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Some Aspects in the Development of Dynamic Meteorology in Russia in 2003–2006

V. N. Lykosov[a] and V. N. Krupchatnikov[b]

[a] *Institute of Numerical Mathematics, Russian Academy of Sciences, ul. Gubkina 8, Moscow, 119991 Russia*
e-mail: lykossov@inm.ras.ru
[b] *Siberian Regional Research Hydrometeorological Institute*
e-mail: vkrup@ommfao1.sscc.ru

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Abstract—A brief review of the studies performed by Russian scientists in dynamic meteorology in 2003–2006 is presented. This review is based on the material prepared by the Commission on Dynamic Meteorology of the National Geophysical Committee of the Russian Academy of Sciences and included in the general information report of the Section of Meteorology and Atmospheric Sciences at the 24th General Assembly of the International Union of Geodesy and Geophysics[1].

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The studies performed by Russian scientists in 2002–2006 in dynamic meteorology and discussed in this review can be conditionally referred to in the following sections: General Atmospheric Dynamics, Large-Scale Processes and Weather Forecasting, Turbulence in the Boundary Layer, and Mathematical Problems of Climate and Ecology. Some parts of the results obtained from these studies was previously published in the paper by Kurgansky and Tolstykh (2004).

1. GENERAL ATMOSPHERIC DYNAMICS

In many problems of dynamic meteorology, atmospheric dynamics can be described with the help of an ensemble of interacting vortices and waves of different scales in the approximation of an ideal fluid. Among these problems is that of adjusting externally disturbed flows to a quasi-equilibrium state, an important task in developing hydrodynamic methods of weather forecasting. In the paper by Yakushkin (2005), it is shown that many problems of geophysical fluid dynamics for the flows of an ideal fluid can be formulated through Hamilton's canonical equations. The main Lagrangian invariants—entropy and potential vorticity—are used as canonical variables. It is shown that three pairs of canonical variables are related to three types of perturbations in an equilibrium state of a fluid (compression, displacement relative to the gravity field, and velocity shear). These perturbations lead to three types of motion: acoustic, gravitational, and vortical. The transition to simplified flow models (in which some types of motion are excluded), which are characterized by a smaller number of canonical variables, is considered.

Hydrostatic and quasi-geostrophic approximations of hydrodynamic equations are often used for a theoretical study of large-scale atmospheric processes and in assimilation procedures for observational data. Gledzer (2003) proposes a sequence of dynamic systems that are intermediate between the geostrophic equations describing slow motions and the exact equations of the motion of a horizontally stratified fluid in an ellipsoidal hollow. It is shown that the inclusion of fast oscillations leads to a significant change in the frequencies of slow motions with an increasing stratification parameter and to a change in the amplitudes of motions as compared to the geostrophic case for which fast modes are filtered out.

An essential element of the classical theory of flow adjustment to a quasi-geostrophic equilibrium is the assumption of an unbounded space. Under real conditions of a bounded atmosphere, however, fast perturbations can return to the region of their generation; so, for a nonlocal perturbation of equilibrium, the most important mechanism of their decay is dissipation. The question is what influence the global deflections from a quasi-geostrophic equilibrium can exert on the atmospheric general circulation and what are the threshold values of these deflections that lead to qualitative changes in the dynamic state of the atmosphere (Gledzer et al., 2006). This paper examines the behavior of a dissipative model similar in energy (in the sense of the existence of different circulation regimes) to an atmospheric system stratified with the background horizontal temperature gradient. For this pur-

[1] *Russian National Report. Meteorology and Atmospheric Sciences, 2003–2006*, Ed. by I.I. Mokhov and A.A. Krivolutsky (National Geophysical Committee RAS, MAX Press, Moscow, 2007).

pose, the regimes of motion that are described by the original equations and approximations commonly used to solve the problems of the theory of atmospheric general circulation are analyzed. The Hadley and Rossby circulation regimes and transitions between them, which are observed in numerical and laboratory experiments, are considered. Particular attention is given to the consistency between different regimes of the exact equations and their quasi-geostrophic approximations.

The paper by Kalashnik (2004) considers some mathematical aspects of deformation frontogenesis theory, which is based on the assumption that the initial temperature lapse rates are steepened by large-scale deformation velocity fields. It is shown that the existence of a sufficiently large number of Lagrangian invariants and of the functional relationship between them make it possible to reduce the system of equations of deformation theory to the system of diagnostic equations. The exact solution to the problem is obtained for a flow with a uniformly distributed potential vorticity. This solution can be compared with in-situ data on the structure of atmospheric fronts.

Investigating the stability of zonal geostrophic flows is one of the central problems of geophysical fluid dynamics. In Kalashnik's paper (2005), the stability of zonal geostrophic flows is analyzed using a linear approximation and taking into account the effects of the medium's compressibility. The quadratic conservation laws are used to derive conditions for symmetric stability (perturbations are independent of the coordinate along the main flow), which imply, in particular, that the flow must be stably stratified and its potential vorticity must be positive. A generalized transfer equation for potential vorticity in a linearized form is formulated to study nonsymmetric stability. Sufficient conditions for the nonsymmetric stability of zonal geostrophic flows, which are analogous to the well-known Rayleigh and Fjortoft conditions for two-dimensional flows of an ideal fluid, are formulated in this approximation.

The nonlinear problem of geostrophic adjustment in a two-component fluid with a density stratification composed of its temperature stratification and of the stratification of an admixture concentration (in the case of the atmosphere, air humidity) is studied analytically in the paper by Kalashnik and Ingel' (2006). It is shown that considering the medium's two-component composition can lead to the appearance of qualitatively new features in the structure of the final geostrophic state. For example, a stationary temperature perturbation of opposite sign and of larger amplitude may form in the region of the initial localized temperature perturbation in the course of adjustment. The frontal surface in the final state may be well pronounced only in the field of one of the thermodynamic variables. These features have no analogues in the case of a one-component medium.

Churilov's publication (2004) studies the stability of flows without inflection points on a velocity profile increasing monotonically from zero to a maximum value. A two-layer model of a stably stratified medium with a stepwise density profile is used for this purpose. It is shown that instability occurs at an arbitrarily small density difference, and the amplitude of perturbations increases on all scales. The velocity of downstream propagation of unstable perturbations increases as the stratification strengthens. The upper boundary of the instability region is determined by the fact that a perturbation comes out of phase resonance with the flow and converts into a neutral oscillation.

