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# Methane emission from Arctic tundra

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**Abstract.** Concerns about a possible feedback effect on global warming following possible increased emissions of methane from tundra environments have lead to series of methane flux studies of northern wetland/tundra environments. Most of these studies have been carried out in boreal sub-Arctic regions using different techniques and means of assessing representativeness of the tundra. Here are reported a time series of $CH_4$ flux measurements from a true Arctic tundra site. A total of 528 independent observations were made at 22 fixed sites during the summers of 1991 and 1992. The data are fully comparable to the most extensive dataset yet produced on methane emissions from sub-Arctic tundra-like environments. Based on the data presented, from a thaw-season with approximately 55% of normal precipitation, a global tundra $CH_4$ source of 18—30 Tg $CH_4$ $yr^{-1}$ is estimated. This is within the range of 42 ± 26 Tg $CH_4$ $yr^{-1}$ found in a similar sub-Arctic tundra environment. No single-parameter relationship between one environmental factor and $CH_4$ flux covering all sites was found. This is also in line with conclusions drawn in the sub-Arctic. However, inter-season variations in $CH_4$ flux at dry sites were largely controlled by the position of the water table, while flux from wetter sites seemed mainly to be controlled by soil temperature.

## Introduction

Northern wetlands and tundra environments contain about 14% of the global stored soil carbon (Post et al. 1982) and are believed to be a large source of atmospheric $CH_4$ (Mathews & Fung 1987; Aselman & Crutzen 1989; IPCC 1990). General Circulation Models of global climate predict a substantial warming over northern latitudes in the future. This information has lead to concerns about a possible feed-back effect on global climate from increased decomposition of organic soil carbon and possible increased emission of $CH_4$ from northern wetlands (IPCC 1990; Christensen 1991).

At present high northern latitudes are associated with the highest atmospheric concentrations of $CH_4$ (Fung et al. 1991) and the lowest

$\delta^{13}C$ values of atmospheric $CH_4$ (Quay et al. 1988, 1991). This provides evidence for a substantial northern biogenic source of $CH_4$. Anaerobic decomposition in soils of northern wetlands and tundra is normally identified as being responsible for this input (IPCC 1990). However, estimates for the magnitude of the northern wetlands source, based on field studies, show substantial variation, ranging from 0.6 to 106 Tg $CH_4$ $yr^{-1}$ or < 1% to 20% of the total atmospheric input (Svensson & Roswall 1984; Sebacher et al. 1986). Recent flux studies in boreal and sub-Arctic regions (Moore et al. 1990; Roulet et al. 1992; Whalen & Reeburgh 1992; Bartlett et al. 1992) and results from a three-dimensional model synthesis of the global $CH_4$ cycle (Fung et al. 1991) seem to be converging in the lower end of this range, between 10 and 35 Tg $yr^{-1}$. This study provides a comparison of these figures with an estimate obtained on the basis of data from true Arctic tundra. The data from fixed sites presented here are also compared to flux estimates found in transect studies in the same region of Arctic Alaska (Whalen & Reeburgh 1990a; Morrissey & Livingston 1992).

A detailed understanding of the factors controlling $CH_4$ flux from tundra soils is important for predicting how the $CH_4$ emission might respond to a changing climate. An increasing number of studies have addressed this problem but no simple presentation of the controlling factors has been found. Most of the field studies have been based on short-term measurements in sub-Arctic or temperate regions and all have been carried out with different techniques and means of assessing representativeness of wetland environments (Svensson & Roswall 1984; Crill et al 1988; Moore et al. 1990; Whalen & Reeburgh 1992; Bartlett et al. 1992) which might account for some differences in results. Directly comparable multiyear time series of flux data are needed to get a better picture of how $CH_4$ flux is controlled by climatic parameters, and such data also provide important possibilities for validating flux models aimed at predicting global tundra responses to climate change. However, only one such study is yet available (Whalen & Reeburgh 1992) and, like most studies of northern wetland and tundra emissions of $CH_4$, it was made in the sub-Arctic. Here are reported emissions and environmental data from a time series of measurements extending through most of the 1991 and part of the 1992 thaw-season at tundra sites on the North Slope of Alaska. A total of 528 independent observations at 22 fixed sites were obtained. The data were collected using the techniques of Whalen & Reeburgh (1988, 1992) which forms the basis for a direct comparison with data from a sub-Arctic tundra-like environment near Fairbanks, Alaska. The size of the global tundra $CH_4$ source as calculated on the basis of data

from true Arctic environments and the controls on the emission are discussed.

## Materials and methods

Methane flux was measured in summers of 1991 and 1992 at permanent tundra sites near the University of Alaska Field Station at Toolik Lake (68°38′N, 149°38′W), 650 kilometres north of Fairbanks on the North Slope of Alaska (Fig. 1). All sites are in the continuous permafrost zone. Measurements were made at 22 stations, on 23 days through the 1991

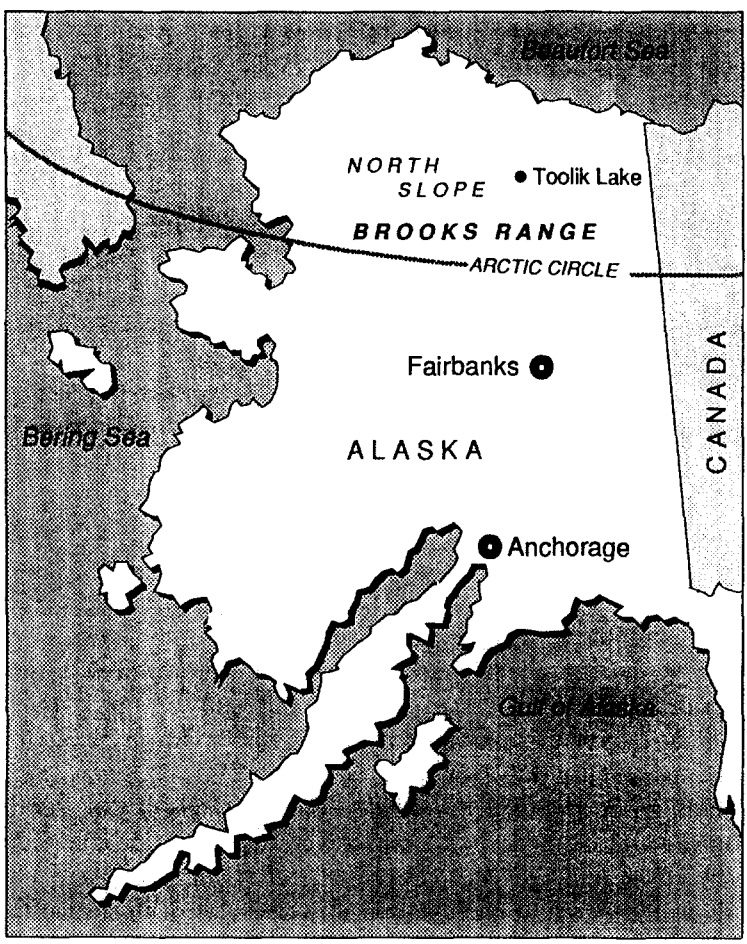



*Fig. 1.* Alaska showing the location of Toolik Lake (68°38′N, 149°38′W).

thaw-season and on 8 days during August 1992. Of these stations, 16 were established by Whalen and Reeburgh in 1987; the remainder were established for this study. Four extra stations were established in 1992 on tussocks (T sites) with approximately 50 meter intervals along a natural moisture gradient up-slope from the Kuparuk River.

