NET EMISSIONS OF CH$_4$ AND CO$_2$ IN ALASKA: IMPLICATIONS FOR THE REGION'S GREENHOUSE GAS BUDGET

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Abstract. We used a biogeochemistry model, the Terrestrial Ecosystem Model (TEM), to study the net methane (CH$_4$) fluxes between Alaskan ecosystems and the atmosphere. We estimated that the current net emissions of CH$_4$ (emissions minus consumption) from Alaskan soils are ~3 Tg CH$_4$/yr. Wet tundra ecosystems are responsible for 75% of the region's net emissions, while dry tundra and upland boreal forests are responsible for 50% and 45% of total consumption over the region, respectively. In response to climate change over the 21st century, our simulations indicated that CH$_4$ emissions from wet soils would be enhanced more than consumption by dry soils of tundra and boreal forests. As a consequence, we projected that net CH$_4$ emissions will almost double by the end of the century in response to high-latitude warming and associated climate changes. When we placed these CH$_4$ emissions in the context of the projected carbon budget (carbon dioxide [CO$_2$] and CH$_4$) for Alaska at the end of the 21st century, we estimated that Alaska will be a net source of greenhouse gases to the atmosphere of 69 Tg CO$_2$ equivalents/yr, that is, a balance between net methane emissions of 131 Tg CO$_2$ equivalents/yr and carbon sequestration of 17 Tg C/yr (62 Tg CO$_2$ equivalents/yr).

Key words: Alaska (USA); global warming potential; greenhouse gas budget; methane consumption and emissions; methanogenesis; methanotrophy.

INTRODUCTION

The atmospheric concentration of methane (CH$_4$) has been increasing 0.6% per decade for the last several decades. While carbon dioxide (CO$_2$) has been responsible for a majority of the radiative forcing associated with greenhouse gases, the high rate of increase in atmospheric CH$_4$ is of concern because CH$_4$ is 23 times more effective on a per unit mass basis than CO$_2$ in absorbing long-wave radiation on a 100-year time scale (Ramanswamy et al. 2001). In recent decades, it has been estimated that 270 Tg CH$_4$/yr are emitted from natural sources globally (Prather et al. 2001), of which ~20% is emitted from northern high-latitude ecosystems, including those in Alaska (Zhuang et al. 2004).

Alaska's ecosystems are expected to experience earlier and more drastic climate changes from global warming compared with lower latitude ecosystems. The projected changes are consistent with changes that have been observed in recent decades, which include increases in

mean annual air temperatures, thawing of permafrost, and longer growing seasons (Keyser et al. 2000, Oechel et al. 2000, Romanovsky et al. 2000, Hinzman et al. 2005). Changes in climate, plant, and soil conditions will have implications for CH$_4$ dynamics and carbon storage in the soils of the region.

One-third of the global soil carbon stocks are located in the Arctic (e.g., Post et al. 1982, Gorham 1991, Turunen et al. 2001). The fate of this stored soil carbon under altered climate is a major question (Billings 1987), because microbes can respond quickly to temperature changes in high latitude ecosystems (e.g., Svensson 1984). Soil microbial activity includes organic matter decomposition under aerobic conditions that releases CO$_2$ to the atmosphere. Under the anaerobic conditions, warming and changes in hydrology could trigger rapid CH$_4$ emissions in response to the early spring thawing in subarctic mire ecosystems (e.g., Moore et al. 1990, Dise 1993, Friborg et al. 1997). Methane dynamics are also influenced by the increase in the depth to which permafrost thaws each summer (e.g., Whalen and Reeburgh 1992) and any changes in the water table of northern peatlands that may result from changes in the water cycle.

To date, there is a lack of comprehensive estimates of net emissions of CH$_4$ for Alaska. Furthermore, the potential effects of regional CH$_4$ emissions have not

been adequately considered in estimating whether the response of regional greenhouse gases will tend to enhance or mitigate warming. In this study, we examined Alaska's CH_4 dynamics, its contributions to the carbon balance, and its contribution to the greenhouse gas budget of the region for the 20th and 21st centuries.

METHOD

Overview

We applied an existing biogeochemistry model, the Terrestrial Ecosystem Model (TEM; Zhuang et al. 2004) to study CH_4 fluxes between Alaskan ecosystems and the atmosphere from 1922 to 2099. First, we used the model to examine the responses of net CH_4 emissions to both past and potential future climate change. Next, we used the concept of global warming potentials to convert net CH_4 emissions into CO_2 equivalent units in terms of global warming effects. Finally, we examined the contributions of net CH_4 emissions to the greenhouse gas budget of Alaskan terrestrial ecosystems for the 20th and 21st centuries. The simulations presented in this study for past climate change are consistent with simulations presented in Zhuang et al. (2004), while the simulations for future climate represent new results.

