

Potential feedback of thawing permafrost to the global climate system through methane emission

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Received 29 May 2007

Accepted for publication 24 September 2007

Published 26 November 2007

Online at stacks.iop.org/ERL/2/045016

Abstract

Large amounts of soil carbon deposited in permafrost may be released due to deeper seasonal thawing under the climatic conditions projected for the future. An increase in the volume of the available organic material together with the higher ground temperatures may lead to enhanced emission of greenhouse gasses. Particular concerns are associated with methane, which has a much stronger greenhouse effect than an equal amount of CO₂. Production of methane is favored in the wetlands, which occupy up to 0.7 million km² in Russian permafrost regions and have accumulated about 50 Gt of carbon (Gt C). We used the permafrost model and several climatic scenarios to construct projections of the soil temperature and the depth of seasonal thawing. To evaluate the effect of such changes on the volume of the seasonally thawing organic material, we overlaid the permafrost projections on the digitized geographically referenced contours of 59 846 wetlands in the Russian Arctic. Results for the mid-21st century climate indicated up to 50% increase in the volume of organic substrate in the northernmost locations along the Arctic coast and in East Siberia, where wetlands are sparse, and a relatively small increase by 10%–15% in West Siberia, where wetlands occupy 50%–80% of the land. We developed a soil carbon model and used it to estimate the changes in the methane fluxes due to higher soil temperature and increased substrate availability. According to our results, by mid-21st century the annual net flux of methane from Russian permafrost regions may increase by 6–8 Mt, depending on climatic scenario. If other sinks and sources of methane remain unchanged, this may increase the overall content of methane in the atmosphere by approximately 100 Mt, or 0.04 ppm, and lead to 0.012 °C global temperature rise.

Keywords: climate change, permafrost, wetlands, methane, modelling

1. Introduction

Permafrost underlies about 25% of land in the northern hemisphere (Zhang *et al* 2000) and there is growing evidence that its distribution and properties will be changed in response to climatic warming. Serious concerns are associated with the potential impact that thawing permafrost may have on the global climate system through release of greenhouse gases (Friborg *et al* 2003, Christensen *et al* 2004).

Arctic soils contain approximately 455 Gt C, or 14% of the global soil carbon, of which about 50 Gt C are accumulated

in the Arctic wetlands (Anisimov and Reneva 2006). Several recent studies indicated high spatial variability with near-zero balance between the sink (photosynthetic uptake) and source (release due to soil decomposition) of carbon in the entire Arctic (Callaghan *et al* 2005, Chapin *et al* 2005, Corradi *et al* 2005). The carbon turnover in the Arctic is projected to increase under the warmer climate; however, the timing of the processes that determine the status of the Arctic as net sink or source is different. Increased trace gas emissions due to soil warming is likely to be the short-term response to climate change. In the longer-term warmer climate,

more protracted growing periods and northward movement of productive vegetation may increase photosynthetic carbon uptake. This letter is focused on the potential changes in the emission component of the carbon turnover in the Arctic.

The effect that the increase in the rate of soil carbon decomposition in the next few decades may have on the radiative forcing depends on the balance between the amounts of carbon emitted as CO₂ and CH₄. Methane has more than 20 times stronger greenhouse effect than an equal amount of CO₂. A few ecosystems in the Arctic, including wetlands, convert part of carbon that has been photosynthetically captured from the atmosphere as CO₂ to methane, which is further released as the product of organic soil decomposition. Because of this, even the areas and ecosystems that have net C-sink status, such as tundra, may enhance the global radiative forcing if a sufficient fraction of carbon is emitted as CH₄ (Callaghan *et al* 2005, Friborg *et al* 2003).

