Bull. Nov. Comp. Center, Num. Model. in Atmosph., etc., 4 (1996), 67–80

Numerical model of methane transport by the ocean currents*

A.V. Scherbakov, V.V. Malakhova

A series of scenario experiments with three-dimensional model of dissolved gas transfer by ocean currents are given. The current domains and climatic state of the ocean are received from three-dimensional model of dynamics of the World Ocean, including seasonal variability. For approximation of domain of the World Ocean the five-degree grid, shifted by 2.5° relatively the equator was used. On a vertical a non-uniform grid, including 6 levels was chosen. Three adaptation experiments with different sources of methane were carried out. The sources were set in those points of lateral boundary, where pressure–temperature conditions of methanegyrats existence are satisfied. The received numerical estimations of the methane content, which can transfer to atmosphere in result of gasgydrats melting, have made 5–15 Tg/year.

Modern view on mechanisms of global warming of atmosphere for the last 150 years owing to greenhouse effect [1], allocates on a share of methane 15% of a gain of average temperature. Though it is four time less, the similar estimation for carbondioxide (61%), it is important to note that the total influence of all gases of greenhouse effect, warming up atmosphere and layer of the ocean, can entail the melting of subbottom methanegydrats and concentrated in the areas of permafrost. That will result in further increase of the methane content in atmosphere. Probably this testifies rather fast increase of the methane content in atmosphere (in 1–2% a year [2]) comparing with the growth of carbondioxide annually in 0.35% [3].

The quantity estimations of methane, which can reach atmosphere by melting of methanegydrats, and time scale of the phenomenon, are the key parameters in this case.

The quantity estimations of methane in submarine methanegydrats change in very wide limits [4], from $1.7 \cdot 10^6$Tg (Tg = Terragramm=10^{12}g) on Makiver [5], up to $4.1 \cdot 10^9$Tg on Dobrynin [6]. In both cases it much exceeds the total methane content in atmosphere, estimated by $4 \cdot 10^3$Tg, (Halil, Ramusen [2]). Therefore the destabilization though 0.23% from the minimum estimation doubles the methane content in atmosphere, that in result of greenhouse effect can increase the average temperature of atmosphere in the next 40–50 years up to 0.3–0.4 K [7].

*Supported by the Russian Foundation of Basic Research under Grants 93-05-8635, 95-05-14588 and INTAS-93-1176.

Total estimations of methane receipt in atmosphere from different sources are resulted in Table 1. Production of methane from various sources is shown in Table 2. As it is evident oceans bring in the insignificant contribution to general balance, only 2.4%. It is much less estimation of methane brought in atmosphere through the melting of subbottom methangydrats [11], 2–4 Tg/year or not more than 0.7%.

Table 1

Estimation, Tg/year	Author	Year
545–1035	Ehhalt, [8]	1974
1490	Wolker*	1977
590–1060	Ehhalt, Schmidt*	1978
450–1000	Hudson, Reed*	1979
580	Logan et al.*	1981
1210	Sheppard*	1982
553	Khalil, Rasmussen [2]	1983
400–640	Cicerone, Oremland*	1988
372–1000	Cicerone, Singer**	1989
405±85	Crutzen**	1991

*The data from work [2].
**The data from work [9].

Table 2

Source	1974, [8]	1983, [2]		1988, [10]
	Tg/year	Tg/year,	%	Tg/year
Wetlands	130–260	150	27	100–200
Cattle	101–220	120	22	65–100
Paddy fields	280	95	17	—
Other	—	88	16	10–100
Anthropogeneous	—	40	7	80–165
Biomass burn	—	25	5	50–100
Oceans	4–6.7 open ocean 0.7–13 shelf	13	2.4	5–20
Tundra	1.3–13	12	2.2	—
Fresh lakes	1.25–25	10	1.8	1–25
Total	529–825	553	100	400–640

However there exist other estimations, (see [4]), showing essentially large meanings of methane current through the submarine methangydrate melting as a result of destabilization (Table 3).

Possible these estimations are strongly overestated [4], as they are based on the assumptions about high-power of methanegydrate deposits and the assumption that their large amount will proceed in gaseous form under the ocean heating. Besides methanegydrats are located below the ocean bottom in a sedimentary layer, which probably may provide an insulation against the

Table 3

Estimation, Tg/year	Author	Year
640	Revelle	1983
900	Chamberlain et al.	1983
8000	Bell	1983

thermal influence. The ocean, having some absorbing ability, will dissolve in itself some part of methane.

