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Mathematical simulation of methane inflow into the atmosphere from decomposed subbottom methanehydrates*

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It is assumed that with the global warming the temperature of the ocean surface begins its raising by 0.08 degrees annually. The climatic model of the ocean is further integrated for the period of 50 years and simulates penetrations of warming from the surface deep into the ocean. A three-dimensional equation of transport of dissolved methane from sources is simultaneously solved which is included in that moment, when warming reaches the area of methanehydrate stability and raises the temperature by a defined magnitude–tolerance. The tolerance in different experiments varied from 0.1 to 2.0 degrees. The flux of methane into the atmosphere has reached 1 Tg after 17 years, and after 50 years it has become 3.8 Tg (at tolerance 2 degrees, respectively, after 12 years it has exceeded 1 Tg and has become 4.2 Tg after 50 years). In the other experiments an instant increase of the winter and the summer surface temperature of the ocean by 3 degrees is assumed. In this case at tolerance of 0.1 degree the flux of methane into the atmosphere has exceeded 1 Tg after 4 years, and has reached 14 Tg after 50 years (at tolerance of 2.0 degrees, accordingly, it has exceeded 1 Tg after 8 years and has become 6.3 Tg after 50 years).

In work [1], a three-dimensional mathematical model of the dissolved gas transport by the ocean currents is used for the quantitative evaluation of the scale of a possible methane inflow into the atmosphere from the decomposed subbottom methanehydrates. The three-dimensional climatic large-scale currents field is obtained from the three-dimensional global model of the ocean dynamics. The task was solved numerically on a spatial grid with resolution of 5 degrees in latitude and in longitude and with 6 levels on the vertical. The model sources of methane are located on the shores of the Arctic and the Southern oceans. As at present there is no detailed information about possibilities and depths of determination of methanehydrates deposits, but nevertheless the opinion about their global presence on the continental slopes of continents and the shelf of the oceans was formed, the sources of methane were set by an indirect way.

A source is understood as a point lying on the ocean boundary, for which the conditions of methanehydrate stability are fulfilled. These conditions are assumed to be broken, and there is a stationary process of methanehydrate

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decomposition. It ensures 100 times raise of concentration at this point in comparison with the initial concentration.

Further it is assumed that when these conditions are validated there will begin the process of methanehydrates decomposition which will ensure 100 times raise of concentration in the neighbourhood of this point as compared with the background values of concentration of 50 ppb characteristic of the ocean surface. Such an approach proves to be correct in terms of the of measurements of methane concentration, Objirov [2], Bolshakov, Egorov [3]. It was assumed that the process of decomposition is stationary in time, and the equation of transport of the dissolved methane has been integrated till it has become stationary. It appeared that the amount of dissolved methane which can enter the atmosphere from the ocean is comparable to the available evaluations and makes up the value from 5 to 15 Tg per year. Probably, this evaluation is overestimated, as it is assumed that there is a constant decomposition of subbottom methanehydrates everywhere, where the pressure–temperature conditions take place. Thus, the realization or not realization of these conditions is not taken into account in any way, and it is impossible to estimate the temporal scale of decomposition. In the given work, the models of climate of the global ocean and the model of methane transport were joined.

The equations, simulating the ocean climate in approximation of linearity of the equations of motion and the flat bottom, look like the following [4]:

$$R_1 u + \ell v = -\frac{1}{a\rho_0 \sin\theta}\frac{\partial p}{\partial \lambda} + \frac{\partial}{\partial z}\nu\frac{\partial u}{\partial z}, \tag{1}$$

$$-\ell u + R_1 v = \frac{1}{a\rho_0}\frac{\partial p}{\partial \theta} + \frac{\partial}{\partial z}\nu\frac{\partial v}{\partial z}, \tag{2}$$

$$\frac{1}{a\sin\theta}\left(\frac{\partial u}{\partial \lambda} + \frac{\partial v \sin\theta}{\partial \theta}\right) + \frac{\partial w}{\partial z} = 0, \tag{3}$$

$$p = -g\rho_0\zeta + g\int_0^z \rho\, dz, \tag{4}$$

$$\frac{\partial T}{\partial t} + \frac{u}{a\sin\theta}\frac{\partial T}{\partial \lambda} + \frac{v}{a}\frac{\partial T}{\partial \theta} + w\frac{\partial T}{\partial z} = \frac{\partial}{\partial z}æ\frac{\partial T}{\partial z} + \frac{\mu}{a^2}\Delta T, \tag{5}$$

$$\frac{\partial S}{\partial t} + \frac{u}{a\sin\theta}\frac{\partial S}{\partial \lambda} + \frac{v}{a}\frac{\partial S}{\partial \theta} + w\frac{\partial S}{\partial z} = \frac{\partial}{\partial z}æ\frac{\partial S}{\partial z} + \frac{\mu}{a^2}\Delta S, \tag{6}$$

$$\rho = \rho(T, S). \tag{7}$$

The boundary conditions:

