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Journal
Journal of Geophysical Research, 103(D22)

ISSN
0148-0227

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Publication Date
1998-11-27

DOI
10.1029/98jd00993

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D22, PAGES 29,005–29,013, NOVEMBER 27, 1998

A CH_4 emission estimate for the Kuparuk River basin, Alaska

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Abstract. Integrated annual methane fluxes measured from 1994 to 1996 at sites representing specific tundra vegetation and land cover types were weighted areally using a vegetation map [*Auerbach et al., 1997*] for the Kuparuk River basin and subareas. Wetland and open water CH_4 emissions dominate the Kuparuk River basin emission estimate. Areal weighting of site fluxes resulted in a regional CH_4 emission estimate of 2.09×10^{10} g CH_4 yr^{-1} for the Kuparuk River basin. The global CH_4 emission obtained by extending areally weighted annual fluxes from this study to global tundra area (7.34×10^{12} m^2) is 5.83 Tg CH_4 yr^{-1}. This is about 15% of the *Fung et al.* [1991] atmospheric tracer model estimate and indicates that the vegetation distribution of the Kuparuk River Basin is not typical of the entire Arctic. Reconciling results from atmospheric tracer model estimates and areally weighted field flux measurements will require accurate high-resolution circumpolar estimates of wetland and open water areas and fluxes.

1. Introduction

The atmospheric concentration of methane (CH_4), a well-known radiatively important trace gas, is increasing at a rate of about 1% per year [*Dlugokencky*, 1994]. Efforts are under way to understand the global CH_4 budget as well as the direct and indirect effects of the increase on climate. Methane emission from high-latitude wetlands is an important term in the global budget, and considerable effort has been directed over the last decade toward obtaining CH_4 flux measurements in a range of locations [*Reeburgh and Whalen*, 1992; *Bartlett and Harriss*, 1993; *Reeburgh et al.*, 1994; *Vourlitis and Oechel*, 1997]. Scaling site level flux measurements up to regional and global scales is an essential part of constructing global and regional material budgets that can be used as a basis for evaluating the effects of climate change. Because of spatial and temporal variability in flux measurements, as well as spatial variability in site types, scaling is difficult [*Matson et al.*, 1989] and is the subject of active investigation using several approaches.

One approach to obtaining emission estimates is to estimate areal coverage of various site types (extensive variable) and multiply by measured fluxes (intensive variable). Vegetation is a key integrator for a range of ecosystem characteristics and functions and has been used in previous studies to determine areal coverage of site types. Many of these studies suffer from the problem that one variable is better understood than the other. For example, the *Matthews and Fung* [1987] global wetland CH_4 emission estimate used a carefully compiled global wetland database, but the only available high-latitude CH_4 flux measurements were from a single Swedish study conducted over a decade earlier [*Svensson*, 1973]. *Whalen and Reeburgh* [1992] used a 4 year time series of CH_4 fluxes from permanent sites, but their areal weighting by vegetation cover types was based on literature values, not actual measurements. The flux transect study of *Whalen and Reeburgh* [1990] involved seasonal CH_4 flux measurements at fixed intervals along the Trans-Alaska Pipeline haul road but required assumptions about the duration of the emission season. Many of the available CH_4 flux measurements, which are reviewed by *Bartlett and Harriss* [1993], have resulted from short-term campaigns that frequently span only a portion of the growing season. Winter flux measurements are rare [*Whalen and Reeburgh*, 1988; *Dise*, 1992]. There is a strong North American bias in CH_4 flux data sets, and additional transect measurements and long-term observations similar to those by *Christensen et al.* [1995] and *Panikov et al.* [1993] are needed.

Methane flux measurements can be made at scales larger than chambers with aircraft boundary layer measurements (100 km) or micrometeorological measurements using towers (100 m). Chamber, tower, and aircraft measurements of CH_4 flux were compared during two recent field campaigns, the Arctic Boundary Layer Experiment (ABLE 3A) (summarized in the *Journal of Geophysical Research, 97* (D15), 1992), and the Northern Wetlands Study (NOWES/ABLE 3B) (summarized in the *Journal of Geophysical Research, 99* (D1), 1992). During ABLE 3A, errors of approximately a factor of 2 between chamber and tower measurements resulted from poor resolution of CH_4-producing habitats in the tower footprint [*Fan et al.*, 1992]. Mean aircraft fluxes [*Ritter et al.*, 1992] were approximately 2 times higher than the tower fluxes. During NOWES/ABLE 3B, CH_4 fluxes measured by these three independent methods agreed to within a factor of 2 at all times and to within a factor of 1.2 most of the time [*Roulet et al.*,

Paper number 98JD00993.
0148-0227/98/98JD-00993$09.00

1994]. This improved agreement during NOWES/ABLE 3B can be attributed to three factors: 1) the dominant CH_4 source was pools on the peatland, which were well resolved by remote sensing, 2) overall fluxes were low and site emissions were similar, and 3) peat temperature was the dominant control on emission (N. T. Roulet, personal communication, 1998). These studies show that although time consuming and tedious, static chamber measurements of CH_4 flux are equivalent and comparable to those obtained by micrometeorological and aircraft boundary layer measurements.

