System-evolutionary analysis of the regional climate changes

E.A. Dyukarev, M.V. Kabanov, and V.I. Shishlov

Institute of Optical Monitoring,
Siberian Branch of the Russian Academy of Sciences, Tomsk

Received November 12, 2001

The system-evolutionary approach to description and analysis of nature and climate changes based on the monitoring data is discussed. Graph-analytical techniques are suggested for analysis of spatiotemporal changes in natural climate systems judging from their images in the space of evaluation functions. As an example, analysis of the recent climate changes in Western Siberia is presented for some periods of evolutional trajectory (short-term temperature drop in 1966–1972, anomalous temperature changes in spring of 1999).

Development of the methodology[1] and techniques of monitoring[2] stimulates development of new methods for analysis of the data of comprehensive monitoring of the environment and climate in order to interpret and predict their changes. This paper is devoted to the analysis of regional climate changes as judged from long-term observations of hydrological and meteorological characteristics and environmental monitoring with the use of the system-evolutionary approach.[3]

The object of study is the natural climate system (NCS) of Western Siberia, which is a part of the continental geosphere with a certain mesoclimate, whose changes are connected both with the global changes in the geosphere and with the changes in the intrasystem relations between elements of the geosphere. The NCS of Siberia as a whole is characterized by some features: the effects of nonzonal components of air mass circulation in Arctic and Middle Asia, large-scale anticyclonic vortices of the Siberian High dominating in winter over the continent,[4] baric formations of the Altai–Sayan mountainous area,[5] as well as large-scale anthropogenic transformations of natural complexes with change of their geospheric functions and properties.

In our previous papers, using graph-analytical methods for analysis, we obtained the results on the secular variability of regional climates[3] with the use of evolution trajectories of the integral evaluation function of the process and cumulative sum of series of meteorological parameters,[6] as well as on the peculiarities of interannual variations and intraannual cycles of regional climate with the use of phase portraits of meteorological parameters and evaluation functions.[7,8] Below we analyze the behavior of NCS of a geographic region as an entire system with the allowance for its structure transformations and reorganization of intersystem relations within the framework of a multilevel system of relations between processes and objects of the geosphere. The proposed approach to analysis of changes in the fields of meteorological parameters from their maps onto a plane allows finer analysis of peculiarities in the spatiotemporal variations of the NCS state and revealing the dominating factors and some cause-and-effect relations.

The capabilities of analysis and interpretation of climatic changes, as well as evaluation of the role of anthropogenic and natural factors in the change of climatic and ecological conditions depend on the level of description and the form of representation of monitoring data, which carry the information about related non-uniformly scaled processes in the multilevel NCS. The problem of interpretation of climate variability can be solved correctly only if the description is complete. The latter requirement means description of all components of processes and phenomena of the climatic cycle and variability of the states of geosphere subsystems, in which they occur.

Methodological principles of analysis

The complexity of description of multilevel related systems with the elements of chronological and structure-functional organization at variations of intrasystem relations between the elements, the process dynamics, and reorganization of their interactions leads to necessary integration of traditional system methods of natural sciences with the methods accounting for evolution and transformation of intersystem relations. In the system-evolutionary approach, the Earth's geosphere is considered as a multilevel organized system of elements related by the process of a single cycle of energy transformation and energy-mass transfer, and the variability of the states of its subsystems is analyzed with the allowance for transformation of their relations, intersystem interactions, and their consequences and possible evolution.

Within the framework of the system-evolutionary approach, the principle of a single system of relations between elements and processes of a multilevel macrosystem reflects the unity of the structure-functional organization and relations, as well as the unity of related phenomena and processes in the sub-systems of different level. The principle of a single cycle of matched processes

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of a multilevel macrosystem reflects the unity of all stages of complex processes in different-level subsystems, including the support systems. The principle of relative consistency of intrasystem and intersystem relations asserts the idea of relativity of existence of the steady state in a system, which is realized in a quasi-equilibrium mode under the condition of consistency of intersystem relations of a subsystem and its relations with other systems of all levels. In this case, the change of any intersystem relations affects the modes of the processes, and this leads to the change of their common result and to transformation of the state of the system.