• for $z = 0$:

$$\nu\frac{\partial u}{\partial z} = -\frac{\tau_\lambda}{\rho_0}, \quad \nu\frac{\partial v}{\partial z} = -\frac{\tau_\theta}{\rho_0}, \quad w = 0, \quad T = T^*, \quad S = S^*; \tag{8}$$

• for $z = H$:

$$\nu\frac{\partial u}{\partial z} = -R_2\int_0^H u\,dz, \qquad \nu\frac{\partial v}{\partial z} = -R_2\int_0^H v\,dz,$$
$$w = 0, \qquad æ\frac{\partial T}{\partial z} = 0, \qquad æ\frac{\partial S}{\partial z} = 0; \tag{9}$$

• at the lateral wall Γ:

$$\mu\frac{\partial T}{\partial n} = 0, \qquad \mu\frac{\partial S}{\partial n} = 0, \qquad u_n = 0; \tag{10}$$

• at the initial instant $t = 0$:

$$T = T^{**}, \qquad S = S^{**}. \tag{11}$$

The method of solution of equations (1)–(10) is described in [4], here it should be noted that for equations (5), (6) on the uniform five-degree grid the horizontal operator is approximated by a nine-point difference scheme obtained by Richardson's extrapolation, and the vertical operator, after introduction of a new variable, condensing the grid near the ocean surface, is approximated by the second up-wind scheme. The advective-diffusion process of transport of the dissolved methane in the sea water, whose concentration is noted by C, we describe by the equation

$$\frac{\partial C}{\partial t} + \frac{u}{a\sin\theta}\frac{\partial C}{\partial \lambda} + \frac{v}{a}\frac{\partial C}{\partial \theta} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial z}æ\frac{\partial C}{\partial z} + \frac{\mu}{a^2}\Delta C. \tag{12}$$

with the boundary conditions

$$z = 0: \quad C = C^*(\theta), \tag{13}$$

$$z = H: \quad æ\frac{\partial C}{\partial z} = 0. \tag{14}$$

On a part of the side cylindrical surface of the ocean Γ_1 the zero methane flux conditions are set and on the other part of the side of the boundary Γ_2, the presence of methane sources is assumed due to decomposition of the subbottom methanehydrates. As opposed to the previous calculations, where the methane concentration on the ocean surface was set to the common constant $C^* = 50$ ppb [1], in these experiments in accordance with data from work [5] the distribution, depending only on a latitude, was given:

$$C^*(\theta) = (1 + \cos(\theta)) \cdot 50\,\text{ppb}.$$

Starting with some quasi-stationary climatic state of the ocean with seasonally varying surface temperature, salinity and wind stress, the numerical integration of the system of equations (1)–(8) with a time step of 10 days begins. Thus it is assumed, that in the global warming of the atmosphere results in the raise of temperature of the ocean surface by the catastrophic scenario [6], i.e., by 0.08 degrees annually. Thus, for the surface waters which are covered with ice all the yearround temperature does not increase. The climatic model of the ocean is further integrated for the period of 50 years and it reproduces the penetration process of warming from the surface deep into the ocean. Simultaneously on each time step the three-dimensional equation of transport of the dissolved methane from sources is solved. The sources are set similarly to the previous experiment. The initial methane concentration is obtained from equation (10) with a field of currents from the stationary climatic state with the boundary conditions (11)–(13).

As opposed to the previous experiments the sources of the dissolved methane are switched on only there and at the moment, where and when warming reaches an area of stability of methanehydrates and raises temperature by the defined magnitude–tolerance, [7]. The tolerance was equal to 0.1 degree in the first experiment and to 2 degrees in the second. Figure 1 shows a summarized methane flux in the atmosphere as function of time for the period of 50 years of warming. At tolerance of 0.1 degree the methane flux has exceeded 1 Tg/yr after 4.6 years and after 50 years has reached 8.7 Tg per year. At tolerance of 2.0 degrees the methane flux has exceeded 1 Tg as short as after 12.5 years and after 50 years has reached only 3.8 Tg.