Methane emission is the difference between CH_4 production in anoxic soil zones and oxidation, which occurs in floodwaters, adjacent to the water table, and in the rhizosphere [*Reeburgh et al.*, 1993; *Whalen et al.*, 1992, 1995]. Factors known to be important in CH_4 emission include temperature, moisture content or water table level, and substrate availability. Vascular transport of subsurface CH_4 by plants is believed to largely bypass this oxidizing zone, so wetlands populated by vascular plants have higher fluxes [*King et al.*, this issue]. While a great deal of information is available on the different factors which influence CH_4 flux from natural sites, no single factor can explain all of the variability. Relationships between soil temperature (or any single variable) and CH_4 emission are site specific and are of little value as general predictors. Parameters that integrate conditions influencing flux appear to be the best predictors over the emission period [*Whalen and Reeburgh*, 1992]. Process-based models have been introduced recently as a means of overcoming the problems of temporal and spatial variability and limited flux data. Development of general process-based models has ranged from models exploiting the relationship between primary production and CH_4 flux [*Aselmann and Crutzen*, 1989; *Whiting and Chanton*, 1993] to application of ecosystem models with heterotrophic respiration terms modified to include CH_4 emission [*Christensen et al.*, 1996]. Recent process-based models for wetlands, which have successfully modeled seasonal cycles of CH_4 emission, are the soil climate model of *Frolking and Crill* [1994], the primary production/soil organic matter decomposition model of *Cao et al.* [1996], and the water table model of *Walter et al.* [1996].

A global estimate of CH_4 emission, based on seasonal changes in atmospheric CH_4 concentration, was made by *Fung et al.* [1991], who used a three-dimensional tracer transport model run with seven different source/sink configurations to estimate CH_4 emission over a range of latitude bands. For northern latitudes poleward of 50°N, where tundra emission can be considered the only source, seasonal variations in CH_4 flux were tuned to produce annual atmospheric concentration changes that matched annual atmospheric CH_4 concentration changes at high-latitude Global Monitoring for Climate Change (GMCC) (now Climate Monitoring and Diagnostics Laboratory (CMDL)) stations. The resulting CH_4 emission estimate for latitudes poleward of 50°N was 35 Tg yr^{-1}.

More recently, *Hein et al.* [1997] have employed an inverse modeling approach to deduce information on CH_4 sources from temporal and spatial variations in atmospheric CH_4 mixing ratios. The inverse modeling approach enabled an objective determination of the range of CH_4 emissions which are consistent with the atmospheric observations, but like the *Fung et al.* [1991] study, it is not possible to select a unique source/sink configuration. Bogs poleward of 50°N were determined to emit about 40 Tg CH_4 yr^{-1}, and Siberian gas releases located east of the Ural Mountains accounted for about 30 Tg CH_4 yr^{-1}.

Table 1. Integrated Annual CH_4 Emission (mg CH_4 m^{-2}) from Kuparuk River Basin Sites, 1994 to 1996

Vegetation	Plots	1994	1995	1996
Barrens				
	T-3	-91	-174	-160
	T-4	-19	-21	-22
	TL-1	-27	-5	-23
Shrublands				
dry, 97.5%	T-9	13	204	292
	T-10	-13	115	214
wet, 2.5%	TL-6	6198	14139	9777
	TL-7	559	3532	3406
Nonacidic tundra				
	TL-3	149	179	177
	TL-4	182	188	195
	S-1	-	-	0
	S-2	-	-	0
	S-3	-	-	0
	S-4	-	-	102
	S-5	-	-	0
	S-6	-	-	0
	S-7	-	-	0
	S-8	-	-	343
	S-9	-	-	0
	S-10	-	-	6
Acidic tundra				
Tussock, 50%	T-6	2058	5591	3249
	HV-1	217	1265	227
	HV-3	572	2291	418
	HV-7	261	942	194
	HV-9	2253	3736	190
Nontussock, 50%	T-5	-10	-2	-21
	T-7	15	41	15
	T-8	41	66	18
	TL-5	77	499	334
	HV-2	71	402	92
	HV-4	0	-1	-3
	HV-5	0	25	0
	HV-6	0	243	1
	HV-8	0	-3	-13
	HV-10	12	97	0
Wet Tundra				
	T-1	NR	2116	1668
	T-2	10874	15005	4191
	TL-14	-	2864	3396
	TL-15	-	6641	10319
	TL-16	-	-	481
	TL-17	-	-	5065
	TL-18	-	-	977
	WM-LC	3005	8298	11311
	WM-HC	704	1007	2064
	M56-1	-	-	1995
	M56-2	-	-	3476
	M56-3	-	-	15106
	M56-4	-	-	6510
	M56-5	-	-	3291
	M56-6	-	-	240
	M56-7	-	-	639
	M56-8	-	-	646
	M56-9	-	-	5282
	M56-10	-	-	3585
	PB-1	-	-	911
	PB-2	-	-	4145
	PB-3	-	-	9348
	PB-4	-	-	10125
	PB-5	-	-	6456
	PB-6	-	-	6738
	PB-7	-	-	6296
	PB-8	-	-	4675
	PB-9	-	-	174
	PB-10	-	-	6140

T, TL, WM=Toolik Lake; S=Sagwon; HV=Happy Valley; M56=mile 56; PB=Prudhoe Bay.

