Bull. Nov. Comp. Center, Num. Model. in Atmosph., etc., 7 (2001), 17–26

Modeling of methane emission from bog ecosystems*

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In this work, a process-based approach is considered to simulate diurnal and seasonal dynamics of the methane flux in bog ecosystems, based on a parameterization of biological and physical-chemical processes leading to emission of CH_4 to the atmosphere as suggested by Walter and Heimann (1999). A one-dimensional model is used to estimate the methane flux from the Michigan site (42°N, 84°W) and the Tomsk research site (56°N, 85°E). The sensitivity of the model to change the climatic factors (water table level, soil temperature) and model parameters are also studied.

1. Introduction

One of the main sources of atmospheric CH_4 are natural wetlands and waterlogged soils of low and temperate latitudes characterized by their anaerobic conditions, high organic matter content, and large area. Among wetlands ecosystems the most important are peatlands concentrated from 50°N to 70°N. They refer to boreal forests and tundra, contributing about 60% of the global annual emission of CH_4 from total wetlands of the Earth (Aselmann and Crutzen, 1989; Matthews and Fung, 1987).

Although the CH_4 emissions from bog ecosystems are significant in the global balance of carbon, there are uncertainties in estimates of the methane fluxes and their response to global climate change. Biological production of methane and its emission to the atmosphere form the cycling of methane in wetland soils that includes complicated physiological processes of plants and two specific groups of micro-organisms (Zavarzin, 1996). Interaction of these processes with natural environments heterogeneous to soil, hydromorphological and other characteristics results in high variability of CH_4 fluxes, changing at the scale of hours and meters. So, extrapolation of point measurements of fluxes to the regional, global, and seasonal scales cannot yield a reliable estimation of CH_4 emission.

This work considers a process-based model to simulate diurnal and seasonal dynamics of the methane fluxes in wetland soils, based on parameterization of methanogenesis, methanotrophic bacteria oxidation of CH_4,

*Supported by the Russian Foundation for Basic Research under Grants 00-05-65449, 01-05-65420 and by the Leading Scientific Schools Grant 00-15-98543.

and transport mechanisms, as suggested by Walter and Heimann (1999). Modeling of the methane emission is based on the known to a certain degree regulations of production and circulation of CH_4 in peatlands. CH_4 emission to the atmosphere is assumed as the result of complicated interactions of biological and physical-chemical processes, occurring in wetland soils, plant primary production, decomposition of soil organic carbon, the methane production under anaerobic conditions, microbial methane oxidation under aerobic conditions (bacterial biofilter), and the methane transport to the atmosphere proceeded by molecular diffusion, ebullition, and through the stems of vascular plants.

As the result of numerous studies the main climatic and soil-ecology factors controlling these processes have be established:

1) the position of the water table, depending on soil moisture content and relief, and strictly differentiating with the depth of peatland zone of aerobiosis (methane oxidation), anaerobiosis (methanogenesis), and transitional states (Dise et al., 1993; Bartlett and Harris, 1993; Christensen et al., 1995; Efremova et al., 1998);
2) soil temperature affecting the intensity of microbiological processes (Whalen and Reeburg, 1992; Westermann, 1993; Hargreaves and Fowler, 1998);
3) quality of suitable substrates (hydrogen, acetate, and combinations, containing methyl groups (Whiting et al., 1991; Whiting and Chanton, 1992; Valentine et al., 1994);
4) transport mechanisms of the methane emitting to the atmosphere from the places of its production: molecular diffusion, bubble diffusion (ebullition), and transport through the stems of vascular plants (Happell et al., 1993; Schimel, 1995; Shannon et al., 1996).

The comparable analysis between model results and observations from the field stations of North America and Western Siberia showed the capability of the model to calculate CH_4 emission from various wetland types with respect to their temperature and hydrological regimes. The model of the methane emission is used to simulate the methane fluxes from bog ecosystems in the model of biosphere incorporated into the global climatic model.

