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A Process-Based Modeling Analysis of Methane Exchanges Between Alaskan Terrestrial Ecosystems and the Atmosphere

Qianlai Zhuang, Jerry M. Melillo, David W. Kicklighter, Ronald G. Prinn, A. David McGuire, Paul A. Steudler, Benjamin S. Felzer and Shaomin Hu

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Abstract

We developed and used a new version of the Terrestrial Ecosystem Model (TEM) to study how rates of methane (CH_4) emissions and consumption in Alaskan soils have changed over the past century in response to observed changes in the state's climate and are likely to change with projected climate changes over this century. We estimate that the current net emissions of CH_4 (emissions minus consumption) from Alaskan soils are about 3 Tg CH_4 yr^{-1}. We project that net CH_4 emissions will almost double by the end of the century in response to high-latitude warming and associated climate changes. If CH_4 emissions from soils of the pan-Arctic region respond to climate changes in the way we project for the Alaskan soils, the net increase in high latitude CH_4 emissions could lead to a major positive feedback to the climate system.

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1. INTRODUCTION

Soils have the capacity to both produce and consume CH_4, a powerful greenhouse gas. A special group of soil microorganisms, the methanogens, is responsible for CH_4 production, while another special group, the methanotrophs, is responsible for CH_4 consumption. Recent estimates put CH_4 emissions from the world's soils at about 150 to 250 Tg CH_4 yr^{-1} [IPCC, 2001], with between about 1/3 and 1/4 (about 65 Tg CH_4 yr^{-1}) emitted from the wet soils of high latitudes [Walter *et al*., 2001a]. Estimates of CH_4 consumption by soil microbes are in the range of 10 to 30 Tg CH_4 yr^{-1}, an order of magnitude lower than the emission estimates [IPCC, 2001]. Most of the CH_4 consumption occurs in well-drained soils of temperate and tropical areas.

Terrestrial ecosystems in high latitudes are predicted to experience earlier and more dramatic environmental changes from global warming compared with lower latitude ecosystems [IPCC,

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2001] including the lengthening of the growing season and permafrost melting [Romanovsky *et al.*, 2001; Vitt *et al.*, 2000]. Furthermore, a substantial part of the global natural wetlands occur in northern high latitudes and form the largest single source of atmospheric CH_4 [e.g., Cao *et al., 1996*; Christensen *et al., 1996*; Melillo *et al., 1996*]. Changes of CH_4 emissions and consumption due to warming and alterations of hydrology in the region have been observed [e.g., Friborg *et al.*, 1997; Whalen and Reeburgh, 1992; West and Schmidt, 1998].

Many of the regional and global estimates of CH_4 fluxes between the land and the atmosphere have been based on limited site measurements and simple extrapolation procedures [e.g., Whalen and Reeburgh, 1990; Whalen *et al*., 1991]. Recently, several large-spatial-scale models [e.g., Cao *et al*., 1996; Liu, 1996; Potter *et al*., 1996; Prinn *et al*., 1999; Ridgwell *et al*., 1999; Walter and Heimann, 2000; Walter *et al*., 2001a,b] have been developed to estimate current and future methane exchanges between the land and the atmosphere. For example, it is estimated that a 26% increase in global wetland CH_4 emissions will occur for a global 1990–2100 warming of 2.5ºC [Liu, 1996; Prinn *et al.*, 1999]. While these models have incorporated some of the factors that control CH_4 fluxes, they have ignored key aspects of the water and soil thermal regimes in high latitudes [e.g., see Goodrich, 1978; Zhuang *et al*., 2001, 2003] that are critical to the timing and magnitude of CH_4 exchanges between the land and the atmosphere in northern ecosystems. Furthermore, most of these models have not been coupled with well-validated terrestrial ecosystem models, and so do not simulate the important links among plant productivity, the availability of labile carbon compounds to microorganisms, and CH_4 emissions. To examine the responses to climate change of methane fluxes between soils and the atmosphere at high latitudes, we have modified our process-based biogeochemistry model, the Terrestrial Ecosystem Model [TEM; Zhuang *et al.*, 2003], and here we present our simulation results for Alaska over the period from 1922 to 2099.