Table 2. Summary of Integrated Annual CH_4 Flux (mg CH_4 m^{-2} yr^{-1}) from Kuparuk Basin Vegetation Types

Vegetation	1994[c]	1995[c]	1996[c]	Average
Barrens[a]	-45.7 ± 22.8 (3)	-66.7 ± 53.9(3)	-68.3 ± 45.8 (3)	-60.2 ± 40.8 (3)
Shrublands[a]	84.5 ± 83.2 (4)	376.4 ± 176.0 (4)	411.5 ± 117.7 (4)	290.8 ± 125.6 (3)
Nonacidic tundra[a]	165.5 ± 16.5 (2)	183.5 ± 4.5 (2)	68.6 ± 32.7 (12)	139.2 ± 17.9 (3)
Acidic tundra[a]	546.4 ± 228.7 (15)	1450.9 ± 457.9 (15)	449.0 ± 316.9 (15)	815.4 ± 334.5 (3)
Wet tundra[a]	4861 ± 3079.0 (3)	5988.5 ± 2134.1 (6)	4663.8 ± 701.8 (29)	5171.1 ± 1971.6 (3)
Open water[b]				
lake	3220 ± 481 (94)	1600 ± 311 (99)	1910 ± 197 (160)	2170 ± 182 (353)
stream	6430 ± 623 (193)	3780 ± 348 (266)	5530 ± 477 (243)	5120 ± 275 (702)
water total (area weighted)	3420 ± 186 (287)	1710 ± 117 (365)	2180 ± 96.1 (403)	2390 ± 74.9 (1055)

[a]Numbers in parentheses are number of time series sites occupied during season.
[b]Numbers in parentheses are number of independent observations.
[c]Season lengths (number of days soil at 10 cm depth was above 0°C) and mean flux season air temperatures at 1 m and 5 m: June 5 to September 13, 1994 (101 days), 9.5°C, 8.8°C; May 30 to September 30, 1995 (124 days), 7.4°C, 6.9°C; May 23 to September 17, 1996 (118 days), 6.1°C, 5.8°.

These high-latitude CH_4 emissions from global models may be considered independent "benchmarks" for comparison of global CH_4 emission estimates based on vegetation distributions and measured fluxes. Global estimates of CH_4 flux for high latitudes, based on flux measurements and areal estimates, are converging on a magnitude of 35 Tg yr^{-1} [*Reeburgh et al.*, 1994, Table 1; *Harriss et al.*, 1993], which is similar to the results from the *Fung et al.* [1991] and *Hein et al.* [1997] studies. This apparent success at the global level is encouraging, but the results cannot be translated to regional estimates of CH_4 emission.

2. Methods

2.1. Approach

The goal of this study was to estimate the magnitudes and understand the controls on CH_4 fluxes from the Kuparuk River basin as part of the Arctic System Science/Land-Air-Ice Interactions (ARCSS/LAII) program's Flux Study [*Weller et al.*, 1995]. Because vegetation is a key integrator and is indicative of CH_4 fluxes, the approach taken in this study was to define sites based on categories (see Figure 1) in the *Auerbach et al.* [1997] vegetation map and perform seasonal time series flux measurements at these sites for as long as possible each year. Static chambers were used in this study because of their reliability under all conditions as well as their ability to measure both positive and negative fluxes from sites representing specific vegetation types. Regional CH_4 fluxes were calculated using vegetation type areal coverage obtained from the *Muller et al.* [1998] hierarchic geographic information system (HGIS).

2.2. Sites

Sites close to the Toolik Lake Field Station which were representative of a range of vegetation types were established during the first two years of this study in consultation with D. A. Walker. Annual integrated CH_4 flux measurements from these sites were used to produce a preliminary emission map [*Regli et al.*, 1996]. On the basis of the important contributions of wetland sites to the total CH_4 emission and the small number of moist nonacidic tundra sites [*Walker et al.*, 1998], additional sites in each of these categories were added at Sagwon, Mile 56, and Prudhoe Bay for validation studies in 1996. Fluxes were measured at the validation sites twice weekly during a transect from Toolik Lake to Prudhoe Bay. Addition of these sites also extended geographic coverage to the entire basin. The vegetation map was also validated [*Muller et al.*, 1998], resulting in increases in the areal coverage of moist nonacidic tundra. Active layer thicknesses ranged from 70 cm at wetland sites to 40 cm at acidic tundra (Happy Valley) sites [*Nelson et al.*, 1997].

