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Scientific paper

Micrometeorological measurements of methane flux at a boreal forest in central Alaska

Masahito Ueyama[1]*, Yoshinobu Harazono[1], Ryo Okada[2], Atsushi Nojiri[3], Eiji Ohtaki[3] and Akira Miyata[4]

[1] *International Arctic Research Center, University of Alaska, Fairbanks, Alaska 99775, U.S.A.*
[2] *Institution of Geosciences, University of Tsukuba, 1-1-1, Tennohdai, Tsukuba 305-8571*
[3] *Graduate School of Natural Science and Technology, Okayama University, 3-1-1, Tsushima-naka, Okayama 700-8530*
[4] *National Institute of Agro-Environmental Sciences, 3-1-1, Kannondai, Tsukuba 305-8604*
**Corresponding author. E-mail: ueyama@iarc.uaf.edu*

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Abstract: Methane (CH_4) flux at a black spruce forest in central Alaska was determined by applying the three types of modified gradient method. One type used the eddy diffusivity obtained by CO_2 flux and CO_2 gradient. Others established the flux gradient relationship assuming Monin-Obukhov similarity. The wind speed and temperature profile functions were corrected for the influence of the roughness sublayer, and then applied to the modified gradient methods. More than 70% of the data were rejected by the strict quality control and a continental climate, such as calm wind.

Although the diurnal variations of CH_4 flux by the three methods were different, the seasonal variation showed similar tendency; a weak emission on snowpack, an obvious emission around spring thaw, and CH_4 uptake in the late growing season. As calculated CH_4 flux was in the same range as with previous studies conducted by the chamber measurement.

key words: boreal forest, methane flux, micrometeorological technique, central Alaska

1. Introduction

Methane (CH_4) is a secondary strong greenhouse gas in the air, so its budget affects global warming. Generally, an anaerobic ecosystem is a major CH_4 source (Whalen and Reeburgh, 1992; Duval and Goodwin, 2000; Huttunen *et al*., 2003), and an aerobic ecosystem is a sink (Whalen *et al*., 1991). However, the exchange between terrestrial ecosystems and the atmosphere is poorly understood, because the distribution of the sink/source and their strength have large variations.

Regional variability in CH_4 emission and uptake is affected by topography and also vegetation type (Whalen *et al*., 1991). In boreal and temperate forests, CH_4 flux is generally in uptake (Gulledge and Schimel, 2000; Kagotani *et al*., 2001; Kim and Tanaka, 2003; Nakano *et al*., 2004). Measurements of CH_4 flux were previously conducted by the chamber method, which provided detailed understanding of the process on a small spatial scale. The benefit of the chamber method is the portable applicability, but methodological problems, such as eliminating natural air turbulence (Friborg *et al*., 1997) and the discontinuous observation with very short sampling period, still remaines. In addition, stand scale CH_4 flux is affected by heterogeneities in environmental conditions, such as temperature, water content of organic horizon and mineral soil, which may be responsible for temporal and regional variations. In such case, micrometeorological techniques are useful for obtaining representative measurements (Simpson *et al*., 1997; Werner *et al*., 2003), and are able to determine the fluxes. Previously, the micrometeorological measurements of CH_4 flux were conducted in a rice paddy (Harazono *et al*., 1995; Harazono and Miyata, 1997; Miyata *et al*., 2000), and natural wetlands (Friborg *et al*., 1997; Simpson *et al*., 1997; Billesbach *et al*., 1998; Werner *et al*., 2003), which were obviously the net source. On the other hand, we have poor understanding of the stand scale CH_4 exchange on boreal upland ecosystems, which largely covered the pan-arctic. Particularly in sub-arctic continental region, unfavorable weather, such as the broad range of temperatures and calm conditions, restricted the continuous observation despite their importance.

In this paper, we have conducted continuous measurement of CH_4 flux at a black spruce forest in central Alaska using the three different types of micrometeorological technique. As the site is subjected to severe cold temperature in winter, applicability of Monin-Obukhov similarity can provide large number of reliable fluxes. In this paper, therefore, we will exmame the applicability of the micrometeorological techniques for CH_4 flux observation in a sub-arctic boreal forest under severe continental climate.

