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Estimation of Methane Emission from Natural Wetlands
in Siberian Permafrost Area

A doctoral dissertation

Tomoko NAKAYAMA

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1. Introduction

Atmospheric methane (CH_4) is a greenhouse gas element that is a critical reactant in the photochemistry of both troposphere and stratosphere (Levy, 1971; Ehhalt, 1974; Logan et al, 1981). Its concentration has doubled over the past 200 years (Craig and Chou, 1982; Stauffer et al., 1985; Khalil and Rasmussen, 1987), and at present increases at a rate of 1 % per year (Steele et al., 1987; Blake and Rowland, 1988; Khalil and Rasmussen, 1990). With this steady increase and possible greenhouse effects of methane to the climate, the global methane budget is not only important to its own right, but also to understand the global climatic change.

Recently, the methane sources have been fairly identified, though the source strength is still poorly quantified. A natural wetland is one of the major sources of methane to atmosphere. It is estimated to have the largest contribution to the global methane emission, with varying estimates (Watson et al., 1990; Tyler, 1991). The area of global wetlands was estimated as 5.3 and $5.7 \times 10^{12} \text{ m}^2$ by Matthews and Fung (1987) and by Aselmann and Crutzen (1989), respectively (Figure 1-1 (a)). Both researches reported that the largest areas occur between 50°N and 70°N , and second in importance is the tropical belt between 10°N and 20°S .

This study aims to quantify the methane emission from the natural wetlands. In particular, the present author attempts to focus on wetlands in permafrost areas that occupy approximately 22 - 25 % of the earth's land surface (French, 1976). The reason is that the methane emission from these wetlands is related to seasonal melting of permafrost, which is considerably reflecting the climate. In

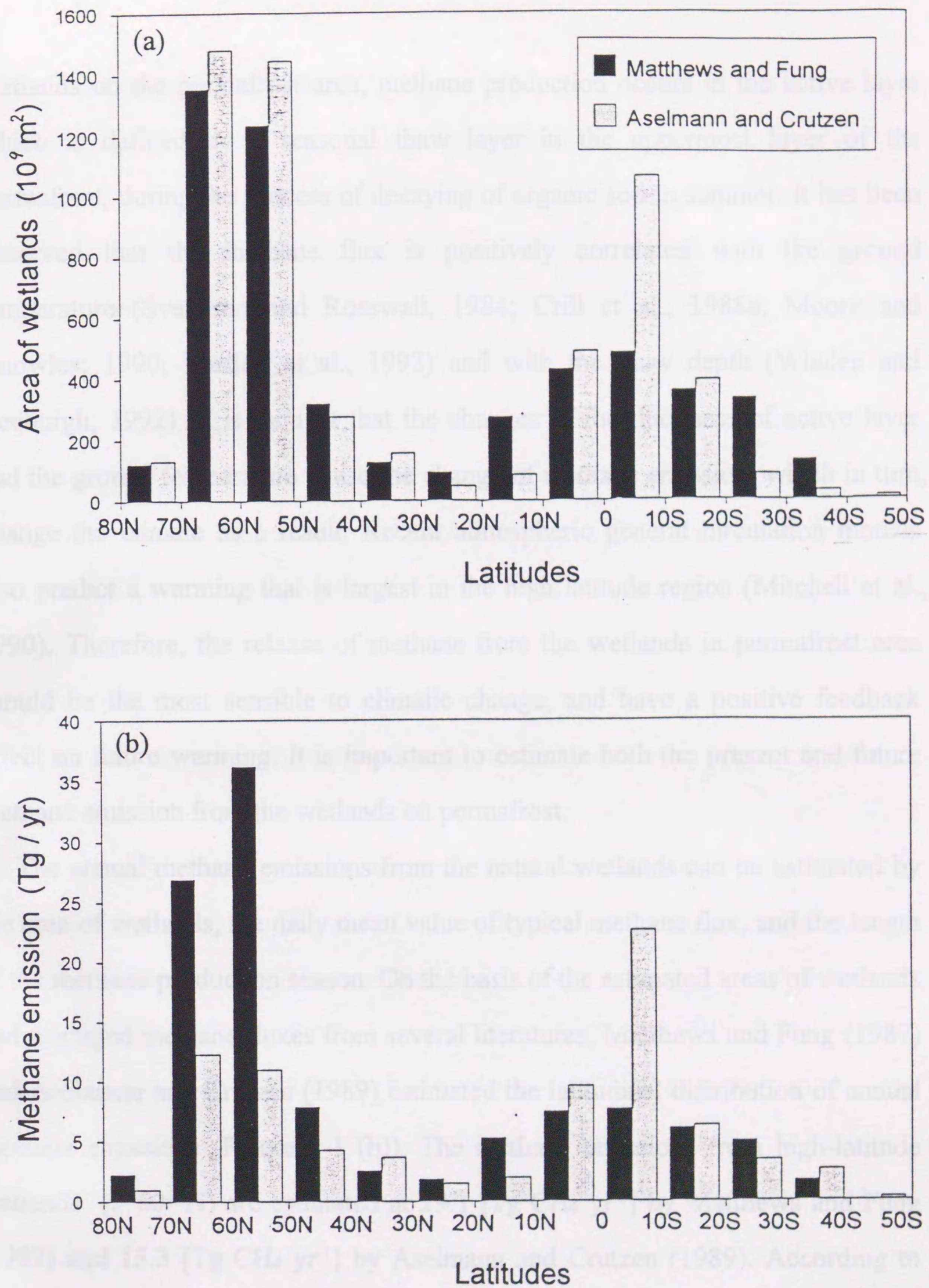


Figure 1-1. Latitudinal distribution of (a) areas and (b) annual methane emissions estimated by Matthews and Fung (1987) and Aselmann and Crutzen (1989).

wetlands on the permafrost area, methane production occurs in the active layer, which is defined by a seasonal thaw layer in the uppermost layer of the permafrost, during the process of decaying of organic soil in summer. It has been observed that the methane flux is positively correlated with the ground temperature (Svensson and Rosswall, 1984; Crill et al., 1988a; Moore and Knowles; 1990; Bartlett et al., 1992) and with the thaw depth (Whalen and Reeburgh, 1992). It is thought that the changes of the thickness of active layer and the ground temperature cause the change of methane emission, which in turn, change the climate as a result. Recent atmospheric general circulation models also predict a warming that is largest in the high latitude region (Mitchell et al., 1990). Therefore, the release of methane from the wetlands in permafrost area should be the most sensible to climatic change, and have a positive feedback effect on future warming. It is important to estimate both the present and future methane emission from the wetlands on permafrost.

The annual methane emissions from the natural wetlands can be estimated by the area of wetlands, the daily mean value of typical methane flux, and the length of the methane production season. On the basis of the estimated areas of wetlands and averaged methane fluxes from several literatures, Matthews and Fung (1987) and Aselmann and Crutzen (1989) estimated the latitudinal distribution of annual methane emissions (Figure 1-1 (b)). The methane emissions from high-latitude wetlands ($> 60^{\circ}\text{N}$) are estimated at $29.1 [\text{Tg CH}_4 \text{ yr}^{-1}]$ by Matthews and Fung (1987) and $13.3 [\text{Tg CH}_4 \text{ yr}^{-1}]$ by Aselmann and Crutzen (1989). According to Matthews and Fung (1987), the methane emission from the wetland in high latitude is considerably larger than that in low latitude. However, these estimations are not accurate due to the lack of the consideration in seasonal and

spatial variabilities of methane flux.

The methane fluxes from high-latitude wetlands have been measured in several limited regions, mainly in North America. The recent estimated values of methane emission from high-latitude wetlands on the basis of the field methane flux measurements vary the following ways; 45 - 106 [Tg CH₄ yr⁻¹] (Sebacher et al., 1986), 19.3 - 32.7 [Tg CH₄ yr⁻¹] (Whalen and Reeburgh, 1988), 38 [Tg CH₄ yr⁻¹] (Whalen and Reeburgh, 1990), 10.9 [Tg CH₄ yr⁻¹] (Bartlett et al., 1992), 22 [Tg CH₄ yr⁻¹] (Fan et al., 1992), 42 ± 26 [Tg CH₄ yr⁻¹] (Whalen and Reeburgh, 1992). The estimates done by Whalen and Reeburgh (1988, 1992) were based on observations from a one year period, while the other studies used averaged fluxes from summer seasons. It should be noted that estimated values generally center between the estimates ranges between 20 and 40 [Tg CH₄ yr⁻¹].

There were few previous measurements of methane flux, in Siberia, Russia, in contrast to North America. Since the wetlands in permafrost area are widely distributed in Siberia, it is necessary to evaluate the methane emission from the wetlands in Siberian permafrost area in order to understand the contribution of the high-latitude wetlands to global methane budget.

The objective of this study is to provide a more accurate estimate in the methane emission from wetlands in Siberian permafrost area, considering the seasonal and spatial variabilities of the methane flux. On the basis of the data acquired from the field observations in the methane flux and other environmental factors in a Siberian permafrost area in 1992 and 1993 as a part of the Joint Siberian Permafrost Studies between Japan and Russia, the daily methane flux is expressed as a function of environmental factors. Using this function, the annual methane flux and emission from Siberian tundra wetlands are estimated taking

seasonal and spatial variations of the environmental factors into consideration. An increase of the annual methane flux from the tundra wetland caused by a possible future climatic warming is also estimated using the function and the future change of the environmental factors.

Concentrations of methane in the past (Figure 2-1) could be obtained from Antarctic and Greenland ice cores (Maynaud et al., 1988; Stauffer et al., 1988; Chappellaz et al., 1990, 1993a). The methane concentration during the last glacial period (about 20,000 and 150,000 years BP) was about 0.33 ppmv (parts per million by volume) in minimum and increased rapidly to about 0.65 ppmv during the transition from the glacial to the interglacial period (about 15,000 and 100,000 years BP).

Ice core data (Figure 2-1) indicate that the atmospheric concentration of methane increased from about 0.7 ppmv between two hundred and two thousand years ago, and increased to 0.9 ppmv one hundred years ago (Craig and Chou, 1982; Rasmussen and Khalil, 1984; Penman et al., 1986). Since that time, the atmospheric concentration of methane has increased gradually to present level.

Atmospheric concentrations of methane have been monitored directly since 1972 when the globally averaged value was 1.51 ppmv (Rasmussen and Khalil, 1981; Steele et al., 1982). Present atmospheric concentration of methane is 1.72 ppmv corresponding to an atmospheric reservoir of about 900 Tg CH_4 ($1 \text{ Tg} = 10^{12} \text{ g}$) and it tends to increase at a rate of 0.5 to 1.3 % per year (Steele and Maynaud, 1984; Steele et al., 1987). Recently, it was reported that there has been a substantial slowing of the global accumulation rate between 1983 and 1990, although the cause has not been understood yet (Steele et al., 1992).

The annual variation of methane concentration shows a significant seasonality, which is characterized by increasing in winter and decreasing in summer (Steele

2. Global methane budget

2-1. Atmospheric methane concentration

The atmospheric concentrations of methane in the past (Figure 2-1) could be obtained from Antarctic and Greenland ice cores (Raynaud et al., 1988; Stauffer et al., 1988; Chappellaz et al., 1990, 1993a). The methane concentration during the last glacial periods (about 20,000 and 150,000 years BP) was about 0.35 ppmv (parts per million by volume) in minimum, and increased rapidly to about 0.65 ppmv during the transitions from the glacial to the interglacial period (about 15,000 and 130,000 years BP).

Ice core data (Figure 2-2) indicate that the atmospheric concentration of methane averaged about 0.7 ppmv between two hundred and two thousand years ago, and increased to 0.9 ppmv one hundred years ago (Craig and Chou, 1982; Rasmussen and Khalil, 1984; Pearman et al., 1986). Since that time, the atmospheric concentration of methane has increased gradually to present level.

Atmospheric concentrations of methane have been monitored directly since 1978 when the globally averaged value was 1.51 ppmv (Rasmussen and Khalil, 1981; Blake and Rowland, 1988). Present atmospheric concentration of methane is 1.72 ppmv, corresponding to an atmospheric reservoir of about 4900 Tg (1 Tg = 10^{12} g), and it trends to increase at a rate of 0.8 to 1.0 % per year (Blake and Rowland, 1988; Steele et al., 1987). Recently, it was reported that there has been a substantial slowing of the global accumulation rate between 1983 and 1990, although the cause has not been understood yet (Steele et al., 1992).

The annual variation of methane concentration shows a significant seasonality, which is characterized by increasing in winter and decreasing in summer (Steele

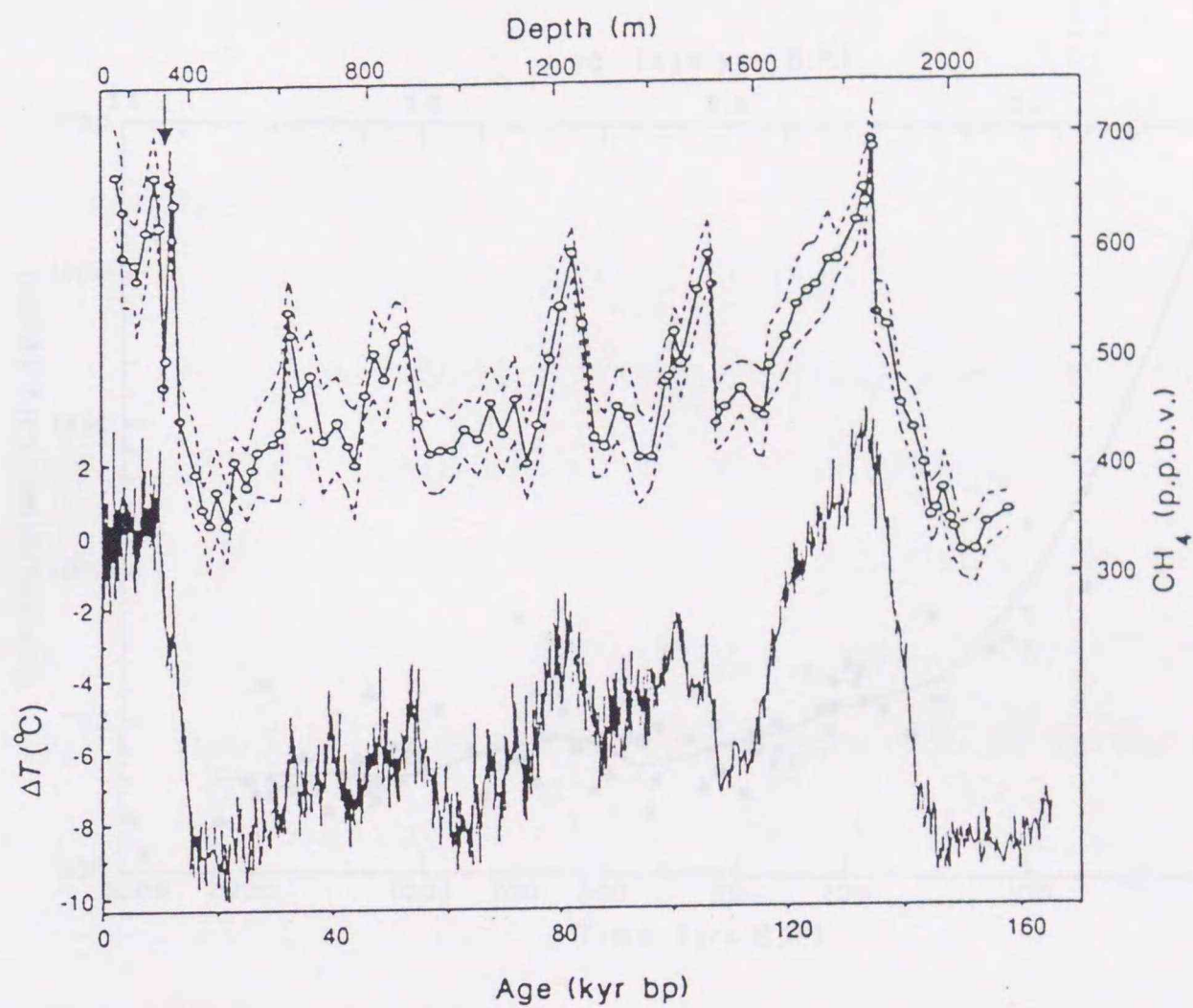


Figure 2-1. Vostok ice-core records. Upper curve: CH_4 record. Circles indicate mean values. Lower curve: isotope surface temperature record as a difference from the annual mean temperature value at present (-55.5°C). (Chappellaz et al., 1990).

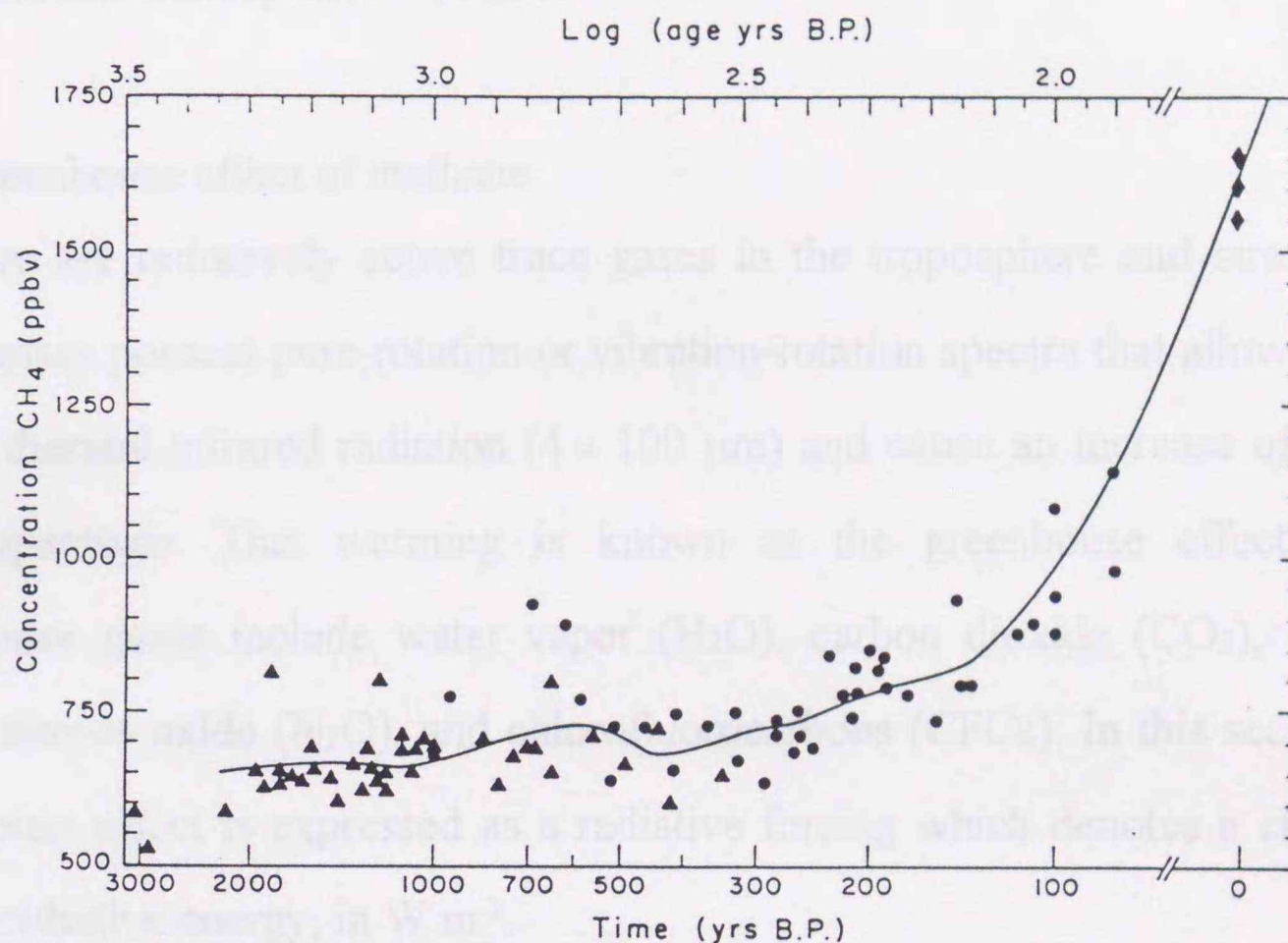


Figure 2-2. Concentrations of methane in the old and ancient atmospheres (100 - 3000 years BP). The circles are data from polar ice cores obtained from Greenland (near the north pole), and the triangles are data from ice cores in the south pole. The present concentration of methane is shown on the right (diamonds). The solid line is the smoothed average concentration based on the data. (Rasmussen and Khalil, 1984).

et al., 1992). The methane concentration also shows a difference between the Northern and Southern Hemispheres by about 0.1 ppmv. The magnitude of the seasonal fluctuation varies with latitudes, being controlled by the spatial variability of source strengths and atmospheric concentration of OH radicals, which oxidize atmospheric methane.

2-2. Greenhouse effect of methane

There are radiatively active trace gases in the troposphere and stratosphere. These gases possess pure-rotation or vibration-rotation spectra that allow them to absorb thermal infrared radiation (4 - 100 μm) and cause an increase of surface air temperature. This warming is known as the greenhouse effect. These greenhouse gases include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). In this section, the greenhouse effect is expressed as a radiative forcing which denotes a change in flux of radiative energy, in W m^{-2} .

The ability of radiative forcing of a greenhouse gas depends on the distribution of the spectral absorption bands with wavelength, the spectroscopic strengths of the bands, and the atmospheric concentration of the gas. Methane has a strong absorption band centered at about 7.7 μm of wavelength. This wavelength is in the window (transparent region) of the atmosphere, although it overlap with the absorption band of N_2O . The concentration of methane rose from 0.7 ppmv at the time of pre-Industrial Revolution to 1.7 ppmv in 1989. Thus, the significant absorption by methane is already occurring and its radiative forcing is approximately proportional to the square root of its concentration (Shine et al., 1990).