Methane in the Arctic soils is produced by bacteria in the anaerobic zone of the active layer (the uppermost layer of permafrost affected by seasonal thawing) underneath the water table. It is then transported to the atmosphere by bubble emission and diffusion through water as well as through the vascular system of plants. Observations indicate that bubble emission may account for 18–50% of the total emission. Up to 80% of methane that is produced in the anaerobic zone is further oxidized in the upper soil layer before it gets to the atmosphere. According to the observations, the resulting carbon emissions as methane from wet and moist tundra ecosystems are about 5% of emissions as CO₂. This fraction may be much larger in wetlands where the high water table favors the production of methane. Direct measurements of the CO₂ and methane exchange show that under current climatic conditions northern wetlands, on average, act as net sinks of carbon of 0.5 g C m⁻² day⁻¹ but large net sources of methane (Friborg *et al* 2003).

Organic materials that are deposited in the Arctic wetlands below the depth of seasonal thawing are currently not involved in the carbon cycle and may become available under warmer climatic conditions. Observations indicate that methane emissions in northern mires and peatlands are responsive to climatic variations. A detailed study of one mire shows that the climatic warming, deeper permafrost thawing and subsequent vegetation changes have been associated with increases in landscape scale methane emissions in the range of 22–66% over the period 1970–2000 (Christensen *et al* 2004). Observations in Northern Sweden indicate that the temperature and microbial substrate availability combined explain almost 100% of the variations in mean annual methane emissions (Christensen *et al* 2003a, 2003b).

In this study we used the permafrost model forced by several climatic scenarios to construct the projections of the ground temperature and depth of seasonal thawing in Northern Eurasia. These data have been used further in the soil carbon model to calculate the potential increase in CH₄ emissions. We used the results of such predictive calculations to evaluate the feedback to the global system from Eurasian permafrost regions and the effect it may have on global temperature.

2. Models, data, and computational approach

We developed a permafrost model that allows calculation of the seasonal thaw depth (active-layer thickness), and the annual mean soil temperature at the surface and at the level of seasonal thawing. The model is based on a simplified approximate solution of the conductive heat transfer equation in a medium with water phase changes. It has low data requirements and uses two climatic parameters, mean monthly air temperature and precipitation, however together with a few other parameters accounting for the effects and properties of snow cover, vegetation, and soil. The mathematical formalism has been detailed in several preceding publications, i.e. Anisimov *et al* (2007, 1997), Sazonova and Romanovsky (2003). All calculations were made in the nodes of a 0.5° lat/long grid spanning the Northern Eurasian permafrost region.

The model was forced by contemporary climatic data and by those projected for the future. Several global and continental scale data sets of major atmospheric parameters (e.g., air temperature and precipitation) have been developed over the last three decades (Mitchell and Jones 2005, Serreze and Hurst 2000, Kallberg *et al* 2004, Matsuura and Willmott 2005). These resources use different input data (e.g., station observations, remote sensing products, and climate model simulations) and have been made available to the scientific community. We used gridded monthly norms of air temperature and precipitation with 0.5° lat/long resolution as baseline data characterizing the modern climate (New *et al* 1999). A set of five scenarios of climate change for the 11-year long time periods centred on 2030, 2050, and 2080 has been constructed by superimposing predictions by CGCM2, CSM_1.4, ECHAM4/OPYC3, GFDL-R30_c and HadCM3 GCMs changes of climatic parameters on baseline data. These GCMs were selected as a result of the survey made in the course of the ACIA (Arctic climate impact assessment) because they account for many key processes in the Arctic and provide a reasonable fit to the observed climatic trends (Symon *et al* 2005). All climate models were forced by the B2 emission scenario. The climatic scenarios are fully documented in the ACIA report and are available on the web sites of the data distribution center of the Intergovernmental Panel on Climate Change (IPCC; <http://ipcc-ddc.cru.uea.ac.uk/> and <http://igloo.atmos.uiuc.edu/IPCC/>).