2.3. Flux Measurements

Methane flux measurements were made using static aluminum chambers [*Whalen and Reeburgh*, 1988] which were inserted in the water-filled channel of a permanently installed base, which isolated 0.076 m^2 of soil surface. The bases were carefully cut into the soil until a seal was obtained and were not disturbed for the duration of the study. The chambers ranged in volume from 4.4 L to 52.2 L to accommodate different vegetation heights and fluxes. For each flux measurement duplicate syringe samples of headspace gas were taken at 15 min intervals over a 45 min period and were analyzed by gas chromatography within one day of collection at the Toolik Field Station. Methane analyses were performed on a Shimadzu mini-2 gas chromatograph equipped with a flame ionization detector and a 1 m Molecular Sieve 5A column. Analytical precision of individual measurements averaged 2%. Methane standards relatable to National Institute of Standards and Technology (NIST) standards were used for calibration. Methane fluxes were calculated using the rate of CH_4 increase determined by linear least squares fits of the chamber CH_4 concentration versus time, base area, chamber volume, and the molar volume of CH_4 at ambient temperature. The precision of an individual flux measurement averaged 7%. The minimum detectable change in CH_4 concentration was about 0.2 ppmv; the practical minimum detectable CH_4 flux was 0.2 mg m^{-2} d^{-1}.

Methane flux at each site was measured at weekly or more frequent intervals throughout the 1994, 1995, and 1996 field seasons. Individual flux measurements from sites were integrated over time to produce an annual emission estimate for each site (Table 1). Magnitudes of the CH_4 flux for each of the vegetation types were consistent and had the same ranking during the three years of this study. Diel variations in CH_4 flux were small compared to between-site variations. Previous work at lower latitudes [*Whalen and Reeburgh*, 1988] as well as measurements at Toolik Lake in 1997 showed no clear relationship among CH_4 flux, soil temperature, and time of day, so diel variations at these sites were not considered. The high

Table 3. Land Cover (Vegetation Type) Areas in *Auerbach et al.* [1997] Kuparuk River Basin Map, Annual CH_4 Emission Based on Average Fluxes from Vegetation Types (Table 2), and Areally Weighted CH_4 Flux for Map Subareas in Plate 1

Land Cover	Area, km²	Area, %	CH_4 Emission, g CH_4 yr^{-1}	Areally Weighted CH_4 Flux, g CH_4 m^{-2} yr^{-1}
Entire map				
barrens	998.54	3.80	-5.99×10^7	
shadow	380.79	1.45	-2.29×10^7	
nonacidic	10079.52	38.37	1.41×10^8	
shrubland	4920.61	18.73	1.43×10^9	
Acidic	4864.12	18.52	3.99×10^9	
open water	1974.58	7.52	4.74×10^9	
wetland	2074.26	7.90	1.07×10^{10}	
snow and ice	41.28	0.16	0.00	
ocean	934.82	3.56	0.00	
Total	26268.51		2.09×10^{10}	0.796
Watershed				
barrens	130.11	1.41	-2.16×10^3	
shadow	16.96	0.18	-2.83×10^2	
nonacidic	4159.56	45.22	5.83×10^8	
shrubland	1620.56	17.62	4.70×10^8	
Acidic	2249.39	24.45	1.84×10^9	
open water	442.65	4.81	1.06×10^8	
wetland	575.95	6.26	2.89×10^9	
snow and ice	3.02	0.03	0.00	
Total	9198.20		6.93×10^9	0.753
Kuparuk				
barrens	10.31	1.37	-6.18×10^5	
shadow	10.15	1.35	-6.09×10^5	
nonacidic	186.15	24.80	2.61×10^7	
shrubland	221.53	29.52	6.42×10^7	
acidic	289.95	38.63	2.38×10^8	
open water[a]	21.34	2.84	5.12×10^7	
wetland	11.13	1.48	5.75×10^7	
Total	750.45		4.35×10^8	0.580
Imnavait				
barrens	0.31	1.47	-1.85×10^4	
shadow	0.00	0.00	0.00	
nonacidic	3.61	17.21	5.04×10^5	
shrubland	6.31	30.15	1.83×10^6	
scidic	10.51	50.18	8.61×10^6	
open water[a]	0.10	0.45	2.40×10^5	
wetland	0.11	0.54	5.82×10^5	
Total	20.93		1.17×10^7	0.560
Toolik				
barrens	0.22	1.02	-1.32×10^4	
shadow	0.00	0.00	0.00	
nonacidic	7.35	33.98	1.03×10^6	
shrubland	7.14	33.04	2.07×10^6	
acidic	4.26	19.70	3.49×10^6	
open water[a]	2.30	10.63	5.51×10^6	
wetland	0.35	1.62	1.81×10^6	
snow and ice	0.00	0.00	0.00	
Total	21.61		1.39×10^7	0.645
E Flight path (148° 55' W)				
barrens	0.14	1.59	-8.79×10^3	
shadow	0.00	0.00	0.00	
nonacidic	3.89	42.50	5.44×10^5	
shrubland	1.55	16.97	4.50×10^5	
acidic	1.26	13.75	1.03×10^6	
open water	0.76	8.31	1.86×10^6	
wetland	1.55	16.89	7.99×10^6	
Total	9.15		1.17×10^7	1.289
W Flight path (149° 30' W)				
barrens	0.1	1.04	-6.00×10^3	
shadow	0.0075	0.8	-4.50×10^2	
nonacidic	3.72	38.70	5.21×10^5	
shrubland	1.25	12.97	3.62×10^5	
acidic	2.32	24.14	1.90×10^6	
open water	0.86	8.89	2.06×10^6	
wetland	1.365	14.19	7.06×10^6	
Total	9.62		1.19×10^7	1.237

