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INTERANNUAL VARIATIONS IN TUNDRA METHANE EMISSION: A 4-YEAR TIME SERIES AT FIXED SITES

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Abstract. This paper summarizes 4 years (1987-1990) of weekly net CH_4 flux measurements at permanent sites representing important plant components of Arctic tundra. The data coincide with variations in precipitation and temperature of interest in regional and global modeling efforts and are useful in placing bounds on the role of tundra in the global CH_4 budget. Precipitation in the study area during the summer emission period ranged from twice to half the long-term mean, and air temperature anomalies were about +2 °C. This data set also permits consideration of temporal (seasonal to interannual) and spatial variability in CH_4 flux. We studied the relationship between the net CH_4 flux and subsurface properties (water table depth, thaw depth, soil temperature, pCH_4 distributions) at these permanent sites during the 1988 and 1989 emission periods. Net CH_4 emission and subsurface properties are largely unrelated. Relationships between soil temperature (or any single variable) and emission are site specific and are of little value as flux predictors. Parameters that integrate conditions influencing flux appear to be the best flux predictors over the emission period. We estimate that Arctic wet meadow and tussock:shrub tundra presently emit about 42 ± 26 Tg CH_4 yr^{-1} to the atmosphere. This estimate has a North American bias, but it is supported by measurements in a range of locations, transect studies, and model calculations.

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INTRODUCTION

Tundra environments occupy some 7% of the Earth's land area and contain about 13% of its stored soil carbon [Post et al., 1982]. The fate of this stored soil carbon under altered climate is a major question [Billings, 1987]. The role of high-latitude wetlands in the global CH_4 budget was poorly known until recently. Prior to 1986, only three publications [Svensson, 1976; Svensson and Rosswall, 1984; Sebacher et al., 1986] reported measurements of CH_4 fluxes from tundra environments. Reports of increases in atmospheric CH_4 concentrations [Rasmussen and Khalil, 1981, 1984; Blake and Rowland, 1988], confirmation of the increase in ice cores [Raynaud et al., 1988; Stauffer et al., 1985], and the realization that trace gases could have an effect on greenhouse warming [Dickinson and Cicerone, 1985; Ramanathan et al., 1985] have stimulated a broad reexamination of the global CH_4 budget [Cicerone and Oremland, 1988; Fung et al., 1991].

Several approaches have been used in assessing the role of high latitude wetlands in the global CH_4 budget. These include vegetation assessments and application of emission data from characteristic areas

[Matthews and Fung, 1987; Aselmann and Crutzen, 1989; Fung et al., 1991], intensive field campaigns in representative areas over relatively short time periods (e.g., ABLE 3A (Yukon-Kuskokwim delta, 1988), ABLE 3B/NOWES (Hudson's Bay lowlands, 1990), flux transects [Sebacher et al., 1986; Whalen and Reeburgh, 1990a], and time series flux measurements at representative sites over several months [Crill et al., 1988; Harriss et al., 1982; Moore and Knowles, 1990; Moore et al., 1990] or a year [Whalen and Reeburgh, 1988]. The work reported here extends the latter study to 4 years, 1987 through 1990. During this period the summer precipitation varied by twice and half of the long-term (~50 yr) mean, and air temperatures were generally 2 °C above the long-term mean. The data allow the first assessment of interannual variability in high-latitude CH_4 flux and are useful in placing bounds on tundra CH_4 emission. Further, the interannual variations in precipitation and air temperature cover a range of interest to global climate change modelers.

METHODS

This study is a continuation of our earlier work [Whalen and Reeburgh, 1988] and uses the same sampling sites and methods.

Sites

Sampling sites were located in a muskeg and along a pond margin (Smith Lake) in the University of Alaska Arboretum (64° 52' N, 147° 51' W, 158.5 m elevation). Physical and vegetative characteristics of the study area are similar to those of Arctic tundra; poorly drained soils are underlain by permafrost and an *Eriophorum vaginatum* L. tussock plant community [Kummerow et al., 1983; Wein and Bliss, 1974] dominates the muskeg, while extensive stands of *Carex* spp. line the margin of Smith Lake. Three permanent sampling stations were located within each of four floristic units or sites: (1) *E. vaginatum* tussocks (T stations), (2) intertussock depressions ("black hole" or BH stations) that are often waterlogged and have a surface layer of detritus or *Sphagnum* spp., (3) mossy areas (M stations) which are elevated relative to the BH stations and contain no *Sphagnum*, and (4) *Carex* stands (C stations). Examples of a T, BH, and M station were grouped or clustered within 1 to 2 m at three locations separated by 10 to 20 m within the muskeg, and C stations were established in three distinct stands of *Carex aquatilis* Wahlenbach separated by about 20 m on the margin of Smith Lake. The sites were dispersed over such a large area that elevated walkways were impractical; firm soils minimized station disturbance during sampling. Paths were worn to the sites, and the stations became somewhat shopworn after 3 years of year-round study; new stations were established in the same muskeg and pond margin before freeze-up in 1989 and were sampled during 1990. We determined that winter CH_4 emissions were insignificant and suspended winter measurements in December, 1989.

Net CH_4 Flux Measurements

Net CH_4 fluxes were determined using static chambers. Each flux chamber consisted of a skirted aluminum base, stackable lucite vertical sections, and a lucite lid. Each lid was fitted with a capillary bleed to equalize pressure and a Swagelok O-seal fitting equipped with a septum for syringe sampling. Water-filled channels provided seals between the chamber components. The aluminum bases were permanently set in the soil at M, BH, and C sites, and isolated an area of 0.075 m^2. Smaller bases (0.023 m^2) were permanently inserted directly into the tops of *Eriophorum* tussocks at T sites from 1987 to 1989; regular bases (0.075 m^2) were used to surround each tussock at the soil surface when new stations were established in 1989. Chamber headspaces were sampled with glass-barrel syringes over a 0.5 to 24 hour time course, and CH_4 concentrations were determined within a few hours of sample collection by gas chromatography. A Shimadzu GC Mini-2 gas chromatograph equipped with a flame ionization detector and sampling valve was used for the analyses. Analytical precision was 2%; working standards were relatable to National Bureau of Standards standards. Methane fluxes were calculated from chamber geometry and the linear change in CH_4 concentration with time.

Other Measurements

All supporting environmental measurements were made at primary stations (T-1, M-1, BH-1, and C-1 in 1987 through 1989; T-4, M-4, BH-4, and C-11 in 1990) whenever CH_4 fluxes were determined; less comprehensive environmental data were collected simultaneously at other stations. Soil environmental variables are measured relative to the soil surface.

The water table level was measured between 1988 and 1990. Shallow wells were bored adjacent to all stations, were cased with perforated PVC pipe to prevent collapse, and were screened to avoid decimating the local vole population.

Soil temperatures were measured with permanently deployed multithermister probes extending from the soil surface to permafrost at all primary stations

except C-1 and C-11, where thermistors extended to 40 and 70 cm, respectively. Mean soil temperatures in the thawed layer at T, M, and BH primary stations were calculated by integrating temperature data from the soil surface to permafrost. Mean soil temperatures to the deepest thermistor were calculated at C primary stations.

Thaw depths were measured by inserting a 3-mm-diameter stainless steel rod to the frozen soil horizon. The thaw season reported at each station (Tables 1-4)

TABLE 1. 1987 Summary Data for CH_4 Flux and Environmental Variables During Thaw Season at Permanent Sampling Stations in the University of Alaska Arboretum

Site	n	CH_4 Flux, mg m^{-2} d^{-1}				Maximum Thaw Depth, cm	Thaw Duration, days	Mean Soil Temperature, °C
		Mean	SEM[a]	Maximum	Median			
BH-1	14	4.4	2.5	33.6	0.8	-45	136	1.0
BH-2	12	2.6	1.3	16.0	1.1	-52	125	
BH-3	13	1.5	0.5	5.6	0.7	-49	131	
C-1[b]	11	14.1	3.2	36.7	10.5			7.7
C-2	11	36.5	5.5	75.2	32.4			
C-3	11	50.0	7.6	104.9	38.4			
M-1	16	1.7	0.5	5.5	0.4	-62	146	3.0
M-2	15	0.5	0.2	2.1	0.2	-55	141	
M-3	15	0.6	0.3	3.8	0.1	-62	141	
T-1[c]	16	51.4	15.9	166.6	15.5	-71	146	3.3
T-2	16	8.7	2.7	30.1	0.6	-83	146	
T-3	16	28.3	8.6	90.3	8.5	-76	146	

[a]SEM is the standard error of mean.

[b]All data for Carex (C) sites taken from May 26 (~3 weeks after spring thaw) until freeze-up.

[c]Thaw depth from top of tussock.

TABLE 2. 1988 Summary Data for CH_4 Flux and Environmental Variables During Thaw Season at Permanent Sampling Stations in the University of Alaska Arboretum

Site	n	CH_4 Flux, mg m^{-2} d^{-1}				Maximum Thaw Depth, cm	Water Table Range, cm	Thaw Duration, days	Mean Soil Temperature, °C
		Mean	SEM[a]	Maximum	Median				
BH-1	18	18.6	8.5	139.5	1.6	-53	-3 to 5	148	1.3
BH-2	18	8.8	7.0	127.9	0.8	-57	0 to 15	148	
BH-3	18	48.2	18.3	292.0	2.3	-58	-6 to 8	148	
C-1	19	2.1	1.3	11.1	0.7			155	8.6
C-2	19	5.3	0.5	11.9	4.0			155	
C-3	19	2.1	0.4	5.2	1.9			155	
M-1	19	23.1	7.8	146.4	11.4	-71	-6 to 0	155	3.1
M-2	19	1.9	0.8	14.0	0.3	-64	-16 to 0	155	
M-3	19	5.3	2.7	43.2	0.3	-70	-18 to 0	155	
T-1[b]	19	28.2	8.3	134.8	5.3	-80	0 to 9	155	4.1
T-2	19	27.5	8.6	143.3	7.4	-88	-10 to 8	155	
T-3	19	126.7	43.7	653.2	4.3	-85	-6 to 2	155	

[a]SEM is the standard error of mean.

[b]Thaw and water table depths from top of tussock and soil surface, respectively.

is the period from initial rod penetration in the spring to surface soil freeze-up in the fall. The "warm rim effect" [Likens and Johnson, 1969] limited permafrost formation in the lake margin, so no thaw depth determinations were made at C stations.