The use of more specific concepts and principles allows us to develop a new system of ideas on the variability of system states at variation of functions and relations of subsystems, as well as to develop new techniques of system-evolutionary analysis.

New techniques of analysis

The sequence of NCS states in the process of continuous many-year cycle of evolution of climate processes and conditions of weather formation can be described by a series of matrix operators:

$$X^{(0)}(M_1),\ X^{(1)}(L_{1i}),\ X^{(2)}(M_i),\ \cdots,\ X^{(p)}(M_k),\ \cdots, \quad (1)$$

where M_i and M_k are the model operators of the corresponding modes of equilibrium dynamics; $X^{(p)}$ is the matrix of characteristics of system states at the stage p, where $p = 0, 1, 2, 3, \dots$; L_{ji} are the operators of transformation of weather-forming conditions. Every weather-forming mode in the region corresponds to a certain model M_i, the matrix of domination coefficients of the processes, matrix of weather classes, matrix of determining weather parameters, and the matrix of evaluation characteristics of parametric fields and phenomena of the atmosphere.

The process of transformation of system characteristics at variation of weather-forming factors Φ_1, Φ_2, Φ_j, Φ_k is described by the equation

$$X^{(p+1)} = X^{(p)} + L^{(p+1)}\ (\Phi_1, \Phi_i, \Phi_j, \Phi_k, X^{(p)}), \quad (2)$$

where $L^{(p+1)}$ is the matrix operator of transformation of the weather-forming conditions and characteristics of the state of the system at the stage $p + 1$.

The increments of the evaluation function Z of the state and the determining meteorological parameters Y_k satisfying the condition of additivity at variation of the leading factor Φ_j of the new mode can be expressed as

$$\Delta Z^{(p+1)}(L_j) = L_{zj}\ (\Phi_1, \Phi_2, \dots, \Phi_n, Z)\ \Delta\Phi_j^{(p+1)}, \quad (3)$$

$$\Delta Y_k^{(p+1)}(L_j) = L_{kj}\ (\Phi_1, \Phi_2, \dots, \Phi_n, Y)\ \Delta\Phi_j^{(p+1)}. \quad (4)$$

These equations serve a basis for diagnosis of the modes from the results of monitoring. The technique of diagnosis of a weather-forming mode is based on the procedures of evaluation of climate-forming factors and measured meteorological parameters Y_k, joint analysis of increments of the evaluation function, meteorological parameters and factors, determination of their combinations and dominating processes with the use of information models of multi-mode processes of weather formation.[9]

Graphical presentation of the determining meteorological parameters and evaluation functions in the phase space give a clear idea of the variability of NCS characteristics in the cycle of climate processes. The procedures of analysis of complex processes are based on the methods of mathematical mapping theory,[10] in which a set of functions of several variables is used for description of maps of complex surfaces on a plane. The map of a surface point with the coordinates (x_1, x_2) onto the point of a plane with the coordinates (y_1, y_2) is described by two functions $y_1 = f_1(x_1, x_2)$, $y_2 = f_2(x_1, x_2)$. For analysis of the spatiotemporal variations of the process, we have to find the map of surface changes on a plane. Toward this end, we suggest using integral transformations of the following form $Z_t = \int_0^t x(t)\,\mathrm{d}t$ and $Z = \int_{t_i}^{t_{i+1}} x(t)\,\mathrm{d}t$. The study of the properties and peculiarities of mapping of quasiperiodic processes obtained with the use of different combinations of integral transformations of meteorological parameters allowed developing some techniques for graphical mapping of NCS states.

The technique of graphical mapping of NCS states includes the processing of series of meteorological data, calculation of evaluation characteristics of meteorological parameters for certain periods (month, season, year), and drawing of the meteorological portrait (points of state, phase trajectories). If the integral evaluation function Z is used as a coordinate, we obtain graphical mapping of the evolution of properties (characteristics) and modes of climate in the characteristic time. The analysis usually involves matched phase portraits, evolution trajectories of many characteristics (solar radiation, air temperature, soil temperature, precipitation, wind velocity, pressure, etc.), as well as portraits of the ensemble of NCS states in the multidimensional phase space of determining meteorological parameters. The proposed description and graphical representation tools were used for development of graphic-analytical methods for analysis of climate processes.[3,6,8] When analyzing the states of a climate system, these methods allow the character of the process to be established, the process itself to be described within the formalism of geometry and trigonometry, and the relatively strict analysis to be conducted from the graphical representation of many-year cycles of the weather formation.