[a] Basin-wide open water flux (Table 1) used to calculate emission from all map subareas. This may not be appropriate for upland areas.

CH_4 emission sites were thoroughly waterlogged and inundated in many cases throughout the flux season. Observations at a water table manipulation experiment site at Toolik Lake showed no relationship between rainfall and CH_4 flux for these sites. On the basis of the small contribution of winter emissions reported by *Whalen and Reeburgh* [1988] and *Dise* [1992], we assume that winter CH_4 emissions from the study area are zero. End points (zero CH_4 flux) of the CH_4 emission season were estimated using soil temperatures. The beginning of the CH_4 emission season was taken as the date at which the soil temperature at 10 cm depth rose above 0°C. Similarly, the end of the emission season was taken as the first day the soil temperature at 10 cm was less than 0°C. The observed fluxes were linearly extrapolated to zero at these dates and were integrated using the trapezoidal rule to obtain annual CH_4 emission.

Methane fluxes from lakes were calculated using the stagnant film method [*Kling et al.*, 1992], which involves estimating the surface film thickness from wind speed and the flux from the film thickness and the water-air concentration difference. Methane fluxes from streams were estimated using measured concentrations and evasion coefficients determined by addition of dissolved SF_6 and a conservative tracer (Rhodamine or NaBr) [*Kling et al.*, 1995].

Integrated annual CH_4 fluxes from similar site types were averaged and are presented in Table 2. Table 2 also contains infomation about emission season length and mean flux season air temperatures. No trends in interannual variability can be discerned. Data and detailed site descriptions are available from the authors or the ARCSS Data Coordination Center web site (http://arcss.colorado.edu).

2.4. Land Cover Areas

The Kuparuk River basin land cover map of *Auerbach et al.* [1997] was used to display the distribution of CH_4 flux based on measured CH_4 fluxes from vegetation types. This map was extracted from an existing mosaic of Landsat multispectral scanner (MSS) frames acquired during cloud- and snow-free conditions during growing seasons from 1976 to 1985. The mosaic was resampled to 50 m pixels. The general land cover types for this map were derived by classification of the MSS image into eight land cover classes, which were used as a guide in selection of CH_4 flux measurement sites. The producer and user accuracies of the map are presented on the Auerbach *et al.* [1997] map and are discussed by *Muller et al.* [1998].

The following assumptions accompanied application of the average integrated CH_4 fluxes to vegetation map areas:

1. Methane emission was considered to take place when the temperature at 10 cm soil depth exceeded 0°C.

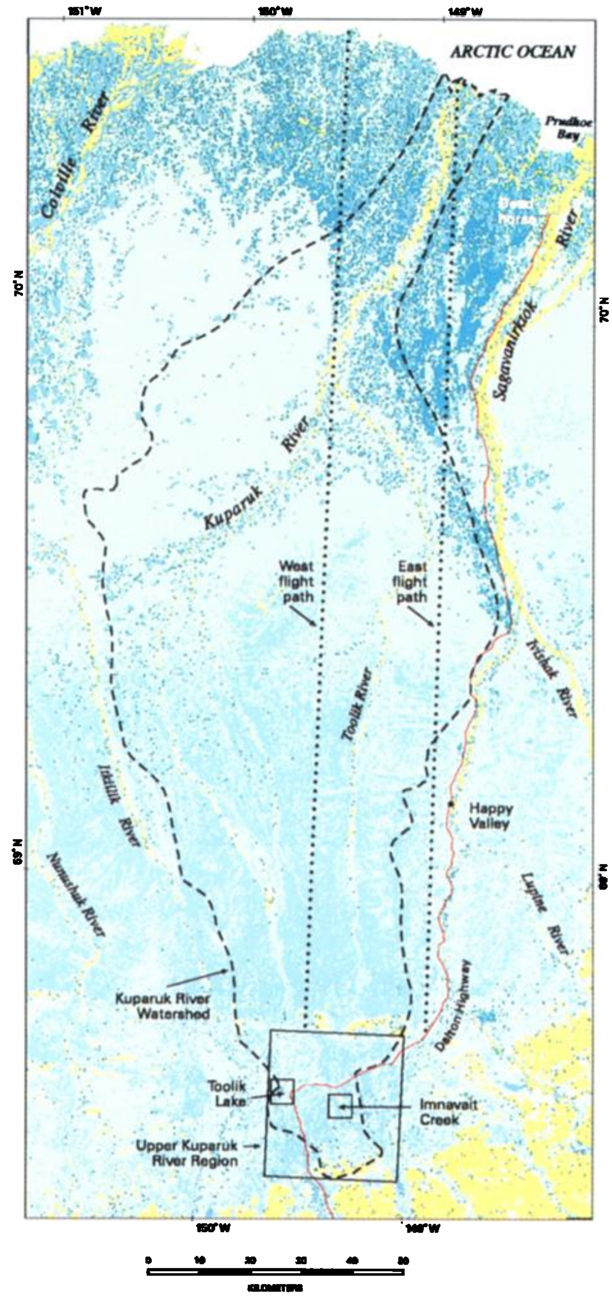
2. Sites where CH_4 fluxes were measured are representative of the vegetation map classification, and the fluxes measured are representative of the vegetation type.