2. Flux evaluation methods

CH_4 fluxes were calculated using three methods based on the flux-gradient theory. By assuming a horizontal homogeneous surface, CH_4 flux, F_{CH4}, is expressed as (*e.g.* Stull, 1988; Arya, 2001)

$$F_{CH4} = -K_{CH4} \frac{\partial \overline{s_{CH4}}}{\partial z}, \quad (1)$$

where s is the density, K is the diffusion coefficient, z is a height and the subscript CH_4 means methane. By assuming the eddy diffusivity for CH_4 is the same as that for CO_2, eq. (1) can be written as (Miyata *et al*., 2000; Werner *et al*., 2003)

$$F_{CH4} = \frac{\Delta s_{CH4}}{\Delta s_{CO2}} F_{CO2} = \frac{M_{CH4}}{M_{CO2}} \frac{\Delta c_{CH4}}{\Delta c_{CO2}} F_{CO2}, \quad (2)$$

where M is the molecular mass, c is the volume mixing ratio, F is the flux and the subscript CO_2 means CO_2. In this paper, we call this methed the 'K_{CO2} method' (Miyata *et al*., 2000).

For second and third methods, we assume the eddy diffusivity for CH_4 is the same as that for heat. With this assumption, eq. (1) can be written as (Monji *et al*., 2002)

$$F_{CH4} = -\frac{k^2 z_d^2}{\Phi_M \Phi_H} \frac{\partial \overline{u}}{\partial z} \frac{\partial \overline{s_{CH4}}}{\partial z}, \quad (3)$$

where k is the von Karman constant (0.4), $\Phi_M = (kz/u_*)/(\partial\bar{u}/\partial z)$, $\Phi_H = (kz/\theta_*)/(\partial\bar{\theta}/\partial z)$, u is the wind velocity, θ is the potential temperature, u_* is the friction velocity and θ_* is the scaling temperature, respectively. The height z_d is determined from the two heights as $z_d = (z_2 - z_1)/\ln(z_2/z_1)$ by applying the logarithmic profile (*e.g.* Monji *et al*., 2002). According to Monin-Obukhov similarity, $\Phi_M\Phi_H$ becomes a universal function of the stability parameter. We parameterize $\Phi_M\Phi_H$ by two stability parameters, (z-d)/L and the Richardson number, Ri. In this paper, we call these methods the '$K_{z/L}$ method' and the 'K_{Ri} method', respectively. Here, d, and L represent the zero-plane displacement and the scaling length (shown in, *e.g.* Arya, 2001).

3. Site and observation

3.1. Site description

The research site was located at a boreal forest in central Alaska (64°52′N, 147°51′W), which stands on discontinuous permafrost. The vegetations of the site are black spruce (*Picea mariana*), short shrubs such as crowberry (*Empetrum nigrum*) and lingonberry (*Vaccinium vitis-idaea*), vascular plants, lichens and mosses (sphagnum and feather). The heights of the black spruce ranged up to 6.0 m but most were less than 1.5 m. The density around the observation tower was 4500 trees/ha. Shrub height was less than 1 m, and the forest floor was tussock tundra.

The permafrost soil thawed from April to September. The leaf area index (LAI), measured by a plant canopy analyzer (LAI-2000, Li-Cor) around the observation tower, was 2.0 above 0 m and 0.2–0.5 above 1.0 m during mid summer.

3.2. Measurement

CH_4, CO_2, energy fluxes and meteorology have been measrued since November 2002, which were conducted at a 10 m tower on a reasonably flat area, with a fetch of more than 400 m for the dominant wind direction. Turbulent fluxes of momentum, heat, water vapor and CO_2 were measured at 6.0 m above the ground with a 3-dimensional sonic anemometer (CSAT3, Campbell) and an open-path infrared gas analyzer (LI-7500, Li-Cor). Turbulent data were collected through a data logger (DRM3, Teac) at 10 Hz, and stored in a magneto-optical disk. Turbulent fluxes were calculated half-hourly, correcting effects of the path-length and sensor separation (Moore, 1986) and air density effect of counter flow (Webb *et al*., 1980).

