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Micrometeorological Measurements of CH₄ and CO₂ Exchange Between the Atmosphere and Subarctic Tundra

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Exchanges of methane and carbon dioxide between the atmosphere and the Arctic tundra were measured continuously near Bethel, Alaska (61°05.41'N, 162°00.92'W), for 5 weeks during July and August 1988. Fluxes were obtained directly using eddy correlation at 12-m altitude, and concentrations were measured sequentially at eight altitudes between 0 and 12 m. A prototype differential infrared absorption methane instrument based on a Zeeman-split HeNe laser was used for determination of methane and a flame ionization detector for total hydrocarbons (THC). Methane was found to account for nearly all the THC concentrations and fluxes. Methane fluxes at the tower site were apportioned to various methane-producing habitats, using a satellite image to classify surface vegetation at 20 × 20 m resolution. The "footprint" of the tower was computed using a Gaussian plume model for dispersion in the surface layer. Grid cells classified as dry tundra (water level 5 cm below surface) emitted methane at an average rate of 11 ± 3 (standard error) $\text{mgCH}_4/\text{m}^2/\text{d}$, and wet meadow tundra (water level near surface) emitted 29 ± 3 $\text{mgCH}_4/\text{m}^2/\text{d}$. Fluxes from lakes depended on wind speed, averaging 57 ± 6 $\text{mgCH}_4/\text{m}^2/\text{d}$ at the site, where the mean wind speed was 5 m s^{-1} . The mean emission rate for tundra (including lakes) around the tower was 25 ± 1 $\text{mgCH}_4/\text{m}^2/\text{d}$, notably smaller than adopted for boreal wetlands in recent inventories of global methane sources. Emissions from major habitats derived from the tower measurements were in reasonable agreement with data from chamber studies. Errors of a factor of ~ 2 accrued in scaling up the chamber data, representing 1 m^2 plots, to the footprint of the tower measurements (10^3 m^2), because the satellite could not fully resolve heterogeneous methane-producing habitats. Fluxes obtained at the tower site were in harmony with fluxes from aircraft overflights. The aircraft data represent mainly afternoon periods with good flying weather, conditions associated with maximum CH₄ fluxes in the tower time series. Mean fluxes from the aircraft are consequently $\sim 2 \times$ higher than seasonal means from the region. Solar irradiance provided the primary control on the net ecosystem exchange (NEE) of carbon dioxide. The mean maximum uptake near the local solar noon was 1.4 ± 0.2 $\text{gC}/\text{m}^2/\text{d}$, and nocturnal respiration averaged 0.73 ± 0.18 $\text{gC}/\text{m}^2/\text{d}$. Net uptake of carbon dioxide averaged 0.30 $\text{gC}/\text{m}^2/\text{d}$ (0.1 tons C/hectare) during the period of the Arctic Boundary Layer Experiment (ABLE 3A). About 6% of the seasonal net uptake was returned to the atmosphere as methane.

1. INTRODUCTION

Concentrations of atmospheric methane doubled during the past 200 years [Craig and Chou, 1982; Stauffer *et al.*, 1985; Khalil and Rasmussen, 1987], and increases of 1% per year continue at present [Steele *et al.*, 1987; Blake and Rowland, 1988; Zander *et al.*, 1989; Khalil and Rasmussen, 1990]. Methane has long been recognized as a critical reactant in the photochemistry of both the troposphere and the stratosphere [Levy, 1971; McConnell *et al.*, 1971; Ehhalt, 1974; Wofsy, 1976] and has been identified as a major greenhouse gas, accounting for about 12% of the increase in global mean radiative forcing during the past decade [Hansen, *et al.*, 1989].

Microbial decay of organic matter in natural wetlands is believed to be a major source of atmospheric methane. Recent global inventories have attributed 100–115 Tg ($1 \text{ Tg} = 10^{12} \text{ g}$) of CH₄ per year to emissions from natural wetlands, 20–25% of the global

source [Matthews and Fung, 1987; Cicerone and Oremland, 1988; Aselman and Crutzen, 1989]. The current uncertainty in the emission rate from natural wetlands is believed to be approximately a factor of 2. Data for northern wetlands, primarily tundra and boreal bogs and fens between 50° and 90° N (primarily in Alaska, Canada, and the USSR) are notably sparse, even though these biomes comprise over one half of the Earth's area of natural wetlands [Matthews and Fung, 1987].

Flux measurements made at northern sites using small enclosures ($<1 \text{ m}^2$) [Svensson and Rosswall, 1984; Harriss *et al.*, 1985; Sebacher *et al.*, 1986; Whalen and Reeburgh, 1988] have demonstrated large variations in time and from site to site. These data form the basis of current CH₄ flux estimates from northern wetlands. Using a portion of this data base, Matthews and Fung [1987] estimated the methane flux from wetland areas north of 60°N to be 63 Tg/a, more than half the global source from natural wetlands. They estimated about 22 Tg CH₄/a to be released from tundra north of 50°, corresponding to about 25 $\text{mgCH}_4/\text{m}^2/\text{d}$ for mean tundra during a 120-day growing season.

Systematic measurement of the spatial and temporal variability of CH₄ emissions from northern wetlands has been established as an important goal of the U.S. Global Tropospheric Chemistry Pro-

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gram [University Center for Atmospheric Research (UCAR), 1986]. Realization of this goal is facilitated by the development and utilization of larger scale techniques for flux measurements, such as eddy correlation, to determine fluxes of methane and other important trace gases over larger spatial domains [Lenschow and Hicks, 1989].

In this paper we report measurements of eddy correlation fluxes and vertical concentration profiles for CH₄ and CO₂ on a 12-m micrometeorological tower at an Arctic tundra site, obtained as part of NASA's Arctic Boundary Layer Experiment (ABLE 3A). The dependence of methane emission rates on time of day, wind direction, and advancing season is examined, allowing us to determine the influence of incident solar radiation, wind speed, and vegetation type on ecosystem uptake of CO₂ and emission of CH₄. The fluxes derived from eddy correlation measurements on the tower are compared with airborne eddy correlation flux data [Ritter *et al.*, this issue] and with enclosure measurements carried out simultaneously at the site [Bartlett *et al.*, this issue; Whiting *et al.*, this issue].

2. STUDY SITE

The experimental site was located in the Yukon-Kuskokwim River Delta in southwestern Alaska, 50 km NNW of Bethel. Figure 1a shows the spatial distribution of vegetation types at the site, classified as discussed below. A 12-m micrometeorological tower (the origin in Figure 1a), located at the west end of the camp, was the main platform for measurements. A diesel generator was located 300 m to the east of the tower, connected to the tower by a wooden boardwalk (for details of the geometry, see Figure 1 in Fitzjarrald and Moore, [this issue]). There were five camp tents set up along the boardwalk, with most instruments housed in the tent closest (20 m) to the tower.

Bartlett *et al.* [this issue] classified the vegetation into two broad categories: wet meadow tundra and dry upland tundra. Wet

meadow tundra, with water levels at or near the surface, consisted mainly of grasses and sedges. Dry upland tundra, with water about 5 cm below, was composed of mosses, lichens, and sedges. The dry tundra was typically criss-crossed with water tracks, narrow bands of lower-lying, wetter soils, apparently reflecting small-scale ice dynamics and drainage patterns. Primary productivity for vegetation in the water tracks is expected to be significantly larger than in surrounding vegetation [Chapin *et al.*, 1988]. Water levels declined as the season advanced in all areas, and the depth to permafrost increased, from about 12 cm initially in the dry tundra to about 20 cm at the end of the experiment.