In addition to the direct radiative effects, many of the greenhouse gases also have indirect radiative effects on climate through their interactions with atmospheric chemical processes. Methane has the following indirect effects. One is oxidation of methane to CO, and further to CO₂. Cicerone and Oremland (1988) calculated that the concentration of atmospheric CO₂ produced by the oxidation of methane must be about 6 % as much as the direct release of CO₂ from anthropogenic sources. Other effects are the chemical productions of tropospheric ozone (O₃) and stratospheric water vapor (H₂O), which are also important greenhouse gases (Chappellaz et al., 1990). These reactions depend on the atmospheric nitrogen oxide (NO_x) concentration (Levine et al., 1985; Thompson and Cicerone, 1986). In high NO_x environments (> 10 pptv; parts per 10¹² by volume), as in present polluted tropospheric air, the increase of methane must lead to the high production of tropospheric O₃.

The change of radiative forcing for a particular gas can be expressed empirically in terms of its concentration change:

$$\Delta F = f(C_0, C) \quad (2-1)$$

Where ΔF is the change in net radiative flux (W m⁻²) corresponding to a volumetric concentrations change from C₀ to C (ΔC). The expressions for some gases are given in Table 2-1. The ΔF for methane is determined by the concentrations of methane and N₂O, whose absorption bands overlap. Direct radiative forcing changes for the different greenhouse gases can be easily compared using the ΔF - ΔC relationships (Table 2-2). The ΔF for methane per molecule is 21 times larger than that for CO₂.

Table 2-1. Expressions of the changes of radiative forcing corresponding to the concentration changes of some greenhouse gases. (Shine et al., 1990).

TRACE GAS	RADIATIVE FORCING APPROXIMATION GIVING ΔF IN Wm^{-2}	COMMENTS
Carbon dioxide	$\Delta F = 6.3 \ln (C/C_0)$ where C is CO_2 in ppmv for C < 1000 ppmv	Functional form from Wigley (1987); coefficient derived from Hansen et al. (1988).
Methane	$\Delta F = 0.036 (\sqrt{M} - \sqrt{M_0}) -$ $(f(M, N_0) - f(M_0, N_0))$ where M is CH_4 in ppbv and N is N_2O in ppbv. Valid for M < 5ppmv.	Functional form from Wigley (1987); coefficient derived from Hansen et al. (1988). Overlap term, f(M, N) from Hansen et al (1988)*
Nitrous Oxide	$\Delta F = 0.14 (\sqrt{N} - \sqrt{N_0}) -$ $(f(M_0, N) - f(M_0, N_0))$ with M and N as above. Valid for N < 5ppmv.	Functional form from Wigley (1987); coefficient derived from Hansen et al.(1988). Overlap term from Hansen et al. (1988)*
CFC-11	$\Delta F = 0.22 (X - X_0)$ where X is CFC-11 in ppbv Valid for X < 2ppbv.	Based on Hansen et al. (1988)
CFC-12	$\Delta F = 0.28 (Y - Y_0)$ where Y is CFC-12 in ppbv Valid for Y < 2ppbv.	Based on Hansen et al. (1988)
Stratospheric water vapour	$\Delta F = 0.011 (\sqrt{M} - \sqrt{M_0})$ where M is CH_4 in ppbv	Stratospheric water vapour forcing taken to be 0.3 of methane forcing without overlap based on Wuebbles et al. (1989)
Tropospheric ozone	$\Delta F = 0.02 (O - O_0)$ where O is ozone in ppbv	Very tentative illustrative parameterization based on value from Hansen et al. (1988).
Other CFCs, HCFCs and HFCs	$\Delta F = A (Z - Z_0)$ where A based on forcing relative to CFC-11 in Table 2.4 and Z is constituent in ppbv	Coefficients A derived from Fisher et al. (1990)

* Methane-Nitrous Oxide overlap term

$f(M, N) = 0.47 \ln [1 + 2.01 \times 10^{-5} (MN)^{0.75} + 5.31 \times 10^{-15} M (MN)^{1.52}]$; M and N are in ppbv.

Note typographical error on page 9360 of Hansen et al. (1988): 0.014 should be 0.14.

Table 2-2. Radiative forcing relative to CO₂ per unit molecule change, and per unit mass change in the atmosphere for present day concentration. (Shine et al., 1990).

TRACE GAS	ΔF for ΔC per molecule relative to CO ₂	ΔF for ΔC per unit mass relative to CO ₂
CO ₂	1	1
CH ₄	21	58
N ₂ O	206	206
CFC-11	12400	3970
CFC-12	15800	5750
CFC-113	15800	3710
CFC-114	18300	4710
CFC-115	14500	4130
HCFC-22	10700	5440
CCl ₄	5720	1640
CH ₃ CCl ₃	2730	900
CF ₃ Br	16000	4730
Possible CFC substitutes:		
HCFC-123	9940	2860
HCFC-124	10800	3480
HFC-125	13400	4920
HFC-134a	9570	4130
HCFC-141b	7710	2900
HCFC-142b	10200	4470
HFC-143a	7830	4100
HFC-152a	6590	4390

Based on the expressions given in Table 2-1 the radiative forcing between 1765 and 1990 is calculated using observed variations of the greenhouse gases. The change in total forcing from 1765 concentrations is shown in Figure 2-3. For the period 1765 to 1990, CO₂ has contributed about 61 % of the forcing, methane 17 % plus 6 % from stratospheric water vapor, N₂O 4 % and CFCs 12 %. For the decade 1980 - 1990, about 56 % of the forcing has been due to CO₂, 11 % due to the direct effects of methane and 4 % via stratospheric water vapor, 6 % from N₂O and 24 % from the CFCs.

2-3. Methane budget

2-3-1. Sources

Annual methane releases from identified sources are summarized in Table 2-3 (Tyler, 1991). Sources of methane are categorized into two groups based on the rate of radioactive carbon-14 in methane. Methane in one group consists of the carbon-14 whose concentration is same as that of present atmospheric methane, since the methane in this group is produced under anaerobic environments in wetlands and digestive organ of any ruminant inhabitants. However, methane in the other group originates from fossil fuel, methane hydrate and volcanoes. This group has a low carbon-14 rate.

Indicated in Table 2-3, the total amount of methane emission differs from 355 to 870 Tg CH₄ within a year, because of the difficulty in extrapolating each of several individual source measurements to a global budget. The degree of uncertainty in the sources is especially large in natural sources, for example, natural wetlands, rice paddies, and termites.

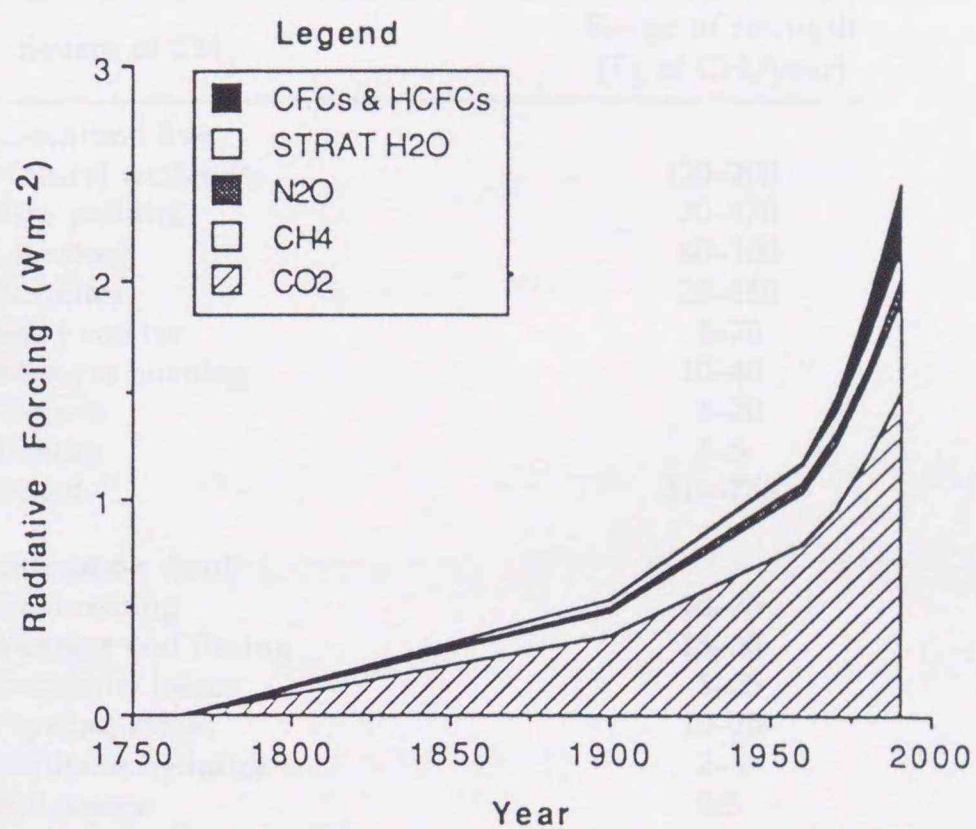


Figure 2-3. Changes in radiative forcing (Wm^{-2}) due to increases in greenhouse gas concentrations between 1765 and 1990. Values are changes in forcing from 1765 concentrations. (Shine et al., 1990).

Table 2-3. Potential annual methane release for identified sources.
(Tyler, 1991).

Source of CH ₄	Range of strength (Tg of CH ₄ /year)
Radiocarbon live	
Natural wetlands	120-200
Rice paddies	70-170
Livestock	80-100
Termites	25-150
Solid wastes	5-70
Biomass burning	10-40
Oceans	1-20
Tundra	1-5
Subtotal	312-755
Radiocarbon dead	
Coal mining	10-35
Venting and flaring	15-30
Industrial losses	5-25
Pipeline losses	10-20
Methane hydrates	2-4
Volcanoes	0.5
Automobiles	0.5
Subtotal	43-115
Total	355-870

2-3-2. Sinks

The major sink for atmospheric methane is a reaction with OH radical in the troposphere. The OH concentration is controlled by a complex set of reactions involving CH₄, CO, NMHC (non-methane hydrocarbon), NO_x, and tropospheric O₃ (Sze, 1977).

On the basis of the rate coefficient of the reaction between CH₄ and OH and the estimated tropospheric distribution of OH. The atmospheric lifetime of CH₄ has been estimated as 8 to 11.8 years (Prinn et al., 1987). The reaction between CH₄ and OH currently produces a sink of methane with the total amounts of 400 to 600 Tg of CH₄ per year. However, the amount may have decreased during the last century because the atmospheric concentration of OH in the troposphere may have decreased. Therefore, the life time of CH₄ would have increased in accordance to increasing concentrations of CO, NMHC, and CH₄ (Sze, 1977).

Soil may also absorb methane and the amount of this sink is estimated as 30 ± 15 Tg CH₄ per year by Harriss et al. (1982).

2-4. Methane emission from wetlands

2-4-1. Methanogenic bacteria

Methanogens (Methanogenic bacteria) are strict anaerobic bacteria which obligatorily produce methane as an end product of energy metabolism. Methanogens belong to the archaeobacteria that are distinguished from eucaryotes (animals, plants, fungi, and protozoa) and eubacteria. Up to date, more than 50 distinct species of methane producing bacteria have been isolated from diverse anaerobic habitat (Jones, 1991).

Methanogens produce methane using low molecular compounds that are

decomposed from complicated organic matter by other bacteria. Methanogenic substrates are H_2+CO_2 , acetate, formate, methanol, and methylamine (Table 2-4). The most common process of methane production is via the H_2 -mediated reduction of CO_2 and transmethylation reaction of acetate.

Numerous physical, chemical, and biological conditions will affect the physiology of methanogens and the ecology of anaerobic ecosystems. Hence, the rate of methane production by a given habitat will be reflective of certain factors. These factors are described in the following section.

2-4-2. Controlling factors affecting microbial production of methane

Temperature

It has been revealed from laboratory studies that the production of methane by methanogenic bacteria, same as other catalysts of chemical reactions, responds sensitively to temperature increases (Koyama, 1963; Zeikus and Winfrey, 1976; Baker-Blocker et al., 1977; Svensson, 1984). Zeikus and Winfrey (1976) investigated the methanogenesis in lake sediments. They sampled the sediments at three difference depths and incubated the samples at the temperature range from 4 to 55 °C. In all cases, the optima were observed between 35 and 40 °C. Svensson (1984) showed that methane was produced from just above 0 °C up to about 37 °C and that the two different populations of methanogens with different temperature optima were observed. The optimum temperature of one population was about 20 °C (Figure 2-4) and the other was between 24 and 28 °C.

Using data recorded by Koyama (1963) on the production of methane from 100 g of paddy soil incubated at temperatures between 5 and 40 °C, Baker-Blocker et al. (1977) generated the following equation using a least-squares

Table 2-4. Substrates and energetics of methane production. (Jones, 1991).

Reactions		$\Delta G_0'$ (kJ/mol of methane) ^a
Hydrogenotrophic reactions		
4 H ₂ + CO ₂ →	CH ₄ + 2H ₂ O	- 135.6
4 Formate →	CH ₄ + 3CO ₂ + 2H ₂ O	- 130.1
4 (2-propanol) + CO ₂ →	CH ₄ + 4 acetone + 2H ₂ O	- 36.5
Aceticlastic reaction		
Acetate →	CH ₄ + CO ₂	- 31.0
Disproportionation reactions		
4 Methanol →	3CH ₄ + CO ₂ + 2H ₂ O	- 104.9
4 Methylamine + 3H ₂ O →	3CH ₄ + CO ₂ + 4NH ₄ ⁺	- 75.0
2 Dimethyl sulfide + 2H ₂ O →	3CH ₄ + CO ₂ + H ₂ S	- 73.8

^a Data from Thauer et al. (1977).

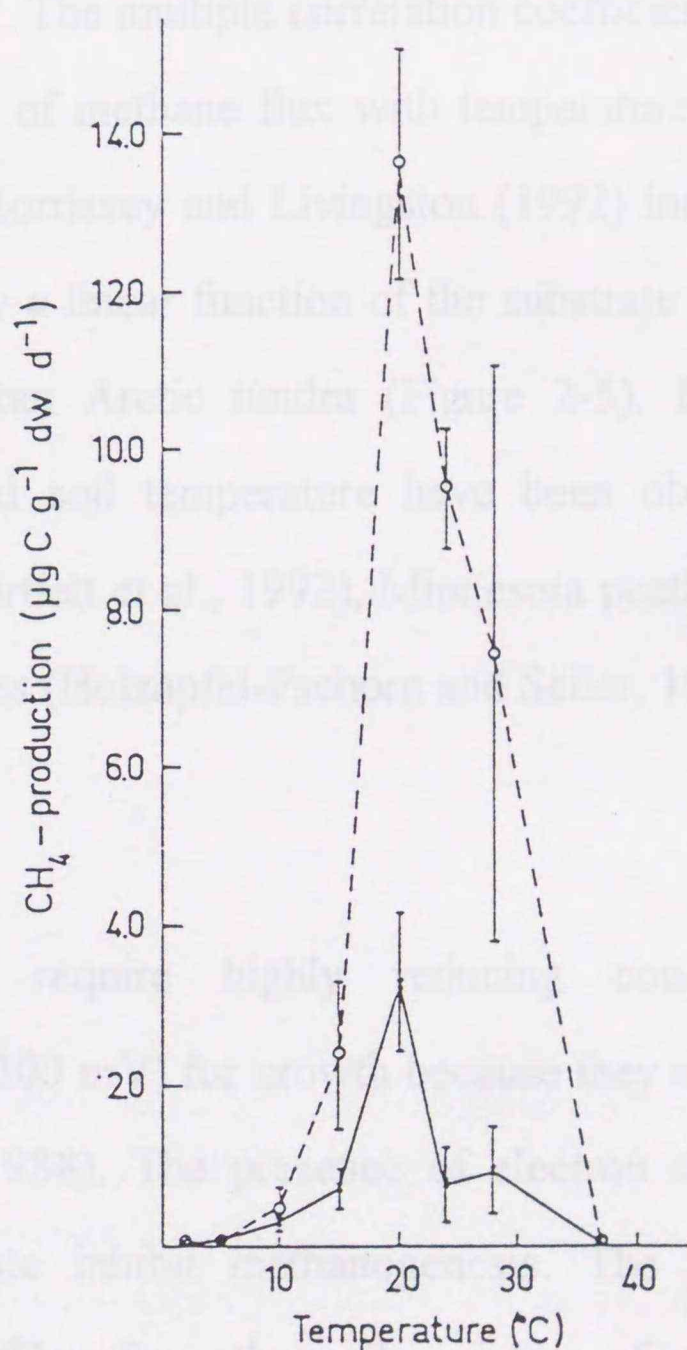


Figure 2-4. Methane formation from acid peat incubated at different temperatures for 1 (—) and 2.5 (---) months. Bars: standard deviation for the means of three replicates. Dw: dry weight. (Svensson, 1984).

multiple regression:

$$flux = 6.3 \times 10^{-5} - 1.9 \times 10^{-4} T + 1.7 \times 10^{-6} T^2 \quad (2-2)$$

Where flux is shown by grams per day and T represents the incubator temperature in °C. The multiple correlation coefficient for dependency is 0.99.

The increases of methane flux with temperature were also observed in field measurements. Morrissey and Livingston (1992) indicated that the methane flux was expressed by a linear function of the substrate temperature at a depth of 10 cm in the Alaskan Arctic tundra (Figure 2-5). Log-linear relations between methane flux and soil temperature have been obtained from Alaskan tundra environments (Bartlett et al., 1992), Minnesota peatlands (Crill et al., 1988a) and Italian rice paddies (Holzapfel-Pschorn and Seiler, 1986).

Soil moisture

Methanogens require highly reducing conditions (oxidation-reduction potential: $E_h \leq -300$ mV) for growth because they are strict anaerobes (Cicerone and Oremland, 1988). The presence of electron acceptors such as O₂, nitrite, nitrate and sulfate inhibit methanogenesis. The methanogens are especially sensitive to O₂. Therefore, the soil moisture of wetlands is a primary factor correlated with methane flux because it controls the isolation from O₂-rich atmosphere. Figure 2-6 illustrates the average fluxes measured along a moisture gradient in Alaska (Crill et al., 1991). The wetter sites show higher methane fluxes. If the water table lies lower than the soil surface, then the methane flux drops to low values.

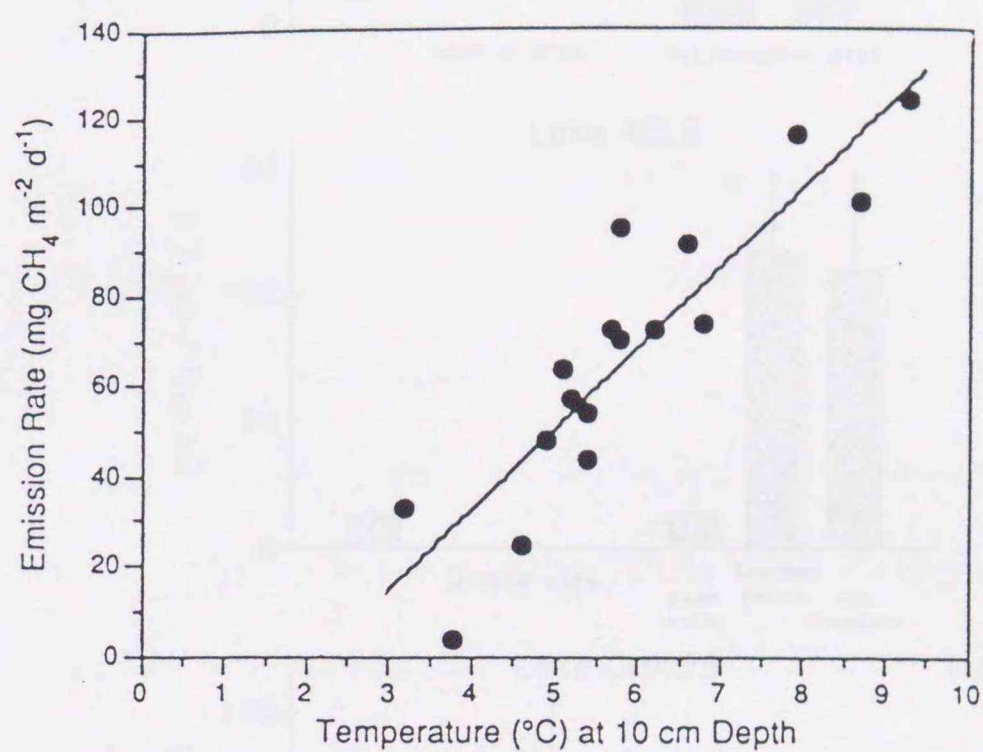


Figure 2-5. Relationships of methane emissions to soil temperatures at 10 cm depth. Solid symbols represent observations from inundated low-centered basins and meadows; the line represents the corresponding least square linear regression predicted values. (Morrissey and Livingston, 1992).