2. Model of methane emission

The design of a one-dimensional model of the methane emission (schematically presented in Figure 1) focuses on the fact that the specific features of methanogenesis in bog ecosystems are linked with oxic-anoxic zonality in

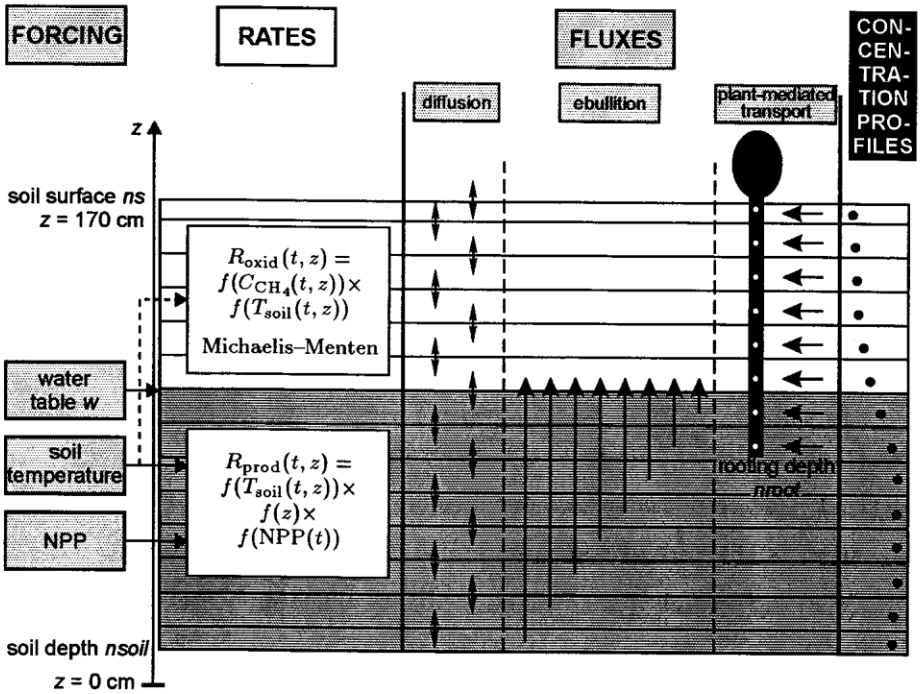

Figure 1. Schematic representation of the methane emission model (from B.P. Walter and M. Heimann, 1999). Outside climatic factors are: $w(t)$ is the water table level, $T_{soil}(t, z)$ is the soil temperature, NPP is the new primary productivity. The water table $w(t)$ can be either below or above the soil surface *ns*. Parameters of peatland are: *nsoil* is the soil depth, *nroot* is the rooting depth. $R_{prod}(t, z)$ is the methane production rate. $R_{oxid}(t, z)$ is the methane oxidation rate. Transport proceeds by (1) molecular diffusion, (2) ebullition, and (3) plant-mediated transport

peatlands: zones of aerobiosis and anaerobiosis are strictly distinguished on the vertical coordinate by the water table level. Biosynthesis of methane occurs below the water table level, the rate of the methane production is assumed to be the function of soil temperature and new primary productivity (NPP). Above the level of the water table methane is oxidized by aerobic methanotrofs, highly specialized bacteria which cannot develop together with anaerobic methanogens. CH_4 oxidation rate is parameterized according to the Michaelis–Menten kinetics. Transport mechanisms emitting methane from anaerobe zone to aerobe one and to the atmosphere are clearly described in the model and present three different processes: 1) molecular diffusion through soil pores, filled with water or air, or through standing water if the water table level is higher than the soil surface; 2) bubble diffusion (ebullition) occurring in the depth of underground soils up to the level of water table; 3) transport through plants and their stems. Outside factors of the model are: the position of water table, soil temperature profile, and NPP.

The methane profile of the peatland with Z depth is described by a one-dimensional continuity equation:

$$\frac{\partial}{\partial t}C_{\mathrm{CH_4}}(t,z) = -\frac{\partial}{\partial z}F_{\mathrm{diff}}(t,z) + Q_{\mathrm{ebull}}(t,z) + Q_{\mathrm{plant}}(t,z) + R_{\mathrm{prod}}(t,z) + R_{\mathrm{oxid}}(t,z), \quad (1)$$

$$\frac{\partial C_{\mathrm{CH_4}}(t,z)}{\partial z} = 0 \quad \text{at} \quad z = 0, \quad (2)$$

$$C_{\mathrm{CH_4}} = C_{\mathrm{atm}} \quad \text{at} \quad z = Z, \quad (3)$$

where

$C_{\mathrm{CH_4}}(t,z)$ is the volume methane concentration ($\mathrm{mol/cm^3}$),