Soil CH_4 profiles were sampled with equilibration samplers [Hesslein, 1976] within 0.5 m of primary stations during the 1988 and 1989 thaw seasons. The 1989 soil CH_4 measurements were made at station C-7. The samplers were made of lucite and had equilibration wells (3 cm3) spaced at 2.5-cm intervals along the sample probe. The equilibration

TABLE 3. 1989 Summary Data for CH_4 Flux and Environmental Variables During Thaw Season at Permanent Sampling Stations in the University of Alaska Arboretum

Site	n	CH_4 Flux, mg m^{-2} d^{-1}				Maximum Thaw Depth, cm	Water Table Range, cm	Thaw Duration, days	Mean Soil Temperature, °C
		Mean	SEM[a]	Maximum	Median				
BH-1	19	9.6	4.9	82.7	0.3	-55	-22 to 8	139	2.9
BH-2	19	10.4	2.7	40.3	8.1	-62	-27 to 10	139	
BH-3	19	17.1	7.7	145.3	7.2	-61	-29 to 7	139	
C-1	20	12.8	2.8	39.8	10.9			151	10.1
C-2	20	15.7	5.4	104.1	6.6			151	
C-3	20	40.4	5.9	80.7	46.2			151	
M-1	19	76.3	20.6	366.9	43.5	-71	-30 to 0	139	5.0
M-2	19	3.9	0.9	13.6	3.0	-75	-40 to 4	139	
M-3	20	6.9	1.8	28.2	4.5	-72	-29 to 0	151	
T-1[b]	20	42.9	6.8	85.5	35.5	-80	-23 to 7	151	4.9
T-2	20	23.5	4.9	82.5	20.3	-96	-32 to 9	151	
T-3	20	79.9	28.2	445.2	21.6	-95	-29 to 7	151	

[a]SEM is the standard error of mean.

[b]Thaw and water table depths from top of tussock and soil surface, respectively.

TABLE 4. 1990 Summary Data for CH_4 Flux and Environmental Variables at Permanent Sampling Stations in the University of Alaska Arboretum, May 21 through September 22, 1990

Site	n	CH_4 Flux, mg m^{-2} d^{-1}				Maximum Thaw Depth, cm	Water Table Range, cm	Mean Soil Temperature, °C
		Mean	SEM[a]	Maximum	Median			
BH-4	17	14.3	5.1	57.4	1.6	-74	6 to 20	2.5
BH-5	17	2.9	1.2	20.1	1.3	-71	0 to 12	
BH-6	17	0.4	0.2	2.9	0.2	-58	0 to 18	
C-11	17	299.6	60.0	930.9	212.3		1 to 48	
C-12	17	644.9	145.7	2216.4	478.0		13 to 62	11.2
C-13	17	411.3	79.8	1289.3	371.1		15 to 65	
M-4	17	7.2	1.7	26.1	5.9	-74	-2 to 15	3.2
M-5	17	3.0	0.7	8.7	2.7	-70	-21 to -9	
M-6	17	1.1	0.3	4.3	0.4	-60	-7 to -25	
T-4[b]	17	89.8	17.1	190.8	92.0	-91	-10 to 10	4.7
T-5	17	136.3	21.8	301.9	126.3	-81	-12 to 1	
T-6	17	64.4	11.2	198.4	65.0	-95	-7 to 11	

[a]SEM is the standard error of mean.

[b]Thaw and water table depths from top of tussock and soil surface, respectively.

wells were filled with degassed distilled water and were covered with a gas-permeable membrane (Teflon FEP, 2 mil thickness), which was held in place with a perforated plate. The samplers were inserted in a snug pilot hole made previously with another sampler and were allowed to equilibrate in the field for 2 weeks. Equilibrated water (2 cm^3) was withdrawn by puncturing the membrane with two hypodermic needles, one attached to a syringe for sample collection and one that served as an air inlet. The syringe contents were injected into capped, He-filled serum vials (30 cm^3) that were allowed to equilibrate 24 hours with periodic shaking before analysis of headspace CH_4. The water table position sometimes fell below the topmost equilibration wells during deployment, and since these wells remained water filled, they sampled gases in the moist soil zone. Bunsen solubility coefficients at 10 °C [Yamamoto et al., 1976] were used to calculate the dissolved CH_4 concentration. Soil CH_4 distributions are expressed as pCH_4 (matm) to present data from both the waterlogged and moist soil zones in comparable units.

RESULTS

Methane Flux Time Series

Figures 1-4 show net CH_4 flux at T, M, BH, and C stations, respectively, from 1987 through 1990. Negative fluxes (net CH_4 consumption) were never observed during the study. Methane emission varied seasonally at all stations, although the seasonality is less evident with the log flux scale. In general, highest fluxes occurred in midsummer, and lowest fluxes were recorded in late winter. Winter emissions were at or near zero at T and BH stations but persisted at 1 to >100 mg CH_4 m^{-2} d^{-1} at some M and C stations. Winter flux characteristics at active stations showed no year-to-year consistency. For example, M-3 showed notable winter CH_4 emission only during 1988-1989, when November through April fluxes varied from 5.7 to 128.9 mg m^{-2} d^{-1}. Similarly, C-3 exhibited little winter activity until 1989, when more limited data (November through December) showed CH_4 emission ranging from 2.5 to 11.1 mg m^{-2} d^{-1}. Thaw season CH_4 emission

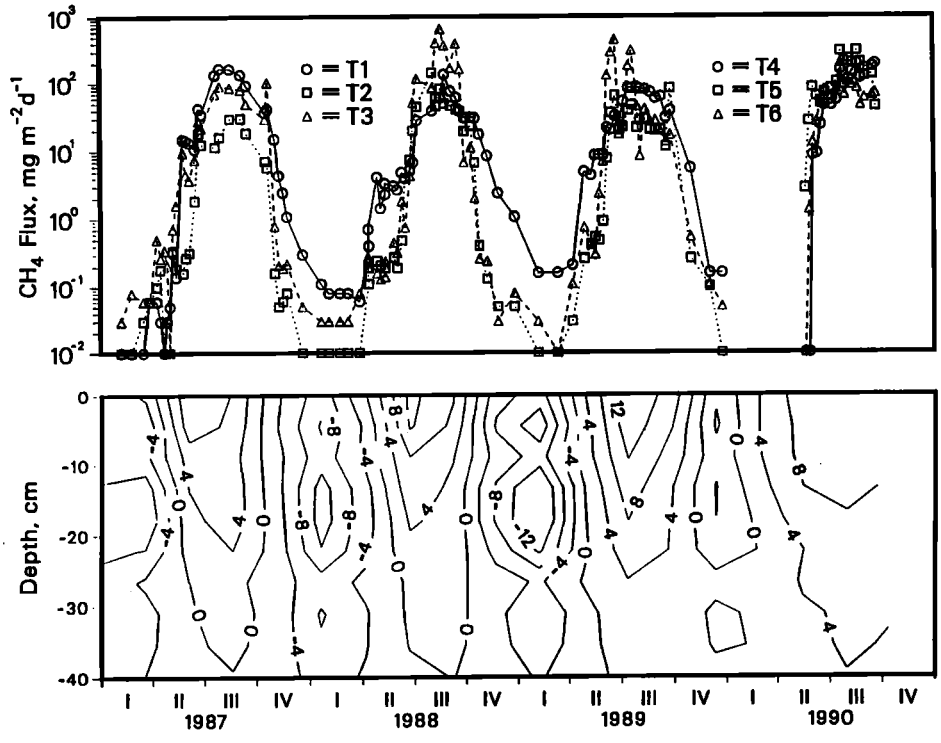

Fig. 1. Net CH_4 flux to atmosphere and soil temperatures for tussock (T) sites in University of Alaska Arboretum, 1987-1990. (Top) Net CH_4 flux versus time for permanent tussock stations. Note log flux scale; fluxes of 0 mg m^{-2} d^{-1} plotted on abscissa. (Bottom) Soil isotherms (4 °C contour interval) on depth versus time plot for stations T-1 (1987-1989) and T-4 (1990). Winter measurements were suspended after December 1989.

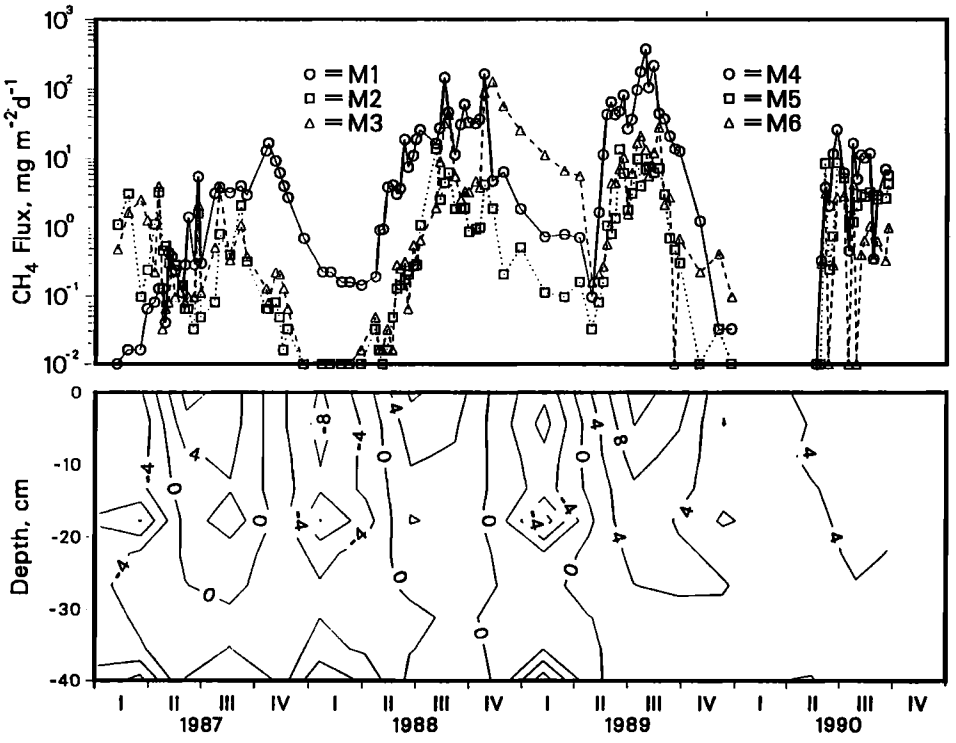

Fig. 2. Net CH_4 flux to atmosphere and soil temperatures for moss (M) sites in University of Alaska Arboretum, 1987-1990. (Top) Net CH_4 flux versus time for three permanent moss stations. Note log flux scale; fluxes of 0 mg m^{-2} d^{-1} plotted on abscissa. (Bottom) Soil isotherms (4 °C contour interval) on depth versus time plot for stations M-1 (1987-1989) and M-4 (1990). Winter measurements were suspended after December 1989.

accounted for 77 to 92%, 33 to 88%, 83 to 95%, and 65 to 88% of annual emission at T, M, BH, and C sites during the calendar years 1987 through 1989. Thaw season emissions would have been >90% at all primary stations if the thaw seasons were considered to extend until soils froze to permafrost. This usually occurred 2 to 3 weeks after freezing of surface soils.