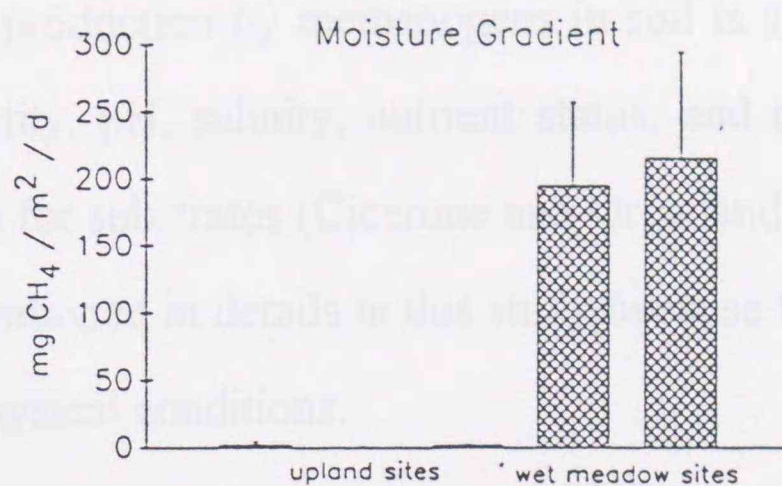
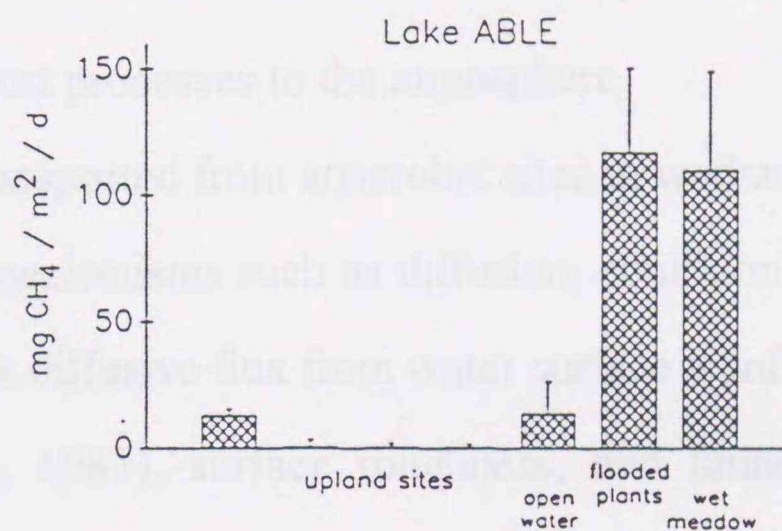
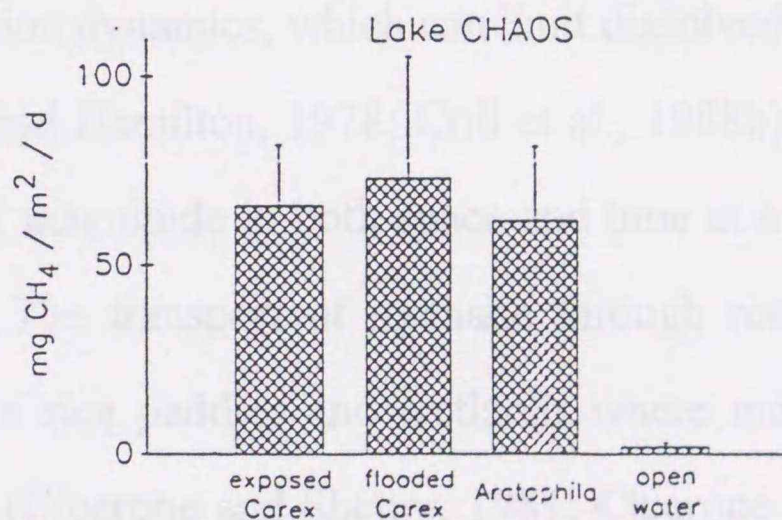


Figure 2-6. Average and standard error of the mean methane flux measured across tundra moisture gradients in the Yukon-Kuskokwim delta, Alaska. The upland sites are dry and the others are either wet, flooded, or open water. (Crill et al., 1991).

Other environmental factors

The methane production by methanogens in soil is also affected by substrate quality and quantity, pH, salinity, nutrient status, and competition with sulfate-reducing bacteria for substrates (Cicerone and Oremland, 1988; Crill et al., 1991). These are not mentioned in details in this study because the present author mainly focuses on the physical conditions.

2-4-3. Transport processes to the atmosphere

Methane is transported from anaerobic sites in wetlands soil to the atmosphere by a number of mechanisms such as diffusion, ebullition, and transport by rooted macrophytes. The diffusive flux from water surface is influenced by wind velocity (Sebacher et al., 1983), surface roughness, and limnological factors such as density stratification dynamics, which can limit dissolved methane transport to the interface (Rudd and Hamilton, 1978; Crill et al., 1988b). The bubble flux should vary by orders of magnitude in both space and time at a single site (Chanton and Martens, 1988). The transport of methane through rooted aquatic plant is the most important in rice paddies and wetlands where macrophytes such as reeds and sedges exist (Cicerone and Shetter, 1981; Cicerone et al., 1983; Sebacher et al., 1985; Holzapfel-Pschorn and Seiler, 1986). Therefore, when the methane flux is discussed, it is important to know the species of dominant vegetation, the number of plants in unit area, and the growth stage of the plants at observational sites.

3. Physical and biological environments of eastern Siberia

3-1. Climate and Permafrost distribution

Figure 3-1 shows a geographical map of Russia, and the shaded portions are highlands or mountains where the altitude is higher than 500 m above sea level. Mean annual air temperature and permafrost distribution are shown in Figure 3-2 (a) (Gavrilova, 1981) and (b) (Pewe, 1983). The air temperature is lower in eastern Siberia than that in western Siberia. The mountains are distributed in east of the Lena river, where it is noted as the coldest regions in the land area of the world, except for the highest point of Antarctica. Permafrost is distributed continuously in eastern Siberia, and the thickness exceeds hundreds of meters. However, in western Siberia, permafrost is distributed discontinuously. Study sites, Tiksi in a tundra and Yakutsk in a taiga, are located in the continuous permafrost area along the Lena river in eastern Siberia (Figure 3-1).

Figure 3-3 shows the mean monthly air temperature and the monthly precipitation at Tiksi (Kunitsky, 1989) and Yakutsk (N.A.O., 1991). The mean annual air temperatures at Tiksi and Yakutsk are -13.4°C and -10.3°C , respectively. The annual range of air temperature at Yakutsk is 60.7°C and is much larger than Tiksi at 40.8°C . The climate in Yakutsk is so-called continental. The monthly mean air temperature in the warmest month is 7.5°C in Tiksi and 18.7°C in Yakutsk. The depth of active layer is 100 cm or deeper in Yakutsk and 50 cm or shallower in Tiksi. The difference of active layer depths is caused by the different summer temperature in Yakutsk from Tiksi. The annual precipitations at Tiksi and Yakutsk, which are 241 mm and 236 mm, respectively, are as low as those in a desert. Because the precipitation is mainly observed in summer, the

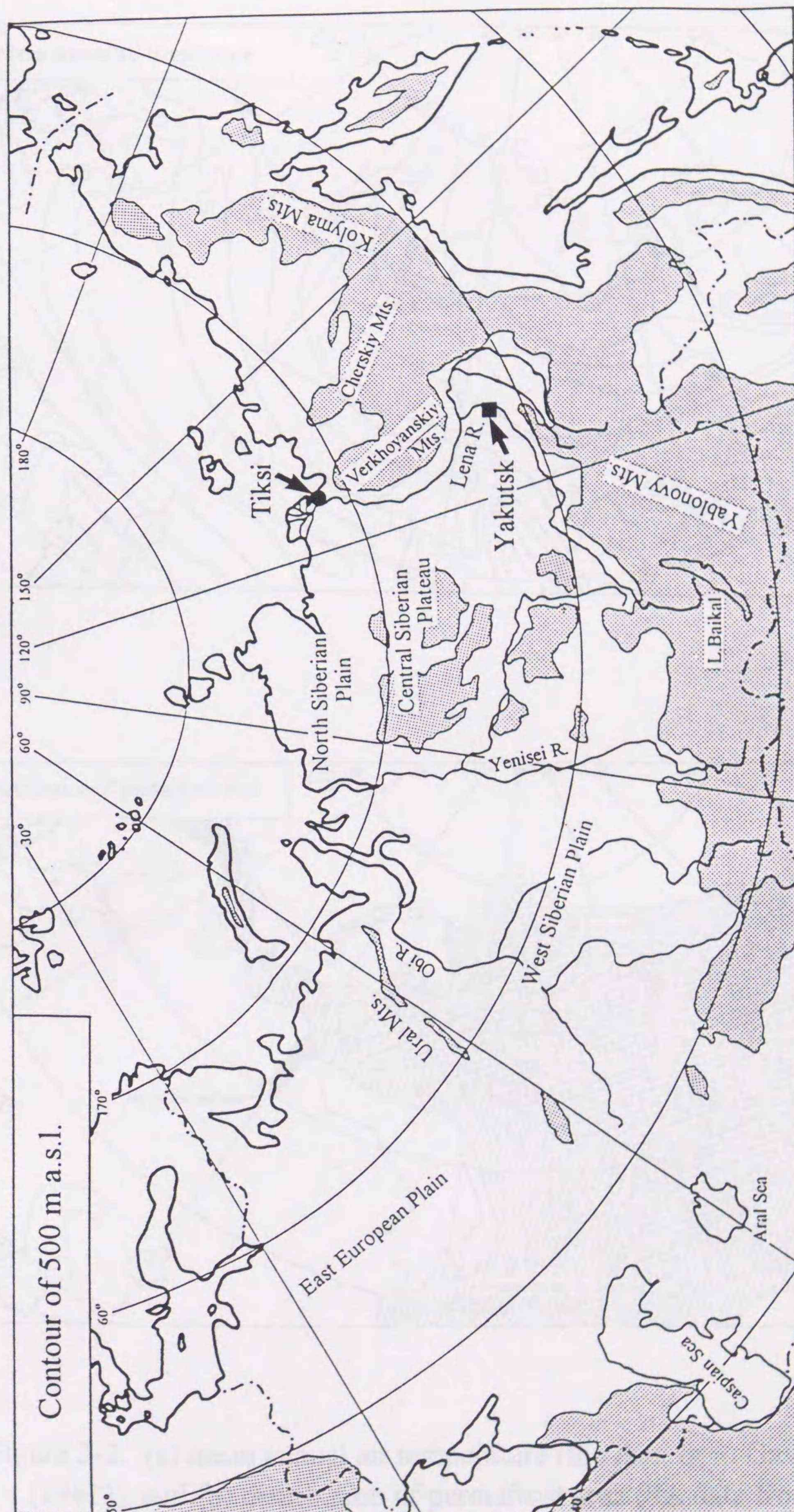


Figure 3-1. Geographical map of Russia. Shaded portions represent the areas where the altitude is higher than 500 m above sea level.

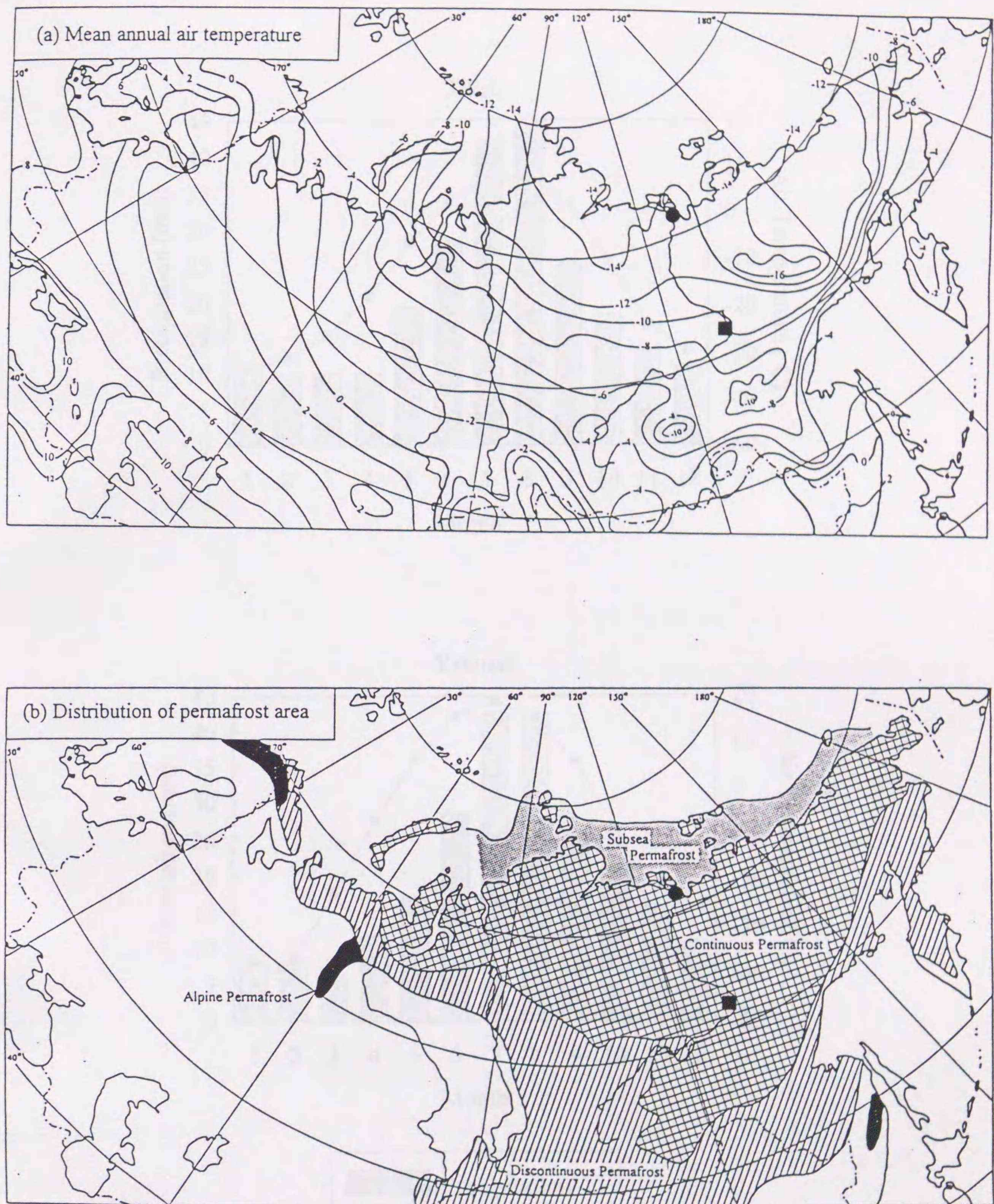


Figure 3-2. (a) mean annual air temperature (the data from Gavrilova (1981)), and (b) distribution of permafrost area (the data from Pewe (1983)), in Siberia. The circle and square indicates the locations of Tiksi and Yakutsk, respectively.

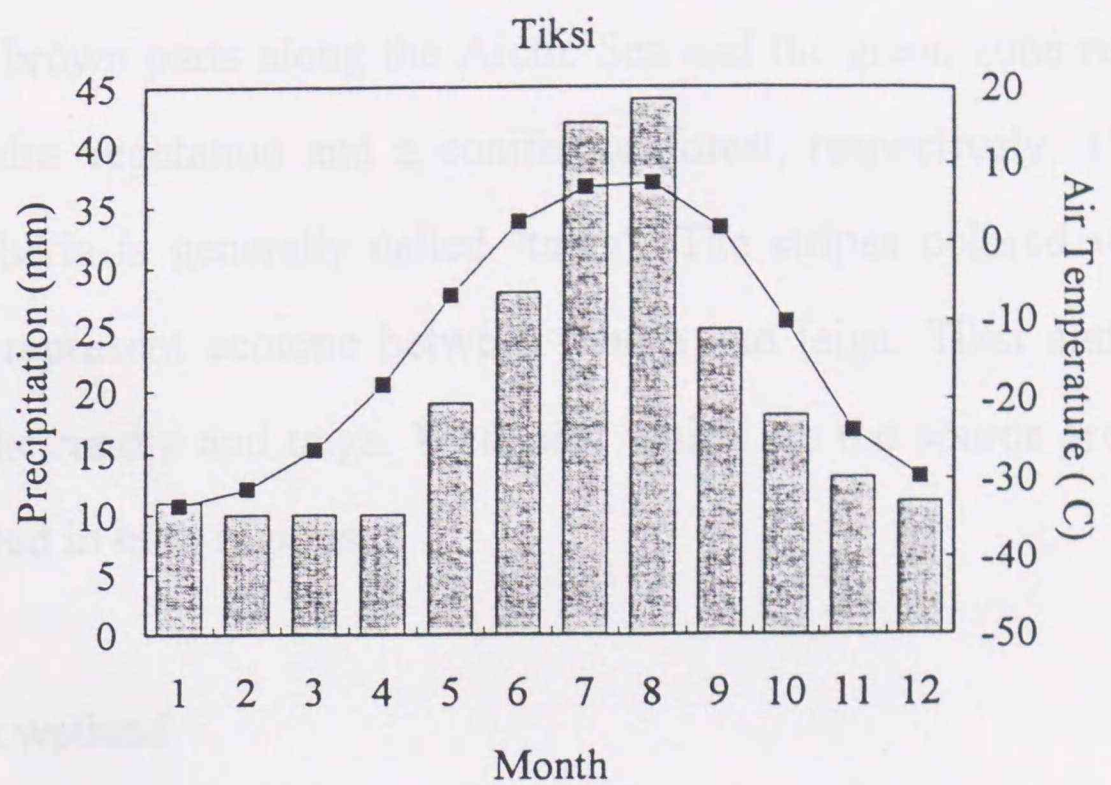
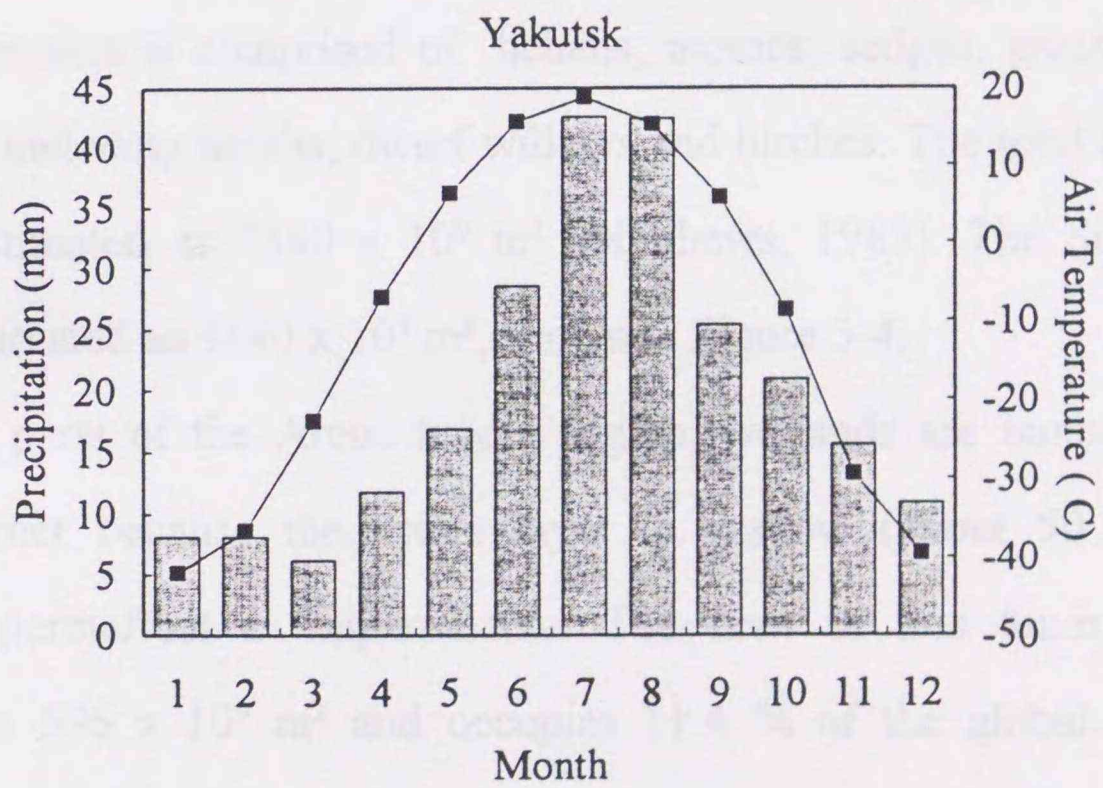
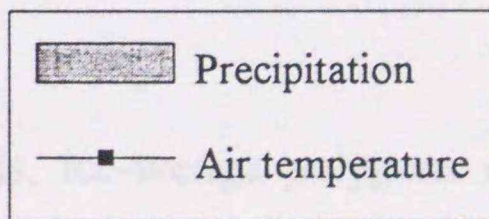


Figure 3-3. Mean monthly air temperature and precipitation at Tiksi and Yakutsk. The data at Tiksi are from Kunitsky (1989); the data at Yakutsk are averaged during 1951-1980, from N.A.O. (1991).

snow accumulation in winter is less than 30 cm at Yakutsk (Gavrilova, 1973).

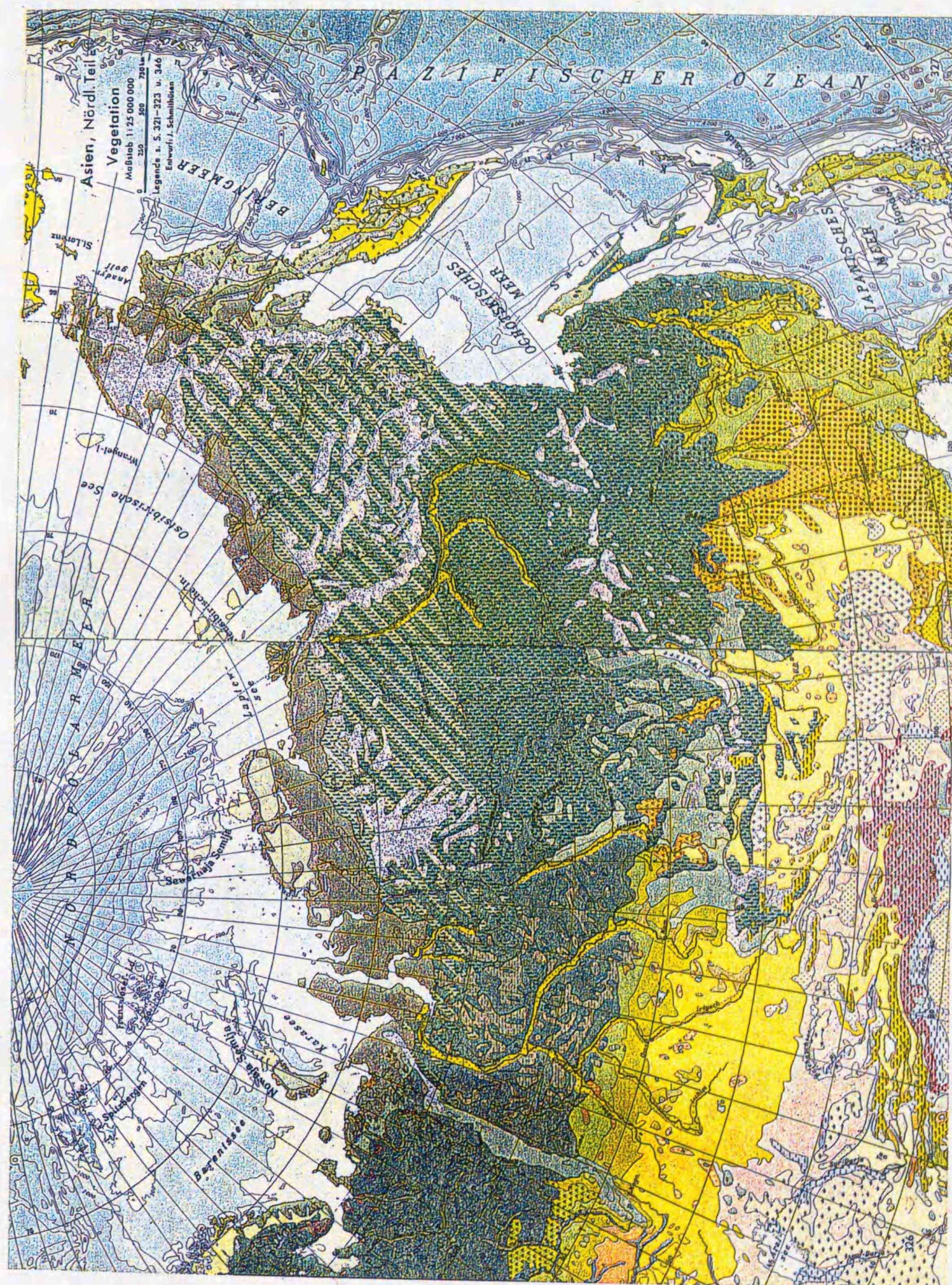
Distribution of vegetation in Siberia is shown in Figure 3-4 (Schmithusen, 1961). The brown parts along the Arctic Sea and the green zone represent some kind of tundra vegetation and a coniferous forest, respectively. The coniferous forest in Siberia is generally called "taiga". The stripes colored with deep and light green represent ecotone between tundra and taiga. Tiksi and Yakutsk are located at the tundra and taiga. Wetlands, which are the source area of methane, are distributed in both regions.