Thus for specification of estimations of possible emissions of methane to the atmosphere from the subbottom methanegydrats and estimation of characteristic time of these process it is required to carry out a series of scenario experiments with mathematical models describing redistribution of a heat in systems atmosphere-ocean-sedimentary layer of sea bottom.

Write down the initial equations of model as follows [12–14]:

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

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

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

$$p = -g\rho_0\zeta + g\int\limits_0^z \rho dz \tag{4}$$

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

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

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

Boundary conditions:

$z = 0:$

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

$z = H:$

$$\nu\frac{\partial u}{\partial z} = -R_2\int\limits_0^H udz, \quad \nu\frac{\partial v}{\partial z} = -R_2\int\limits_0^H vdz, \tag{9}$$

$$W = 0, \quad æ\frac{\partial T}{\partial z} = 0, \quad æ\frac{\partial S}{\partial z} = 0;$$

at the lateral wall Γ:

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

at the initial moment $t = 0$: $T = T^{**}$, $S = S^{**}$.

The equations are presented in the spherical coordinate system (λ-latitude, θ-the addition of longitude up to 90°, the axis z is directed vertically downwards); u, v, w – velocity vector components, t – time, ρ_0, ρ – the mean value and the anomaly of density, $\zeta = \xi - \frac{p_{at}}{g\rho_0}$ – the reduced level, p_{at} – atmospheric pressure, $z = \xi(\lambda, \theta)$ – the equation of ocean surface, $R_1 u$, $R_1 v$ – the parametrisation of horizontal turbulent viscosity, ν – the vertical turbulent viscosity coefficients, æ, μ – the vertical and horizontal turbulent temperature and salinity difussion coefficients, $\ell = 2\omega \cos\theta$ – the Coriolis parameter, a, ω, g – the radius, the angular velocity and acceleration of gravity of the Earth, respectively, τ_λ, τ_θ – the wind stress, T^*, S^* – the known climatic distribution of temperature and salinity at the surface of ocean, R_2 – coefficient of bottom friction, n – the normal to lateral cylindrical wall, H – the constant depth of ocean.

The method of solving a problem (1)–(10) is described in detail in [12, 13], here we shall only mention that for equations (5)–(6) on the uniform five-degree grid the horizontal operator is approximated by the nine-dot difference scheme, received by the Richardson extrapolation, and the vertical operator, after introduction of new variable, condensing a grid at a surface of ocean, is approximated by the second up-wind scheme.

The advective-diffusion transport of methane, the concentration of which is designated by C, we shall describe by the equation:

$$\frac{\partial C}{\partial t} + \frac{u}{a\sin\theta}\frac{\partial C}{\partial \lambda} + \frac{v}{a}\frac{\partial C}{\partial \theta} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial z}æ\frac{\partial C}{\partial z} + \frac{\mu}{a^2}\Delta C, \tag{11}$$

with boundary conditions:

$$z = 0: \qquad C = C^*(\lambda, \theta), \tag{12}$$

$$z = H: \qquad æ\frac{\partial C}{\partial z} = 0. \tag{13}$$

The conditions of absence of methane flux are set on a part of a lateral cylindrical wall of ocean Γ_1:

$$\text{on } \Gamma_1: \qquad \mu\frac{\partial C}{\partial n} = 0, \tag{14}$$

and on the other part of lateral wall Γ_2, presence of methane sources is supposed at the expense of methanegydrts decomposition, which provides increased concentration of dissolved methane,

$$\text{on } \Gamma_2 : \qquad C = C^{**}, \tag{15}$$

which exceeds background meanings, characteristic of an open part of ocean. In the calculations it was belived that $C^* = 1, C^{**} = 100$ conditional units, the concentration in 1 cond. unit $= 5 \cdot 10^{-5}$ ml/l.

With the help of described model three scenario experiments were carried out. The model of ocean dynamics (1)–(10) was used for calculation of a climatic state of the World Ocean, encluding three-dimensional current fields $u(\lambda, \theta, z)$, $v(\lambda, \theta, z)$, $W(\lambda, \theta, z)$, which are used further for the solution of equation (11) as stationary one. The equation (11) is solved with the help of the same finite-difference scheme as well as equations of heat and salt transfer (5), (6).

