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Temporal and spatial differences of methane flux at arctic tundra in Alaska

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Abstract: High latitude ecosystems were thought to enhance CH_4 emission in relation to the current arctic warming. However, we have little information about this potential feedback mechanisms on climate change, thus, model parameterization is insufficient and the observational data are required.

We observed CH_4 flux at several types of tundra in Alaska over the growing seasons since 1995. From these observed data, we examined current CH_4 emission and its controlling factors on Alaskan tundra. Then we discussed about spatial and temporal differences in CH_4 flux.

Daily trend of half hourly CH_4 flux had little relation with soil temperature, but the seasonal trend of daily flux changed with soil or water temperature. Cumulative CH_4 fluxes during the growing seasons were 8.1 gCH_4m^{-2} on wet sedge tundra at Happy Valley in 1995, 3.3 gCH_4m^{-2} on non-acidic moist tundra in 1996, and 3.58–8.24 gCH_4m^{-2} on wet sedge tundra at Barrow between 1999–2003. Non-acidic tundra had low CH_4 emission with low CO_2 accumulation. There was large spatial difference in CH_4 flux caused by tundra type, and the large temporal difference at the wet sedge tundra reflected yearly weather variability.

key words: Arctic ecosystem, CH_4 flux, temporal and spatial variability, tundra, warming climate

1. Introduction

The arctic tundra is an important ecosystem for global climate change because of its enormous carbon storage in the soil (Post *et al*., 1982) and the seasonally thawed layer may have considerable effects on atmospheric concentration of greenhouse gases (GHG) (Oechel *et al*., 1993). Warming climate is widely observed in the arctic and sub-arctic (Hinzman *et al*., 2005), and many GCMs and climate models have predicted remarkable warming in the arctic in the near future (Martin *et al*., 1997; Rigor *et al*., 2000; Polyakov *et al*., 2002). The warming trend in the arctic ecosystems makes the

decomposition rate of organic matter in the permafrost increase, resulting in increase of GHG such as carbon dioxide (CO_2) and methane (CH_4) in the atmosphere (Mathews and Fung, 1987; Oechel *et al*., 1993). Conversely the warm climate shortens the snow-cover period and prolongs the growing season over the arctic ecosystems, which may provide greater CO_2 accumulation and biomass production (Oechel and Vourlitis, 1997; Oechel *et al*., 2000; Vourlitis *et al*., 2000). The arctic warming is also making the upper soil layers dry, which may reduce CH_4 production but increase CO_2 emission. However, we have little information of potential feedback mechanisms of these GHG budgets on the climate change, especially for CH_4 budget in the arctic ecosystems.

Considering CH_4 in terms of its global warming potential (GWP), which is thought to be at least 23 times (100-yr horizon) stronger than that of CO_2 in the atmosphere (Houghton *et al*., 2001). Its major source in nature is anaerobic ecosystem such as tundra and wetlands; however, some of produced CH_4 in the rhizosphere are oxidized at upper soil layer, moss layer and vascular system of plants under aerobic conditions (Joabsson and Christensen, 2001; Christensen *et al*., 2003). Many models have been proposed to reveal the potential feedback mechanisms of the CH_4 exchange between each ecosystem and atmosphere. However, model parameterization of CH_4 budget is insufficient because observational data available to parameterize are few. There are several problems in observational data acquisition; one is difficulties of field observation of CH_4 in the Arctic by methodological limitation including power supply under severe weather, another is heterogeneous distribution of wet/mesic/dry types of vegetation which makes it difficult to understand each of its contribution of CH_4 emission and/or uptake as an average.

We have been applying meteorological flux observation methods to arctic tundra ecosystems since 1993, in which we applied gradient techniques to determine CH_4 flux. These measurement methods have great advantages allowing continuous flux observations over growing seasons, large-scale flux evaluation as hectare scale (namely, stand scale), and data acquisition available to analyze relationship between CH_4 flux and meteorological conditions.

In this paper, the daily variation and intra-seasonal changes of CH_4 flux determined by micrometeorological techniques over several types of tundra in Alaska are shown, then the current CH_4 flux levels and spatial difference among arctic tundra are discussed. We also examined temporal differences of CH_4 flux at Alaskan tundra by using five years of records from field observations at Barrow.

2. Observation sites, vegetation and methods

2.1. Site description and measurement methods

Our meteorological CH_4 flux observation at Alaskan tundra started at Barrow in mid-June in 1993 and continued until the end of August, then the observations were carried out at Prudhoe Bay between mid-June and mid-August in 1994 and at Happy Valley between early June and late August in 1995, respectively. These CH_4 flux measurements were continued one to two days a week because of the limitation of applicability of CH_4 analyzer. Since 1996, we used a Non Dispersive type Infra-Red CH_4 (NDIR-CH_4; Horiba, GA-360, Japan) analyzer (Harazono *et al*., 1995) and a

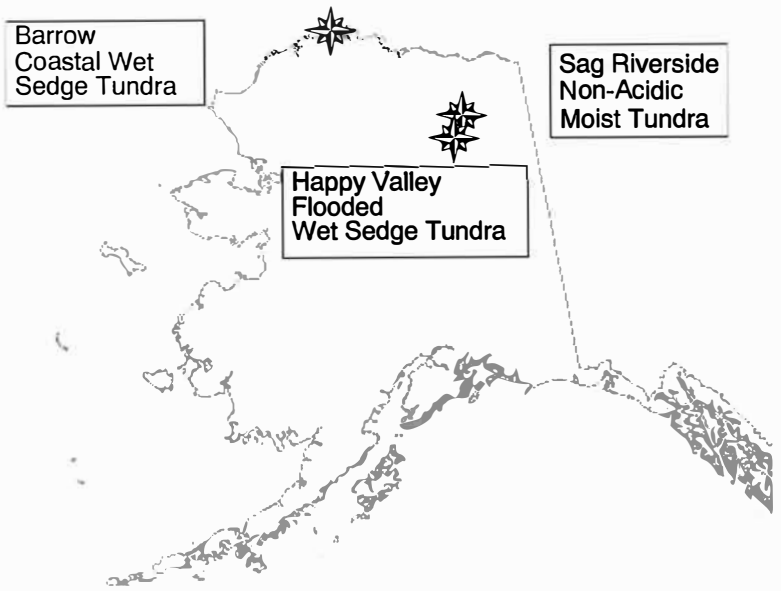

Fig. 1. Locations of CH_4 flux observation sites in the arctic tundra in Alaska and their vegetation types.