To measure CH_4 and CO_2 concentration gradients, air inlets of the air sampling were set at 2 heights (8, 2 m). The ambient air at two heights was sampled continuously through Teflon tubes (ID 6 mm) with the flow capacity of 12 liter per minute, and was switched every 3 min by electric valves. The concentration of CH_4 was measured by a FID-CH_4 gas analyzer (FIA-510, Horiba), and CO_2 by a NDIR-CO_2 gas analyzer (LI-820, Li-Cor). The gas concentration data were collected between 120 to 180 s after the line switched through a data logger (CR10X, Campbell) at 5-s intervals, and 30-min average was used for each. The FID-CH_4 analyzer was calibrated once a day, around 0800 hour using two reference standard gases (0 ppm, 3.0 ppm).

Supporting micrometeorological data such as wind speed, temperature, humidity, radiation, and precipitation were measured at the tower. Wind speed at 3 heights (2, 6, 8 m) by three cup anemometers (03101–5, Young), air and soil temperature at 6 heights (0.1, 0.5, 1, 2, 4, 8 m) and 4 depths (0.05, 0.15, 0.3, 0.5 m below the ground level) by thermocouple thermometers and air temperature and humidity at 2 heights by temperature and humidity sensors (HMP45D, Vaisala) installed in ventilated psychrometer, upward and downward short wave radiation by two radiometers at 4.7 m (PCM3, Kipps & Zonen), net radiation by a radiometer at 4.7 m (Q7, Campbell), surface temperature by an infrared thermometer (505, Minolta) and precipitation by a rain gauge (TE525MM, Campbell) were measured. The micrometeorological data were collected through a multiplexer (AM16/32, Campbell) and data loggers (CR10X and CR23X, Campbell) at 10-s intervals and each 30-min average were used. Thaw depth at 8 points were measured by inserting a brass rod into the frozen soil once or twice a week. LAI at 10 points were measured using a plant canopy analyzer (LAI-2000, Li-Cor) once a week during the growing season. Thaw depth and LAI were measured 5 and 10 times at each point, respectively, and the averages were used.

4. Results and discussions

4.1. Wind condition

The wind speed histograms at the site are shown in Fig. 1, to demonstrate calm climate. More than 55% of observation periods were calm; wind speed at 8 m (U_1) was below 1.0 m s^{-1}. At 2 m, more than 80% and 90% of wind speed (U_2) were below 0.5 m s^{-1} and 1.0 m s^{-1}, respectively. We carefully checked the accuracy of the wind speed measurements; the wind speed below 0.5 m s^{-1} was not reliable to apply Monin-Obukhov similarity because of the sensor limitation, in which wind profile did not indicate a similar tendency to the Businger and Dyer representation (Businger *et al*., 1971; Dyer, 1974, abbreviated as B-D hereafter). Consequently, more than 80% of the data were rejected in calculation of K_{Ri} method.

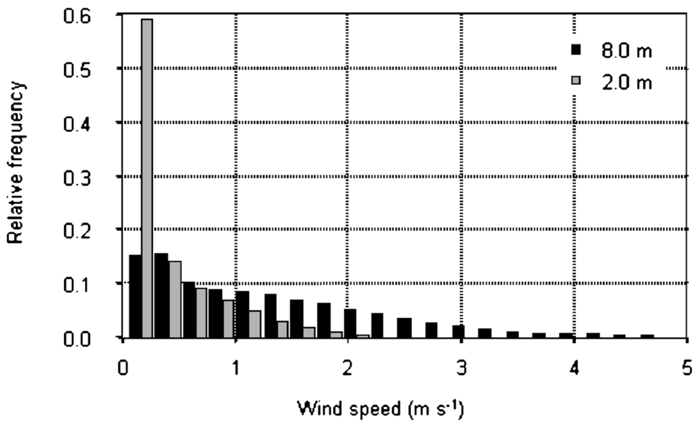

Fig. 1. Histograms of wind speed at 8 and 2 m height of the measurement tower, during 2003. Half hourly data were binned by wind speed into class of 0.25 m s^{-1}.