Locations of areas covered by lake, upland and wet meadow tundra, shown in Figure 1a, were derived [Bartlett *et al.*; this issue] using a System Probatoire d'Observation de la Terre (SPOT) satellite image (resolution 20 m × 20 m). Areas of each type are summarized in Figure 1b for sectors selected to discriminate among measurements obtained with the wind traversing different types of vegetation. The sector between 120° and 170° was dominated by dry tundra, 170°–230° was mostly wet tundra with a small lake (Lake Biospherics Research: Emissions from Wetlands (BREW)), and 230°–360° was a mixture of dry and wet tundra without significant lakes. The sector 0–120° was influenced by two large lakes and includes the generator. Lake ABLE, the closest, served as runway for float planes that provided transportation to the nearest town (Bethel). The lakes were 0.5–1 m deep, with relatively lush growth of vegetation (*Carex* spp., *riophorum* spp.) at the margins.

We examined flux measurements for wind directions between 0 and 120°, for chemical (CH₄, CO₂, and O₃ [Jacob *et al.*, this issue]) and physical tracers (momentum, sensible heat, and latent heat; [Fitzjarrald and Moore, this issue]), and concluded that the data were not systematically biased by the presence of the tent structures at the site. We include data from this sector in our analysis, excluding brief periods of pollution from the generator using observations of NO_x as an indicator (see below).

Fig. 1a. Three surface types (lake, dry upland, and wet meadow tundra) are distinguished for the site, based on a SPOT satellite image (resolution 20 × 20 m). The tower is located at the origin. Four sectors are divided to represent regions of the Arctic tundra with different distributions of surface vegetation. The circle is 1000 m radius.

Fig. 1b. Summary of surface compositions for each sector within 1000 m of the tower, at 100-m intervals. Lake, horizontal lines; dry upland tundra, slanted lines; wet meadow tundra, vertical lines. Sectors: (a) 0–120°, (b) 120°–170°, (c) 170°–230°, (d) 230°–360°.

Observations were obtained continuously during the second half of the growing season, between July 14 and August 12, 1988. The weather was generally warm and dry during the first 3 weeks and relatively cool and wet thereafter. The mean temperature at 12 m for the 30 days of measurement was 10°C at night, 18°C in the day. Soil temperatures were more or less constant at $5 \pm 1^\circ\text{C}$ at 1-cm depth [D.R. Fitzjarrald, unpublished data, 1988]. Fog with depth of about 1 m was frequently observed after sunset when the wind was quiet near the surface, indicating strong stratification. High concentrations of CH₄ and CO₂ built up in this layer, and the rate of accumulation (and subsequent depletion) were carefully computed from our continuous profiling data to obtain accurate estimates of surface emissions.

3. EXPERIMENT

Fluxes of CH₄ and CO₂ were measured directly using the eddy correlation method. A three-axis sonic anemometer, capable of measuring wind velocities and ambient temperature at 20 Hz [Fitzjarrald and Moore, this issue], was mounted at the top of the micromet tower. The sensor was rotated to keep the tower downwind to minimize interference. Air was sampled at $\sim 7 \text{ dm}^3 \text{ min}^{-1}$ through an inlet located 0.5 m behind of the sonic anemometer, then drawn through Teflon tubes and distributed to the chemical sensors. Atmospheric CH₄ was measured using a fast response flame ionization detector (FID) and by a prototype fast response HeNe laser methane monitor. Ambient CO₂ was measured using a Beckman (Model 865) nondispersive infrared CO₂ analyzer. Air samples were preconditioned to a constant temperature and dew point (2°C) using a Teflon-coated aluminum

cell cooled thermoelectrically to about 0°C, and filled with glass beads. A mercury manostat (Gilmont Absolute Pressure Control) was used to dampen pressure fluctuations at high sample flow rate as required to achieve fast response. The gains for CO₂ and CH₄ instruments were measured by adding to the inlets small flows of concentrated standard mixtures. The 90% response time was slightly better than 1 s for THC, CH₄ and CO₂ measurements. Measurements were collected at 8 Hz.

Methane and CO₂ concentrations were measured consecutively at 8 altitudes on the tower, using duplicate instrumentation for CH₄ and a Binos nondispersive infrared analyzer for CO₂. Air samples were drawn through Teflon tubes (4.5 mm ID) at 10.8, 8.5, 6.1, 4.3, and 3.1 m above ground, on booms extending 1 m from the tower, and from tubes fixed to the guy wire, 7–8 m NW of the tower, at 1.5, 0.5, and 0.02 m above the ground (see Figure 2). Each level was sampled for 4 min, requiring 32 min to obtain a profile. Temperature and dew point of the air were preconditioned as for the flux measurement. The instruments were periodically calibrated with reference gases using the same pressure, temperature, and dew point as for air samples, and at the same flow rate through the FID (100 cm³ min⁻¹).

3.1. The Flame Ionization Detector

The flame ionization detector (FID for Gas Chromatograph GC-6A, Shimadzu) measures current between its electrodes car-

Fig. 2. Schematic drawing of the sampling tower. Points labeled are 1, inlet for eddy correlation instruments at 12 m, lashed to the rotating boom that carried the tri-axial sonic anemometer; 2–9, inlets for profile instruments at 10.8, 8.5, 6.1, 4.3, 3.1, 1.5, 0.5, and 0.02 m altitude, respectively; 10 inlet selection box for profiling. Inlets were protected from rain by small funnels. For locations of additional instrumentation, see Harriss et al. [this issue].

ried by ions produced in a hydrogen flame by chemi-ionization of CH radicals. Air was pumped from flux and profile inlet lines by small Teflon diaphragm pumps to the sample inlet jets of the FIDs, with gas chromatographic column omitted to obtain fast response to the total hydrocarbon (THC) concentration in air. The FIDs were calibrated using standards of known CH₄ concentration in air, with < 50 ppb nonmethane hydrocarbons (NMHC). The gain of the eddy correlation FID was determined by adding a known flow of CH₄ standard (100 ppm in air) to the inlet. The profile instrument was calibrated by substituting flows from two standards (high and low, bracketing air levels) using a microprocessor (MKS 250B) to maintain constant pressure and flow in the FID sample line. Measurements are reported as equivalent CH₄ concentrations. Methane provided by far the dominant contribution to the FID response, both for fluxes and concentration measurements, as shown in the next section.

3.2. HeNe Laser Methane Instrument

The prototype Zeeman-split HeNe methane instrument used in this study has been described by *McManus et al.* [1989a]. The instrument exploits the coincidence of the 3.39 μm (2947.91 cm^{-1}) He-Ne laser transition with the P7 absorption line in the ν_3 band of CH₄. By applying a transverse magnetic field over a portion of the plasma column, the laser can be made to operate at two Zeeman-split frequencies ($\pm 0.555 \text{ cm}^{-1}$) on either side of the absorption line as well as at the unsplit frequency. A differential absorption measurement can therefore be obtained by alternately tuning the laser to each of these frequencies.

The instrument, shown schematically in Figure 3, may be described in terms of four subsystems: the laser, the control and signal processing electronics, the optical system (including the multipass sample cells), and the gas handling system. The reference cell, nominally identical to the two sample cells, contained a standard gas mixture of approximately 1.6 ppm CH₄ in air, at the same pressure as the sample cells. The output from the reference cell detector was used to equalize the power on the three laser

lines, compensating for CH₄ absorption in the reference cell, and to control the laser frequency. Ideally, differences in detected power between the split and unsplit lines should be proportional to the difference in CH₄ concentration between the sample air and reference gas.

