Permafrost degradation and methane: low risk of biogeochemical climate-warming feedback

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Gao, Xiang, C Adam Schlosser, Andrei Sokolov, Katey Walter Anthony, Qianlai Zhuang, and David Kicklighter. “Permafrost degradation and methane: low risk of biogeochemical climate-warming feedback.” Environmental Research Letters 8, no. 3 (September 1, 2013): 035014.</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1088/1748-9326/8/3/035014">http://dx.doi.org/10.1088/1748-9326/8/3/035014</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>IOP Publishing</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/83184">http://hdl.handle.net/1721.1/83184</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td></td>
</tr>
<tr>
<td>Detailed Terms</td>
<td><a href="http://creativecommons.org/licenses/by/3.0/">http://creativecommons.org/licenses/by/3.0/</a></td>
</tr>
</tbody>
</table>
Permafrost degradation and methane: low risk of biogeochemical climate-warming feedback

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2013 Environ. Res. Lett. 8 035014

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 18.51.1.88
This content was downloaded on 09/12/2013 at 16:00

Please note that terms and conditions apply.
Permafrost degradation and methane: low risk of biogeochemical climate-warming feedback

Xiang Gao¹, C Adam Schlosser¹, Andrei Sokolov¹, Katey Walter Anthony², Qianlai Zhuang³ and David Kicklighter⁴

¹ Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, USA
² Water and Environmental Research Center, University of Alaska, Fairbanks, AK, USA
³ Departments of Earth and Atmospheric Science, Purdue University, West Lafayette, IN, USA
⁴ The Ecosystems Center, Marine Biology Laboratory, Woods Hole, MA, USA

E-mail: xgao304@mit.edu

Received 29 March 2013
Accepted for publication 20 June 2013
Published 10 July 2013
Online at stacks.iop.org/ERL/8/035014

Abstract
Climate change and permafrost thaw have been suggested to increase high latitude methane emissions that could potentially represent a strong feedback to the climate system. Using an integrated earth-system model framework, we examine the degradation of near-surface permafrost, temporal dynamics of inundation (lakes and wetlands) induced by hydro-climatic change, subsequent methane emission, and potential climate feedback. We find that increases in atmospheric CH₄ and its radiative forcing, which result from the thawed, inundated emission sources, are small, particularly when weighed against human emissions. The additional warming, across the range of climate policy and uncertainties in the climate-system response, would be no greater than 0.1 °C by 2100. Further, for this temperature feedback to be doubled (to approximately 0.2 °C) by 2100, at least a 25-fold increase in the methane emission that results from the estimated permafrost degradation would be required. Overall, this biogeochemical global climate-warming feedback is relatively small whether or not humans choose to constrain global emissions.

Keywords: permafrost, methane, climate feedback

Online supplementary data available from stacks.iop.org/ERL/8/035014/mmedia

1. Introduction

There is general agreement that 21st century warming will be pronounced at higher latitudes. One likely ramification of this warming will be the increased vulnerability of the large carbon reservoirs in the Arctic and boreal permafrost (Schuur and Abbott 2011). Permafrost thaw influences local hydrology, vegetation composition, and ecosystem functioning (Smith et al 2005, Christensen et al 2004). Of particular concern is the permafrost in near-surface, carbon-rich, ice-rich soils. Increased thawing of these soils can transform the hydrologic landscape to aid in the formation/expansion of saturated areas such as lakes and wetlands (Zimov et al 1997, Shindell et al 2004). Subsequently, anaerobic decomposition of thawed organic carbon results in emission of methane, a potent greenhouse gas, which could constitute a positive feedback to the climate system (Walter et al 2006, Anisimov 2007).
Despite the importance of the Arctic eco-hydrologic system, considerable uncertainty remains in projections of permafrost degradation and estimates of current high latitude CH$_4$ flux and future methane emission in response to climate change. Prior studies demonstrate that the extent of near-surface permafrost degradation could differ dramatically as a result of model deficiencies in soil physics and discretizations (Lawrence and Slater 2005, Delisle 2007, Alexeev et al 2007, Lawrence et al 2008). A comprehensive assessment of CH$_4$ fluxes that combines inverse modeling with process modeling and flux extrapolation gives a total range of 20–72 TgCH$_4$ yr$^{-1}$ for northern regions (EPA 2010). Recent estimates of methane emission increases over the 21st century also vary widely, from 34 to 70 TgCH$_4$ yr$^{-1}$ from northern wetlands (Shindell et al 2004, Koven et al 2011) and from 1.84 (Huissteden et al 2011) to 13 TgCH$_4$ yr$^{-1}$ (Bastviken et al 2011) from the high latitude lakes. Such a wide range of estimates raises questions about how severe methane emission from Arctic permafrost thaw would contribute to future global-scale climate feedbacks (Huissteden et al 2011, Delisle 2007, Schuur and Abbott 2011).