4.2. Parameterization of the turbulent transfer

Determination of the turbulent transfer parameters in the flux-gradient relationship is important to fix the CH_4 flux, particularly in $K_{z/L}$ and K_{Ri} methods, which is based on Monin-Obukhov similarity. The zero-plane displacement was determined for this forest, using correlation between the stability function $\zeta(=(z\text{-}d)/L)$ and the normalized standard deviations of vertical wind, temperature, specific humidity and CO_2 density assuming Monin-Obukhov similarity. The zero-plane displacement showed a clear seasonal variation (Table 1), which changed from 1.6 m in summer to 0.8 m in winter, in relation to the development of canopy structure. The seasonal variation could reflect the undergrowth density, which changed through the year due to leaf development, leaf

Table 1. Zero-plane displacement (d) used in the modified gradient method.

Period (DOY)	Value (m)
0–113	0.8
114–192	1.2
193–225	1.5
226–253	1.6
254–281	1.2
282–365	0.8

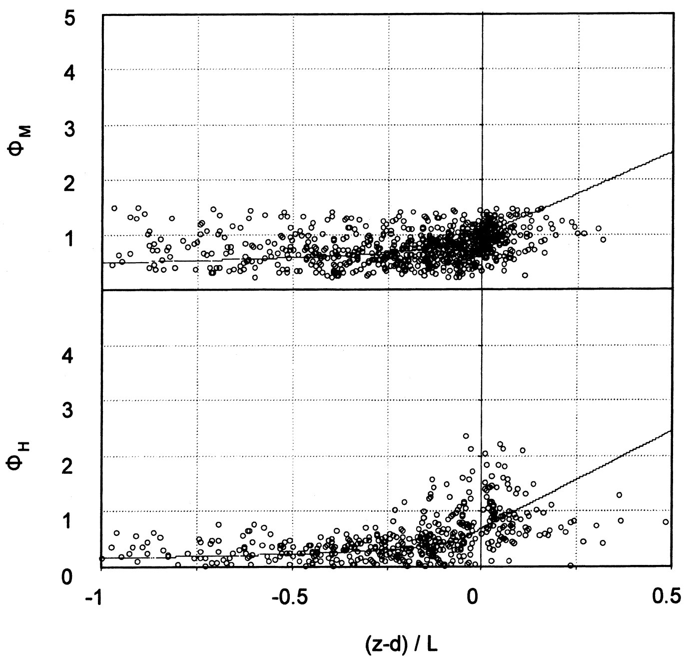

Fig. 2. The nondimensional wind and temperature profile as a function of (z-d)/L obtained at the black spruce forest for year-round data. The solid lines are the Businger-Dyer representation.

fall and snow cover.

We examined the applicability of Monin-Obukhov similarity, using the relationships between wind speed, temperature and ζ. Figure 2 indicates the nondimensional profile functions of wind speed, Φ_M, and temperature, Φ_H, plotted against ζ, in which the data of wind speed below $0.5\ \mathrm{m\ s^{-1}}$ were rejected (shown in Section 4.1). The solid lines were B-D representation. Although the data was scattered, we found that Φ_M and Φ_H followed the formula by the B-D representation in the range $-0.5<\zeta<0.25$. On the other hand, under strong unstable conditions, Φ_M did not follow the formula. One of the possibilities was inaccurate measurement of wind speed, in which the cup anemometer might be overestimate the wind speed gradient under strong unstable condition. However, because nondimensional profiles showed the similar tendency to B-D in the range $-0.5<\zeta<0.25$, we decided to apply Monin-Obukhov similarity to this range.

As previously reported, flux-profile relationships over tall vegetations were affected by the roughness sublayer (Garratt, 1978; Mölder *et al.*, 1999), in which the actual eddy diffusivity were much higher than those predicted by Monin-Obukhov similarity. Within the roughness sublayer, the correction of flux-profile relationships was often applied, accordingly (*e.g.* Mölder *et al.*, 1999). To examine the influence of the roughness sublayer, we calculated Φ_M and Φ_H under neutral condition, $-0.1<\zeta<0.1$, which resulted in $\Phi_M=0.82$ and $\Phi_H=0.72$, respectively. The obtained values ranged within the typical values over forests (Garratt, 1978; Denmead and Bradley, 1985; Ueyama *et al.*, 2004), suggesting that Monin-Obukhov similarity could be applicable if we applied the correction of the roughness sublayer.