3-2. Tundra wetland

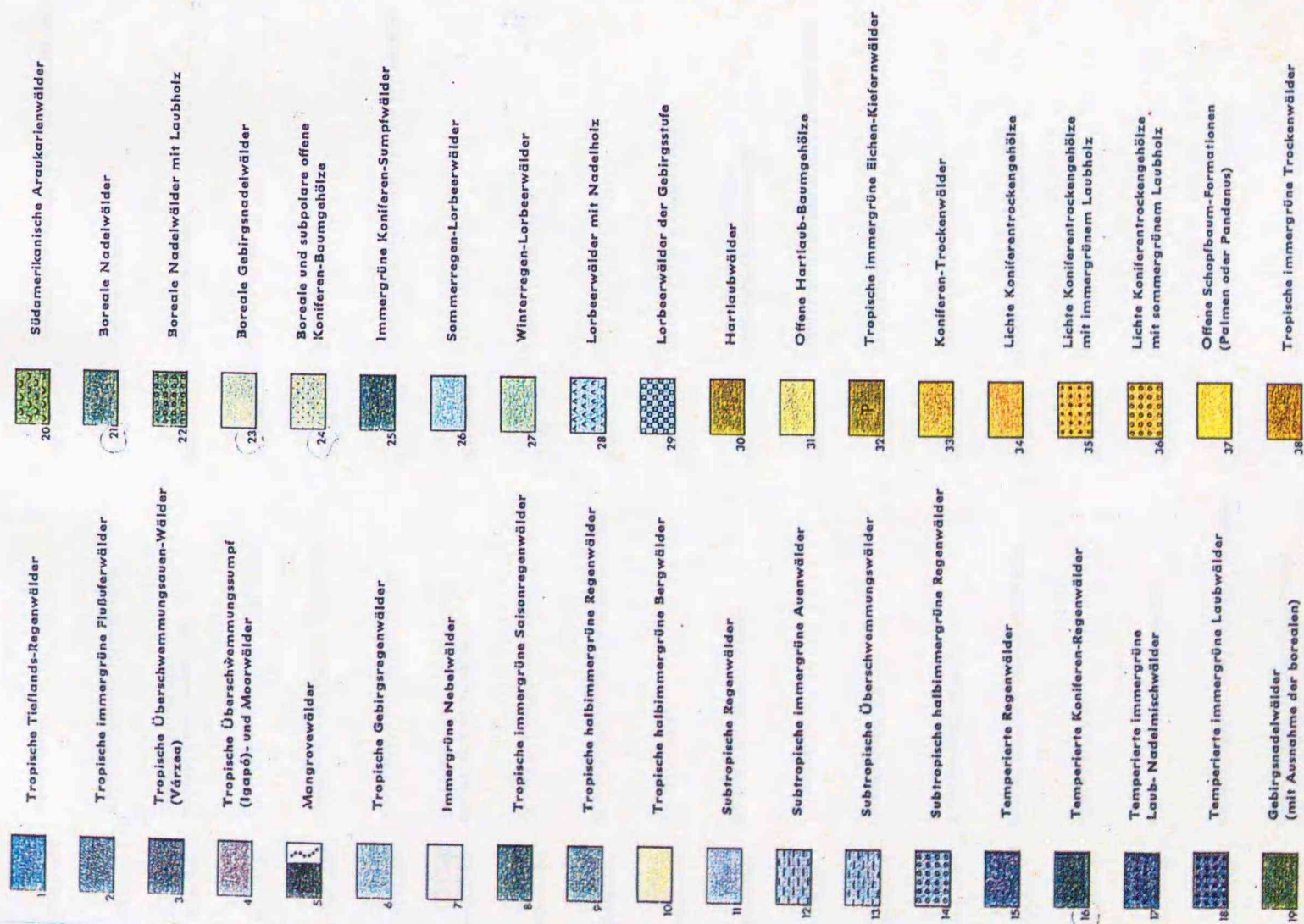
The term "tundra" is defined as treeless terrain, with a continuous cover of vegetation found at both high latitudes and high altitudes (N.R.C.C., 1988). Tundra vegetation is comprised of lichens, mosses, sedges, grasses, forbs and low shrubs, including heaths, dwarf willows and birches. The total area of global tundra is estimated as $7340 \times 10^9 \text{ m}^2$ (Matthews, 1983). The Siberian tundra region is estimated as $1440 \times 10^9 \text{ m}^2$, shown in Figure 3-4.

In some parts of the Arctic tundra region, wetlands are temporally formed during summer because the active layer is shallow (about 50 cm) and the underlying permafrost is impermeable. The area of this tundra wetland is estimated as $596 \times 10^9 \text{ m}^2$ and occupies 11.4 % of the global wetland area (Chappellaz et al., 1993b). The area of Siberian tundra wetland has not been reported exactly.

In most tundra wetlands, ice-wedge polygons develop and characterize the polygonal pattern on the ground surface (Photo 3-1). A schematic profile of an ice-wedge polygon is shown in Figure 3-5. The upheaved part of about 20 to 30

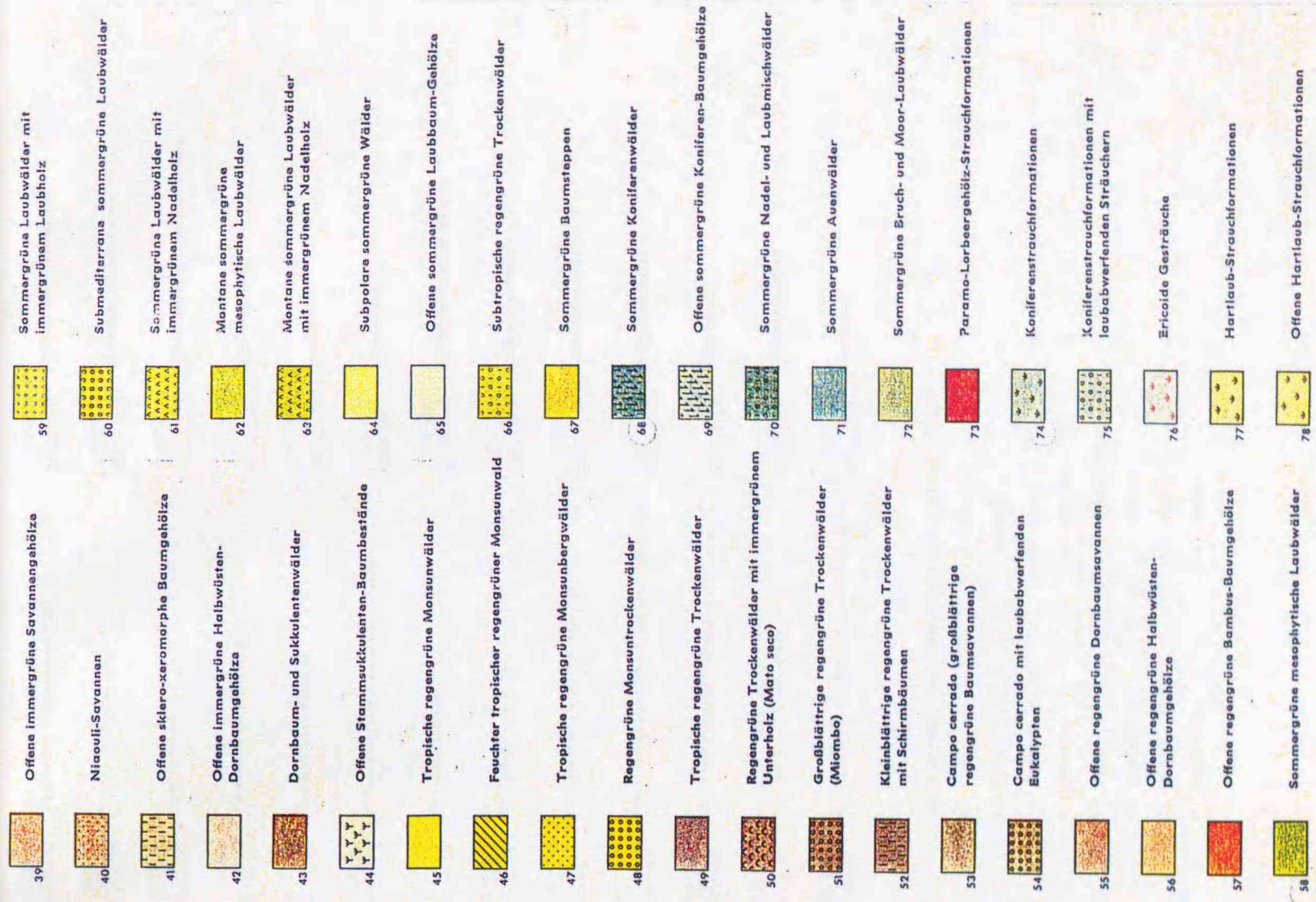


LEGENDE ZU DEN VEGETATIONSKARTEN



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Figure 3-4. Legend of vegetation. (Schmithusen, 1961).



21 LA 8 - F 226

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Figure 3-4. Legend of vegetation. (Schmithusen, 1961).



Photo 3-1. An aerophoto of ice-wedge polygons in tundra wetland.
(Kalakhari Island, taken in July, 1992).

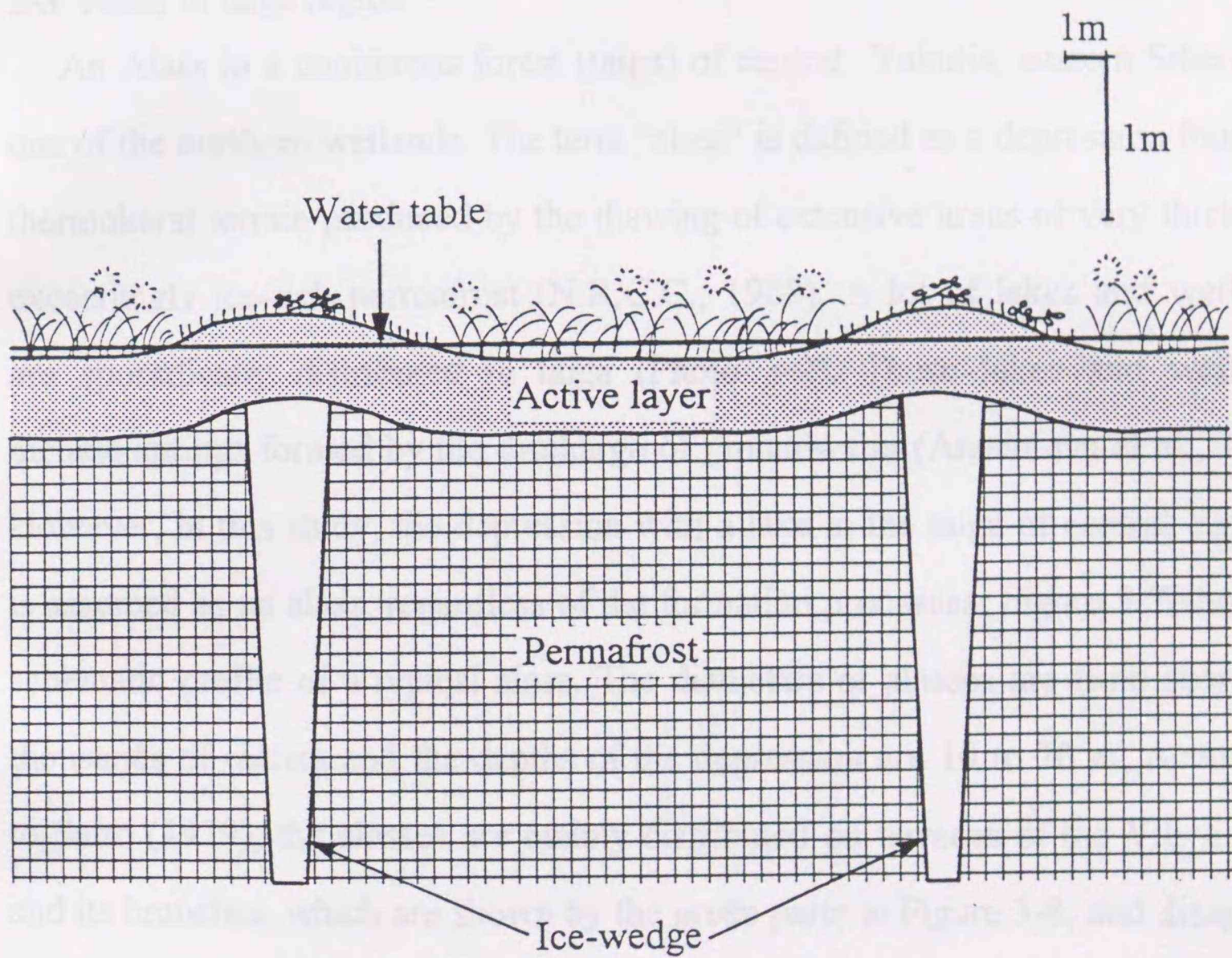


Figure 3-5. Schematic profile of an ice-wedge polygon.

cm, which is underlain by the ice-wedge, is comparatively dry and the upheaved surface is covered with moss and small shrubs. The depressed part is inundated and contains sedge type vegetation. Figure 3-6 shows a pattern of ice-wedge polygons on Kalakhari Island near Tiksi, surveyed in 1992. The length of a side of a polygon is 10 to 20 m. The shaded portions indicate the depressed parts and are about 40 % of the land area in this figure.

3-3. Alass in taiga region

An Alass in a coniferous forest (taiga) of central Yakutia, eastern Siberia, is one of the northern wetlands. The term "alass" is defined as a depression found in thermokarst terrain produced by the thawing of extensive areas of very thick and exceedingly ice-rich permafrost (N.R.C.C., 1988). A lot of lakes and wetlands are sporadically distributed in taiga (Photo 3-2). These lakes and wetlands include springs formed by the discharge of groundwater (Anisimova et al., 1973). However, in this study, the depression with a lake in the taiga of central Yakutia is assumed as an alass, regardless of the formation processes. Figure 3-7 shows a schematic profile of a typical alass. The diameters of alasses are from scores to thousands of meters and the depths of the depression are 10 to 20 m. According to Saito (1979), the alasses are mainly distributed on terraces of the Vilyyi river and its branches, which are shown by the green parts in Figure 3-8, and disappear around the mountainous region in southern Yakutsk. The number of alasses of more than 50 m in diameter around Yakutsk, exactly of lakes not alasses, can be counted using a map of Yakutsk and its environs (1/200,000). There are 1146 alasses in $4.8 \times 10^9 \text{ m}^2$. Table 3-1 shows the distribution of the lake's diameters. This table indicates that the lakes with diameters from 200 to 300 m are the most

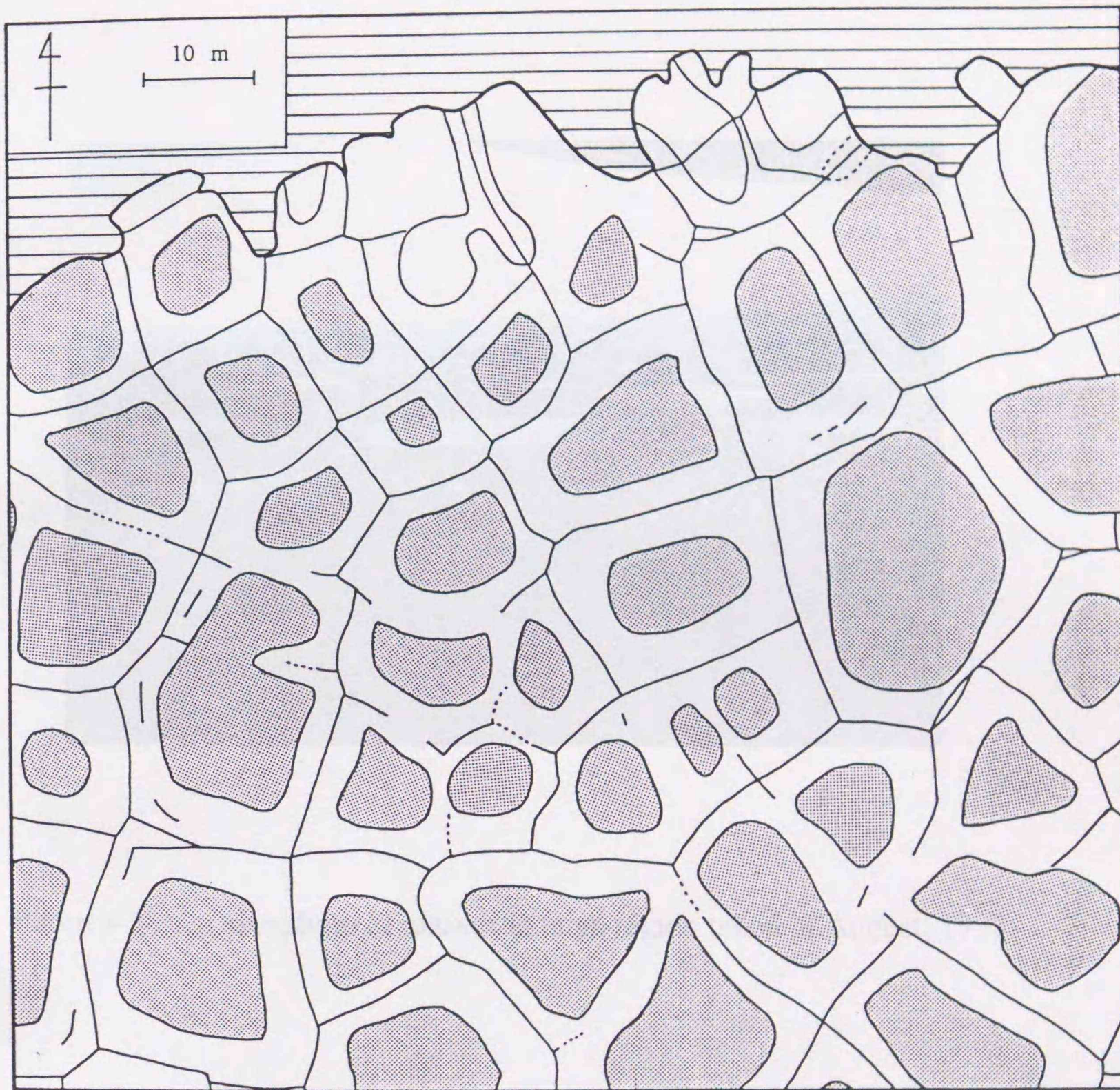


Figure 3-6. Pattern of ice-wedge polygons in Kalakhari Island. Shaded portions represent depressed parts which are inundated or wet and contains sedge type vegetation.



Photo 3-2. An aerophoto of alasses in taiga region taken in August, 1993.

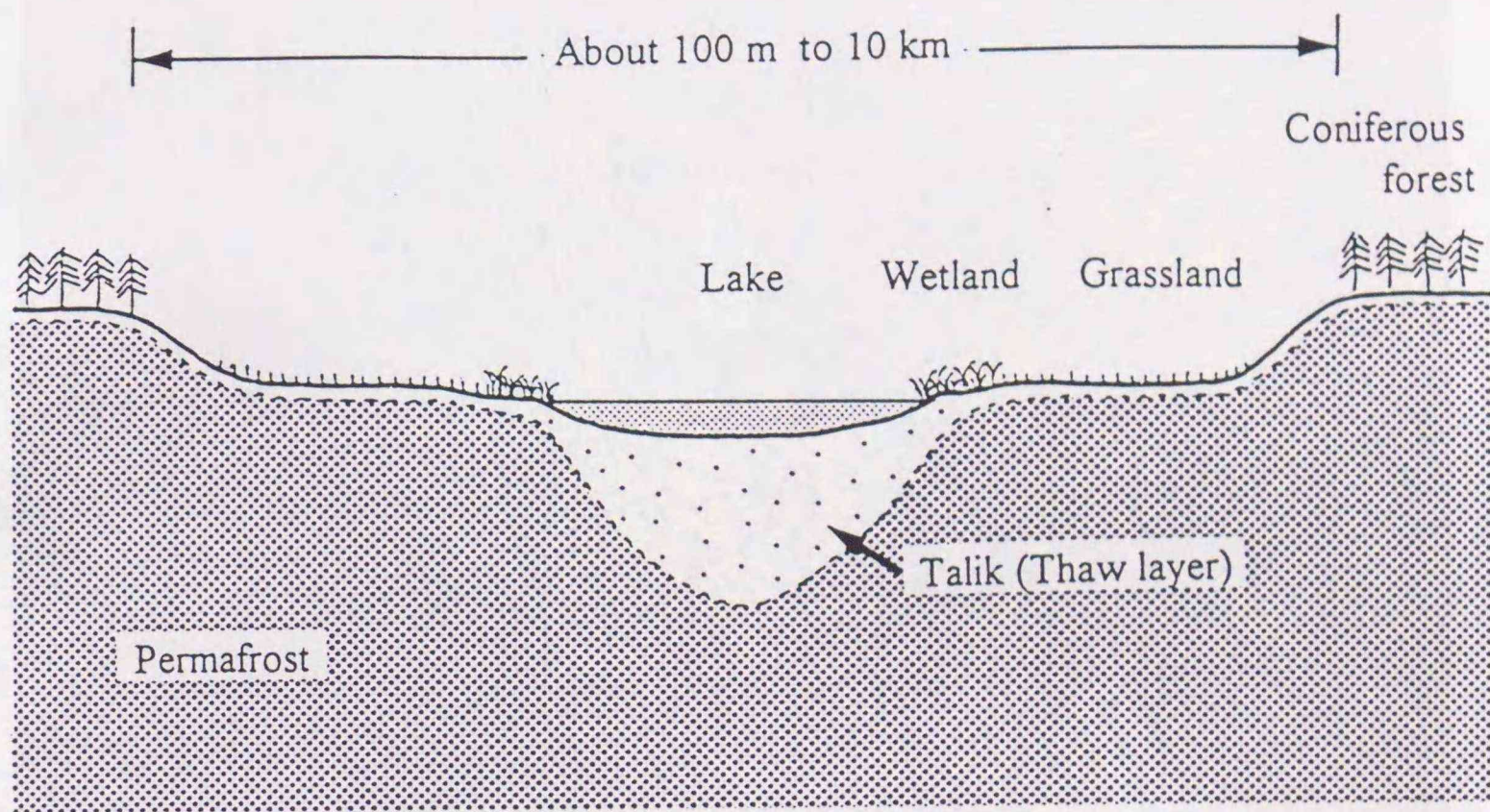


Figure 3-7. Schematic profile of a typical alass. The diameter of the alass is from scores to thousands of meters and the depth of the depression is 10 to 20 m.