In the paper by Kurgansky (2003), the general problem of determining the velocity vector is considered for a steady three-dimensional flow of a compressible fluid in the case where this flow occurs along the stream tubes that are formed by the intersection of the isosurfaces of adiabatic invariants (Ertel's potential vorticity and specific entropy). In the quasi-geostrophic approximation, a formula is derived to determine the velocity vector from the given distribution of potential temperature at isobaric surfaces.

Some atmospheric vortex structures (e.g., spouts, tornadoes, and horizontally oriented eddies in the planetary boundary layer) have a distinct helical structure. In Kurgansky's paper (2005), the kinematic properties of the helicity flux vector are discussed for adiabatic flows in a compressible baroclinic atmosphere. It is shown that the balance equation of helicity for steady flows with an identically vanishing field of Ertel's potential vorticity has a solution with a zero vector of the helicity flux. An analytic example of an axisymmetric vortex is given for which the conditions of vanishing helicity, potential vorticity field, and helicity flux vector are fulfilled simultaneously.

Tropical cyclonic vortices of anomalously high intensity are among the extreme weather events. Although numerical modeling is one of the main methods of their study, laboratory experiments significantly enhance our knowledge of vortex formation. Results of a laboratory study of conditions for the excitation of a large-scale spiral vortex from a localized heat source in a rotating fluid were discussed in the paper by Bogatyrev et al. (2006). The influence of convection and background rotation on the threshold of spiral-vortex excitation was investigated for various fluids in cells with different geometries. It was found that the threshold of vortex excitation lies in the region of turbulent convection and a relatively slow rotation and has almost no dependence on the Prandtl number.

The boundaries between the eye (with no or small cloud amount and slight winds), the axisymmetric cloud top (where the radius of maximum winds is located), and jetlike "tails" (or rainbands) can be clearly seen in satellite pictures of deep typhoons (Dobryshman, 2004). In this paper, a hydrodynamic model of the relation between the structure of the wind field and the curvature of the radial profile of surface pressure is considered for three parts of the typhoon: at small radii (up to 60 km), at large radii (100–600 km), and at radii over 700 km, where the circulation regime changes from cyclonic to anticyclonic. It is shown that deep typhoons may have two radii of maximum winds: at the first radius (closer to the center) the wind is weaker than at the second, which is located at a distance of three to four radii of the eye. In the second region, the axisymmetric structure of the wind field breaks down and various regimes with singularities may form. In the third region, the pressure gradient practically vanishes and an anticyclonic circulation dominates at distances over 1000 km from the center.

The mutual influence of tropical cyclones is now much more poorly understood than the cyclones themselves. As a rule, such investigations are restricted to a study of the influence of interaction between two cyclones on their motion. At the same time, each of the cyclones changes the state of the medium (in particular, decreases the heat content of the upper ocean) and thus affects the subsequent cyclones. Under the conditions of limited resources of an energy source, the cyclones existing simultaneously compete to some extent with each other. Two nonlinear models describing the interaction of tropical cyclones with the upper ocean and with each other have been considered in the paper by Yaroshevich and Ingel' (2006). It is shown that the model reproduces some important qualitative features of the evolution of tropical-cyclone intensity.

For a characteristic of the integral effect of the atmospheric and oceanic structures, Mokhov (2006) has introduced a special quantity (the action), whose dimension is [energy] × [time]. A similar characteristic of the system determined by the time integration of the Lagrangian function is used in theoretical physics. In his paper, calculations of the action are presented for blocking anticyclones, or blockings, which bring about significant climatic anomalies such as extreme frosts in the winter and droughts in the summer. In particular, it is noted that the enhancement of the integral effect of winter blockings, which induce extreme frosts particularly in Eurasia and in the eastern part of North America, should be expected against the background of global warming caused by the increased CO_2 concentration in the atmosphere, according to the analyzed model data. This is due to increases in the number of continental winter blockings, their duration, intensity, and sizes. The results suggest that the occurrence of extremely low temperatures (like frosts at the beginning of 2006 in some regions of Eurasia, particularly in Russia) does not contradict the general tendency toward global warming.

The manifold of unsteady hydrodynamic flows generates the manifold of the regimes of transport of various pollutants in the atmosphere. The regimes of Lagrangian chaos and passive-tracer transport, which arise in two-dimensional vortex flows described by the equations of Hamiltonian dynamics, are analyzed in the paper by Kostrykin and Yakushkin (2003). It is shown that the Lagrangian transport includes transport along equiaction contours, transport in action, and a mixing of the tracer concentration in the entire region. Particular attention is given to the transport in action, which is determined by the location of hyperbolic singular points and separatrices of the flow. It is shown that a decrease in the separatrix region size leads to the formation of stagnant zones.

In Klyatskin's monograph (2005), the problems of passive-tracer diffusion in random flows are considered in both the Eulerian and Lagrangian representations. Particular attention is given to the coherent phenomena that occur with probability equal to unity in almost all scenarios of the diffusion process. For example, they include tracer-particle clustering in a random compressible velocity field with a potential component, low-inertia tracer-particle clustering in a random incompressible velocity field, the sharpening of the density-field gradients, and the fractalization of concentration contours in a divergence-free velocity field. All these phenomena are considered with the use of a unified method based on analyzing one-point spatiotemporal probability density functions.

2. LARGE-SCALE PROCESSES AND WEATHER FORECASTING

The main processes that form the annual climate cycle are associated with seasonal changes in tropospheric temperature conditions over the continents, in large-scale atmosphere–ocean interaction, and in the heat and mass exchange between latitudes. The separation of four seasons, two of which may be called extreme (winter and summer) and two transitional seasons (spring and fall), corresponds to variations in the annual cycle of the incoming solar radiation, which has extreme values in winter and summer and which significantly changes in transitional seasons. In (Kurbatkin, 2003; Kurbatkin et al., 2004), numerical modeling of the atmospheric general circulation and reanalysis data are used to examine interannual anomalies of the seasonal circulation that are caused by violations of the normal annual cycle: a weakening or strengthening of the atmospheric circulation in winter or summer and the slowdown or acceleration of seasonal transitions. Particular attention is given to extreme transitional-season anomalies of the annual cycle of the Northern Hemisphere general circulation, which are induced by infrequent and vast sea-surface temperature anomalies (warm in spring and cold in the fall). Such anomalies of sea-surface temperature change the continent–ocean temperature contrasts in a transitional season to the values opposite of climatic ones and strongly modify planetary pressure waves, thus altering the tropospheric thermal conditions. In particular, it is shown that, in the years when anomalously weak pressure troughs were observed off the eastern coasts of the continents in winter, a low pressure over the ocean occurred in the subsequent spring instead of a climatic high pressure and it was warm in the west of the continents and cold in the east.