We used multipass absorption cells of the type described by *Herriot et al.* [1964], with mirror spacing of 16 cm and optical path of 11.7 m. The instrument had two sampling cells, one for fast response ($\sim 0.7 \text{ s}$) eddy correlation measurements and a second for slower ($\sim 30 \text{ s}$) profile concentration measurements. All three cells (reference, fast response, slow response) were operated at ~ 100 torrs to optimize differential absorption for the fixed splitting of 0.555 cm^{-1} between laser lines.

The sensitivity of the prototype instrument was about 20–30 ppb rms for a 1-s averaging time. For measurement time constants, τ , between 0.7 and 30 s the signal to noise ratio varies as $\sqrt{\tau}$. An improved version of this prototype, using a modestly larger sample cell to reduce the influence of interference fringes, has a demonstrated sensitivity of 5 ppb rms for a 1 s averaging time [*McManus, et al.* 1989b] and long-term drift of similar magnitude over periods of many days.

4. RESULTS

4.1. Computation of Eddy Correlation Fluxes

Eddy correlation fluxes were computed from covariances between vertical wind (w) and concentrations (c) of trace gases, with the coordinate system rotated to make the fluctuating component of w perpendicular to the streamlines [*McMillen*, 1986]. Eddies important for vertical transport typically had time scales from a few seconds to a few minutes. A net upward or downward flux of a trace gas is represented by a statistically significant positive or negative covariance. In this study we calculated fluxes by first subtracting 4-min running means from 8-Hz measurements of w and c , then averaging the product of the residuals over 1-hour intervals to obtain acceptable statistical significance. Fluxes were

Fig. 3. Schematic of the Zeeman tuned HeNe infrared methane instrument.

also computed using subtraction of running means of 1 min or 2 min, giving results essentially the same as obtained using 4-min running means.

Data for sensible heat flux, where instruments with 20-Hz bandpass were sampled at 8 Hz, were manipulated to test for possible errors associated with the slower response of the trace gas analyzers. Heat fluxes computed from raw data were compared to results obtained by smoothing data with a low-pass running mean filter with 0.3 s time constant. Fluxes derived from smoothed data varied by less than 5% from unfiltered fluxes, indicating that the bandpass for the trace gas instruments was sufficient to obtain eddy correlation flux measurements at this site without correction [Hicks and McMillen, 1988].

Measurements of trace gases were retarded by the transit time for air in the sampling system. The delay time was estimated by computing covariances for a range of time lags; the maximal covariance identifies the delay time. Delay times were determined to be 5.0(±0.2), 4.5(±0.1), and 7.5(±0.2) s for the FID, CO₂ (Beckman), and HeNe laser signals, respectively, in excellent agreement with time delays recorded for step inputs applied to the inlets in the field.

More than 600 hours of THC and CO₂ flux data and about 100 hours of CH₄ fluxes were obtained during the 30 days of measurement. Periods influenced by pollution from the generator, amounting to about 10 hours of data, were excluded by removing intervals with elevated, rapidly fluctuating concentrations of NO_x [Bakwin *et al.*, this issue]. A total of 640 concentration profiles for THC and CO₂ were obtained between July 14 and August 12, with data missing for July 21–23 due to equipment failure. About 25 concentration profiles were obtained from the prototype optical CH₄ monitor.

4.2. Comparison of the FID and HeNe Laser Flux Measurements

Figure 4 shows hourly flux data for ~100 hourly intervals between July 17 and August 7 when both the FID and the laser instrument were operating successfully. The flux measurements scatter about a 1:1 line. Figure 5 shows two time series for fluxes measured by the two instruments, for July 26–27 and August 6–7. Fluxes measured by the laser instrument track the FID fluxes, but

Fig. 4. Comparison of the FID and the IR HeNe laser instrument flux measurements. The line represents a 1:1 relation.

showed larger hour-to-hour variability as expected from the greater sensitivity to ambient temperature changes and the lower signal-to-noise ratio of the laser instrument.

Measurement errors may be attributed to (1) random uncorrelated instrument noise, (2) inaccuracy associated with chemical sensor resolution, and (3) atmospheric (flux) variability [Lenschow and Kristensen, 1985; Businger and Delany, 1990]. The fluxes might be underestimated by ~10% because the instruments could not resolve CH₄ variations smaller than 0.1 ppb. Fan [1991] examined the contributions to errors in the methane flux, using information on the integral time scale for eddies in the surface layer and the signal-to-noise ratio of the chemical sensors (standard deviation due to atmospheric concentration variations/instrument noise). The standard deviations for 1-hour average fluxes due to points 1 and 3 represented 10–30% and 20–60% of the flux for the FID and the HeNe laser instruments, respectively. Uncertainties associated with instrument noise and resolution were in most cases larger than errors associated with atmospheric variations. The mean difference between hourly averaged flux measurements by the FID and laser instruments was 0.15±1.3 (standard error) mgCH₄/m²/d, not significantly different from zero, consistent with the view that the dominant source of measurement error was random. Statistically significant systematic differences could not be detected.

4.3. Comparison of the FID and HeNe Laser Concentration Measurements

Figure 6 shows THC and CH₄ concentration data from all 8 heights, along with the regression line:

$$\text{THC}(\text{ppb}) = -107(\pm 48 \text{ s.d.}) + 1.052(\pm 0.024 \text{ s.d.})\text{CH}_4(\text{ppb})$$

$$(r^2 = 0.90, N = 201),$$

where s.d. is the standard deviation. The residual standard error from the regression, 67 ppb, is notably larger than the noise levels of FID (about 1 ppb for 3-min average) and the prototype CH₄ analyzer (about 2 ppb for 3-min average). Both instruments exhibited significant zero drift, due to the variability of the thermal environment, and this likely accounts for most of the excess residual error. There may also be a contribution from varying amounts of NMHC. The proportionality coefficient (1.050) would suggest a contribution of approximately 90–120 ppb NMHC to the measured THC in ambient air (3–7%). The results indicate (at the 95% confidence level) that CH₄ represents 90% or more of THC.

The measurements from the FID and infrared HeNe laser instruments were strongly correlated, with approximately 1 to 1 proportionality, both for fluxes and concentrations. Hence we regard THC and CH₄ as equivalent and discuss tundra emission rates using primarily the extensive data set obtained by the FID.

4.4. Concentration Profiles of CO₂ and CH₄

The net exchange or surface flux of CH₄ or CO₂ from the ecosystem is defined by

$$NEE = F + \frac{d}{dt} \int_0^{12m} c(z) dz \quad (1)$$

where F is flux of CH₄ or CO₂ measured at 12 m, and $\frac{d}{dt} \int_0^{12m} c(z) dz$ is the rate of change in trace gas content of the air column between the sensor and the ground ("storage"). Simultaneous measure-

Fig. 5. Time series of continuous flux measurements from (a) July 26–27 and (b) August 6–7. Circles are for THC (measured by the FID) and triangles are for methane (measured by the IR-HeNe laser instrument).

ments of concentration profiles and fluxes at 12 m are required to estimate surface emissions of CH₄, or net photosynthesis/respiration of the ecosystem, since storage terms may be significant, particularly at night.