The uniform five-degree grid shifted by 2.5° relatively the equator and lateral wall Γ is inserted in the first experiment [14] in the polygonal area approximating the World Ocean from 72.5°S to 62.5°N. Boundary walls of the ocean are assumed vertical, the bottom is considered flat – $H(\lambda, \theta) =$ 4000m. Two grids condenseding at the surface of ocean under the square-law are entered on vertical coordinate. On one grid with integer-valued meanings of index k

$$z_k = (\eta_N - \eta_0)^2 \cdot [(k - 1/2)/N]^2, \tag{16}$$

where $\eta_N^2 = H + \alpha$, $\eta_0 = \alpha$, $\alpha = 120$sm, variables u, v, T, S,ρ are defined. The dots of the second grid lay in the middle of intervals

$$\frac{z_{k+1} + z_k}{2}, \quad z_{1/2} = 0, \ z_{N+1/2} = H, \ N = 12, \tag{17}$$

and serve for definition of variables w and p. In this experiment, where a part of lateral wall Γ_2 represetns the line of crossing of a lateral wall with flat bottom, the flux of methane through surface of ocean 3.1 Tg/year is received [14].

Two other experiments differed from first by that the Arctic basin was included in calculation domain. The inclusion of the Arctic basin is caused by prospective presence of methangydrat deposits on rather small depth of the order 100–200 meters. At global warming just the Arctic basin, during of the order of 50 years [15], will get warm fast due to deep convective mixing. The methangydrats located here will be destabilisated first of all.

Northern boundary of area was lifted up to the Northern pole so, that the first calculation points lay on a circle of latitude 87.5°N, but they are 72, as well as on all other parallels. Therefore a step grid on a longitude appears to be rather small at a pole, but as the implicit scheme is used in numerical model, it does not bring additional computing difficulties characteristic for explict schemes because of Currant's condition.

The data on climatic boundary conditions were added from the Levitus Atlas [16], and further a problem of modeling of normal annual circle of the ocean thermogydradinamics fields was solved. The numerical integration proceeded from homogenous on a horizontal initial distribution of temperature and salinity for model time 98 years. Contrary to the previous accounts on ocean modeling climate the resolution in a vertical was reduced by half in this model. Two-component model (1) – (10) with the equation for salinity was used in this case. The received results adequately reproduce the ocean climate.

At first the previous experiment was repeated in a new calculation domain, the integration was carried for 2000 years from an initial condition $C^0 = 1$, and the stable solution was received with accuracy 10^{-7}. The flux through a surface of the ocean has increased up to 5.5 Tg/year. The methane content contained in each layer and in all ocean was calculated (Table 4).

Table 4

	Experiment		
	1	2	3
Flux, Tg/year	5.5	15.8	5.2
Methane content, Tg			
in all ocean	1101.4	1364.8	721.8
in layers			
28 m	4.2	10.6	4.0
250 m	39.2	83.0	36.6
694 m	110.0	186.4	90.6
1361 m	190.6	279.7	148.0
2250 m	273.8	366.9	201.7
3361 m	393.6	438.2	241.0

In the second experiment on methane distribution the sources were given in those points of lateral wall, where the pressure–temperature conditions of methangydrats existence are satisfied [4]. It means, that in comparison with the first experiment [14], the sources are added in the points of lateral wall on depth Z m

$$\begin{aligned} z &= 250\text{m}, \quad \text{if } T < 0^\circ, \\ z &= 694\text{m}, \quad \text{if } T < 8^\circ, \\ z &= 1361\text{m}, \quad \text{if } T < 16^\circ, \\ z &= 2250\text{m}, \quad \text{if } T < 19^\circ, \end{aligned} \tag{18}$$

and in all points on depth z=3361 m.

Equation (11) was integrated up to the stable state from initial homogeneous distribution. It takes 320 years of model time, and in the next time steps the solution has coincided with accuracy 10^{-7}. It is clear, that conditions (18) much increase methane content in the ocean, as the conditions on the 5-th and 6-th m horizons are satisfied in all points of lateral border, and in high latitudes methane sources occur near to a surface. It has resulted essentially large concentration values of dissolved methane on all depths and increse its flux to the atmosphere.