3. Water tracks in the shrubland vegetation type were represented by weighting CH_4 fluxes from wet sites in the water tracks. The CH_4 flux weighting was 2.5% wet site flux to 97.5% moist shrubland site flux based on areal measurements of fine scale vegetation maps [*Walker and Walker*, 1996].

4. Acidic tundra was represented as 50% tussock and 50% nontussock or intertussock area, and fluxes were calculated accordingly.

5. The areas identified as shadow in the Landsat MSS images are on steep terrain and were grouped with barrens as CH_4 sinks.

The HGIS system of *Muller et al.*, [1998] was used to determine land cover areas (vegetation types) for the whole map



Map Color	Emission Class (Site Type)	Emission (mg CH4 m^{-2} y^{-1}) Range	Mean
Yellow	Low Sink to Neutral (Barrens, Shadows)	-200 – 0	-60
White	Neutral to Low Source (Non-acidic tundra, Shrublands)	0 – 500	140, 290
Light blue	Moderate Source (Acidic tundra)	500 – 2500	820
Medium blue	Intermediate Source (Streams and Lakes)	2500 – 3500	2990
Dark blue	High Source (Wet tundra)	> 3500	5170

Plate 1. Map of mean annual methane flux (mg CH_4 m^{-2} yr^{-1}) for the Kuparuk River basin, 1994-1996. Based on time series methane flux measurements at sites representative of landcover classes in the vegetation map of *Auerbach et al.* [1997]. Methane emission (g CH_4 yr^{-1}) for the map and map subareas is shown in Figure 1 and in Table 3.