Figure 7 shows mean concentrations (averaged over 27 days) of CH₄ and CO₂ as functions of time of day and altitude. Concentrations of THC were highest near the ground at all times of day, indicating a surface source. Concentrations of THC increased after sunset and declined rapidly after sunrise (see Figure 7a), reflecting onset and breakup of nocturnal stratification. These patterns varied from day to day, depending on the stability of the surface layer, and on wind direction, as discussed in the following sections. The daytime (0800–2200 hours) mean concentration was 1825 ± 7 (s.e.) ppb, somewhat above the globally averaged concentrations of atmospheric CH₄, about 1690 ppb at the time of this study [Khalil and Rasmussen, 1990].

Concentrations of CO₂ decrease with altitude at night and increase in the day, reflecting production by respiration at night and uptake by photosynthesis in the day. The stratification of the surface layer and its erosion modulate the variations of CO₂, as shown by the changes in column content between 0 and 12 m

(storage) in Figure 8. The parallel buildup and ventilation of CH₄ and CO₂ at night provide a measure of the ratio of nocturnal fluxes, allowing an independent estimate of CH₄ emissions based on knowledge of ecosystem respiration at night, or vice versa (see section 4.6).

4.5. Eddy Correlation Fluxes of CO₂ and CH₄

Flux measurements, averaged according to hour of the day, are presented in the top panel of Figure 8a for CO₂ and in Figure 8b for CH₄, together with the average rate of change in column content (storage) between surface and 12 m above the ground (middle panels). Net ecosystem exchanges (NEE) of CO₂ and CH₄, computed using (1), are presented in the lower panels. Hourly averaged fluxes of THC and CO₂ ranged from 0 to 100 mgCH₄/m²/d and from -4 to 4 gC/m²/d, respectively. Standard deviations about the means in Figure 8 primarily reflect environmental factors, mainly variation in cloudiness in the case of CO₂ or variation of wind speed and direction in the case of CH₄ (see below).

Previous observations in tundra systems [Sebach et al., 1986; Whalen and Reeburgh, 1988; Svensson and Rosswall, 1984] indi-

Fig. 6. Comparison between measurements of THC (by the FID) and CH₄ (by the infrared HeNe methane instrument) at eight altitudes. The solid line is a least squares fit through all the data points: $\text{THC} = -107 (48 \text{ s.d.}) + 1.052 (0.024 \text{ s.d.}) \text{CH}_4$ ($r^2 = 0.90$, $N = 201$).

cate that vegetation type and soil water levels are important factors regulating CH₄ emissions, which respond also to temperature, availability of nutrients, depth of the active layer, and rate of CH₄ oxidation at the soil-air interface. Chamber measurements at the ABLE 3A site indicate that emission rates from dry tundra are much smaller than from wet tundra [Bartlett *et al.*, this issue]. Variations in wind direction and in the effective footprint of the tower can therefore introduce variance into the flux data. Additional variance may be associated with emissions from lakes and ponds, which respond to variations in surface wind speed and to diurnal temperature changes in shallow sediments.

Surface fluxes of CH₄ during the day were significantly larger (~50%) than at night, as found at other Arctic sites [Whalen and Reeburgh, 1988]. In comparing tower fluxes to data from aircraft or enclosures, it is important to allow for diurnal changes, since the latter experiments were carried out mostly or exclusively in the daytime. The interpretation is complicated by diurnal variations in wind direction [Fitzjarrald and Moore, this issue] and in the tower footprint (see below), which could contribute to observed differences between day and night.

Vertical profiles were more variable for CH₄ than for CO₂, reflecting spatial heterogeneity of CH₄ emission sources near the tower. Analysis of the data indicates that errors in estimating storage terms and flux divergence at the tower, induced by variations of emission rate over the footprint of the tower, may contribute errors up to $\pm 20\%$ in determinations of NEE for CH₄, with the largest errors at night. Errors in storage terms are insignificant for CO₂ surface fluxes.

Incident solar irradiance has the strongest influence on CO₂ flux, which may vary also with habitat [Miller *et al.*, 1976; Tietzen and Delting, 1983; Whiting *et al.*, this issue]. Strong diurnal variations were observed in the net ecosystem exchange at the tower, as expected. Ecosystem respiration at night averaged $0.73 \text{ gC/m}^2/\text{d}$, with little variation ($\sigma = 0.18 \text{ gC/m}^2/\text{d}$) during the dark period. A rapid decrease in NEE is observed at sunrise, about 0800 local

Fig. 7. Mean concentrations of (a) THC (ppb) and (b) CO₂ (ppm) as a function of altitude and local time.

Fig. 8. Mean diurnal variations of fluxes (top), rates of change in column storage between 12 m and the surface (middle), and net ecosystem exchanges (NEE) (bottom) of (a) CO₂ and (b) THC. Error bars represent standard deviations of hourly measurements.

Fig. 8. (continued)

time, reflecting onset of photosynthesis. Net uptake of CO₂ showed a broad maximum, about 1.4 gC/m²/d, between 1000 and 1500 hours (Figure 8a), notably earlier than the peak of incident solar radiation (Figure 9). Net uptake decreased slowly in the afternoon, with a gradual switch from net photosynthesis to net respiration at sunset (2100–2200 local time). The early maximum in photosynthesis and the gradual decrease of CO₂ uptake in the afternoon probably reflect high leaf temperatures and water deficits [Chapin and Shaver, 1985; Lechowicz, 1981, 1982; Oechel, 1976; Stoner and Miller, 1975].

Figure 10 shows trends in NEE for CO₂ and THC observed during the experiment. Rates of photosynthesis declined significantly from July to August (Figure 10a) as the incident solar flux decreased (Figure 10c). Nighttime fluxes of CO₂ stayed nearly constant through the observation period. Emissions of THC declined by about 50% after August 3, significant at the 95% confidence level. This decline may have been associated with the decreased temperatures, mean water levels [Bartlett *et al.*, this issue], and other seasonal factors.

We employed a strategy of conditional averaging to quantify the influence of wind direction and wind speed on THC and CO₂ emission rates. Net ecosystem exchange rates were grouped according to three conditions: (1) wind direction, aggregated according to sectors selected to capture maximum variation of vegetation type, (2) wind speed, and (3) atmospheric stability. Data were grouped into 3–5 classes for each conditional variable, to maintain sample sizes sufficient for statistical significance, i.e., adequate to determine a representative mean value for each class by averaging over of variability due to other factors other than those of interest. Results are summarized in Figures 11 and 12.

Fig. 9. Diurnal variations of (a) incident solar irradiance (I), (b) ambient temperature (T) at 12 m, and (c) difference between the dry bulb and wet bulb temperatures (ΔT). Error bars represent standard deviations of hourly measurements.

Wind directions were grouped in four sectors as shown in Figure 1, providing different weights for key vegetation types (lake, upland, and wet meadow tundra). Three atmospheric stability classes were chosen based on the Obukhov length (L) and roughness height (z_0), according to criteria of Myrup and Ranzieri [1976]. The Obukhov length was computed using measurements of momentum and sensible heat fluxes at the tower [Fitzjarrald and Moore, this issue]. Roughness height was estimated to be about 1 cm from the linear relation between wind speed (u) and friction velocity (u^* , square root of momentum flux) [Jacob *et al.*, this issue]. For a roughness height of about 1 cm, the atmosphere is considered unstable, neutral, and stable, respectively, for $1/L < -0.02$, $-0.02 < 1/L < 0.02$, and $1/L > 0.02 \text{ m}^{-1}$ [Myrup and Ranzieri, 1976]. Measurements grouped in the unstable and neutral stability classes were divided into 5 intervals of wind speed: 0–3, 3–4, 4–5, 5–6, 6–8.3 m/s, giving a total of 44 classes of data. For stable conditions, the surface wind speed was considered zero regardless of the velocity at 12 m, because air near the ground was decoupled from 12 m.