The technique of analyzing interannual variability of the temperature in the surface layer of the atmosphere is based on the study of the trajectory of the evaluation function $Z(T)$, determination of amplitudes at singular points (annual extremes) of the evaluation function of diurnally mean temperatures $Z_i(T)$ and $Z_j(T)$, and calculation of estimates of the temperature conditions of the warm $Z_S = Z_j(T) - Z_i(T)$ and cold $Z_W = Z_{i+1}(T) - Z_j(T)$ seasons, as well as integral annual estimates of the thermal balance $Z_Y = Z_i(T) - Z_{i-1}(T)$. Figure 1 shows the time dependence of the integral evaluation function Z for different meteorological stations. The annual behavior of the integral evaluation function and its main characteristics: duration of the annual cycle τ_C, durations of the warm τ_S and cold τ_W seasons, and the corresponding characteristics of the integral estimates Z_S and Z_W are shown on a larger scale. The dashed plots correspond to the evolution trajectories of the temperature conditions.[3]

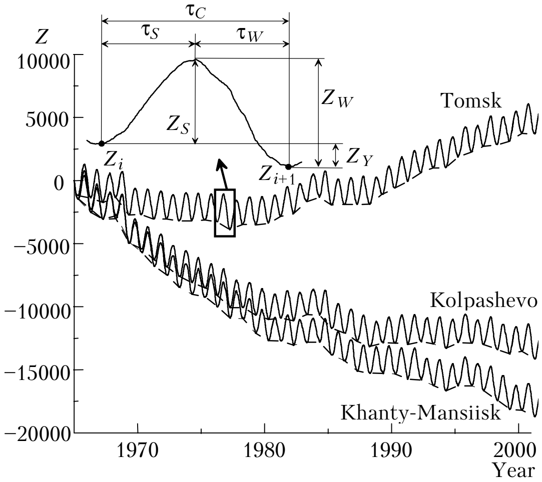

Fig. 1. Variation of integral evaluation temperature functions Z in time and their evolution trajectories for Tomsk, Kolpashevo, and Khanty-Mansiisk.

The technique of comparative analysis of the elements of annual cycle of meteorological parameters provides combination of geometric maps of the same element corresponding to different years on the same phase portrait and their joint processing. This technique determines the interannual variations of annual-cycle elements and the range of their many-year variability, as well as reveals particular modes and abnormal years.

The technique of spatiotemporal analysis of mesoscale processes for revealing the cause-and-effect relations and establishing the key factors in weather-forming processes for particular geographic regions is based on the joint analysis of meteorological portraits of different regions with the allowance for their geographic position. In particular, the joint analysis of variability of the monthly mean temperature and monthly increments of the evaluation function with the allowance for consistency of chronological relations of geographic regions and dominant mesoscale processes in the atmosphere determines the behavior of weather-forming processes and their spatial distribution. Physical interpretation of the space-time behavior of various climatic processes involves also the use of synoptic maps, as well as aerological and space information.

The technique of analysis of spatiotemporal variations of the temperature (radiative) conditions of NCS studies mapping of state evolution of regions in one phase portrait in the plane of evaluation functions in the warm Z_S and cold Z_W seasons. Mapping of a series of states of a quasiperiodic process at different spatial points (Fig. 2) allows analysis of the spatiotemporal variability of cycles of climatic processes to be performed.