The stations are grouped in six floristically different units representative of Arctic tundra:

1) *Eriophorum* tussocks (T sites).
2) Waterlogged intertussock areas without vegetation ('black holes', BH sites).
3) Mosses invaded to various extent by vascular plants (M sites).
4) *Carex* at a pond margin mixed with *Eriophorum* (C sites).
5) 'Depressed' waterlogged areas with *Eriophorum* and *Carex* (D sites).
6) 'Elevated' areas surrounding the depressions with a variety of plants such as mosses and vascular plants including small shrubs (E sites).

C, D and E sites are typical for areas characterised as 'wet' tundra while BH (although waterlogged), M and T sites largely represent 'moist' tundra areas. Whalen & Reeburgh (1988, 1992) did not consider D and E sites, so for comparative reasons these sites are not used when scaling up to global tundra areas. However, the inclusion of additional D and E stations offered the possibility for studying $CH_4$ emissions from a wet, highly organic, tundra-soil environment in more detail.

Net $CH_4$ fluxes were determined by a static chamber technique using aluminium bases and plexiglas covers sealed by water-filled channels. The chamber areas were 0.075 $m^2$ except at the BH sites where they were 0.023 $m^2$. Four duplicate 8 ml samples were taken at maximum 20 minute intervals with glass syringes, and methane was analysed at Toolik Lake Field Station using a gas chromatograph (Shimadzu GC-8A) equipped with a flame ionisation detector and a molecular sieve column. Ultrapure nitrogen was used as carrier gas. Methane flux was calculated from chamber size and the linear change of $CH_4$ concentration with time. The minimum detectable flux varied between 0.2 and 1.2 mg $CH_4/m^2/day$ depending on chamber volume:area ratios. Fluxes lower than the minimum detectable flux were considered zero. The sampling method is described in more detailed by Whalen & Reeburgh (1988, 1992). Soil temperatures at 1, 3, 5, 7, 9, 11 and 13 cm depth were obtained with a thermistor string and hand-held thermometer (Omega 866). Water table position was measured at each station in wells relative to soil surface and thaw depth was determined by inserting a steel rod to the freezing horizon. Soil pH were measured in slurries of soil and distilled water.

The mean air temperature at Toolik Lake in the summer of 1991 (June

1 to Aug. 31) was 8.4 °C (LTER 1991), the same as the long-term average (L. Hinzman, pers. comm. 1991). The total precipitation for the same period was 10.6 cm (LTER 1991) which is substantially lower than the long-term average of 20.2 cm (L. Hinzman, pers. comm. 1991). The long-term averages were measured at Imnavait Creek watershed 11 kilometres east of Toolik Lake. The corresponding long-term averages obtained at Fairbanks Airport for the three summer months are 15.1 °C and 12.6 cm accumulated precipitation (NOAA 1991).

## Results and discussion

### *Scale of emission*

The mean, maximum and median emission as measured at all stations in 1991 and 1992 are presented in Table 1. The emissions found in earlier more sporadic measurements at the same sites (Whalen & Reeburgh, unpublished) were all within the ranges found in this study. The highest emission from each floristic unit was measured in 1992.

Fluxes at three sites were used to calculate a seasonal integrated flux from each floristic unit. The thaw-season was estimated to cover 100 days based on weather information from the region supplied by the Water Research Center, University of Alaska, and unpublished LTER weather data from Toolik Lake (LTER 1991). In order to encompass the thaw-season, one week was added to the integrated curve before the first sampling date and two weeks after the last to allow emissions to approach zero. As observed in most other field studies of $CH_4$ emission the sites showed a substantial natural variation. The standard deviation (Tables 1 and 2) was particularly high at the *Carex* sites due to episodic events of very high emission.

The daily mean and seasonal integrated fluxes as measured at the different units in 1991 are presented in Table 2. Whalen & Reeburgh (1992) observed how annual overall averaged flux rates at their sites near Fairbanks responded to precipitation anomalies. This points to the importance of having similar patterns of precipitation when comparing integrated fluxes from different studies and years, and corresponds with the assumption that moisture limits $CH_4$ oxidation in the soil and hence increases the flux (see below). In Whalen and Reeburgh's four-year time series from the Fairbanks area the year 1987 had similarly low precipitation as 1991 at Toolik Lake (approx. 55% of normal) and 1987 is therefore chosen for comparing sub-Arctic with the Arctic tundra flux reported here.

*Table 1.* Summary of $CH_4$ flux observed during the 1991 thaw season and in August 1992 on the North Slope of Alaska. Stdev is the standard deviation of mean.

| | $CH_4$ flux mg/m²/day | | | |
|---|---|---|---|---|
| | *n* | Mean | Stdev | Max | Median |
| BH1 | 28 | 0.45 | 0.53 | 2.25 | 0.3 |
| BH2 | 28 | 2.4 | 2.78 | 11.45 | 1.58 |
| BH3 | 28 | 0.16 | 0.24 | 0.83 | 0 |
| M1 | 28 | 12.85 | 5.09 | 23.26 | 13.59 |
| M2 | 28 | 2.5 | 2.32 | 8.53 | 2.18 |
| M3 | 27 | 18.28 | 7.65 | 36.57 | 19.61 |
| T1 | 28 | 95.25 | 74.03 | 252.41 | 82.72 |
| T2 | 28 | 35.15 | 18.9 | 65.63 | 36.46 |
| T3 | 28 | 32.09 | 26.71 | 114.73 | 25.4 |
| T4[a] | 5 | 5.45 | 0.71 | 6.5 | 5.47 |
| T5[a] | 5 | 0.37 | 0.52 | 1.03 | 0 |
| T6[a] | 5 | 0.19 | 0.42 | 0.95 | 0 |
| T7[a] | 5 | −0.32 | 0.32 | 0 | −0.4 |
| C1 | 27 | 36.63 | 39.76 | 176.19 | 20.95 |
| C2 | 27 | 373.28 | 567.83 | 2228.17 | 151.58 |
| C3 | 27 | 39.39 | 23.73 | 108.34 | 34.53 |
| D1 | 28 | 116.62 | 36.57 | 205.51 | 124.07 |
| D2 | 28 | 35.39 | 24.81 | 116.8 | 29.38 |
| D3[b] | 21 | 50.06 | 28.83 | 109.56 | 53.04 |
| E1 | 28 | 34.44 | 25.94 | 104.12 | 27.24 |
| E2 | 28 | 47.51 | 29.94 | 132.67 | 42.34 |
| E3[b] | 19 | 10.79 | 4.34 | 16.53 | 11.96 |

[a] only measured in 1992
[b] only measured in 1991

*Emission from floristic units.* All comparable units with a sizeable emission (C, T and M) had higher daily mean emission on the true Arctic tundra (Table 2) but only the difference between the M sites was significant at the $p = 0.05$ level.