Figure 11 shows means and standard deviations for net exchange of THC in each group. We excluded 14 classes with fewer than 4 hours of measurement. Influences from adjacent sectors were tested by examining data falling within the average standard deviation of the wind direction during a 1-hour interval, $\sim 15^\circ$. Shifting the boundaries between sectors by this amount had little effect on the analysis ($< 10\%$ change in the NEE associated with a particular vegetation type).

Fig. 10. Five-day means of (a) CO₂ flux, (b) THC flux, and (c) photosynthetically active radiation (PAR) for the 30 days of measurements. Error bars represent 95% confidence limit. Squares represent daytime averages (0800–2000), diamonds nighttime averages (2000–0800).

In sectors 0–120° and 170°–230°, where lakes were located a short distance from the tower, the emission rate for CH₄ depends significantly on wind speed. The relation is weaker, and observed only at low wind speed, in the sector 230°–360°, where lakes were small and farther away. In the sector 120°–170°, with mostly dry tundra and no lakes, dependence on wind speed was not apparent. Mean emissions from the predominantly dry sector (120°–170°) were smaller than from the wettest sector (170°–230°) or from the lake-dominated sector (0–120°) (see Figure 12b). The conditional averages obtained here may be combined with information on tower footprint, derived in the appendix (see Figure 13), to quantify the factors controlling CH₄ emissions on spatial scales of ~10³ m. This analysis is carried out in section 5.

Figure 12a shows the average NEE for CO₂ for day and night, for each sector. Nocturnal respiration is essentially the same in all directions, but daytime uptake is markedly smaller in the sector dominated by dry tundra (120°–170°). The smaller rate for photosynthesis in dry tundra, as compared to wet tundra, is consistent with observations [Whiting *et al.*, this issue] based on chamber measurements. Significant photosynthesis occurred in the lake-dominated sector (0–120°), likely associated with emergent vegetation at the lake margins.

The average methane emission rate for the whole experiment at the tower, 25 mgCH₄/m²/d, represents 6% of the net daily uptake of CO₂ (Figure 8a), similar to values obtained for analogous systems. Sebach *et al.* [1986] estimated that methane losses in a coastal tundra corresponded to 8.6% of net primary productivity (NPP). Similar estimates for a minerotrophic wetland [Svensson,

1983] and an English bog [Clymo and Reddaway, 1971] indicated release of 11% and 1–6% of NPP as CH₄, respectively.

4.6. Methane Flux Derived From Nighttime Variations of CH₄ and CO₂

Concentrations of CH₄ and CO₂ usually increased after sunset when the surface layer became stratified, rising at times to more than 2500 ppb and 400 ppm, respectively. These correlated concentration changes, shown in Figure 14, are a direct indication of rates of surface emissions. The observed ratio of THC to CO₂ in nighttime enhancements represents approximately the fraction of mineralized carbon released to the atmosphere as hydrocarbons.

Figures 14a and 14b show scatter plots of THC and CO₂ concentrations at night, from 2200 to 0800 local time. Linear functions were fitted through measurements for individual levels 1–8, and for aggregated data from levels 1–7, as shown in Table 1. Regressions for individual levels 1–7 were not significantly different from the fit to the aggregate data, but level 8, inside the canopy of dry upland tundra, is different.

The regression coefficient for levels 1–7, 0.0178 (± 0.003) ppm/ppm, is close to the geometric mean of the set of ratios of THC and CO₂ fluxes at night, 0.020 ppm/ppm (coefficient of variation 125%, *N* = 206). The coefficient for level 8, 0.0075 (± 0.002) ppm/ppm, is notably smaller, evidently reflecting the relatively low rates for CH₄ production by the dry tundra sampled by this inlet.

Whiting *et al.* [this issue] measured respiration for dry and wet tundra using enclosures, obtaining CO₂ emission rates of 0.48 and 2.0 gC/m²/d, respectively. If we adopt the dry tundra respiration rate and the observed ratio of 0.0075 ppm/ppm (ΔTHC/ΔCO₂) at level 8, we would predict a THC flux of 5 mgCH₄/m²/d, in harmony with chamber measurements of CH₄ emission from dry tundra (mean of 3 mgCH₄/m²/d) [Bartlett *et al.*, this issue]. For the higher tower altitudes, the nighttime mean CO₂ flux at the tower (0.73 gC/m²/d (Figure 12)) and the observed covariance ratio (0.0178 ppm/ppm) would imply a nighttime mean CH₄ emission of 17 mgCH₄/m²/d, close to the observed value (21 mgCH₄/m²/d). These results demonstrate consistency between measurements of CO₂ and CH₄ concentrations and fluxes, lending confidence to the mean fluxes computed from tower data.

5. DISCUSSION

5.1. Methane Emissions From Lake, Dry Upland, and Wet Meadow Tundra

Bartlett *et al.* [this issue] scaled-up chamber data for CH₄ emissions to the Yukon-Kuskokwim River Delta. They grouped chamber measurements of CH₄ emission rates into three classes based on surface type: dry upland tundra, wet meadow tundra, and lakes. Mean CH₄ emissions from wet tundra were 80 mgCH₄/m²/d, while dry tundra emitted only 3 mgCH₄/m²/d. Lake emissions, estimated by Bartlett *et al.* [this issue] from surface concentrations and an assumed piston velocity, were intermediate, 44 mgCH₄/m²/d for Lake ABLE. These data were meticulously extrapolated to regional scale using a Landsat scene where each 500m x 500m pixel was assigned to one of these surface types and assumed to have the associated mean emission rate.

We may help elucidate the uncertainties associated with extrapolating point measurements to large scales, as needed to apply remote sensing techniques, by performing a similar scaling-up exercise for the tower site and comparing to direct flux measurements. Tower observations respond to ecosystem activity over scales

Fig. 11. Net ecosystem exchange for THC versus wind speed at 12 m (zero wind is assumed at the surface for stable conditions) in the four sectors: (a) 0–120°, (b) 120–170°, (c) 170–230°, (d) 230–360°. Error bars represent 95% confidence limits.

(~10³ m) readily resolved by remote sensing instruments, whereas most of the available flux data represent chamber observations on much smaller scales.

We can write the net exchange of THC measured at the tower as a sum of contributions from the three surface types within the footprint:

$$NEE = F + \frac{d}{dt} \int_0^{12m} c(z) dz = \sum_{i=1}^3 f_i \phi_i \quad (2)$$

where i (=1,2,3) indicates surface type, lake, dry upland tundra, wet meadow tundra, respectively, ϕ_i is the emission rate of the i th surface type, and f_i is the effective weight of the i th surface type as it contributes to the measured NEE in each stability class and sector. The set of $\{f_i\}$ is given in Table 2a. The effective weights are computed by integrating the area of each surface type in a sector weighted by the associated probability density for contributions to the tower flux. Figure 13 shows the probability density as a function of distance from the tower, calculated as shown in the Appendix for slightly unstable, neutral, and slightly stable atmos-

pheric conditions, as defined by Turner [1969], using the Gaussian solutions to the atmospheric diffusion equation in three dimensions [Seinfeld, 1986, p. 590]. Surfaces 100–200 m upwind have the largest contributions; areas beyond 1000 m may be neglected.