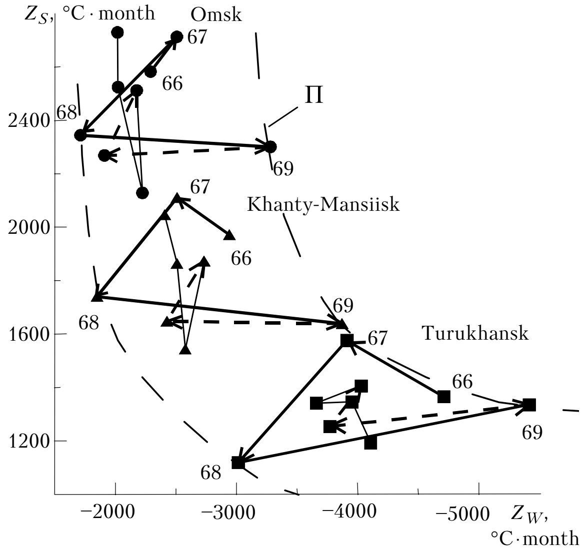

Fig. 2. Mapping of NCS states with respect to temperature conditions in the plane of evaluation functions of the warm (Z_S) and cold (Z_W) seasons.

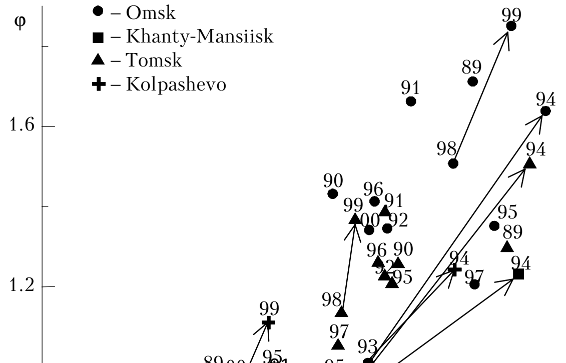

Fig. 3. Mapping of NCS states in the plane of characteristics of the ratio of evaluation functions φ and the duration ratio of the cold and warm seasons τ.

The technique of analysis of NCS state variations, their spatial peculiarities, and direction is based on mapping of states in different NCS regions on one portrait in the plane of evaluation characteristics of the annual cycle: characteristics of the ratio of evaluation functions $\varphi = Z_S/Z_W$ and characteristics of the duration ratio of the cold and warm seasons $\tau = \tau_S/\tau_W$. The analysis of this mapping (Fig. 3) reveals the dependences of evaluation characteristics of the process on the duration ratio of the cold and warm seasons, determines the direction of interannual changes in the NCS states, and establishes their peculiarities from the abrupt change in the direction of interannual variations. Thus, NCS zones with different direction of interannual variations can be separated and their dependence on climate-forming factors can be found.

The combination of description and graphical representation tools, as well as techniques of analysis allows variability of the processes, characteristics of system states, and intersystem relations to be analyzed jointly based on dissimilar information on objects and processes of different scale and level.

Some results of analysis

Analysis of secular variations of monthly mean temperatures and precipitation shows[6] that in the 19th century and early in the 20th century all regions of the taiga zone of Siberia were characterized by moderately cold damp climate. The taiga NCS of Western Siberia was a single system of mesoscale level having a single dominating cycle of climate processes with spatially homogeneous variations of thermal conditions. The taiga NCS is characterized by the lack of coordination between atmospheric climatic processes with land taiga ecosystems and specific water-cycle processes (precipitation interception by tree crowns, decreased evaporation of soil cover, moisture content by mossy cover) and heat exchange through tree crowns, which lead to elongation of snow thawing processes in the forest and shortening of the warm season, decrease of soil warming-up, and conservation of frozen ground. This causes non-coordination between the thermal conditions (heat deficit in May and June at the maximum of solar radiation) and radiative conditions (astroclimate of the latitude belt). Consequently, climate and biogeocenological phenomena, i.e., relations between the climate system and biosystems, are non-coordinated as well.