Model description

Our model, TEM, explicitly simulates the processes of CH_4 production (methanogenesis) and CH_4 oxidation (methanotrophy), as well as the transport of the gas between the soil and the atmosphere (Fig. 1a). The net CH_4 emissions from soils to the atmosphere are the total of the CH_4 fluxes at the soil/water–atmosphere boundary via different transport pathways (Fig. 1b; Zhuang et al. 2004). The transport pathways include molecular diffusion, ebullition, and plant-mediated emissions through the stems of vascular plants. Methane production is modeled as an anaerobic process that occurs in the saturated zone of the soil profile. The CH_4 production of soil is influenced by the carbon substrate availability, soil temperature, soil pH, and the availability of electron acceptors, which is related to redox potentials. Methane oxidation, which is modeled as an aerobic process that occurs in the unsaturated zone of the soil profile, is a function of soil CH_4 concentration, soil temperature, soil moisture, and redox potential.

In TEM, we assumed that the production of root exudates during the growing season enhances methanogenesis by increasing the availability of organic carbon substrate. To capture the effect of spatial and temporal variations in root exudates on methanogenesis, we used simulated net primary productivity (NPP) as an index of variation in methanogenic substrate (Zhuang et al. 2004). While organic substrates associated with fine root mortality are assumed to be available throughout the year, the ratio of monthly NPP to the maximum monthly NPP of the ecosystem is used to represent the additional availability of root exudates during the growing season. We modeled the effects of organic carbon substrates associated with root mortality on methanogenesis based on the distribution of roots in the soil profile. We assumed the carbon substrate availability is evenly distributed throughout the rooting zone. Below the rooting zone, we assumed the carbon substrate availability decreased exponentially with depth (Zhuang et al. 2004).

Methanogenesis and methanotrophy were driven by the daily soil temperature profile, which was simulated with a soil thermal module (STM; Zhuang et al. 2001, 2002, 2003). The sensitivity of these processes to temperature was assumed to vary for different ecosystem/soil conditions. For example, in wetland wet/moist tundra ecosystems where higher soil CH_4 concentrations exist, methanotrophy has a stronger temperature dependence ($Q_{10} = 2.2$) than occurs in the corresponding upland tundra ($Q_{10} = 1.1$). In wetland ecosystems oxidation is assumed to be mostly controlled by enzyme activity (King and Adamsen 1992), whereas in the upland tundra ecosystems oxidation is mostly controlled by the rate of CH_4 supply from the atmosphere (Zhuang et al. 2004). The STM module also simulated the depth of the soil active layer, which is the depth that determines the lower boundary of microbial activity in the soil. In wetlands, the daily soil water content and the water table depth in soils were determined using a water-balance approach that considers precipitation, runoff, drainage, snow sublimation, and evapotranspiration (Zhuang et al. 2004). In uplands, the daily soil water content was determined using the hydrological module described by Zhuang et al. (2002, 2004).

Model simulation

Input data sets.—For static spatially explicit data sets of soil texture, elevation, and vegetation, we used the data sets from Zhuang et al. (2003). To simulate methane dynamics, we also used the static data sets of the distribution of wet soils and fractional inundation from Matthews and Fung (1987) 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 daily time series data of air temperature, precipitation, and vapor pressure from the Vegetation Ecosystem Modeling and Analysis Project (Kittel et al. 2000). Specifically, we used the historical climate (1922–1996) and the future HadCM2 scenario (1997–2099) for this study. The atmospheric CO_2 concentration data for the historical period (1765–1990) was developed from Enting et al. (1994). The future atmospheric CO_2 concentrations (1990–2100) were predicted by processing the IS92a emission data (Enting et al. 1994) through the Bern global carbon cycle model (Joos et al. 1996), which was used to calculate terrestrial and oceanic uptake of atmospheric CO_2.