Flame Ionized Detector type CH_4 analyzer (FID-CH_4; Horiba, APHA-360, Japan) after spring of 2000. These improvements allowed measuring CH_4 concentration continuously at the sites. In this paper we show relatively longer recorded results, obtained after the observation at Happy Valley during the growing season in 1995. The location and categorized vegetation types are shown in Fig. 1.

CH_4 flux measurement at Happy Valley (69° 10′N, 148° 51′W, elevation 430 m) was conducted by applying an aerodynamic method in which a gas chromatograph (Shimadzu, GC-9A, Japan) was used to determine CH_4 concentration gradient. Two standard calibration gases, 0 and 3.964 ppm (Scott Specialty Gases, USA, EPA protocol compliance class) were used for calibration. Sampling bags (Tedlar bag, 20 liter) were used to collect air samples over 30 min from two heights (0.6 and 2.0 m) of the tower at two-hour interval. The measurements were conducted almost twice a week and each continued 36–48 hrs. CO_2 and energy fluxes were also measured simultaneously by applying an eddy correlation technique using three-dimensional sonic anemometer (Kaijo, DAT600, Japan) and open pass CO_2/H_2O analyzer (Advanet, E009a, Japan). Other micrometeorology such as wind speed, solar radiation, air temperature, vegetation-surface temperature, relative humidity and soil/water temperature were also measured. Happy Valley site was inland wet sedge tundra where the standing water was 0.15–0.2 m in depth and the maximum active layer depth was 0.62 m, which was deep peat soil layer in summer. The dominant vegetation was sphagnum moss, sedge, and other vascular plants (*Carex aquatilis* Wahlenb, *Eriophorum sheuchzeri* Hoppe).

The first continuous CH_4 flux observation was conducted over non-acidic moist tundra located in northeastern part of Kuparuk Basin (Sagavartiktok riverside, 69° 30′

20″N, 148°13′30″W, elevation 170 m, hereafter we state Sag-river site) from June 4 to September 10 in 1996. Vegetation at the site was mesic tundra, consisted of vascular plant, moss and a few short shrubs. The density and height of vascular plants were low compared to the Happy Valley site. The NDIR-CH_4 analyzer (Horiba, GA360, Japan) was applied to determine CH_4 concentration (two standard gases 1.68 and 3.98 ppm air-balanced by Takachiho Chemical Industry, Japan, were used twice a day at 8 AM and 5 PM for calibration). The analyzer allowed continuous CH_4 concentration measurements with a 10 ppb realizable limit and good reproducibility at fields (Harazono *et al*., 1996). The vertical CH_4 concentration gradient was measured by alternating air samples from two heights of the tower (0.5 and 2.5 m) by switching the sampling lines at three-minute intervals. CH_4 flux was determined using the improved aerodynamic method (Harazono *et al*., 1996; Miyata *et al*., 2000) applying measured friction velocity (u_*) and sensible heat flux (H) by the simultaneous eddy correlation measurement at the site.

Continuous long-term CH_4 flux observations have been conducted at Barrow since 1999 spring. Barrow site (71°19′12.5″N, 156°37′20.211″W, elevation 1 m) was completely wet tundra located at the northern edge of a dried lagoon called the Central Marsh in Barrow. Vegetation consists of wet sedges, grasses, moss and lichens, and the dominant species is *Arctophila fulva* (Walker and Acevedo, 1987; Oechel *et al*., 1995). The vegetation was completely flooded after spring thaw (Harazono *et al*., 2003; Oechel and Vourlitis, 1997). We applied the NDIR-CH_4 analyzer and improved aerodynamic method (Miyata, 2001) to determine CH_4 flux the same way as Sag-river site, in which air sampling heights were different (0.7 and 2.9 m). After 2000 spring, we applied the FID-CH_4 analyzer to improve the CH_4 concentration measurement during cold season. Two standard gases 0 and around 3 ppm (different numbers within five years) were used at 8 AM for calibration. Supporting micrometeorological data were also measured at the observation tower (6.2 m tall). Details of the measurement at the Barrow site are reported in Harazono *et al*. (2003).

2.2. *CH_4 Flux calculation methods*

CH_4 flux was determined by gradient method according to the Monin-Obukhov similarity; there is a relationship between turbulent transport of a subject and its vertical profile within boundary layer over a flat canopy. Fortunately, the boundary layer conditions of our measurement sites were verified to have enough fetch length for dominant wind direction, we were able to apply improved aerodynamic method. Details of the method are introduced in Harazono *et al*. (1996), Harazono and Miyata (1997), Miyata *et al*. (2000), and Miyata (2001), and the outlines were as follows.

From Monin-Obukhov similarity theory, the vertical flux of a gas F is related to the mean vertical gradient of the mass mixing ratio s (Fowler and Duyzer, 1989; Denmead, 1994):

$$F = -\bar{\rho}_a K_g(z) \frac{\partial \bar{s}}{\partial z} = -\bar{\rho}_a \frac{\kappa u_*(z-d)}{\phi_g(\zeta)} \frac{\partial \bar{s}}{\partial z}, \quad (1)$$

where, $K_g(z)$ is the eddy diffusivity at a height z, and d, u_*, ρ_a and κ are the zero plane displacement determined from measured wind profile, the friction velocity, the density

of dry air, and von Karman's constant (=0.4), respectively. The term $\phi_g(\zeta)$ in eq. (1) is the correction to the eddy diffusivity as a function of the Monin-Obukhov stability parameter ζ defined as

$$\zeta = -(z-d)\frac{\kappa H \frac{g}{\theta}}{u_*^3}, \tag{2}$$

$$\phi_h = (1-16\zeta)^{-1/2}, \quad (\zeta \leq 0) \tag{3a}$$

$$\phi_h = 1+5\zeta, \quad (\zeta \geq 0) \tag{3b}$$

where, θ, H and g are potential temperature, sensible heat flux, and acceleration of gravity, respectively.

