

# Model Diagnostics of Variations in Methane Emissions by Wetlands in the Second Half of the 20th Century Based on Reanalysis Data

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This work is dedicated to model assessments of variations in methane emissions into the atmosphere by terrestrial ecosystems for different regions and the Earth as a whole based on variations in the near-surface temperature of the atmosphere and precipitation derived from the reanalysis data for the second half of the 20th century. The statistically significant general trend of increase in methane fluxes from bog systems into the atmosphere under global warming is diagnosed.

Recently, interactive blocks of the carbon cycle have been introduced into global 3D climatic models that are used for assessing natural and anthropogenic environmental variations [1] (see also [2–4]). These works revealed the positive feedback between the climate and the carbon cycle. Such an approach leads to additional increase in the content of carbon dioxide in the atmosphere as compared with the assessments without regard for the influence of climatic variations on fluxes between the atmosphere and the underlying surface.

In addition to carbon dioxide exchange, methane exchange provided largely by bogs/swamps [5–7] should also be taken into consideration in the carbon cycle block in global climatic models. Variations in the methane cycle and bog regime during climatic variations may result in significant regional and global consequences. For example, the effect of the so-called “methane bomb” related to the discharge of large volumes of this greenhouse gas into the atmosphere due to global warming and degradation of permafrost seems to be potentially significant. Approximately two thirds of the Russian territory is occupied by permafrost. Additional increase in methane emission into the atmosphere can also be provided by intense gas and oil production.

Methane is a greenhouse gas, third in significance after water vapor and carbon dioxide with respect to its integral radiation impact on the present-day climatic system. Moreover, in terms of radiation calculated per one molecule, methane is 20 times more efficient than carbon dioxide. Taking into consideration the characteristic lifetime of molecules of greenhouse gases in the atmosphere, the so-called global warming potential of methane over a period of 20 yr is more than 60 times higher than that of carbon dioxide. With increasing the time interval, this ratio decreases: slightly higher than 20 for a period of 100 yr and less than 10 for a period of 500 yr [8].

It should be noted that the available estimates of global methane emission vary in wide limits [8–11].

In [12], probable variations in the methane emission by boreal ecosystems of northern Eurasia were estimated based on reconstructions of increase in the global near-surface temperature approximately by 1 K for the climatic optimum of the Holocene (approximately 6 ka ago), by 2 K for the optimum of the Mikulino Interglacial (approximately 125 ka ago), and by 1K in the initial 21st century. In the last case, the emission appeared to increase by a quarter. Moreover, the authors noted that a decrease in methane emission by natural ecosystems of northern Eurasia should be expected in the case of further warming. The decrease in methane emissions by boreal ecosystems of these regions in warmer periods of 6 and 125 ka ago is explained by soil desiccation.

For diagnostics of variations in methane emissions by wetlands, we used a model block of the methane cycle based on the algorithm from [13]. When assessing methane fluxes related to ecosystems in permafrost environments, we took into consideration the fact that methane emission depends largely on the soil temperature, its moisture, and defrosting depth [14], although it is influenced, for example, in the tundra, by many other

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interrelated factors. In the proposed model, the complete methane flux  $F_{\text{CH}_4}$  is as follows:

$$F_{\text{CH}_4} = \sum_{i=1}^N \Theta(T_i) [2f_i - 1] P_i \Delta z_i q(T_i),$$

where  $T_i$  is temperature ( $^{\circ}\text{C}$ ) of the  $i$ -layer,  $\Delta z_i$ ,  $f_i$  is its relative moisture (the share from the maximal moisture content under saturation),  $N$  is the complete number of soil layers,  $\Theta(T_i)$  is the Heaviside function (1 at  $T_i > 0^{\circ}\text{C}$  and 0 at  $T_i \leq 0^{\circ}\text{C}$ ),  $P_i$  is the methane production by  $i$ -layer, and  $q(T_i) = Q^{(T_i - 2)/T_0}$ . According to [13],  $Q = 2$ ,  $T_0 = 10^{\circ}\text{C}$ . It should be noted that we did not take into account the dependence of methane fluxes on the substrate quantity. In the proposed model, productivity ( $P_i$ ) depends linearly on the integral of positive temperature values  $T_{\Sigma}$  in  $^{\circ}\text{C}$  (degree-days):