Summary data for CH_4 flux during the 1987 through 1990 thaw seasons are given in Tables 1-4. Thaw season CH_4 emission at each station is so variable that both mean (and standard error) and median fluxes are given as measures of central tendency. Mean and median fluxes for T stations for all years and means and medians for C stations during 1987 and 1990 generally ranked highest when within-year comparisons of data from all stations were made. These stations consistently showed high emission throughout the thaw season. Mean and median fluxes at M stations (except M-1) were consistently low. Black hole (BH) stations frequently showed high mean, but low median fluxes. This resulted from episodic emission on one or two dates (e.g., BH-3 in 1988; Table 2). Minimum fluxes approached zero in most cases and are not given.

Within-site and spatial variations in thaw season CH_4 fluxes were remarkably high. Coefficients of variation (CV) for CH_4 emission from T, M, BH, and C sites averaged 84, 118, 93, and 67% (n = 62 to 73; stations separated by 10 to 20 m). The CV for CH_4 flux from T-M-BH clusters (all data) averaged 96% (n = 198; stations separated by 1 to 2 m).

Methane fluxes (mg m^{-2} d^{-1}) for each station (Figures 1 - 4) were averaged, and these were integrated (trapezoidal rule) over time to give annual emission estimates for each site (Table 5). Methane emission from the T site showed little interannual variability, ranging over a factor of only 1.7. In contrast, annual emissions at the BH and M sites ranged over factors of 7 and 10, respectively, and the data for the C site varied by a factor of 74.

Annual flux estimates for each tundra component in Table 5 were weighted as in the work by Whalen and Reeburgh [1988] to estimate global tundra CH_4 emission for 1987 through 1990 (Table 6). Overlap in percent ground cover occupied by each site type causes total areal coverage to exceed 100%. Nonetheless, three points are clear in Table 6. First, tussocks (T site, *Eriophorum*) are responsible for

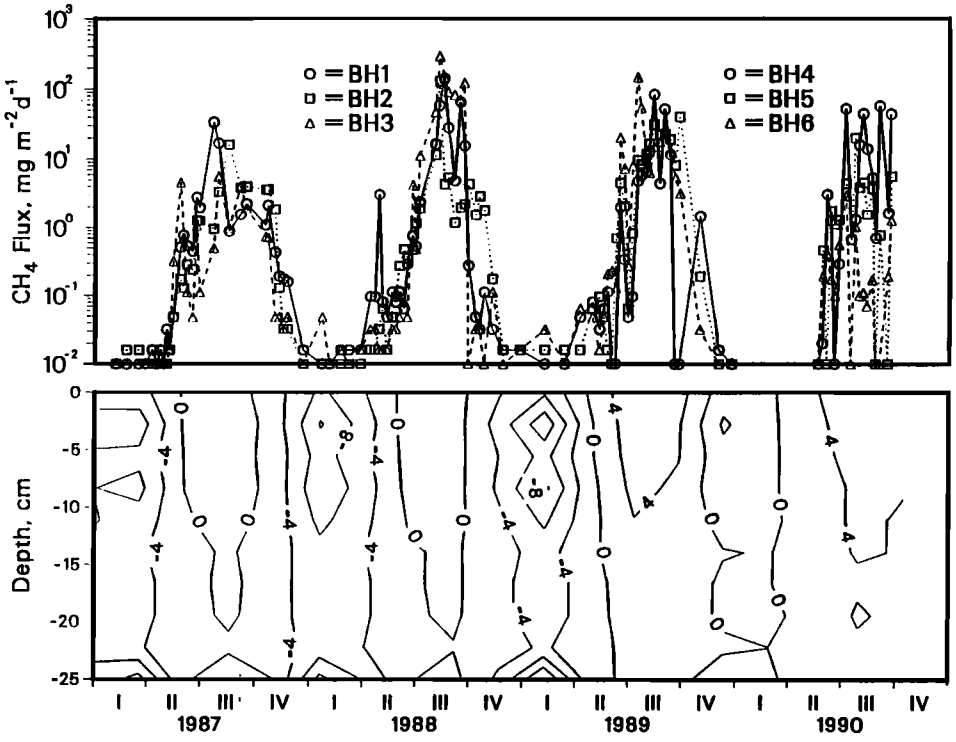

Fig. 3. Net CH_4 flux to atmosphere and soil temperatures for intertussock depression or black hole (BH) sites in University of Alaska Arboretum, 1987 1990. (Top) Net CH_4 flux versus time for three permanent black hole stations. Note log flux scale; fluxes of 0 mg m-2 d-1 plotted on abscissa. (Bottom) Soil isotherms (4 °C contour interval) on depth versus time plot for stations BH-1 (1987-1989) and BH-4 (1990). Winter measurements were suspended after December 1989.

most of the CH_4 emitted from tussock:shrub tundra. Second, the C site (*Carex*) accounts for most of the CH_4 emission from wet meadow tundra; it is the dominant plant form and annual CH_4 emission was roughly equal to or exceeded that of the M site in all study years except 1988 (Table 5). Finally, the annual source strength of tundra in the global CH_4 budget is highly variable. The mean global emission calculated from the 1987-1989 estimates is 42 ± 26 Tg CH_4 yr-1. Including the 1990 global emission estimate, which contains the unusually high *Carex* emission rate (Tables 5 and 6), gives a global emission estimate of of 57 ± 39 Tg yr-1.

Environmental Variables

Air temperature and precipitation data from the study area are presented in Figures 5 and 6. Air temperatures during the study were generally higher than the long-term mean. Only 9 of 48 months showed negative temperature anomalies. Air temperature anomalies were about +2 °C during the June through September emission period. Cumulative annual precipitation varied from 16 cm (1987) to 47 cm (1990), or from 60 to 170% of the long-term mean of 28 cm. Summer rainfall is critical in regulating water table position in the muskeg. Soils are water-saturated at freeze-up, and the snow pack is largely exported by runoff before surface soils thaw, so that little standing water remains. Summer rainfall during 1987 through 1989 was low; precipitation during this period was only 56 to 67% of the the long-term mean value of 16 cm. In contrast, 1990 summer precipitation totaled 30 cm, or about 190% of the long-term mean.

Tables 1-4 contain summary data for environmental variables at permanent sampling stations from the 1987-1990 thaw seasons, respectively. Annual ranks of the duration of thaw, maximum thaw depth, and mean soil temperature for sites followed a predictable pattern based on local topography. Tussocks are taller than the surrounding vegetation, so they thaw earlier. The lake margin experiences early thaw due to the high heat content of the eulittoral zone. The duration of thaw varied from 125 to 155 days, with the longest thaw seasons observed at T and C stations. Maximum thaw depths averaged about -85, -70 and -55 cm at T, M, and BH stations. Mean soil

temperatures of approximately 9 °C at C stations were 5 °C higher than at stations located in the muskeg. Muskeg soil temperatures averaged 1° to 5 °C, with means increasing in the order BH, M, and T.

The water table position at T, M, and BH stations was always at or above the soil surface at fall freeze-up and at spring thaw, as noted above. Low summer precipitation (Figure 6) resulted in a progressive lowering of the water table level through the thaw season at these stations to local minima of -18 and -40 cm in 1988 and 1989 (Tables 2 and 3). Soils remained saturated throughout the thaw season at only two stations (T-1 and BH-2) in 1988, while no soils remained saturated in 1989. The summer

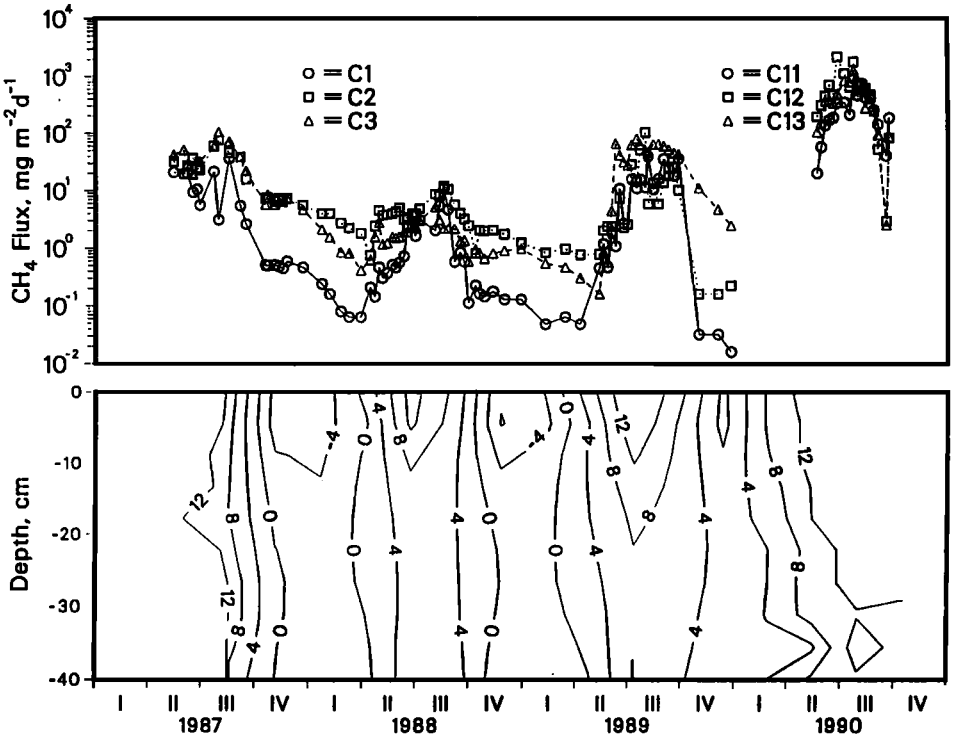

Fig. 4. Net CH_4 flux to atmosphere and soil temperatures for *Carex* (C) sites in University of Alaska Arboretum, 1987-1990. (Top) Net CH_4 flux versus time for three permanent *Carex* stations. Note log flux scale. (Bottom) Soil isotherms (4 °C contour interval) on depth versus time plot for stations C-1 (1987-1989) and C-11 (1990). Winter measurements were suspended after December 1989.

TABLE 5. Methane Emission by Tundra Site Types

	Year			
	1987	1988	1989	1990
(T) *Eriophorum*	8.05 ± 2.5	11.38 ± 2.88	8.11 ± 1.80	13.64 ± 1.20
(C) *Carex*	4.88 ± 0.73	0.81 ± 1.09	4.27 ± 0.67	60.60 ± 8.66
(M) Moss	0.47 ± 0.16	4.38 ± 1.35	4.78 ± 1.56	0.54 ± 0.12
(BH) Black Hole	0.62 ± 0.28	3.90 ± 1.09	2.12 ± 0.66	0.79 ± 0.36

Emission measured in g CH_4 m^{-2} yr^{-1}. Integrated annual CH_4 flux for each site ± 1σ. Integration period for 1987, 1988, and 1989 was January 1 to December 31. No winter measurements were made in 1990; data for 1990 assume CH_4 flux increases linearly from May 1 to May 21 (date of first flux determination) and decreases linearly from September 22 (date of last flux determination) to October 15.