Physical mechanisms of the annual evolution of continental-scale seasonal anomalies of tropospheric temperature and general circulation are described in the paper by Kurbatkin (2006). From physical considerations and analyzing multiyear observations it is assumed that there is a relationship in some years between large negative tropospheric temperature anomalies over the continents in winter and positive anomalies in the subsequent summer. It is also shown that large winter negative anomalies can stabilize the annual climate cycle by equalizing the temperature anomalies over the oceans and continents when the low-frequency variability of intensifying planetary waves generates extreme events on a hemispheric scale.

Internal gravity waves propagating from the sources located in the troposphere play an important role in the dynamics of the middle and upper atmosphere. Orography, convective processes, and turbulence of planetary jet streams make the largest contribution to the generation of these waves. In the paper by Gavrilov et al. (2005), a parametrization is proposed for the dynamic and thermal effect of internal gravity waves on the circulation of the middle atmosphere. Unlike the previously suggested approaches, this parametrization takes into account the latitudinal inhomogeneities of the sources of these waves. On the basis of model calculations, it is shown that this factor significantly influences the structure of flows in the stratosphere and mesosphere.

Quasi-two-day waves in the wind velocity field are a typical feature of the circulation of the middle- and high-latitude summer mesosphere. It is conventional to regard these oscillations as the manifestation of a westward-propagating planetary wave with zonal wave number 3 or 4. The spectra of day-to-day wind variations in the mesosphere/lower thermosphere measured by a radar at Dikson and Esrange are examined in the paper by Merzlyakov et al. (2005). The estimates of the zonal wave numbers and directions of wave propagation suggest that eastward-propagating quasi-two-day velocity oscillations with a zonal wave number of about 2 may manifest themselves in the northern high latitudes in winter. One probable cause of oscillations of this kind is the instability of the winter jet stream.

The frequencies, areas, and depths of cyclones and anticyclones in the Euro–Atlantic region are analyzed in the paper by Bardin and Polonsky (2005) for different phases of the North Atlantic Oscillation from the NCEP/NCAR reanalysis data for winters from 1952 to 2000. This oscillation is now treated as the component of the Arctic Oscillation. It is shown that the positive phase of the North Atlantic Oscillation, which has prevailed in recent decades, is characterized by positive values of the time coefficient of the first mode of expanding the pressure field in empirical orthogonal functions and is accompanied (as opposed to the negative phase) by a statistically significant increase in the frequency of cyclones in the North Atlantic (between 55° and 75° N) and in the southeastern Mediterranean, as well as by their intensification. The frequency of cyclones is lower in the positive phase in the midlatitudes of the North Atlantic (between 35° and 55° N) and over most of Europe. The frequencies of anticyclones during the intense phase of the North Atlantic Oscillation increase between 30° and 40° N, while their depths and areas increase in the subtropics and over northeastern Europe.

Interannual and long-term variations in the characteristics of atmospheric centers of action are analyzed in the paper by Mokhov and Khon (2005) by using empirical data from the late 19th century to the early 21st century and reanalysis data. Statistically significant tendencies toward the intensification of the Aleutian Low and of the North Atlantic centers of action in the second half of the 20th century are noted. The tendencies of change of the Siberian High that are obtained from different empirical data differ from one another. A statistically significant correlation of the characteristics of the North Pacific centers of action with El Niño/La Niña events is noted. During El Niño (La Niña) events, the Aleutian Low deepens (weakens) and shifts eastward (westward). The Hawaiian High weakens (intensifies) and moves south (north). It is shown that the connection between characteristics of the North Pacific centers of action and the sea's surface temperature in the El Niño and La Niña regions increased in the late 20th century. It is also found that the 4- to 6-year cyclicity of the Aleutian and Hawaiian centers of actions, which is typical of El Niño, enhanced by the late 20th century.

The sensitivity of characteristics of the Northern Hemisphere atmospheric centers of action in the winter is analyzed in the paper by Khon and Mokhov (2006) on the basis of models of different complexities as compared to observational data. The climate model of intermediate complexity and the atmosphere–ocean general circulation models are used for analysis. The global models are shown to be able to describe not only the average regimes of the atmospheric centers of action, but also their dynamics. In particular, model simulations reproduce a statistically significant connection between the characteristics of the North Pacific centers of action and El Niño/La Niña events, which was found from observational data.

An analysis of various observational data performed in the paper by Ivanov et al. (2003a) shows that periodic oscillations in the range from 20 to 60 days, which account for 10 to 30% of the total intraseasonal variability, take place in the middle latitudes of the Northern Hemisphere. The most intense intraseasonal oscillations are observed in the upper troposphere. The distribution over Russia of the intensity of the spectral density of meteorological parameters in the range of 30–50 days suggests the existence of two regions in which their intensity is especially large: southeastern Asia and eastern Europe. The calculations have shown that intraseasonal oscillations modulate the intensity of synoptic-scale oscillations and that a constant phase shift between them takes place during some intervals several months long. From the estimates of the time variability of the boundary-layer parameters (wind, temperature, and turbulent fluxes), it is also concluded that there are well-defined maxima at periods of 25–40 and 50 days.

Improving the accuracy of weather forecasting is a task of practical significance. Studies on this task are being conducted in the following direction (Tolstykh and Frolov, 2005): increasing the accuracy of the numerical solution to the thermohydrodynamic equations of the atmosphere, improving the evaluation of the initial state of the atmosphere, improving parametrizations of subgrid-scale physical processes, and considering chaotic properties of atmospheric processes. A review of the current state of the first two aspects is presented in their paper. The modern computational technology of weather forecasting should adequately reproduce atmospheric processes, both synoptic (with periods from several hours to several days) and mesometeorological (with scales from tens of minutes to a few hours). The forecast accuracy is determined by the accuracy of predicting a phase trajectory in a space of dimension 10^7 or higher. Thus, it is necessary to use the nonhydrostatic equations and, given the constraints imposed by an operational technology and computer resources, to apply efficient numerical methods.