2. MODEL FRAMEWORK AND INPUT DATASETS

We developed a CH_4 dynamics module for TEM that explicitly considers the processes of methanogenesis and methanotrophy, and the important CH_4 transport mechanisms including diffusion and plant-mediated emissions through hollow stems. We then linked the CH_4 dynamics module to two other modules within TEM: (1) a soil-thermal module that simulates daily soil thermal regime, including soil temperature profile, active layer depth, and permafrost dynamics for the soils [Zhuang *et al*., 2001]; and (2) a multiple-layer soil water module of moss, organic soil, and mineral soils layers [Zhuang *et al.*, 2002] that has been enhanced to consider fluctuations in water-table depth.

We calibrated the model using CH_4 flux measurements made at the two major field sites of the Boreal Ecosystem-Atmosphere Study (BOREAS) [Sellers *et al*., 1997; Newcomer *et al*., 2000], and at the tundra sites at Toolik Lake Field Station, Alaska (68°38"N, 149°38'W) [http://ecosystems.mbl.edu/ARC/, unpublished data]. We used the data set of Matthews and Fung [1987] to define the distribution of wet soils in Alaska, and a data set from the International Geosphere-Biosphere Programme (IGBP) to assign spatially-specific soil-water pH [Carter and Scholes, 2000]. In addition, we used data on daily air temperature, precipitation, and vapor pressure from the Vegetation Ecosystem Modeling and Analysis Project [VEMAP; see http://www.cgd.ucar.edu/vemap]. We refer to the period from 1922 to present as the "historical period," and the period now until 2099 as the "future period."

3. HISTORICAL NET METHANE EMISSIONS

Over recent decades, we estimate that Alaskan soils have been a net source of about 3 TgCH_4 yr^{-1} to the atmosphere (**Table 1**); that is state-wide emissions of about 4 Tg CH_4 yr^{-1}, and uptake of 1 Tg CH_4 yr^{-1}. Across Alaska, we simulated significant spatial variability in net CH_4 emissions (**Figure 1**). In our simulations, positive net CH_4 emissions mainly occurred in tundra of northern Alaska (latitudes higher than 67°N) and the western coastal region of the state. Uptake of CH_4 (i.e. negative net CH_4 emissions) mostly occurred in the drier forest areas of interior Alaska (latitudes between 62° and 67°N) and the southern Alaskan forested areas. The simulated spatial patterns of methane emissions during the growing season (May to September) are generally similar to those estimated by Matthews and Fung [1987] (Fig. 1c,d). When we checked our modeled emissions against measurements we found that the mean modeled estimates (20 mg CH_4 m^{-2} day^{-1}) for forested areas during the growing season are higher than the measurements for forested areas (11 mg CH_4 m^{-2} day^{-1}) [Whalen and Reeburgh, 1990]. On the other hand, we found that the mean modeled estimates (60 mg CH_4 m^{-2} day^{-1}) for the tundra during the growing season agreed well with the measured values (52 mg CH_4 m^{-2} day^{-1}). Because the number of sites with flux measurements is relatively small, we are attempting to obtain additional data for further comparisons to help refine our model.

Table 1. Contribution of tundra and taiga ecosystems to net methane emissions (Tg CH_4 yr^{-1}) from 1980 to 1999 and from 2080 to 2099 in Alaska.

	1980-1999			2080-2099		
	Tundra	**Taiga**	**Total**	**Tundra**	**Taiga**	**Total**
Northern Alaska	1.40	0.05	1.45	2.21	0.08	2.29
Interior Alaska	0.37	0.73	1.10	0.65	1.30	1.95
Southern Alaska	0.60	–0.02	0.58	1.36	0.11	1.47
Alaska	2.37	0.76	3.13	4.22	1.49	5.71

[*] Positive values indicate methane emission to the atmosphere, while negative values indicate methane uptake by the soils.