TABLE 6. Global Tundra Methane Emission Estimate

Site	Percentage Cover[a]	Methane Emission, Tg yr^{-1} 1987	1988	1989	1990
		Tussock and Low Shrub Tundra (6.46×10^{12} m^2)[b]			
Eriophorum	24 - 45	8.6 - 30.7	13.2 - 41.4	9.8 - 28.8	19.8 - 43.1
Carex	3 - 7	0.8 - 2.5	0 - 0.9	0.7 - 2.2	10.3 - 31.3
Moss	37 - 63	0.7 - 2.6	7.2 - 23.3	7.7 - 25.8	1.0 - 2.7
Black Hole	30	0.7 - 1.7	5.4 - 9.7	2.8 - 5.4	0.8 - 2.2
Σ Tussock		10.8 - 37.5	25.8 - 75.3	21.0 - 62.2	31.9 - 79.3
		Wet Meadow Tundra (0.884×10^{12} m^2)			
Carex	80 - 90	2.9 - 4.5	0 - 1.5	2.5 - 3.9	36.7 - 55.1
Moss	10 - 20	0.03 - 0.11	0.3 - 1.0	0.3 - 1.1	0 - 0.1
Σ Wet Meadow		2.9 - 4.6	0.3 - 2.5	2.8 - 5.0	36.7 - 55.2
Σ Tundra		13.7 - 42.1	26.1 - 77.8	23.8 - 67.2	68.6 - 134.5

[a]Kummerow et al., 1983; Walker et al., 1987.

[b]Total tundra area is 7.34×10^{12} m^2 [Matthews, 1983]; wet meadow tundra area is taken as all nonforested bog north of 50°N [Matthews & Fung, 1987; Table 5].

rainfall deficit was greater in 1989 than 1988 (7 cm versus 5 cm), and this is reflected in a greater water table reduction for 1989. Data for 1990 (Table 4) are not directly comparable to previous data due to station relocation. During this year of elevated precipitation (Figure 6), BH stations within the muskeg remained waterlogged throughout the thaw season. The magnitude and areal extent of the drop in water table level over the growing season at T and M stations was roughly comparable to that observed at similar stations in 1988 (Table 2).

Water table levels at C stations are reported for 1990 only. Stations were initially established on the Smith Lake margin midway between the Fall 1986, low water mark and the historic high water mark. The water table level was below the 70-cm-deep gauging wells late in the low summer precipitation years of 1988 and 1989. The new C stations were established at roughly the same elevation for 1990 sampling; the water table was above the soil surface throughout this summer of high rainfall (Table 4).

Rank correlations between CH_4 flux and environmental data are given in Table 7. The best relationship was found between CH_4 emission and centimeter-degrees. We define centimeter-degrees as the absolute value of the product of thaw depth and mean soil temperature to permafrost. Eleven of 12 possible correlations were statistically significant, showing a positive response in CH_4 emission to increasing centimeter-degrees. Increasing CH_4 emission was also significantly correlated with increasing depth of thaw (r_s negative; depth defined relative to soil surface). Mean soil temperature increases were positively correlated with increases in CH_4 emission, but the relationship was weak; only 4 of 12 possible correlations were statistically significant. Qualitatively, a positive relationship between CH_4 emission and soil temperature is evident by comparing soil temperature distributions with flux in Figures 1-4. The relationship between water table position and CH_4 flux was unclear. Three of 9 correlations were significant. A lowered water table was correlated with enhanced emission (r_s negative) in two cases and with reduced emission in one instance (r_s positive).

Soil pCH_4 Distributions and CH_4 Emission

Figures 7 and 8 give changes in water table position, thaw depth, soil pCH_4 distributions, and atmospheric CH_4 flux at primary stations for the 1988 and 1989 thaw seasons. As expected, the thaw depth increased at all stations during both summers. The water table level decreased initially through both

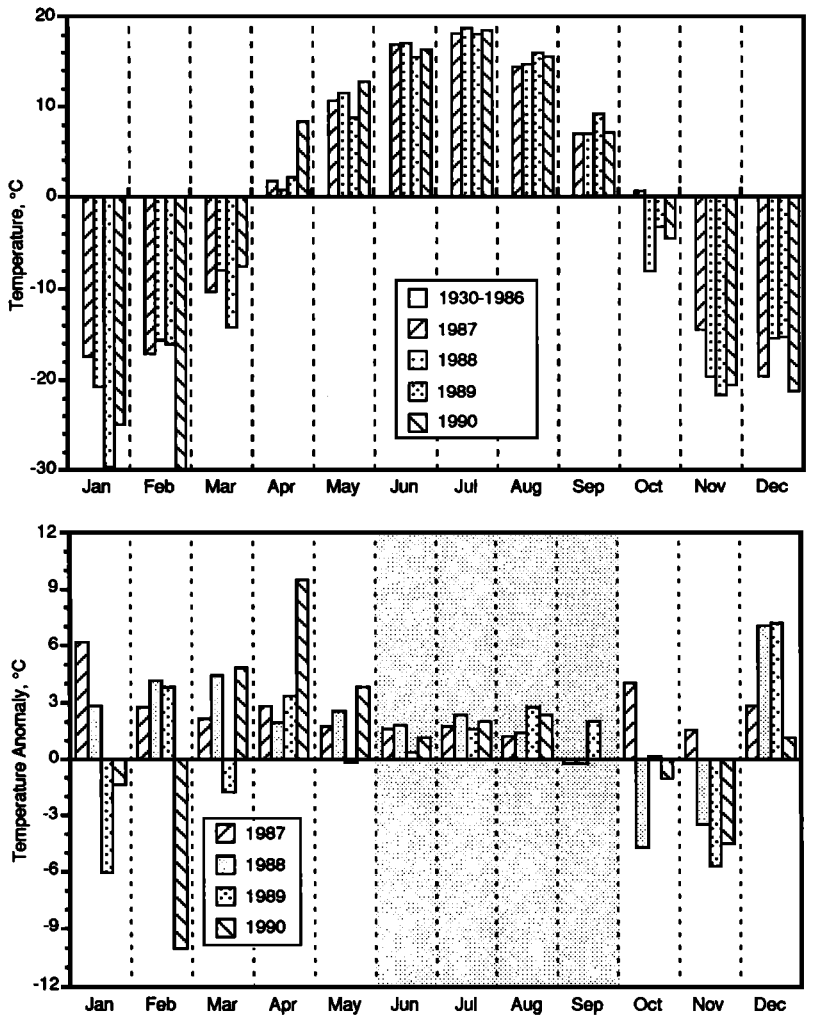

Fig. 5. Air temperatures (in degrees Celsius) in the University of Alaska Arboretum. Long-term means and conditions during study period. (Top) Mean monthly air temperatures. (Bottom) Air temperature anomaly (difference in long-term mean and monthly mean values) during study period. Shading denotes the major emission period. Data from National Oceanic and Atmospheric Administration (NOAA) [1986, 1987, 1988, 1989, 1990] records for Fairbanks International Airport, 6 km south of study sites.

summers but rose slowly after midseason in 1988. Most early season soil pCH_4 distributions show a 5- to 15-cm surface zone of low concentration (< 5 matm), a 5- to 10-cm gradient of rapidly increasing pCH_4, and a deep zone where pCH_4 remains relatively constant at 200 to 400 matm.

Overall, the relationship between soil pCH_4 distributions and CH_4 flux was not consistent and clear. Data for 1988 (T-1, M-1, and BH-1; Figures 7a-7c) show low fluxes associated with a relatively small CH_4 pool in June and early July. A July increase in soil pCH_4 and mid to late August increases in flux suggest a 2 to 3 week lag between increases in soil pCH_4 and emission. Late season changes in soil CH_4 concentrations accompany a slight rise in water table level and appear unrelated to emission.

Relationships in the 1989 soil CH_4 and flux data are even less clear. A striking midseason increase in soil CH_4 was observed only at M-1 (Figure 8), when CH_4 emission and the soil pCH_4 were clearly out of phase; highest emissions occurred in late July and early August when soil CH_4 was low. Methane emission declined steadily to the end of the season following the early September increase in the soil CH_4 pool. The soil CH_4 pool showed a gradual

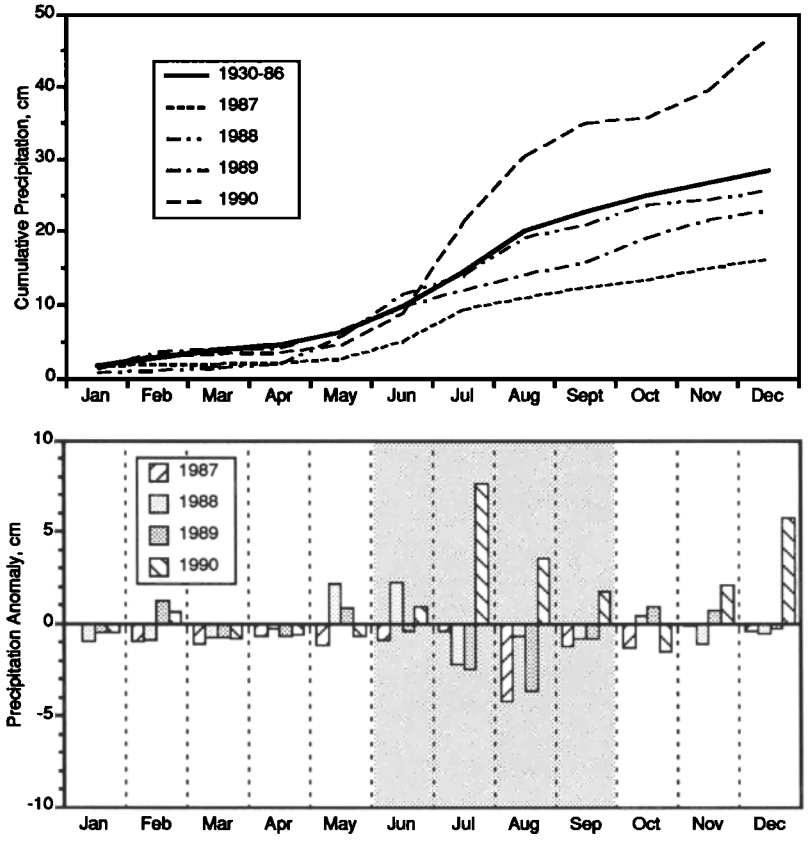

Fig. 6. Precipitation (in centimeters, water-equivalent) in the University of Alaska Arboretum. Long-term mean and conditions during study period. (Top) Cumulative precipitation. (Bottom) Precipitation anomaly (difference in long-term mean and monthly mean values) during study period. Shading denotes the major emission period. Data from NOAA [1986, 1987, 1988, 1989, 1990] records for Fairbanks International Airport, 6 km south of study sites.