Simulation protocol.—To extrapolate the model to all of Alaska, we applied the parameterizations for both tundra and boreal forest (taiga) ecosystems described in
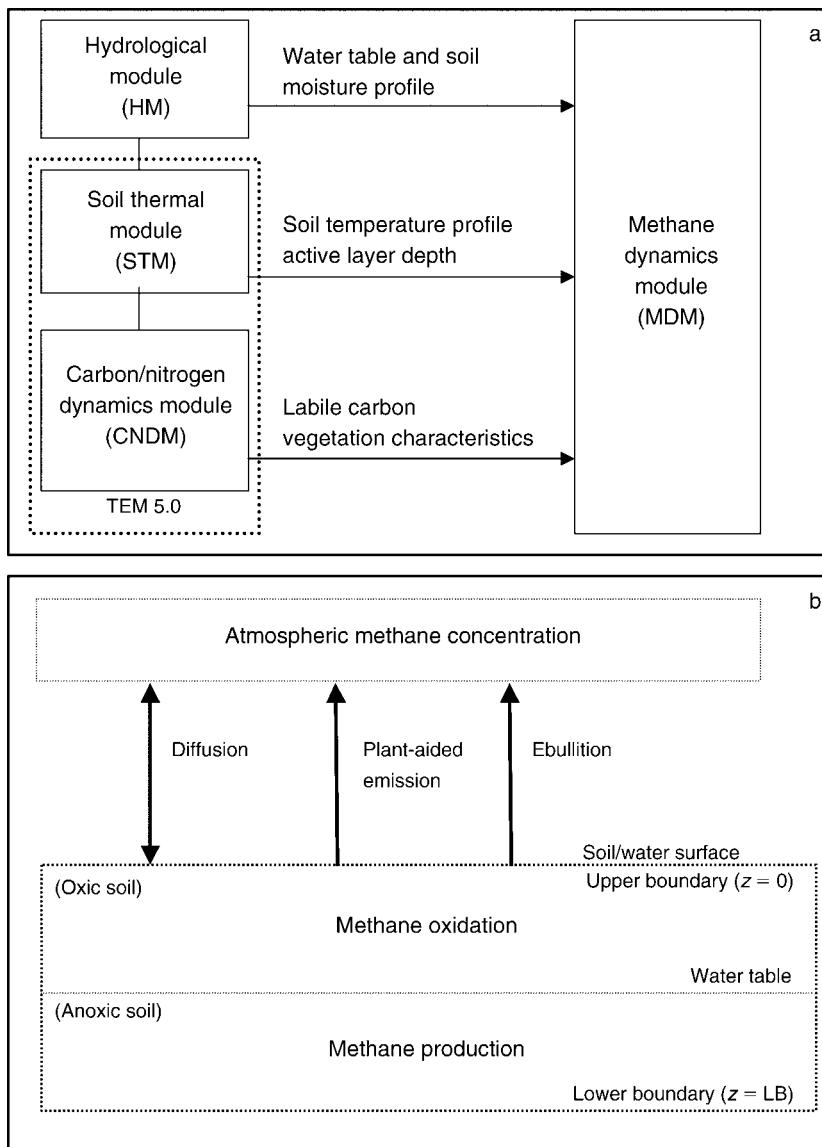
FIG. 1. The schematic diagram of the new version of a biogeochemistry model (terrestrial ecosystem model [TEM]) including: (a) the overall model structure which features a soil thermal module (STM; Zhuang et al. 2001), a hydrologic module (HM) based on Zhuang et al. (2002), a carbon/nitrogen dynamics module (CNDM) from TEM 5.0 (Zhuang et al. 2003), and a methane dynamics module (MDM); and (b) the more detailed structure of the MDM including the separation of soil into anaerobic and aerobic zones by water table position. The soil profile is divided into 1-cm layers that are referenced by their depth z from the upper boundary ($z = 0$) to a lower boundary (LB, $z > 0$). The CH$_4$ fluxes between soils and the atmosphere are calculated considering different transport pathways. For more details about the model, see Zhuang et al. (2004).

a previous study (Zhuang et al. 2004) to simulate both CH$_4$ consumption and emissions. We conducted the simulation at a daily time step and at the spatial resolution of 0.5° latitude × 0.5° longitude to estimate CH$_4$ fluxes from both wetland and upland ecosystems in Alaska from 1922 to 2099. Both wetland and upland ecosystems were assumed to occur in each 0.5° grid cell. The ecosystem-specific CH$_4$ flux estimates were then area-weighted for each grid cell as defined by the wet soil and fractional inundation data sets of Matthews and Fung (1987). We defined the regional net CH$_4$ emissions as the difference between CH$_4$ emissions from wetland ecosystems and CH$_4$ consumption in upland ecosystems.

RESULTS AND DISCUSSION

Regional net methane exchanges

Over recent decades, we estimated that Alaskan soils have been a mean net source of ~3 Tg CH$_4$/yr to the atmosphere (Table 1), that is, statewide emissions of ~4 Tg CH$_4$/yr, and a consumption of 1 Tg CH$_4$/yr (Table 2). Our simulations are characterized by significant

TABLE 1. Contribution of tundra and taiga ecosystems to net methane emissions (Tg CH_4/yr) from 1980 to 1996 and from 2080 to 2099 in Alaska.

Region	Area (Mha)	1980–1996			2080–2099		
		Tundra	Taiga	Total	Tundra	Taiga	Total
Northern Alaska (above 67° N)	36.2	1.40	0.05	1.45	2.21	0.08	2.29
Interior Alaska (62–67° N)	54.9	0.37	0.73	1.10	0.65	1.30	1.95
Southern Alaska (below 62° N)	58.4	0.60	−0.02	0.58	1.36	0.11	1.47
Alaska	149.5	2.37	0.76	3.13	4.22	1.49	5.71

Note: Positive values indicate that methane emissions to the atmosphere are greater than methane consumption by soils, while the negative value indicates that methane consumption by the soils is greater than methane emissions.

spatial variability in net CH_4 emissions across Alaska (Fig. 2). The highest rates of net CH_4 emissions mainly occurred in tundra of northern Alaska (latitudes higher than 67° N) and in the western coastal region of the state. Net consumption of CH_4 (i.e., negative net CH_4 emissions) generally occurred in the drier forest areas of interior Alaska (latitudes between 62° and 67° N) and the southern Alaskan forested areas as well as dry tundra ecosystems. For the state as a whole, tundra ecosystems contribute 77% to the total net emissions (Table 2). In contrast, boreal forests contribute 45% of the total CH_4 consumption of the state.