By using u_* and H obtained from the simultaneous eddy flux measurements, the stability parameter ζ and therefore $\phi_h(\zeta)$ were determined by eq. (3a) and eq. (3b). Then, we calculated the CH_4 flux from the CH_4 concentration gradient using eq. (1). Based on the previous studies (Denmead, 1994; Dyer and Hicks, 1970; Webb, 1970) and the site conditions, we put dimensionless gradients as $\phi_g = \phi_h$.

3. Results and discussions

3.1. Methane flux at inland wet sedge tundra

The average CH_4 concentration at Happy Valley was around 1.85 ppm with little daily variation in June, then the concentration increased to 1.96 ppm in July and then decreased to 1.91 ppm in August. The atmospheric CH_4 concentration at Barrow Station, NOAA-CMDL during 1995 summer was less than 1.85 ppm as daily base (Russell *et al*., 2004), so the CH_4 concentration over the inland wet sedge tundra was higher than background concentration and also higher than 1.825 ppm measured at Alaskan tundra previously (Fan *et al*., 1992). The amplitude in daily CH_4 concentration was very small in June, but fluctuated largely in July and August, especially in daytime, which did not show a typical diurnal pattern with temperature or solar radiation.

CH_4 flux measurements were intermittently conducted 21 times at Happy Valley between June 7 and August 31 in 1995. Air sampling was conducted over 30 min, so that the determined CH_4 fluxes represented half-hourly numbers. Monthly means of daily patterns of half-hourly CH_4 flux were shown in Fig. 2. Half-hourly CH_4 flux ranged between 0 and 5 $mgCH_4m^{-2}h^{-1}$ with large fluctuation around 10 $mgCH_4m^{-2}h^{-1}$ and the CH_4 flux level in July was lower than that in other months. Previous results, mostly determined by chamber techniques, showed clear diurnal patterns of CH_4 flux at arctic and sub-arctic tundra and wetland (Fan *et al*., 1992; Moore *et al*., 1994a; Moosavi and Crill, 1997; Werner *et al*., 2003), however, the diurnal trends in Fig. 2 did not show clear patterns in each month even though water temperature showed clear diurnal variations. The unclear diurnal patterns were also reported at northern wetland determined by eddy correlation method (Edwards *et al*., 1994), therefore, previous results in tundra by chamber methods might include chamber effect of increased temperature on flux measurement during daytime.

Seasonal variations of daily-integrated CH_4 flux and the water temperature at the

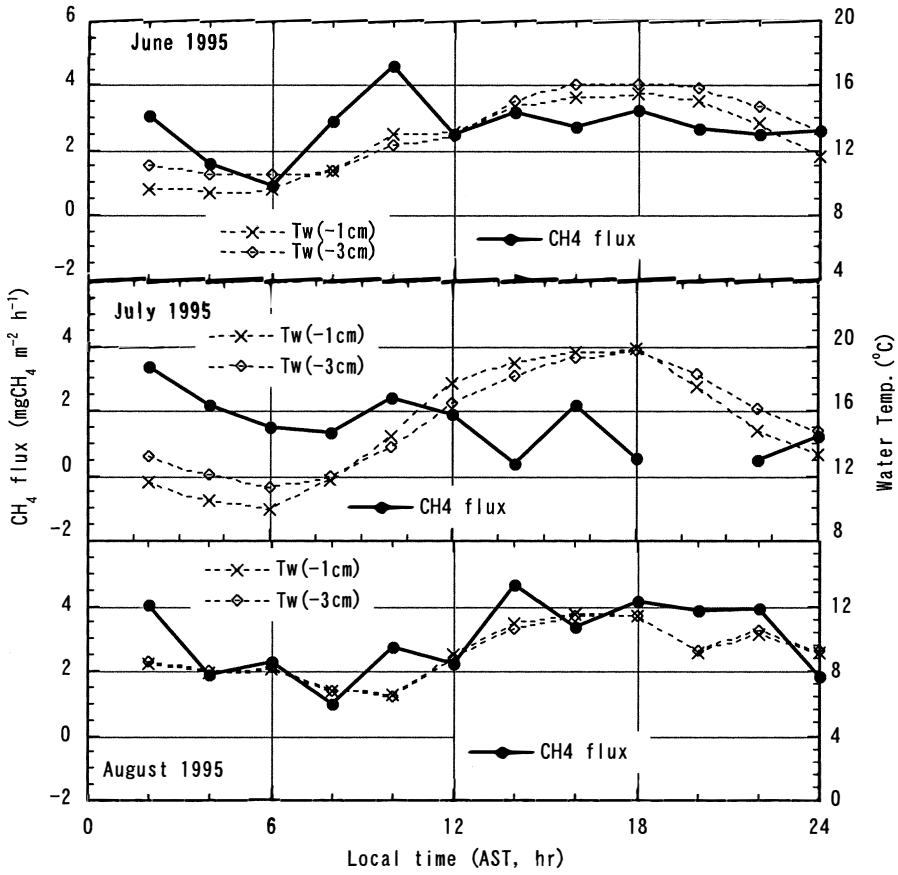

Fig. 2. Diurnal trends of monthly averaged half-hourly CH_4 flux and water temperature in the inland flooded sedge tundra at Happy Valley, Alaska, during the growing season in 1995.

site were shown in Fig. 3 (A). Also seasonal trends of water level and thaw depth were shown in Fig. 3 (B). Daily-integrated CH_4 flux ranged 21–112 $mgCH_4m^{-2}d^{-1}$ in June, 41–45 $mgCH_4m^{-2}d^{-1}$ in July, 33–129 $mgCH_4m^{-2}d^{-1}$ in August, respectively. Low flux level during mid summer was also observed at Alaskan arctic tundra (Moore *et al.*, 1994b). High CH_4 concentration at the site (shown above) during growing season might be related regionally with large CH_4 emissions.

