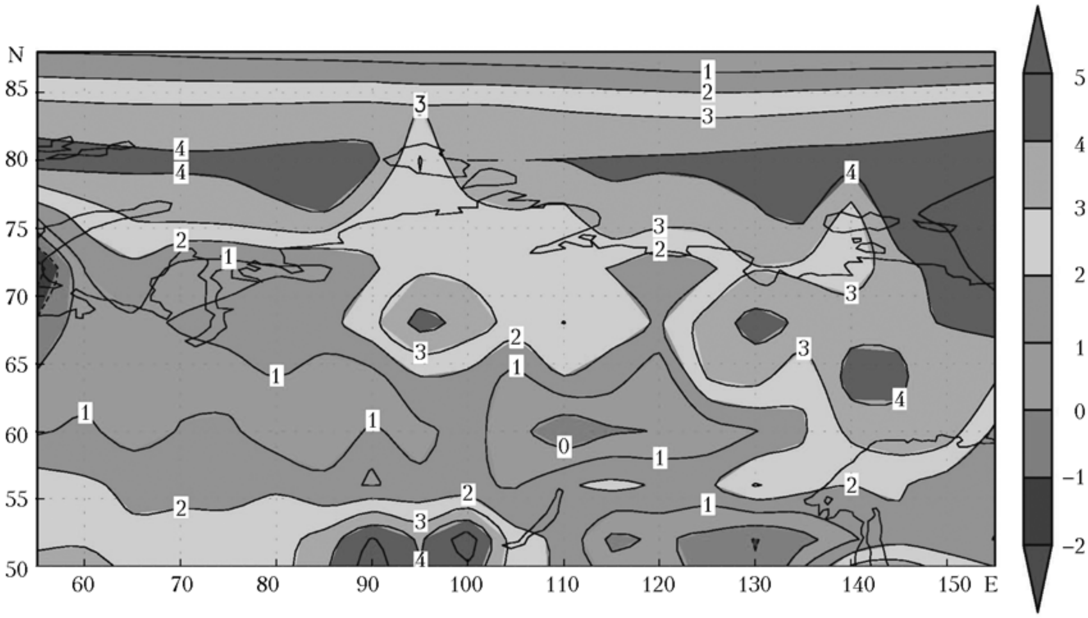

Fig. 6. Field of systematic errors of reconstruction of air temperature at the level of 2 m (in Kelvins) with the joint model of general circulation of the atmosphere and ocean.

According to the conditions of the CMIP program, global warming was also modeled along with the control experiment on reconstructing the model climate. To do this, the increase of atmospheric concentration of carbon dioxide was set at a rate of 1% per year from the value in the beginning of the experiment.[27] It is approximately twice as large as the observed rate of the CO_2 content increase. Duration of this numerical experiment was 80 years, and duplication of the CO_2 concentration occurs approximately by the 70th year of integration by the model. The response of the model to the increase of the carbon dioxide concentration means the difference between the data of the experiment with the increase of CO_2 and the results calculated in the control experiment during the past 20 years of the model time (1961–1981). As the calculated results showed, the regional (for the territory of Siberia) distributions of the response of near-ground temperature and precipitation to duplication of the carbon dioxide content also have localizations (compare, in particular, with the data in Fig. 1), which is the most pronounced in the case of the field of precipitation.

Estimation of regional consequences of global warming

As has been expected, significant changes will occur in the fields of temperature and precipitation under conditions of the increased concentration of greenhouse gases, the problem is urgent on estimating (based on monitoring and modeling) the subsequent impact of this process on the state of permafrost, which covers the big part of the territory of Russia. The threshold value of 0°C for temperature related with phase transitions water→ice and ice→water is critical for northern regions, because under conditions of essential warming of climate one should expect dramatic acceleration of the process of the permafrost degradation, already observed at present. This, in its turn, can become a trigger for the erosion and settling of soil with unfavorable consequences for both ecological system and human economic activity in these regions.

Also essential is the fact that releasing such very active greenhouse gases accumulated in the permafrost as carbon dioxide and methane occurs during this process. In its turn, it can affect (along with other factors) the atmospheric circulation. On the other hand, the danger of unfavorable impact of warming on water objects (in particular, drying shallow water reservoirs and wetlands) and on the forest areas (the increase of frequency of fires) becomes more probable.

Among the peculiarities of the grounds of permafrost one can select the presence of the so-called active layer, in which the processes of freezing and melting occur due to seasonal variations of the heat budget component on the atmosphere–soil interface. Dynamics of the active layer depends on the heat flux coming from the soil surface, its structure and thermal properties, amount of liquid water, the presence of vegetation cover, thermal regime of deeper layers of the permafrost, etc. As interannual variations of temperature can penetrate to the depth of frozen soil down to some tens of meters, and systematic (geographically distributed) long-term measurements of temperature at such depths are absent, the method of mathematical modeling is the main tool for solving the problems of estimation of the degree of vulnerability of soils in the regions of permafrost with respect to the climate changes. Either archived data of the network of meteorological stations[28] or the results calculated using global climate models[29–31] are used as input parameters.