We projected that the annual rates of net CH_4 emissions from Alaska will increase dramatically in the future. From 2000 to 2099, the increase rate is 0.026 Tg CH_4/yr (Fig. 3b, d), with gross emissions (0.028 Tg CH_4/yr) increasing much more rapidly than consumption (~0.001 Tg CH_4/yr). Our simulations projected that net CH_4 emissions will about double by the end of this century (6 Tg CH_4/yr, Table 1) relative to current emission rates (3 Tg CH_4/yr, Table 1). Although CH_4 consumption will increase slightly, especially in the forests of the coastal zone, CH_4 emissions will dominate in the region with wet tundra ecosystems being the major source (Fig. 2). The ecosystems in southern Alaska experience the largest changes in the net CH_4 emissions with rates in the last decade of the 21st century that are almost three times current rates (Table 1). In these simulations, we have not considered the effects of projected increases in the atmospheric concentration of CH_4 during this period on soil methane consumption, and therefore the simulations may underestimate the consumption rate and overestimate net methane emissions from the region.

Comparison with site-specific observations

We compared our modeled net methane fluxes against site measurements in Alaska for recent years. We found that, for boreal forest ecosystems, the mean modeled estimates of net methane emissions (20 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$) during the growing season are just above the high end of the range of measurements (7–19 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$; Whalen and Reeburgh 1990a). For tundra ecosystems, the mean modeled estimates of net methane emissions (60 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$) during the growing season are well within the range of measured values (33–82 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$; Whalen and Reeburgh 1990a, Reeburgh et al. 1998). However, the simulated mean daily emissions rate in the 1980s of the whole Yukon-Kuskokwim Delta is ~50 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$ from June to September, which is at the low end of the observed rates from 15.6 to 426 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$ (Bartlett et al. 1992). In addition, the simulated annual emissions (5884 mg $\cdot m^{-2} \cdot yr^{-1}$) from wet tundra in the 1990s are within the range of the observations from field studies (2240–9838 mg $CH_4 \cdot m^{-2} \cdot yr^{-1}$; King et al. 1998). Similarly, we compared our simulated net methane consumption rates in upland ecosystems that exhibit net uptake. For both forests and tundra, our modeled estimates are at the high end of the range or above the range of the measured values. During the 1980s, the simulated mean consumption rate for boreal forests was 3.9 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$, which is higher than the estimates by Whalen et al. (1991, 1992), Gulledge and Schimel (2000), and Billings et al. (2000), who measured consumption rates in boreal forest soils of <2 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$. The estimate of 3.9 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$ in our simulations is at

TABLE 2. Methane emission and consumption and net emissions (Tg CH_4/yr) from 1980 to 1996 and from 2080 to 2099 in Alaskan ecosystems.

Ecosystem	Area (Mha)	1980–1996			2080–2099		
		Emissions	Consumption	Net emissions	Emissions	Consumption	Net emissions
Tundra	84	2.8	−0.49	2.4	4.8	−0.62	4.2
Taiga	63	1.2	−0.44	0.75	2.0	−0.52	1.5
Others†	3	0.01	−0.05	−0.04	0.04	−0.07	−0.03
Total	150	4.01	−0.98	3.1	6.84	−1.07	5.7

Note: Positive values indicate methane emissions to the atmosphere, while negative values indicate methane consumption by the soils.

† Other ecosystems include temperate deciduous or conifer forests, grassland, and xeric shrubland, which are not classified into either tundra or taiga in the Alaskan ecosystems.
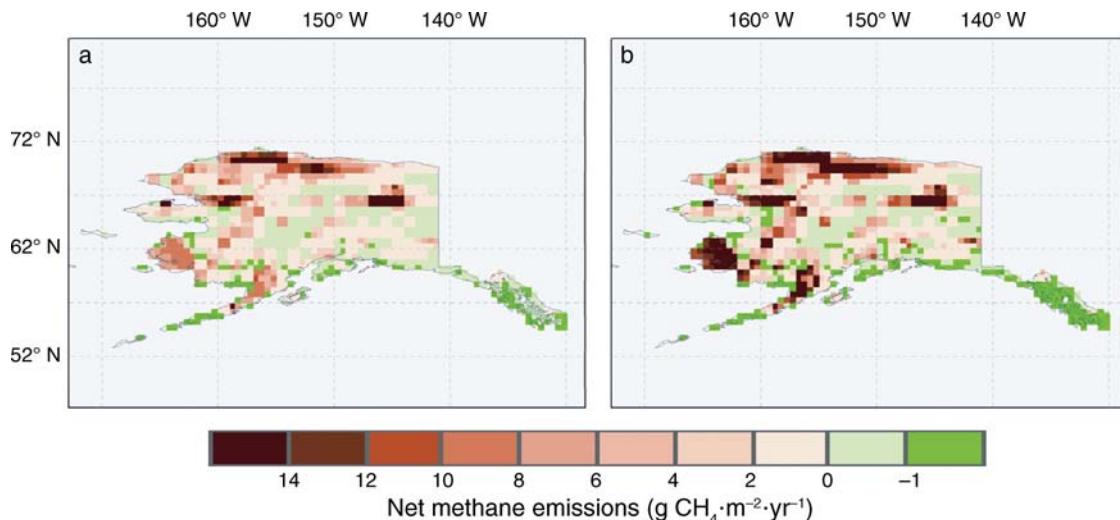
FIG. 2. Spatial patterns of simulated annual net methane emissions across Alaska during (a) the 1980s, and (b) the 2080s. Positive values indicate net release of methane to the atmosphere, and negative values indicate net consumption of atmospheric methane by soils.