Soil thermal properties were calculated using parameterizations that take into account soil type, soil moisture and ground ice content. We calculated winter-average snow depth at each node using monthly precipitation data. The density, thermal conductivity, and heat capacity of snow were prescribed at 300 kg m⁻³, 0.23 W m⁻¹ K⁻¹ and 2090 J kg⁻¹ K⁻¹, respectively. Vegetation types with prescribed thermal properties and soil type were obtained from the digital global ecosystems database (1992). The model was validated by the data from the Circumpolar Active Layer Monitoring program (Brown *et al* 2000) and used to calculate permafrost parameters under current and projected climatic conditions. The ultimate goal of such calculations was to evaluate the changes in the volume of organic material that will additionally become available due to deeper seasonal thawing of permafrost.

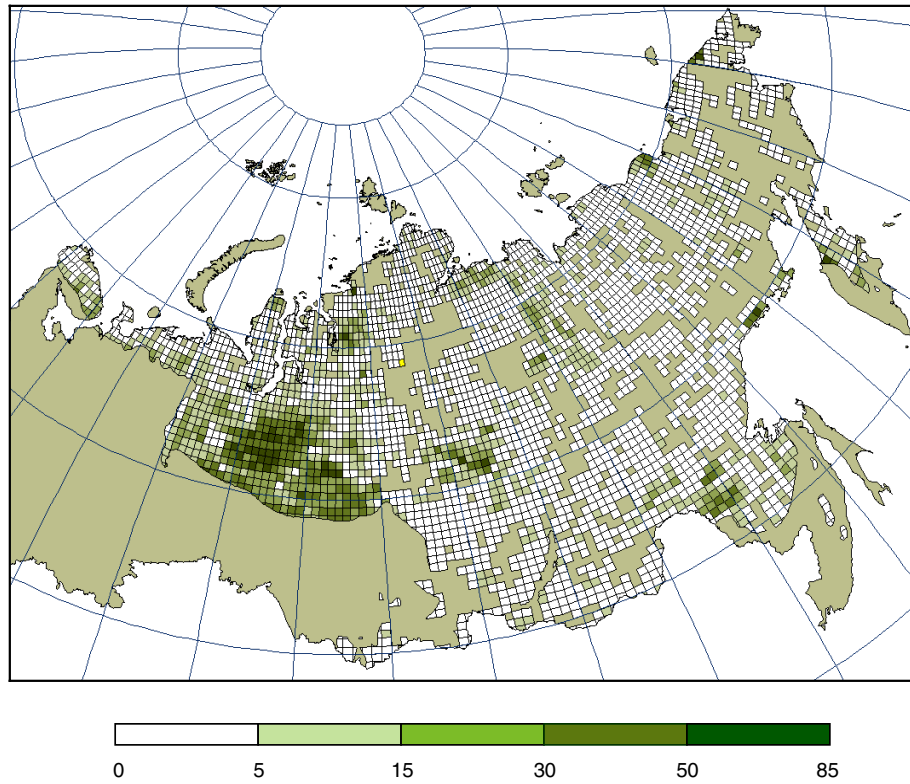


Figure 1. Fraction of land area occupied by wetlands in Russian permafrost region.

In the Arctic soils the uppermost organic layer is relatively shallow (typically 10–20 cm) and is subject to complete thawing every season. The projected thickening of the active layer will thus mostly affect the lower mineral soil and will not lead to any noticeable increase in the amount of the organic-rich substrate for methanogenic microbial activity. The main factor governing the greenhouse gas emissions in such regions will be the changing soil temperature. However, this is not the case in the Arctic wetlands, where peat deposits extend far below the depth of seasonal thaw propagation. The future methane emissions here will be governed by both the changing soil temperature and the increased availability of microbial substrate.