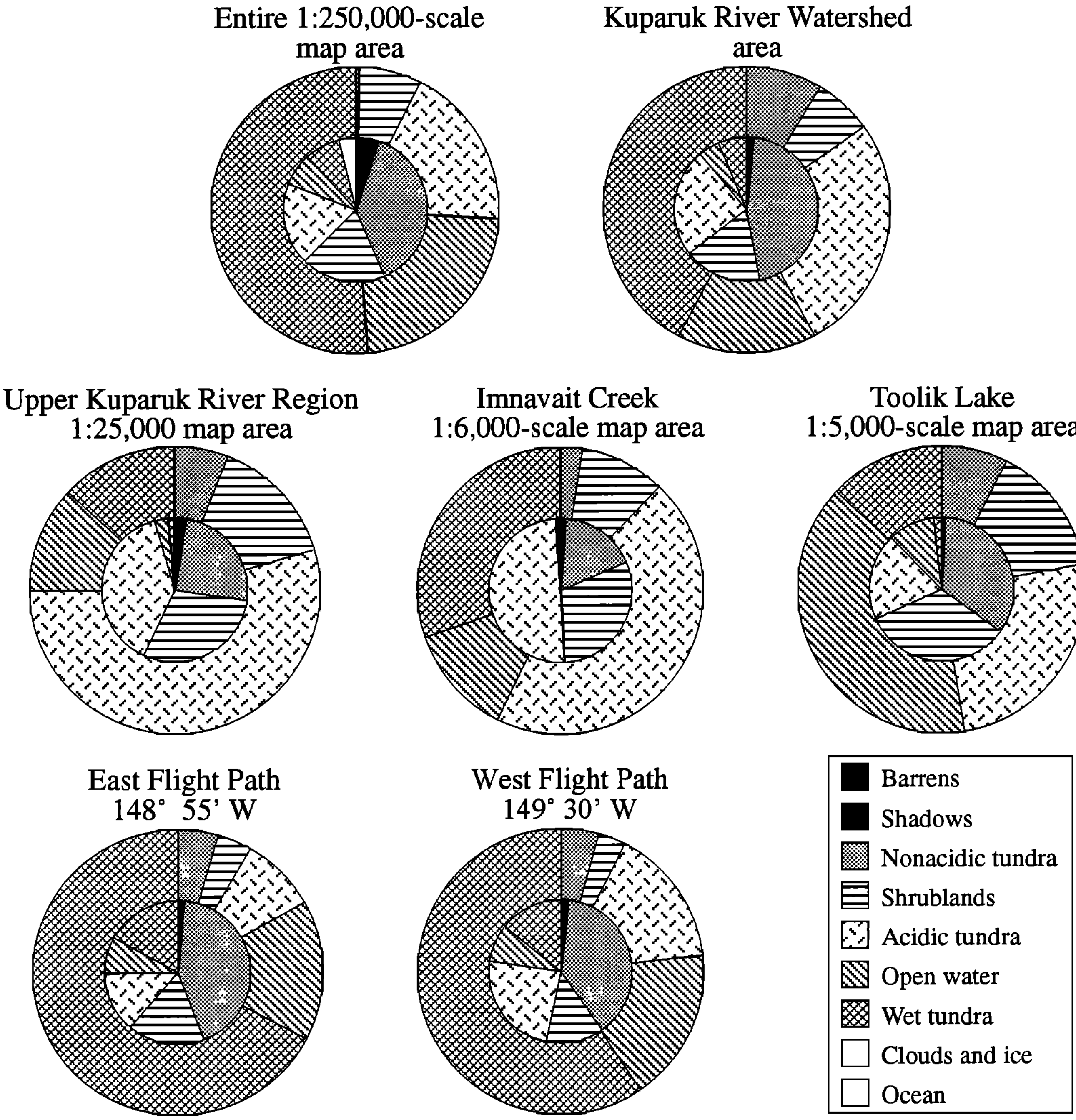


Figure 1. Pie charts (in %) showing land cover distribution (inner pie) and annual CH_4 emission (outer pie) for selected map areas. Data from Table 3.

(1:250,000), the Kuparuk watershed (1:250,000), the upper Kuparuk (1:25,000), Imnavait (1:6000), and Toolik Lake (1:5000) map subareas outlined in Plate 1. One pixel-wide (50 m) bands were sampled along the two N-S flight line transects (148° 55' and 149° 30') to estimate CH_4 flux from an area representing the flight lines. Each of the land cover areas was multiplied by the appropriate average integrated flux presented in Table 2. The CH_4 emission from each land cover category was summed to obtain an estimate of emission from the total map area. The land cover class areas and calculated annual CH_4 emission are presented in Table 3. Figure 1 presents nested pie charts showing land cover distribution (inner pie) and annual CH_4 emission (outer pie) for each of the above map subareas and the two flight paths.

3. Results and Discussion

3.1. Fluxes

Integrated CH_4 flux data for each site for the 1994, 1995, and 1996 field seasons are presented in Table 1. Average integrated fluxes derived from these measurements for each of the land cover categories or vegetation types considered in this study are presented in Table 2. The overall CH_4 flux results are shown in Plate 1 as a map showing the distribution of CH_4 fluxes.

Nonacidic tundra, acidic tundra, and shrublands are the dominant land cover or vegetation type in all of the maps. However, the tabulations in Table 3, as well as Figure 1, show clearly that CH_4 emission for the Kuparuk River basin is dominated by wetland sites and open waters. Wetlands and open waters are less prevalent in upland regions, but they are overrepresented for the basin as a whole by the two flight lines, as shown by differences in the areally weighted CH_4 fluxes for the various map units and Figure 1.

3.2. Uncertainties

It is difficult to evaluate errors in a map like Plate 1. User and producer errors associated with land cover classes were evaluated by *Muller et al.* [1998] and suggest a map accuracy of about 85%. Areas like barrens and water have distinctive spectral signatures, so their areas can be evaluated quite accurately. However, it is difficult to evaluate the water status of areas dominated by sedges (acidic, nonacidic, and wet tundra), and some moist tundra could be wetlands. Results of the land cover map validation [*Muller et al.*, 1998] suggest that wetlands were underestimated by 30%. Because of the typical small size of many wetlands, estimation of wetlands would decrease with larger pixel sizes. Further, many of the wetland areas border streams and have dimensions of the order of the pixel size, so they could be also be misclassified. Thus we suspect that wetland areas are underrepresented in this study.

The major source of errors in the emission calculation results from spatial and temporal variability in the CH_4 fluxes and errors in the annual integration. Integrated annual fluxes for the low flux sites (shrublands, nonacidic tundra) have standard deviations that range from 16% to 40%, but their contribution to the overall CH_4 emission is small. For simplicity, we have used a basin-wide estimate of integrated annual flux for open water areas. There are differences in the distributions of lakes and streams, and thus CH_4 flux, between the map units. Fluxes associated with acidic and wet tundra have standard deviations of about 40%, but the fluxes themselves are between 5- and 40-fold greater than the low emission categories, so uncertainties in the regional estimates are dominated by wetland and open water emissions. Considering possible misclassification of the high-emission categories and the observed spatial variability in wetland emission, we expect that Figure 1 and Table 3 are accurate to no better than $\pm$ 50-70%.