To apply the $K_{z/L}$ and K_{Ri} method, the product of $\Phi_M\Phi_H$ determined every 30 min was plotted against the ζ and Ri, in which the data, wind speed $U_2<0.5\ \mathrm{m\ s^{-1}}$, were rejected (shown in Section 4.1). Figure 3 shows the individual values of $\Phi_M\Phi_H$. Although the data were scattered, we found that $\Phi_M\Phi_H$ followed the previously fixed equations (Businger *et al.*, 1971; Kaimal and Finnigan, 1994), with reasonable reliability ($r^2=0.53$ in eq. (4) and $r^2=0.46$ in eq. (5)).

$$\begin{aligned} \Phi_M\Phi_H &= \mathbf{a}(1-16\zeta)^{-3/4} && \text{for } \zeta\le 0, \\ \Phi_M\Phi_H &= \mathbf{a}(1-5\zeta)^2 && \text{for } \zeta>0, \end{aligned} \tag{4}$$

$$\begin{aligned} \Phi_M\Phi_H &= \mathbf{a}(1-16Ri)^{-3/4} && \text{for } Ri\le 0, \\ \Phi_M\Phi_H &= \mathbf{a}(1-5Ri)^2 && \text{for } Ri>0, \end{aligned} \tag{5}$$

where **a** is the correction coefficient for the roughness sublayer, 0.59, derived from $\Phi_M\Phi_H$ under neutral condition. We determined the CH_4 flux from the $K_{z/L}$ and the K_{Ri} method using eqs. (3), (4) and (5) in the range $-0.5<\zeta$ or $Ri<0.25$.

4.3. Quality control

In order to determine CH_4 flux throughout the measurement period, and also to obtain more flux data numbers as possible, the following criteria for quality control were applied. The measurements of turbulent transfer by the eddy correlation method have considerable uncertainties under calm nighttime (*e.g.* Goulden *et al.*, 1996). For practical solution, a correction according to u_* filtering was generally applied. We excluded the data, filtered by threshold of $u_*<0.1\ \mathrm{m\ s^{-1}}$ in nighttime from the calculation

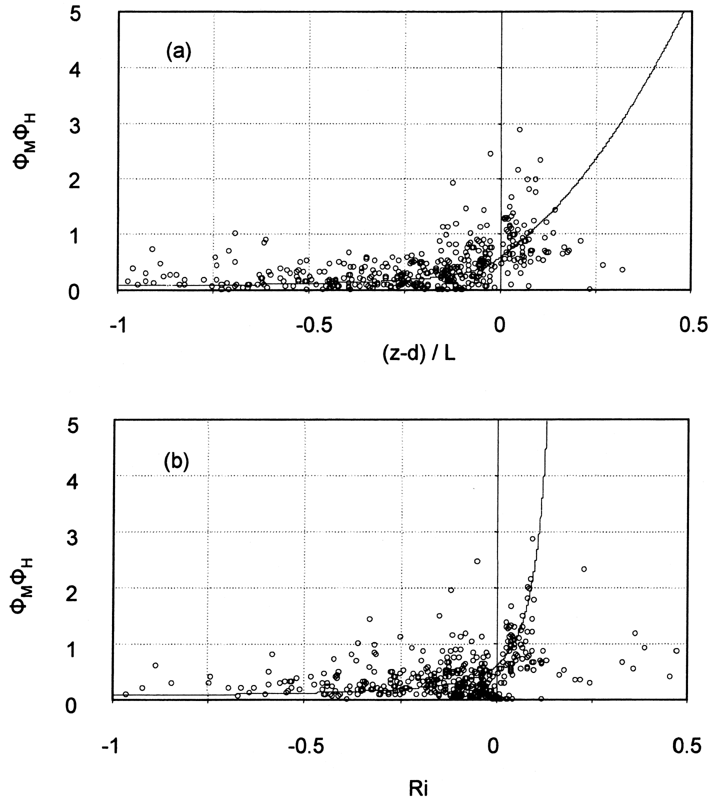

Fig. 3. Relation between $\Phi_M\Phi_H$ and (z-d)/L and Richardson number obtained at the black spruce forest for year-round data. The curves in the figures are eq. (4) and eq. (5), respectively.