The higher emission at the C sites (daily mean 112.3 ± 71.8 compared to 33.5 mg $CH_4/m^2$/day, Table 2) is due to episodic events; if these are excluded the emission from *Carex* becomes similar to the Fairbanks data. Episodic events were measured repeatedly in 1991 and 1992 at one site (C2). In the first two weeks of July 1991 this site emitted $CH_4$ at a rate more than seven times higher (1.5 g $CH_4/m^2$/day) than the normal range for *Carex* (<200 mg $CH_4/m^2$/day, Fig. 2). On August 3, 1992, C2 reached a peak emission of 2.2 g $CH_4/m^2$/day. C2 also showed the highest emission in the limited early measurements (Whalen & Reeburgh, unpublished).

*Table 2.* The daily mean and integrated annual $CH_4$ flux from sites on the North Slope in 1991 and in the Fairbanks area of Alaska in 1987. The daily mean is of thaw season flux in three chambers ± standard error (mg $m^{-2}$ $day^{-1}$). Net annual $CH_4$ flux ± standard deviation (g $m^{-2}$ $yr^{-1}$) from the North Slope and the Fairbanks equivalent were both integrated under a mean flux curve by the trapezoidal rule. The net flux from the North Slope is based on a total number of measurements averaging 60 for each unit and is multiplied by a factor representing the winter flux (see text). Fairbanks net flux is integrated from January 1 to December 31, 1987.

| Site type | Daily mean $CH_4$ flux | Fairbanks equivalent | Integrated net $CH_4$ flux | Fairbanks equivalent |
|---|---|---|---|---|
| Tussock | 42.8 ± 16.3 | 29.5 ± 12.3 | 4.73 ± 1.2 | 8.05 ± 2.5 |
| Intertussock | 0.6 ± 0.4 | 2.8 ± 0.9 | 0.067 ± 0.04 | 0.62 ± 0.28 |
| *Carex* | 112.4 ± 71.8 | 33.5 ± 10.5 | 8.83 ± 3.4 | 4.88 ± 1.09 |
| Moss | 9.2 ± 3.8 | 0.9 ± 0.4 | 1.24 ±0.14 | 0.47 ± 0.16 |
| Depressions | 61.6 ± 24.8 | — | 6.0 ± 1.1 | — |
| Elevations | 22.7 ± 7.2 | — | 2.1 ± 0.27 | — |

The episodic events at C2 are not related to any similar changes in measured environmental factors. They are unlikely to be due to physical releases of large methane bubbles since such releases would have disturbed the linearity of concentration change in the sampling chamber with time. Also the events lasted consistently for several days (Fig. 2), which is unlikely for a sudden physical release of large methane bubbles. However, although it was not observed during the measurements, a steady stream of smaller bubbles cannot be ruled out as cause for the events, given the sampling system used. Windsor et al. (1993) show how such episodic emission could be associated with a reduction in overburden pressure followed by a lowered water table. The events could also be associated with 'hot spots' for microbial activity which has been reported to occur due to the presence of particulate organic carbon in the soil (Parkin 1987). Isotopic analysis of methane from C2 is presently being carried out to try and determine whether the cause of the events is increased $CH_4$ production, ebulition, or possibly decreased consumption rates. In any case the event reported here illustrates the importance of detailed time series of flux data when the aim is to extrapolate and estimate annual emissions. The frequency and scale of these events would have a major impact on the global estimates if neglected or not measured. Windsor et al. (1993) reports that seasonal estimates become 7—22% lower when measured episodic events are excluded from calculations. The global estimate of this study would be 21—25% lower if the episodic event were excluded.

The T sites on the North Slope show a higher (non-significant) daily

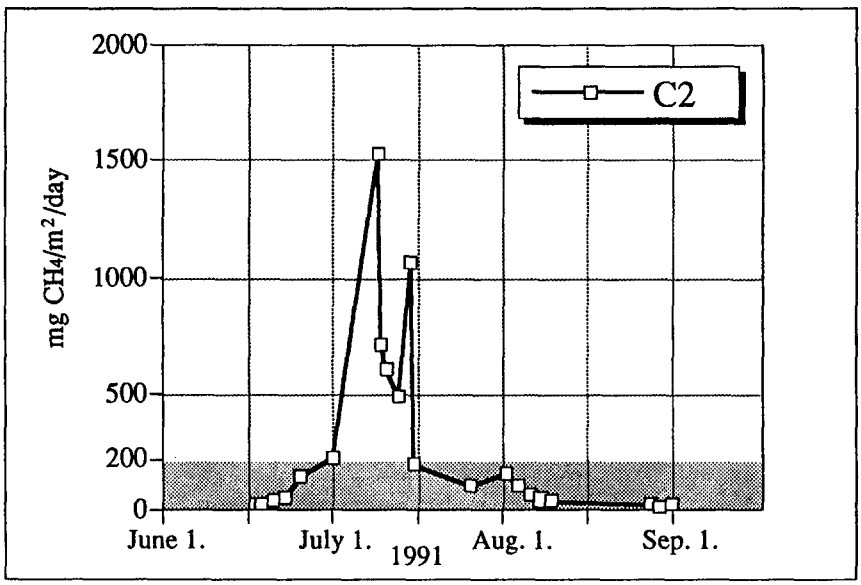



*Fig. 2.* Episodic event of $CH_4$ emission at a *Carex* site (C2). Previous measurements at all *Carex* sites and the 1991—92 data for C1 and C3 all have emission rates in the grey area (below 200 mg $CH_4$ $m^{-2}$ $day^{-1}$).

mean emission (42.8 ± 16.3 as opposed to 29.5 mg $CH_4/m^2/day$ in Fairbanks) which turns into a lower seasonal integrated flux (Table 2) due to difference in the length of thaw-seasons. The study carried out in 1992 of additional T sites on a transect with a natural gradient in water table position showed rapidly decreasing $CH_4$ flux when moving up slope into dryer tundra areas (T4—7 in Table 1, see section below). This indicates the 1991 data from moist T sites used for the above integration might overestimate average tussock flux since the 1991 T sites (T1—3) are the downslope part of the transect. The top chamber on the transect also showed consumption of atmospheric $CH_4$ by tundra soils but not enough data was obtained for determining the significance of this in terms of global tundra methane emission estimates. However, Bartlett et al. (1992) and data from dryer sites in a transect study from Prudhoe Bay to the Arctic circle in 1992 (Whalen & Reeburgh, unpublished) also showed negative net $CH_4$ fluxes, so it seems that it may be necessary to account for a small dry tussock sink in extrapolations of tussock flux.