The improvement of estimating the initial atmospheric state is related not only to developing an observational network, but also to developing data assimilation methods. The current assimilation systems use either a variational approach or a dynamic–stochastic approach (Kalman filter). Variational data assimilation procedures, which are used in most operational assimilation systems, are considered in detail in the paper cited above. The limitation of the variational approach is that, unlike the Kaman filter algorithm, it either disregards the time variability of the forecast error covariances or considers this variability approximately. Moreover, in the variational approach, the initial state is estimated from observations over a limited time interval, while the Kalman filter consists of successive steps of estimating the atmospheric state from the newly arriving data. In Klimova's papers (2003, 2005), a new suboptimal algorithm based on the Kalman filter theory is proposed and investigated. It extends the algorithm of observational-data assimilation and consists of the forecast–analysis cycle. In the proposed algorithm, the forecast error covariances are calculated from simplified models. The models are based on a method of splitting into physical processes, on the properties of the vertical normal modes of the model, and on the quasi-geostrophic approximation. The asymptotic behavior of the Kalman filter algorithm is estimated depending on the properties of a dynamic system, forecast errors, and model noises. It is shown that the proposed simplified models are able to calculate covariance matrices and can be used in a meteorological data assimilation procedure.

One important element of an objective analysis of meteorological fields is their correlation functions. By taking into account the structure of these functions, it is possible to minimize the interpolation error of meteorological fields to regular-grid points. Horizontal anisotropy of the three-dimensional correlation functions of geopotential, temperature, and wind is estimated in the paper by Aldukhov and Gordin (2005). The largest anisotropy is shown to occur in the tropical zone at the tropopause level and above. Fields of directions of the highest horizontal correlation that depend on latitude and height are constructed.

Empirical orthogonal functions (EOFs) are also used in atmospheric physics to analyze both empirical data and numerical modeling results. As a rule, they are used to study the spatial structure of meteorological fields. In recent years, however, this approach has been more often used to analyze time-dependent functions. Spectral properties of time-dependent EOFs are considered in the paper by Galin (2003). There, it is theoretically shown that the periods of the principal components are close to the dominant periods in the corresponding Fourier expansion; and the longer the time interval in which the EOFs are defined, the better the degree of this closeness. These conclusions are confirmed by analyzing the results of numerically modeling the atmospheric general circulation.

3. MESOSCALE PROCESSES

The task of hydrodynamically modeling the meteorological fields is known to be extremely difficult because of the multiscale character of atmospheric motions (from planetary-scale waves to small turbulent eddies) on which viscous dissipation occurs. The difficulty in modeling boundary-layer dynamics in regions of complex configuration (orography, plant canopy, urban areas, etc.) is caused by the diversity of spatial and temporal scales within which the corresponding processes take place. For example, in the problem of air quality in an urbanized area, it is possible to separate an "urban" scale (the typical size of a city is several tens of kilometers), on which a primary pollution emission occurs, from a "mesoscale" (several hundreds of kilometers), on which secondary air pollution and its scattering take place (Kurbatskii and Kurbatskaya, 2006a). In this paper, a three-parameter model of turbulence for the atmospheric boundary layer over an urbanized surface is presented. To calculate the turbulent momentum and heat fluxes, the authors of the paper used explicit algebraic expressions obtained from the corresponding transport equations in the approximation of weakly equilibrium turbulence and prognostic equations for the turbulent kinetic energy, its dissipation rate, and the temperature variance. Comparing the numerical results with published data and other numerical models has shown that the proposed model is able to reproduce the most important structural features of the turbulence over an urbanized surface. This model has been supplemented by a calculation of passive-pollutant transport (Kurbatskii and Kurbatskaya, 2006b). The turbulent concentration fluxes are calculated from the completely explicit algebraic expressions that are obtained by simplifying the transport equations for turbulent fluxes in the approximation of weakly equilibrium turbulence. The numerical results of calculating the dispersion of pollution show that dynamic (urban roughness) and thermal (urban island of heat) factors have a large effect on the dispersion of pollution over an urbanized surface and that a city influences the daytime concentration of pollutants far away from it.

Several studies are devoted to a numerical modeling of the structure of air flows in an urban landscape, which has a complicated configuration and depends strongly on the specific meteorological and local morphological conditions. For example, in the paper by Shlychkov et al. (2006), the most dangerous environmental situations, which occur under conditions of stable stratification and slight winds, are considered. To simulate an air microcirculation, a hydrodynamic model of flows in geometrically complicated regions has been developed with an individual description of flows around individual buildings. The computed dynamic parameters can be used to solve the transfer and diffusion equation for a passive admixture. An example of a calculation for one of the residential districts of the city of Novosibirsk is given. It is shown that urban development plays the role of a mechanism of ecological self-protection due to the transport of the basic pollution flux toward the edge of the residential district. At the same time, the urban building complexes shield outer flows and weaken local internal circulations, thus hampering the efficient ventilation of a district. In these cases, anthropogenic pollutants generated within the city may significantly worsen the ecological situation in the megalopolis.

In large cities, the increase in the surface concentration of pollutants is caused by various anthropogenic sources, the most important of which are vehicular traffic, emissions from industrial plants and big heat power stations, and emissions from local boilerhouses. Understanding the processes of accumulating harmful pollutants in an urban atmosphere is impossible without targeted theoretical and experimental studies to identify the basic features of meteorological processes for the region in question. A detailed picture of the accumulation process can be obtained from a mathematical model, and gaps in the data on the conditions in which the process occurs can be filled in with instrumental data on atmospheric sounding (Starchenko and Belikov, 2003; Starchenko, 2004). To obtain operational quantitative estimates of the quality of urban air, regular measurements of the air composition should be conducted in combination with the use of simple prognostic relationships based on the results of processing empirical data and on the data of a scenario analysis performed using prognostic multidimensional numerical models. The paper by Starchenko et al. (2005) is devoted to studying the effect of meteorological conditions on the distribution of chemically inertial harmful pollutants in the atmosphere for the city of Tomsk. Comparing the numerical results with the historical data of meteorological observations and ecological monitoring has led to the conclusion that unfavorable meteorological situations for Tomsk, like those for many other cities of western Siberia, are calm conditions combined with temperature inversions and a slow veering of wind, which forces the "transported" pollutants to return again to the city.