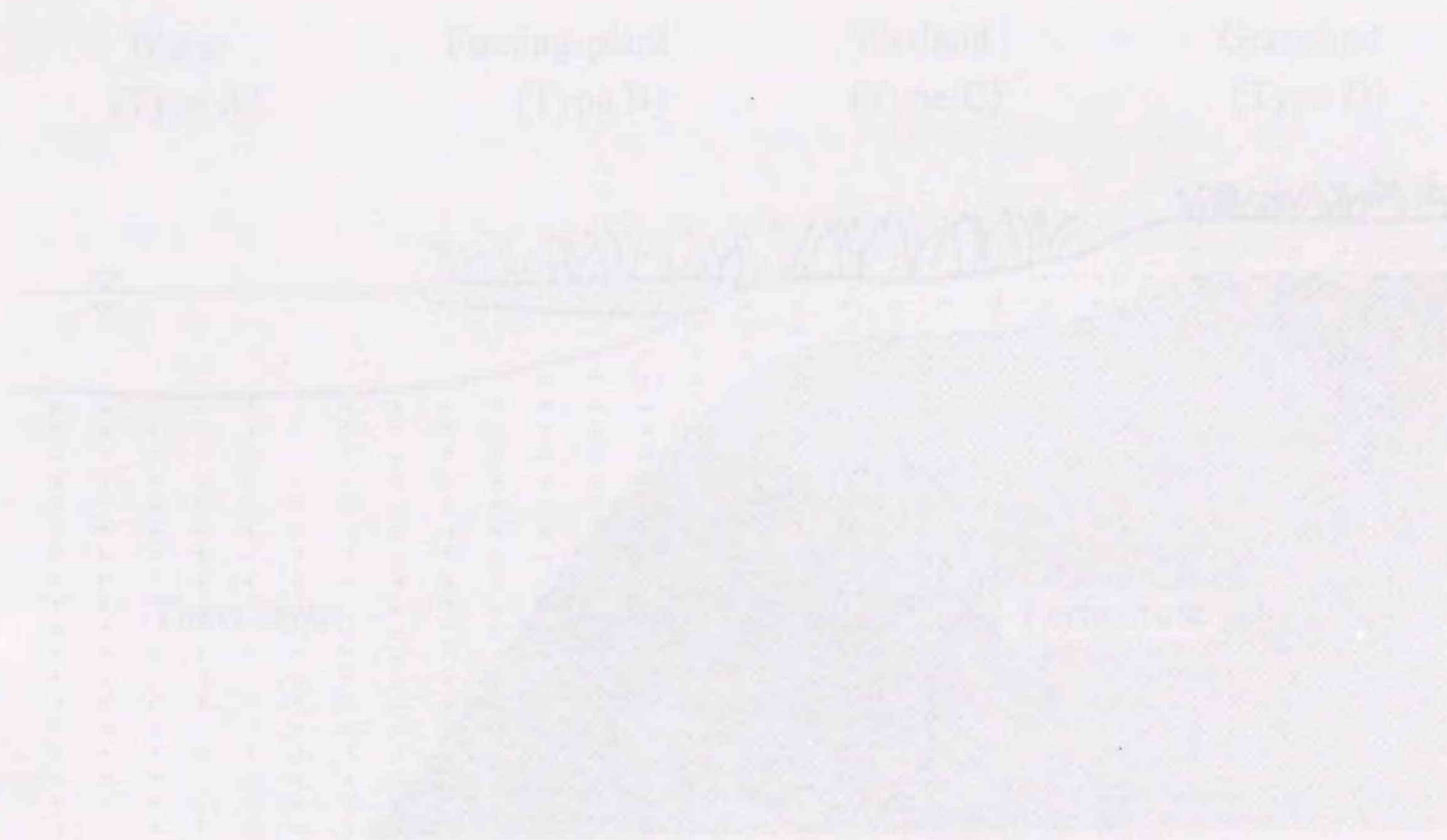
Figure 3-8. Geographical map of central Yakutia. It is a part of the Baikal-Amur railroad map (in Russian).

Table 3-1. Frequency distribution of diameters in lake around Yakutsk.

Rank of diameter	Frequency	Accumulated ratio (%)
0 - 100 m	7	0.61
100 - 200 m	322	28.71
200 - 300 m	479	70.51
300 - 400 m	151	86.68
400 - 500 m	86	91.19
500 - 600 m	40	94.68
600 - 700 m	19	96.34
700 - 800 m	15	97.64
800 - 900 m	6	98.17
900 - 1000 m	4	98.52
1000 m -	17	100.00

frequent and the diameters of 70 % of the 1146 alasses are less than 300 m.

In general, lakes and wetlands in an alass are originated by melt water from an ice-rich permafrost. The mats of floating plant with about 5 m width and 30 cm thickness are observed along the shoreline of some alasses. The environments within an alass can be categorized into four types based on micro relief, vegetation, and soil moisture conditions; A: water area, B: floating-plant area, C: wetland area, and D: grassland area (Figure 3-9). In the C type, the level of water table was at or above the ground surface. On the contrary, the water table was at least 15 cm or more from the surface in the D type.



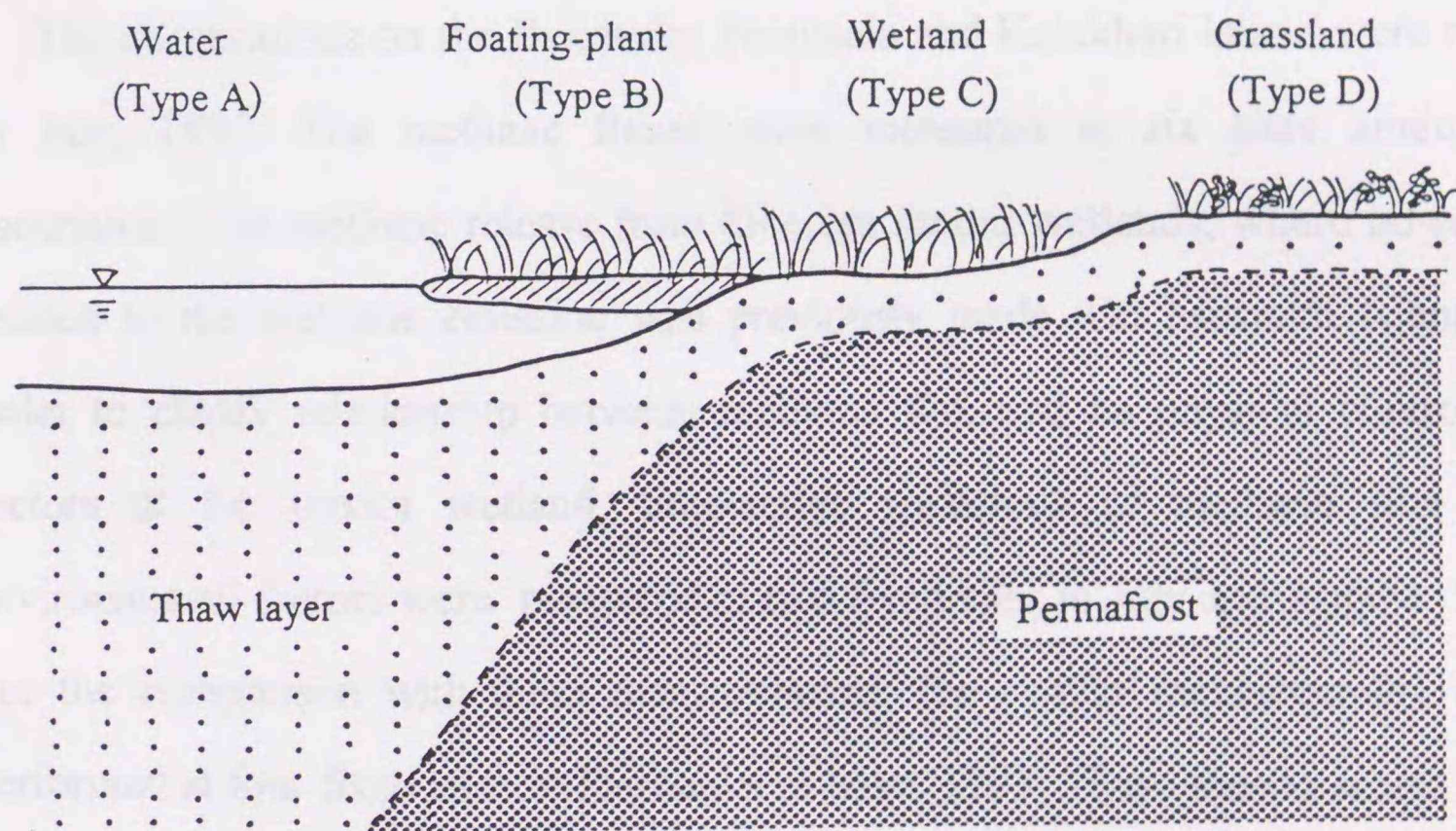


Figure 3-9. Environmental types of a typical alaskan coastal plain. Some alaskan coastal plains don't have floating-plant area (type B).

4. Methane flux measurements in Siberian permafrost area

4-1. Introduction

The methane flux measurements in a Siberian permafrost area were carried out at the tundra wetlands near Tiksi ($71.5^{\circ}\text{N}\sim 72.0^{\circ}\text{N}$), and at the alasses around Yakutsk ($62.0^{\circ}\text{N}\sim 62.1^{\circ}\text{N}$), in Sakha Republic, Russia. Similar observations were also made at a forested bog in Fairbanks, Alaska, USA (64.9°N). Tiksi is located at the mouth of the Lena river and Yakutsk is located in a taiga area around the middle of the Lena river (Figure 3-1). The observational sites are summarized in Table 4-1.

The observations on the Bykovsky Peninsula and Kalakhari Island were made in July, 1992. The methane fluxes were measured at six sites aiming at ascertaining the methane release from Siberian tundra wetlands, where no report related to the methane emission was previously made. On Mustakh Island, in order to clarify relationship between methane flux and its physical controlling factors at the tundra wetland, time-series variations of methane flux and environmental factors were measured at two fixed sites in July and August, 1993. For the comparison with these measurements, the similar measurements were performed at four fixed sites in Fairbanks in May, 1993. These measurement sites are classified into four groups based on levels of water table; (1) waterlogged: water table is above ground surface, (2) wet: between 0 and 3 cm below the surface, (3) moist: between 3 and 10 cm, and (4) dry: 10 cm below. The second letters of the site names (Table 4-1), for example "W" in KW and "D" in MD denote a waterlogged or wet condition and a moist or dry condition, respectively.

The methane flux measurements at alasses in taiga area around Yakutsk were

Table 4-1. List of observational sites in this study.

Tundra wetlands				
Site	Region	Place	Lat. and Long.	Water condition
BW1	Siberian	Bykovsky P.	71.8°N, 129.5°E	Wet
BW2				Wet
BD1				Dry
BD2				Dry
KW	Siberia	Kalakhari Is.	72.0°N, 128.8°E	Wet
KD				Dry
MW	Siberia	Mustakh Is.	71.5°N, 130.0°E	Waterlogged
MD				Dry
FW1	Alaska	Fairbanks	64.9°N, 147.8°W	Waterlogged
FW2				Waterlogged
FD1				Moist
FD2				Moist

Waterlogged: Water table is above surface

Wet: Water table is between 0 and 3 cm below surface

Moist: Water table is between 3 and 10 cm

Dry: Water table is below 10 cm

Alasles in taiga region

Site	Region	Place	Lat. and Long.	Environmental type	Period
KY	Siberia	Yakutsk	62.0°N, 129.4°E	Type A-D	Aug. 3 and Aug. 9, 1993
LC			62.0°N, 129.4°E	Type A and C	Aug. 2, 1993
MG			62.1°N, 129.5°E	Type A-D	Aug. 11, 1993
RS1			62.1°N, 129.3°E	Type A, C and D	Jul. 30 and Aug. 13, 1993
RS2			62.1°N, 129.1°E	Type A, C and D	Aug. 5, 1993
SC			62.0°N, 129.4°E	Type B, C and D	Aug. 6, 1993

made in August, 1993. The methane fluxes from several alasses were measured in summer, 1992 by Ohta et al. (1993). They reported that the flux values were scattered from 0 to 113 [$\text{mg CH}_4 \text{ m}^{-2} \text{ hour}^{-1}$]. There is no previous research on methane emission in this region except their works. In this study, in order to characterize the scattering methane fluxes by environments in an alass, the methane fluxes were measured at several sites categorized as type A, B, C, and D (see Section 3-3).

4-2. Method of field observation

4-2-1. Methane flux measurements

Net methane fluxes were determined by means of chamber technique. Open-bottomed chambers were placed at measurement sites and the methane fluxes were calculated from temporal changes of methane concentration of the enclosed air. This technique is a conventional way to measure the flux of atmospheric trace gas from soil to air.

Aluminum and acrylic resin chambers and stainless collars were adopted in the field observations. A tube for air sampling, thermometer and tedlar-bag for adjusting pressure were installed on the chamber (Figure 4-1). The collars were permanently set into the soil at fixed sites in Mustakh Island and Fairbanks, and the chamber fit into a water-filled channel of the collar. Dimensions of the chambers were 30 x 30 x 60 cm (tundra wetlands and alasses: aluminum), 30 x 30 x 25 cm (tundra wetlands: aluminum) and 49 x 49 x 60 cm (alasses: acrylic resin). The acrylic resin chamber with a float was used for the measurements of methane flux from water surface of a lake. The dimension of this chamber was 57 x 57 x 31 cm.

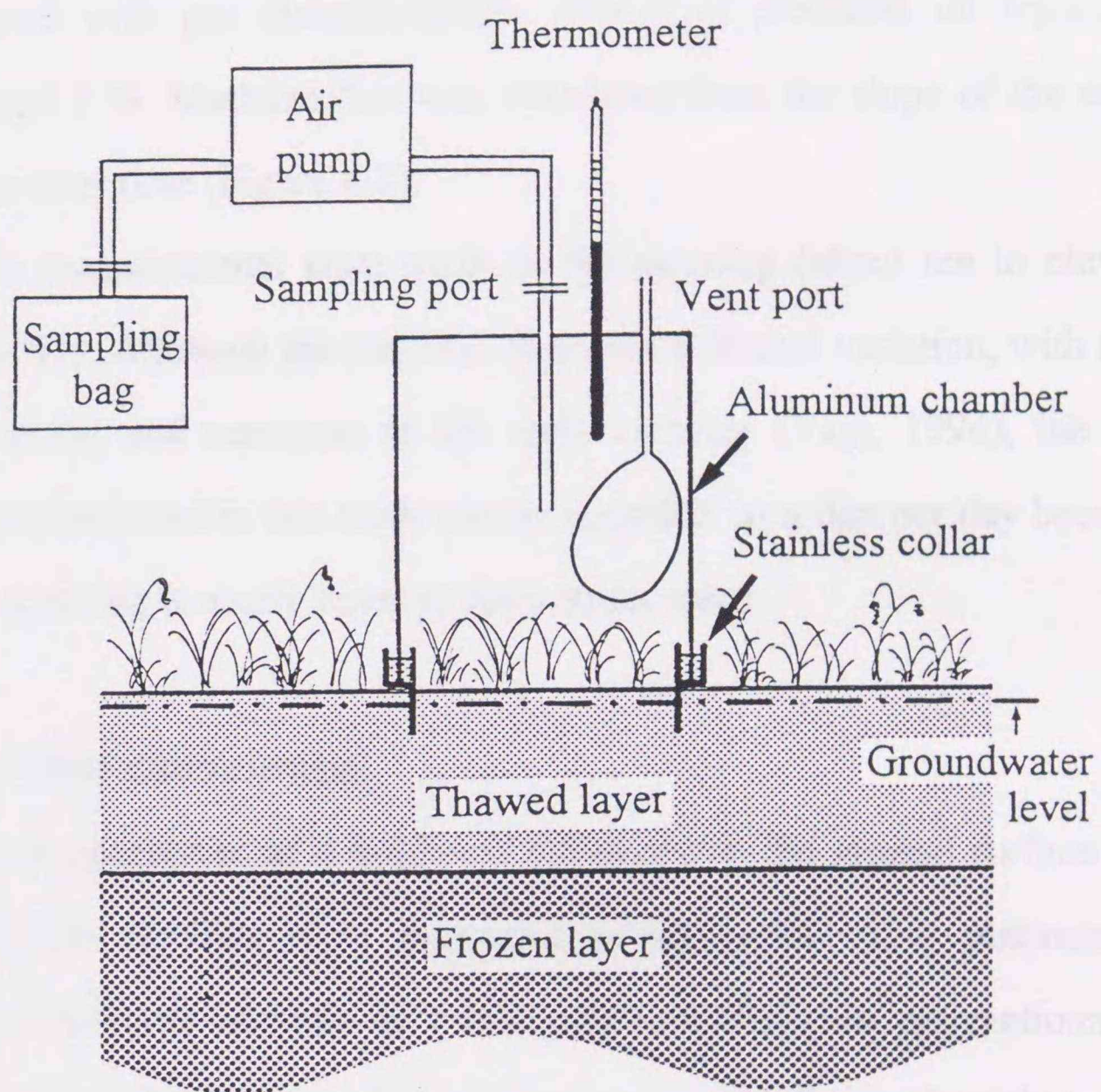


Figure 4-1. Chamber technique for the measurement of methane flux.

Air in the chamber was sucked into a sampling bag by a pump and stored in it for later analysis. Sampling at each site was conducted four times at 10 min-interval over a 30-min period. These samples were analyzed in the laboratory of Hokkaido University, NIES (National Institute for Environmental Studies), and UAF (University of Alaska, Fairbanks), using a flame ionization detector equipped with gas chromatograph. Analytical precision on replicate samples averaged 2 %. Methane flux was calculated from the slope of the concentration change over time (Figure 4-2).

The measurements were made in the morning (about ten to eleven o'clock), once a day. Although the methane flux shows diurnal variation, with maximum in the evening and minimum in the early morning (Yagi, 1994), the flux per 30 minutes measured in this study can be regarded as a flux per day because the flux in the morning is nearly equal to daily mean value.

4-2-2. Other measurements

Air temperatures at a height of 1.5 m above the ground surface and ground temperature profiles were measured automatically using platinum resistance thermosensors at intervals of 1 hour and recorded with conventional solid-state memory type data loggers. These sensors were installed midway between wet and dry type sites in each place. Using the ground temperature profile, daily mean temperature was calculated from an average of temperatures at several depths within active layer. In this study, this temperature is called MDGT (mean daily ground temperature) and used as the representative ground temperature. Meteorological observations (humidity, wind velocity and direction, and insolation) were also made automatically on Mustakh Island. The temperature

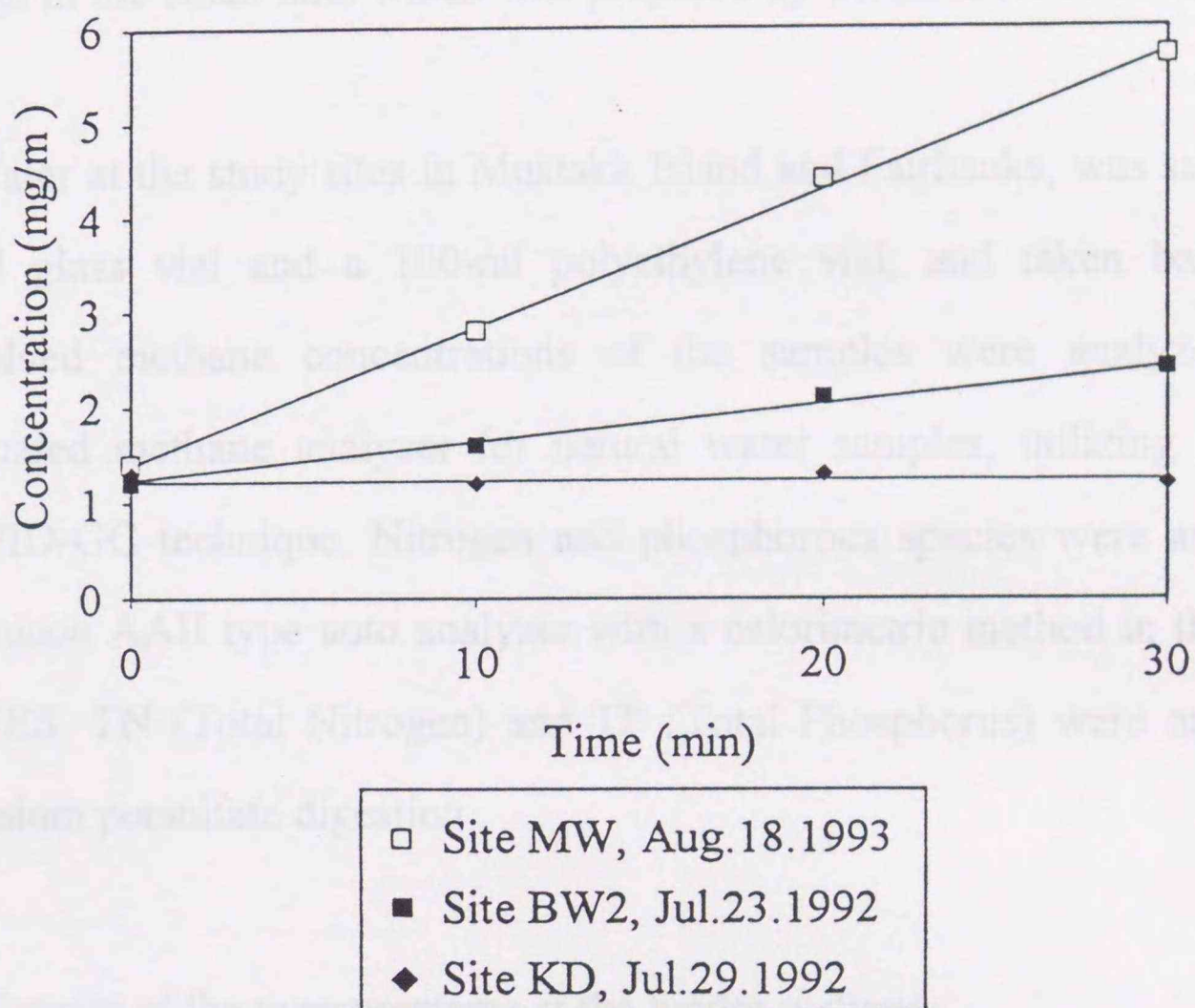


Figure 4-2. Changes of methane concentration in chamber at the sites of MW, BW2 and KD.

measurements were continued through a whole year in Kalakhari Island, Mustakh Island, and Yakutsk.