Since the measurements at Happy Valley were intermittent, the estimation to fill the data-gap is demanded to evaluate the seasonal CH_4 budget. We examined the relationships between CH_4 flux and measured factors for better estimation. The half-hourly CH_4 fluxes did not relate to soil or air temperature, however, we found a better multiple regression formula (eq. 4) empirically for daily integration of CH_4 flux to fill the data-gaps, which was function of water temperature of 22 cm depth (*Tw*), water level (*Dw*, cm) and thaw depth (*Dth*, cm). Contributions of *Dth* and *Dw* on the daily-integrated CH_4 flux was negative and that of *Dth* was quite low compare to that of *Dw* at the flooded sedge site, which might be explained that the deep water acted as diffusion

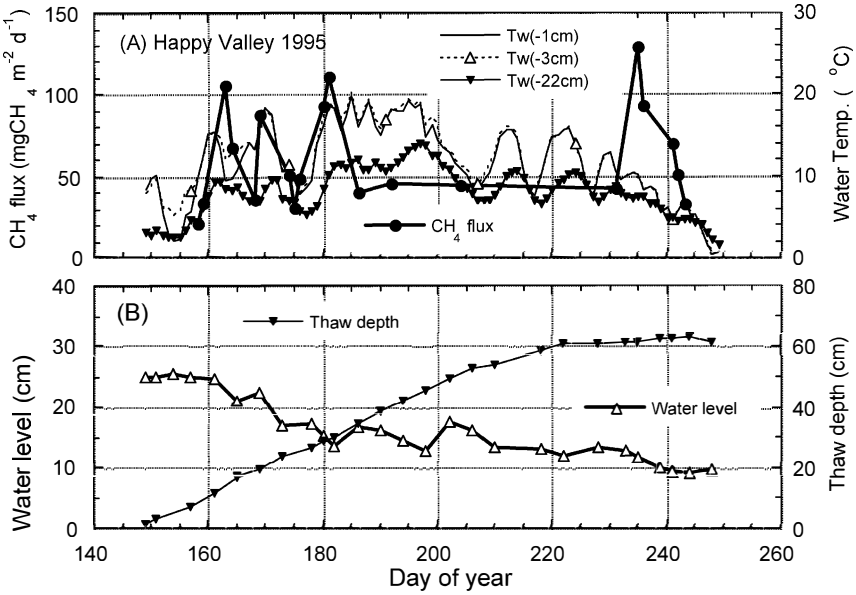

Fig. 3. Intra-seasonal changes of daily amount of CH_4 flux (observed) and daily mean water temperatures (1, 3 and 22 cm in depth) in the inland flooded sedge tundra during the growing season in 1995.

resistance between soil layer and the atmosphere (Miyata *et al*., 2000) and accelerator of CH_4-oxidation within water (Yagi, 1994).

$$CH_4\text{flux} = 12.8Tw - 0.44Dth - 4.2Dw - 55.8. \quad (4)$$
$$(\text{determination coefficient} = 0.44,\ n = 15)$$

The estimation according to eq. (4) with available data in Fig. 3 provided the cumulative CH_4 flux of 8.1 gCH_4m^{-2} in the flooded sedge tundra at Happy Valley between DOY 151–252 (101 days) in 1995. The total flux was similar to those previously estimated such as 6.4 gCH_4m^{-2} during 130 days of growing period (Moore *et al*., 1994b), 8.7 gCH_4m^{-2} during 100 days at Alaskan wet tundra (Sebacher *et al*., 1986), 18.7 gCH_4m^{-2} during 130 days and 12 gCH_4m^{-2} during 120 days at Alaskan wet tundra (Bartlet *et al*., 1992).

3.2. Methane flux at non-acidic moist tundra

CH_4 concentration and CH_4 flux were measured continuously at Sag-river site during the growing season in 1996. The average CH_4 concentrations in daytime were around 1.82 ppm from early June to mid-August, and then it increased gradually up to 2.05 ppm in early September. There was no obvious daily variation in CH_4 concentration with time course. Diurnal patterns of weekly averaged half-hourly CH_4 flux and soil temperatures at depths of 1, 5 and 10 cm are shown in Fig. 4 for major five periods. The averaged half-hourly CH_4 flux fluctuated and we can't find diurnal patterns of CH_4 flux in association with the time courses in soil and air temperature throughout the