Apart from the direct numerical modeling of the accumulation of harmful pollutants in an urban atmosphere, semiempirical models are used for practical applications (e.g., monitoring the dispersal of pollutants from motorways in street canyons). The main task solved by these models is the estimation of pollution-level characteristics (concentration averages and variances) on time scales from one to a few hours. In this case, a full consideration of the meteorological conditions and local features of pollution dispersal in an urban development area is required. A semiempirical model that uses Markov processes to estimate air pollution for the city of Krasnoyarsk was proposed in the paper by Taseiko and Mikhailyuta (2004).

Numerous observations of cloud systems show that, in an unstably stratified atmosphere, there are regular cloud arrays with horizontal sizes varying from several kilometers to several tens of kilometers. Among cloud arrays of this kind, it is possible to note frequently observed hexagonal cells with clouds at the center and a cloud-free space at the edge and hexagonal cells with clouds at the edge and a clear space at the center. The paper by Ivanov et al. (2003b) considers the identification of a type of cellular structure and the calculation of its parameters from measurements of the vertical wind velocity at an immobile site. From measurements it is shown that, during convection, the spectrum of the variability of meteorological parameters contains isolated harmonics that retain their amplitude and phase for a few hours. The results indicate that, under certain conditions, vertical convective exchange occurs in the boundary layer and its mechanism is close to that observed in an unstably stratified fluid at critical Rayleigh numbers (with molecular viscosity and heat conduction).

Results of numerically modeling convection in a horizontal unstably stratified incompressible fluid layer with constant coefficients of kinematic viscosity and thermal conductivity cooled or heated at a constant rate are described in the paper by Alekseeva and Vel'tishchev (2003). It was found that the convective heat fluxes are determined only by the Rayleigh number and depend neither on the height nor on the heating (cooling) rate of the fluid layer. At a fixed Rayleigh number, the penetrative ability of convection (the depth of penetration of positive heat fluxes into a stably stratified layer) decreases with an increase in the heating (cooling) rate of the convective layer.

Processes of the formation of fire storms arising from massive burning in large cities are studied with the use of a numerical solution of gas dynamics equations for a multiphase medium in the paper by Andrianov et al. (2003). It is shown that the generation of a mesocyclonic flow over a fire, intense energy release accompanied by moisture release into the atmosphere, and the presence of moist unstable layers are favorable factors for their formation. The vertical vortex arising over a fire has a flow pattern similar to that normally observed in a tornado. In particular, the typical radius of the central area where such a flow occurs is 100–200 m, and the pressure decrease near the axis of the vortex reaches 50%.

Results of the study of a mechanism of cloud formation in the area of intense convective activity over forest fire zones are presented in a series of works (Mal'bakhov et al., 2004; Dubrovskaya et al., 2005; and Mal'bakhov and Shlychkov, 2006). One preliminary conclusion of these studies is that rapid cloud formation may occur during forest fires as a result of intense convection, when heat, moisture, and aerosol are transported into the troposphere over burning zones. Aerosol that has a small particle size (less than 1 μm) is an additional factor of the formation of water vapor condensation nuclei in the areas above the zero-temperature isotherm. On the other hand, if aerosol particles are larger than 1 μm, they may cause the crystallization of supercooled droplets and less intense precipitation.

The current stage of the development of mathematical models of a climate system is characterized by the steady improvement of their spatial resolution and by the abandonment of the hydrostatic approximation (still at a regional level). These tendencies bring up new problems in parametrizing subgrid-scale processes, among which the interaction between the atmosphere and a hydrologically heterogeneous terrain (a land surface covered mostly by a dense net of water bodies such as lakes, rivers, and bogs) plays an important part. Western Siberia (where water bodies occupy more than 50% of the region), Karelia, and North America may be remarkable examples of such a hydrologic heterogeneity.

Results of an analysis of field data obtained from aircraft and ground-based measurements over the Lena River valley are presented in the paper by Strunin and Hiyama (2005a). The aircraft experiment carried out in the vicinity of Yakutsk from April 24 to July 19, 2000, revealed two features in the structure of the atmospheric boundary layer over the cold water surface where the river is more than 10 km wide. When the boundary layer was unstable, a mesoscale thermal internal layer formed over the cold patch on the surface in which the vertical turbulent heat and water vapor fluxes differed radically from the background profiles. Another feature is that the cold water surface of relatively a small (about 10 km) horizontal extent generated a local breeze circulation which significantly changed the structure of horizontal advection up to the formation of reverse-flow zones.

The use of wavelet analysis (Strunin and Hiyama, 2005b) made it possible to divide air motions in the atmospheric boundary layer into turbulent (with scales from 20 m to 2 km) and mesoscale (from 2 to 20 km) components. It was found that empirical profiles of the heat, moisture, and momentum fluxes differed significantly between the turbulent and mesoscale components. All turbulent fluxes decreased monotonically with height, while the role of mesoscale motions became more important with height and reached a maximum in the middle of the boundary layer. It was shown that the turbulent heat fluxes were larger than the mesoscale fluxes during the whole period of observations, while the contributions of the two components to the fluxes of water vapor were nearly the same.

For studying the interaction between the atmosphere and the underlying surface of complex configuration (plant canopy, orography, hydrologic net, etc.), numerical experiments were performed with a mesoscale atmospheric model in which thermodynamic processes in water bodies were parametrized (Stepanenko et al., 2006). It was shown that the model was able to adequately reproduce both a breeze circulation over a separate large lake and a complicated structure of breeze motions over a hydrologically heterogeneous land surface (for example, western Siberia), as well as a classical mountain–valley circulation. The technology developed was used to estimate the accuracy of parametrizations of mesoscale fluxes in atmospheric general circulation models under conditions of a strong hydrologic heterogeneity of the land. It was shown that the mosaic method of aggregation, which is widely used in climate models, calculates the area-averaged heat and evaporation fluxes with a satisfactory accuracy.

With the increasing performance of computer systems, the prospect for constructing a mesoscale model of the atmospheric boundary layer on the basis of large-eddy simulation becomes realistic. A mathematical model for describing local atmospheric processes over a limited area with the direct modeling of coherent structures in a stratified atmospheric boundary layer was proposed by Shlychkov (2006). The model is designed to calculate the evolution of wind, temperature, humidity and precipitation fields, turbulence characteristics, and the transport of pollutants over a thermally, orographically, and landscape-heterogeneous underlying surface.