The thaw-season emissions at M sites are significantly higher in the north (9.2 ± 3.8 mg $CH_4/m^2/day$) when compared with 1987 Fairbanks data (0.9 mg $CH_4/m^2/day$). Next to *Carex* the mosses were shown by

Whalen & Reeburgh (1992) to have the highest interannual variability and the significance of the difference found here is therefore questionable.

BH sites show the lowest emission observed anywhere for this unit (0.6 ± 0.4 mg $CH_4/m^2/day$) and have significantly lower emission on the North Slope when compared to Fairbanks in 1987 (2.8 mg $CH_4/m^2/day$). Although waterlogged, the constantly low temperatures (due to shading by the tussocks) and shallow organic layer in the soil (Table 3) might explain the low flux. BH emission could be considered below the 'noise' level.

Emission at D sites (61.6 ± 24.8 mg $CH_4/m^2/day$) are in the general range of *Carex* and are probably well representative of the emission from wet meadow tundra environments. E sites have microtopographical and floristic characteristics in common with tussocks and mosses and could, as the emission (22.7 ± 7.2 mg $CH_4/m^2/day$) also indicates, be considered a combination between the two.

In general vascular plant communities (C, T, D and E) have the highest emission. This is in accordance with most other flux studies. The flux:plant relationships have been quantified as functions of plant biomass (Morrissey & Livingston 1992; Whiting & Chanton 1992) and also of the number of vascular plant tillers present in the sampling chamber (Christensen, unpublished).

*Emission from wet meadow and moist tundra.* For comparative reasons the weighting method of Whalen & Reeburgh (1988, 1992) was used when calculating overall fluxes from wet meadow and moist tussock tundra. The percentage cover of the different floristic units within these two types of tundra was taken from Kummerow et al. (1983) and Walker et al. (1987) (Table 4).

On the basis of daily mean flux (Table 2) and percentage coverage of each unit the thaw-season mean of wet meadow tundra flux for the area surveyed is calculated to 97 ± 6 mg $CH_4/m^2/day$ (range due to uncertainty in percentage cover estimates). This is significantly higher than the corresponding estimate (29 ± 2 mg $CH_4/m^2/day$) calculated on the basis of 1987 data from Whalen & Reeburgh (1992). However, it is more comparable with an overall estimate (110 ± 6 mg $CH_4/m^2/day$) based on a four-year average (Whalen & Reeburgh 1992) and the transect-based estimate of 90 mg $CH_4/m^2/day$ partly obtained in the same region as this study (Whalen & Reeburgh 1990a). The result presented here is higher than Morrissey & Livingston's (1992) recent estimate of 64 mg $CH_4/m^2/day$ for wet meadow flux in the same region as the present study. The lower estimates of Whalen & Reeburgh's (1992) 1987 data and Morrissey & Livingston (1992) are probably due to no extreme emissions (like the episodic events reported here) were measured in these studies.

*Table 3.* Soil environment data from different floristic units at sites near Toolik Lake as observed between June 15 and Aug 30 1991. Temperatures in °C are measured as an average (± range) of the top 13 cm of the soil. Water table position is measured in cm (mean ± range) relative to soil surface (negative value being below soil surface). Thaw depth and depth of the organic layer are measured in cm below soil surface. Soil pH was measured in slurries of top 10 cm soil.

| | BH | M | T | C | D | E |
|---|---|---|---|---|---|---|
| *Temperature* | | | | | | |
| mean (°C) | 2.3 ± 2.4 | 3.4 ± 3.1 | 7.6 ± 6.1 | 8.0 ± 7.2 | 7.3 ± 4.1 | 9.7 ± 6.3 |
| *Water table* | | | | | | |
| mean (cm) | 14.1 ± 7 | −9.2 ± 12 | −13.5 ± 9 | −4.1 ± 13 | 5.7 ± 5 | −11.8 ± 6 |
| *Thaw depth* | | | | | | |
| mean (cm) | 27.5 | 16.9 | 63.5 | 47.6 | 44.4 | 62.6 |
| min. | 12 | 0 | 19 | 31 | 23 | 37 |
| max. | 30 | 20 | 70 | 51 | 50 | 70 |
| *Organic layer depth (cm)* | < 10 | 10 | > 30 | > 40 | > 30 | > 30 |
| *pH* | 5.4 | 5.4 | 4.5 | 4.9 | 4.5 | 4.5 |

*Table 4.* Global tundra $CH_4$ emission estimate. See text for sources.

| Site type | Percent cover | $CH_4$ flux g $m^{-2}$ $yr^{-1}$ | Annual $CH_4$ emission Tg $yr^{-1}$ |
|---|---|---|---|
| | *Tussock and low shrub tundra (6.46 × $10^{12}$ $m^2$)* | | |
| *Eriophorum* | 24—45 | 4.73 | 7.3—13.8 |
| *Carex* | 3—7 | 8.83 | 1.7—4.0 |
| Intertussock | 30 | 0.067 | 0.1 |
| Moss | 37—63 | 1.24 | 3.0—5.0 |
| Total tussock | | | 12.1—22.9 |
| | *Wet meadow tundra (0.884 × $10^{12}$ $m^2$)* | | |
| *Carex* | 80—90 | 8.83 | 6.2—7.0 |
| Moss | 10—20 | 1.24 | 0.1—0.2 |
| Total wet meadow | | | 6.3—7.2 |
| **Total tundra** | | | **18.4—30.1** |
| Total tundra based on Fairbanks data | | | 19.3—32.7 |

Thaw season moist tussock tundra flux is calculated to 25 ± 8 mg $CH_4/m^2$/day. This is again higher than Whalen & Reeburgh's (1992) 1987 estimate of 13 ± 4 mg $CH_4/m^2$/day. It is more in line with their transect result of 31 mg $CH_4/m^2$/day (Whalen & Reeburgh 1990a) and within range of the multiyear Fairbanks average of 35 ± 10 mg $CH_4/m^2$/day (Whalen & Reeburgh 1992). Bartlett et al. (1992) and Morrissey & Livingston (1992) find substantially lower tussock tundra emissions (around 3 mg $CH_4/m^2$/day). The tussock sites used for the integration in this study and by Whalen & Reeburgh (1992) are clearly part of the tussock tundra environment but there is very little overlap with the tussock tundra flux range observed by Bartlett et al. (1992) and Morrissey & Livingston (1992). This might indicate these two studies having a bias towards dry tussock tundra in a similar fashion to the above mentioned wet tussock bias in the present study.