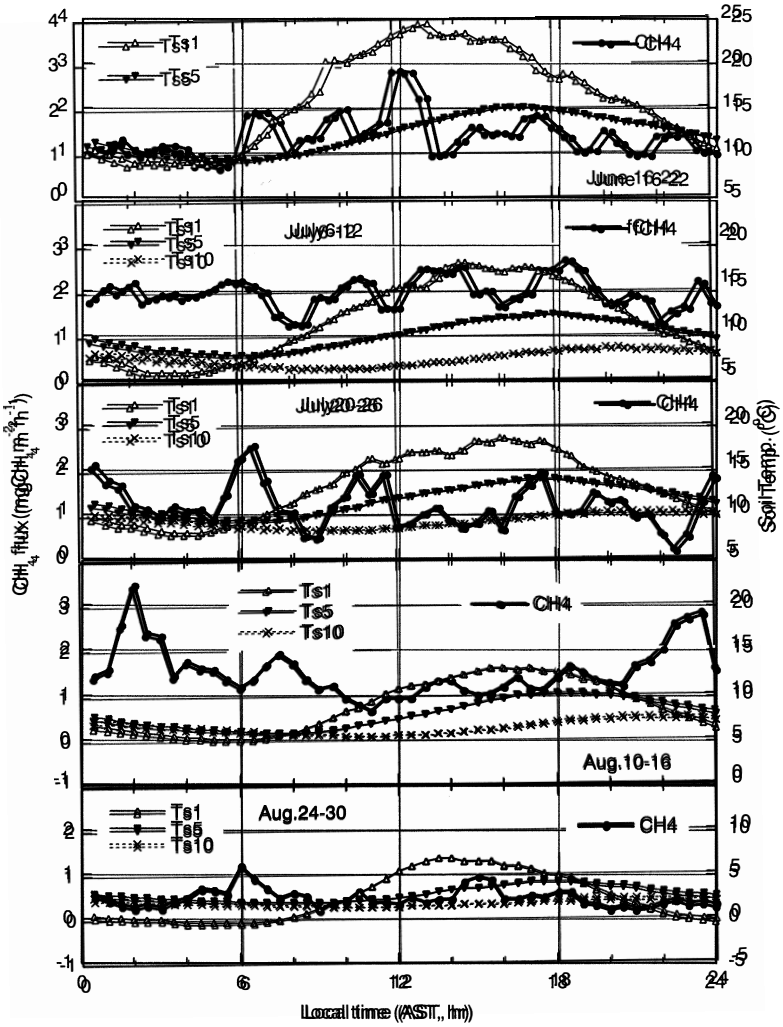

Fig. 4. Diurnal trends of weekly averaged half-hourly CH_4 flux and soil temperature (1, 5, 10 cm in depth) over the non-acidic moist tundra at Sagavartiktok riverside (Sag-river site), Alaska, during the growing season in 1996.

observed period. The fluctuations might be the reflection of wind condition and heterogeneity of the field, where small ponds, submerged plots and dry spots of the tundra were present. Weak CH_4 uptakes were measured sometimes as half-hourly base, which were also observed at other sub-arctic wetland and tundra under drained conditions (Bartlett *et al*., 1992; Moore *et al*., 1994a; Nakano *et al*., 2004). The oxidization at aerobic soil parts within the site might have strong effect on the fluctuation in measured half-hourly CH_4 fluxes.

The weekly averaged half-hourly fluxes were lower than 2 $mgCH_4m^{-2}h^{-1}$ by mid-June (no figure), then increased gradually. In late June, the average flux levels

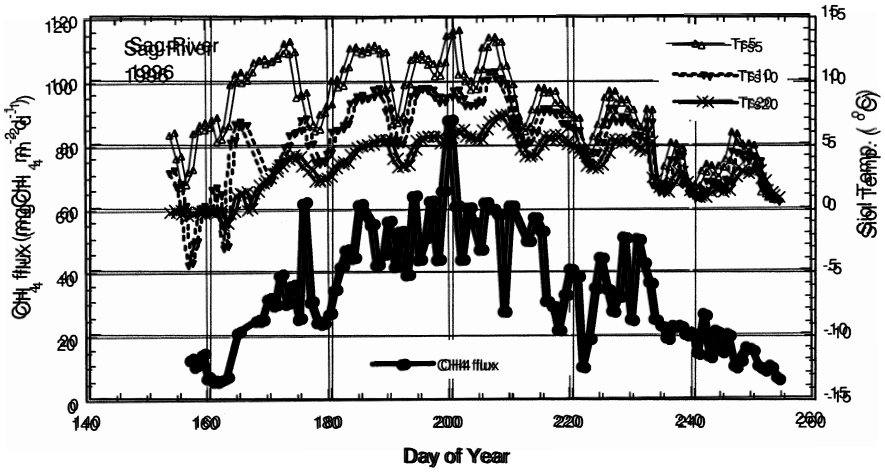

Fig. 5. Intra-seasonal changes of daily amount of CH_4 flux and daily mean soil temperatures (5, 10 and 20 cm in depth) in the non-acidic moist tundra at Sag-river site during the growing season in 1996.

increased to around 3 $mgCH_4m^{-2}h^{-1}$ in daytime, and then continued almost similar averages until late July. However the weekly average levels fluctuated and did not show clear diurnal pattern. After mid-August the weekly averaged CH_4 flux level decreased gradually, also we observed high level fluxes after dusk and before dawn when the midnight sun was gone. The high levels during dusk and dawn might be caused by the low CH_4 oxidation in relation to low wind speed during nighttime. In late August, the weekly average CH_4 flux decreased to less than 1 $mgCH_4m^{-2}h^{-1}$.

Seasonal changes of daily amount of CH_4 flux and soil temperatures are shown in Fig. 5. The daily amounts changed day by day and were affected by weather condition, but the seasonal change related to that of soil temperatures at a depth of 10 cm. The daily amounts of CH_4 flux were low by mid-June (DOY165) with around 10 $mgCH_4m^{-2}d^{-1}$, then increased up to around 50 $mgCH_4m^{-2}d^{-1}$ in early July. The maximum daily CH_4 efflux was 87.7 $mgCH_4m^{-2}d^{-1}$ measured in mid-July (DOY201). After early August, the CH_4 flux decreased gradually to 20 $mgCH_4m^{-2}d^{-1}$ in late August. In September the daily CH_4 flux was less than 10 $mgCH_4m^{-2}d^{-1}$. The maximum level of daily CH_4 flux at Sag-river site was almost two thirds of that on the flooded tundra at Happy Valley. The total efflux during the observation period DOY155–253 (98 days) in 1996 was 3.24 gCH_4m^{-2}. Non-acidic moist tundra acted as a CH_4 source, but its source level was weak.

3.3. Methane flux at coastal wet sedge tundra

The Barrow site was established to reveal the temporal variability of greenhouse gas budget, so the data were basically collected continuously through the year. The sensors and gas measuring equipments at the site were maintained continuously during snow-free periods, however, were intermittently maintained almost every two months during snow-covered period, which resulted in some lacking data in fluxes during winter

through spring. In this section, we show data mainly obtained during vegetation growing seasons in 1999, 2000, and 2001 to examine the spatial difference of CH_4 flux compared to other sites above.