4. TURBULENCE IN THE BOUNDARY LAYER

One of the central problems of turbulence theory is the intermittency of turbulent fluxes, which makes the field of energy dissipation very variable. The models of energy transfer within the spectrum were considered by Gledzer (2005). The cascade models proposed by A.M. Obukhov as an approximation for the hydrodynamic equations with a quadratic nonlinearity describe the interaction of geometrically similar structures that exist in the flow. It is shown that the cascade models demonstrate a stepwise energy transfer from larger to smaller perturbations. The interactions between scales are correlated, but the energy flux within the spectrum is not constant and increases as the perturbation scale decreases. Perturbations in the dissipative and inertial wave number ranges have the largest deviations of amplitudes from their averages, and this breaks down the cascade process. The cascade process resumes only as a result of the action of external forces.

The continuum model for energy transfer within the spectrum is based on the Navier–Stokes equations in the Fourier representation that are rewritten so that the integral of motion corresponds not to the total energy of the whole volume but to energy per unit volume. Stationary solutions described by such a model may correspond to the regimes in which large-scale motions stopped because the flux of energy from external forces no longer balances the outflow of energy into the dissipation range. The inclusion of intermittency and its related structures in the turbulent flux results in the appearance of non-Kolmogorov exponents in the power laws for the velocity and dissipation moments. When these structures are filtered out, the model produces a classical picture of the interaction between velocity perturbations of different scales with traditional values of the corresponding similarity exponents.

Studies of the role of helicity in turbulent flows were continued in 2003–2006 (Ponomarev et al., 2003; Ponomarev and Chkhetiani, 2005; and Chkhetiani, 2005. See also Kurgansky and Tolstykh, 2004). Considering helical properties of turbulence changes the structure of the Reynolds stress tensor and, thus, the Ekman velocity spiral. The hydrodynamic stability of the Ekman hodograph modified by a nonzero helicity is considered in the paper by Ponomarev et al. (2003), where it is shown that, due to the presence of an inflection point in the velocity profile, the threshold value of instability decreases slightly. Both the spatial scale and orientation of the most unstable modes also change. In the paper by Chkhetiani (2005), a stationary solution to the Reynolds equations is obtained for a vortex perturbation of one of the simple background shear flows characterized by a linear velocity field with a cylindrical symmetry. Intense vortex structures are often formed against the background of similar flows. The solutions to the Reynolds equations with turbulent helicity demonstrate that stationary vortex structures can arise in a convergent linear velocity field. Such a vortex is characterized by intrinsic helicity, which is due to the additional vertical transfer along the axis of the vortex, by the more intense vertical vorticity, and by the smaller characteristic scale.

Studies of atmospheric dust devils, which often arise on hot days in deserts and steppes, are not only of scientific interest, but they are also important from the practical point of view (for example, for aeronautical meteorology). Of particular interest is the transport of coarse-dispersed and submicron aerosol under convective conditions in desertified lands. Simultaneous measurements of the aerosol-microstructure fluctuations and of the turbulent fluctuations of wind speed and temperature in the dried-up part of the Aral seabed were analyzed by Gorchakov et al. (2004). These data are used to estimate the parameters of vortices and vortex structures arising in the convective atmospheric boundary layer over a desertified land. It is shown that, in areas of high vorticity, the microstructure of the intravortex aerosol generated by the underlying surface in wind-induced transport can be approximated by a power-law distribution with an exponent of –1.5. The vertical convective fluxes of aerosol, heat, and kinetic energy are also calculated; and it is shown that these fluxes are much larger than the corresponding vertical turbulent fluxes. The basic parameters of dust devils are estimated. It is shown, in particular, that their diameters vary widely, from 40 m to 9 km.

Based on the principle of maximum informational entropy, Kurgansky (2006) has proposed an exponential size (apparent diameter) distribution for dust devils. Two independent sets of statistical data on dust devils observed in the United States showed good agreement with this exponential distribution, although the average diameters of the vortices in these two data sets differed by a factor of 5 from each other. It was also found that the average diameter of a dust-devil vortex is close to the absolute value of the Monin–Obukhov scale, the result previously obtained for dust devils in Australia. The distribution of particles in a vortex is of interest for practical applications, for example, in radiolocation and in estimating wind pressure. The horizontal motion of heavy particles in an intense stationary axisymmetric vortex is investigated by Ingel (2004). On the basis of an analytic solution, it is shown that particles tend to accumulate on the periphery of the vortex.

A diagnostic study of the structure of concentrated tornado-like vortices was performed by Okulov et al. (2004) during laboratory modeling in a cylindrical tank with a rotating lid. The results of this study reflect the general properties of variations in the structure of vortices when their intensity is increased. The laboratory experiment confirmed the formation of axisymmetric vortices at their moderate intensity. An experimental analysis of the loss of symmetry and stability in the concentrated vortices made it possible to determine the boundaries of transitions in an axisymmetric flow from the regime without any decay of the axial vortex to regimes with a different number of decay zones and to a three-dimensional unsteady flow.

Using the balance equation of the integral helicity for swirling stratified flows, Chefranov (2003) has introduced a single scale-invariant criterion of the similarity of such flows. The criterion is independent of any arbitrariness in the choice of the length and time scales and is defined as the ratio of characteristic values of helicity and reduced acceleration of gravity. This criterion can be used to estimate the adequacy of modeling real atmospheric processes of vortex and helix genesis in a laboratory.

Local processes in the atmospheric boundary layer, where the effects of the interaction between the flow and the underlying surface and means of turbulent exchange play a key role, still remain poorly investigated. For example, it was shown by Ingel (2006) that a change in the effective coefficient of turbulent exchange with height could be sufficient to generate a noticeable slope flow in a stratified medium even in the absence of any buoyancy sources. It was found that, if the exchange coefficient increases with height, negative temperature perturbations arise at the ground and a katabatic flow forms. Also, the stronger the stability of background stratification is, the larger the amplitudes of perturbations are.

The paper by Koprov et al. (2004) is devoted to an experimental study of coherent structures in the atmospheric boundary layer. It is shown that convective structures in the atmospheric surface layer are formed by the penetration of domelike singly connected warm-air volumes into the colder overlying layers. These structures are transported at a rate close to the wind speed at a height approximately half the magnitude of the Monin–Obukhov scale. The temperature profile inside the volume occupied by the subsiding cold air is very close to the adiabatic profile. The convective structure is asymmetric: the leading front has sparse isotherms, and isolines at the rear are thickened (microfront). The intermittency of the temperature field is also connected with the boundaries of convective structures. This connection is reflected in the wide variability of the dissipation of kinetic energy.