$$P_i = \alpha_i + \beta_i T_{\Sigma}.$$

The methane flux from the surface of bogs/swamps related to thawing depends on the seasonal thaw depth in the permafrost. The model from [14] was used for its calculation. This model represents a generalized solution of Stephan's problem with the annual temperature variations at the lower boundary of the atmosphere and account for the influence of snow and moss covers. In contrast to the standard version of Stephan's problem, the above model is applicable both in permafrost regions and areas with seasonal soil freezing. The depth of seasonal thaw/freeze depends on the annual variation of the near-surface temperature and precipitation. The influence of the effect of snow metamorphism was ignored. The seasonal thaw depth was assessed based on the thickness of the active layer and temperature of the soil surface. Only soil layers to a certain limit depth were included in the calculations. In the last model of the standard version, the depths of 15 and 60 cm were accepted for tropical and extratropical zones, respectively. Similar depth values are obtained for the organic carbon content in soil at the characteristic peat density of  $200 \text{ kg/m}^3$  based on data from <http://soils.usda.gov/use/worldsoils/mapindex/soc.html>. Deeper layers were ignored in calculations of methane emissions by wetlands.

In model calculations of methane fluxes and their variations, we used annual mean data of the ERA-40 reanalysis [15] for the near-surface temperature and precipitation in 1958–2000 with a resolution of  $2.5^{\circ}$  along the latitude and longitude. In the standard version of the model, methane fluxes were calculated based on the following parameters:  $\alpha_i = 42.5 \text{ mg CH}_4 \cdot \text{m}^{-3} \cdot \text{day}^{-1} \cdot ^{\circ}\text{C}^{-1}$  and  $\beta_i = 0.0375 \text{ mg CH}_4 \cdot \text{m}^{-3} \cdot \text{day}^{-1} \cdot ^{\circ}\text{C}^{-1}$ . The bog depth was accepted as 0.6 m.

At these parameters, the proposed model reproduces relatively well the available values of methane fluxes.

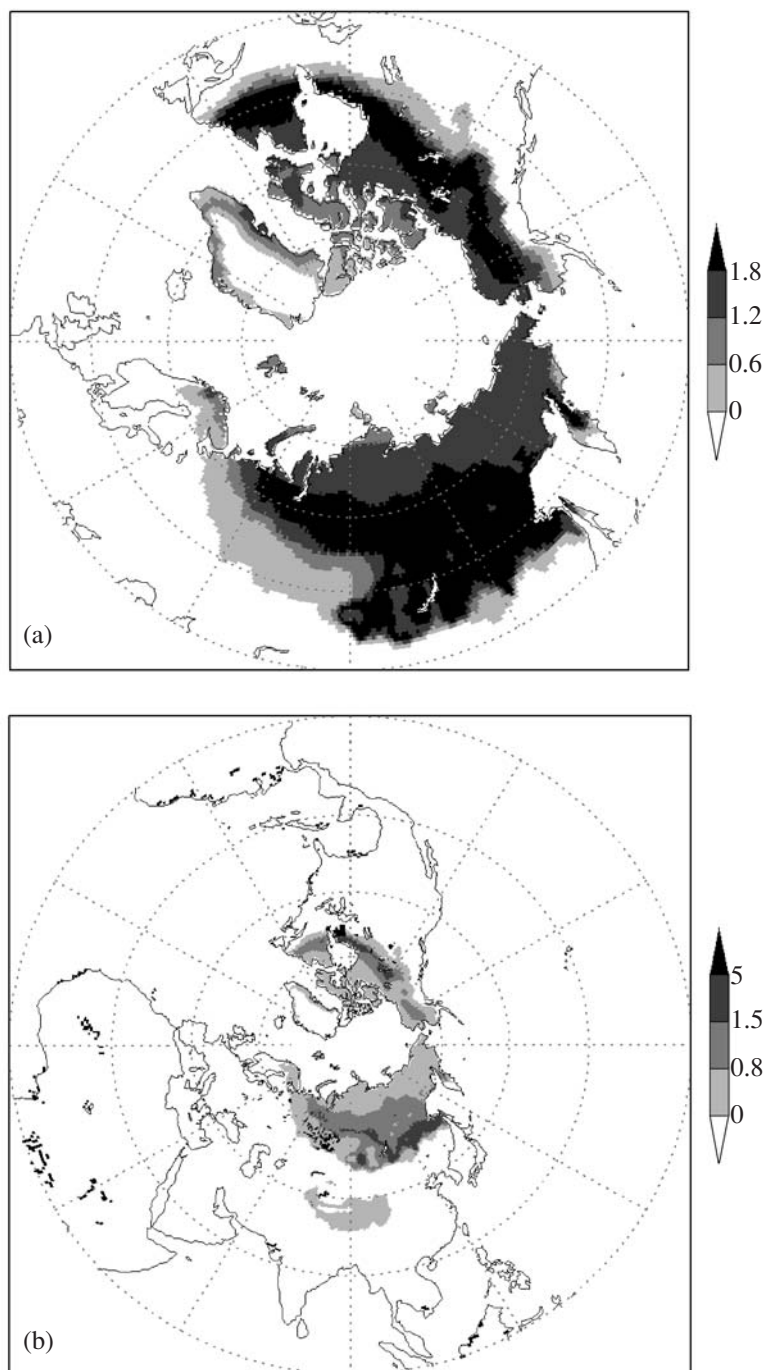
Figure 1 presents spatial distributions of the calculated depth of seasonal thaw (a) and annual mean methane fluxes (b) in the Northern Hemisphere for the period of 1958–2000. It should be noted that the decisive contribution is provided by relatively small bogs/swamps in low (tropical) latitudes.