The actual overall mean daily flux measured in the Fairbanks area in the thaw season 1987 is significantly lower than the corresponding figure from the 1991 North Slope data presented here (11—19 as opposed to 26—41 mg $m^{-2}$ $day^{-1}$). This suggests that the source strength of the true Arctic tundra might be higher than the sub-Arctic equivalent, but such a conclusion is uncertain given the high interannual variability of the fluxes from the different floristic units (Whalen & Reeburgh 1992). Also the net

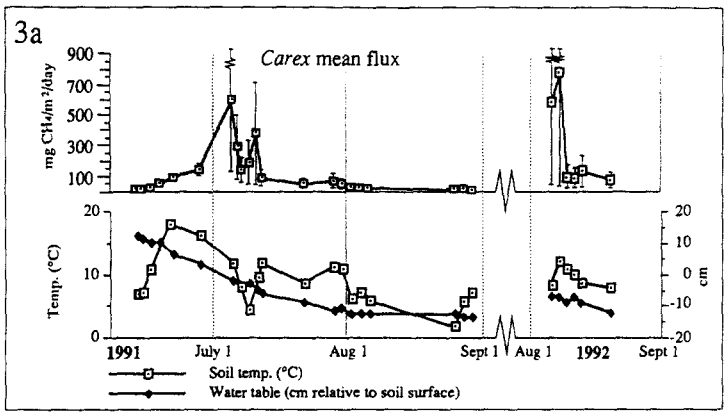
fluxes based on seasonal integration (rather than simple means) calculated below show a smaller difference between overall fluxes.

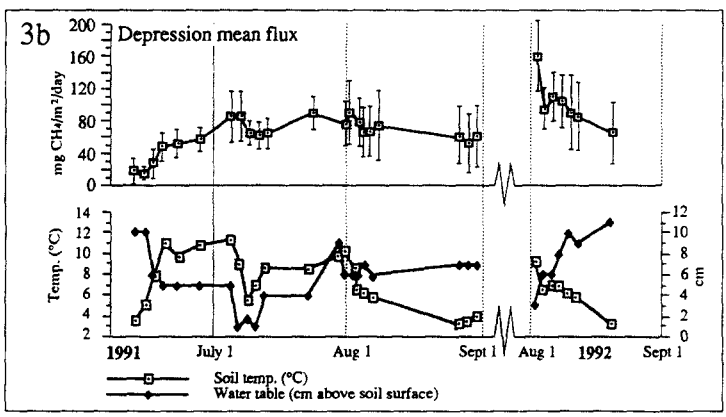
*Global extrapolation.* Seasonal net flux for each unit was calculated by integrating the area under the mean flux curve using the trapezoidal rule. To calculate the annual emission, a factor representing the assumed winter flux based on observations by Whalen & Reeburgh (1988) was multiplied the seasonal integrated flux (winter emission as percentage of annual flux: *Carex* 9%, Tussocks 5%, Black holes 4%, Mosses 43%, Depressions 9% estimated, and Elevations 5% estimated). The possible effect on winter emission of difference in winter length between the North Slope and Fairbanks is assumed to be compensated by a thinner active layer in the north limiting the potential porewater reservoir in winter (Dise 1992). Total tundra area was estimated as $7.34 \times 10^{12}$ m$^2$ (Mathews 1983) with $0.884 \times 10^{12}$ m$^2$ wet meadow tundra (Mathews & Fung 1987) and the remaining $6.46 \times 10^{12}$ m$^2$ being moist tussock tundra. Global tundra $CH_4$ emission based on 1991 data from Toolik Lake is then calculated to be 18—30 Tg yr$^{-1}$ (Table 4). As described above this estimate is obtained in a relatively dry year and is probably low compared to a long-term mean. The 1992 data from Toolik Lake, obtained partly in a very wet period, all show the highest fluxes measured anywhere in this study. Although I did not obtain enough data for a direct comparison, 1992 would seem to have produced a higher global estimate (Fig. 3).

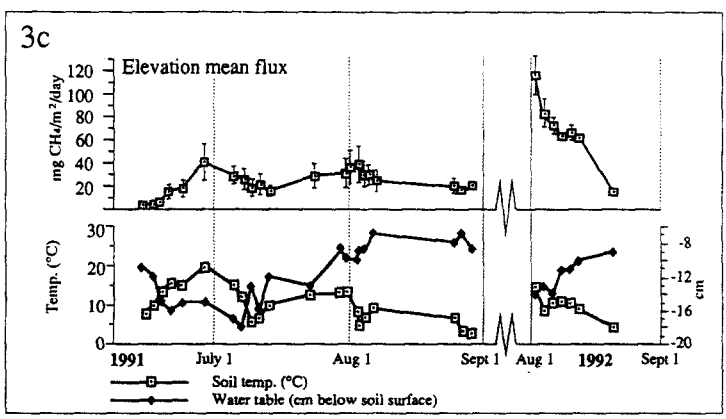
As mentioned above the thaw-season is approximately 100 days on the Arctic tundra, but up to 150 days in the sub-Arctic. When scaling up, the differences in the integrated fluxes and the length of the thaw-season compensate, and the global estimates of this study and the Fairbanks 1987 data become very similar: 18—30 and 19—33 Tg yr$^{-1}$ respectively (Table 4, Whalen & Reeburgh 1988). These figures are a little lower than, but not conflicting with, the figure of 35 Tg yr$^{-1}$ that was suggested in a recent three-dimensional model synthesis of the global $CH_4$ cycle (Fung et al. 1991) and they are within the overall range of 42 $\pm$ 26 Tg yr$^{-1}$ estimated by Whalen & Reeburgh (1992).