TABLE 7. Spearman's Rank Correlation Coefficients (r_s) for Correlations Between CH_4 Emission During the Thaw Season and Environmental Variables at Primary Sampling Stations in the University of Alaska Arboretum

	Primary Sampling Station											
	Black Hole				Moss				Tussock			
Year	87	88	89	90	87	88	89	90	87	88	89	90
n	13	18	19	16	15	19	19	16	15	19	19	15
Thaw depth	-0.80	-0.80				-0.89			-0.94	-0.88	-0.69	-0.91
Thaw days[a]	0.82	0.78		0.68		0.90			0.94	0.91	0.66	0.93
Soil temperature[b]	0.87		0.71			0.65	0.74					
Water table depth	ND				ND	-0.73			ND		-0.66	0.71
centimeter-degrees[c]	0.87	0.73	0.82			0.77	0.75		0.74	0.68	0.74	

Only values of r_s significant at $\alpha = 0.01$ are given. ND means no data collected.
[a]First day of sample collection (May 21) taken as first day of thaw for 1990.
[b]Mean to depth of permafrost.
[c]Absolute value of product of thaw depth and mean soil temperature to permafrost.

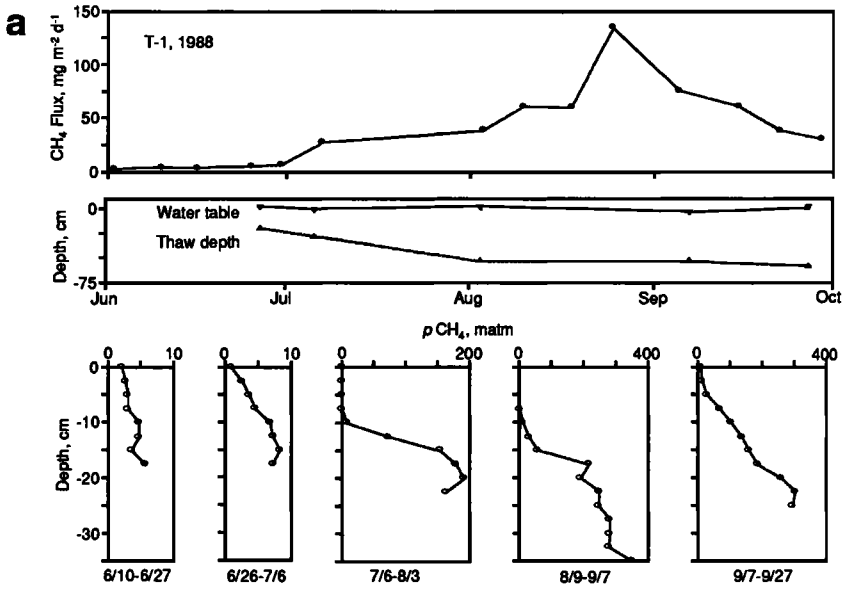

Fig. 7. (Top) Net CH_4 fluxes, (middle) water table and thaw depths, and (bottom) subsurface pCH_4 distributions for (A) T-1, (B) BH-1, and (C) M-1 stations, June - September, 1988. *Carex* (C-1) station was not sampled during 1988. Each of the pCH_4 versus depth panels integrates conditions up to the sampling date. Water table and thaw depth were measured when the equilibration samplers were retrieved.

increase throughout the season at T-1, while emission remained generally constant (Figure 8). Methane emission and soil CH_4 distributions appear to be uncoupled at BH-1 (Figure 8) and C-7 (Figure 8).

DISCUSSION

Global Tundra Emission Estimates

One of our goals was to determine net CH_4 emission and its temporal and spatial variability in representative tundra floral associations.We view the annual emission from each site (Table 5) as a "reagent grade" budget constituent of known uncertainty that can be appropriately combined and weighted to produce regional and global CH_4 emission estimates. We have extended site emissions from this study (Table 5) using our previous weighting scheme [Whalen and Reeburgh, 1988] to annual global CH_4 emission estimates for 1987-1990 in Table 6. These emission estimates incorporate uncertainties in areal coverage as well as the variations in annual site fluxes (Table 5).

The representativeness of sites in a heterogeneous landscape is crucial in regional extrapolation of fluxes to global budgets [Matson et al., 1989]. We are confident that our weighting scheme, which considers the floral or site composition in two major tundra subdivisions (tussock:shrub and wet meadow tundra), provides a reasonable framework for several reasons. First, CH_4 fluxes from these major tundra subdivisions are dominated by two site types: *Eriophorum* tussocks (T) and *Carex* (C). These sites account for 24-45% and 80-90% of the areal coverage and contribute 50-94% and 89-100% of the annual CH_4 flux, respectively, from the two tundra subdivisions (Table 6). Uncertainties in areal coverage alone result in 1.5- to 2.4-fold variations in annual CH_4 emission estimates for tundra. Second, stations established in similar floristic units at the Toolik Lake Long Term Ecological Research site showed similar CH_4 emission rates (mg m^{-2} d^{-1}) during two to three midsummer visits during 1987 through 1989. A more complete summer flux time series obtained at these sites during 1991 (T. Christensen, Cambridge Univ., personal communication, 1991), was weighted by the Whalen and Reeburgh framework and gave an annual emission of 18-30 Tg CH_4. Third, transect measurements [Whalen and Reeburgh, 1990a], which provide an independent check, gave an emission estimate of 38 Tg CH_4 yr^{-1} for tundra, which agrees with the present results. Finally, a three-dimensional tracer model study [Fung et al.,1991], which adjusts CH_4 source strengths as a function of latitude and requires a match between the model output and observed seasonal CH_4 variation at

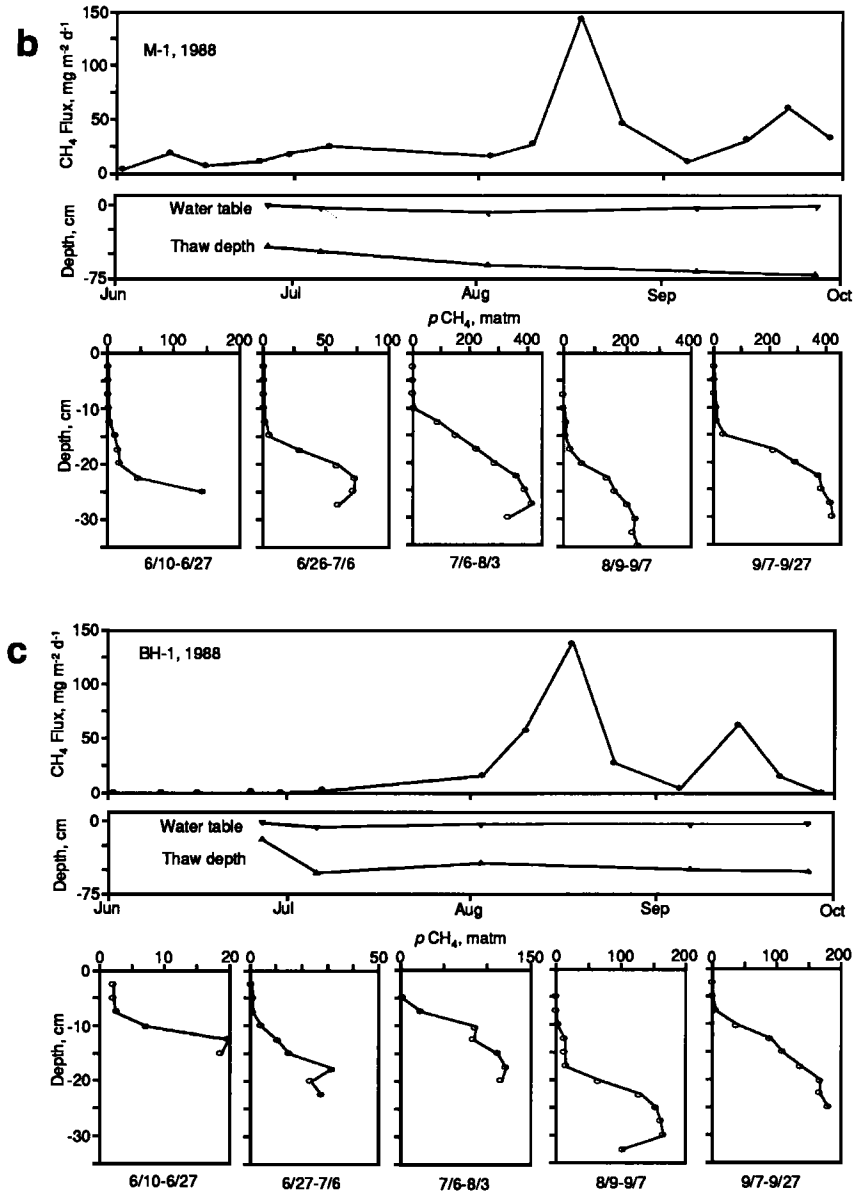

Fig. 7. (continued)

Global Monitoring for Climate Change stations [Steele et al., 1987], agrees with the above estimates. For high northern latitudes, where tundra is the only CH_4 source, the model requires a source strength of 35 Tg CH_4 yr^{-1}.

We are confident scaling-up from long-term emission records at fixed sites, but there are still uncertainties. Unusual conditions, such as the high summer precipitation in 1990, and the resulting high CH_4 fluxes from the C site, can distort any emission estimate by extending local anomalies to a regional or larger scale. Thus, we consider the CH_4 emission estimates from 1987 to 1989 (Table 6) as most representative. Longer time series and a better understanding of the controls on CH_4 fluxes are needed. Also, our budget constituent sites and essentially all studies (Table 8) suffer from a North American bias; time series studies in representative tundra and peatland areas of Siberia are needed to insure correct regional weighting in future tundra CH_4 emission estimates.

Table 8 summarizes high-latitude CH_4 emission estimates. The earliest estimate [Svensson, 1976] is based on a CH_4 flux:moisture relationship.