Herein we apply an integrated assessment model framework to examine future near-surface permafrost and saturated-area extent as well as the global climate-feedback strength associated with subsequent methane emissions—all bracketed within known sources of uncertainty. Additionally, a model sensitivity analysis is presented that examines the extent to which additional methane emissions provide a more salient (positive) climate-warming feedback (hereinafter a global temperature increase of 0.2 $^\circ$C is considered a salient feedback). Our study focuses on the methane emission under saturated (anaerobic) soils, thus CO$_2$ release from thawing soils and its feedback is not included here.

### 2. Model

The MIT Integrated Global System Model (IGSM) quantifies various sources of uncertainty in climate projections. The IGSM includes sub-models of the natural earth system coupled to a global economic model (The Emission Prediction and Policy Analysis or EPPA) (Sokolov et al 2005). The IGSM sub-model of atmospheric dynamics and chemistry is two-dimensional in altitude and latitude coupled to a mixed layer ocean component. The parameterizations of physical processes (convection, radiation, etc) resemble the Goddard Institute for Space Studies (GISS) climate model (Hansen et al 1983). Its radiation scheme includes all significant greenhouse gases and 11 types of aerosols. The model of atmospheric chemistry represents climate-relevant reactive trace-gases and aerosols and includes: convergent and convective transports; parameterized north–south eddy transport; local true production or loss due to surface emission or deposition; and atmospheric chemical reactions (Wang et al 1998). The Community Land Model (CLM) version 3.5 (Oleson et al 2008) is implemented as the IGSM land-surface scheme. CLM explicitly treats thermal and hydrologic frozen soil and freeze/thaw processes as well as snow processes. The IGSM consistently depicts the global and zonal profiles of present-day climate and potential climate change when compared with observations (Sokolov and Stone 1998) and the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) archive (Sokolov et al 2009, Schlosser et al 2013), respectively.

We assess the present-day near-surface permafrost and climate change-induced degradation by forcing CLM off-line with atmospheric data obtained from the IGSM fully coupled transient 20th and 21st century climate change integration (Sokolov et al 2009). The IGSM is forced from 1861 to 1990 by observed changes in greenhouse gas (GHG) concentrations and from 1991 forward by emissions of GHG and aerosol precursors projected by the EPPA model (Sokolov et al 2009). The suite of model simulations encompasses the range in emission pathways (Unconstrained Emission (UCE) and Greenhouse gas Stabilization (GST) emission scenarios) as well as the large-scale transient climate response (TCR) that aggregates the effect of three key climate parameters (climate sensitivity, ocean heat uptake rate, and net aerosol forcing) (table 1). We attempt to assess uncertainty in our projections resulting from the climate response as well as from emissions. As such, climate-parameter values and emission rates are chosen in combination to produce the high (95%), median (50%), and low (5%) percentiles of the probability distributions of surface-air temperature increase from a 400-member ensemble simulation. Projected unconstrained anthropogenic emissions are quite sensitive to the choice of uncertain economic model parameters (such as population growth, labor productivity, etc), therefore

