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# ГАЗОДИНАМІКА

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***Buyadzhi V. V., Sofronkov A. N., Glushkov A. V., Khetselius O. Yu., Dubrovskaya Yu. V., Svinarenko A. A.***

*Odessa State Environmental University*
*E-mail: buyadzhivv@gmail.com, a_sofronkov@ukr.net*

## New energy, angle momentum and entropy balance approach to modelling climate and macroturbulent atmospheric dynamics, heat and mass transfer at macroscale. I. General Formalism

*We present elements of a new non-stationary balance approach to modelling global mechanisms of climate and macro turbulent atmospheric low-frequency processes, including processes of heat-mass transfer at spatial and temporal macro scales, teleconnection effects etc. The main forming factor is a triplet of interacting solitons: "the planetary soliton of Hadley cells - the entire complex of atmospheric fronts - the Rossby soliton wave packet". The approach is based on the using balance relationships for entropy, energy and angular momentum, spectral theory of atmospheric macroturbulence, atmospheric moisture flow in further connection with the continuity of atmospheric circulation forms (teleconnection, genesis of fronts). Particular application is studying a spatial-temporal picture of the long-term atmospheric pollutants (including distribution of radionuclides after accidents at the nuclear power plant like Fukushima etc) in the atmosphere with accounting for the macro turbulent, circulation low-frequency processes.*

**Introduction.** Understanding and quantitative description of global mechanisms in atmospheric low-frequency processes, teleconnection effects etc attracts a fundamental interest in a modern physics of climate and heat-and mass transfer in complex atmospheric system " [1-20]. It should be noted that at present time there are different, quite consistent approaches to modelling global atmospheric macroprocesses and respectively the methods of modelling temporal and spatial dispersion of different pollutants in atmosphere and other geospheres (look for example, [21-30]). One should mention such methods as MLDP0 (Modèle Lagrangien de Dispersion de Particules d'ordre 0), HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory Model), NAME (Numerical Atmospheric-dispersion Modelling Environment), RATM (Regional Atmospheric Transport Model), FLEXPART (Lagrangian Particle Dispersion Model), model of the European Center for Mdium-Range Weather Forecasts (ECMWF) and others [7,11,26,30]. Nevertheless, correct quantitative description of the global atmospheric processes, the heat-and mass transfer processes in an atmosphere, macromodelling dispersion of the pollutants in an atmosphere remains very actual and hitherto unsolved problem. Below we present the elements of a new approach, which is based on the entropy, energy, moment balance relationships for the global atmospheric low-frequency processes, theory of atmospheric macrotur-

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bulence and circulation over the position of the front sections. The fundamental idea is that the main process-forming factor is a triplet of interacting solitons: "the planetary soliton of Hadley cells - the entire complex of atmospheric fronts - the Rossby soliton wave packet" [22-24].

**Advanced balance approach to macroatmospheric processes and a triplet of the interacting Hadley cells – Rossby – atmospheric fronts solitons.** Nowadays it has become preferable to use single-factor models for the diagnosis and prediction of the atmospheric macrocirculation. However, these models do not reveal a dynamics of the process, but are only a summary statement of the state. For example, the forecast of climate changes in these models can only be done by studying trends in heat balance maps. In our opinion, the "heat balance" should be replaced by the "entropy indicator" of the climate state. This index satisfies the equation of the entropy balance. Moreover, it contains a time derivative, which does not exist in the heat balance equation. The problem is only that the entropy balance is calculated in the low-frequency range of climate change. Such a low-frequency range can only be in planetary-scale processes that form global climate change. It is well known [1, 22, 23] that such processes include wave oscillations such as the planetary soliton - the Hadley cells. These cells attract a great interest. For example, the only so far discovered process with a two-year cycle is the "southern process with El Niño", which is deciphered on the Hadley cells. The change in the state of the Hadley cells on a global scale will be the basis for saturation of the entropy balance equation, the minimum of which should be expected at the characteristic middle of the stage of the climatic epoch. A change in the energy of a soliton can occur if a moment of its destruction appears at low-frequency interaction with another, long-existing wave process, also of the soliton type. As a result of this interaction, a third soliton must arise. The second and third solitons are known: the Rossby solitons (blocks emerging from the tropical belt), which basically determine the nature of the atmosphere's circulation and the corresponding weather complex, and the soliton of the atmospheric fronts[22]. On the fronts, up to 30% of the solar energy is realized in the processes of wet convection to an effect of the atmospheric moisture flow. The thermodynamic front solenoids are so energy-saturated that they are a natural barrier to energy dissipation into mesoprocesses, the horizontal scale of which is much smaller than the transverse dimension of the front. Moreover, the transfer of energy from the mesoprocesses of the surface layer to the side of larger waves by the mechanism of "negative viscosity" is not carried out through the front. It explains that the main climate-forming (or global macro circulation) factor is a triplet of the solitons: "the planetary soliton of Hadley cells - the whole complex of atmospheric fronts - the Rossby soliton wave packet". The entropy balance equation should calculate the balance in the complex of the soliton triplet without mutual energy exchange (the active phase of the climatic stage), whereas the increasing entropy corresponds to a mutual energy exchange between the elements of the soliton triplet. All three elements of the soliton triplet determine the dynamic change in the complex of weather, while the factors that form the heat balance (radiation and heat fluxes) are basically subject to the annual course of insolation and do not form low-frequency processes of a climate-like dynamics. The triplet of these solitons can be parametrized by means of the following model.