The weights in Table 2a are independent of the wind speed, as follows from the Gaussian plume representation (see the appendix). The CH₄ emission rate may itself increase with wind speed (u) (see Figure 11), however, and hence we parameterize ϕ_i as a linear function of u ,

$$\phi_i = a_i + b_i u \quad (3)$$

where a_i is the emission from i th surface type at zero wind, and b_i is the corresponding proportionality coefficient for wind-induced emission. Equations (2) and (3) combine to give

$$F + \frac{d}{dt} \int_0^{12m} c(z) dz = \sum_{i=1}^3 f_i (a_i + b_i u) \quad (4)$$

Here the parameters a and b are assumed to be properties of the

Fig. 12. Mean NEE for (a) CO₂ and (b) THC showing differences between day (squares) and night (diamonds) and between sectors. Error bars represent the 95% confidence limits.

vegetation, and therefore independent of sector or stability class, while the $\{f_i\}$ depend on sector and class as shown in Table 2a. The net CH₄ exchange measured at the tower, in each sector and stability class, can therefore be apportioned to contributions from lake, upland, and wet meadow tundra upwind of the tower, using (4), the $\{f_i\}$ from Table 2a, with a least squares fit to determine optimal values for the a_i and b_i . (Note that the $\{f_i\}$ could be written as $\{f^{k,j}_i\}$, where k denotes the sector and j the stability class, and NEE would be $NEE^{k,j}$, the conditionally averaged mean. Superscripts have been omitted here for simplicity.)

Table 2b gives the optimal values for $\{a_i, b_i\}$, fit to the data for 30 combinations of wind direction and stability class with statistically significant mean fluxes (Figure 11). In order to determine which parameters account for the sample variance, four models ("hypotheses") were considered where some of the a_i and b_i were set to zero. In model I, all three surface types (lake, dry upland tundra, and wet meadow tundra) are allowed finite surface emission at zero wind and nonzero response to increasing wind velocity. The regression indicates insignificant emissions from lakes at zero wind speed (a_1), and negligible influence of wind speed on fluxes from dry tundra ($b_2 \sim 0$). Model II therefore set b_2 equal to zero; b_2 and a_1 were set to zero in hypothesis III. Coefficients for hypotheses II and III had smaller standard deviations than in hypothesis I, with little change in residual error of the fit and insignificant change in the values of other coefficients. Models I, II, and III account for 77% of the variance about the mean for the

Fig. 13. Tower footprint at altitude $h = 12$ m, plotted against distance (m) from the tower: (a) the contribution (percent) to the probability density for each 50-m interval along the abscissa, and (b) the cumulative probability density (from tower base to an upwind distance), both integrated in the cross-wind direction. The model of slender Gaussian plumes was used (appendix, (A3) and (A6)).

conditionally averaged data, hence our claim that most of the variance in Figure 11 can be attributed to environmental influences on emissions.

In hypothesis IV, we set b_3 (wind-dependent component for wet tundra) to zero, in addition to a_1 and b_2 . The standard errors of the coefficients are similar for models I-IV, but model IV accounts for only 66% of the variance, significantly smaller (at the 75% confidence level) than obtained in models I-III, suggesting that emissions from wet meadow tundra may increase at higher wind speeds. This dependence could be an artifact reflecting the prevalence of wet tundra at lake margins: some pixels labelled wet meadow likely include lake surfaces (and vice versa).

The accuracy of the probability density functions adopted here for the tower footprint cannot be verified, and we would therefore like to determine the sensitivity of model results to details of the functions shown in Figure 13. A simple test is to use exclusively distribution curves for each stability class, ignoring information on the observed stability, and to examine the coefficients for the same four models in each case as shown in Table 2b. The coefficients do not change significantly from the standard model, indicating that the association of emission rates with surface type is insensitive to details of assumed tower footprints, reflecting instead variation of flux with wind direction and wind speed.

Fig. 14. Nighttime concentrations of THC and CO₂ are well correlated when the gases are emitted from the surface and accumulated in the surface layer. Levels 1–7 were located between 0.5–10.8 m and level 8 at 0.02 m above ground.

5.2. Comparison of Enclosure, Aircraft, and Micrometeorological Methane Flux Measurements

Table 3 compares fluxes from the three surface types derived from eddy correlation measurements and from the enclosure studies of Bartlett *et al.* [this issue]. The tower data indicate substantially higher emissions from “dry tundra” pixels than reported by

TABLE 1. Results of Least Squares Fit to Nighttime (2300–0700 LT) Concentrations of THC Versus CO₂

Level	N	Slope	std	t value	R ²	rse
1	260	0.0152	0.0011	13.83	0.43	0.085
2	260	0.0160	0.0010	15.39	0.48	0.088
3	260	0.0171	0.0010	16.86	0.52	0.096
4	260	0.0186	0.0010	18.56	0.57	0.106
5	259	0.0187	0.0009	19.90	0.61	0.109
6	259	0.0193	0.0007	25.78	0.72	0.109
7	259	0.0174	0.0006	29.04	0.77	0.110
8	259	0.0075	0.0002	35.36	0.83	0.119
1–7	1817	0.0178	0.0003	57.76	0.66	0.101

Here, std, standard deviation of the slope; rse, residual standard error.

TABLE 2a. Area-Weighted Contributions (Percent) to the Tower Footprint from Lake, Dry Upland Tundra, and Wet Meadow Tundra

Sector	Stability Class	Lake	Dry Upland Tundra	Wet Meadow Tundra
0–120°	U	48	44	8
	N	41	44	15
	S	34	46	20
120°–170°	U	0	72	28
	N	0	81	19
	S	0	83	17
170°–230°	U	9	26	65
	N	11	26	63
	S	12	34	54
230°–360°	U	2	67	31
	N	3	55	42
	S	4	51	45

Stability classes (U, unstable; N, neutral; S, stable) are defined according to Myrup and Ranzieri [1976].

TABLE 2b. Methane Fluxes From Lake, Dry Upland, and Wet Meadow Tundra Derived From the Least Squares Fit to Group Mean Measurements of the NEE of THC

	Model			
	I	II	III	IV
a_1	9.9 (9.9)	11.3 (9.4)		
a_2	14.6 (4.6)	12.3 (2.2)	12.7 (2.2)	11.3 (2.5)
a_3	12.4 (6.2)	14.4 (5.1)	16.4 (4.8)	29.3 (3.0)
b_1	8.4 (2.3)	8.1 (2.2)	10.4 (1.1)	11.3 (1.2)
b_2	−0.6 (1.0)			
b_3	3.9 (1.3)	3.4 (1.0)	2.9 (0.9)	
rse	4.4	4.3	4.3	5.0
r^2	0.77	0.77	0.77	0.66

Model: $NEE = \sum_{i=1}^3 f_i(a_i + b_i u)$, where $i=1,2,3$ for lake, dry upland tundra, and wet meadow tundra, respectively, f_i is the effective area-weighted fraction, and u is the wind speed. Models differ in the number of significant or independent variables as shown (see text). Here, rse, residual standard error of the regression; r^2 , fraction of variance explained by the model.

TABLE 3. Comparison of Tower and Enclosure Measurements

Vegetation Type	Tower Data	Enclosure Data
Dry upland tundra	11.3 (±2.5)	3.0 (±2.5)
Wet meadow tundra	29.3 (±3.0)	79. (±25.)
Lake ABLE	56.5 (±6.0)	44. (±1.0)

Data are given in units of mgCH₄/m²/d. Uncertainties indicated are “standard errors” of fitted parameters for the tower data and of measurements for the enclosure data. Enclosure data for lake flux is calculated from surface CH₄ concentrations and assumed exchange velocity [Bartlett *et al.*, this issue].

the enclosure studies (11 versus 3 mgCH₄/m²/d) and significantly lower emissions from “wet tundra” pixels than observed over wet tundra (29 versus 79 mgCH₄/m²/d). Contributions from lakes were similar, a somewhat surprising result, since Bartlett *et al.* [this issue] had to infer fluxes indirectly for lakes.