We used a two-step procedure to calculate the changes in the volume of seasonally thawing organic substrate under the projected climatic conditions. Firstly, we calculated the temperature and seasonal thaw depth of peat in Russian permafrost regions for the selected climatic scenarios and time slices. In these calculations the soil parameters in the permafrost model were expressed through soil moisture using empirical equations that were derived using an analysis of our field data for the wetlands in West Siberia:

$$\begin{aligned}
 \lambda_f &= 0.08 \exp(3.88w_f), \\
 \lambda_{th} &= (615 \times w_{th} + 22.2) \times 10^{-3}; \\
 C_{v,f} &= C_d \times \rho + 2090 \times w_f, \\
 C_{v,th} &= C_d \times \rho + 4180 \times w_{th}.
 \end{aligned}
 \tag{1}$$

In these equations subscripts ‘f’ and ‘th’ designate parameters of the frozen and thawed soils, respectively; λ is the soil thermal conductivity, $W m^{-1} K^{-1}$; w the volumetric soil moisture/soil ice content; C_v the volumetric heat capacity, $J m^{-3} K^{-1}$; C_d the dry soil heat capacity, $J kg^{-1} K^{-1}$; and ρ the dry soil density, $kg m^{-3}$. Peat dry density and heat capacity were prescribed at $200 kg m^{-3}$, and $220 J kg^{-1} K^{-1}$, respectively. In various calculations soil moisture/soil ice content was set to 0.6 and 0.8. Such a setup corresponds to the hypothetical situation when the entire Russian permafrost is occupied by wetlands.

Several studies based on different methods that include field surveying, analysis of large-scale topographic maps, aero photography, and satellite remote sensing concluded that wetlands occupy 0.35–0.7 million km^2 in the Russian permafrost regions. A review of results by various authors is given in the paper by Anisimov and Reneva (2006). In West Siberia wetlands are widespread over 50%–80% of land, and they occupy a much smaller fraction in other permafrost regions. In this study we explicitly took into account the distribution, size, and location of wetlands. To accomplish this task we digitized 1000 000 scale topographic maps and developed a database containing geographically referenced contours of 59 846 wetlands in Russian permafrost regions. We used these data to construct the wetland mask that indicates the fraction of land area they occupy in each node of the grid with 0.5° lat/long resolution spanning the Russian permafrost region (figure 1).

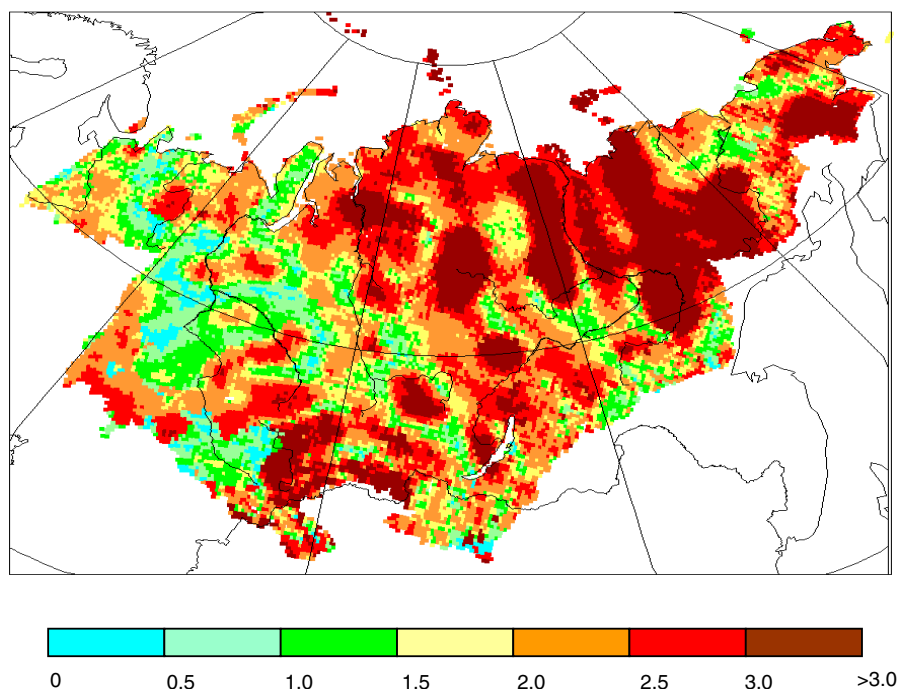


Figure 2. Projected changes in the soil temperature averaged over the warm period. GFDL climatic scenario for 2050.