### Table 1. Summary of simulation experiments conducted in this study.

<table>
<thead>
<tr>
<th>TCR</th>
<th>Emission</th>
<th>Notes</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (95%)</td>
<td>Median (1330 ppm CO$_2$ equivalent)</td>
<td>+17 regional patterns</td>
<td>HTCRC</td>
</tr>
<tr>
<td>Median (50%)</td>
<td>Baseline</td>
<td></td>
<td>MTCR</td>
</tr>
<tr>
<td>Low (5%)</td>
<td>+17 regional patterns</td>
<td></td>
<td>LTCR</td>
</tr>
<tr>
<td></td>
<td>+17 regional patterns</td>
<td></td>
<td>MTCR_HEM</td>
</tr>
<tr>
<td>Median (50%)</td>
<td>High (95%) (1660 ppm CO$_2$ equivalent)</td>
<td></td>
<td>MTCR_LEM</td>
</tr>
<tr>
<td>Low (5%)</td>
<td>(970 ppm CO$_2$ equivalent)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Greenhouse gas stabilization (GST) | Median (560 ppm CO$_2$ equivalent) | +17 regional patterns | H560        |
| Low (5%) | (970 ppm CO$_2$ equivalent) | +17 regional patterns | L560        |
the three different levels of emission rates are considered for the UCE scenario. Conversely, the GST emission scenarios are heavily constrained to meet a stabilization target and thus have very similar emission pathways (although the cost of achieving these stabilizations differ). Therefore only the median-emission pathway is considered for the GST scenario. Overall, the median UCE and GST emission scenarios here are roughly equivalent to the IPCC’s Representative Concentration Pathways 8.5 and 4.5, respectively. A downscaling technique (Schlosser et al 2013) expands the IGSM zonal near-surface meteorology to generate corresponding longitudinal patterns (supplementary materials available at stacks.iop.org/ERL/8/035014/mmedia). The climatology of these patterns is derived from observations and the resulting geographic fields compare favorably with the observations (supplementary figures 1, 2 available at stacks.iop.org/ERL/8/035014/mmedia). Pattern shifts in response to human-forced change are also applied for 21st century climate change based on climate-model results from the IPCC AR4 archive (Schlosser et al 2013). As such, the uncertainty in regional climate change characterized by each IPCC AR4 participating climate model can be considered. With the forcing fields, a set of CLM simulations (table 1) has been conducted at a $2^\circ \times 2.5^\circ$ resolution through the 21st century.

With regard to modeling the landscape, CLM, like any land-surface scheme, coupled within earth-system models, does not explicitly track surface subsidence induced by ice-rich permafrost thaw. These thermokarst landforms occur at spatial scales well below those resolved in regional and global models, and so the surface water retention—if any—that directly results from this (thermokarst) process would be underrepresented and the resulting methane emissions be underestimated. The extent to which these fine-scale processes support a climate-warming feedback at the regional scale will be addressed in our sensitivity analysis. Nevertheless, our model framework captures large-scale hydro-climate processes (i.e. precipitation, evaporation, sub-surface soil physics) that are highly relevant to large-scale saturated-area expansion, methane emissions, and resulting radiative forcing. Our intent here is not to provide a deterministic prediction of permafrost thaw and inundation, but rather to examine through an integrated assessment model framework the temperature feedback from a range of plausible CH$_4$ emission responses that could occur as a result of human-induced climate warming and to examine a threshold of methane-emission increase for such temperature feedback to be salient. We assume any modeled inundation of thawed permafrost regions takes the form of wetlands and lakes. Using this simplified land-surface modeling approach coupled to an earth-system model (i.e. the IGSM), we are able to determine what threshold of methane-emission increase would result in a salient positive climate-warming feedback.