We assume that each of these solitons can be analytically determined by solving the known Karteweg-de Vries equation:

$$V_t - 6V^2 V_x + V_{xxx} = 0. \tag{1}$$

Here $V$ is the velocity, the subscripts mean the derivative with respect to the corresponding coordinate. The asymptotic solution (1) for time $t \to \infty$ has the form:

$$V(x,t) = (3t)^{-1/3} r(0)\mathrm{Ai}(Z) - (3t)^{-2/3} i \frac{r'(0)}{2} \mathrm{Ai}'(Z) + \mathrm{O}\left(\frac{1}{3t}\right), \tag{2}$$

where $Z = x(3t)^{-1/3}$ ; $r$ – generalized parameter of the soliton wave radiation matrix; $\mathrm{Ai}(Z)$ – Airy function. The solution of Eq.(2) can be represented in the low-frequency range in the vicinity of $x = 0$ as a series of $Z$. The soliton of Hadley cells, forming a circumpolar vortex, occupies an area comparable to the hemisphere of the Earth; the Rossby soliton occupies a space of an order of magnitude smaller, while the transverse dimension of the front soliton is only about 30 km. The Rossby soliton is manifested as a result of the low energy transfer of the nonlinear interaction of these two solitons. In view of the apparent incomparability of the geometric area dimensions of these solitons, it becomes necessary to replace the coordinate of the space (x) by the energy coordinate ($E$). In this coordinate, all three solitons are comparable. The $E$-coordinate is formed on the basis of spectral modes of N-soliton solutions. The N-soliton solution has the following structure for the Karteweg-de Vries equation:

$$\psi_N = \sum_{\mu=0,i} \exp\left( \sum_i \mu_i \left( \eta_i + i\frac{\pi}{2} \right) + \sum_{i \le 1 \le j} \mu_i \mu_j A_{ij} \right), \tag{3}$$

where $\eta_i = k_i Z - k_i^3 t$ – wave vector in coordinate ($Z$, $t$); $\mu_i$, $\mu_j$ – weight coefficients of particular solutions of the kink and antikink type; $A_{ij}$ – matrix of a soliton nonlinear wave radiation:

$$\mathbf{e}^{A_{ij}} = \left( \frac{k_i - k_j}{k_i + k_j} \right)^2. \tag{4}$$

Operator $\sum_{i \le 1 \le j} \mu_i \mu_j A_{ij}$ in the solution (4) determines the energy transformation from the spectrum of $N$-solutions with radiation, i.e. transfer of the wave energy between the solitons. The construction (2) - (4) is to be introduced into the equation of the entropy balance:

$$\rho \frac{\partial S}{\partial t} + \nabla \cdot \frac{\vec{J}_q}{T} = \frac{|P| \cdot \vec{Y}}{T} + \frac{\vec{J}_q \cdot \vec{X}_q}{T}, \tag{5}$$

where $\rho$ – is the substantial density of the medium through which the entropy flux $S$ is carried out; $\vec{J}_q$ – the entropy flux vector; $T$ is the temperature of the weighted average convection condition in the frontal systems, consistent with the Hadley cells; $\vec{X}_q = \nabla T$ – entropy productivity; $\vec{Y}_q = \nabla x \vec{V} + 2\vec{\omega}$ – an absolute vortex; $|P|$ – antisymmetric deformation tensor in space. Note that the third term in equation (5) specifies the irreversible course of the process in time.