In the early 20th century, the climate in Southwestern Siberia transferred from taiga to steppe conditions. This transition gave rise to structure reconstruction of land ecosystems, degradation of soil cryosphere, co-evolution of atmospheric and land hydrometeorological processes, and reorganization of NCS intersystem relations. The warm season became longer at the transient stage. Thus, after 1920, the steppe climate dominates in Omsk. This climate is characterized by the integral evaluation $Z_S = 76–85°C \cdot$ month, positive annually mean temperature, the warm season $\tau_S = 180–210$ days long, the positive April temperature (0.5 – 6.5°C), and the annual amplitude of monthly mean temperatures of 42–48.4°C ($T_{max} = 22.2$, $T_{min} = -26.2$°C). The transient stage terminated by 1930 in Barabinsk and by 1939 in Tomsk, but in the latter with shortening of the warm season down to 160 days and negative values of the annually mean temperature, as well as stepwise (for 1–2 years) variability of the behavior of climate conditions. Stepwise changes occurred in 1941, 1944, 1946, 1949, 1950, 1953, 1968, and 1984 and were accompanied by the state of cold advection and longer duration of transformation of cooling at deep anticyclone. The deep anticyclone of winter 1968/69, from which mesoscale changes and the cooling stage of 1968–1976 (see Fig. 1) began, stands out.

Analysis of variability of the evaluation functions (Z_S, Z_W) and durations of the warm and cold seasons (τ_S, τ_W) shows that in the cooling period (1966–1974) variations of the evaluation functions in the analyzed regions are weakly connected with variations of the duration of the cold and warm seasons. Thus, from analysis of maps of spatiotemporal variations of NCS states through the set of functions Z_S and Z_W for every region (some of them are shown in Fig. 2), it follows that variations in the same direction occurred simultaneously in all regions (directions are shown by arrows). As this took place, the NCS in all regions completed the cycle of transitions and came back (return is shown by dashed arrows) to the initial state (state area of 1963–1966). The profile Π of the spatial distribution of the evaluation functions kept during the transitions. The Table presents the data (initial state Z_S^0 and Z_W^0 and deviations at the stages p: $y^{(p)} = Z_S^{(p)} - Z_S^0$, $x^{(p)} = Z_W^{(p)} - Z_W^0$) illustrating the variations of NCS states in nine regions. These results are indicative of a single cycle of mesoscale climate processes within the same West-Siberian NCS.

Table. Variations of NCS states as judged from evaluation functions in the warm (Z_S) and cold (Z_W) seasons

Evaluation functions	Omsk	Berezovo	Tomsk	Khanty-Mansiisk	Barnaul	Surgut	Aleksandrovskoe	Krasnoyarsk	Turukhansk
Z_S^0	2582	1632	2253	1889	2655	897.9	881.5	1528	1365.8
Z_W^0	−2291	−2561	−2627	−2509	−2102	−2365	−2342	−1454	−3910
Y^1	129.9	115.1	82.6	222.1	14.7	766.2	749.4	116.6	210.5
X^1	578.3	317.8	709.2	661	159.8	722.9	660.3	138.1	895.3
Y^2	−238	−226	−219	−147	−197	−660	−555	−208	−246.9
X^2	−989	−1632	−818	−1362	−969	−445	−493	−698	−1504
Y^3	−282	−280	−129	−249	−185	136.4	247.9	240.1	−29.9
X^3	380.3	−301	545	84.3	314.5	238.8	230	−51.5	140.1
Y^4	−314	−220	−248	−240	−231	−133	−72.5	35	−111
X^4	114.7	−592	254	−222	31.2	164	168	−140	−119.6
Y^5	−70.7	−246	−30.6	−15.3	−132	–	–	–	40
X^5	66.7	−314	428.1	−67.1	233.7	–	–	–	253.2
Y^6	–	−294	–	–	–	–	–	–	−24.1
X^6	–	−252	–	–	–	–	–	–	−42.8