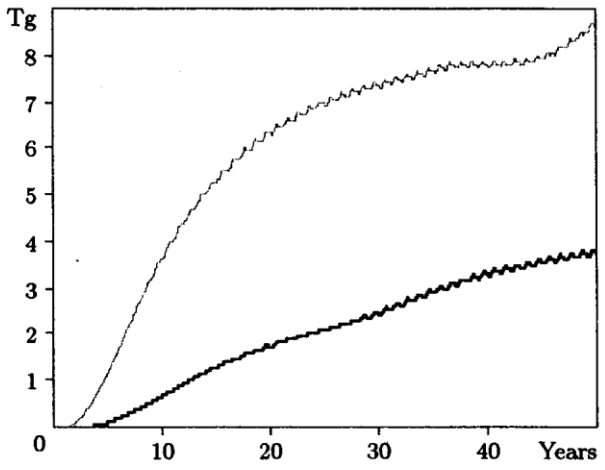

Figure 1. Time modification of the methane flux from the ocean into the atmosphere from decomposed methanehygrates for 50 years after beginning of warming (in Tg per year)

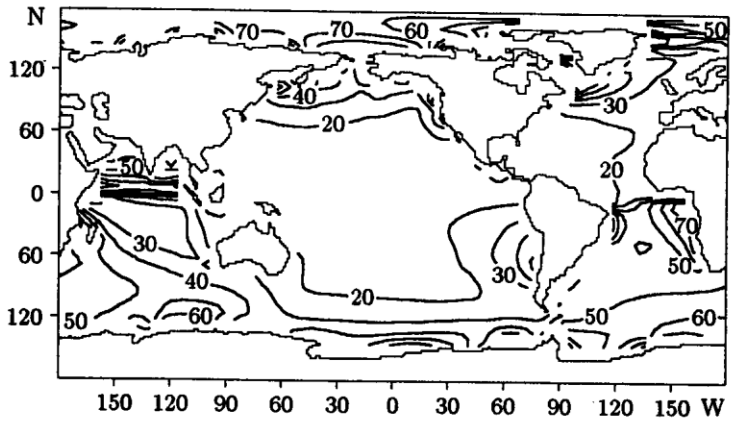

Figure 2. Isolines of the dissolved methane at a depth of 562 m after 50 years after beginning of warming at tolerance of 0.1 degree (the values on isolines are indicated in conditional units; 1 conditional unit = 50 ppb)

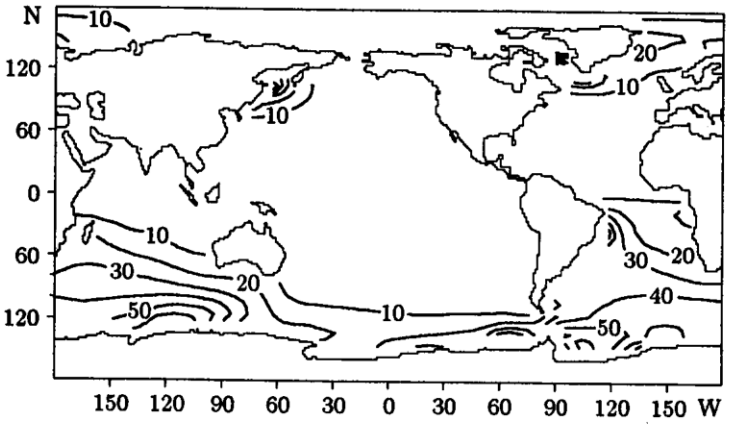

Figure 3. Isolines of the dissolved methane at a depth of 562 m after 50 years after beginning of warming at tolerance of 2.0 degrees (the values on isolines are indicated in conditional units; 1 conditional unit = 50 ppb)

In Figure 2 the distribution of the dissolved methane concentration at the depth of 562 m after 50 years of catastrophic warming is shown. We can see that at tolerance of 0.1 degree methanhydrates begin decomposing on all the coasts of Siberia, Canada and the Antarctic Continent, as well as in tropics of the Atlantic ocean, in the Arabian see and Bengal gulf. If the hair latitude fast penetration of the warmed surface water deep into the ocean it occurs due to the fall-winter convective mixing, warming in tropics is connected with the vertical velocity field.

The methane concentration values in high latitudes are quantitatively comparable with values of the previous calculations [1]. The areas of decomposed methanehydrates considerably decrease with tolerance of 2 degrees, Figure 3. They remain only there, where warming penetrates deep down due to the convective mixing.

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