the high end of field-based estimates of 0.4–4.15 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$ in temperate evergreen and deciduous forest soils (Keller et al. 1983, Steudler et al. 1989, Crill 1991). The simulated mean consumption rate in tundra ecosystems (5.4 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$) is above the high end of the estimated range 0.2–4.2 mg $CH_4 \cdot m^{-2} \cdot d^{-1}$ in moist tundra (King et al. 1989, Whalen and Reeburgh 1990a, b). In developing our estimates of methane consumption by soils, we did not consider the potential

effects of soil moisture limiting methane diffusion through unsaturated soils. As a result, our model may overestimate actual consumption rates, though as has been pointed out earlier, we may also have neglected processes that may underestimate consumption rates.

Influences of climate change on net methane emissions

To explore the effects of climate change on methane emissions from wetlands, we conducted a sensitivity
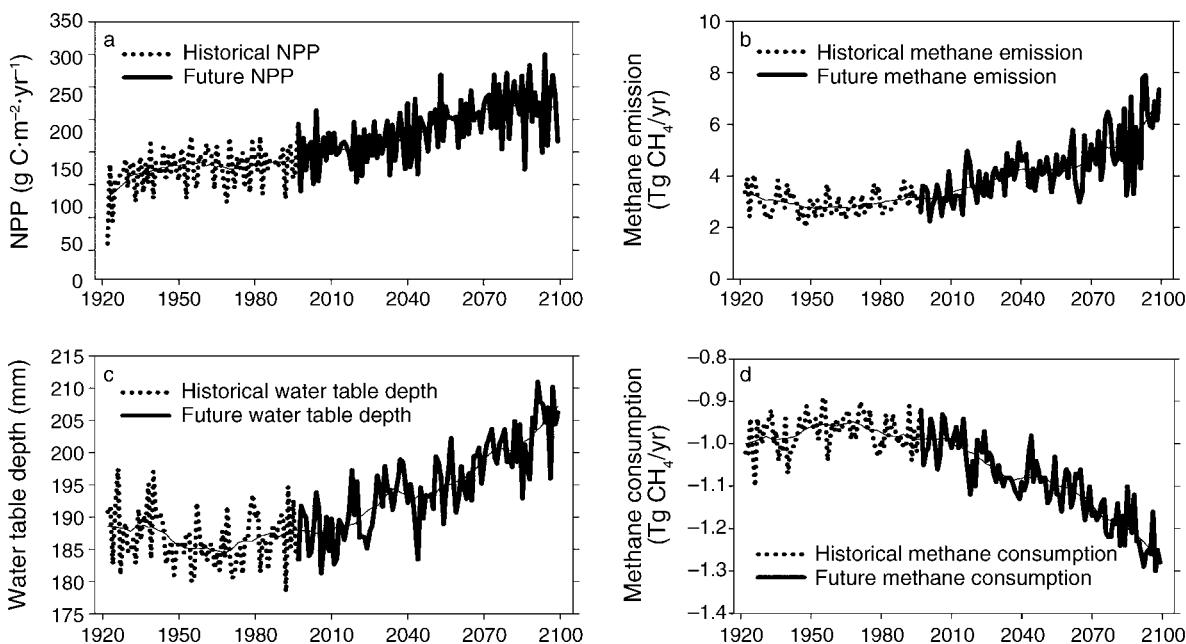
FIG. 3. Interannual variations from 1922 to 2099 of (a) simulated net primary production (NPP), (b) simulated methane emissions, (c) depth to the water table, and (d) simulated methane consumption. The thin lines represent the decadal running mean for each of those variables.

TABLE 3. Sensitivity analyses of net CH_4 emissions to the climate drivers, the carbon substrate availability, and water table depth at the NSA-FEN site for 1994 and 1996.