At Barrow site, CH_4 flux increased rapidly after spring thaw in each year and the peak flux occurred in mid-July. Figure 6 shows the monthly averaged diurnal patterns of CH_4 flux and soil temperature of 1cm at Barrow site between early June and end September in 2000. Since the site was flooded, the soil temperature of 1 cm depth was equivalent to that of 10–15 cm depth under water surface, in which the actual water level varied slightly during the flooded period. As same as other sites, the diurnal patterns of half-hourly CH_4 flux were almost flat and the diurnal pattern did not relate to that of

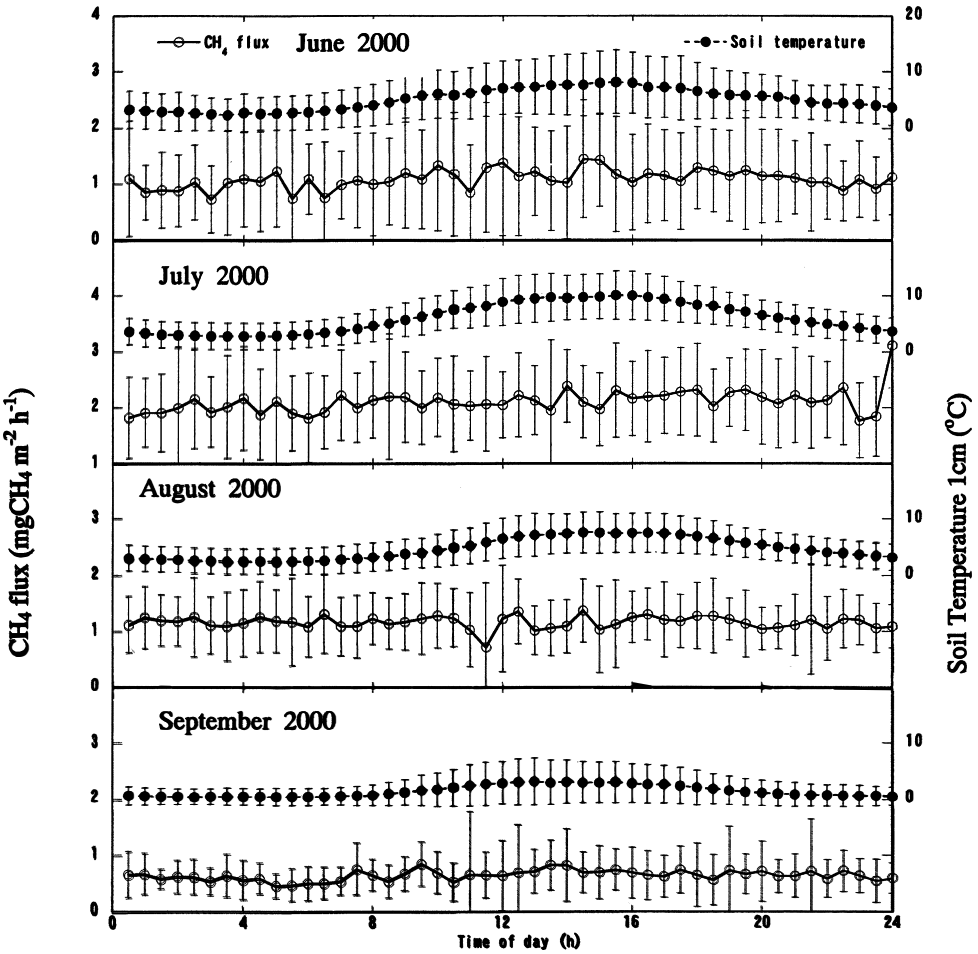

Fig. 6. Diurnal trends of monthly averaged half-hourly CH_4 flux and soil temperature of 1 cm in depth over wet sedge tundra at Barrow, Alaska, during the growing season in 2000. The soil depth of 1 cm was comparable to 10–15 cm below water surface. Bars show standard deviation for each CH_4 flux and soil temperature.

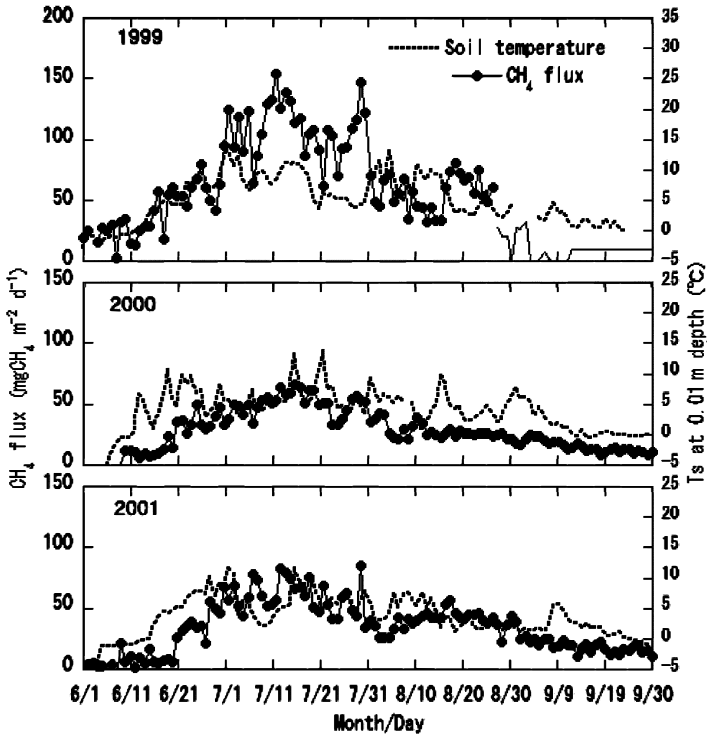

Fig. 7. Intra-seasonal changes in daily amount of CH_4 flux and daily mean soil temperatures (1 cm in depth, which was 10–15 cm below water surface) in the wet sedge tundra at Barrow during 1999, 2000, and 2001 growing seasons.

soil temperature. We also found little diurnal patterns in two-weekly averaged CH_4 flux and monthly averaged CH_4 flux for years 1999, 2001 and after.