Equation (5) must be rewritten for the coordinate *E*, i.e. it must correspond to the Riemannian geometry of the N-dimensional phase space of the spectral modes of N-soliton solutions. The soliton of the Hadley cells and the front soliton describe the curvature of the Riemannian space in the form of axial vectors, whereas the Rossby soliton contains mainly polar vectors. As is known, the tensor products of a tensor on axial vectors by a tensor on polar vectors give, as a result, the tensor of polar vectors. This means that the Rossby soliton, selecting the wave energy of the planetary soliton of the circumpolar vortex and the soliton of the fronts, gradually destroys them, translating them into a soliton of polar vectors. But the soliton of the front has a constant energy supply from wet convection and after its regeneration on the Rossby waves restores the structure of the planetary soliton. The cycles of such regeneration serve as the basis for low-frequency oscillations in the macroprocesses (climate) forecast and substantially exceed the periods of the frequency sweep of the solution (1). The, the long-period oscillation cycles of the tensor density arise in the Riemannian space time, as the energy losses generated by the wave radiation from the planetary soliton to the Rossby waves are compensated by the frontal soliton at the expense of the energy of the hydrologic cycle carried out in it. The curvature of the Riemannian space must also ensure the irreversibility in time of the tensor | P | in equation (5). The friction losses are removed by the same mechanism. The form of the metric tensor of the Riemannian space for this problem was published in [22]. The Rossby solitons exist relatively a little time to be important for climate prediction. However, the fact of the repeated existence of blocking processes during the year ensures the existence of a total time interval sufficient for a significant increase in the field of the tensor density. This will be the time period that gives the necessary frequency in the task of forecasting the macroatmospheric processes. Two main solitons give wave energy to either Rossby solitons or progressive waves of temperate latitudes. But waves of temperate latitudes have a tensor analogy in axial vectors and therefore can not affect either the planetary soliton or the fronts. The energy costs for wave radiation in their direction are compensated by the latent energy of the phase transitions in the solitons of the fronts. The energy of the fronts cannot cause an energy overflow of the planetary soliton or solitons and the Rossby waves, as a process is limited by the solar constant. This nonlinear oscillatory process is stable in time and can exist long enough in time and commensurate with the time interval of climatic stage. The initial conditions in the sense of the Cauchy problem do not exist, because the system of solitons must enter a steady oscillatory regime over a long time interval of prehistory.

**Advanced angle momentum balance approach and spectral analogue of atmosphere dynamics equations in a low-frequency range.** As some elements of our theory were in details presented earlier [23-25], we are limited only by the key aspects. An advanced non-stationary angular momentum balance equation of in the planetary dynamic movements of air masses is written in the following standard integral form [24]:

$$
\begin{aligned}
&\frac{\partial}{\partial t}\int \rho M dV=\int_{\phi_1}^{\phi_2}\int_{0}^{H}\int_{0}^{2\pi}\rho v M d\phi dz d\lambda+\int_{0}^{H}\int_{\phi_1}^{\phi_2}\int_{0}^{2\pi}\left(p_E^i-p_W^i\right)a\cos\phi dz d\phi d\lambda+\\
&+\int_{\phi_1}^{\phi_2}\int_{0}^{2\pi}\int_{0}^{H}\tau_0 a\cos\phi d\phi d\lambda 2\pi,
\end{aligned}
\tag{6}
$$

where $M = \Omega a^2 \mathbf{cos}\varphi + \mathrm{u}a\mathbf{cos}\varphi$ – angular momentum; $\Omega$ – the angular velocity of rotation of the Earth; $a$ – radius of the Earth; $\varphi$ – Latitude ($\varphi_1 - \varphi_2$ – separated latitudinal belt between the Arctic and polar fronts); $\lambda$ – longitude; $u$, $v$ – zonal and meridional components of the wind velocity; $\rho$ – air density; $V$ – the entire volume of the atmosphere in this latitude belt from sea level to the average height of the elevated troposphere waveguide - $H$ (in notations [1] $H = \infty$); $p_E^i - p_W^i$ – the pressure difference between the eastern and western slopes of the $i$-th mountains; $z$ – height above sea level; $\tau_0$ – the shear stress on the surface. From the point of view of physics, the cycle of balance of angular momentum in the contact zones with the hydrosphere and lithosphere becomes a singularity. This singularity can be detected through the occurrence of zones of fronts and soliton-type front. Then the kernel of equation (1) can be defined in the density functional ensemble of complex velocity potential [23, 24]

$$
f=\overline{v_\infty}z+\frac{1}{2\pi}\sum_{k=1}^{n}q_k\ln\left(z-a_k\right)+\frac{1}{2\pi}\sum_{k=1}^{p}\frac{M_k e^{\alpha_k i}}{z-c_k}-\frac{i}{2\pi}\sum_{k=1}^{m}\Gamma_k\ln\left(z-b_k\right) \tag{7}
$$