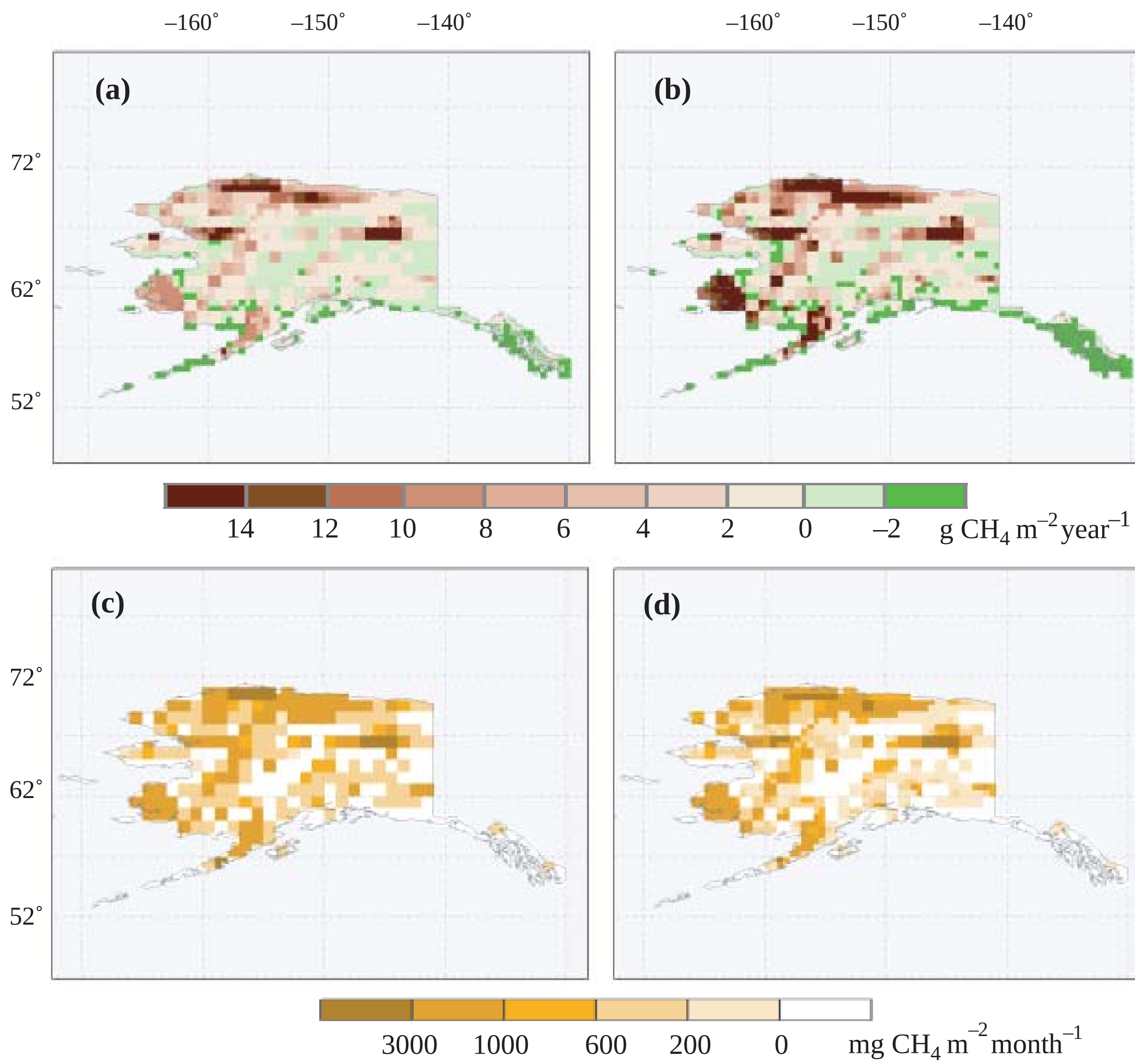

Figure 1. Spatial patterns of simulated annual net methane emissions across Alaska during (a) 1980s, and (b) 2080s. The spatial patterns of net monthly methane emissions during the growing season (May to September) of the1980s (c) estimated by Matthews and Fung [1987], and (d) estimated by TEM. Positive values indicate net release of methane to the atmosphere and negative values indicate net uptake of atmospheric methane by soils.

4. FUTURE NET METHANE EMISSIONS

We project that the annual rates of net CH_4 emissions from Alaska will increase dramatically in the future (**Figure 2**a). Our simulations show that net CH_4 emissions will about double by the end of this century (6 Tg CH_4 yr^{-1}) relative to current emission rates (3 Tg CH_4 yr^{-1}, Table 1). Although CH_4 consumption will increase slightly (Fig. 2b), future net CH_4 emissions will be dominated by enhanced CH_4 production.