3. Results and discussion

Each model grid, having a 3.5 m soil-column depth, is identified as containing permafrost if monthly soil temperature in at least one sub-surface soil layer remains at or below 0°C for two or more consecutive years. Delisle (2007) argued the likely overestimates of permafrost degradation with a 3.5 m soil-column depth. Lawrence et al (2008) found that the rate of near-surface permafrost loss is not strongly affected by inclusion of the deep thermal reservoir associated with new soil layers. In our CLM simulations, the near-surface permafrost area, poleward of 45°N and excluding glacial regions, is $11.2 \times 10^6$ km$^2$ averaged from 1970 to 1989 (annual values vary from 10.9 to 11.5 $\times 10^6$ km$^2$ during that period) with median TCR and emission parameters. The result falls on the lower bound of the observationally based range of continuous and discontinuous permafrost extent (11.2 to 13.5 $\times 10^6$ km$^2$) over the same period (Zhang et al 2000). The lack of subgrid soil-column representation may prevent the explicit simulation of the sporadic or isolated permafrost categories, and thus contribute to our lower extent. Through the 21st century, the simulations indicate a nearly linear near-surface permafrost degradation rate, with the potential for 75% loss for the low TCR and nearly 100% loss for the high TCR cases by 2100 under a median-emission UCE scenario (figure 1). We also find that uncertainties in emissions (dotted lines) are as important as climate-response uncertainty (thick solid lines), in terms of contributing to the total uncertainty in projected permafrost changes. Under a GST scenario of 560 ppm CO$_2$-equivalent concentration by 2100, permafrost degradation reduces substantially, with 20% loss for low TCR and 40% loss for high TCR by 2100. In addition, uncertain regional climate change (figure 1, light thin lines) may accelerate the permafrost thaw by 5%−10% due to enhanced warming over land imposed by the climate-model patterns.

Next we estimate the potential methane-emission increase. In areas of permafrost, ground water level is greatly influenced by the existence of the underlying impervious permafrost layer. Surface infiltration and water released by the melting of frozen soil supply water to the thawed zone above the permafrost layer. Unless the soil is relatively pervious and
the terrain has sufficient slope to permit lateral drainage, the water table may rise to, or near, the ground surface. We draw from previous work (Koven et al 2011, Gedney et al 2004) and interpret the model’s diagnoses of land area where the water table has reached the ground surface (or ‘saturated land area’) as a concurrent CH₄-emitting area. The calculation of ‘saturated soil fraction’ in CLM explicitly accounts for the aforementioned major hydrologic and topographic controls of water table variations for an unconfined aquifer. To confirm that our simulated saturated land area is a reasonable proxy of inundated area, important to control large-scale CH₄ emission, we compared the simulation with the 1993–2007 global inundated areas inferred from multiple satellite observations (Prigent et al 2007). Satellite observations capture, but do not discriminate among, inundated wetlands, rivers, and small lakes. CLM-simulated saturated areas also do not make these distinctions. Further, both estimates will not capture localized inundated areas—yet as we will show in a sensitivity analysis, these localized effects will require orders of magnitude larger emissions to impact the global temperature biogeochemical feedback response considered herein. Despite these considerations, satellite reconstruction provides a first-order estimate of global inundation (Prigent et al 2007). Our simulated saturated areas are mostly consistent with the temporal patterns of the satellite reconstruction at large spatial scales (supplementary figure 3 available at stacks.iop.org/ERL/8/035014/mmedia). Over the region of our interest (poleward of 45°N), the simulations agree within ~1% of the satellite estimate with the 15-year annual means of 8.00 × 10², 7.93 × 10², and 8.00 × 10² km² under low, median, and high TCR with median-emission parameters against the observation of 8.04 × 10² km². In terms of expansion of CH₄-emitting areas across the 21st century scenarios, the model-predicted saturated area integrated north of 45°N increases 15%–25% by 2100 for the low and high TCR, respectively, under the median-emission UCE scenario (figure 2). Under the GST scenario, the expansion of saturated areas is limited to 5% and 15% for the low and high TCR, respectively. Uncertain regional climate changes can enhance saturated-area expansion, especially for the high TCR of the UCE scenario, to as much as 30%–50% by 2100 (thin red lines). Overall, the total estimated saturated area increases from 5% to 50% by 2100 across all the projections.