Seasonal variations of daily amount of CH_4 flux were shown in Fig. 7 for 1999, 2000, and 2001 seasons. Spring thaw in each year were June 13 in 1999, June 16 in 2000 and June 18 in 2001. Daily CH_4 flux before spring thaw in 1999 was low level with maximum up to 20 $mgCH_4m^{-2}d^{-1}$ at Barrow site, and we could not find remarkable increase in CH_4 emission around spring thaw. Large amount of CH_4 emission during spring thaw is debatable issue affecting annual CH_4 budget; large amount of CH_4 was released in relation with replaced air by snowmelt-water, which has been observed at several tundra (*e.g.* Wagner *et al.*, 2003). After spring thaw, daily amount of CH_4 flux increased gradually and reached to 154 $mgCH_4m^{-2}d^{-1}$ in mid-July. After that the daily amount maintained high levels with fluctuation between 30 and 120 $mgCH_4m^{-2}d^{-1}$ that reflected the change in production and oxidation in relation to changeable weather at the site. The CH_4 flux observation in 1999 season stopped at the end of August to prevent system damage by icing. CH_4 flux level, right before the closure of measurement, was still high around 50 $mgCH_4m^{-2}d^{-1}$.

Compared to 1999, the intra-seasonal variations of daily amount of CH_4 flux in 2000 and 2001 had small amplitude with lower peak levels, especially in 2000. At the

beginning of the measurement around spring thaw; the daily CH_4 flux was less than 10 $mgCH_4m^{-2}d^{-1}$ in 2000 (before June 16) and almost the same level in 2001 (June 18), while it was almost doubled in 1999 (June 13). Differences in environmental factor among these three years is soil temperature, shown in Fig. 7, which increased above zero about two weeks earlier than the spring thaw in 1999, while that delayed a week in 2000 and 2001. Soil temperature below zero may be a key trigger to know the activity of methanogen bacteria. Mid-summer peaks of daily CH_4 flux levels were also lower in 2000 and 2001 than that in 1999, which increased gradually up to 66 $mgCH_4m^{-2}d^{-1}$ in 2000 and to 85 $mgCH_4m^{-2}d^{-1}$ in 2001. The inter-annual differences are discussed in the latter section.

The seasonal amount of CH_4 flux were determined for four months (120 days) between June and September, in which data gap were filled by applying Mean Diurnal Variation method (MDV; Falge *et al*., 2001). However, we could not apply the MDV for after August 28, 1999, so that we applied simple model fitting according to Cao *et al*. (1996). The model is consisted by both CH_4 production and oxidation, in which the production is functions of soil temperature and water level and the oxidation is function of gross primary production (GPP) of the vegetation (Mano, 2003). The seasonal budgets at wet sedge tundra were 8.24 gCH_4m^{-2} in 1999, 3.58 gCH_4m^{-2} in 2000 and 4.12 gCH_4m^{-2} in 2001, respectively.

As we could not find clear diurnal patterns and the relationship between CH_4 flux and soil temperature based on half-hourly data, however CH_4 flux related to soil temperature as daily base over growing season. The relationship to temperature was normally expressed using Q10 value, namely the coefficient for the exponential relationship between temperature and CH_4 flux, multiplied by ten. Q10 and the contribution (R^2) in each year were 2.7 (0.11), 6.4 (0.22), and 4.0 (0.20) respectively.

3.4. Spatial and temporal difference of CH_4 flux in the arctic tundra in Alaska

As shown in figures above, we could not find clear diurnal patterns of CH_4 flux at several types of Alaskan tundra, in which soil or water temperature had little relation to CH_4 flux as hourly base. Also other micrometeorology such as solar radiation, wind speed, air temperature, and humidity had little influence on hourly CH_4 flux. However, the daily variations of CH_4 flux were observed in other wetland (Fan *et al*., 1992; Verma *et al*., 1992) and in rice paddy (Miyata *et al*., 2000), which showed higher levels during daytime.

The depth of thawed layer increased gradually after snow-melt in tundra vegetation, so the soil temperature at deep layer was close to that of thawed permafrost (nearly 0°C), which resulted in low and almost constant temperature. The methanogen bacteria was active at deep soil layer where it is anaerobic and the temperature range varied little within a day. While soil temperature changes seasonally thus, the CH_4 production might not change in relation to diurnal changes in temperature but related to seasonal changes. There are many reports on relationship between CH_4 flux and seasonal soil temperature for wetlands (Sebacher *et al*., 1986; Morrissey and Livingston, 1992; Frolking and Crill, 1994; Moosavi *et al*., 1996; Suyker *et al*., 1996), and this relationship was normally applied to fill the data gap and to extend large-scale estimation (Fung *et al*., 1991). However, the reported Q10 ranged widely between 1.7 and 7.0 (Moore *et*

al., 1994b; Chapman and Thurlow, 1996), which showed heterogeneity of vegetation types with differences in activity of methanogen bacteria and organic supply (Valentini *et al*., 1994). Also, Q10 at the Barrow site showed large inter-annual variability among three years. Our Barrow results suggest that the inter-annual variability in Q10 may be caused by different weather, thus, we have to consider the importance of micro-meteorological factors to control CH_4 flux as the same contribution as those of soil conditions.

One key factor on CH_4 flux at the ecosystem level may be amount of CH_4 oxidation; CH_4 is oxidized by the methanotrophic bacteria when the rhizosphere is aerobic, namely if oxygen exist in the soil layer methane is oxidized. Vascular plants transport oxygen from atmosphere to rhizosphere through their tissue providing aerobic conditions especially around their roots. Also decrease of water level and increase of water flow lead to oxygen rich rhizosphere by its diffusion. As a result, CH_4 oxidation takes place at soil surface, in the soil layer, and within plant tissue. Moss is also the aerobic portion in the tundra ecosystems. The strengths of oxidation by vascular plants showed large differences (0–90%) among plant species (Joabsson and Christensen, 2001). Thus, the CH_4 sink can be distributed anywhere in the tundra vegetation at the ecosystem level.