$F_{\mathrm{diff}}(t,z)$ is the diffusive flux of methane through the soil ($\mathrm{mol/s/cm^2}$),

$Q_{\mathrm{ebull}}(t,z)$ is the sink of methane due to ebullition ($\mathrm{mol/s/cm^3}$),

$Q_{\mathrm{plant}}(t,z)$ is the sink due to plant-mediated transport ($\mathrm{mol/s/cm^3}$),

$R_{\mathrm{prod}}(t,z)$ is the methane production rate,

$R_{\mathrm{oxid}}(t,z)$ is the oxidation rate of CH_4,

$C_{\mathrm{atm}}(t,z) = 0.076 \cdot 10^{-6}\ \mathrm{mol/cm^3}$.

Methane production rate R_{prod}. It is assumed that the rate of biochemical CH_4 formation in bog soils is governed by two factors of environment: 1) the presence and quality of a suitable substrate which is directly connected with NPP; 2) soil temperature (Westermann, 1993; Valentine et al., 1994).

Methanogenesis rate is described as follows:

$$R_{\mathrm{prod}}(t,z) = R_0 \cdot f_{\mathrm{org}}(z) \cdot f_{\mathrm{in}}(t) \cdot f(T) \cdot Q_{10}^{(T(t,z)-T_{\mathrm{mean}})/10},$$

where

R_0 is a tuning parameter indirectly including the influence of pH soil,

$f_{\mathrm{org}}(z)$ describes relative changes of substrate availability with depth,

$f_{\mathrm{in}}(t)$ is the variation of substrate availability with time,

$f(T)$ is a step function being 1 if $T(t,z) \geq 0$ and 0 otherwise,

Q_{10} is the rate of the variation of CH_4 flux due to 10°C change of the soil temperature,

T_{mean} is the annual mean soil temperature.

Methane oxidation rate R_{oxid}. The model assumes that R_{oxid} is parameterized according to Michaelis–Menten kinetics:

$$R_{\text{oxid}}(t,z) = -\frac{V_{\max} C_{\text{CH}_4}(t,z)}{K_m + C_{\text{CH}_4}} Q_{10}^{(T(t,z)-T_{\text{mean}})/10},$$

where

$V_{\max}$ is a oxidation potential,

K_m is the Michaelis–Menten coefficient lying in the order of $(1 \div 5) \cdot 10^{-9}$ mol/cm^3.

In the model, the methane oxidation occurs only in non-watered layers of soil. Although, by a certain number of authors, it has been noted that when the level of the water table is above the soil surface methane oxidation is possible. It may occur due to turbulent diffusion when the presence of oxygen in a standing water column makes oxidation reaction possible.

Diffusion F_{diff}. The diffusive flux F_{diff} is calculated using Fick's first law:

$$F_{\text{diff}} = D_{\text{CH}_4}(z)\frac{\partial}{\partial z} C_{\text{CH}_4}(t,z),$$

where D_{CH_4} is the diffusion coefficient (cm^2/s).

Ebullition Q_{ebull}. It is known that as soon as the methane concentration exceeds a certain threshold concentration C_{thresh}, the methane bubbles are formed (Shannon et al., 1991; Chanton et al., 1992). In the model, it is assumed that ebullition occurs if the methane concentration lies in the order of $(500 \div 1000) \cdot 10^{-9}$ mol/cm^3:

$$Q_{\text{ebull}}(t,z) = -k_e \cdot f(C_{\text{CH}_4}) \cdot (C_{\text{CH}_4}(t,z) - C_{\text{thresh}}),$$

where

k_e is a rate constant of the unit 1/h,

$f(C_{\text{CH}_4})$ is a step function being 1 if $C_{\text{CH}_4} \geq C_{\text{thresh}}$ and 0 otherwise.