We overlaid the wetland mask on the map with projected changes in the seasonal thaw depth to evaluate the volume of organic material that may become available as substrate for microbial activity. These data together with the projected soil temperature have been used in the carbon model to estimate the changes in the methane emissions.

The dynamic model of soil carbon has been detailed in several previous publications (Anisimov *et al* 2005a, 2005b). It is based on a system of four differential equations that describe the emission of methane as a function of production and oxidation rates, and intensity of three transport mechanisms by the bubble emission, diffusion through water, and transport through the vascular system of plants. The model contains several empirical parameters and was validated using data from observations.

We used the results of numerous calculations with the full-scale carbon model simulating a large variety of soil and temperature conditions to derive a simple parameterization that links the relative changes of methane flux with soil temperature and active layer thickness:

$$J_2/J_1 = \exp 0.1(T_2 - T_1)\sqrt{H_{d2}/H_{d1}}. \quad (2)$$

Here J is the methane flux, T the ground temperature averaged over the warm period, and H_d the active-layer thickness; subscripts 1 and 2 designate the current and the future time slices.

3. Results and discussion

Results from the permafrost model indicate that the projections of the soil temperature and depth of seasonal thawing differ

in regional details depending on climatic scenarios. For any given scenario the changes are not uniform either in space or in time. The scenarios are in general agreement, predicting 10%–15% increase in the depth of seasonal thawing over most of the permafrost area by 2025, 15%–25% increase by the middle of the century, and 30% and more by 2080. This is consistent with the conclusions of the previous studies (Anisimov and Belolutskaia 2004, Sazonova *et al* 2004, Walsh *et al* 2005). An important feature in the pattern of seasonal thawing traceable over the whole century-scale period is the larger increase in the active-layer thickness in the northernmost locations along the Arctic coast and in East Siberia where wetlands are sparse, and moderate increase in West Siberia where wetlands are widespread.

The maps in figures 2 and 3 show the projected changes in the soil surface temperature averaged over the warm period and changes in the seasonal thaw depth for peat under the ‘median’ GFDL scenario for 2050.

The differences between the climatic scenarios are also apparent in the large-scale parameters, such as the total volume of the seasonally thawing peat over the entire permafrost region (table 1). Additional uncertainty is associated with the soil moisture content, which is largely governed by the position of the water table.

The estimated annual net flux of methane from the Russian northern wetlands is 24–33 Mt, of which 22.2 Mt come from West Siberia. As follows from our results on carbon modeling, by the mid-21st century it may increase by 25%, or by 6–8 Mt year⁻¹. This estimate was obtained through overlay of the wetland mask on the projections of the active-layer thickness and the soil temperatures, and thus takes into