Direction of change in factor	Air temperature		Precipitation		Vapor pressure		Depth to water table		NPP†	
	Change‡ (°C)	Effect (%)	Change‡ (%)	Effect (%)	Change‡ (%)	Effect (%)	Change‡ (mm)	Effect (%)	Change‡ (%)	Effect (%)
Increase	2.0	+31§	20	+7.2	20	+0.2	10	−20	20	+8
Decrease	2.0	−13	20	−1.7	20	−11	10	+20	20	−8

† NPP, net primary productivity.

‡ Daily air temperature, precipitation, vapor pressure, water table depth, and NPP are uniformly changed by corresponding percentage or magnitude values for the years 1994 and 1996.

§ Percentage is calculated based on two-year average net emissions of 7 g $CH_4 \cdot m^{-2} \cdot yr^{-1}$ in the control simulation, which is conducted using driving data sets described in Zhuang et al. (2004).

study with the model for a fen site at the Northern Study Area (NSA) of the Boreal Ecosystem–Atmosphere Study (BOREAS) in Canada (see Sellers et al. 1997, Newcomer et al. 2000). The ability of the model to capture the seasonal and interannual variations in methane emissions observed at this site has already been shown in an earlier study (Zhuang et al. 2004). The model's parameterization and driving data sets for this site have been described in Zhuang et al. (2004). For the fen site, our analyses indicated that CH_4 emissions are influenced by both climate change and changes in the availability of carbon to methanogens (Table 3). Specifically, the changes of air temperature between −2° and +2°C resulted in −13% to +31% changes of CH_4 emissions, with 2°C changes influencing soil temperature and active layer depth, and thereby affecting the CH_4 production process. Precipitation changes of −20% and +20% resulted in −1.7% to +7.2% changes in net methane emissions. Our analyses suggested that the primary mechanism is that the increase or decrease in precipitation raises or lowers the depth of the water table, thus enhancing or inhibiting the methane production. Changes in vapor pressure of −20% to +20% resulted in −11% to +0.2% changes in net methane emissions by altering the soil hydrological cycle. Our analyses suggested that the 20% increase in vapor pressure decreases vapor pressure deficit to limit evapotranspiration and raise the depth of the water table, which slightly enhances methane emissions. In contrast, the decrease of vapor pressure by 20% resulted in an 11% decrease in net emissions because of a lower water table. By directly manipulating the water table depth, we found that net emissions increase by 20% for a

water table raised by 10 mm, and that net emissions decrease by 20% for a water table lowered by 10 mm. As an illustration of the importance of the linkage of labile carbon availability to the methanogenesis, our sensitivity study showed that a change of NPP (±20%) is positively correlated to a change of CH_4 emissions (±8%).

To examine the responses of methane consumption to changes in climate and changes in substrate availability to methanotrophs, we conducted a sensitivity study for a boreal forest stand at the Bonanza Creek Long Term Ecological Research site outside Fairbanks, Alaska. This ecosystem had been shown to be a net consumer of CH_4 from the atmosphere (Whalen et al. 1991, 1992). The model's parameterization and driving data sets for this site were described in Zhuang et al. (2004). Our analyses suggested that CH_4 consumption was affected by several factors in a complex way (Table 4). For example, changes in air temperature between −2° and +2° C resulted in −3.1% to 1.3% changes in CH_4 consumption. Interestingly, when we increased daily precipitation by 15%, we observed a decrease of CH_4 consumption at the site for 1990. Our analyses suggested that the increase of soil moisture surpassed the optimum moisture prescribed for the site, which is 0.6 cm^3/cm^3, thereby limiting the CH_4 oxidation rate (see Zhuang et al. 2004). In contrast, the decrease in precipitation by 15% resulted in a slight increase of CH_4 consumption at the site. As we expected, the increase of daily vapor pressure by 10% reduces evapotranspiration, and increases soil moisture, which remained below the optimum soil moisture, to cause a slight increase of consumption. As for the effects of soil CH_4 concentra-

TABLE 4. Sensitivity analyses of net CH_4 consumption to the climate drivers and soil CH_4 concentration availability at a boreal forest at the Bonanza Creek LTER site for 1990.

Direction of change in factor	Air temperature		Precipitation		Vapor pressure		Soil CH_4	
	Change (%)†	Effect (%)	Change (%)†	Effect (%)	Change (%)†	Effect (%)	Change (%)†	Effect (%)
Increase	2.0	+1.3‡	15	−4.2	10	+0.4	10	+7.4
Decrease	2.0	−3.1	15	+0.8	10	−1.7	10	−7.8

† Daily air temperature, precipitation, vapor pressure, and soil methane concentration are uniformly changed by corresponding percentage or magnitude values for the year 1990.

‡ Percentage is calculated based on two-year average net emissions of 0.13 g $CH_4 \cdot m^{-2} \cdot yr^{-1}$ in the control simulation, which is conducted using driving data sets described in Zhuang et al. (2004).

TABLE 5. Pearson correlations between annual methane emission and consumption and environmental variables across the Alaskan region from 1922 to 2099.