The ebullient flux $F_{\text{ebull}}(t)$ is obtained by integrating $Q_{\text{ebull}}(t,z)$ over the whole water saturated zone:

$$F_{\text{ebull}}(t) = \int_{\text{nsoil}}^{w(t)} Q_{\text{ebull}}(t,z)\, dz.$$

Plant-mediated transport Q_{plant}. According to the results from numerous studies, the presence of bog vascular plants provides an effective mechanism of the methane transport to the atmosphere (Chanton et al., 1992; Happell et al., 1993; Shannon et al., 1996). The rate $Q_{\text{plant}}(t,z)$ at which methane is removed by plants is parameterized as follows:

$$Q_{\text{plant}}(t,z) = -k_e \cdot T_{\text{veg}} \cdot f_{\text{root}}(z) \cdot f_{\text{grow}}(t) \cdot C_{\text{CH}_4}(t,z) \cdot (1 - P_{\text{ox}}),$$

where

k_p is a rate constant of the unit 0.01/h,

T_{veg} is a parameter depending on the density of plant stands and the plant types and describing the availability of plant-mediated transport at a site,

$f_{\text{root}}(t)$ is the vertical distribution of roots in the soil,

$f_{\text{grow}}(t)$ is a function describing the growing state of the plants,

P_{ox} is a fraction of the methane oxidating in phizosphere.

The methane flux due to plant-mediated transport is calculated from:

$$F_{\text{plant}}(t) = \int_{\text{nroot}}^{\text{ns}} Q_{\text{plant}}(t,z)\,dz.$$

The total methane emission to the atmosphere is calculated by adding all the fluxes from the different transport mechanisms:

$$F_{\text{tot}}(t) = F_{\text{diff}}(t, z = u) + F_{\text{ebull}}(t) + F_{\text{plant}}(t),$$

where u is either the water table $w(t)$ (if $w(t) > ns$) or the soil surface ns. The ebullient flux $F_{\text{ebull}}(t,z)$ contributes only to the total flux, if the water table is at or above the soil surface.

For the model of the methane emission the level of water table is an outside climatic factor. Without having measurements to calculate the profile of water table there has been used the equation based on hydromorphological interactions of water-bogged balance, surface relief, physical properties of peatland obtained by K.E. Ivanov (1957). Together with the equation describing the dependence of peat growing rate from the water table level the given equation presents the evolution of bog relief (Alexandrov et al., 1994):

$$\begin{aligned} &\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\left\{\int_0^h K(f-z)dz\right\}\frac{\partial h}{\partial x}\right) + U, \quad \frac{\partial f}{\partial t} = F(f,h), \\ &h|_{x=a} = h|_{x=-a} = h_0(t), \quad f|_{x=a} = f|_{x=-a} = f_0(t), \\ &h|_{t=0} = h_1(x), \quad f|_{t=0} = f_1(x), \end{aligned} \tag{4}$$

where

f is the height of surface bog,

h is the height of water table,

a is a bog radius,

U is effective rainfall,

K is a vertical coefficient of filtration of water-penetrated layers forming peatland.

It is assumed that $K(f-z) = ke^{-b(f-h)}$, $F(f,h) = F_1(f-h) - \gamma h$, where k, b are parameters obtained from mean values of filtration coefficient of peat for upper bogs, γ is a rate of decomposition of organic matter in a stable aerobiosis zone. The dependence of growing peat from the water table level F_1 can be obtained from the basic model of the joint balance of organic matter and nitrogen (Logofet, 1984). For longer time periods (few dozens of years) the bog surface and the water table level develop a dome like form.

As to such a key climatic factor as soil temperature its profile has been calculated by the one-dimensional model of "air–vegetation–snow–soil" (Volodin and Lykossov, 1996). For the given stage of the study total regional estimates have been used as values of NPP for peatlands in Michigan and West Siberia.

3. Results

Figure 2 shows the methane profile of peat soil obtained by the use of the methane emission model as compared to the measurement data of CH_4 concentrations (Shannon and White, 1994) at one of the stations located in Michigan peatlands. The model was run only during a month period because of the climatic information for that period. Although there is a qualitative agreement between the results and the data, this temporal limit did not allow to compare seasonal structures of the methane profile. Within this monthly period concentrations in the soil were observed higher at the beginning of the month than at the end. If consider magnitudes of fluxes, then a greater fraction of methane emits to the atmosphere by the vegetation, and that the data at the beginning of the month reflect the greater methane concentration in the soil, than that of the modeled. This may be explained that transport mechanism of CH_4 through vegetation reaches too early in time the optimal regime.