and the complex velocity, respectively, will be

$$
v=U+iV=\frac{df}{dz}=\overline{v_\infty}+\frac{1}{2\pi}\sum_{k=1}^{n}\frac{q_k}{z-a_k}-\frac{1}{2\pi}\sum_{k=1}^{p}\frac{M_k e^{\alpha_k i}}{\left(z-c_k\right)^2}-\frac{i}{2\pi}\sum_{k=1}^{m}\Gamma_k/\left(z-b_k\right), \tag{8}
$$

where $w$ – complex potential; $v_\infty$ – complex velocity general circulation background (mainly zonal circulation); $b_k$ – coordinates of vortex sources in the area of singularity; $c_k$ – coordinates of the dipoles in the area of singularity; $a_k$ – coordinates of the vortex points in areas of singularity; $M_k$ – values of momenta of these dipoles; $\alpha_k$ – orientation of the axes of the dipoles; $\Gamma_k$, $q_k$ – values of circulation in the vortex sources and vortex points, respectively.

Further we consider an advanced spectral analogue for equation of motion for dynamics of the atmosphere in the low frequency range [22-24]. Note that the macroturbulent atmosphere equations are low-frequency ones in its basis and there is a lot of experience of their solving by spectral methods (see [27-29]). The method for calculating a turbulence spectra should be based on the standard tensor equations of turbulent tensions. One could write the system of equations for the Reynolds tensions, moments of connection of the velocity pulsations with entropy ones and the corresponding closure equations [23, 24]. The technique of using Reynolds tension tensors of the second rank is well known (for example, in the form of an analytical representation). The master equations (velocity x-, y-components $U, V$) with accounting the Coriolis force an be rewritten as (look [24]):

$$\frac{\partial V'^2}{\partial t}=-\frac{i}{a}\left[\overline{V'^2}L_1\left(\bar{V}\right)+2\bar{V}\overline{V'L_1\left(V'\right)}+\overline{V'^2L_1\left(V'\right)}\right]-$$
$$-\frac{i}{a}\left[L_2\left(\bar{V}\right)\overline{V'U'}+\bar{V}\overline{U'L_2\left(V'\right)}+\bar{U}\overline{V'L_2\left(V'\right)}+\overline{V'U'L_2\left(V'\right)}\right]+ \quad (9a)$$
$$+4\omega i\cos\theta\overline{V'^2}+\frac{2i}{a}\overline{V'L_6\left(\Phi'\right)},$$

$$\frac{\partial U'^2}{\partial t}=-\frac{i}{a}\left[\overline{V'U'}L_3\left(\bar{U}\right)+\bar{V}\overline{U'L_3\left(U'\right)}+\bar{U}\overline{V'L_3\left(U'\right)}+V'U'L_3\left(U'\right)\right]-$$
$$-\frac{i}{a}\left[\overline{U'^2}L_4\left(\bar{U}\right)+2\bar{U}\overline{U'L_4\left(U'\right)}+\overline{U'^2L_4\left(U'\right)}\right]-4\omega i\cos\theta\overline{U'^2}+\frac{2i}{a}\overline{U'L_5\left(\Phi'\right)}, \quad (9b)$$

where, as usually:

$$L_j=\frac{\partial(...)}{\partial\theta}-\left(-1\right)^j\frac{i}{\sin\theta}\frac{\partial(...)}{\partial\lambda}+b_j\operatorname{ctg}\theta(...)\,,\ b_j=1, j=1,4;\ b_j=-1, j=2,3;\ b_j=0, j=5,6.$$

The simplified modelling supposes remaining only two operators, say, in the equation (9c): $\frac{\partial\overline{V'U'}}{\partial t}=\frac{i}{a}\overline{V'L_6\left(\Phi'\right)}$ expressing $\Phi'$ through $\varphi$ complex potential of the velocity $f$, and the velocity components $U,V$ – in terms of functions $\psi$ of the same velocity potential. The important parameter of the turbulent processes is the kinetic energy of turbulent vortices $b^2=\overline{u'_k u'_k}$, which can be found from the equation (with physical explanations of any term):

$$\frac{\partial b}{\partial t}+\frac{\partial u_k b^2}{\partial x_k}+\frac{\partial}{\partial x_k}\left(\overline{u'_k u'_i u'_j}+2\overline{u'_k p'}\right)=-2\overline{u'_k u'_i}\frac{\partial u_i}{\partial x_k}-2\frac{g}{\theta_0}\overline{w'\theta'}. \quad (10)$$

| Advection | Turbulent diffusion | Effect of forces of tension | Interaction of Reynolds tension and averaged motion | Generation for account for swimming forces |
|---|---|---|---|---|