This study is the first to systematically incorporate negative fluxes or soil consumption of CH_4 and emission from open waters in a regional CH_4 emission estimate. Total CH_4 emission is heavily influenced by the areal coverage of the two highest CH_4 emission land cover categories, wetlands, and open waters. Oxidation of atmospheric CH_4 by soils in areas classified as barrens and shadows is less than 0.16% of the total emission in this study. Consumption of atmospheric CH_4 by soils accounts for between 2 and 9% of the global CH_4 budget, and an estimated 50% of the CH_4 produced in wetland environments is oxidized before it reaches the atmosphere [*Reeburgh et al.*, 1993]. Measurement of CH_4 oxidation in the Kuparuk watershed [*Whalen et al.*, 1995] confirms this general observation, so the largest effect of oxidation occurs before emission, and our chamber measurements of net emission give no information on the extent of subsurface oxidation.

3.3. Parallel Work

Shippert [1997] has also estimated CH_4 emission in the Toolik Lake area using a different approach to scaling up CH_4 fluxes from site measurements. The study, which was conducted in parallel with the present work and involves many of the same CH_4 flux data, focused on three images of the Toolik Lake area, one derived from a SPOT (Système pour l'Observation de la Terre) multispectral image, an ERS-1 (European Remote Sensing satellite) SAR (synthetic aperture radar) image, and a digital elevation model based on aerial photographs. The first two images were resampled to have 60 m pixels. A slope image with 60 m grid cells was calculated from the digital elevation model. Methane fluxes were measured in combination with soil moisture, temperature, pH, aboveground biomass, slope, and inundation by water. Using a regression tree approach, CH_4 emission was explicitly linked to environmental conditions rather than vegetation types. However, the environmental conditions that defined the terminal nodes in the regression analysis were also related to vegetation type. The weighted CH_4 emission rate for the Toolik Lake area was 750 mg CH_4 m^{-2} yr^{-1}, which compares reasonably with the 645 mg CH_4 m^{-2} yr^{-1} calculated for the Toolik Lake area in this study (Table 3).

The Siberian coastal transect measurements of *Christensen et al.* [1995] provide general flux magnitudes but no seasonal or integrated CH_4 flux information. Their results indicate the presence of large areas of mesic low CH_4 emission tundra along the north Siberian coast. Railroad [*Crutzen et al.*, 1998; *Bergamaschi et al.*, 1998) and aircraft (*Tohjima et al.*,1996] transects of Siberia point to oilfields and wetlands as large local to regional CH_4 sources.

4. Summary and Conclusions

This study involves a straightforward application of vegetation-specific CH_4 fluxes to a HGIS to obtain estimates of CH_4 emission from the Kuparuk River basin (26.3 x 10^3 km^2). The CH_4 flux database involves measurements from the 1994-1996 emission seasons and includes consumption of atmospheric CH_4 by soils as well as emission from open waters. Nonacidic tundra, acidic tundra and shrublands are the dominant land cover or vegetation type in all of the map subareas. Wetland and open water CH_4 fluxes are the most variable of the land cover classes studied and are at least an order of magnitude larger than fluxes from shrublands or acidic and nonacidic tundra. Thus they dominate CH_4 emission for the Kuparuk River basin and map subareas. The Kuparuk River basin emits 2.09 x 10^{-10} g CH_4 yr^{-1} (0.02 Tg CH_4 yr^{-1}) to the atmosphere.

Assuming that the vegetation distribution and CH_4 emission resulting from this work are similar for the entire arctic and extending the areally weighted CH_4 fluxes for the entire map and the Kuparuk River watershed, 0.796 and 0.753 g CH_4 m^{-2} yr^{-1}, to a global tundra (7.34 x 10^{12} m^2) CH_4 emission estimate gives emissions of 5.84 and 5.52 Tg CH_4 yr^{-1}. This is about 15% of the "benchmark" estimate of *Fung et al.* [1991] and suggests that the vegetation distribution is not typical of the entire arctic.

Future work in this area should be directed toward reconciling field measurements and atmospheric model estimates. This work should involve application of existing CH_4 flux measurements to a range of high-resolution vegetation maps of the circumpolar arctic which are under development. The results from this study and that of *Christensen et al.* [1995] suggest large areas of vegetation with characteristic modest CH_4 fluxes. Despite attempts to avoid "hot spot" biases by systematic time series and transect sampling, it may well be that the global high-latitude CH_4 budget is dominated by large, high-emission wetland areas like the Canadian Hudson Bay lowlands (3.2 x 10^{10} m^2) and the largely unstudied west Siberian Lowlands (5.4×10^{10} m^2), as suggested by *Harriss et al.* [1993].

Acknowledgments. This work was supported by NSF grants OPP 9216138 and OPP 9318531 (and supplement). Soil temperatures used to estimate the duration of the flux season were provided by L. D. Hinzman, G. Vourlitis, and J. Laundre. S. C. Whalen and Chad Staiger assisted in establishing the initial sites, and Peg Shippert, Lara Savage, Isa Woo, Dean Kawamoto, and Kristin Marshall assisted with flux measurements and transects. We are grateful to these individuals and to the Toolik Lake camp and PICO management and staff for their assistance during this study.

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(Received August 12, 1997, revised March 11, 1998; accepted March 11, 1998.)