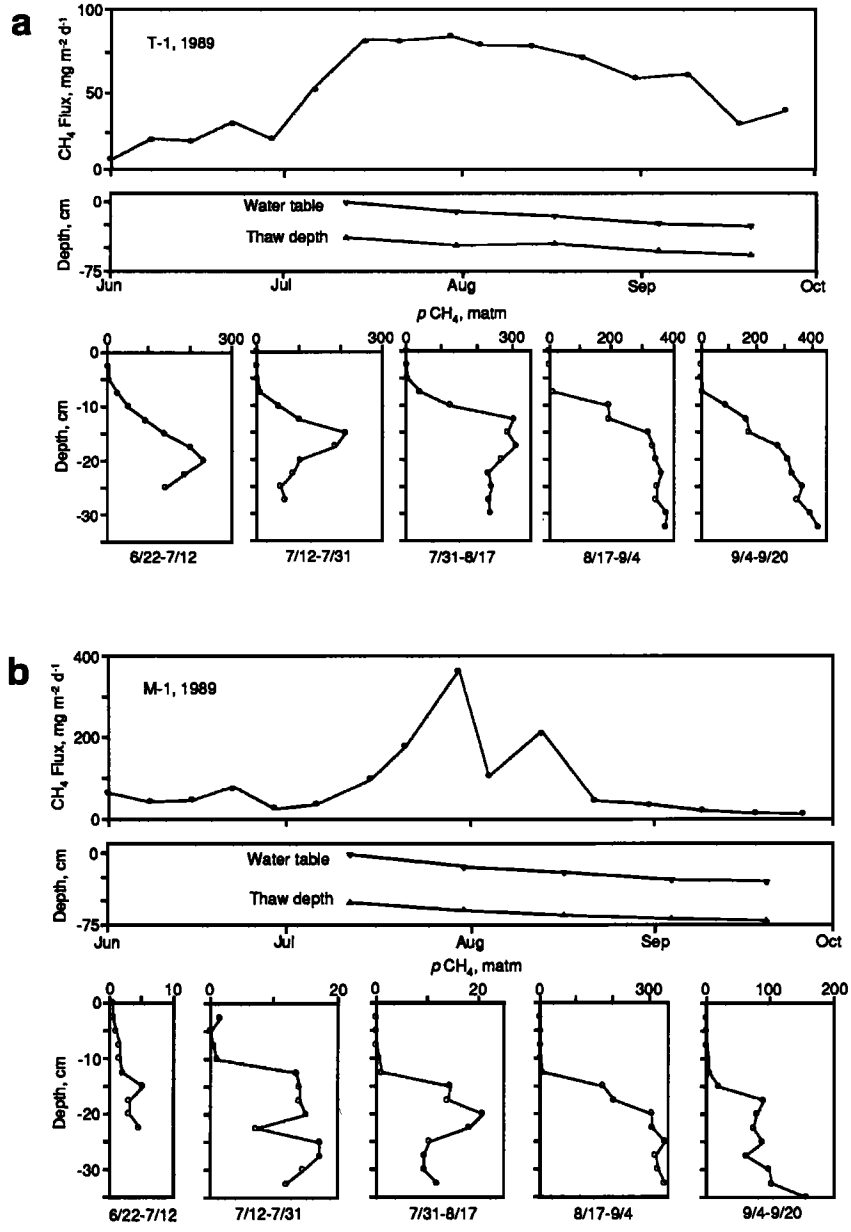

Fig. 8. (Top) Net CH_4 fluxes, (middle) water table and thaw depths, and (bottom) subsurface pCH_4 distributions (Bottom) for T-1, BH-1, M-1, and C-7 stations, June - September, 1989. Each of the pCH_4 versus depth panels integrates conditions up to the sampling date. Water table and thaw depth were measured when the equilibration samplers were retrieved.

Subsequent estimates result from transect studies [Sebacher et al., 1986; Whalen and Reeburgh, 1988], time series flux measurements at fixed locations [Crill et al., 1988; Whalen and Reeburgh, 1988; Moore et al., 1990], literature CH_4 flux data applied to refined estimates of global wetland areas [Matthews and Fung, 1987; Aselmann and Crutzen, 1989], and a model estimate [Fung et al., 1991] based on latitudinal source strengths and observational constraints. Variations in study types, assumptions, and regional definitions are responsible for the wide range of estimates, but recent studies seem to be converging on a tundra source strength of about 35 Tg CH_4 yr^{-1} [Reeburgh and Whalen, 1992].

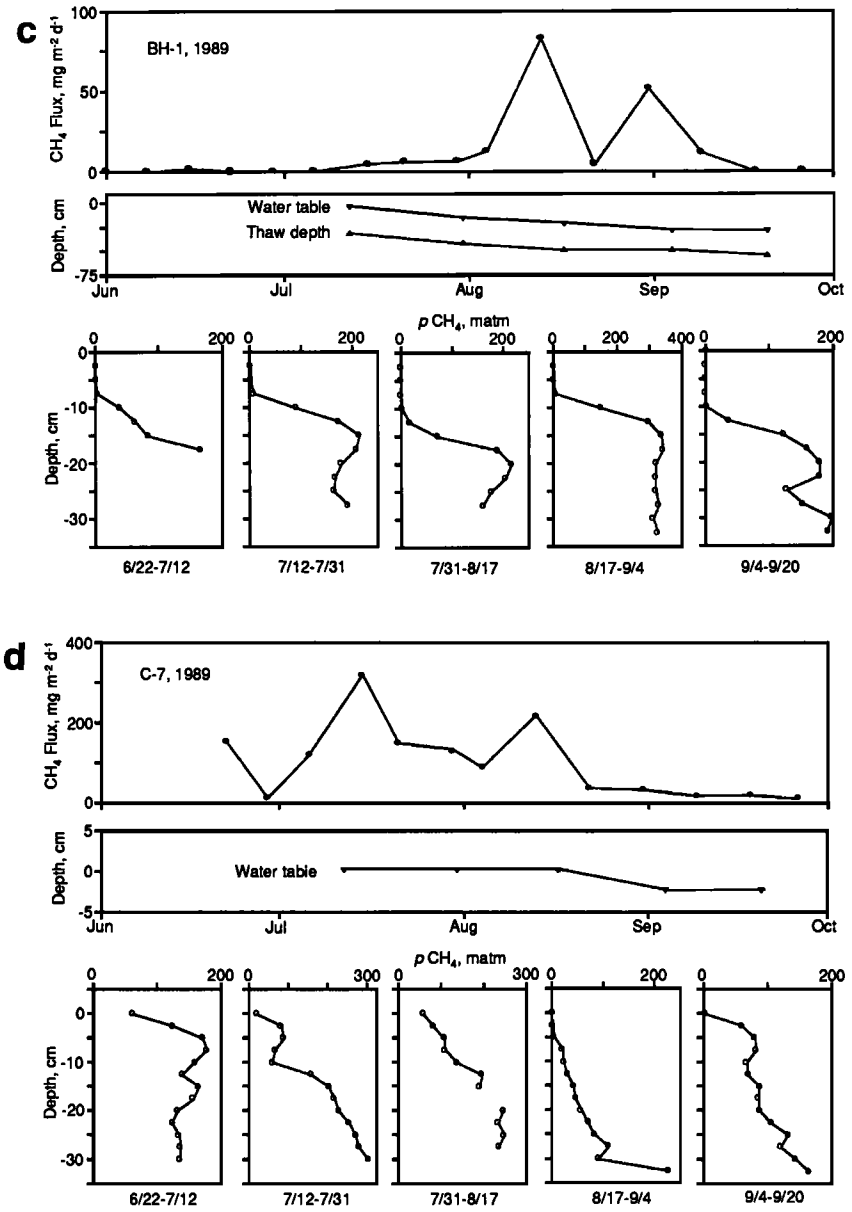

Fig. 8. (continued)

Variability in CH_4 Emission

Previous high-latitude studies at fixed sites have reported variability in rates of CH_4 emission ranging over 3 orders of magnitude on seasonal [Crill et al., 1988; Moore et al., 1990; Bartlett et al., 1992] and annual [Whalen and Reeburgh, 1988] scales. Matthews and Fung [1987] note that refinement of global CH_4 emission estimates will be achieved only through CH_4 flux determinations over several years at representative wetland sites. This study reports the first multiyear CH_4 emission measurements for Arctic tundra plant associations.

This study fortuitously encompasses a range of environmental conditions useful for modelers. Air temperature anomalies were a uniform +2 °C during all summers covered by this study (Figure 5), so that a temperature effect cannot be estimated from an interannual emission rate comparison. Precipitation was 60 to 190% of the long-term mean during the summers of 1987-1989 and 1990, respectively (Figure 6), allowing meaningful comparison of

TABLE 8. High-Latitude CH_4 Emission Summary

Reference	Region	Location	Study Type		CH_4 Emission, Tg yr^{-1}
Svensson [1976]	Arctic tundra	Stordalen, Sweden	summer fluxes extended with moisture relationships		1 - 25
Sebacher et al. [1986]	tundra and taiga	Alaska	flux transect, Arctic and boreal regions		46 - 106
Matthews and Fung [1987]	forested bog, 50°-70°N	-	estimated area x literature emission rates	20	62
	nonforested bog, 50°-70°N	-	"	42	
Crill et al. [1988]	all bogs >40°N	Minnesota peatlands	summer flux time series at permanent sites		72
Aselmann and Crutzen [1989]	wetlands, 50°-70°N	-	estimated area x literature emission rates		23
Moore et al. [1990]	northern fens	Quebec, Canada	summer flux time series at permanent sites		14
Fung et al. [1991]	wetlands >50°N	-	three dimensional tracer model, estimated sources (scenario 7)		35
Bartlett et al. [1992]	Arctic tundra >60°N	Yukon Delta, Alaska	summer flux time series at permanent sites		10.5
Whalen and Reeburgh [1988]	Arctic tundra (1987)	University of Alaska Arboretum	annual flux time series at permanent sites		19 - 32[a]
This study	Arctic tundra (1988)	"	"		26 - 78
This study	Arctic tundra (1989)	"	"		24 - 67
This study	Arctic tundra (1990)	"	thaw season flux time series at permanent sites		
	69 - 135				
Whalen and Reeburgh [1990]	Arctic tundra	Alaska	flux transect, Alaska Pipeline Haul Road	38	53
	taiga	"	"	15	
Whalen et al. [1991]	moist taiga	Bonanza Creek Experimental Forest, Alaska	thaw season flux time series at permanent sites		-0.8

[a]Does not include uncertainty in annual emission; including this (Table 6) results in an emission range of 14 - 42 Tg CH_4 yr^{-1}

annual emission estimates for a precipitation effect. The tundra CH_4 flux varied from 28 to 52 Tg yr^{-1} during 1987-1989 and was 102 Tg yr^{-1} in 1990 (midranges of data in Table 6) The data suggest a range of variations in annual CH_4 emission of about twofold for years with summer precipitation similar to the long-term mean and about fourfold for years with unusually high summer precipitation.