of CH_4 flux in K_{CO2} and $K_{z/L}$ method. When the CO_2 gradient was small relative to the CH_4 gradient ($\Delta c_{CH4}/\Delta c_{CO2} > 0.004$) or values of $\Phi_M\Phi_H$ were low ($\Phi_M\Phi_H < 0.04$), the CH_4 flux were also excluded. The data within the range $-0.5 < \zeta$ or $Ri < 0.25$ were selected in the calculation in $K_{z/L}$ and K_{Ri} method, and those, $U_2 < 0.5$ m s^{-1}, were also rejected. Finally, we excluded a few large numbers, because the extremely large values could have an overpowering influence on the mean seasonal flux (Simpson *et al.*, 1997).

4.4. Comparison of fluxes determined by different methods

As described above, CH_4 flux was determined by the three different methods. We could not compare each method on half-hourly bases, because each method had a trade-off relationship. We examined the diurnal variations binned half-hourly average over 14-day interval. Examples of the diurnal variation of CH_4 flux were shown in Fig. 4. Although the CH_4 fluxes derived from the three methods were different, the fluxes derived from K_{CO2} and $K_{z/L}$ method showed similar tendency during Day of Year (DOY) 127–140, in which obvious CH_4 emission occurred. The CH_4 flux by K_{Ri} method did not show the clear diurnal variation, despite of a relatively source tendency. During DOY 225–238, on the other hand, the fluxes by K_{CO2} and $K_{z/L}$ showed the

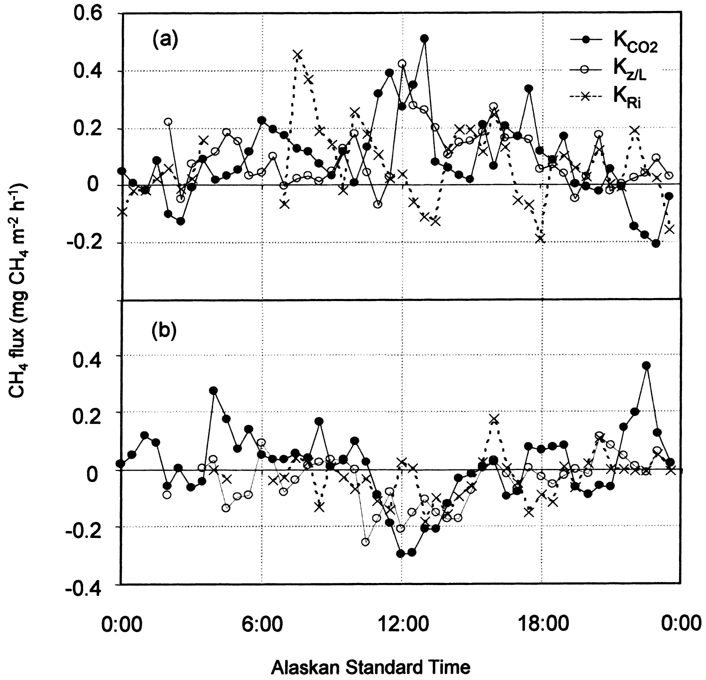

Fig. 4. Comparisons of diurnal variations of mean half-hourly CH_4 flux derived from three different modified gradient methods over DOY 127–140 (a), and 225–238 (b) in 2004.

obvious uptake around noon, while those by K_{Ri} exhibited a sink tendency without the diurnal pattern. The intermethod difference was possibly due to the different quality control criteria. For example, K_{Ri} employed fluxes under windy conditions, which might reflect different fetch compared to those by K_{CO2} and $K_{z/L}$. The K_{Ri} method also only used mean variables, but others used both mean and turbulent variables, which might cause the difference.