In the used version of the model based on data of reanalysis for the period of 1958–2000, the average value of global intensity of methane emissions by wetlands is  $143 \text{ Mt CH}_4/\text{yr}$ . Similar estimates were reported in [9, 10]:  $145 \pm 30$  and  $145 \pm 41 \text{ Mt CH}_4/\text{yr}$ , respectively. Our estimates of the methane flux are higher for extratropical latitudes ( $28 \text{ Mt CH}_4/\text{yr}$ ) and lower for tropical latitudes ( $115 \text{ Mt CH}_4/\text{yr}$ ) than in [10] ( $29$ – $69$  and  $65$ – $117 \text{ Mt CH}_4/\text{yr}$ , respectively).

Figure 2a illustrates calculated annual variations in global methane emission by wetlands for the period of 1958–2000. Figure 2b presents the correlation between global methane fluxes and variations in the global near-surface temperature of the atmosphere. According to Fig. 2a, the integral methane emission has increased since the mid-1970s and had decreased prior to this period since the 1950s. These variations in global fluxes are largely induced by tropical bogs/swamps. In extratropical latitudes, the integral methane flux increased during the period of 1958–2000. Figure 2c presents variations in the methane flux normalized to corresponding average values for the period of 1958–2000, for the Earth as a whole and for its tropical and extratropical latitudes. It is seen that the global methane flux changed annually by no more than 6% in the second half of the 20th century. Moreover, relative anomalies of the methane flux in extratropical latitudes are notably stronger: approximately up to 10% or more.

Based on the linear regression (straight line in Fig. 2b), we estimated the sensitivity coefficient of the global methane flux to variations in the global near-surface temperature:  $9.9(\pm 2.5) \text{ Mt CH}_4/\text{K}$  or  $7\%/K$  at the correlation coefficient  $r = 0.53$  (the standard deviation of the regression coefficient is given in parentheses). The sensitivity coefficient of the methane emission to variations in the global near-surface temperature for low latitudes ( $30^{\circ} \text{N}$ – $30^{\circ} \text{S}$ ) is slightly higher ( $10.3(\pm 2.3) \text{ Mt CH}_4/\text{K}$  or  $9\%/K$  at  $r = 0.58$ ). A less significant trend is obtained for the growth of methane flux with the increase of the near-surface temperature in extratropical latitudes:  $1.5(\pm 0.7) \text{ Mt CH}_4/\text{K}$  or  $5.5\%/K$  at  $r = 0.58$  for the belt of  $30^{\circ}$ – $90^{\circ}$  in the Northern Hemisphere.