It is unlikely that differences between the 1990 annual flux estimates and those from previous years resulted from station relocation. Parallel sampling of new and old stations on a single occasion during 1990 showed no statistically significant differences in fluxes for new and old stations of any site type (Mann-Whitney Test; $p>0.05$; data not shown). New C stations were established at roughly the same elevation as previous stations. We conclude that the increased emission at C stations in 1990 (Tables 5 and 6) resulted from a ~40 cm rise in the summer water table due to record rainfall. Increased CH_4 emission from this site type was largely responsible for the high 1990 emission estimate, as noted above.

We also present the first data for interannual variations in CH_4 emission from representative tundra CH_4 budget constituent sites. Although summer air temperature and precipitation were roughly comparable in 1987-1989, there were obvious differences in the site fluxes (Table 5) and the relative contribution of C, M, and BH site types to the annual CH_4 emission estimate (Table 6). We have no ready explanation for these differences but suspect they are due to interannual variations in the submeter scale interactions of biological, physical, and chemical parameters and processes. Improved understanding of these interactions is necessary to further resolve the twofold interannual differences in overall annual CH_4 emission.

Correlations With Environmental Variables

Other investigators have reported strong relationships between CH_4 flux and temperature. We had limited success in correlating mean soil temperature with CH_4 emission at primary sites (Table 7). Correlation coefficients were not improved by selecting temperature at a single depth or by use of a running mean temperature as the independent variable (data not shown). Linear [Svensson and Rosswall, 1984], polynomial [Baker-Blocker et al., 1977], log-linear [Holzapfel-Pschorn and Seiler, 1986; Crill et al., 1988; Moore and Knowles, 1990; Bartlett et al., 1992], and exponential [Moore et al., 1990] relationships between CH_4 flux and air or soil temperature have been reported. The variety of functions used suggests that the relationship between CH_4 flux and temperature is not unique or straightforward.

The lack of statistical correlation between water table depth and seasonal CH_4 emission at our muskeg sites (Table 7) appears to result from analysis of data for the entire thaw season. A low late summer water table corresponds with reduced CH_4 flux (Figures 7 and 8). However, early season (May) emissions from waterlogged soil were also low as a result of a thin thawed soil zone. Combining all data for a season results in a low r_s. Highest CH_4 emissions are generally observed during midsummer, when the thawed zone is rapidly increasing, but the water table is falling. Seasonal studies in temperate swamp [Wilson et al., 1989] and wetland [Yavitt et al., 1990] soils also report poor correlation between water table level and CH_4 flux. In contrast, transect studies showed a closer relationship between CH_4 flux and water table position ($r = 0.42$ to 0.54) [Sebacher et al., 1986; Harriss et al., 1988; Whalen and Reeburgh, 1990a] or soil moisture content ($r = 0.77$ to 0.93) [Svensson, 1976, 1980]. It is likely that the CH_4 emission response to changing environmental conditions occurs rapidly and is masked in whole-season correlations.

The parameters thaw depth and centimeter-degrees show the best correlation with CH_4 emission (Table 7) because these variables integrate conditions important in determining net CH_4 emission. Specifically, centimeter-degrees is a reasonable index of net microbial activity because it accounts for the mean soil temperature and the depth of the active zone.

Controls on CH_4 Emission

The measurements of net CH_4 emission reported here are the difference between CH_4 production and microbially mediated CH_4 oxidation. This oxidation occurs before the CH_4 is emitted to the atmosphere, and is an important control on tundra CH_4 emission. Reeburgh et al. (The Role of Microbially-Mediated Oxidation in the Global CH_4 Budget, submitted to *Nature*, 1992) estimate that global CH_4 oxidation is about 200 Tg yr^{-1} larger than the estimated ~ 500 Tg yr^{-1} emitted to the atmosphere. Methane oxidation by soil microbial communities has been regarded a negligible term in the global CH_4 budget, but a body of evidence from moist soils [Born et al., 1990; Keller, et al. 1990; Steudler et al., 1990] is accumulating that suggests it plays an important role in the global CH_4 budget. Soils equilibrate rapidly with the atmosphere [Whalen and Reeburgh, 1990b], and the microbial CH_4-oxidizing community has a high capacity and low threshold for CH_4 oxidation

[Whalen et al., 1990]. Whalen et al. [1992] estimate that about half of the CH_4 production in tundra systems is oxidized in the moist aerobic zone and show that the extent of CH_4 oxidation is sensitive to changes in water table level, which directly affects the extent of the oxidized surface zone. For example, laboratory studies [Whalen et al., 1992] suggest that lowering the tundra water table 10 - 20 cm in areas free of vascular plants would reduce the net flux of CH_4 to zero, and further reductions in water table could permit oxidation of atmospheric CH_4. Thus oxidation could provide a negative feedback on CH_4 increases in portions of the wetland term. The CH_4 flux record from the Great Dismal Swamp [Harriss et al., 1982] also illustrates this process.

Soil pCH_4 Distributions and CH_4 Flux

Soil pCH_4 distributions suggest a surface zone of rapid CH_4 oxidation and a subsurface zone of CH_4 production (Figures 7 and 8). Methane profiles (1 μM CH_4 ≡ 0.52 matm CH_4 at 10 °C) were similar to those reported for Minnesota peatlands [Crill et al., 1988] and subarctic tundra [Bartlett et al., 1992]; a surface zone of low CH_4 concentration (<10 μM) overlies a zone of rapidly increasing CH_4 and a deep zone of 200-500 μM CH_4. Methane concentration isolines for boreal fen soils [Moore et al., 1990] suggest a smaller vertical gradient, with concentrations ranging from about 50 to 300 μM over similar depths.

Sequential soil CH_4 distributions are an integrating indicator of microbial activity. We expected CH_4 emission to track changes in the soil CH_4 pool, which can be seen in temporal sequences from single stations (Figures 7 and 8). Instead, we found that CH_4 flux and pool size were generally unrelated over time. Similar results have been reported for a boreal fen [Moore et al., 1990] and Subarctic tundra [Bartlett et al., 1992]. This decoupling could be the result of comparing measurements that respond to different time scales. The static chamber flux determinations are essentially instantaneous rate measurements (snapshots), while the soil CH_4 determinations result from integration over the equilibration period (time exposure). However, the boreal fen CH_4 distributions cited above were instantaneous (pore waters syringe-sampled) and CH_4 pool sizes determined in a salt marsh with equilibration samplers were well correlated with CH_4 flux [Bartlett et al., 1987]. It is likely that this decoupling is an additional indication of the complex biotic and abiotic factors determining net CH_4 emission.

Predictors and Feedbacks

Several lines of evidence suggest that the tundra system is too complex for a a single environmental variable to serve as a universal and successful indicator of CH_4 flux. First, a variety of functions have been used to relate CH_4 flux and temperature (see above). Second, significant relationships often involve special conditions. For example, Sebacher et al. [1986] reported good correlation between water table depth to 10 cm and CH_4 emission in a transect study, and Wilson et al. [1989] required a step function to relate soil temperature to emission. Third, relationships reported in Table 7 were best when data were simply ranked using a nonparametric statistic. Finally, pooling all data for one variable by station or year or by station and year resulted in few significant correlations, despite the fact that the increase in sample size allows a smaller value of r_s for statistical significance. Moore et al. [1990] noted that correlation between CH_4 flux and a single environmental variable in high-latitude fens may, in part, be specious because variables influencing flux are not entirely independent. This view is supported by our observation that CH_4 emission was best correlated with variables that serve as environmental integrators (Table 7). Attempts to identify predictors of CH_4 emission should focus on parameters that integrate factors important in CH_4 production and consumption.

Recent papers that have addressed feedbacks on trace gas emissions [Khalil and Rasmussen, 1989; Lashof, 1989] assume that increased temperatures will result in higher CH_4 fluxes, i.e., a positive feedback. These studies focus on the influence of a single variable (temperature) on a single biological process (methanogenesis) and do not consider other effects of climate change, namely regional changes in water table level [Mitchell, 1989] and rates of CH_4 oxidation. Functions that successfully relate CH_4 flux to temperature are largely limited to inundated wetlands (see above) where CH_4 production is the dominant biological process influencing emission. We expect that CH_4 flux-temperature relationships will deteriorate as water tables fall below the soil surface and oxidation becomes important. The ratio of oxidized:reduced soil zones will increase, favoring both aerobic decomposition and CH_4 oxidation. Laboratory studies with packed peat columns [Moore et al., 1989] showed that CH_4 emission decreased logarithmically, while CO_2 emission increased linearly as water table decreased. Moreover, changes in soil temperature will not be uniform with depth and the effect of increased soil temperature will be greater for CH_4 consumption than production.

Finally, the increased depth of thaw in permafrost areas will not have as great a stimulatory effect on methanogenesis as predicted [Khalil and Rasmussen, 1989; Lashof, 1989], because deeper peat is likely to be refractory [Farrish and Grigal, 1988; Yavitt et al., 1988]. A temperature feedback will be important in coupled biogeochemical-atmospheric models, but water table position will be a better integrator; waterlogged soils are zones of CH_4 production, while moist soils are areas of CH_4 consumption. Carefully executed field experiments involving manipulations of water table and temperature are needed to resolve the treatment of feedbacks in coupled biological models. One simple hydrologic model for northern fens indicates that a falling water table has a greater impact than increased soil temperature on CH_4 emission [Roulet et al., 1992].

SUMMARY

On the basis of a 4 year study at permanent sites we estimate that tundra contributes 42 ± 26 Tg yr^{-1} to the net atmospheric CH_4 budget. This large, multiyear data set, obtained under a range of moisture and temperature conditions, restricts the range of tundra CH_4 source strength estimates and also shows the effects of local extrema. Results from multiple permanent sites also suggest that single-parameter relationships used to predict CH_4 flux are site-specific and point to the need for an integrating predictor.

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REFERENCES

Aselmann, I., and P. J. Crutzen, Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity and possible methane emissions, *J. Atmos. Chem., 8,* 307-358, 1989.

Baker-Blocker, A., T. M. Donahue, and K. H. Mancy, Methane flux from wetland areas, *Tellus, 29,* 245-250, 1977.

Bartlett, K. B., D. M. Bartlett, R. C. Harriss, and D. I. Sebacher, Methane emissions along a salt marsh salinity gradient, *Biogeochemistry, 4,* 183-202, 1987.

Bartlett, K. B., P. M. Crill, R. L. Sass, R. S. Harriss, and N. B. Dise, Methane emissions from tundra environments in the Yukon-Kuskokwim Delta, Alaska, *J. Geophys. Res.,* in press, 1992.

Billings, W. D., Carbon balance of Alaskan tundra and taiga ecosystems: Past, present and future, *Quat. Sci. Rev., 6,* 165-177, 1987.

Blake, D. R., and F. S. Rowland, Continuing worldwide increase in tropospheric methane, 1978-1887, *Science, 239,* 1129-1131, 1989.