Thaw depths were detected by inserting a stainless steel rod with a diameter of 1 cm from the ground surface to the bottom of the active layer. Water table levels below the surface were determined by monitoring an electric resistance change in the small hole which was prepared by penetration of the stainless steel rod.

Water at the study sites in Mustakh Island and Fairbanks, was sampled into a 30-ml glass vial and a 100-ml polyethylene vial, and taken back to Japan. Dissolved methane concentrations of the samples were analyzed using an automated methane analyzer for natural water samples, utilizing a purge and trap/FID-GC technique. Nitrogen and phosphorous species were analyzed by a Technicon AAII type auto analyzer with a calorimetric method in the laboratory of NIES. TN (Total Nitrogen) and TP (Total Phosphorus) were analyzed after potassium persulfate digestion.

4-3. Results of the measurements at the tundra wetlands

4-3-1. Bykovsky Peninsula and Kalakhari Island, Siberia

Site description

Locations of the Bykovsky Peninsula and Kalakhari Island are shown in Figure 4-3. On the Bykovsky Peninsula, ice complexes of 40 m thick, which are a special type of massive ice in permafrost, were exposed on some parts of shoreline, and ice-wedge polygons developed in a thermokarst depression with a diameter of several kilometers. The measurements were performed at four sites. There were two dry sites, one on the terrace of the ice complex (BD1) and the

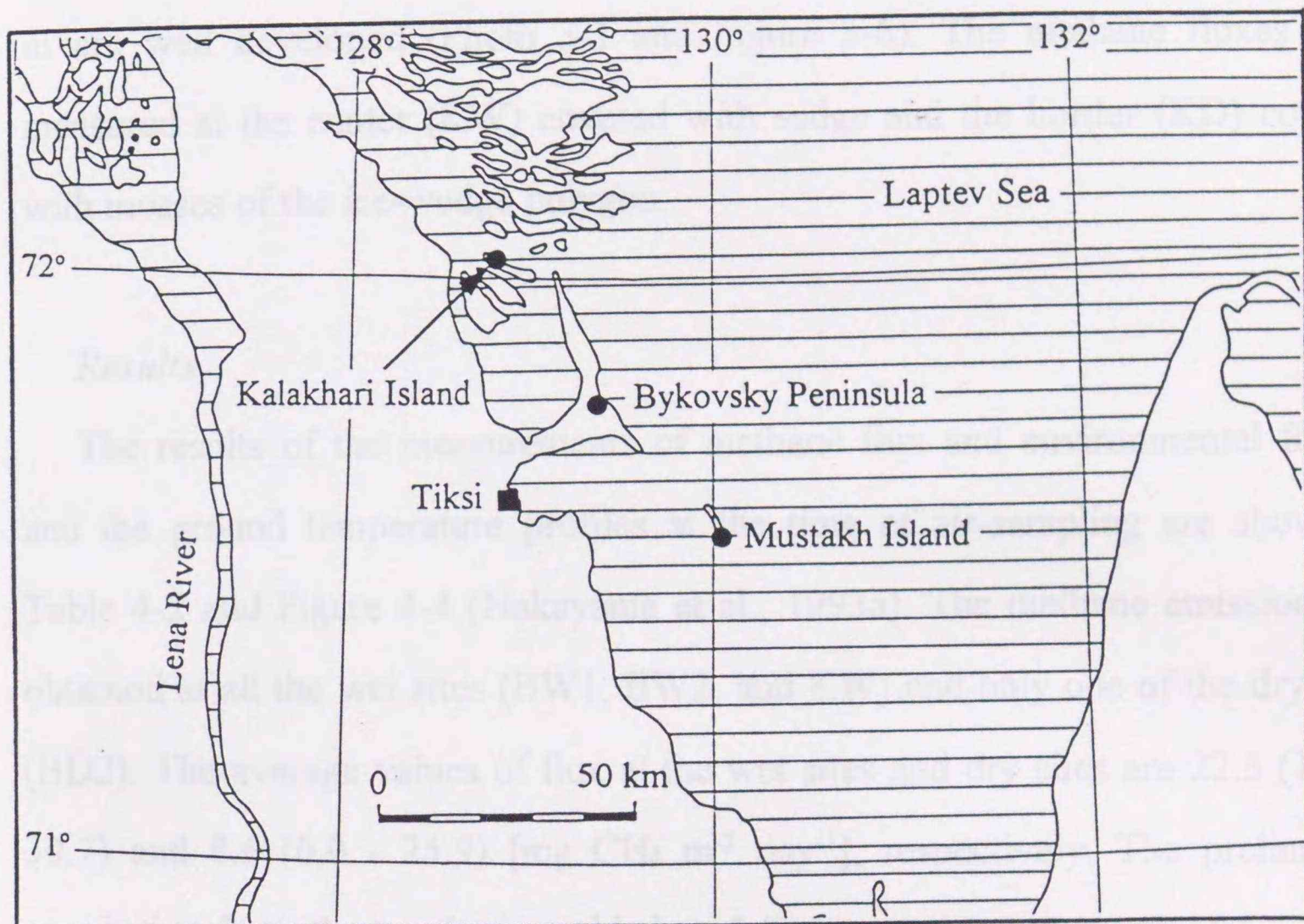


Figure 4-3. Locations of observational sites in Siberian tundra wetland.

other at border of an ice-wedge polygon in the depression (BD2). And two wet sites at center of the ice-wedge polygon in the depression (BW1 and BW2). The wet sites are covered with sedge and the dry sites with mosses and small shrubs.

Kalakhari Island has a very flat surface which is about 4 m a.s.l., composed of a Holocene peat layer. Ice-wedge polygons with an average diameter of about 15 m are well developed (Photo 3-1 and Figure 3-6). The methane fluxes were measured at the center (KW) covered with sedge and the border (KD) covered with mosses of the ice-wedge polygon.

Results

The results of the measurements of methane flux and environmental factors, and the ground temperature profiles at the time of air-sampling are shown in Table 4-2 and Figure 4-4 (Nakayama et al., 1993a). The methane emission was obtained at all the wet sites (BW1, BW2, and KW) and only one of the dry sites (BD2). The average values of flux at the wet sites and dry sites are 22.3 (12.2 - 30.7) and 8.6 (0.0 - 25.9) [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$], respectively. The preliminary conclusion from the results is yielded as follows; methane flux values from wet sites were gained amounts on the order of 10^2 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$], while small values were traced from the dry sites, in the Siberian tundra wetland. Although methane flux apparently does not to correlate with air and surface temperature, the following relationship between methane flux and ground temperature at the 10 cm depth was observed. At four sites (BW1, BW2, BD2, and KW), methane was emitted while the ground temperatures were higher than 5 °C. However, there was no methane emission at two other sites (BD1 and KD) where the ground temperatures were lower than 2.6 °C (Figure 4-4).

Table 4-2. Summary data for methane fluxes and environmental factors
on the Bykovsky Peninsula and Kalakhari Island in 1992.

Site	BW1	BW2	BD1	BD2	KW	KD
Date	7.20.92	7.23.92	7.19.92	7.20.92	7.29.92	7.29.92
Time	12:03	11:27	16:15	14:23	12:10	11:07
Methane flux (mg/m ² /day)	30.7	24.0	-	25.9	12.2	-
*Air temperature (°C)	11.8	10.0	8.1	11.8	6.1	6.1
*Surface temperature (°C)	9.4	10.5	6.2	9.4	6.5	6.5
*10 cm ground temperature (°C)	5.2	6.2	2.6	5.6	5.5	1.7
Thaw depth (cm)	27.0	40.0	14.0	16.5	40.0	25.0
Water table level (cm)	-3.0	0.0	-	-	-3.0	-

* Temperature at the time of air sampling

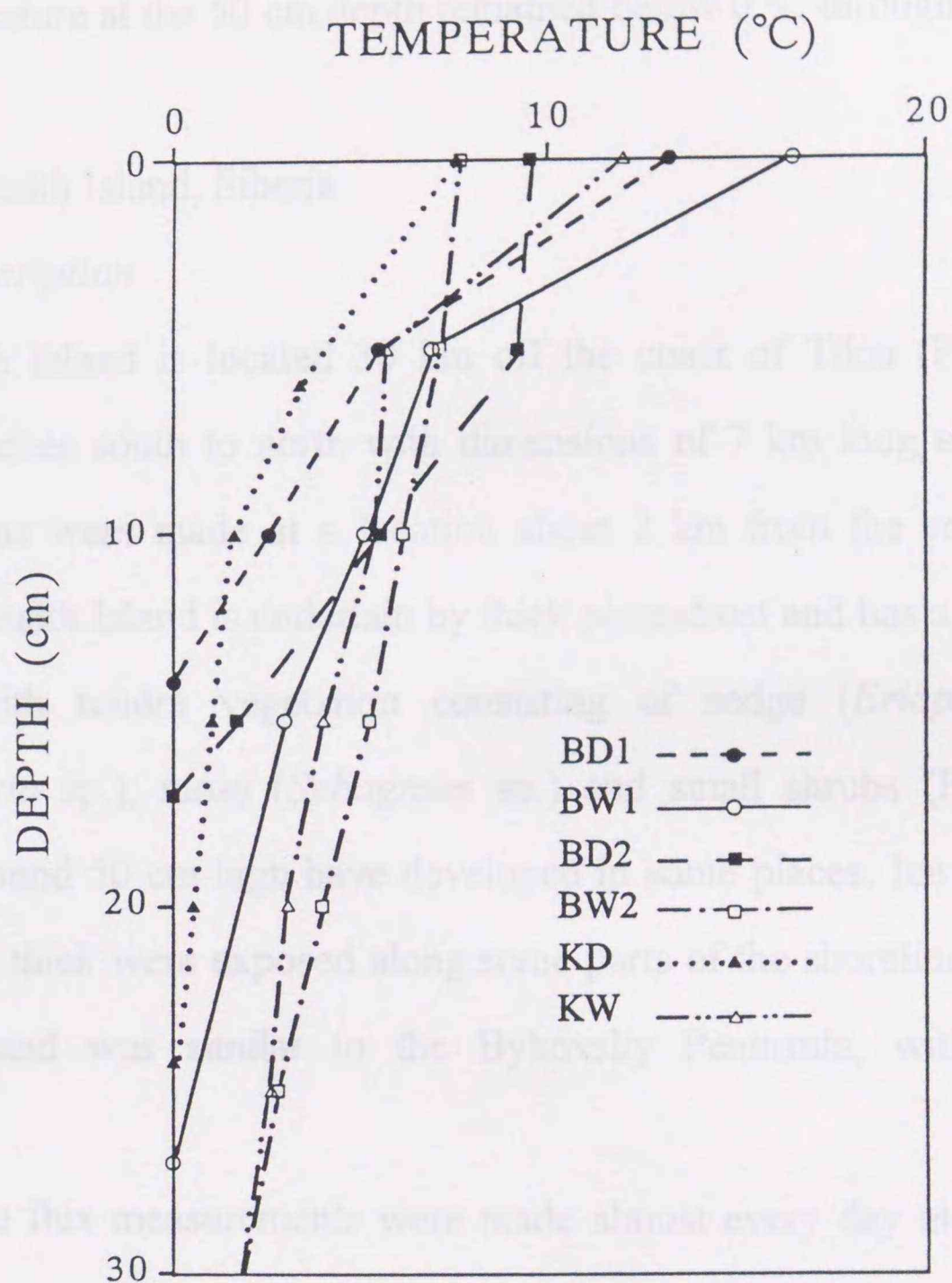


Figure 4-4. Ground temperature profiles at the time of methane flux measurements on the Bykovsky Peninsula and Kalakhari Island.

Air, and ground temperature at the depths of 0, 20, and 50 cm, were measured automatically from August, 1992 to July, 1994 (Figure 4-5). The air and surface temperature were above 0 °C from the middle of June to the middle of September. The temperature at the 50 cm depth remained below 0 °C through the year.

4-3-2. Mustakh Island, Siberia

Site description

Mustakh Island is located 30 km off the coast of Tiksi (Figure 4-3). This island stretches south to north with dimensions of 7 km long and 0.5 km wide. Observations were made at a location about 2 km from the south edge of the island. Mustakh Island is underlain by thick permafrost and has a very flat surface covered with tundra vegetation consisting of sedge (*Eriophorum* sp. and *Deschampsia* sp.), moss (*Sphagnum* sp.) and small shrubs (Photo 4-1). Peat mounds around 50 cm high have developed in some places. Ice complexes from 10 to 20 m thick were exposed along some parts of the shoreline. The landscape of this island was similar to the Bykovsky Peninsula, with rather simple vegetation.

Methane flux measurements were made almost every day at two fixed sites; One was a waterlogged site covered with sedge (MW) and the other was a dry site covered with moss (MD).

Results

Time-series variations of the methane flux, thaw depth and MDGT (Mean daily ground temperature) are shown in Figure 4-6. At the MW site, the positive fluxes were obtained during the observational period. The range of flux values

DAILY MEAN TEMPERATURE AT KALAKHARI

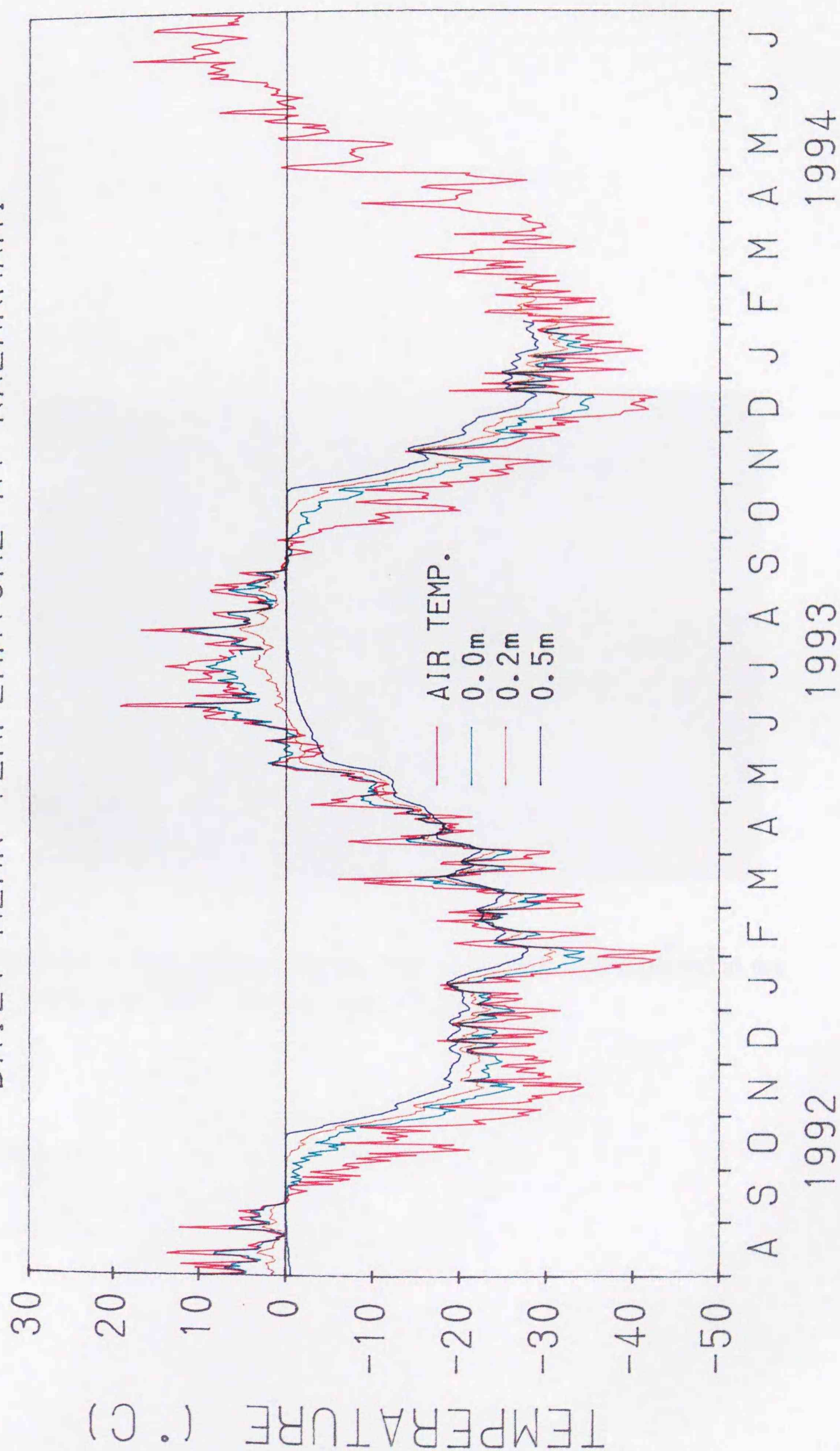


Figure 4-5. Annual variation of air and ground temperatures on Kalakhari Island from August, 1992 to July, 1994.



Photo 4-1. Observational sites on Mustakh Island. Collar placed at the center is the MW site (The arrow shows).

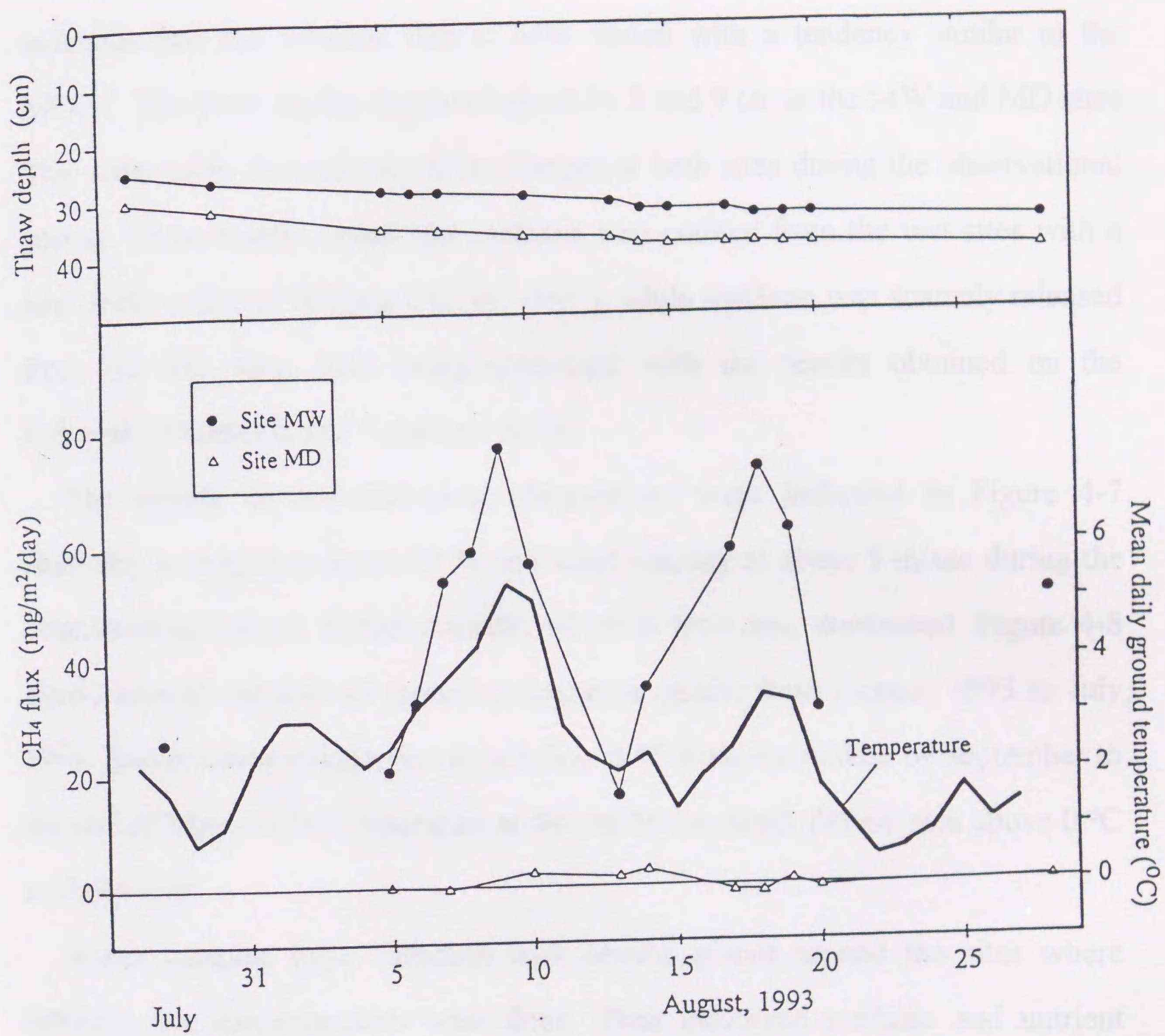


Figure 4-6. Methane flux, thaw depth, and MDGT variations at the sites of MW and MD (Mustakh Island), in July and August, 1993.

was from 15.9 to 76.3 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$] and the mean value is 46.3 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$]. The fluxes at the MD site were nearly zero (-1.5 to 2.3 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$]). The MDGT at these sites fluctuated between 0.5 and 5.3 °C. Figure 4-6 indicates that the methane flux at MW varied with a tendency similar to the MDGT. The thaw depths increased about by 8 and 9 cm at the MW and MD sites. The water table showed very little changes at both sites during the observational period. These results reveal that methane was emitted from the wet sites with a rate of the order of 10^1 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$], while methane was scarcely released from the dry sites, thus being consistent with the results obtained on the Bykovsky Peninsula and Kalakhari Island.