*Environmental controls*

Methane flux, soil temperature and water table height as measured at the different floristic units through the 1991 and 1992 seasons are illustrated in Fig. 3. Table 3 summarises general soil environment data obtained during the same period. Thaw depth developed at all sites from 10—30 cm below soil surface when sampling started on June 15 to the depth of


3a
Carex mean flux
mg CH4/m2/day
900
700
500
300
100
Temp. (°C)
20
10
0
cm
20
10
0
-10
-20
1991
July 1
Aug 1
Sept 1
Aug 1
1992
Sept 1
Soil temp. (°C)
Water table (cm relative to soil surface)


3b
Depression mean flux
mg CH4/m2/day
200
160
120
80
40
0
Temp. (°C)
14
12
10
8
6
4
2
cm
12
10
8
6
4
2
0
1991
July 1
Aug 1
Sept 1
Aug 1
1992
Sept 1
Soil temp. (°C)
Water table (cm above soil surface)


3c
Elevation mean flux
mg CH4/m2/day
120
100
80
60
40
20
Temp. (°C)
30
20
10
0
-8
-12
-16
-20
cm
1991
July 1
Aug 1
Sept 1
Aug 1
1992
Sept 1
Soil temp. (°C)
Water table (cm below soil surface)

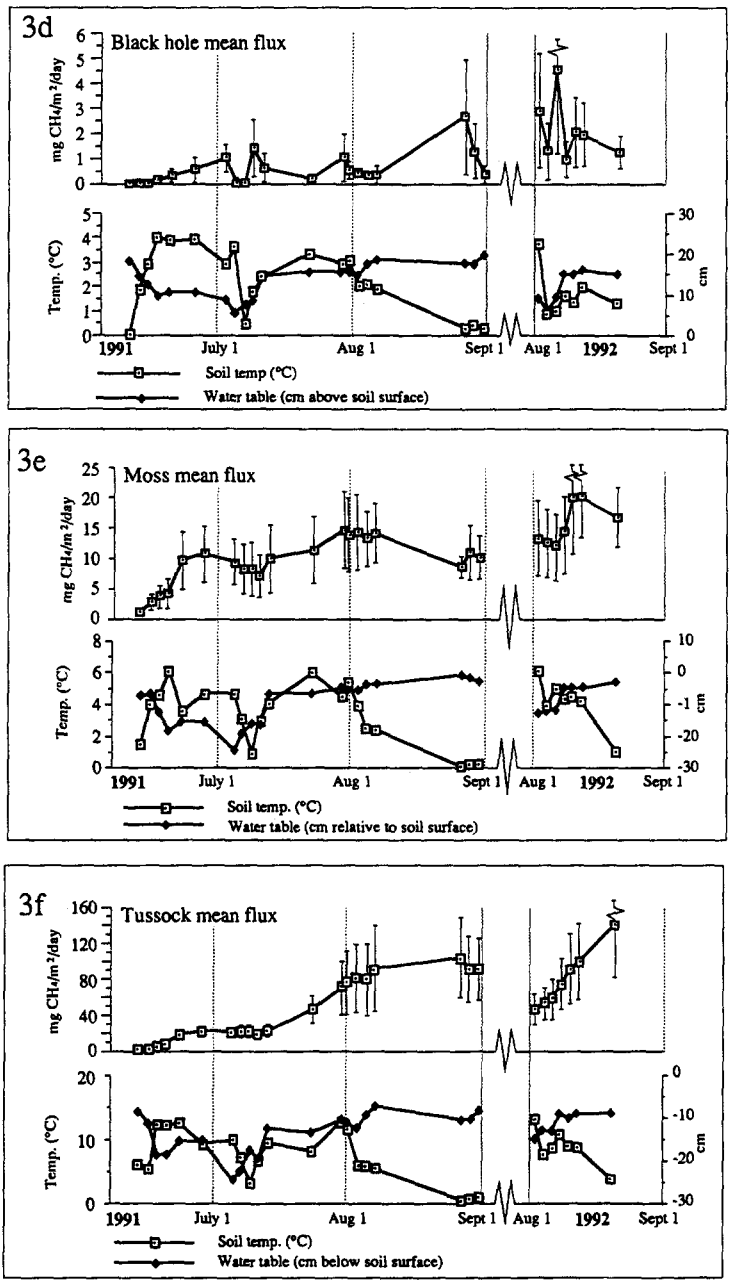



*Fig. 3.* Mean $CH_4$ flux, soil temperature (mean of the top 13 cm) and water table height at six different floristic units (a: *Carex*; b: Depression; c: Elevation; d: Black Hole; e: Moss; f: Tussock) through the 1991 and 1992 thaw seasons near Toolik Lake on the North Slope of Alaska. Error bars indicate standard error of means ($n$ = 3). Bars are absent where standard error is smaller than symbol.

bedrock (50—70 cm) before the end of June. This thaw depth was maintained at most sites until sampling stopped on September 1. Only the Moss sites experienced surface freeze-up before that (on August 28).

The flux and soil environment data presented here seem generally to support Whalen & Reeburgh's (1992) recent conclusion that single-parameter relationships used to predict methane flux are site-specific. However, correlations with soil temperature and water table at the *Carex* site seems to indicate a possible rank order of controls where, once the water table drops below the soil surface and allows increasing rates of microbial oxidation to occur, a simple temperature/flux relationship is overruled (Fig. 3a). At the C sites the water table gradually declined throughout the 1991 season and around July 1 it dropped below the soil surface (Fig. 3a). If the episodic event at C2 is excluded and the two periods are considered separately, a linear correlation with temperature ($r^2 = 0.79$, $n = 6$) is seen in the waterlogged period. When the water table dropped below the soil surface the flux decreased and correlated logarithmically with the falling water table ($r^2 = 0.84$, $n = 14$). A very similar correlation between drying of *Carex* sites and decreasing emission was reported by Bartlett et al. (1992).

These results suggests that on a short-term basis temperature might independently control emission at the waterlogged sites while moisture controls emission from sites where the water table fluctuates below the soil surface. This could explain the correlations found, and interaction between temperature and moisture might account for lack of relationships when temperature is related to all-season flux data from dry/moist sites. However, such simple explanations are challenged by the complexity of controlling factors found by Whalen & Reeburgh (1992) and by results of Bartlett et al. (1992), who found a good correlation between soil temperature and flux at dry upland tundra sites. Taking into account the complexity of controlling factors, particularly when the water table is below the soil surface, simple correlations between all-season flux and single environmental parameters should not be expected. However, floristic units in a constantly wet environment could be expected to show better correlation between soil temperature and flux relative to dryer sites assuming that high moisture content limits oxidation. This is not entirely the case although in the early season (mid to late June) the emissions at all sites generally increased with the progressive warming of the soil. A period of very cold weather in early July caused a dramatic fall in soil temperatures and was followed by reduced flux at most sites, in particular the wet C, D and E sites (Figs. 3a—c). In spite of this, only C sites showed a significant positive association between soil temperature and flux when all-season data are compared using Spearman's rank correlation test (Table 5).