The processes of interaction between the atmospheric boundary layer and the land surface play a crucial role in the dynamics of large-scale phenomena such as the Indian monsoon. In the paper by Satyanarayana et al., 2003), a coupled one-dimensional model of the atmospheric boundary layer and the active soil layer with a detailed description of thermodynamic processes was used to analyze data from the Land Surface Processes Experiment (LASPEX-97) carried out in India in 1997. Two data sets were used: one for a dry period and another for a wet period at a semiarid station in Anand (22.4° N, 72.6° E, northwestern India). The results of a comparative analysis of the data from numerical experiments with observations showed that the proposed model is suitable for use in monsoon circulation models.

Nonhydrostatic three-dimensional models of the atmospheric boundary layer and of the upper ocean layer are described by Glazunov and Lykossov (2003). These models are able to reproduce large-scale (comparable to mixed-ocean thickness) eddy structures induced by both thermal convection and surface wind stress. The models are combined into a coupled model of interacting boundary layers. The interaction between the models is due to the exchange of momentum, heat, and moisture fluxes through the water–air interface. In constructing the models, a methodology of large-eddy simulation is used. In this methodology, large-scale eddies, which play an important role in the transfer of momentum, heat, and moisture (salinity) inside the boundary layers, are described explicitly. Small-scale (spatial scales smaller than the mesh size of the model's grid) turbulence is taken into account via parametrizations that relate the energy of subgrid-scale motions to the characteristics of slower processes. The systems of differential equations of the model consist of Reynolds-type equations for describing the evolution of momentum, heat, and moisture (or salinity); the continuity equation for an incompressible fluid; and the equations of state for moist air and seawater. The set of equations is closed by additional evolution equations for the turbulent kinetic energy of small-scale eddies and for the dissipation rate of turbulent energy.

Along with widespread diffusion-type turbulent closures (using equations for the turbulent kinetic energy and for its dissipation rate), various dynamic-type closure schemes have been implemented which are designed for large-eddy simulation under the assumption of turbulent-flux anisotropy (Glazunov, 2006). In particular, a finite-difference model was developed in which a conservative scheme of the fourth order of accuracy was used to spatially approximate the nonlinear terms of the momentum balance equation and a mixed model was applied for turbulence closure. In the model, the parameter describing the dissipation rate of turbulent energy was calculated dynamically by the proposed and implemented algorithm for seeking a generalized solution to the overdetermined system of linear equations. All model algorithms, including the numerical scheme and turbulence closure, were chosen so as to ensure the suitability of the model for the domains of arbitrary configuration.

A series of long-term numerical experiments were carried out to model turbulence in a channel bounded by two identical infinitely extended rough plates. The spatial resolution of the model was about 10^7 grid points. The numerical modeling results were compared to laboratory measurements and to the results of a direct numerical modeling that was performed at maximum achievable Reynolds numbers (at the current level of computer facilities). It was shown that the proposed model, despite a partially dissipative turbulence closure, displayed some features inherent in turbulent fluxes (mean velocity profile, spectral energy distribution, etc.).

5. MATHEMATICAL PROBLEMS OF CLIMATE AND ECOLOGY

Studies related to the elaboration of a mathematical theory of climate based on the use of methods of the theory of dynamic systems developed rapidly in (Dymnikov and Gritsun, 2005; Dymnikov et al., 2003, 2005, 2006). One of the main goals of this theory is to work out a methodology for estimating the sensitivity of the climate system to small external forcings that would provide a constructive method for estimating the climate changes induced by these forcings. Although the basic method of investigating the climate system is mathematical (numerical) modeling, the problem is as follows: what must the climate model reproduce and how accurate should it be so that its sensitivity to small external forcings is close to the sensitivity of a real climate system. To answer this question, the operator of the model's response to small external forcings should be found in an explicit form.

For this purpose, a real climate system is assigned a certain mathematical object which represents an idealization of the system under study and which can be called an "ideal" model. It is assumed that such an ideal model exists and that the observed dynamics of the climate system is a realization of a trajectory generated by this model. It is also assumed that an ideal model belongs to a class of dissipative dynamic systems. The theory under consideration must predict the behavior of the trajectory for sufficiently long (in the range of infinity) time intervals. The corresponding results are usually formulated in terms of a global attractor. Then it is assumed that the system being studied has a global attractor, which implies a certain manifold in the phase space so that all trajectories going out from any point of the phase space are attracted with time to this manifold. Formally, the evolution of the dynamic system can be divided into two steps: motion to the attractor and motion on the attractor and in its vicinity. In studying the response of the climate system to small external perturbations, the dynamics of the climate system is considered on the attractor of the system; for its qualitative analysis, one should use comprehensive models of the climate system that describe the current climate more or less successfully.

In an analysis of the response of the climate system to changes in the concentration of atmospheric greenhouse gases, it is convenient to use the terms "dynamic" response and "radiative" response. It is shown (Volodin and Diansky, 2003; Volodin et al., 2004) that the radiative response plays a key role in the total response of the climate system to a change in the concentration of carbon dioxide. This is manifested in the fact that the sensitivity of the climate system to the atmospheric CO_2 increase is determined mostly by the amount of heat consumed to warm the ocean and also depends on how the Earth's radiation balance changes as a result of the variation in cloud amount due to the climate change. At the same time, it is important to adequately reproduce the dynamic response, the main component of which is the Arctic Oscillation. The variation in the Arctic Oscillation index was examined in the paper by Volodin (2003) from the results of numerically modeling the atmospheric general circulation (for a perpetual January) under external forcings specified as zonal symmetric sources of cooling that are located at different latitudes and heights. It is shown that the projection of the model response onto the Arctic Oscillation is maximal for a source located in the high-latitude lower stratosphere. If the cooling source is located in the higher stratospheric layers, the Arctic Oscillation is strongly excited only in the stratosphere, while the response in the troposphere is small.

Mokhov and Smirnov (2006a) (see also Mokhov and Smirnov, 2006b) examined the mutual dynamics of the North Atlantic and Arctic oscillations and

El Niño–Southern Oscillation from different data by using nonlinear techniques for estimating the coupling between oscillatory systems from time series. The methods based on phase-dynamics modeling and nonlinear prediction models (a nonlinear variant of Granger causality) were used. From both these methods and various characteristics of the oscillations, the inference about the effect of El Niño–Southern Oscillation on the North Atlantic Oscillation in the latter half of the 20th century and in the early 21st century was made with a confidence probability of no less than 0.95. No inverse influence was found with a similar degree of reliability.