The results of meteorological observations were indicated in Figure 4-7. Humidity averaged at about 70 % and wind velocity at about 5 m/sec during the observational period. Easterly winds, which is from sea, dominated. Figure 4-8 shows annual variation of ground temperature profile from August, 1993 to July, 1994. Surface temperature was kept below 0 °C from the middle of September to the end of May, while temperature at 40 and 60 cm depth did not rise above 0 °C a whole year.

Water samples were collected from several places around the sites where methane flux measurements were done. Their dissolved methane and nutrient concentrations were then analyzed. The dissolved methane concentrations ranged from 39.3 to 6046.7 [nM] (average: 1345.7 [nM], $n=10$). The concentrations of TP (Total Phosphorus) and TN (Total Nitrogen) ranged from 0.016 to 0.585 [mg P l^{-1}] (average: 0.148 [mg P l^{-1}], $n=13$) and from 0.317 to 3.526 [mg N l^{-1}] (average: 1.669 [mg N l^{-1}], $n=13$), respectively. TP and TN concentrations are related to biomass of the environment and anaerobic condition. Although the

JUL. - AUG., 1993 MUSTAKH, SIBERIA

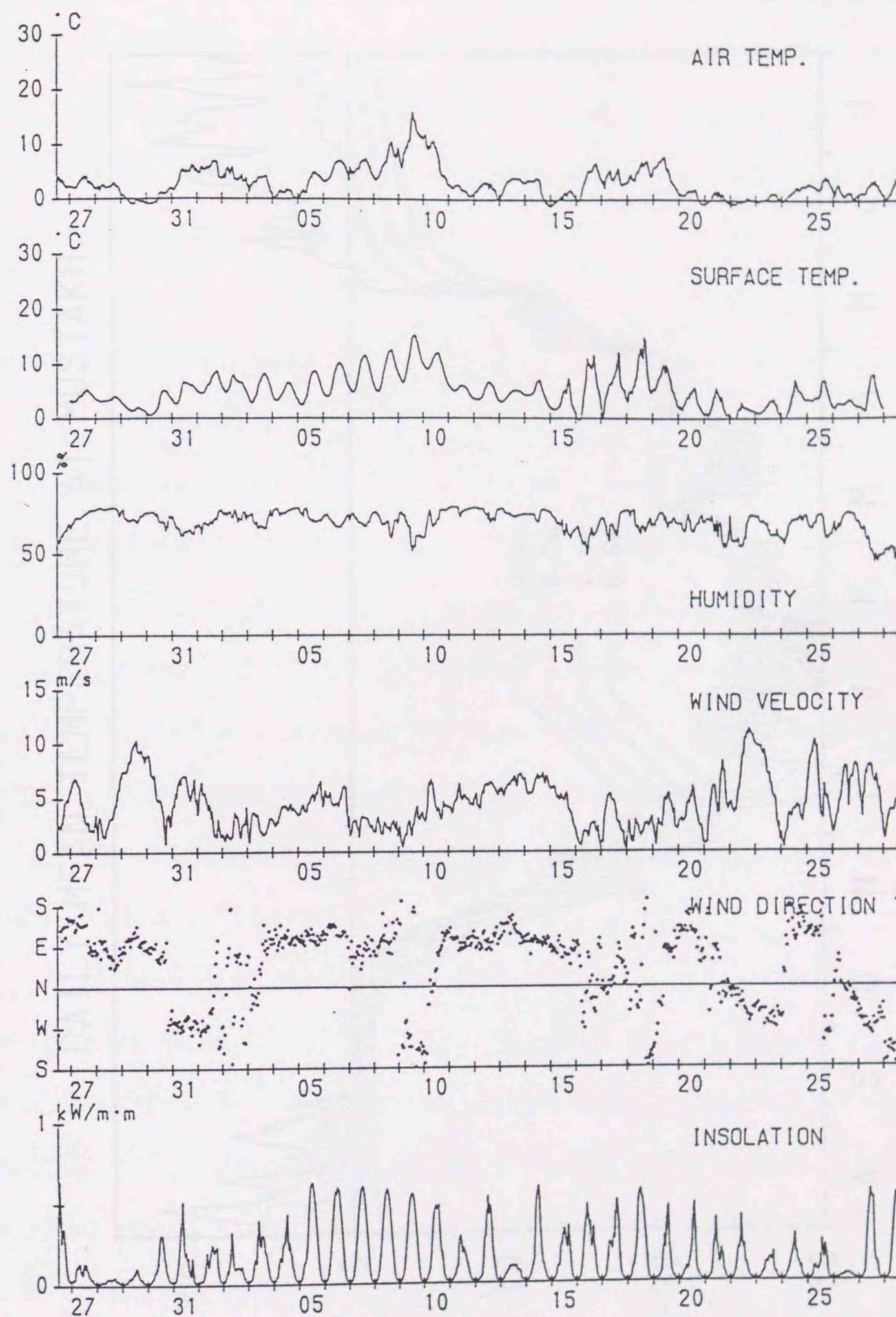


Figure 4-7. Results of meteorological observation on Mustakh Island, July and August, 1993.

DAILY MEAN TEMPERATURE AT MUSTAKH

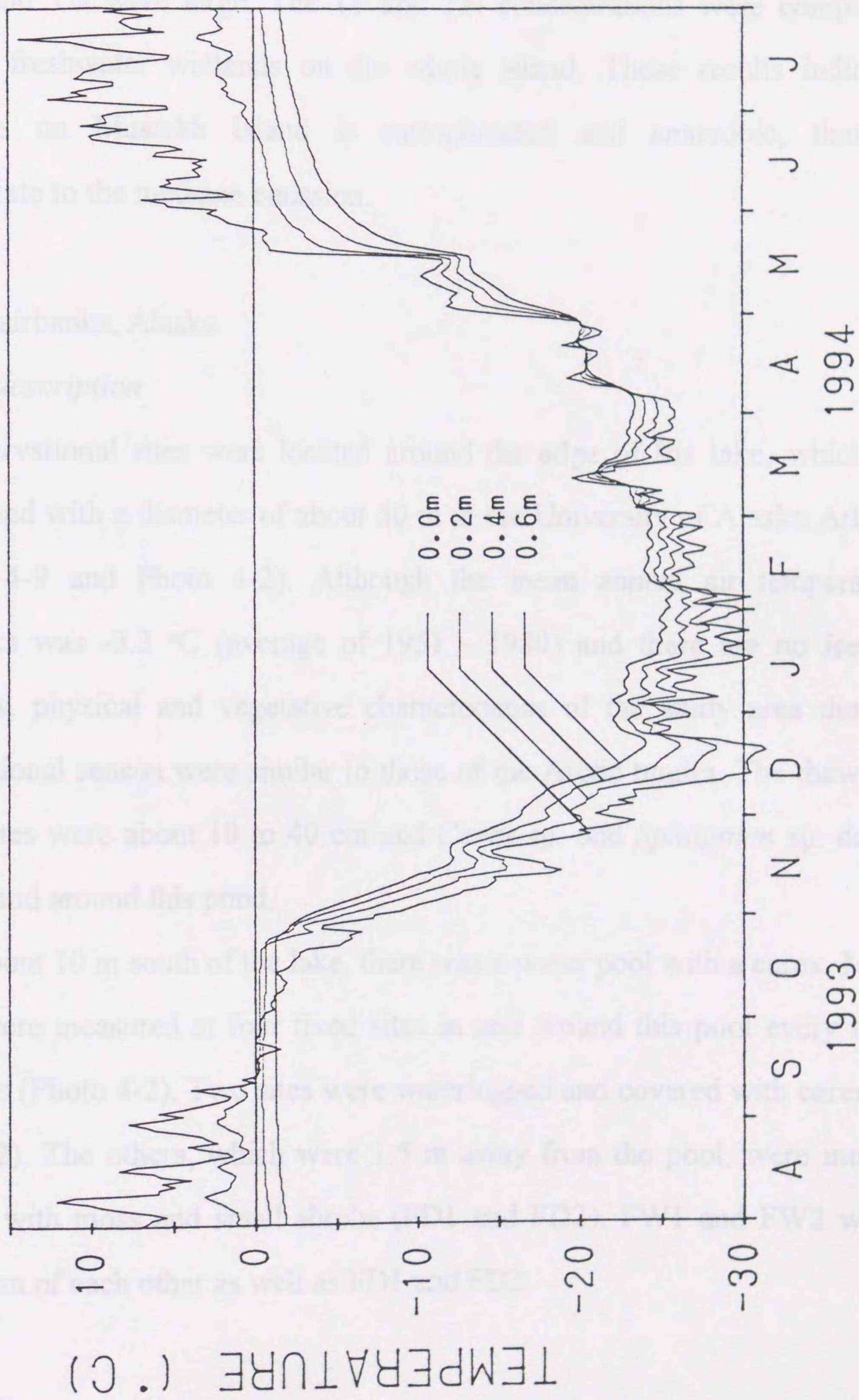


Figure 4-8. Annual variation of ground temperatures on Mustakh Island from August, 1993 to July, 1994.

concentrations in Mustakh Island showed spatial variations, the dissolved methane concentrations showed high values at the sites where the concentrations of TP and TN were large. The TP and TN concentrations were comparatively high at freshwater wetlands on the whole island. These results indicate the wetlands on Mustakh Island is eutrophicated and anaerobic, thus being appropriate to the methane emission.

4-3-3. Fairbanks, Alaska

Site description

Observational sites were located around the edge of Iris lake, which was a small pond with a diameter of about 50 m in the University of Alaska Arboretum (Figure 4-9 and Photo 4-2). Although the mean annual air temperature at Fairbanks was -3.3°C (average of 1951 - 1980) and there are no ice-wedge polygons, physical and vegetative characteristics of the study area during the observational season were similar to those of the Arctic tundra. The thaw depths of the sites were about 10 to 40 cm and *Carex* sp. and *Sphagnum* sp. dominate the wetland around this pond.

At about 10 m south of the lake, there was a water pool with a carex. Methane fluxes were measured at four fixed sites in and around this pool every three or four days (Photo 4-2). Two sites were waterlogged and covered with carex (FW1 and FW2). The others, which were 1.5 m away from the pool, were moist and covered with moss and small shrubs (FD1 and FD2). FW1 and FW2 were set within 1 m of each other as well as FD1 and FD2.

Results

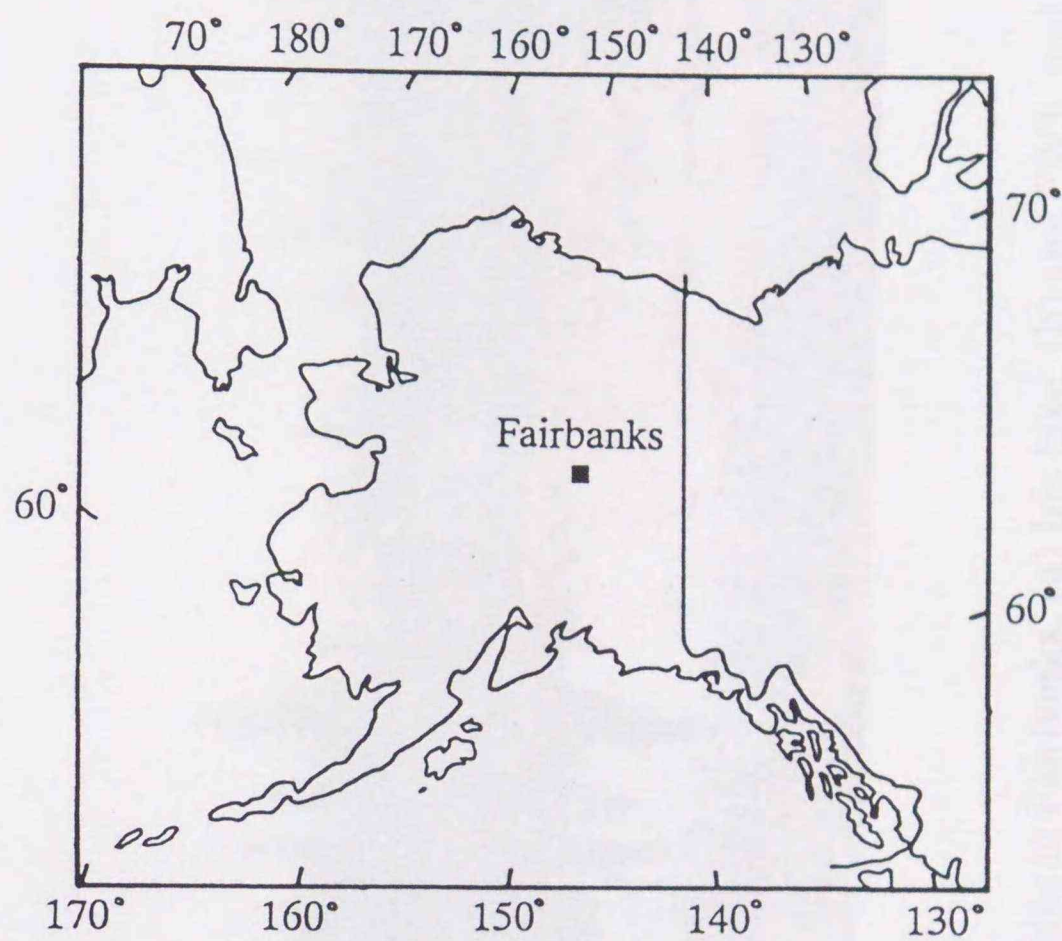


Figure 4-9. Location of Fairbanks, Alaska.

(a) Iris lake

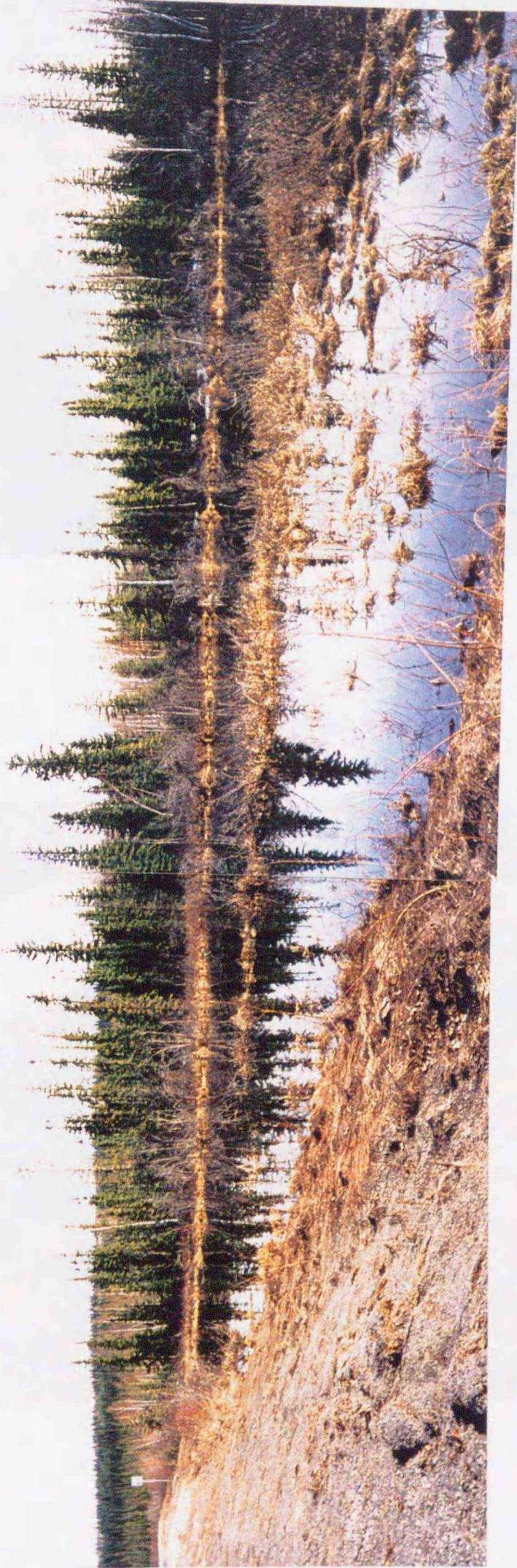


Photo 4-2. Observational sites in Fairbanks. (a) Iris lake, (b) site FW1, and
(c) site FD1.

(b) site FW1



(c) site FD1



Photo 4-2. Observational sites in Fairbanks.

The results of the measurements at Fairbanks are shown in Figure 4-10. At the FW1 and FW2 sites, all values of the methane fluxes were positive (2.9 to 93.8 [mg CH₄ m⁻² day⁻¹]) and gradually increased day by day. On the other hand, values of fluxes at FD1 and FD2 sites were almost zero during the observational period (-0.1 to 3.6 [mg CH₄ m⁻² day⁻¹]). MDGT at these sites rose gradually through the period and ranged from 1.2 to 5.5 °C. The thawing of frozen soil progressed rapidly and thaw depths increased by 24 cm and 13 cm at FW1 and FD1, respectively.

There was little difference in the methane fluxes between FD1 and FD2. The difference of fluxes between FW1 and FW2 were also small, although the fluxes at FW2 were a little larger than those at FW1 on the latter half of the observational period. This difference might be caused by some effects of physical factors, for example, thaw depth at FW2 was deeper than that at FW1. The fluxes at FW and FD sites were very different from each other, because of the difference in soil moisture. Fluxes on the order of 10¹ [mg CH₄ m⁻² day⁻¹] were obtained at waterlogged sites, while methane fluxes at moist sites were nearly zero. The same tendency was observed in Siberian tundra wetlands.

Water of the pool of FW site and Iris lake was sampled at several times during the observational period and their dissolved methane and nutrient concentrations were analyzed. The same tests were taken with water from Mustakh Island. The dissolved methane concentrations ranged from 388.2 to 3646.8 [nM] (average: 1726.5 [nM], n=17). The concentrations of TP varied between 0.055 and 0.171 [mg P l⁻¹] (average: 0.094 [mg P l⁻¹], n=16) and the concentrations of TN between 0.824 to 3.193 [mg N l⁻¹] (average: 1.601 [mg N l⁻¹], n=16). These concentration values are almost similar to those of Mustakh Island. The time-series variation of

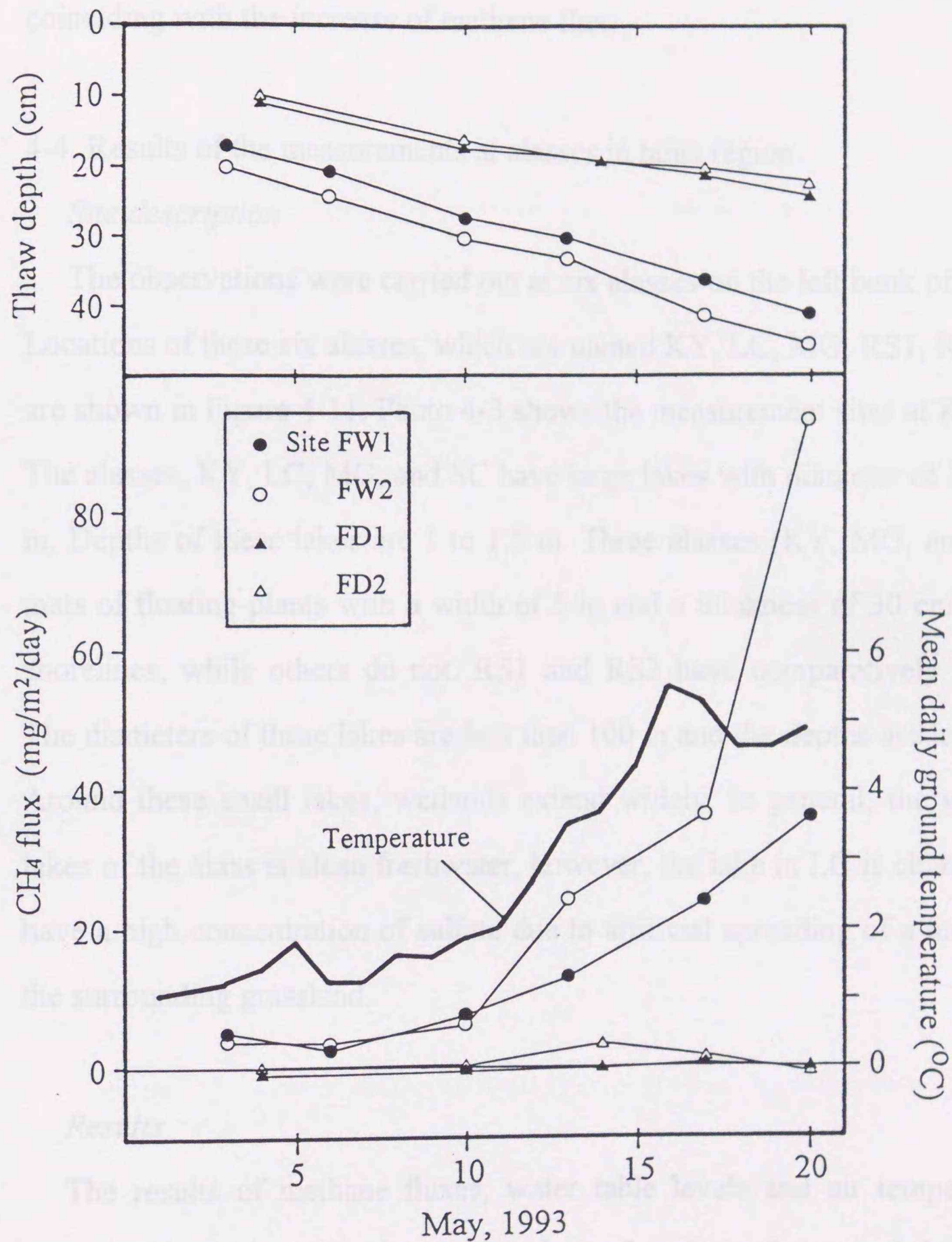


Figure 4-10. Methane flux, thaw depth, and MDGT variations at the sites of FW1, FW2, FD1, and FD2 (Fairbanks), in May, 1993.

these concentrations showed a rapid increase on 17 May. These results imply that the biomass in the water increased and the water became anaerobic, thus coinciding with the increase of methane flux.