*Table 5.* Spearman's rank correlation ($r_s$) coefficient for correlations between $CH_4$ emission and environmental variables. Only values of $r_s$ significant at $p < 0.05$ are shown.

| | C | D | E | BH | M | T |
|---|---|---|---|---|---|---|
| *n* | 20 | 20 | 21 | 20 | 19 | 20 |
| Soil temp. | 0.52 | | | | | −0.46 |
| Water table | | | | | 0.57 | 0.54 |

The reason for absence of statistically significant relationships is that the same temperature generally corresponds with higher flux at the end of the thaw-season compared to measurements at the start of the season (Figs. 3b, c, e, f), a pattern also found by Svensson & Roswall (1984). One way of explaining this is by an increasing 'background' emission which is not influenced by the immediate soil environment but by the progressing season. The exact nature of this background emission needs to be studied further, but simple explanations could be increased microbial population size, an increasing supersaturated content of methane in the soil water, or a combination of these factors. However, other things being equal, the consequence is an increased emission throughout the summer. It is hypothesized that this background emission may be quantified as an increasing function of degree days, and if this factor is subtracted from the measured flux a better measure of production over time is provided.

An arbitrary 'pool' is calculated by subtracting start-season from end-season emissions at the same soil temperatures and the background emission is calculated in the following way:

$$p = f_{end} - f_{start}$$

$$b_i = \frac{p \times dd_i}{dd_n}$$

$$cf_i = mf_i - b_i$$

where $p$ is the 'pool' and $f_{start}$ and $f_{end}$ are flux at equivalent temperatures at the start and end-season, respectively. Background emission ($b_i$) is equal to the fraction of degree days on the day in question ($dd_i$) to all season degree days ($dd_n$) multiplied by $p$. The corrected flux ($cf_i$) is then calculated by subtracting the background emission from the actual measured flux ($mf_i$).

Below follows a sample calculation of corrected flux on julian day 195

(July 14) at the D sites: $f_{start}$ = 17.8 mg/m$^2$/day (June 15); $f_{end}$ = 60.3 mg/m$^2$/day (Aug. 30); $dd_{195}$ = 293; $dd_n$ (Aug. 30) = 619; $mf_{195}$ = 64.2 mg/m$^2$/day.

$$p = 60.3 - 17.8 = 42.5 \text{ mg m}^{-2} \text{ day}^{-1}$$

$$b_{195} = \frac{42.5 \times 293}{619} = 20.1 \text{ mg m}^{-2} \text{ day}^{-1}$$

$$cf_{195} = 64.2 - 20.1 = 44.1 \text{ mg m}^{-2} \text{ day}^{-1}$$

Table 6 show how linear relationships for all data comparisons between flux and soil temperature change to become statistically significant at the wet D and E sites when data are corrected as described. Looking at the raw data from the D and E sites (Table 6), the first period (June 15—July 6) with increasing soil temperature shows substantially higher regression slopes than the last period (Aug. 1—Aug. 30) with decreasing temperature (slopes: 7.2 and 2.4 over 4.6 and 1.65, respectively). This is in accordance with the theory which implies the flux will be more strongly affected by increasing than by decreasing temperatures due to the increasing pool. Also this difference between slopes should diminish when the data are corrected and this is in fact what tends to happen at the D sites (from 7.2

*Table 6.* Regression analysis for the association between methane flux and mean soil temperature at Depression and Elevation sites. Comparisons of both raw and corrected (Cor.) data as described in the text are shown. Temperature was increasing consistently in the period between June 15 and July 6. It was decreasing between Aug. 1 and Aug. 30. Probability level, $p$, is from an F test with * = $p < 0.05$, ** = $p < 0.01$ and *** = $p < 0.001$. NS: Not significant.

| | Slope | | $r^2$ | | $p$ | |
|---|---|---|---|---|---|---|
| | Raw | Cor. | Raw | Cor. | Raw | Cor. |
| D sites | | | | | | |
| June 15—July 6 | 7.2 | 6.7 | 0.76 | 0.79 | ** | ** |
| Aug. 1—Aug. 30 | 4.6 | 6.0 | 0.83 | 0.88 | ** | ** |
| All season | 3.5 | 5.3 | 0.18 | 0.62 | NS | *** |
| E sites | | | | | | |
| June 15—July 16 | 2.4 | 2.5 | 0.55 | 0.80 | NS | ** |
| Aug. 1—Aug. 30 | 1.7 | —[a] | 0.49 | —[a] | NS | —[a] |
| All season | 0.6 | 1.2 | 0.06 | 0.41 | NS | ** |

[a] Too few observations available (see text).

and 4.6 to 6.7 and 6.0; Table 6). The corrected data for the last period at the E sites could not be compared due to a shortage of data. A limited number of observations at the end of the season could not be used when calculating the correction at E sites because the calculation required equivalent start- and end-season temperatures. This could only be obtained at the E sites by excluding the last two data points in the season.

Whalen & Reeburgh (1992), measuring $p_{CH4}$ distributions in soil water at their sites in the summers of 1988 and 1989, found no clear relationships between $p_{CH4}$ and $CH_4$ flux. Their sites were generally dryer than the two used for the correlation above, but 1988 was relatively wet and best suited for comparison with the sites in this study. That year Whalen & Reeburgh observed an increase in soil $p_{CH4}$ over the season followed by dramatic late season increases in $CH_4$ flux, which could support the theory described above.

The calculation of the corrected flux will not have any implications for annual flux estimates. It is solely an attempt to better explain seasonal variations in $CH_4$ at wet sites.

Both M and T sites show significant non-parametric correlations with water table (Table 5) which corresponds with the hypothesis that at these dryer sites the water table becomes the primary control on emission by determining the rate of methane oxidation.

In August 1992 a transect of T sites was established at 50 meter intervals up-slope from the Kuparuk River. The transect showed a gradual decrease in $CH_4$ emission when moving from the moist T1, with the highest water table to T7 with the water table below bedrock (Fig. 4). T7 showed a small rate of $CH_4$ consumption when it was first sampled on August 7. Following heavy rainfall and a water-table rise of 15 cm, the consumption stopped but resumed when the water table had fallen again (Fig. 5). The observations at the transect gives further evidence for a strong water table control on $CH_4$ flux in tussock environments and also shows the potential for dryer tundra areas to act as an atmospheric $CH_4$ sink.

The 1991 data from the T sites also show a smaller inverse correlation with temperature (Table 5). This can be biologically reasonable only if methane-oxidising bacteria are highly sensitive to the decreasing temperature while methane producing bacteria are not. The methane-oxidising bacteria are more exposed to temperature changes simply because the aerobic zone is closer to the soil surface, but laboratory studies on temperature dependency of the two groups of bacteria (from equivalent soil environments) are needed to determine whether their responses differ in a way that can account for the possible relationship seen here. BH show no significant relationship with environmental parameters.