The test has been performed on the model sensitivity to the choice of the parameters R_0, $V_{\max}$, T_{veg}, and *nroot*. For the station in Michigan the following values are taken: $R_0 = 0.6$, $V_{\max} = 45$ μ·mol/day, $T_{\text{veg}} = 15$, $nroot = 50$ cm. The change of R_0 influences on the CH_4 emission value: increasing of R_0 leads to greater methane fluxes. The choice of $V_{\max}$ influences on the fluxes when the level of water table is below the soil surface.

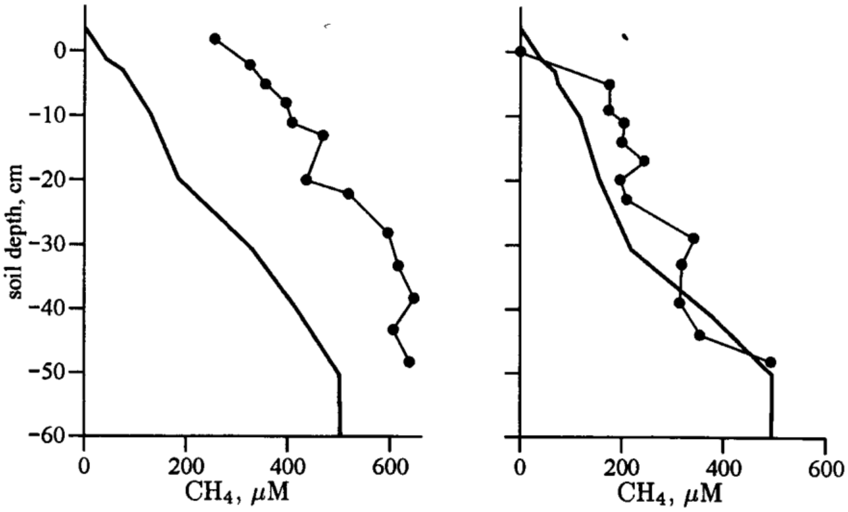

Figure 2. Comparison between modeled (thick line) and observed (full circle) methane concentrations in the soil at the Michigan site (42°N, 84°W) (observational data from Shannon and White, 1994)

The lower values of V_{max} lead to greater CH_4 emission, because in this case the CH_4 oxidation rate decreases. The impact of T_{veg} parameter depends also on the position of water table. If water table is lower than the soil surface, then with lower T_{veg} the fraction of methane transported by molecular diffusion increases. The *nroot* parameter determines vertical distribution of substrate in the soil. In the zone of root system the substrate presence is constant, and then it decreases exponentially. Thus, the greater value of *nroot* leads to the increasing of the methane emission.

Tests on affecting changes in climatic factors found out the following: the degree of the CH_4 emission dependence on soil temperature is connected with the position of water table. When the level of bog waters is higher than the soil surface the impact of temperature dominates. As to transport mechanisms it should be noted that for the Michigan station the main mechanism of the methane transport into the atmosphere is that of the transport through vegetation which is in agreement with observations (Shannon et al., 1996). Its fraction in the total CH_4 flux makes up 80%, further comes bubble diffusion $\sim$ 19.9% and around of 0.1% refers to a molecular diffusion. The total CH_4 flux value was $\sim$ 100 mg/m^2/day, which refers to the lower estimation of fluxes, according to measurements.

The CH_4 estimations have been performed for the oligotroph bogs of the Tomsk station (56°N, 85°E) related to the boreal zone of the West Siberian lowland. Estimations of $\sim 30 \div 35$ mg CH_4/m^2/day turned to be close to measurements performed on the Kirghiz bog, $\sim 0.9 \pm 1.3$ mg/m^2/h (Panikov et al., 1997; Efremova et al., 1998).

4. Conclusions

Comparison of the model results with measurements for over a monthly period (June, 1992) shows the model's ability to simulate the methane profile in the soil and to realistically calculate the CH_4 fluxes into the atmosphere. Sensitivity of the model fluxes to changing of the soil temperature and position of water table is easily satisfied. The model has been tested only on the two sites representing different nature conditions, the results encourage. Further studies and data sets are necessary to improve the model and test it more thoroughly with a data set consisting not only of time series of the input and the output data of the model but the methane production rate, the methane oxidation rate, and the fraction of methane transported by the different transport mechanisms.

Acknowledgements. We would like to thank V. Lykossov for the given code of the "air–vegetation–snow–soil" model.

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