Variable	Emissions	Consumption
Soil temperature†	0.85	0.97
Annual precipitation	0.15	0.29
Soil moisture‡	0.02	0.05
Depth to water table§	0.82	0.96
Net primary productivity (NPP)	0.51	0.60

† The simulated mean annual soil temperature within organic soil layer (°C).

‡ The simulated mean soil moisture at about organic soil layer (mm^3/mm^3).

§ The simulated water table depth relative to the soil surface (mm).

tion on methanotrophy, our simulation indicated that the 10% increase of soil CH$_4$ concentrations could enhance consumption by 7.4%. In summary, changes in climate exert effects on CH$_4$ consumption in complex ways.

Our analyses for the region indicate that increases in soil temperature, labile carbon availability, and depth to the water table associated with climate change are the major factors that cause an increase in CH$_4$ emissions on an annual basis (Table 5). Specifically, methane emissions were strongly correlated ($N = 178$ years, $P < 0.01$) with soil temperature ($r = 0.85$), depth to the water table ($r = 0.82$), and NPP ($r = 0.51$). The significant influence of soil temperatures on methane emissions is consistent with the conclusion that soil temperature is a key factor in determining methanogenesis (e.g., Bellisario et al. 1999, Wickland et al. 1999, Pearce and Clymo 2001;

Figs. 4c and 3b). In our simulations, we found that emissions were positively correlated with water table depth. On average, the depth to the water table across Alaska was lowered 0.1 mm per year because of warming over the two centuries (Fig. 3c). The decrease of CH$_4$ production to this small change was more than compensated by the enhancement of methanogenesis due to increases in soil temperatures (Fig. 4c). Thus, over the two centuries of our simulations, we did not see negative correlations between the increase in depth to the water table and regional CH$_4$ emissions, a correlation which has often been observed in field studies (e.g., Heikkinen et al. 2002) and our site-level sensitivity studies (Table 3).

For CH$_4$ consumption in Alaska, our analyses indicated that annual CH$_4$ consumption was strongly related to soil temperature and depth to the water table (Table 5). The lowering of the water table in some parts of Alaska due to increases in air temperature (Fig. 4a) and increases in evapotranspiration resulted in an increase in CH$_4$ consumption (Fig. 3d). The correlation between depth to the water table and CH$_4$ consumption has been documented in field experiments (e.g., Nykänen et al. 1998, Heikkinen et al. 2002). In addition, a definite positive trend in both air temperatures (+6°C) and soil temperatures (+4°C) in Alaska is noticeable over our projected study period while trends in precipitation and soil moisture are much harder to distinguish from interannual variability (Fig. 4). Although simulated methane consumption is not as sensitive to temperature ($Q_{10} = 0.8–3.5$; Zhuang et al. 2004) as simulated methane productions ($Q_{10} = 3.5–7.5$; Zhuang et al. 2004), the
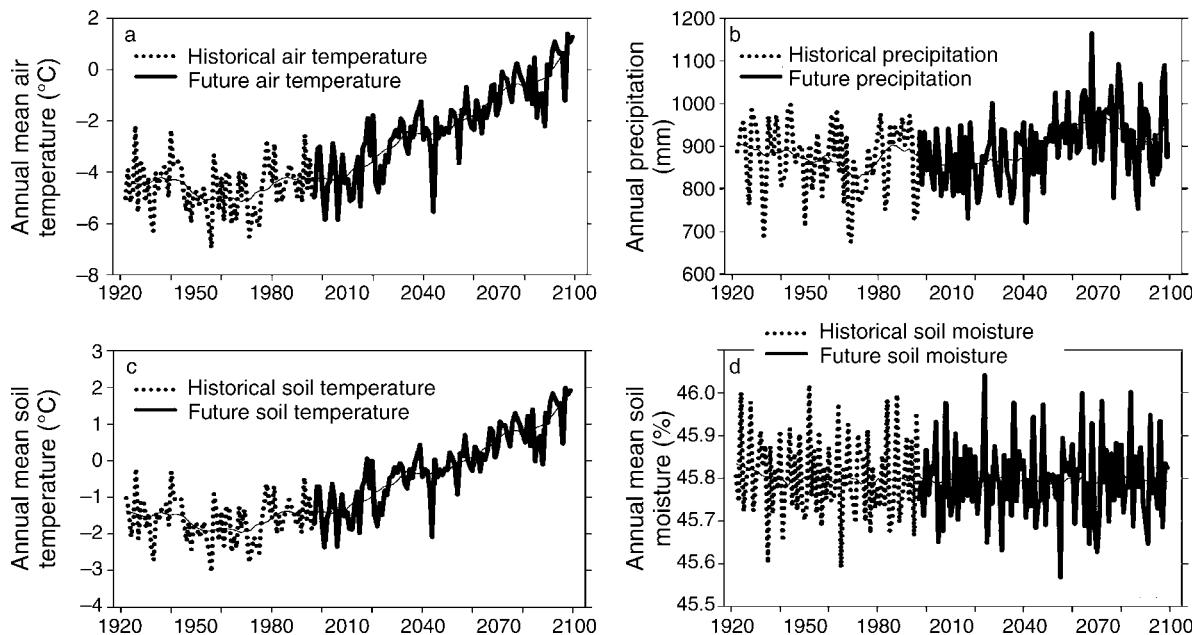
FIG. 4. Interannual variations from 1922 to 2099 of (a) air temperatures, (b) precipitation, (c) simulated soil temperature of the top 20 cm in the soil, and (d) simulated mean soil moisture. The thin lines represent the decadal running mean for each of these variables.