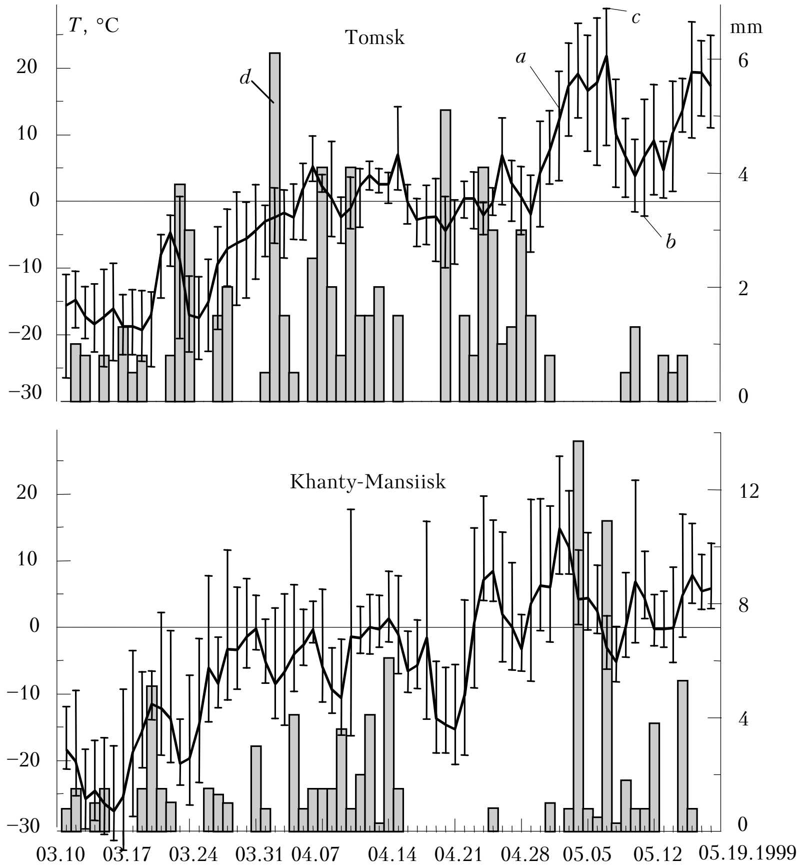

Fig. 4. Variations of monthly mean temperature (*a*), minimum (*b*) and maximum (*c*) diurnal temperatures, and total diurnal precipitation (*d*) in spring 1999 as measured at stations in Tomsk and Khanty-Mansiisk.

Analysis of variations of evaluation characteristics of warming processes during warming (1980–1990s) shows that variations of the evaluation functions are rather closely connected with variations of the durations of the cold and warm seasons. Figure 3 shows the NCS states for four regions using the sets of characteristics of φ and τ. It can be seen that there exists some dependence of the ratio of integral estimates on the season duration, though it is ambiguous (one value of τ corresponds to different values of φ), and variations of the NCS states in these regions at sharp warming (1982–1983 and 1994–1995) have the same direction (solid arrows).

Additional useful possibilities of system-evolutionary analysis of nature and climate changes are also open for interpretation of fragments of evolution trajectories of the regional NCS's. To illustrate these possibilities, let us analyze the interannual variations of NCS states in Khanty-Mansiisk and Kolpashevo, where warming was terminated already in the cycle of 1995–1996. In the cycle of 1998, sharp changes in the direction (dashed arrows in Fig. 3) of the states are connected with elongation of the cold season due to cold April of 1999. To study this conclusion, detailed analysis of the seasonal behavior of monthly mean temperatures and precipitation in different regions, as well as peculiarities of variation of atmospheric processes was performed. The seasonal behavior of temperature and precipitation are plotted in Fig. 4. It can be seen from this figure that the weather was cold in all regions of Western Siberia late in March of 1999.

Warming in early April began with income of the western cyclone. In April 4–6, the daytime temperature in Tomsk rose up to +10°C due to advection of heat and moisture, and intense thaw began. However, in Kolpashevo and Khanty-Mansiisk the cold weather kept until April 22 under the effect of an anticyclone, which moved to the southeast from Novaya Zemlya due to abnormal circulation in the upper atmosphere.[11] The circulation in the atmosphere turned to the summer type in March, but the stable development of the near-polar anticyclonic vortex did not occur because of the blocking effect of an extended anticyclone covering Siberia and vast territories of the Arctic and Canada.[12]

The baric field transformed under the effect of unstable polar vortex in early April. Cold air masses from the Arctic penetrated to the continent through a trough in the atmosphere over the European territory of Russia, and a cyclone from Volga region moved to the Southwestern Siberia. At the northwest near Novaya Zemlya, anticyclones originated in April and then moved to the southeast through Northwestern Siberia and the Krasnoyarsk Region. The transformation in the stratosphere to the summer type of circulation terminated only by May 1, i.e., 19 days later than the mean date.