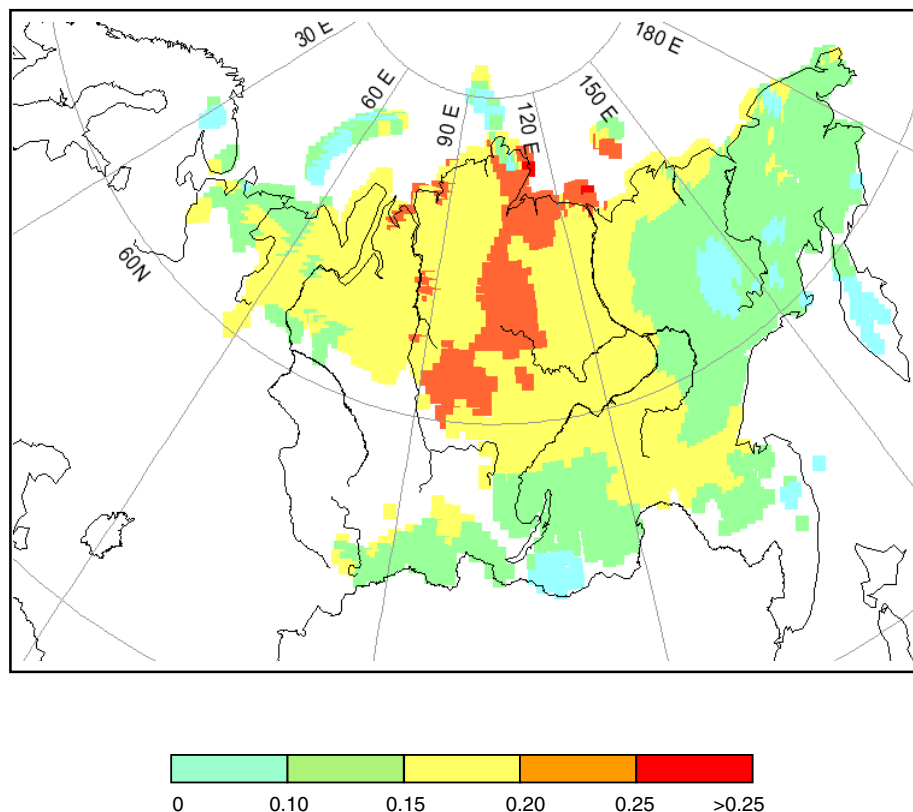


Figure 3. Projected changes in the depth of seasonal thawing for peat, in units of m. Calculations were made for soil moisture content 0.8 m/m. GFDL climatic scenario for 2050.

Table 1. Projected changes in the volume of the seasonally thawing peat in Russian permafrost regions under the CGCM2, GFDL-R30 and ECHAM4 climatic scenarios for 2025, 2050, and 2080 in units of km³. Calculations were made for the volumetric soil moisture content prescribed to 0.6 m/m and 0.8 m/m (upper and lower numbers in the table, respectively).

	2025	2050	2080
CGCM2	61.0/68.5	80.5/88.5	92.5/99.0
GFDL-R30	81.0/91.0	138.0/150.5	154.0/173.0
ECHAM4	147.5/162.0	229.0/249.0	274.5/289.0

account the spatial distribution of wetlands. The projected increase is compatible with the current annual net source of about 20 Mt resulting from the balance between the much larger global source (about 550 Mt) and sink (about 530 Mt) of methane.

The average residence time of methane in the atmosphere is 12 years (Prather and Ehhalt 2001). If other sinks

and sources remain unchanged, by the mid-21st century the additional annual 6–8 Mt source due to thawing of permafrost may increase the overall amount of atmospheric methane by approximately 100 Mt, or 0.04 ppm. Given that the sensitivity of the global temperature to 1 ppm of atmospheric methane is approximately 0.3 °C (Ramaswamy 2001), additional radiative forcing resulting from such an increase may raise the global mean annual air temperature by 0.012 °C. This result indicates that many of the recent publications, both scientific and in the mass media, overstress the concerns associated with thawing wetlands in Russian permafrost regions and the effect it may have on global climate system.

This estimate has been obtained under the assumption that the soil hydrological regime, and particularly the water table in the Arctic wetlands, will not be changed. Drying or wetting of tundra is concurrent with warming and may have a significant effect on greenhouse emission and radiative forcing. Better drainage conditions and enhanced evapotranspiration under

Table 2. Sensitivity of methane emissions to variations of the climatic, hydrological, and soil parameters.