Isolines of dissolved methane at depth of 28m are given in Figure 1. Figure 2 showes a direction of vertical velocity on depth 139 m and boundary points in whose vicinity the methane sources by (18) for depth 250 m are placed. The sources lay only near the Antarctica and on the coast of the Arctic Ocean. However the large values of concentration up to 20–30 condi-

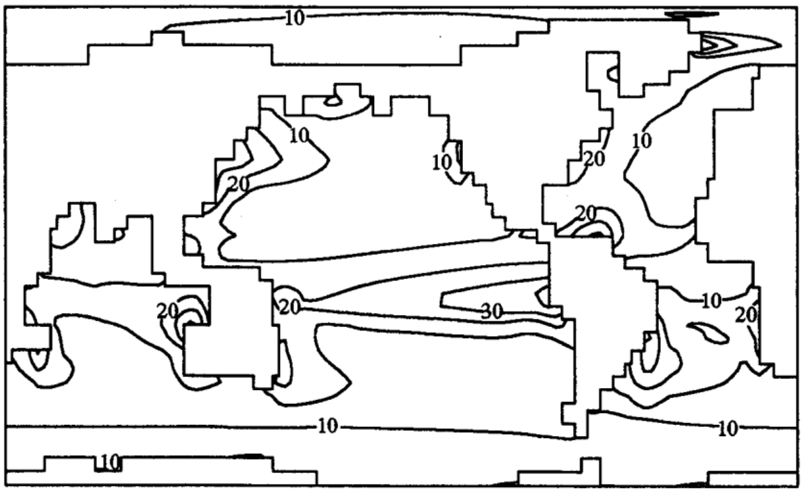

Figure 1. Isolines of dissolved methane in conditional units on depth 28 m, received in the second experiment. One conditional unit is equal $5 \cdot 10^{-5}$ml/l