trend in soil temperatures would still lead to increased consumption and a correlation between soil temperatures and consumption rate, especially if no trends occur in other environmental factors. The importance of soil temperature to the consumption rate is also consistent with the laboratory studies of Whalen and Reeburgh (1996) for soils with the high CH_4 concentrations. This result differs from the results of several field studies in temperate and tropical ecosystems (e.g., Steudler et al. 1989, Wickland et al. 1999), which indicated that moisture across the growing season is a predictor of CH_4 uptake outside of high latitude regions. Our lower correlations between soil moisture and consumption rate, however, are consistent with the results of field studies in Alaskan taiga forest stands (Gulledge and Schimel 2000).

Contributions of net methane emissions to greenhouse gas budgets of Alaskan ecosystems

Our simulations indicated that during the period of 1980–1996, the net CH_4 emissions from Alaskan soils (3.13 Tg CH_4/yr) were equivalent to 72 Tg CO_2/yr with respect to global warming potentials (GWPs), calculated on a 100-year time horizon, i.e., one gram of CH_4 is equivalent to 23 g of CO_2 (IPCC 2001). Estimates by other researchers suggested that during this same period, Alaska's boreal forest ecosystems sequestered between 2.3 and 11.5 Tg C/yr (Yarie and Billings 2002, McGuire et al. 2004). From these estimates, we assumed that Alaskan terrestrial ecosystems sequestered ~10 Tg C/yr, which are equivalent to 37 Tg CO_2/yr based on molecular masses (i.e., 12 g of carbon exist in 44 g of carbon dioxide). When we combine the net CH_4 emissions expressed in CO_2 equivalents with the terrestrial sink expressed in the same units, we estimated that Alaska's terrestrial ecosystems functioned as a mean net greenhouse gas source of 35 Tg CO_2 equivalents/yr to the atmosphere during the period of 1980–1996.

For the future, Yarie and Billings (2002) estimated that the Alaskan boreal forests would sequester 17 Tg C/yr under a 5°C increase of air temperatures over the next century. Based on these estimates and our calculations of CH_4 emissions for the end of the 21st century, we estimated that the region would act as a larger source of greenhouse gases at 69 Tg CO_2 equivalents/yr to the atmosphere in the future. The enhanced CH_4 emissions would create a positive feedback to the climate system.

Influence of additional factors on future methane emissions

In the analyses of projected CH_4 dynamics for Alaska, a number of additional factors should be considered. In our analyses, we used the wetland distribution and inundation fractional databases of Matthews and Fung (1987), which represent the static wetland distribution without considering the wetland expansions or drying due to drainage and permafrost thawing (McGuire et al. 2004). While the dynamics of wetland distribution is not currently available for our simulations, regional hydrological modeling approaches such as the TOPMODEL approach (Stieglitz et al. 1997) might be useful for characterizing changes in wetland redistribution with climatic changes. Another important factor would be fire disturbance, which could also contribute CH_4 emissions to the atmosphere (e.g., van Der Werf et al. 2004). For example, French et al. (2004) estimated that fire emissions of CO, CO_2, and CH_4 in Alaska contributed a total of 4.5 Tg C/yr to the atmosphere. From 1989 to 1997, CH_4 emissions from fires contributed an average of 0.064 Tg CH_4/yr and with maximum emissions ~0.34 Tg CH_4/yr in 1990. Therefore, in future calculations of greenhouse gas budgets for Alaska, fire emissions of these gases should be taken into account.

CONCLUSIONS

Our simulations showed that both CH_4 emissions and consumption would increase in the future, with wet tundra ecosystems functioning as the major emission sources of methane and dry tundra as well as taiga ecosystems acting as the major sites of methane consumption. Net CH_4 emissions are significantly related to soil temperature, water table depth, and carbon substrate availability. While the warming trend enhances NPP and carbon sequestration of Alaskan ecosystems, there are also positive feedbacks between the warming trend and the atmospheric CH_4 emissions from Alaskan ecosystems. We estimated that Alaska currently acts a source of greenhouse gases to the atmosphere at 35 Tg CO_2 equivalents/yr. By the end of the 21st century, we estimated that the region would act as a source of greenhouse gases of 69 Tg CO_2 equivalents/yr to the atmosphere. If our projected changes in greenhouse gas budgets for Alaska in response to climate change are typical for the entire Pan-Arctic region, 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).

Program on the Science and Policy of Global Change, which is supported by a consortium of government, industry, and foundation sponsors.

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