Born, M., H. Dörr, and I. Levin, Methane consumption in aerated soils of the temperate zone, *Tellus Ser. B, 42,* 2-8, 1990.

Cicerone, R. J., and R. S. Oremland, Biogeochemical aspects of atmospheric methane. *Global Biogeochem. Cycles, 2,* 299-327, 1988.

Crill, P. M., K. B. Bartlett, R. C. Harriss, E. Gorham, E. S. Verry, D. I. Sebacher, L. Mazdar, and W. Sanner, Methane flux from Minnesota peatlands, *Global Biogeochem. Cycles, 3,* 371-384, 1988.

Dickinson, R. E., and R. J. Cicerone, Future global warming from trace gases, Nature, *319,* 109-115, 1986.

Farrish, K. W., and D. F. Grigal, Decomposition in an ombrotrophic bog and a minerotrophic fen in Minnesota, *Soil Sci., 145,* 353-358, 1988.

Fung, I., J. John, J. Lerner, E. Matthews, M. Prather, L. P. Steele and P. J. Fraser, Three-dimensional model synthesis of the global methane cycle, *J. Geophys. Res., 96,* 13,033-13,065, 1991.

Harriss, R. C., D. I. Sebacher, and F. P. Day, Methane flux in the Great Dismal Swamp, *Nature, 297,* 673-674, 1982.

Harriss, R. C., D. I. Sebacher, K. B. Bartlett, D. S. Bartlett, and P. M. Crill, Sources of atmospheric methane in the South Florida environment, *Global Biogeochem. Cycles, 2,* 231-243, 1988.

Hesslein, R. H., An in situ sampler for close-interval interstitial water studies, *Limnol. Oceanogr., 21,* 912-914, 1976.

Holzapfel-Pschorn, A., and W. Seiler, Methane emission during a cultivation period from an Italian rice paddy, *J. Geophys. Res., 91,* 11,803-11,814, 1986.

Keller, M., M. E. Mitre, and R. F. Stallard. Consumption of atmospheric methane in soils of central Panama: Effects of agricultural

development, *Global Biogeochem. Cycles, 4*,21-27, 1990.

Khalil, M. A. K., and R. A. Rasmussen. Climate-induced feedbacks for the global cycles of methane and nitrous oxide, *Tellus Ser. B, 41*, 554-559, 1989.

Kummerow, J. B., B. A. Ellis, S. Kummerow, and F. S. Chapin III, Spring growth of shoots and roots in shrubs of an Alaskan muskeg, *Am. J. Bot., 70*, 1509-1515, 1983.

Lashof, D. A., The dynamic greenhouse: Feedback processes that may influence future concentrations of atmospheric trace gases and climate change, *Clim. Change, 14*, 213-242, 1989.

Likens, G. E., and N. M. Johnson, Measurements and analysis of the annual heat budget for the sediments in two Wisconsin lakes, *Limnol. Oceanogr.*, 14, 155-135, 1969.

Matson, P. A., P. M. Vitousek, and D. S. Schimel, Regional extrapolation of trace gas flux based on soils and ecosystems, in *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere*, edited by M. O. Andreae and D. S. Schimel, pp. 97-108, John Wiley, New York, 1989.

Matthews, E., Global vegetation and land use: New high-resolution data bases for climate studies, *J. Clim. Appl. Meteorol., 22*, 474-487, 1983.

Matthews, E., and I. Fung, Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources,*Global Biogeochem. Cycles, 1*, 61-86, 1987.

Mitchell, J. F. B., The greenhouse effect and climate, *Rev. Geophys., 27*, 115-139, 1989.

Moore, T. R., and R. Knowles, The influence of water table levels on methane and carbon dioxide emissions from peatland soils, *Can. J. Soil Sci., 69*, 33-38, 1989.

Moore, T. R., and R. Knowles, Methane emissions from fen, bog and swamp peatlands in Quebec, *Biogeochemistry, 11*, 45-61, 1990.

Moore, T., N. Roulet, and R. Knowles, Spatial and temporal variations of methane flux from subarctic/northern boreal fens, *Global Biogeochem. Cycles, 4*, 29-46, 1990.

National Oceanic and Atmospheric Administration (NOAA), Local climatological data, Fairbanks, Alaska, annual summary with comparative data, report, Asheville, N. C. 1986.

NOAA, Local climatological data, Fairbanks, Alaska, annual summary with comparative data, report, Asheville, N. C. 1987.

NOAA, Local climatological data, Fairbanks, Alaska, annual summary with comparative data, report, Asheville, N. C. 1988.

NOAA, Local climatological data, Fairbanks, Alaska, annual summary with comparative data, report, Asheville, N. C. 1989.

NOAA, Local climatological data, Fairbanks, Alaska, annual summary with comparative data, report, Asheville, N. C. 1990.

Post, W. M., W. R. Emanuel, P. J. Zinke, and A. G. Stangenberger, Soil carbon pools and world life zones, *Nature, 298*, 156-159, 1982.

Ramanathan, V., R. J. Cicerone, H. B. Singh, and J. T. Kiehl, Trace gas trends and their potential role in climate change, *J. Geophys. Res., 90*, 5547-5566, 1985.

Rasmussen, R. A., and M. A. K. Khalil, Atmospheric methane (CH_4): Trends and seasonal cycles, *J. Geophys. Res., 86*, 9826-9832, 1981.

Rasmussen, R. A. and M. A. K. Khalil, Atmospheric methane in the recent and ancient atmospheres: Concentrations, trends and the interhemispheric gradient, *J. Geophys. Res., 89*, 11,599-11,605, 1984.

Raynaud, D., J. Chappelez, J. M. Barnola, Y. S., Korotkevich, and C. Lorius, Climatic and CH_4 cycle implications of glacial-interglacial CH_4 change in the Vostok ice core, *Nature, 333*, 655-657, 1988.

Reeburgh, W. S., and S. C. Whalen, High latitude systems as CH_4 sources, in. *Trace Gas Exchange in a Global Perspective*, edited by B. Svensson and D. Ojima, Munksgaard, Copenhagen, in press, 1992.

Roulet, N., T. Moore, J. Bubier, and P. Lafleur, Northern fens: CH_4 flux and climate change, *Tellus*, in press, 1992.

Sebacher, D. I., R. C. Harriss, and K. B. Bartlett, Methane emissions to the atmosphere through aquatic plants, *J. Environ. Qual., 14*, 40-46, 1985.

Sebacher, D. I., R. C. Harriss, K. B. Bartlett, S. M. Sebacher and S. S. Grice, Atmospheric methane sources: Alaskan tundra bogs, an alpine fen and a subarctic boreal marsh, *Tellus Ser. B, 38*,1-10, 1986.

Seiler, W., A. Holzapfel-Pschorn, R. Conrad, and D. Scharffe, Methane emission from rice paddies, *J. Atmos. Chem., 1*, 241-268, 1984.

Stauffer, B., G. Fischer, A. Neftel, and H. Oeschger, Increases in atmospheric methane recorded in Antarctic ice core, *Science, 229*, 1386-1388, 1985.

Steele, L. P., P. J. Fraser, R. A. Rasmussen, M. A. K. Khalil, T. J. Conway, A. J. Crawford, R. H. Gammon, K. A. Masarie, and K. W. Thoning, The global distribution of methane in the troposphere, *J. Atmos. Chem., 5*, 125-171, 1987.

Steudler, P. A., R. D. Bowden, J. M. Melillo, and

J. D. Aber, Influence of nitrogen fertilization on methane uptake in temperate forest soils, *Nature, 341,* 314-316, 1990.

Svensson, B. H., Methane production in tundra peat, in *Microbial Production and Utilization of Gases (H_2, CH_4, CO)*, edited by H. G. Schlegel, G. Gottschalk and N. Pfennig, pp. 135-139, E. Goltze, Göttingen, Germany, 1976.

Svensson, B. H., Carbon dioxide and methane fluxes from the ombrotrophic parts of a subarctic mire, *Ecol. Bull.*, 30, 235-250, 1980.

Svensson, B. H., and T. Rosswall, In situ methane production from acid peat in plant communities with different moisture regimes in a subarctic mire, *Oikos, 43*, 341-350, 1984.

Walker, D. A., N. D. Lederer, and M. D. Walker, Permanent vegetation plots, data report, Dep. of Energy R4D Proj., INSTAAR, Univ. of Colo.,Boulder, March 31, 1987.

Wein, R. W. and L. C. Bliss, Primary production in arctic cottongrass tussock tundra communities, *Arc. Alp. Res., 6,* 261-274, 1974.

Whalen, S. C., and W. S. Reeburgh, A methane flux time series for tundra environments, *Global Biogeochem. Cycles, 2,* 399-409, 1988.

Whalen, S. C., and W. S. Reeburgh, A methane flux transect along the Trans-Alaska Pipeline Haul Road. *Tellus Ser. B, 42,* 237-249, 1990a.

Whalen, S. C., and W. S. Reeburgh, Consumption of atmospheric methane by tundra soils, *Nature, 346*, 160-162, 1990b.

Whalen, S. C., W. S. Reeburgh, and K. A. Sandbeck, Rapid methane oxidation in a landfill cover soil, *Appl. Environ. Microbiol., 56*, 3405-3411, 1990.

Whalen, S. C., W. S. Reeburgh and K. S. Kizer, Methane consumption and emission from taiga sites, *Global Biogeochem. Cycles, 5*, 261-273, 1991.

Whalen, S. C., W. S. Reeburgh, and C. E. Reimers, Control of tundra methane emission by microbial oxidation, in *Landscape Function: Implications for Ecosystem Response to Disturbance, A Case Study in Arctic Tundra, Ecol Stud. Ser.*, edited by J. F. Reynolds and J. D. Tenhunen, Springer-Verlag, New York, in press, 1992.

Wilson, J. O., P. M. Crill, K. B. Bartlett, D. I. Sebacher, R. C. Harriss, and R. L. Sass, Seasonal variation of methane emission from a temperate swamp, *Biogeochemistry, 8,* 55-71, 1989.

Yamamoto, S. , J. B. Alkauskas and T. E. Crozier, Solubility of methane in distilled water and seawater, *J. Chem. Eng. Data, 21,* 78-81, 1976.

Yavitt, J. B., G. E. Downey, and D. M. Downey, Potential methane production and methane oxidation in peatland ecosystems of the Appalachian Mountains, United States, *Global Biogeochem. Cycles, 2,* 253-268, 1988.

Yavitt, J. B., G. E. Lang, and A. J. Sextone, Methane fluxes in wetland and forest soils, beaver ponds, and low-order streams of a temperate forest ecosystem, *J. Geophys. Res., 95,* 22,463-22,4745, 1990.

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