Variability in the tropical stratosphere is determined mostly by quasi-biennial oscillations whose period at different levels varies from 2 to 3 years. These oscillations affect the global stratospheric circulation by modulating the intensity of both polar vortices. Variations in the intensity of the polar vortex in the lower stratosphere influence the sign and duration of the Arctic Oscillation in the lower troposphere. This is important for the chemistry of the polar stratosphere and for estimating the climate response to the increased concentration of greenhouse gases in the troposphere; it also has practical significance because slow variations in stratospheric dynamics may make it possible to predict the phase and duration of the Arctic Oscillation for more than two weeks. Results of an analysis of the stability of trajectories under conditions of chaotic advection (Lagrangian turbulence) were presented in the paper by Krupchatnikov and Borovko (2005), which studied the interaction between the main flow and unsteady Rossby waves. It was shown that this is the main mechanism of airmass mixing and of the decay of the polar vortex and ozone layer.

On the basis of the mathematical theory of climate, it has been possible to construct a linear operator relating the vector of perturbations of the problem's parameters to the vector of the response to these perturbations under the natural condition so that their norm is small (Dymnikov and Gritsun, 2005). The method of calculating the dynamic response operator of climate models and of a real climate system (calculating a perturbation of the first moment) is based on the dissipation–fluctuation relationships for systems with a large number of positive Lyapunov exponents. It was shown that the dissipation–fluctuation theorem calculates the response operator from statistical characteristics of the model's chaotic attractor for a wide class of atmospheric models. The approximate response operator reproduces both the value and the spatial structure of the linear part of the response of the atmospheric general circulation model with a high accuracy. This result provides a methodological basis for studying the sensitivity of certain characteristics of a real climate system to variations in external parameters with the use of calculations immediately from observations. It was also possible to formulate the inverse problem, i.e., to find a perturbation that would be optimal for a prescribed response. The external perturbation optimally exciting the Arctic Oscillation was constructed on the basis of observational data and simulation results. It was shown that the projection of the response of the atmospheric general circulation model to a prescribed zonal symmetric heat source onto the Arctic Oscillation is maximal for a heat source located in the polar lower stratosphere. An analogous conclusion is also valid when the response operator was constructed using the NCEP/NCAR reanalysis data for 1948–2002.

The problem of hydrodynamic weather prediction is complicated by the fact that the trajectory of the system to be predicted is unstable with respect to errors in the initial data and with respect to small constantly acting perturbations. Therefore, the problem of stability is a key problem in the predictability of atmospheric processes (Dymnikov, 2004). This study is devoted to investigating the potential predictability of large-scale atmospheric processes of the first kind, i.e., with respect to perturbations in the initial data. Potential predictability implies the time during which the trajectory is attracted to the neighborhood of a stationary statistical solution. The method of stochastic regularization is used to reduce the problem to an estimation of the time of attraction to a stationary solution of the Fokker–Planck equation. With a dynamic–stochastic equation used as an example, it is shown that the most predictable space is the subspace related to the Arctic Oscillation and to the Pacific–North American Pattern.

Currently, the problems of ecological forecasting and projecting under conditions of changing climatic processes and environmental quality are becoming high-priority problems because they are directly linked to the security and quality of life. To solve ecological problems, interdisciplinary studies are being actively developed and multifunctional informational prognostic systems are constructed on the basis of modern computational facilities and technologies (Penenko and Tsvetova, 2003; Aloyan et al., 2005). These systems include various modifications of atmospheric climate models, as well as modifications of models of the transport and transformation of multicomponent admixtures in the gas and aerosol states.

A cycle of studies on the development of methods for solving the interrelated issues of ecology and climate, which were devoted to the problems of ecological forecasting and projecting under conditions of changing climatic processes and changing environmental quality, were carried out in 2003–2006 (Penenko, 2003, 2004; Penenko and Tsvetova, 2004, 2005). The specific character of this class of problems is that it is necessary to consider a wide spectrum of interacting processes for long time intervals in regions of various scales under conditions of uncertainty in external and internal perturbation sources. It is also necessary to take into account feedbacks when changes in the climate system are induced by anthropogenic and natural impacts. Therefore, for the purpose of forecasting and projecting, it is useful to apply a scenario which can give the necessary estimates of the ecological prospect. One important role in this approach is played by adequately including the hydrodynamic background, which is calculated by the models with the maximum possible consideration for real data. Relationships between the model sensitivity and functionals of generalized data give a constructive basis for the formation of direct and inverse relations between various elements of the modeling system. The resulting sensitivity functions synthesize the solution of direct and adjoint problems.

A new and high-priority element in the developed approach is the construction and assimilation of high-information guiding phase spaces in the base models (Penenko and Tsvetova, 2006). The models of this class are based on the principles of the decomposition of processes according to the scales of perturbations. The guiding phase space plays the role of a large-scale background. The interrelations between the guiding spaces and the models of processes are performed in an assimilation mode. For this purpose, specially developed fast data assimilation procedures are used (Penenko, 2005) which are based on the variational principle of minimization of a certain total measure of uncertainties in models and data. They are equivalent in accuracy to the assimilation procedures with adjoint equations and to the Kalman filtering-type procedures, but they outperform them with respect to the algorithmic efficiency. The guiding spaces are constructed using the accessible actual information and models that have a sufficient degree of predictability and informativeness for the processes under study.

Informative factor spaces are constructed using algorithms for the orthogonal decomposition of multidimensional multicomponent fields of the functions of the climate system's state with the identification of principal components and principal factors. This approach makes it possible to represent the arrays of data on the multiyear dynamics of the processes under study as a set of orthogonal subspaces arranged in decreasing order by their informativeness in accordance with the specified criteria and, on their basis, to construct the long-term scenarios of the hydrometeorological background for calculating ecological situations. To test this technique, the NCEP/NCAR reanalysis database for a period of over 50 years was used. With the complex approach being developed, the existence of high ecological risk and vulnerability zones in the climate system was established. Preliminary estimates were obtained for the impact regions of these zones, and their connections with the classical centers of action of the climate system were determined.

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