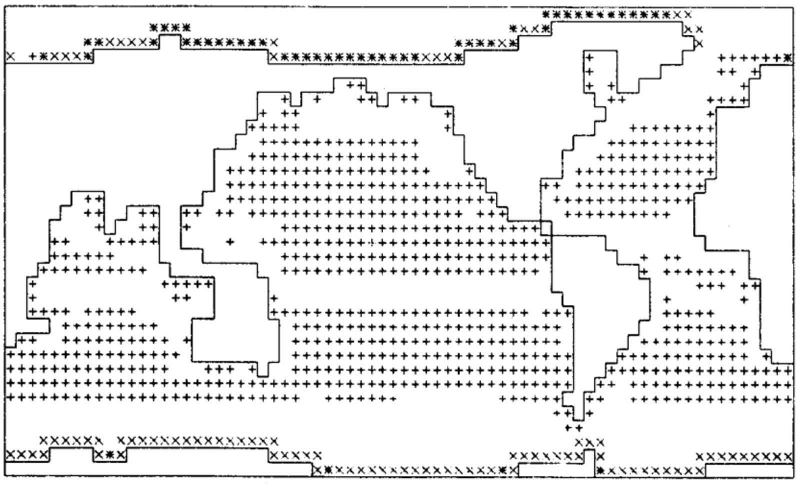

Figure 2. Vertical velocity on depth 139 m, x – methane sources on depth 250 m

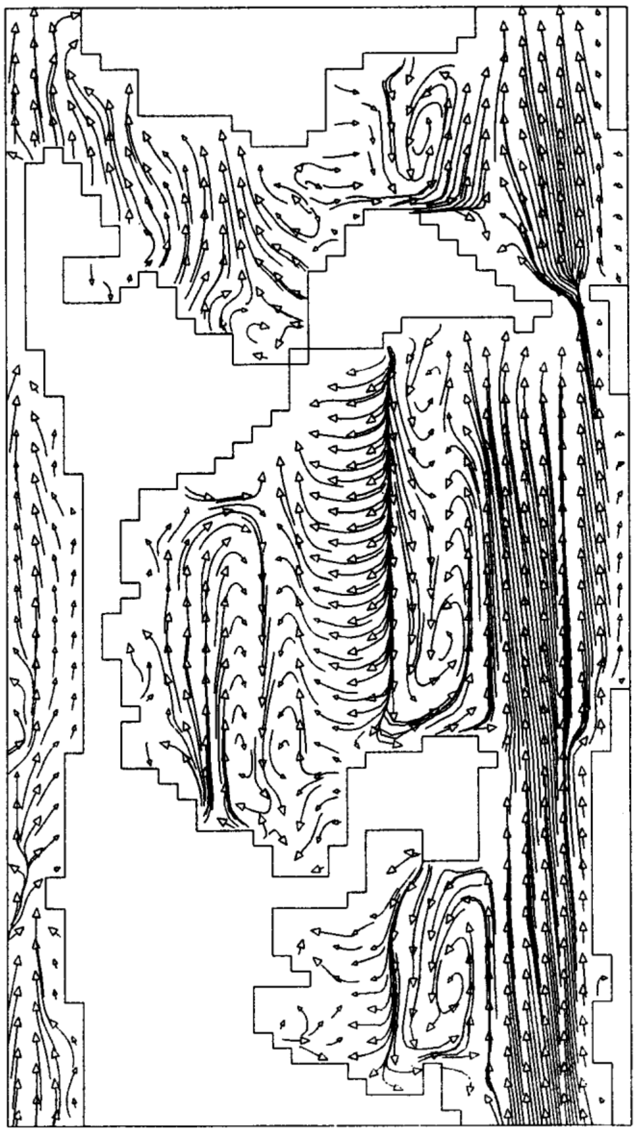

Figure 3. Horizontal velocity of the depth 28 m

tional units are located in coastal areas with upwelling. It occurs at western coasts of the Pacific and Atlantic Oceans in northern hemisphere. Horizontal circulation has strong influence on methane distribution (Figure 3). So the high concentration values in tropics of the Pacific Ocean are caused by current of western direction from East coast almost up to Western. The advective methane transfer is also appreciable in the Curosio current area.

The similar conclusions can be made from the analysis of dissolved methane on 694m depth (Figure 4), directions of vertical velocity on 472m depth (Figure 5) and horizontal circulation (Figure 6). The highest concentration values (up to 80 conditional units) have been resulted in the Arctic