Differences of order $2 \times$ arise in scaling-up chamber data to the tower footprint using the 20×20 m pixels of the SPOT image to classify vegetation type. Tundra ecosystems are very heterogeneous, with dramatic variations of soil moisture and plant assemblages on length scales from centimeters to kilometers. Pixels classified as "dry" unavoidably include some wet soils, and vice versa. Lake margins and drainage channels are likewise often not resolved. The SPOT image provides resolution higher than typically used in regional remote sensing studies, and the magnitude of the differences clearly indicates the need for caution in scaling-up point data to regional scales using remote sensing data.

The errors incurred in scaling-up flux data could perhaps be mitigated if information on fractional coverage of surface types could be incorporated into satellite imagery. A vast expansion of the available data would be required, however, to significantly improve large-scale extrapolations. Moreover, even fine-scale vegetation classification cannot account variance observed within a surface type; for example, fluxes at wet meadow sites ranged over two orders of magnitude, apparently reflecting variations in methane-producing substrates, soil temperatures, nutrient inputs, primary productivity, and other factors [Harriss and Sebachner, 1981; Sebachner et al., 1986; Bartlett et al., this issue]. Seasonal variations may also be substantial.

Table 4 compares fluxes from aircraft overflights with tower flux data for O₃ and CH₄. The tower data were averaged over the afternoon of each flight, to account for averaging associated with turnover of the planetary boundary layer. We focused on aircraft measurements after solar noon (1500 local time), corresponding to the smallest flux divergence in the boundary layer [Ritter et al., this issue]. The tower and aircraft data are remarkably close for both the ozone and methane fluxes. Methane fluxes were, however, about twice as high in the coastal tundra as measured from the tower site, reflecting largely differences in soil moisture and surface vegetation [see Figure 18 in Ritter et al., this issue].

It is important to note that the aircraft flux flights took place on warm, rain-free days in the afternoon, times favoring peak emissions (see Figure 8b). The average tower flux for these afternoons, $55 \text{ mgCH}_4/\text{m}^2/\text{d}$, was more than twice as large as the grand mean of the tower flux measurements, implying that aircraft observations (averaging $50 \text{ mgCH}_4/\text{m}^2/\text{d}$) were likely biased, by roughly a factor of 2, as compared to the mean for the region in the growing season. This bias should be taken into account when scaling-up aircraft data to obtain regional fluxes.

Estimates for methane emissions from the global tundra, reported from previous studies based on enclosure measurements [Svensson and Rosswall, 1984; Sebachner et al., 1986; Whalen and Reeburgh, 1988, 1990; Bartlett et al., this issue], are summarized

in Table 5. The estimates span a wide range due to adoption of different global areas for the various types of bogs and fens and various rates and periods for CH₄ emission from each type of vegetation. Arctic tundra lakes are important sources of methane, about half the flux in the Yukon-Kuskokwim delta, but these are not considered in most global estimates.

Present results suggest that global sources of CH₄ from tundra should be at the lower end of the range shown in Table 5. The ABLE 3A site is considerably wetter than average, and should therefore produce more CH₄/m²/yr than global mean tundra. Nevertheless, methane fluxes measured on the tower over the 30-day period averaged 25 ± 1 (s.e.) $\text{mgCH}_4/\text{m}^2/\text{d}$, lower than, or equivalent to, data used for global mean tundra in most estimates. A low emission rate is supported by aircraft, tower, and chamber data.

If the mean tower emission rate applied to the global tundra area of about $7.3 \times 10^{12} \text{ m}^2$ [Matthews, 1983], for a typical active period of 120 days [Bartlett et al., this issue; Whalen and Reeburgh, 1988; Sebachner et al., 1986; Matthews and Fung, 1987], a total of 22 Tg/a would be released globally by arctic tundra. This is only about 5% of the global CH₄ source. The careful extrapolation by Bartlett et al. [this issue], which accounts for the prevalence of dry tundra over the globe, suggests about half as much CH₄ derived from global tundra. These results point toward a relatively minor role for tundra in the global CH₄ budget. This conclusion should apply unless tundra lands elsewhere are for some reason much more productive than the relatively wet terrain in the Yukon-Kuskokwim River delta.

6. SUMMARY

Eddy correlation flux measurements and concentration profiles for THC and CO₂ were combined to provide a comprehensive record of atmosphere-biosphere exchange for these gases over a 30-day period in July–August 1988, in the Yukon-Kuskokwim River Delta of Alaska. A prototype methane monitor successfully measured CH₄ concentrations and fluxes, showing that net ecosystem exchanges of THC were >90% due to methane.

Lakes and wet meadow tundra provided the major sources of methane. Emissions from lakes were strongly dependent on the surface wind speed. The average fluxes from lake, dry tundra, and wet tundra, identified from 20×20 m pixels in a SPOT satellite image [Bartlett et al., this issue] were 11 ± 3 , 29 ± 3 , and $57 \pm 6 \text{ mgCH}_4/\text{m}^2/\text{d}$, respectively. The mean emission rate for the site was $25 \text{ mgCH}_4/\text{m}^2/\text{d}$ during the 30-day period. Mean fluxes depended on wind direction reflecting the angular distribution of surface types at the site. The average emission rate was lower

TABLE 4. Flux Comparison: Tower Versus Aircraft

Date	Flight	Hour (local time)	O ₃		CH ₄	
			Tower	Aircraft	Tower	Aircraft
July 28	16	1500–2000	7.8	9.0	40	42
July 31	18	1500–2000	6.7	10.0	90	95
Aug. 09	26	1500–2000	8.0	7.2	(20–67)	40

Data are given in units of ppb cm/s for O₃ flux and $\text{mgCH}_4/\text{m}^2/\text{d}$ for CH₄ flux. There were no tower measurements for CH₄ flux on 9 August due to equipment failure. The afternoon values for August 8 and 10 were 20 and 67 $\text{mgCH}_4/\text{m}^2/\text{d}$.

TABLE 5. Global Tundra Methane Emission Estimates

Reference	Flux*, Tg/a	Comments
<i>Matthews and Fung</i> [1987]	10	60°N-80°N
	22	50°N-80°N
<i>Whalen and Reeburgh</i> [1988]	19-33	50°N-80°N
<i>Whalen and Reeburgh</i> [1990]	38	50°N-80°N
<i>Bartlett et al.</i> [this issue] [†]	11±4	60°N-80°N
This study [†]	11±3	60°N-80°N
	12±3	50°N-80°N

Total tundra area is $7.3 \times 10^{12} \text{ m}^2$ [Matthews, 1983]; wet tundra area is $0.5 \times 10^{12} \text{ m}^2$ between 60°N-80°N, or $0.9 \times 10^{12} \text{ m}^2$ between 50°N-80°N; dry tundra makes up the balance.

*Ranges for global estimates reflect reported uncertainties in basic flux data, not uncertainties associated with scaling up.

[†]Lake fluxes are excluded to be consistent with previous flux estimates; lakes provided ~50% of the flux at the tower site, significantly more than expected for global tundra.

than reported in many earlier data sets, even though the site was wetter than the global mean tundra and therefore expected to be more productive. The tower results are in harmony with measurements of CH₄ flux at the site obtained using traditional chamber methods [Bartlett et al., this issue] and with aircraft eddy correlation flux measurements.