We also estimated the sensitivity of the methane flux to variations in different model parameters. For example, under conditions of the nearly linear dependence of methane emission on the effective depth of bogs/swamps, doubling of the depth results in doubling of the fluxes. The analysis of the spatial distribution of differences between methane fluxes in the 1990s and 1960s revealed regional variations up to 20% or more, for example, for West Siberia. It appeared that the region incorporates areas with both positive and nega-

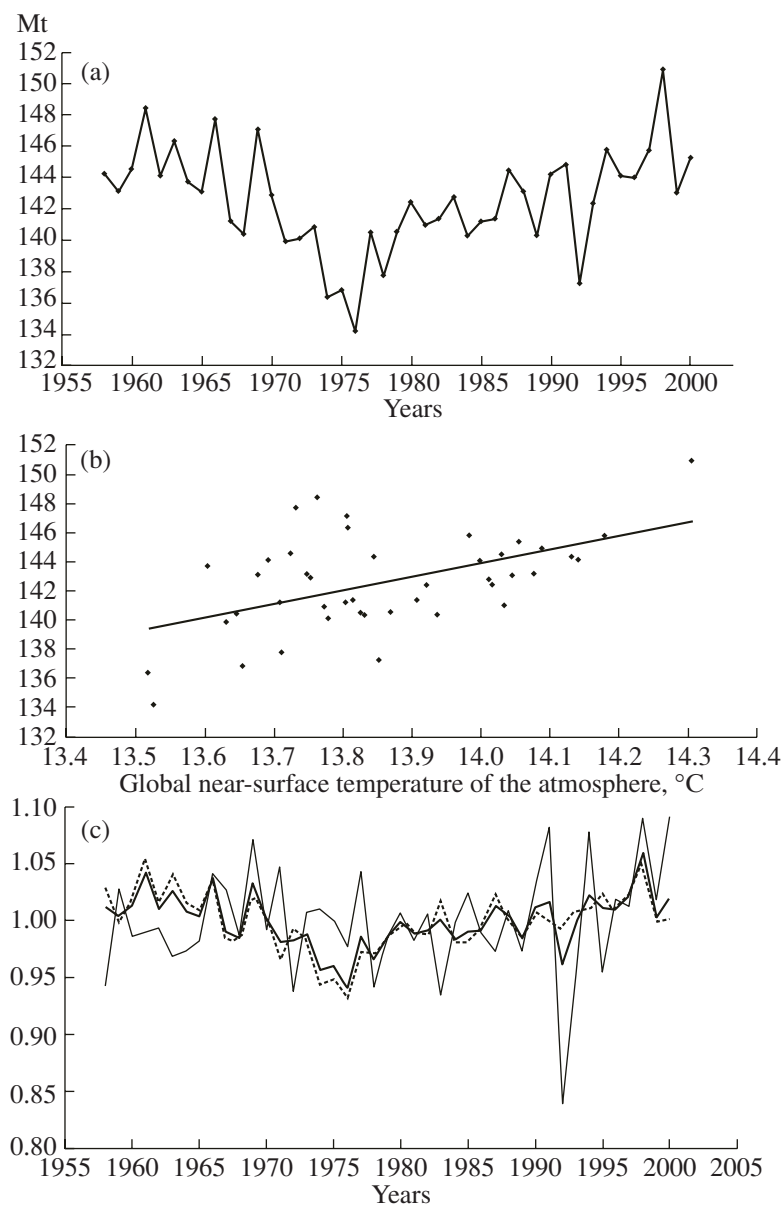


**Fig. 1.** Distributions of calculated seasonal defrosting depths (m) (a) and annual methane fluxes ( $\text{g} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ ) (b) in the Northern Hemisphere for the period of 1958–2000.

tive variations. The decrease in methane fluxes is explained by the corresponding variations in defrosting depths.

In the case of further global warming, we can expect a general increase in methane fluxes into the atmosphere from terrestrial ecosystems due to the dependence of these fluxes on the temperature and prolongation of frost-free periods. Moreover, regional

trends of variations in methane fluxes depend on regional variations in the hydrological regime. Increase in precipitation due to increase in soil humidity should intensify the temperature effect, while desiccation of soils and reduction of bogs/swamps should decrease methane emission by wetlands. Our estimate of the global increase in methane emission by 7% in the case of warming by 1 K is consistent with estimates in [12].



**Fig. 2.** The global methane flux (Mt) correlated with time (a) and global near-surface temperature of the atmosphere ( $^{\circ}\text{C}$ ) (b) and normalized (to corresponding annual values for the entire period) methane flux values for the entire Earth (solid curve) for tropical (dashed line) and extratropical (thin line) latitudes (c) calculated for the second half of the 20th century using the reanalysis data.

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