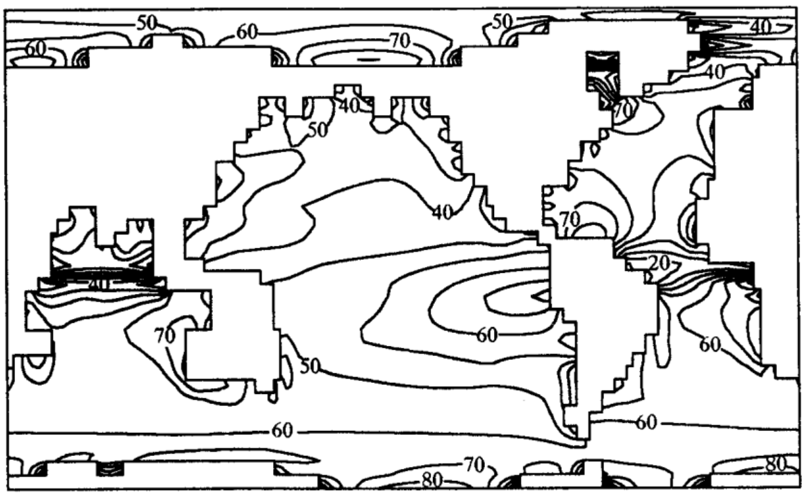

Figure 4. Same as Figure 1, but on depth 694 m

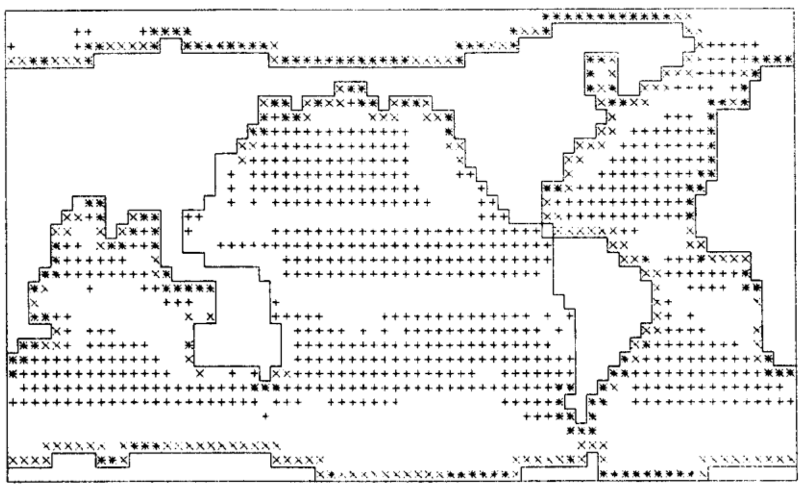

Figure 5. Vertical velocity on depth 472 m, x - methane sources on depth 694 m

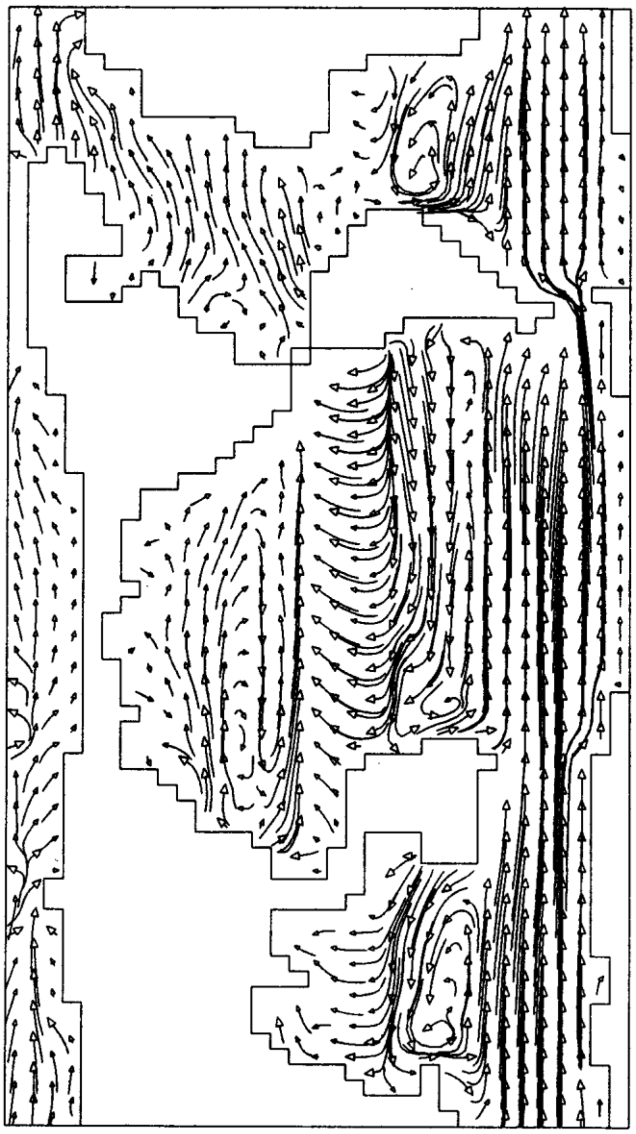

Figure 6. Same as Figure 3, but at the depth 694 m

and Antarctica coastal polar waters as methane sources, here as on this depth and on upper and low depths, were given. That it is seen from the zonal average field in Figure 11 the same concerns all other depths till the seventh (Figure 7).

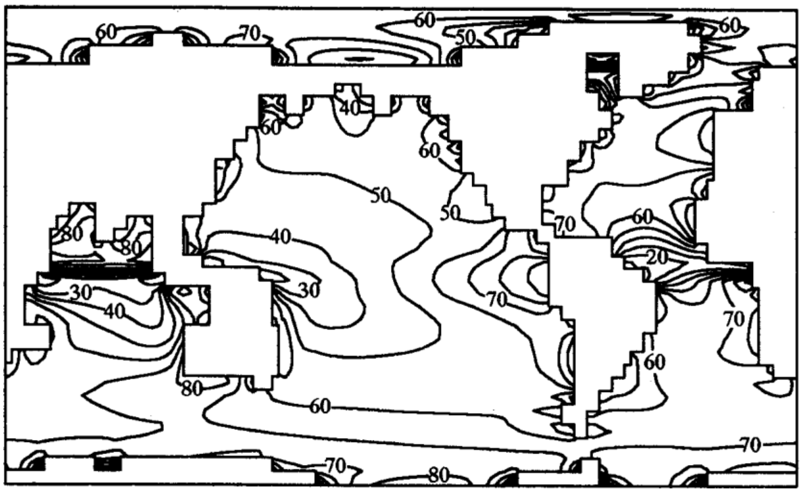

Figure 7. Same as Figure 1, but on depth 3361 m

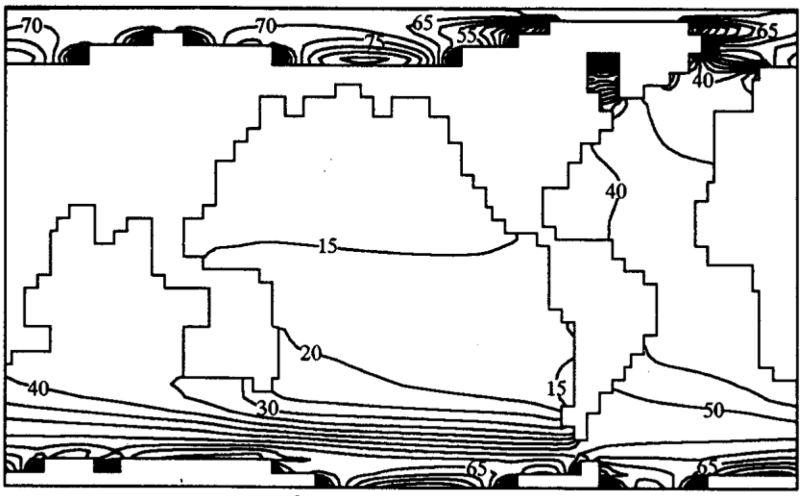

Figure 8. Isolines of dissolved methane in conditional units on depth 3361 m, received in the third experiment