Table 1 shows spatial difference of seasonal budgets of CH_4 flux during each growing season, in which results obtained by meteorological methods at other tundra were included. The unit of CH_4 flux was converted to carbon per square meter in the Table 1. The largest emission was 14 gCm^{-2} estimated by Bartlett *et al*. (1992) and lowest was 1.35 gCm^{-2} by Moore *et al*. (1994b) and there is large difference. Our accumulated numbers based on continuous measurements were middle range among the previous estimations. The large spatial difference could be caused not only by different CH_4 production potential but also by oxidation at each type of tundra with different weather.

Table 2 shows the temporal differences in seasonally integrated CH_4 flux, NEE and gross primary production (GPP) at Barrow site. NEE and GPP were determined from simultaneous CO_2 flux observations at the site. Depending on the data limitation, the

Table 1. Spatial difference of CH_4 flux in high latitude ecosystems over their growing seasons.

Ecosystem type	Location	Year & period	CH_4 gCm^{-2}	Reference
Wet sedge	Barrow 71 N, 156 W	1999–2001 (120 days)	3.09–6.18	This study
Non-Acidic, moist tundra	69.3 N, 148 W	1996 (98 days)	2.40	This study
Flooded wet sedge	69 N, 148.5 W	1995 (101 days)	6.07	This study
Wet sedge	Alaska	100 days	6.7	Sebacher *et al*., 1986
Flooded mire	Average	120 days	1.35–12.4	Moore *et al*., 1994b
Wet tundra	Alaska	130 days	14	Bartlett *et al*., 1992
Wet tundra	Average	120 days	9	Bartlett *et al*., 1992

Cited previous results are only observed by meteorological methods with relatively long term observations.

Table 2. Temporal differences of net ecosystem CO_2 exchange (NEE), gross primary production (GPP), CH_4 flux and the carbon ratio of CH_4 flux to GPP.

Year	NEE gCm^{-2}	GPP gCm^{-2}	CH_4 flux gCm^{-2}	C-ratio to GPP %
1999	−168	228	6.18	2.71
2000	−91	143	2.69	1.88
2001	−88	137	3.09	2.26
2002	−129	175	4.19	2.39
2003	−181	233	1.92	0.82

gap-fill of data was temporally applied for seasons of 2002 and 2003, so that the final numbers during these seasons may be a little different. In the Table 2, we can find large yearly differences in NEE and CH_4 flux, in which high NEE were results of high productivity of tundra vegetation and the yearly difference was mainly caused by weather in early period in each growing season (Harazono *et al*., 2003). While, CH_4 flux was a budget of production and oxidation in the tundra, and the CH_4 production was basically related to gross primary production (GPP) which is equivalent to the supply index of substrate from photosynthesis (Christensen *et al*., 2003). The carbon ratio of CH_4 to GPP (CH_4/GPP) is an index to examine the oxidation, in which high number means high substrate supply and high methanogen activity, while low number means low methanogen activity and/or high oxidation.

We found yearly differences not only in GPP and CH_4 flux, but also the carbon ratio CH_4/GPP at the same tundra. The yearly differences in the ratio of CH_4/GPP might be the reflection of differences in CH_4 oxidation. 2003 season was low CH_4 emission and its carbon ratio CH_4/GPP was as low as 0.82% compared to normally observed value of 3% (Whiting and Chanton, 1993). The low CH_4 emission in 2003 season might be caused by draught condition at the site with low water level and low precipitation during the growing season, resulting in low CH_4 production and high oxidation under aerobic condition. Furthermore we had little snowfall during previous cold season 2002–2003, which caused a small discharge of snow-melt water into the marsh site resulting in low water level at the beginning of the growing season. Compared to the 2003 season, 1999 season also had low precipitation, but we had plenty of snow accumulation during the previous cold season 1998–1999, which provided enough discharge water into the marsh site resulting in high CH_4 production under anaerobic rhizosphere and high substrate supply (high GPP in Table 2) under clear weather conditions (Harazono *et al*., 2003).

Many models provide reasonable estimation of CH_4 production, but there are still uncertainties in the oxidation mechanism. In order to reveal CH_4 budget in the tundra ecosystems, we have to reveal the contribution of environmental factors on the oxidation mechanism, especially relation between the mechanism and meteorology. Also the CH_4 production was deeply related with plant productivity during short growing period, so that the weather condition is more important on the CH_4 budget in the arctic ecosystem. The long cold period in the Arctic is another problem to estimate the CH_4 budget in tundra vegetation; we have to improve the CH_4 flux measurement especially during cold

period to overcome the limitation of data availability.

4. Conclusions

Daily trends of half hourly CH_4 flux have little correlation with soil temperature nor solar radiation at inland and coastal tundra, thus we state that the hourly CH_4 flux in the arctic tundra showed little diurnal pattern. On the other hand, the seasonal trend of daily-integrated CH_4 flux changed with soil temperature. Cumulative CH_4 flux during vegetation growing season of flooded sedge tundra at Happy Valley was 8.1 gCH_4m^{-2} in 1995 (101 days) and that at moist tundra (non-acidic) was 3.3 gCH_4m^{-2} in 1996 (98 days). At Barrow site, CH_4 flux increased rapidly after snowmelt and the peak flux occurred in mid-July. Peak levels in each year showed large temporal differences with 55–205 $mgCH_4m^{-2}d^{-1}$ and the cumulative CH_4 flux varied 2.56–8.24 gCH_4m^{-2} (1.92–6.18 gCm^{-2}) among five growing seasons between 1999–2003. The carbon ratio of emitted CH_4 to the gross primary production (GPP) of the wet tundra varied temporally.

Observed CH_4 fluxes at several types of tundra showed large spatial difference, but were within the range obtained by previous studies. CH_4 flux in wet sedge tundra at Barrow showed large inter-annual variability (coefficient of variance 35%) rather than that in CO_2 flux (coefficient of variance 24%). In order to improve the understanding of CH_4 budget at arctic tundra, the oxidation mechanism has to be investigated more and further observations during cold period must be promoted.

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