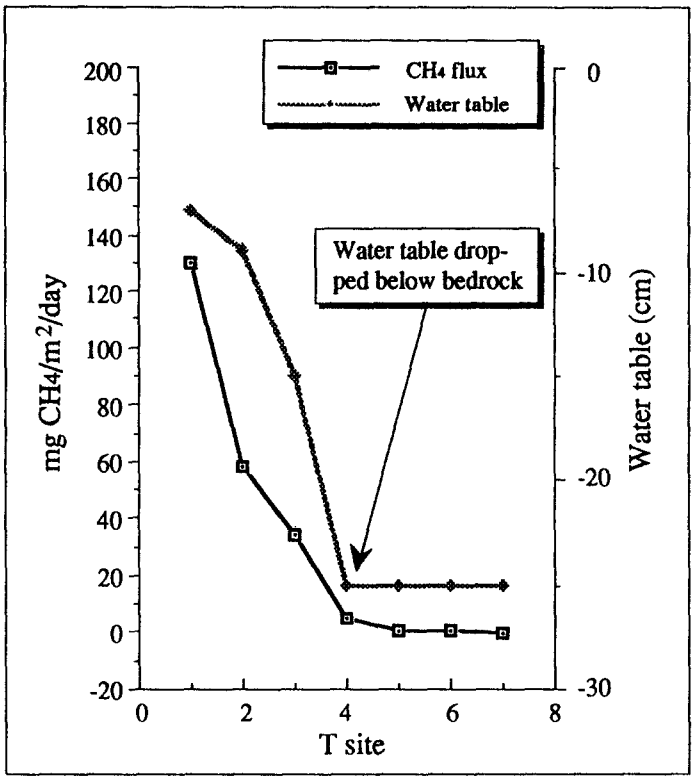



*Fig. 4.* Methane flux and water table position at seven T sites on a transect with approximately 50 meter intervals up slope from Kuparuk River on August 7 1992.

In general methane flux at the moist and dry upland tundra sites, T and M, seems to be controlled primarily by the water table while flux at the wetter meadow sites, D, E and C (when inundated) seems to be controlled mainly by temperature. It is assumed that at the wet sites the observed relationship is reflecting temperature dependency of the methanogenic bacteria, which is in line with results from earlier studies (Svensson & Roswall 1984; Crill et al. 1988; Moore et al. 1990; Bartlett et al. 1992). When the water table drops below the soil surface the microbial methane oxidative activity in the aerobic soil layer becomes the key biological factor controlling net flux to the atmosphere. The limitation of the oxidation can be quantified as the position of the water table, although it has not been shown that it is the actual aerobic space which is controlling the methane oxidation. However, moisture has been identified as limiting soil microbial oxidation of $CH_4$ in many studies (Steudler et al. 1989; Yavitt et al. 1990; Bartlett et al. 1992) and a significant effect on microbial $CH_4$

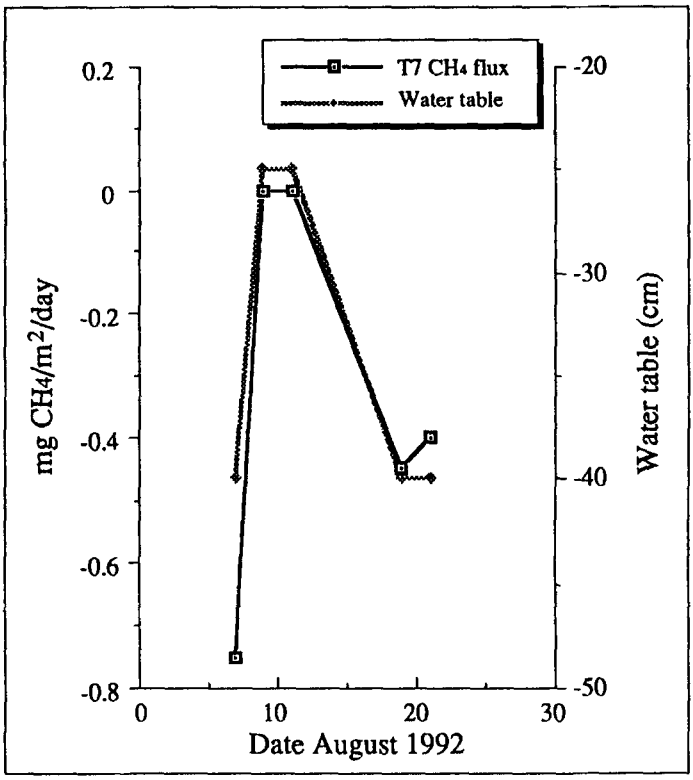



*Fig. 5.* Methane uptake by site T7 near Kuparuk River as observed during August 1992. The rise in water table around August 10 was from an unidentified position below bedrock (here illustrated as −40 cm) to a position just above bedrock.

oxidisers on net $CH_4$ flux from sub-Arctic tundra soils have also been shown (Whalen & Reeburgh 1990b). Various soils comparable to wetlands have been shown capable of consuming more than 90% of the methane potentially available (King 1990; Oremland & Culbertson 1992) and it has been estimated that about 55% of the $CH_4$ produced in global tundra soils is oxidised before entering the atmosphere (Reeburgh et al. 1993).

It appears that each of the production and oxidation processes have their own independent relationships with temperature and moisture. The balance between the impact of these parameters on the two processes gives the net emission from the soil. It should be noted, however, that the two factors are interlinked also in terms of the thermodynamics of the soil thermal regime (moisture is an important control on the soil thermal diffusivity) and in terms of their effects on different components of the

microbial community. Hence, the two factors need coupling when establishing predictive models and also such models should include parametrisation of the soil thermodynamics.

## Conclusions

Based on a time series of flux measurements at a true Arctic tundra site, global tundra $CH_4$ emission is estimated at 18—30 Tg $CH_4$ $yr^{-1}$ (in a relatively dry year). This is within Whalen & Reeburgh's (1992) estimate of 42 ± 26 Tg $CH_4$ $yr^{-1}$ and supports Fung et al.'s (1991) suggested 35 Tg $CH_4$ $yr^{-1}$. Episodic events might account for a high proportion of the total flux, and there are indications from this study that global dry tussock tundra flux might be slightly overestimated in the present calculation, and also that extrapolations should include a tundra sink term. No single parameter relationship between one environmental factor and $CH_4$ flux covering all sites was obtained. However, inter-season variations in $CH_4$ flux at dry sites seemed to be largely controlled by water table fluctuations while wetter sites were controlled primarily by soil temperature.

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