In the next third experiment the sources existence was supposed only in high latitudes of the South and Arctic Oceans, i.e., to the North 62.5°N and to the South 62.5°S. In such conditions the problem was computed on 360 model years. The received horizontal distributions (Figures 8–10) show localization of the highest methane content at the Arctic and South Oceans

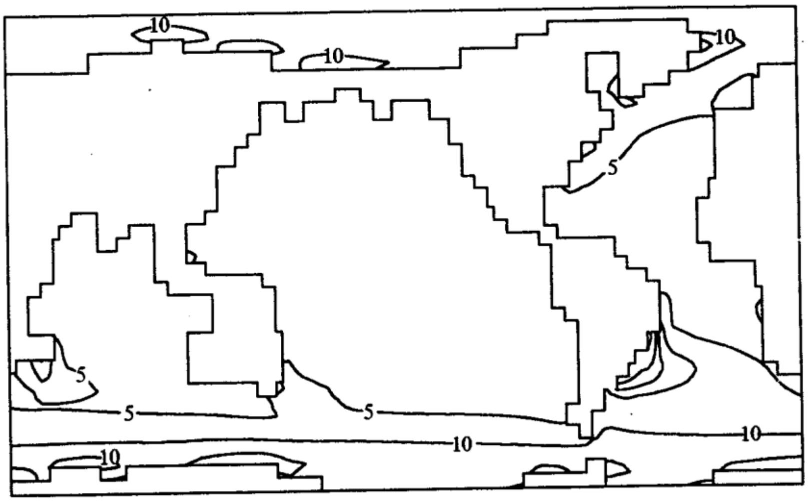

Figure 9. Same as Figure 8, but on depth 28 m

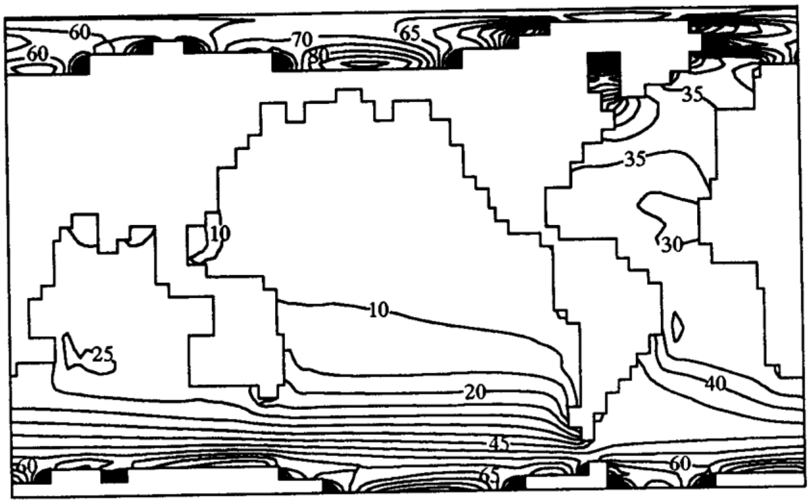

Figure 10. Same as Figure 8, but on depth 694 m

coasts. In the open parts of the oceans the high concetration values turn out on large depths, however their values by an order of magnitude are less, than in second experiment, the average concentrations at calculation levels have decreased in 2 times (see Table 4). Zone averadged fields of dissolved methane (Figures 11–12) show that the sources are located in most part of the Arctic Ocean coast begining with depth 250m and further on all levels till the bottom of the ocean. The quantitative values here, as well as at the Antarctica, are close to the parameters of the second experiment. The gas flux to the atmosphere in this experiment has decreased three times and is equal 5.2 Tg/year.