It is known that the soil surface of the vast area occupied by tundra and forest-tundra is covered by mosses and lichens, which have very low heat conductivity and serve thermo-isolator in the processes of mass and energy exchange between the soil and the atmosphere. Peatbogs play the same role in some regions occupied by taiga (for example, in Western Siberia). The moss thickness can reach 10 cm and more, the peat thickness can be greater than 0.5 m.

The effect of the thickness of the heat-insulation layer on the process of seasonal soil melting under conditions of permafrost was analyzed[28] using a single-dimensional model of the processes of heat and moisture transfer in soil and snow. This thickness turned out an important parameter affecting the depth of melting the frozen soil in summer. In some cases, when the frozen soil has temperature close to zero, the value of this parameter is the key one for the existence of the permafrost.

An important element of natural environment of high and mid-latitudes is snow cover. Physical processes occurring here (compression of snow under metamorphism and gravity, phase transitions, etc.) essentially affect thermal regime of the active layer of the permafrost. Comparison of the measurement results on soil temperature at different levels obtained in 1971–1973 in Yakutsk[32] and the results of calculations taking into account the snow compression and without it[28] is shown in Fig. 7 as an illustration.

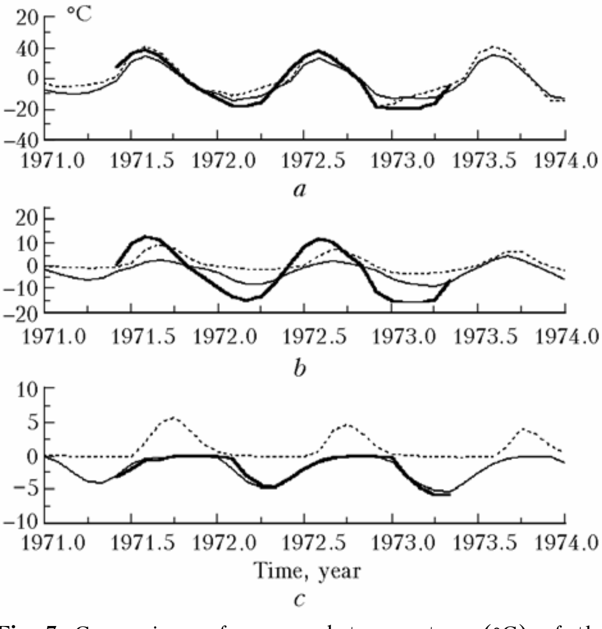

Fig. 7. Comparison of measured temperature (°C) of the active layer of permafrost in Yakutsk (solid bold line) with calculated results using a model taking into account snow compression (thin solid line) and without it (dotted line) at the depth of 10 (*a*), 50 cm (*b*), and 2 m (*c*).

It is important to note that integration in the aforementioned model was carried out using the observed atmospheric data covering the period from 1937 until 1984. So, the fact that the results of modeling taking into account snow compression during the interval from 1971 until 1973 considered are in a good agreement with the measurement data well confirms the adequacy of this model to the physical system considered. In general, comparison[28] of the calculated results with the data available showed their good agreement that enables one to consider this model as one of the tools for solving various problems in the investigation of the natural environment. In particular, an important problem is joint analysis of data of monitoring of the current state of cryolytosphere on the territory of Russia (North Ural, Siberia, Far East), among them, under conditions of anthropogenic loading,[33] and the results of forecast of its future evolution. Such investigations are useful both for further improvement of the mathematical models and for rational planning of the observational programs.

The account of hydrological processes

In connection with the progress reached to date in computers and development of the systems of parallel programming, the modern stage of development of mathematical models of the climate system is characterized by permanent improvement of the spatial resolution and refusal (at regional level) from hydrostatic approximation. These tendencies give rise to new problems in detailed description of the physical processes of the subgrid scales, among which interaction of the atmosphere with different types of the underlying surface on land is important.

One of the key problems here is description of the processes of interaction of the atmosphere with the set of hydrological objects, the most important part of which is lakes and wetlands. It is especially important for northern territories of Eurasia (West Siberian plain, Karelia, Finland) and North America (bigger part of the territory of Canada), where this system is most dense and where, as experiments with climate models show, regional temperature changes related to global warming are pronounced most strongly.

For adequate parameterization of the processes of interaction of the atmosphere and land under these conditions, it is necessary for the corresponding block of the climate model to take into account the effect of "hydrological inhomogeneity" of the underlying surface. It becomes of special importance here to compare different approaches to solving this problem based on the use of the series of long-term climate and ecological observations in individual regions. An example of such a comprehensive investigation is the integrated project on the study of Great Vasyugan Bog carried out by the initiative of SB RAS.