Seasonal trends of daily integrated fluxes are shown in Fig. 5 for comparison of three methods, in which the missed data were filled using a mean diurnal variation method based on 14-day averages (Falge *et al.*, 2001). Figure 5 also shows the data acquisition rate. Despite of the daily differences, the seasonal courses of the fluxes were similar, in which obvious emission occurred around DOY 120, neutral around DOY 230, and CH_4 uptake around DOY 270 were calculated among each methods. The low data acquisition rates occurred because of observation failure, for example between DOY 140 and 210 when K_{CO2} and $K_{z/L}$ method was not applicable. In addition, the low data acquisition rates were also caused by the strict quality control. K_{Ri} method was difficult to apply under calm conditions. In order to improve the data acquisition rate, we modified the observation system since April in 2005; we employed sensitive cup anemometers (AF750, Makino); the air buffer tanks equipped to stabilize the gas concentration measurement. Although the data acquisition rate was relatively low in the present study, the obtained data was much larger than that by chamber measurements.

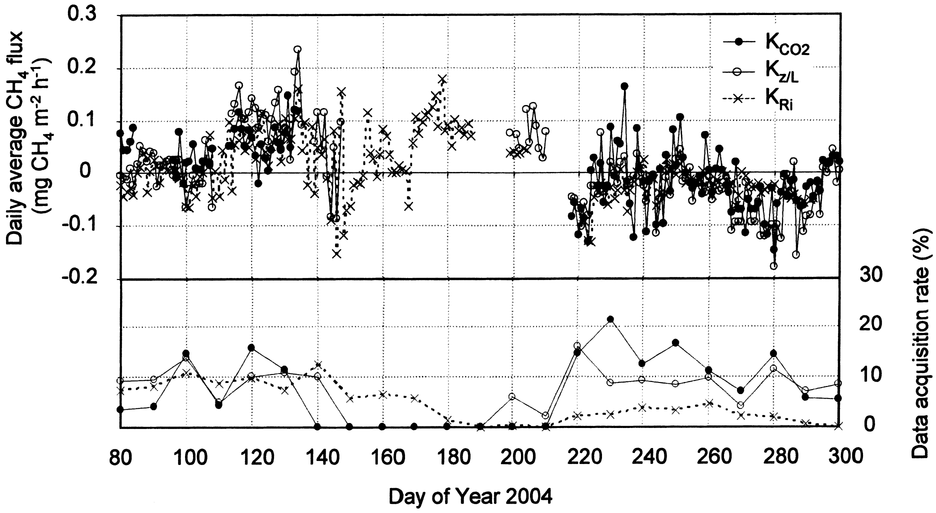

Fig. 5. Seasonal variations of CH_4 flux and data acquisition rate calculated using the three different modified gradient methods in 2004.

4.5. Seasonal variation of methane flux

Assuming that the methodological differences might be statistically reduced by averaging, we only discuss the seasonal variation of CH_4 flux as daily averages. Figure 6 shows the seasonal course of the daily average CH_4 flux calculated from the three methods, in which the bars represent the standard deviations. Surface albedo, soil temperature at 5 cm, precipitation, snow, and thaw depth were also shown in Fig. 6.

Surface albedo clearly showed a first day of the snow-free day, around DOY 115. CH_4 flux until the spring thaw was a weak source, 0.01 mg $CH_4\,m^{-2}\,h^{-1}$, in which soil temperature was below zero. The emission rate from the snowpack was comparable to a previous study (Mast *et al.*, 1998). Although the emission rate was quite low, it might be an important source considering the long period of cold season. Just after the spring thaw, CH_4 flux was positive, suggesting that the snow water made the soil into anaerobic conditions. The trapped CH_4 by the permafrost might be emitted in relation to the thawing soil. Between DOY 140 and 220, the CH_4 flux showed increase trend with fluctuation, but showed obviously positive. The fluctuation of CH_4 flux might reflect to heterogeneous distribution of the production and the oxidation in this period. During the late growing season, CH_4 flux was a net sink. The observed consumption rate was comparable to a previous study in boreal upland ecosystems (Whalen *et al.*, 19991).