For CH₄ emission estimates, we interpret our inferred total saturated area (hereinafter inundated area) into two types of CH₄-emitting surfaces: wetlands and lakes. We assumed a wetland:lake ratio of 3.35 (77% versus 23% coverage, respectively) based on the occurrences of these wet surface types north of 45°N in the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll 2004). Alternative interpretations of the inferred total inundated area (as wetlands or lakes only) show little effect on the resulting CH₄ emission estimates (provided below). We further account for a key distinction for lakes: yedoma versus non-yedoma based on a contemporary atlas of yedoma regions. Yedoma regions are underlain by ice-rich, organic-rich Pleistocene-age soil (Zimov et al 1997), and measurements taken at yedoma lakes show significantly higher ebullition CH₄ fluxes (139 g-CH₄ m⁻² yr⁻¹) than non-yedoma counterparts (5.9 g-CH₄ m⁻² yr⁻¹) (Walter et al 2006, 2012). In each grid cell, CH₄ emissions are calculated independently for each CH₄-emitting surface type and then aggregated. Additionally, we model the temperature regulation of methanogenesis in each surface type using a Q₁₀ relationship (supplementary materials available at stacks.iop.org/ERL/8/035014/mmedia). We estimate a CH₄ emission of 21 Tg-CH₄ yr⁻¹ from lakes and wetlands poleward of 45°N at 2010. This, combined with additional 25 Tg-CH₄ yr⁻¹ from northern bogs (Schlosser et al 2007), falls within the range (20–72 Tg-CH₄ yr⁻¹) of a comprehensive assessment of CH₄ emissions for northern regions from top-down and bottom-up techniques (EPA 2010). By the end of the 21st century, under the UCE scenario, increases in decadal averaged (2091–100) annual CH₄ emission from inundated area expansion and Q₁₀ warming range between 5.6–8.9 Tg-CH₄ yr⁻¹ and 9.7–15.1 Tg-CH₄ yr⁻¹ for the low and high TCR cases, respectively, of which approximately 80% is contributed by wetlands and 20% by lake (figure 3). This is mostly associated with the larger percentage of inundated area we specify for wetlands. Nevertheless, these increases, which are at most 75% of the 2010 estimate from lakes and wetlands, are considerably lower than the IGSM estimated human global CH₄ emission increase of 349 Tg-CH₄ yr⁻¹ over the same period (supplementary figure 4 available at stacks.iop.org/ERL/8/035014/mmedia). Under the GST scenario, the CH₄ emission increases by 2100 are substantially lower relative to the UCE scenario. The decadal averaged annual emission increases are 0.8–1.7 Tg-CH₄ yr⁻¹ and 2.3–4.1 Tg-CH₄ yr⁻¹ for the low and high TCR cases, respectively. However, unlike the UCE scenario, these increases are quite comparable to the corresponding IGSM estimated global CH₄ human-emission increase at 4 Tg-CH₄ yr⁻¹ through the 21st century (supplementary figure 4). Across all the modeled scenarios, about 52–58% of these aforementioned emission increases are a result of warming pre-existing inundated areas with the remaining increases due to newly formed inundated areas from permafrost thaw.

To assess the potential climate-warming feedback from these increases in CH₄ emissions, we then integrate the fully
Figure 3. Increases in decadal averaged (2091–2100) annual CH$_4$ emission (Tgyr$^{-1}$, poleward of 45$^\circ$N) with respect to 2011–20 as a result of the warming and expansion of yedoma lakes (Y), non-yedoma (NY) lakes, wetlands (W), and total inundated areas for the low and high TCR under the UCE and GST scenarios, respectively. Each scenario contains 18 ensemble members (17 members of model-based pattern shifts and one member of climatological pattern). Whisker plots show the minimum, maximum, and plus/minus one standard deviation about the ensemble mean.