At present, wetlands are represented in climate models as corresponding specification of one or another part of the underlying surface ignoring thermodynamic processes in their depth, the role of which in mass and energy exchange between the atmosphere and land has not yet been sufficiently studied. At the same time, certain experience has been accumulated up to now in solving the problems related with some aspects of interaction of the atmosphere and wetlands (see, for example, the papers devoted to hydraulics of wetlands[34] and investigations of the processes of generation and transfer of methane[35]). Lakes also essentially affect the structure of the near-ground layer of the atmosphere and, hence, the fluxes of heat, water vapor, and momentum.

In the majority of the models of weather forecast and in climate models, the effects related with comparatively small and shallow lakes are either ignored or parameterized very roughly assuming, for example, that the water reservoir is well mixed over depth. Actually, this means that the lake is considered as an element of the underlying surface. In reality, lakes in high and mid-latitudes are vertically stratified in density during the major part of the year. At the same time, description of the effect of vertical stratification based on modern theories of turbulent mixing and in three-dimensional approximation is the task that yet requires significant computational resources. It is the most essential restriction, if especially taking into account the processes of heat and moisture transfer in the soil layer located under the reservoir bottom during long time.

A compromise in the development of parameterization of the effect of wetland–lake objects is presented in Ref. 36, which combines the sufficient completeness of physical description of the processes of heat and moisture transfer in the reservoir–soil system and computational efficiency of the corresponding algorithms for its realization. For this purpose, a one-dimensional model of thermohydrodynamics of a reservoir interacting with near-ground layer of the atmosphere and the soil was developed. It considers the processes of diffusion and transfer of heat and moisture by flows, transfer of moisture under the effect of gravity, its phase transitions, the processes of evolution of ice and snow cover, heat and moisture exchange with the atmosphere. Thus, in the first approximation, all principal processes forming the short-period (diurnal) and long-period (seasonal and interannual) variability of the state of the reservoir–soil system are taken into account in the model. The data of regular long-term meteorological observations during the period from 1936 until 1984 in Siberia and Yakutia were used as an atmospheric impact.

Analysis of the results of numerical experiments with data of field measurements[37] at lake Syrdakh in Central Yakutia showed that the model adequately reconstructs the following principal parameters of its climatic regime: mean depth of winter freezing, time of the beginning and finishing of freezing-over of the lake, mean evaporation in warm season, evolution of the temperature profile. Besides, melting layer under the considered lake is reconstructed, existence of which is also confirmed by the data of observations.

Thus, certain basis exists for investigations into the physical processes and mechanisms determining interaction of the atmosphere (in particular, its near-ground layer) with hydrologically inhomogeneous land surface under conditions of observed and future climate changes.

It is necessary to develop a three-dimensional non-hydrostatic mathematical model of the dynamics of the boundary layer, combined with the model of heat and moisture transfer in soil (covered with vegetation and/or snow) and in lake–wetland systems. Based on numerical modeling and climate-ecological monitoring, it is expedient to construct and examine an improved algorithm for parameterization of the processes of interaction of the atmosphere and land in hydrodynamical models of climate.

Conclusion

The results of analysis of the empirical data discussed above are evidence of the basic climatic changes in Siberia during the past decades. The mathematical modeling performed show that the possible cause of such changes can be the global warming processes observed now. The attempt undertaken to bring together two yet essentially different methodological approaches (empirical and mathematical modeling) for investigations of such dynamical climatic system as Siberia seems to be quite promising. Such an attempt is the necessary step toward further basic researches and completely meets the idea of "integrated regional research" mentioned in the introduction. At the same time, comparison of two approaches to the study of climatic changes performed above reveals some unsolved problems, including the methodological ones.

One of such methodological problems is related with the necessity of matching the initial notations and terms. The empirical parameters analyzed above (annual and monthly mean temperatures, amplitudes of seasonal variations, long-term periodicities, etc.) are quite evident for illustration of the observed climate changes in separate regions, but already do not agree with the parameters being used for description of the climate variability in mathematical modeling. Moreover, many of the empirical parameters, as the frequently used term of "regional climate system" do not yet correspond to mathematically rigorous definitions of climate and climate systems.

Another one problem, common for both approaches, is related to the necessity of developing the effective techniques for quantitative estimation of the fractions, which different factors produce in the total effect on the observed climate changes. To solve this problem, in processing data of instrumental observations, it is necessary to seek a sufficient set of the measured parameters and technical tools for comprehensive monitoring,[6] and in making mathematical modeling, it is necessary to develop the theory of sensitivity of the climate system to small external impacts.[38] In both cases, urgency of the problem is determined not only by the problems of interpretation and forecast of the modern climatic changes, but also by the continued discussion on scientific justification and efficiency of the Kyoto Protocol.

The aforementioned and some other problems of integrated regional investigations cannot be considered unsolvable. However, development of a new paradigm for description of the cause and effect relations at global and regional changes of the environment and climate depends on successful solution of these problems.

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