5. Conclusion

It is important to estimate the CH_4 exchange at the stand scale in the sub-arctic. In these locations, however, the continuous observation has been previously limited by the sever climate. In order to evaluate the applicability of the meteorological tech-

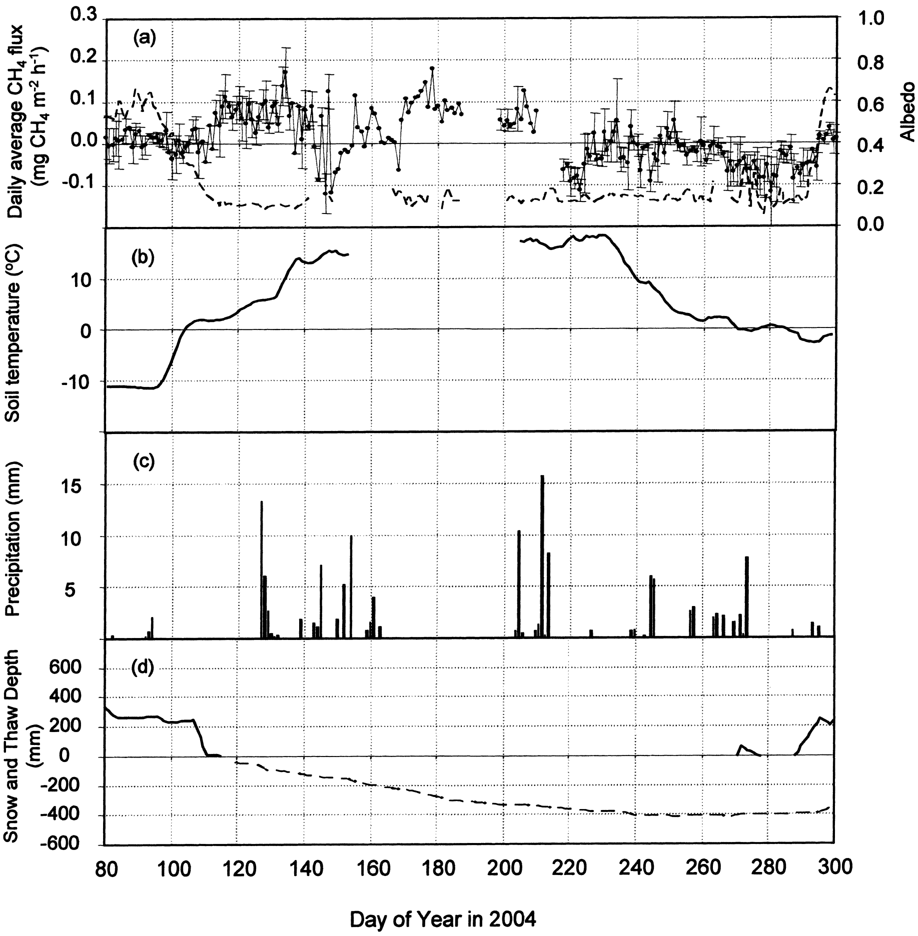

Fig. 6. Seasonal variations of CH_4 flux and meteorology in 2004; daily average of CH_4 flux and albedo (a), soil temperature below 5 cm (b), daily amount of precipitation (c), and snow and thaw depth (d). Points and error bars in (a) are means and standard deviations between the three modified gradient methods, respectively.

nique, three types of modified gradient method were examined to evaluate the CH_4 flux at a black spruce forest in central Alaska. One type is to use the eddy diffusivity obtained by CO_2 flux and CO_2 gradient. Others are to establish the flux gradient relationship assuming Monin-Obukhov similarity.

In order to apply Monin-Obukhov similarity, nondimensional profile of wind speed and temperature were estimated. The profile functions were corrected for the influence of the roughness sublayer, and then applied to the modified gradient methods. More than 70% of the data were rejected by the strict quality control.

Although the diurnal variations of CH_4 flux by the three methods were different, the seasonal variation showed the similar tendency; a weak emission on the snowpack, an obvious emission around the spring thaw, and CH_4 uptake in the late growing season.

Calculated CH_4 flux was in the same range compared with previous studies conducted by the chamber measurement.

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