coupled IGSM and exogenously prescribe the corresponding CH$_4$ emission increases through the 21st century. With the full capacity of IGSM’s atmospheric chemistry, the assessment of such feedback is coupled within the atmospheric methane cycle to account for the change in the balance of atmospheric methane oxidation rates, methane lifetime and concentration as a result of increased methane emission. For the UCE scenario, the ensemble-mean result shows no discernable temperature feedback as the increases in anthropogenic emissions overwhelm the emission response from inundated area warming and expansion (not shown). For the ensemble-mean GST scenario, no salient global temperature feedback is discernable for either the high or the low TCR case in response to the added CH$_4$ emission (figure 4(a)). Among all the simulations performed (table 1), only one member of the GST scenario ensemble, which accounts for uncertain regional climate changes, exhibits a small temperature feedback of approximately 0.1$^\circ$C towards the end of this century, although this warming is somewhat overshadowed by interannual variability. Although the range of the end-of-century increase in CH$_4$ emission (0.8–4.1 Tg-CH$_4$ yr$^{-1}$) is comparable to the human-induced CH$_4$ emission increase (4 Tg-CH$_4$ yr$^{-1}$) under the GST scenario, it is still quite low (on the order of 1%) when compared with the current level of human CH$_4$ emission rates ($\sim$345 Tg-CH$_4$ yr$^{-1}$ at 2010, supplementary figure 4), and particularly when considering all greenhouse gas emissions. Further IGSM tests indicate that a 1% CH$_4$ emission increase has a very minor effect on radiative forcing (supplementary figure 5 available at stacks.iop.org/ERL/8/035014/mmedia).

Given the uncertainty in our CH$_4$ emission estimates caused by parameter uncertainty as well as the aforementioned model limitations, we attempt to characterize the relative strength of the derived CH$_4$ emission response, particularly with respect to additional CH$_4$ emissions needed to achieve a salient climate-warming feedback. We perform sensitivity experiments by augmenting the CH$_4$ emissions and repeating the 21st century IGSM projections. Each run separately considers: scaling the aforementioned estimated CH$_4$ emission increases by 10-, 25-, 50-, and 100-fold; as well as applying the UCE scenario. Results for the GST scenario at the high TCR are examined. We find that the 10-fold increase would not support a salient temperature-feedback response (figure 4(b)). The 100-fold increase produces a temperature response of about 0.8$^\circ$C by 2100, but salient only after mid-century. The UCE scenario causes temperature to rise $\sim$1.5$^\circ$C by 2100. At a 25-fold emission increase, a discernable, additional warming of 0.2$^\circ$C is evident only in the last decade of the 21st century.

Overall, these results cast a quantitative insight on the strength and range of the global climate-warming biogeochemical feedback from near-surface permafrost thaw and subsequent CH$_4$ emission. This model-based investigation is the first of its kind in its use of an integrated assessment model to systematically account for key sources of uncertainty stemming from human-emission
pathways, global climate sensitivity, and regional climate change shifts. The increase in CH$_4$ emission due to potential Arctic/boreal thawed, inundated area warming and expansion represents a weak climate-warming feedback within this century. This is consistent with previous studies (Anisimov 2007, Huissteden et al. 2011, Delisle 2007) that also imply a small Arctic lake/wetland biogeochemical climate-warming feedback. Riley et al. (2011) discussed many deficiencies and uncertainties that currently exist in modeling methane production and emission—most of them are also applicable for this study. Fundamental processes resulting in small-scale inundation (e.g. thermokarst lake dynamics) are lacking here—such landforms have been shown to increase rapidly and may have a large impact on CH$_4$ fluxes (Turetsky et al. 2007). Further, buffering effects from lake drainage are not explicitly considered, however these drainage effects would further weaken the already small feedback found (Huissteden et al. 2011, Avis et al. 2011). Further uncertainty arises from: the simulated grid fractional saturation that is of first-order importance to CH$_4$ emission estimates; spatially heterogeneous field-based CH$_4$ emission flux; parameters associated with the temperature dependence of CH$_4$ production; and a possible increase of geological and hydrate emissions (particularly in areas underlain by relatively thin permafrost). Although the satellite reconstruction provides a good estimate of global inundation, it is inadequate in characterizing small, isolated water bodies, including some of those formed by the thermokarst process. Other factors that could be important but not explicitly considered include: the insulating peat (Lawrence et al. 2008) and fire disturbance for permafrost thaw as well as soil-moisture and vegetation dynamics, and methane oxidation removal processes ongoing in soils, sediments, and water. However, many of these factors may serve as buffering effects on the CH$_4$ emission response, and small feedback as well. Nevertheless, among these aforementioned considerations that could enhance CH$_4$ emission response, an order of 25-fold increase to our modeled response would be required to change our overall conclusion: the biogeochemical global climate-warming feedback from increased CH$_4$ emissions due to thawed, inundated area warming and expansion is relatively small, whether or not humans choose to constrain global emissions.