So, chronological (positional) non-coordination of the Asian anticyclone and polar vortex caused peculiarities of transformation of atmospheric circulation (change of the baric field structure, formation of a cold upper trough in the west and anticyclones in the east), which led to formation of two different weather-forming processes on the territory of Western Siberia.

Conclusion

Within the framework of the system-evolutionary approach to the study of regional climate changes, the description of variability of the states of a natural-climatic system through increments of integral evaluation functions (with the use of multilevel information model of weather formation and tools for graphical representation of the ensemble of system states) allowed us to develop techniques and information technology of joint analysis of the variability of the processes, characteristics of the NCS state, and intersystem relations based on dissimilar information about objects and processes having different scales and levels. Their use in analysis of instrumental data allows illustrative description of the climate evolution in Western Siberia, peculiarities of variation of intersystem relations, and their manifestation in variations of characteristics of the NCS state. From some results of the system-evolutionary analysis of the regional nature and climate changes, we can draw now the following conclusions:

– variability of climate conditions in different regions at middle latitudes of the Northern Hemisphere is determined by the peculiarities of transformation of the baric field structure and the varying relations of domination of climate processes in the NCS, which depend significantly on the evolution of air masses in the process of movement and interaction of atmospheric formations in both the upper and lower atmospheric layers;

– in spite of the spatially inhomogeneous non-coordination of temperature and radiative conditions in Western Siberia, as well as non-coordination of climatic and biotic relations, there are many-year periods with the same interannual variability of temperature conditions in different regions, what allows the NCS of Western Siberia to be considered as an entire system of mesoscale level with the transformable structure and reorganization of weather-forming cycles.

The above conclusions are the results of the first stage of our research and seem to be useful for the following system description of natural and anthropogenic factors determining the current natural-climatic changes in Western Siberia.

References

1. M.V. Kabanov, *Regional Monitoring of the Atmosphere.* Part I. *Scientific and Methodic Foundations*, ed. by V.E. Zuev (SB RAS Publishing House, Tomsk, 1997), 210 pp.
2. M.V. Kabanov, ed., *Regional Monitoring of the Atmosphere.* Part III. *Unique Measuring Systems* (SB RAS Publishing House, Tomsk, 1997), 238 pp.
3. M.V. Kabanov, ed., *Regional Monitoring of the Atmosphere.* Part IV. *Natural and Climatic Changes* (Rasko, Tomsk, 2000), 270 pp.
4. N.V. Vakulenko, A.S. Monin, and Yu.A. Shishkov, Dokl. Ros. Akad. Nauk **371**, No. 6, 802–805 (2000).
5. V.V. Sevost'yanov, *Climate of Mountain Regions of Altay and Sayan Mountains* (Tomsk State University Publishing House, Tomsk, 1998), 201 pp.
6. E.A. Dyukarev and V.I. Shishlov, *Analysis of climatic changes using phase portraits,* SPIE **4678** (2001) (to be published).
7. E.A. Dyukarev and V.I. Shishlov, in: *Proceedings of the II International Symposium on Environmental Monitoring and Rehabilitation*, Tomsk (2001), pp. 121–123.
8. E.A. Dyukarev and V.I. Shishlov, *Estimation of aperiodic changes of climate parameters,* SPIE **4678** (2001) (to be published).
9. V.I. Shishlov, in: *Fundamental Problems of Environmental Protection and Ecology of Natural-Territorial Complexes of Western Siberia. Proceedings of Scientific Conference*, Gorno-Altaisk (2000), pp. 46–48.
10. V.I. Arnold, *Theory of Catastrophes* (State Physical and Mathematical Press, Moscow, 1990), 128 pp.
11. O.N. Belinskii, L.V. Kirienko, and M.G. Naishuller, Meteorol. Gidrol., No. 7, 122–124 (1999).
12. O.N. Belinskii, L.V. Kirienko, and M.G. Naishuller, Meteorol. Gidrol., No. 8, 120–122 (1999).