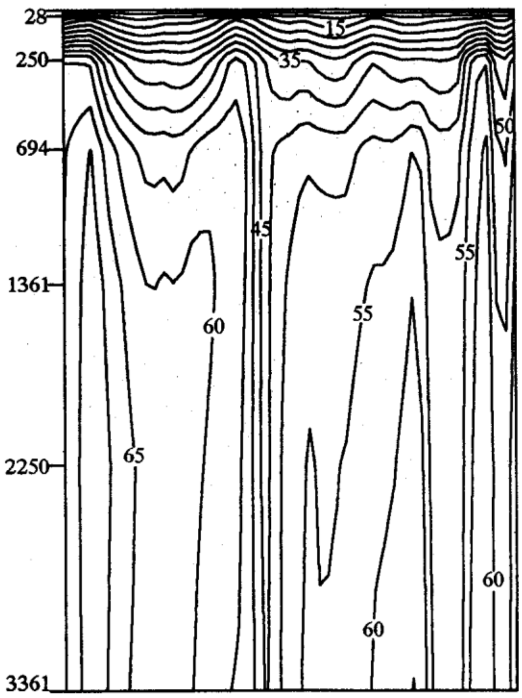

Figure 11. Isolines of zonal averadged dissolved methane on meridianal planes, received in the second experiment

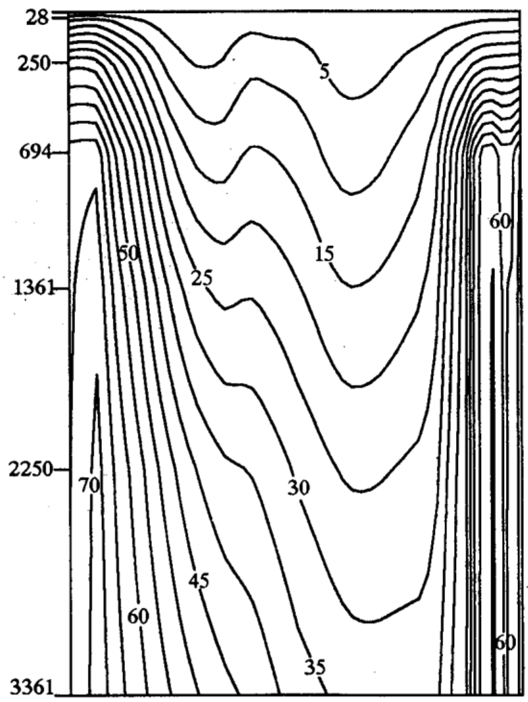

Figure 12. Isolines of zonal averadged dissolved methane on meridianal planes, received in the third experiment

References

[1] United Nation, *Intergovernmental Panel On Climate Change: Policy Makers Summary*, (March 12, 1990).

[2] M.A.K. Khalil and R.A. Rasmussen, *Sources, sinks, and seasonal cycles of atmospheric methane*, J.Geophys.Res.,88 (C9), 5131–5144, 1983.

[3] G.J. MacDonald (Ed), *The long-term impacts of increasing Atmospheric carbon dioxide levels*, Ballinger, Cambridg, Mass., 1982.

[4] K.A. Kvenvolden, *Methane hydrates and global climate*, Global biogeochemical cycles, **2**, No. 3, 1988, 221–229.

[5] R.D. McIver, *Gas hydrates in long-term energy resources*, **1**, edited by R.F.Meyer and J.C. Olson, Pitman, Boston, Mass., 1981, 713–726.

[6] V.M. Dobrynin, V. P. Korotajev and D.V. Plyuschev, *Gas hydrates: a possible energy resource*, 727–729, ibid.

[7] R.A. Rasmussen and M.A.K. Khalil, *Atmospheric methane (CH): Trends and seasonal cycles*, J.Geophys.Res., 86 (C10), 1981, 9826–9832.

[8] D.H. Ehhalt, *The atmospheric cycle of methane*, Tellus, **26**, No. 1–2, 1974, 58–70.

[9] N.M. Bazhin, *Sources and drains atmospheric methane*, Chemistry in interests of steady development, No. 1, 1993, 321–396.

[10] R.J. Cicerone, R.S. Oremland, *Global Biogeochem*, Cycl, 2, 1988.

[11] *Gas Hydrates and Ocean Drilling*, Workshop by K. Kvenvolden and E. Suess. JOADES Journ., **17**, No. 3, 1991, 29–31.

[12] A.V. Scherbakov, *Numerical model of ocean climate*, Mathematical models in ocean dynamics research, Novosibirsk, 1988, 31–47 (in Russian).

[13] A.V. Scherbakov, *Experiments with Numerical Climatic Model of the World Ocean*, Preprint No. 859 Computing Center USSR, Novosibirsk, 1989 (in Russian).

[14] A.V. Scherbakov, *Modeling of methane distribution in the World Ocean*, Works of Computing Center USSR, Novosibirsk, Series Mathematical Modeling in Geophysics, **2**, 1992, 41–58 (in Russian).