Acknowledgment

The authors gratefully acknowledge the Department of Energy Climate Change Prediction Program Grant DE-PS02-08ER08-05 and Office of Science (Biological and Environmental Research) US Department of Energy in supporting this work.

References


Avis C A, Weaver A J and Meissner K J 2011 Reduction in areal extent of high-latitude wetlands in response to permafrost thaw Nature Geosci. 4 444–8

Anisimov O A 2007 Potential feedback of thawing permafrost to the global climate system through methane emission Environ. Res. Lett. 2 024016

Bastviken D, Tranvik L J, Downing J A, Crill P M and Enrich-Prast A 2011 Freshwater methane emission offset the continental carbon sink Science 331 50


EPA (Environmental Protection Agency) 2010 Methane and nitrous oxide emissions from natural sources EPA 430-R-10-001 (Washington, DC: US Environmental Protection Agency)

Gedney N, Cox P M and Huntingford C 2004 Climate feedback from wetland methane emissions Geophys. Res. Lett. 31 L20503


Schauf E A G and Abbott B 2011 Climate change: high risk of permafrost thaw Nature 480 32–3

Smith L C, Sheng Y, MacDonald G M and Hinzman L D 2005
Disappearing Arctic lakes Science 308 1429

Sokolov A P and Stone P H 1998 A flexible climate model for use
in integrated assessments Clim. Dyn. 14 291–303

Sokolov A P, Stone P H, Forest C E, Prinn R, Sarofim M C, 
Webster M, Saltsev S and Schlosser C A 2009 Probabilistic 
forecast for twenty-first-century climate based on uncertainties 
in Emissions and climate parameters J. Clim. 22 5175–204

Sokolov A P et al 2005 The MIT Integrated Global System Model 
(IGSM) Version 2: Model description and baseline evaluation 
MIT Joint Program on the Science and Policy of Global 
Change Report vol 124

The disappearance of relict permafrost in boreal North 
America: effects on peatland carbon storage and fluxes Glob. 
Change Biol. 13 1922–34

methane seeps along boundaries of arctic permafrost thaw and 
melting glaciers Nature Geosci. 5 419–26

Walter K M, Zimov S A, Chanton J P, Verbyla D and Chapin F S III 
2006 Methane bubbling from Siberian thaw lakes as positive 
feedback to climate warming Nature 443 71–5

Wang C, Prinn R G and Sokolov A 1998 A global interactive 
chemistry and climate model: formulation and testing 
J. Geophys. Res. 103 3399–418

Zhang T, Heginbottom J A, Barry R G and Brown J 2000 Further 
statistics on the distribution of permafrost and ground-ice in 
the Northern Hemisphere Polar. Geogr. 24 126–31

Zimov S A, Voropaev Y V, Semiletov I P, Davidov S P, 
Prosiannikov S F, Chapin F S, Chapin M C, Trumbore S and 
Tyler S 1997 North Siberian lakes: a methane source fuelled by 
Pleistocene carbon Science 277 800–2