Changes in CH ₄ emission	Changes in climate parameters	Source
Global, ±20%	Uniform ±1 °C temperature change	Walter <i>et al</i> (2001)
Global, ±8%	Uniform ±20% precipitation change	
60°–90° N zone, +19%	Uniform +2 °C temperature change	Cao <i>et al</i> (1998)
60°–90° N zone, +21%	Uniform +2 °C temperature and +10% precipitation change	
60°–90° N zone, +38%	+10 cm thaw depth	Zhuang <i>et al</i> (2004)
60°–90° N zone, 0 to +25%	+10 cm water table rise	Walter <i>et al</i> (2001)

warmer climate may lower the water table and improve soil ventilation, ultimately shifting the currently existing balance in favor of CO₂ rather than CH₄ production, in which case the effect on the global temperature will be even smaller than the estimate in our study.

This study is based on the fixed wetland distribution and type, whereas more appropriate would have been to consider them as dynamic ecosystems responding to climatic change. This is particularly important in the southernmost sporadic and discontinuous permafrost zones, where some of the projected changes in the wetlands as well as in the associated vegetation and landforms have already been observed, with implications for the methane emissions. As illustrated by direct observations, daily methane emission in the wetland may increase from 40 mg m⁻² to more than 180 mg m⁻² after the disappearance of permafrost, largely due to changes in vegetation and topography (ground subsidence) that ultimately result in upward displacement of the water table (Turetsky *et al* 2000).

The estimate obtained in this study may be checked for consistency with the other published results, although the range is large and direct comparison is not always possible. Several studies have addressed the sensitivity of the methane emission to variations of the climatic, hydrological, and soil parameters. The results are summarized in table 2.

Various estimates use different metrics to characterize the changes of methane fluxes, span different regions and time slices, and have been obtained under different assumptions about the future climatic changes that may be summarized as follows.

Our result for the mid-21st century indicates that the annual emission of methane from Russian permafrost region may increase by 6–8 Mt, i.e. by 20%–30% compared to the current 24–33 Mt. Climatic scenarios used in this study suggest that by 2050 the mean annual temperature will increase by 0.8–1.2 °C globally and by 2.2–3.2 °C in the 60°–90° N latitudinal zone (Symon *et al* 2005, chapter 4).

Shindell *et al* (2004) presented the modeled methane emissions from global as well as extratropical (32°–90° N) wetlands. The study involved calculations with both fixed and flexible wetland distribution that was responsive to temperature and precipitation and took into account the topography. The estimated increase in global annual methane emission under the projected 2 × CO₂ equilibrium climate was 99 and 121 Mt, or 63% and 78% for the fixed and flexible wetland distributions, respectively. These estimates are very close to our result if we account for the difference in climatic projections, i.e. the 3.4 °C global temperature increase in GISS-based climatic scenario used in Shindell *et al* (2004) compared to the 0.8–1.2 °C range by 2050 in our study.

The Northern high latitude annual emissions in the simulations with fixed distribution, the most comparable to our setup, increased from 24 to 52 Mt, i.e. by 117%. In these calculations, temperatures at Northern high latitudes warmed by about 3–5 °C together with 0.4–0.8 mm daily precipitation increase. Even if we introduce the 1.5–2.0 correction factor to scale the result obtained with our climatic scenarios to the temperature range used in Shindell's study, our estimate for the

Russian permafrost region will be two times lower. This may in part be attributed to the effect of the increase in precipitation that is not taken into account in our study and by the regional differences in climatic scenarios, but is most likely explained by the conceptual difference in the models used.

Christensen and Cox (1995) presented results for the Arctic region that are based on a method similar to Schindell's model forced by the 2 × CO₂ equilibrium climate scenario. A projected annual temperature increase by 4 °C and precipitation by 0.3 mm day⁻¹ led to an increase in annual methane emission from 17.1 to 26.6 Mt, i.e. by 56%, which is consistent with our result scaled to similar climatic forcing.

Acknowledgment

This study is supported by the Russian Foundation for Basic Research, grants no. 07-05-00209 and 07-05-13527.

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