Here $g$ is the magnitude of the acceleration vector due to the planet's gravity, $\theta_0$ is the equilibrium potential temperature, $\theta'$, $p'$ are departures from equilibrium values. The equations for the velocity's correlates are in details listed in [23,24]. Components of tensor of the turbulent tensions are (spectral modes of velocity field):

$$\hat{V}^2=\sum_{k=1}^{\infty}\sum_{s=-k}^{k}V_{k,s}T_{1,s}^{k}\left(\sum_{q=1}^{\infty}\sum_{j=-q}^{q}V_{q,j}T_{1,j}^{q}\right)=\sum_{k=1}^{\infty}\sum_{s=-k}^{k}\sum_{q=1}^{\infty}\sum_{j=-q}^{q}V_{k,s}V_{q,j}\times\sum_{\nu=|k-q|}^{k+q}\sigma_{1,1,2}^{k,q,\nu}\sigma_{s,j,s+j}^{k,q,\nu}T_{2,s+j}^{\nu}=\overline{v'_1v'_1}=b^2 \quad (11)$$

Equating the velocity components determined in the global circulation model and model (6), one could find spectral matching between the wave numbers that define the functional elements in the Fourier-Bessel series with the source element of a plane field theory. It provides principally new basis for the macrocirculation atmospheric processes description. Such an approach is a key block in the balance approach to modelling global mechanisms of macro turbulent atmospheric low-frequency processes etc. In the next paper we will present the concrete simplified scheme to calculating the balance of an energy and angular momentum, atmospheric macroturbulence with elements of a chaos, atmospheric moisture flow in connection with the continuity of atmospheric circulation forms.

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***Буяджи В.В., Софронков О.Н., Глушков О.В.,***
***Хецеліус О.Ю., Дубровська Ю.В., Свинаренко А.А.***

## Новий балансовий по ентропії, енергії і кутовому моменту підхід до моделювання клімату та макротурбулентної динаміки атмосфери, тепломасопереносу в макромасштабі. І. Загальний формалізм

АНОТАЦІЯ

*Представлені елементи нового балансового підходу до моделювання глобальних механізмів кліматичних і макротурбулентних атмосферних низькочастотних процесів, у т.ч., процесів тепло-масо-переносу , ефектів телеконнекції тощо. Основним процес-формуючим фактором є взаємодія триплету солітонів: «планетарний солітон осередків Гадлея – комплекс атмосферних фронтів – хвильової пакет солітонів Россбі». Підхід заснований на використанні балансових співвідношень по ентропії, енергії і кутового моменту, спектральній теорії атмосферної макротурбулентності і вологообороту у зв'язку із наступністю форм атмосферної циркуляції (телеконнекція, генезис фронтів). Одним із застосувань підходу є моделювання просторово-часових полів дисперсії забруднювачів (напр., хімічних забруднювачів типу з'єднань з галогенами, радіонуклідів після аварій на АЕС типу Фукусіми і т.і.) в атмосфері з урахуванням макротурбулентних циркуляційних низькочастотних процесів.*

***Буяджи В.В., Софронков А.Н., Глушков А.В., Хецелиус О.Ю.,***
***Дубровская Ю.В., Свинаренко А.А.***

## Новый балансовый по энтропии, энергии и угловому моменту подход к моделированию климата и макротурбулентной динамики атмосферы, тепло-массо-переноса в макромасштабе. I. Общий формализм

АННОТАЦИЯ

*Представлены элементы нового балансового подхода к моделированию глобальных механизмов климатических и макротурбулентных атмосферных низкочастотных процессов, в т.ч., процессов тепло-массо-переноса, эффектов телеконнекции и др. Основным процесс-формирующим фактором является взаимодействие триплета солитонов: «планетарный солитон ячеек Гадлея – весь комплекс атмосферных фронтов – волновой пакет солитонов Россби». Подход основан на использовании балансовых соотношений для энтропии, энергии и углового момента, спектральной теории атмосферной макротурбулентности и влагооборота в связи с преемственностью форм атмосферной циркуляции (телеконнекция, генезис фронтов). Одно из применений подхода включает моделирование пространственно-временных полей дисперсии загрязнителей (напр., загрязнителей типа соединений галогенов, радионуклидов после аварий на АЭС типа Фукусимы и т.д.) в атмосфере с учетом макротурбулентных циркуляционных низкочастотных процессов.*