Maximum uptake of CO₂ by the tundra was observed to be 1.4 gC/m²/d between 1000 and 1500 hours, and nocturnal respiration averaged 0.73 gC/m²/d. Net uptake of CO₂ was 0.30 gC/m²/d for the 30 days of measurement; methane efflux accounted for 6% of CO₂ net uptake.

We presented an assessment of errors incurred in scaling up chamber data, representing 1-m² plots, to the footprint of the tower measurements (10³ m). The scaling procedure relied on assignment of a surface type and associated CH₄ flux to each 20 × 20 m pixel in the SPOT image. At this resolution, heterogeneous methane-producing habitats were not fully resolved; tower fluxes for pixels assigned to wet or dry tundra differed from chamber data for that surface type by approximately a factor of 2, apparently as a result of the admixture of habitats at satellite resolution. Accrual of significant errors appears inevitable in extrapolation of in situ measurements to regional scales using satellite imagery unless variance within pixel areas can be accounted for.

APPENDIX: ESTIMATE OF THE TOWER FOOTPRINT

The upward flux F of CH₄ measured at altitude h on the tower represents the sum of contributions from a certain fetch of surfaces (the "footprint" of the tower):

$$F = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} g(x,y) \phi(x,y) dx dy \quad (\text{A1})$$

with

$$\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} g(x,y) dx dy = 1 \quad (\text{A2})$$

Here $\phi(x,y)$ is the surface emission flux at location (x,y) , and $g(x,y)$ is a probability density representing the contribution of point (x,y) to the footprint. The coordinate system is defined with

origin at the tower and with the x axis pointing in the upwind direction.

Interpretation of F in terms of surface properties requires an evaluation of $g(x,y)$. Recent theoretical studies [Schuepp et al., 1990; Leclerc and Thurtell, 1990] have evaluated the cross-wind integral $f(x)$, representing the contribution to the footprint from a line source at distance x from the tower:

$$f(x) = \int_{-\infty}^{+\infty} g(x,y) dy \quad (\text{A3})$$

Schuepp et al. [1990] used a two-dimensional analytical solution of the diffusion equation, while Leclerc and Thurtell [1990] used a numerical Lagrangian model. The two approaches yielded similar results [Schuepp et al., 1990]. We resolve here the cross-wind structure of the footprint with a steady state Gaussian plume solution of the three-dimensional atmospheric diffusion equation [Seinfeld, 1986, p. 590]. An elemental source located at $(x,y,0)$ produces at the tower a concentration d^2c_{xy} :

$$d^2c_{xy} = \frac{\phi(x,y) dx dy}{\pi \sigma_y \sigma_z u} \exp \left[-\frac{y^2}{2\sigma_y^2} - \frac{h^2}{2\sigma_z^2} \right] \quad (\text{A4})$$

Here u is the wind speed, and σ_y and σ_z are Pasquill-Gifford dispersion parameters which are functions of x and of atmospheric stability. We parameterize σ_y and σ_z following Turner [1969] as given by Seinfeld [1986, p. 577]:

$$\sigma_y(x) = \exp[I_y + J_y \ln x + K_y (\ln x)^2] \quad (\text{A5a})$$

$$\sigma_z(x) = \exp[I_z + J_z \ln x + K_z (\ln x)^2] \quad (\text{A5b})$$

Table A1 lists values of the coefficients I , J , K corresponding to the Pasquill-Gifford stability classes C, D, E (slightly unstable, neutral, and slightly stable conditions, respectively). Using the flux-gradient assumption, we derive $g(x,y)$ directly from $\partial(d^2c_{xy})/\partial z$:

$$g(x,y) = \frac{\alpha}{\sigma_y \sigma_z^3} \exp \left[-\frac{y^2}{2\sigma_y^2} - \frac{h^2}{2\sigma_z^2} \right] \quad (\text{A6})$$

where α is simply a normalization factor to satisfy equation (A2):

TABLE A1. Gaussian Plume Dispersion Coefficients in Equation (A5)

Parameter	Pasquill-Gifford Stability Class		
	C	D	E
I_y	-2.054	-2.555	-2.754
J_y	1.0231	1.0423	1.0106
K_y	-0.0076	-0.0087	-0.0064
I_z	-2.341	-3.186	-3.783
J_z	0.9477	1.1737	1.3010
K_z	-0.0020	-0.0316	-0.0450

The dispersion parameters σ_y and σ_z are calculated as $\sigma_y(x) = \exp[I_y + J_y \ln x + K_y (\ln x)^2]$, $\sigma_z(x) = \exp[I_z + J_z \ln x + K_z (\ln x)^2]$. Values for the coefficients I , J , K are from Turner [1969] as given by Seinfeld [1986, p. 577]; x , σ_y , σ_z are in units of meters.

$$\alpha = \left[\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \frac{\exp\left[-\frac{y^2}{2\sigma_y^2} - \frac{h^2}{2\sigma_z^2}\right]}{\sigma_y \sigma_z^3} dx dy \right]^{-1}. \quad (\text{A7})$$

Figure A1 shows the two-dimensional field of $g(x,y)$ computed from equation (A6) for a neutral atmosphere. The cross-wind extent of the footprint is small. We find that >99% of the footprint is contained within 15° of the x -axis for stability classes C and higher. Highly unstable conditions (classes A and B) would cause a wider cross-wind spread, but such conditions are infrequent in the surface layer.

Figure 13 shows the cross-wind integral $f(x)$ computed from equations (A3) and (A6). Under neutral conditions we find that 50% of the flux is contributed by surfaces less than 300 m from the tower, with a maximum probability density for $x_{\max} = 150$ m. In comparison, *Schuepp et al.* [1990] obtained $x_{\max} = 240$ m for a roughness height $z_o = 0.5$ cm (as measured at the ABLE 3A tower [Fitzjarrald and Moore, this issue]. *Leclerc and Thurtell* [1990] presented results from a Lagrangian numerical simulation with conditions $z_o = 0.6$ cm and $h = 9$ m, similar to those at the ABLE 3A tower. They found that 50% of the flux was contributed by surfaces less than 400 m from the tower. Our calculated footprints are slightly shorter than those calculated by *Schuepp et al.* [1990] and *Leclerc and Thurtell* [1990]; a possible explanation is that the

Turner [1969] dispersion parameters overestimate turbulence over the relatively smooth tundra surface.

We use our calculated footprints in section 5 to decompose the fluxes F observed at the tower as the sums of contributions from three surface types (lakes, wet meadow tundra, dry tundra), each with uniform emission ϕ_i ($i=1,2,3$). The decomposition is based on the integral probability density f_i , representing the fraction of the tower footprint contributed by surface type i :

$$F = \sum_{i=1}^3 f_i \phi_i \quad (\text{A8})$$

We compute values of f_i for three stability classes (C,D,E) and four wind sectors (see section 5):

$$f_i = \int_0^{+\infty} f(x) S_{ij}(x) dx \quad (\text{A9})$$

Here $S_{ij}(x)$ is the fractional area occupied by surface type i at distance x from the tower in sector j , and $f(x)$ is taken from Figure 13. Use of the cross-wind integral $f(x)$ in equation (A9) is justified by the short cross-wind extent of the footprint. Data for $S_{ij}(x)$ are taken from a map with 20×20 m² resolution (Figure 1). The resulting values of f_i are listed in Table 2a.

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Fig. A1. Footprint of the tower at $h = 12$ m height under neutral conditions. We show the two-dimensional probability density $g(x,y)$ computed with equation (A6) as a function of upwind distance x and cross-wind distance y .

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