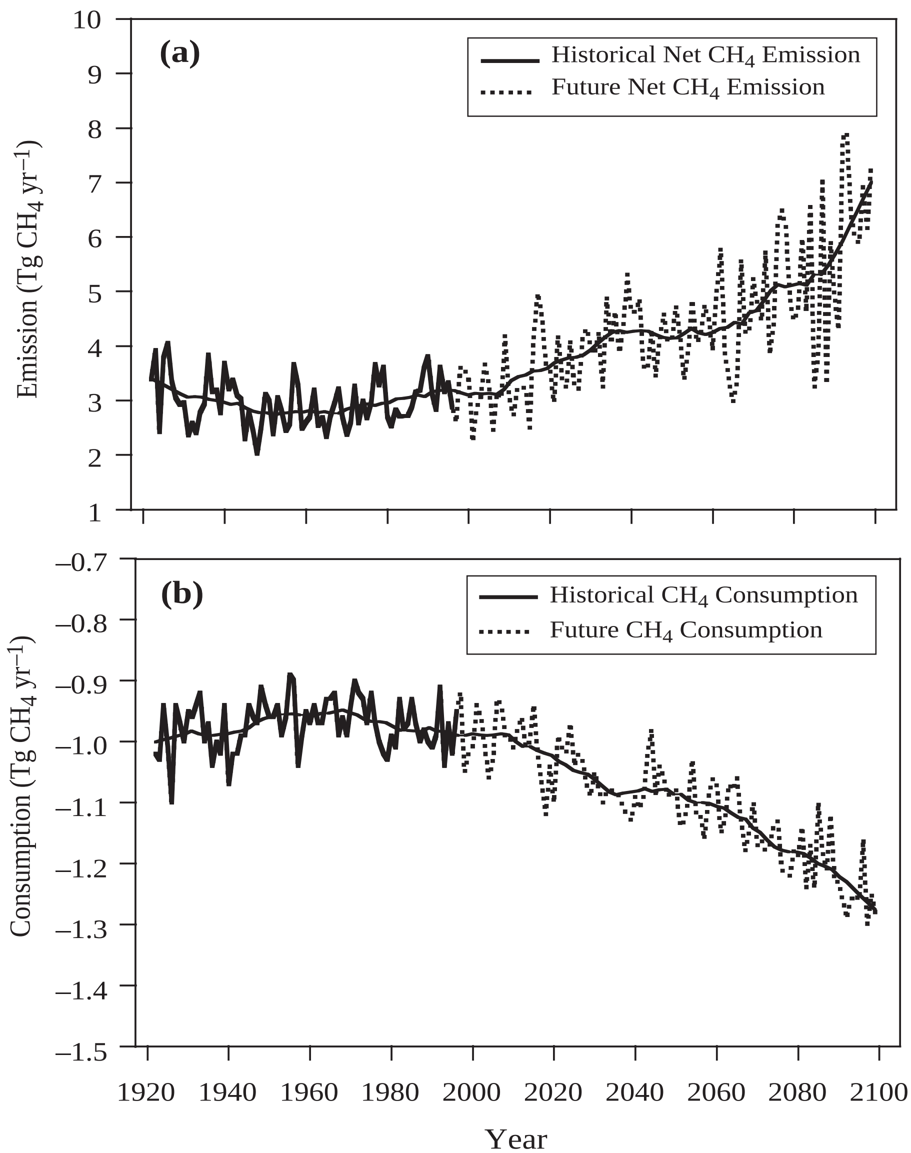

Figure 2. Inter-annual variations of simulated (a) net methane emissions and (b) methane consumption from 1922 to 2099. Solid lines indicate the historical period and dotted lines indicate the future period. The thin solid lines indicate the negative exponential smoothed data for each time series to show the trend with the time. Positive values indicate net releases of methane to the atmosphere and negative values indicate methane uptake by methanotrophs.

Our analyses indicate that increases in soil temperature and labile carbon availability associated with climate change in high-latitude ecosystems are the major factors that cause an increase in net CH_4 emissions. A lowering of water table depth in some parts of Alaska due to the rising of air temperatures and increased evapotranspiration result in the slight increase of CH_4 consumption.

Our preliminary analyses suggest that the projected changes in net CH_4 emissions for Alaska in response to climate change are likely to be typical of the response of the entire pan-Arctic region. If this is correct, then climate change at high latitudes could lead to a major positive feedback to the climate system by causing a continuous cycle of increased CH_4 emissions from the vast area of wet soils in the Arctic and Boreal regions and further warming. Currently, high-latitude CH_4 feedbacks to the climate system are not included in most coupled atmosphere-land-ocean general circulation models that are framing the policy debate on future climate change. Inclusion of these feedbacks would likely increase the projections of the globally averaged surface temperature at the end of this century, with the upper end of the range exceeding the current IPCC estimate of 5.8°C [IPCC, 2001].

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