4-4. Results of the measurements at alasses in taiga region

Site description

The observations were carried out at six alasses on the left bank of Lena River. Locations of these six alasses, which are named KY, LC, MG, RS1, RS2, and SC, are shown in Figure 4-11. Photo 4-3 shows the measurement sites at KY and RS2. The alasses, KY, LC, MG, and SC have large lakes with diameter of 200 to 1000 m. Depths of these lakes are 1 to 1.5 m. Three alasses (KY, MG, and SC) have mats of floating-plants with a width of 5 m and a thickness of 30 cm along their shorelines, while others do not. RS1 and RS2 have comparatively small lakes. The diameters of these lakes are less than 100 m and the depths are less than 1 m. Around these small lakes, wetlands extend widely. In general, the water in the lakes of the alass is clean freshwater, however, the lake in LC is characterized to have a high concentration of sulfate due to artificial spreading of a fertilizer over the surrounding grassland.

Results

The results of methane fluxes, water table levels and air temperatures are presented in Table 4-3 and average values of methane fluxes and their ranges at each type sites are summarized in Figure 4-12. The fluxes were positive values at all the sites (0.0 to 1921.7 [mg CH₄ m⁻² day⁻¹]). Since spatial variability of these values are very large, the data within range of mean value $\pm$ standard deviation

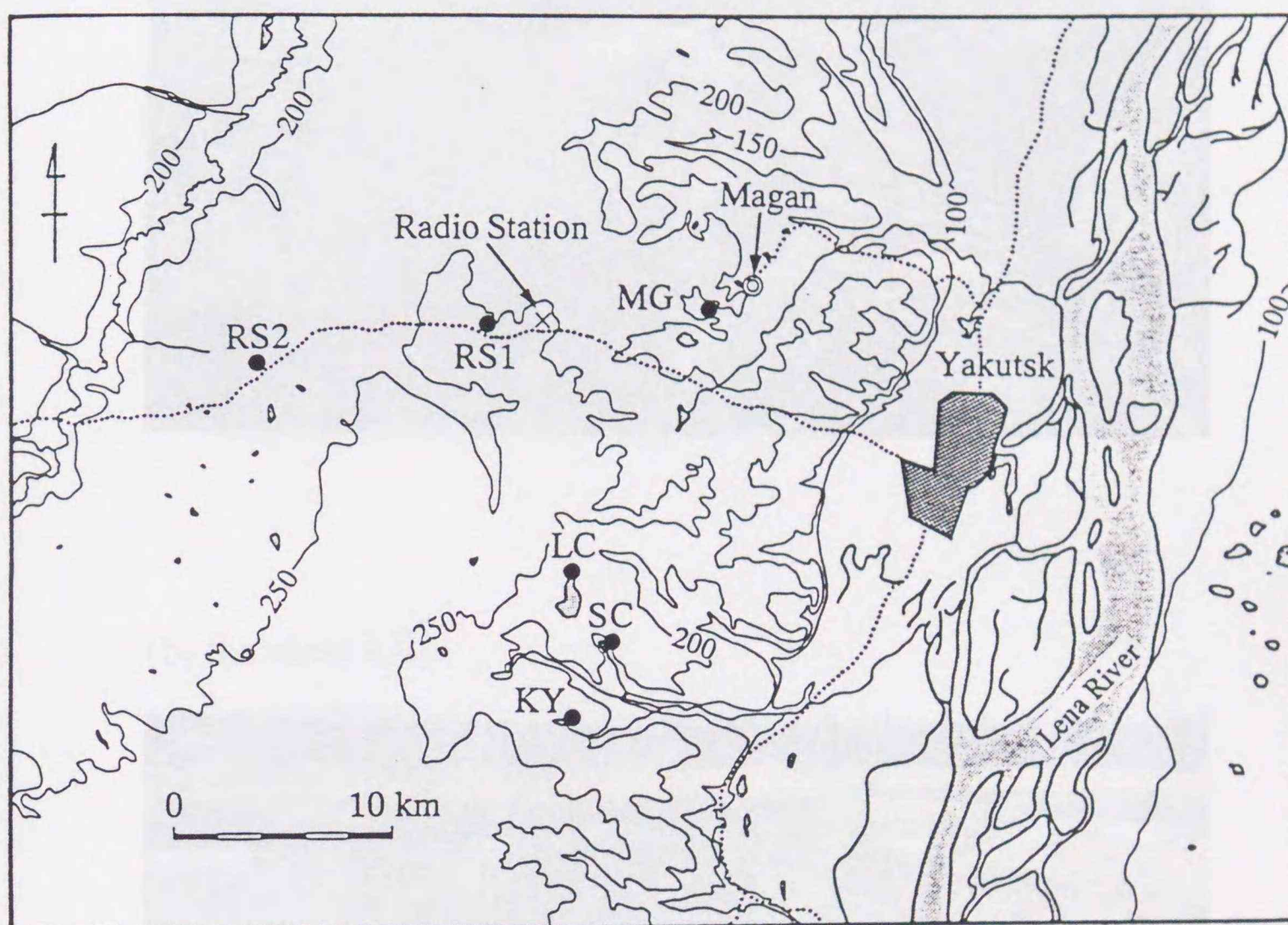


Figure 4-11. Location of observational alasses around Yakutsk.

(a) the alass KY



(b) the alass RS2.

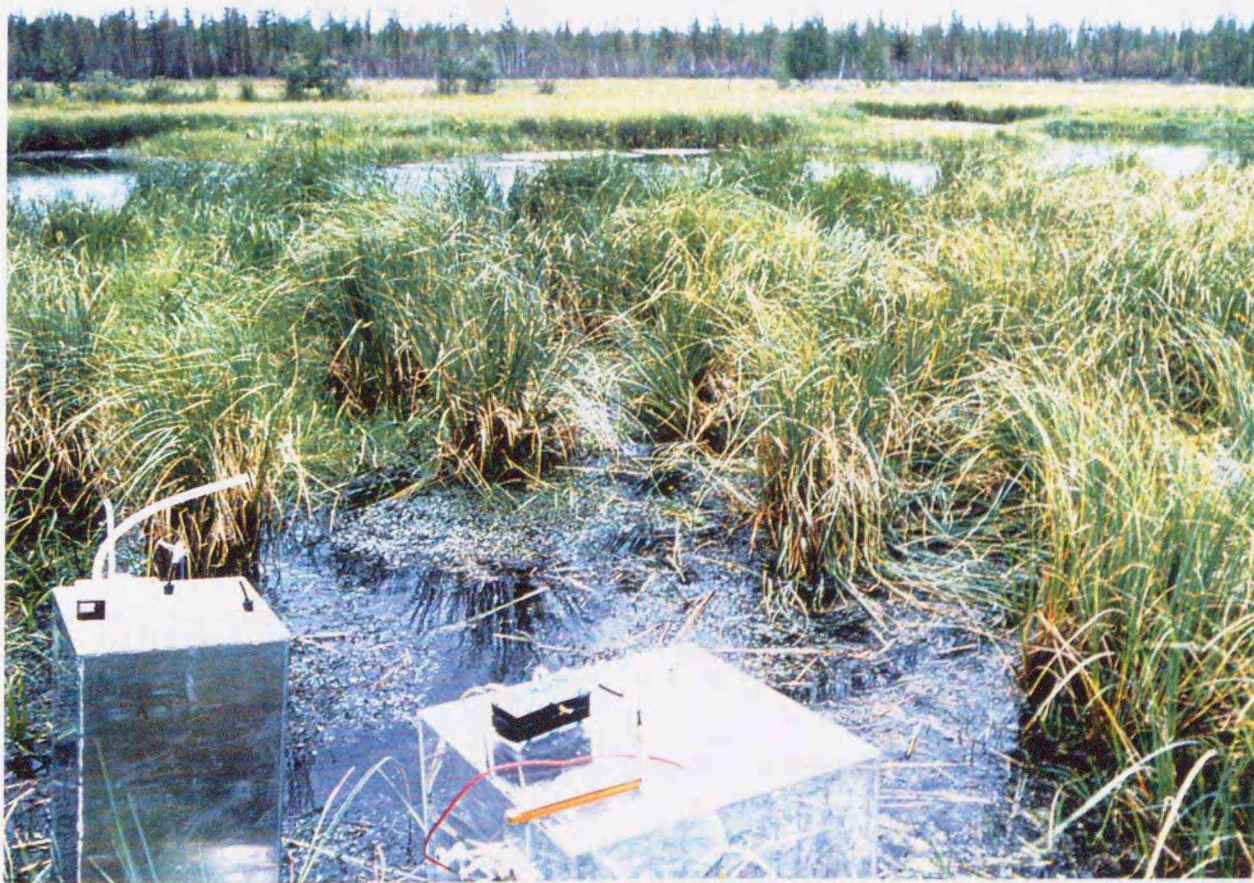


Photo 4-3. Alass around Yakutsk. (a) the alass KY, and (b) the alass RS2.

Table 4-3. Results of methane flux measurements at alasses around Yakutsk in 1993.

Site	Date	Type of site	Methane flux mg/m ² /day	Water table cm	Air temperature °C	Lake size
KY	AUG.3	D	38.1	-30	21.2	Large
	AUG.9	A	255.2			
		B	301.3		20.6	
		B	375.9		20.5	
		C	223.0	-7	23.2	
		C	321.4	-15	20.9	
		D	32.1	-24	19.3	
LC	AUG.2	A	3.1			Large
		A	39.7			
		C	9.0	-3	21.9	
		C	11.8	-1	15.4	
MG	AUG.11	A	133.1			Large
		B	358.2		21.9	
		B	402.0		21.5	
		C	177.8	7	24.0	
		D	77.9	-21	23.5	
RS1	JUL.30	A	184.6			Small
		C	512.3	-2		
		C	1022.5	-2		
	AUG.13	A	351.2			
		C	338.5	-10	22.0	
		C	900.5	0	17.4	
		C	1921.7	-5	17.6	
		D	53.2	-39	21.0	
RS2	AUG.5	A	829.8			Small
		C	475.9	15	17.9	
		C	671.9	16	17.3	
		C	1041.2	8	17.4	
		D	67.8	-17	14.1	
SC	AUG.6	B	109.6		21.9	Large
		C	232.8	0	24.2	
		D	0.0	-	24.3	

are used for the following discussion.

The fluxes are characterized depending on different environmental types. Except for LC, the diffuse and bubble fluxes of methane from lake surface

(type A) averaged $231.0 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ and ranged from 120.1 to 351.2

$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$. These are comparable with type A fluxes in

lake water

probably

flux values

$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$. These are comparable with type A fluxes in

type C area except for LC were averaged from $177.8 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ at MG

to $1041.2 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ at X02. In type D area, the values of fluxes were

32.1 to $67.8 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ and similar to those in other lake areas due to

on low water level

Figure 4-12 shows the variation of ground temperatures of soil at 10, 20,

30, and 40 cm depths in August and September 1993. Ground temperatures at 10, 20,

30, and 40 cm depths in August and September 1993. Ground temperatures at 10, 20,

30, and 40 cm depths in August and September 1993. Ground temperatures at 10, 20,

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30, and 40 cm depths in August and September 1993. Ground temperatures at 10, 20,

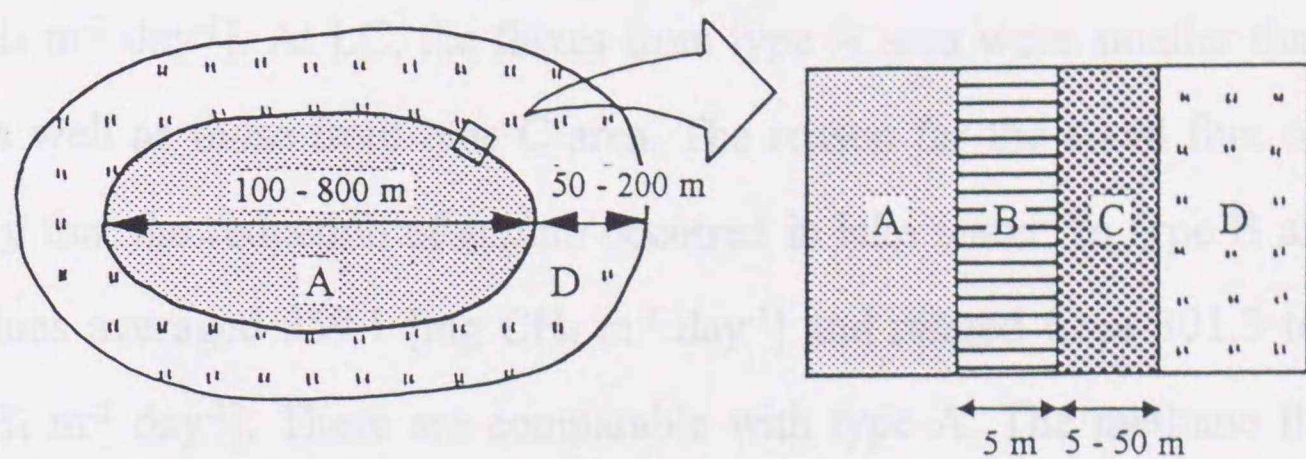
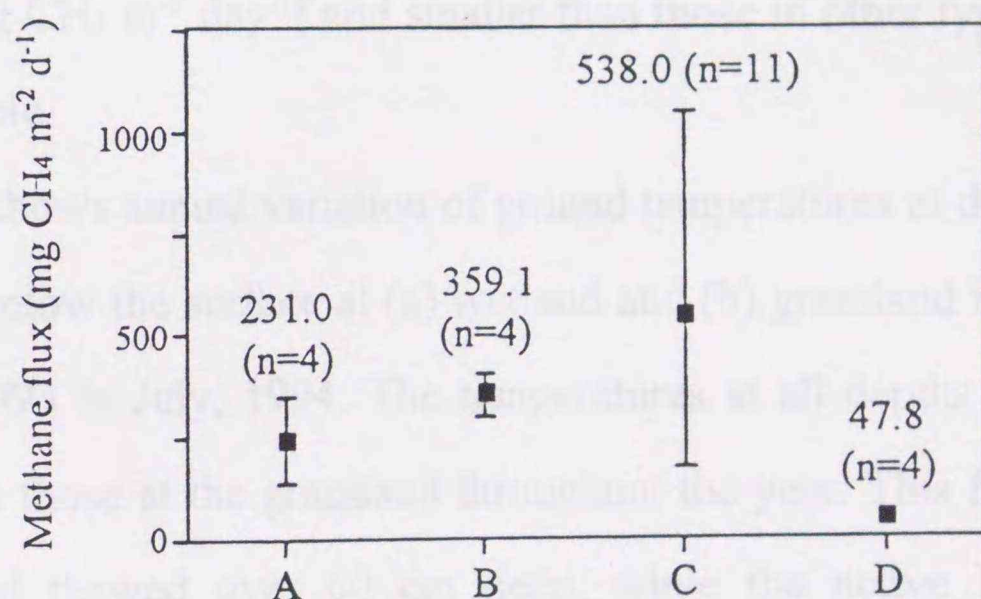
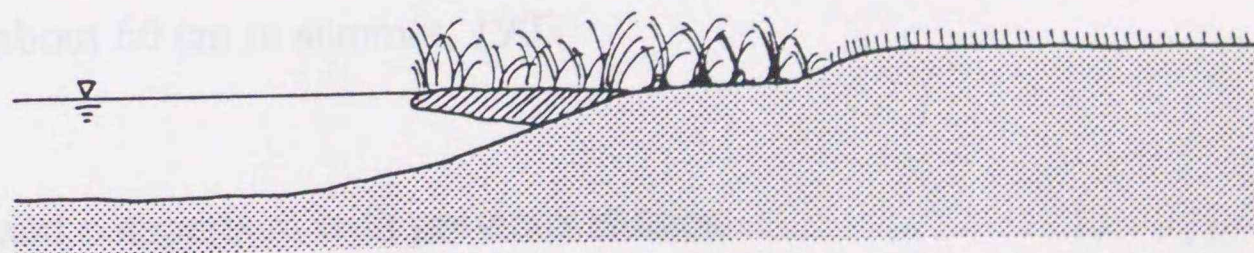


Figure 4-12. Results of methane flux measurements at the alasses around Yakutsk in August, 1993.

are used for the following discussion.

The fluxes are characterized depending on different environmental types. Except for LC, the diffusive and bubbling fluxes of methane from lake surface (type A) averaged 231.0 [mg CH₄ m⁻² day⁻¹] and ranged from 133.1 to 351.2 [mg CH₄ m⁻² day⁻¹]. At LC, the fluxes from type A area were smaller than other lakes as well as those from type C area. The reason for the small flux of LC is probably that the reduction of sulfate occurred in lake water. In type B area, the flux values averaged 359.1 [mg CH₄ m⁻² day⁻¹] and ranged from 301.3 to 402.0 [mg CH₄ m⁻² day⁻¹]. These are comparable with type A. The methane fluxes in type C area except for LC were scattered from 177.8 [mg CH₄ m⁻² day⁻¹] at MG to 1041.2 [mg CH₄ m⁻² day⁻¹] at RS2. In type D area, the values of fluxes were 32.1 to 67.8 [mg CH₄ m⁻² day⁻¹] and smaller than those in other type areas due to its low water table.

Figure 4-13 shows annual variation of ground temperatures at depths of 10, 20, 40, and 60 cm below the surface at (a) wetland and (b) grassland in the alass KY from August, 1993 to July, 1994. The temperatures at all depths at the wetland were larger than those at the grassland throughout the year. This figure indicated that the wetland thawed over 60 cm deep, while the active layer depth of grassland was about 60 cm in summer, 1993.

4-5. Summary and comparison with previous studies

Summary

The results of time-series observations of methane fluxes and environmental factors in Mustakh Island and Fairbanks are summarized in Table 4-4. The physical conditions such as thaw depth and MDGT were similar in both Mustakh

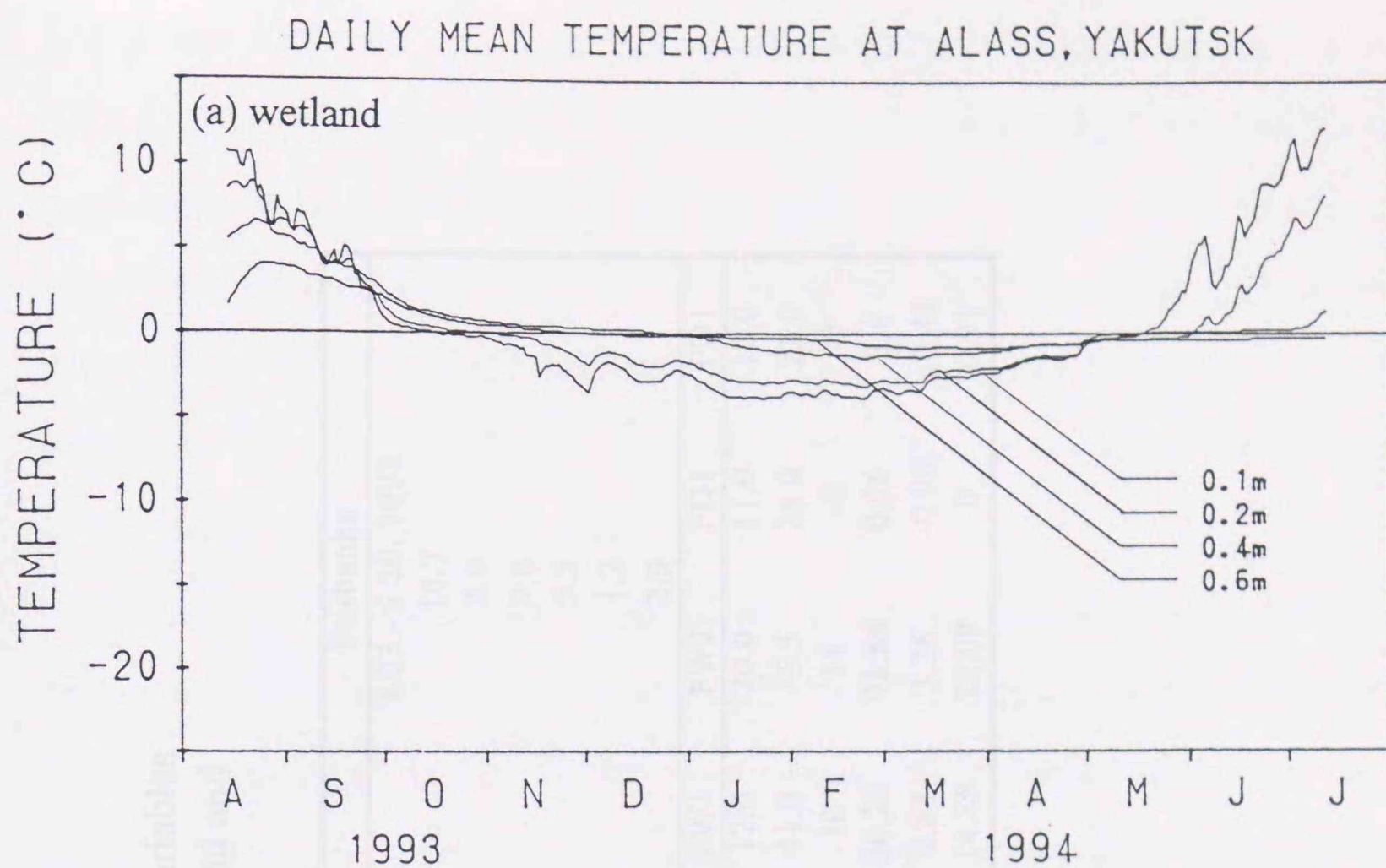
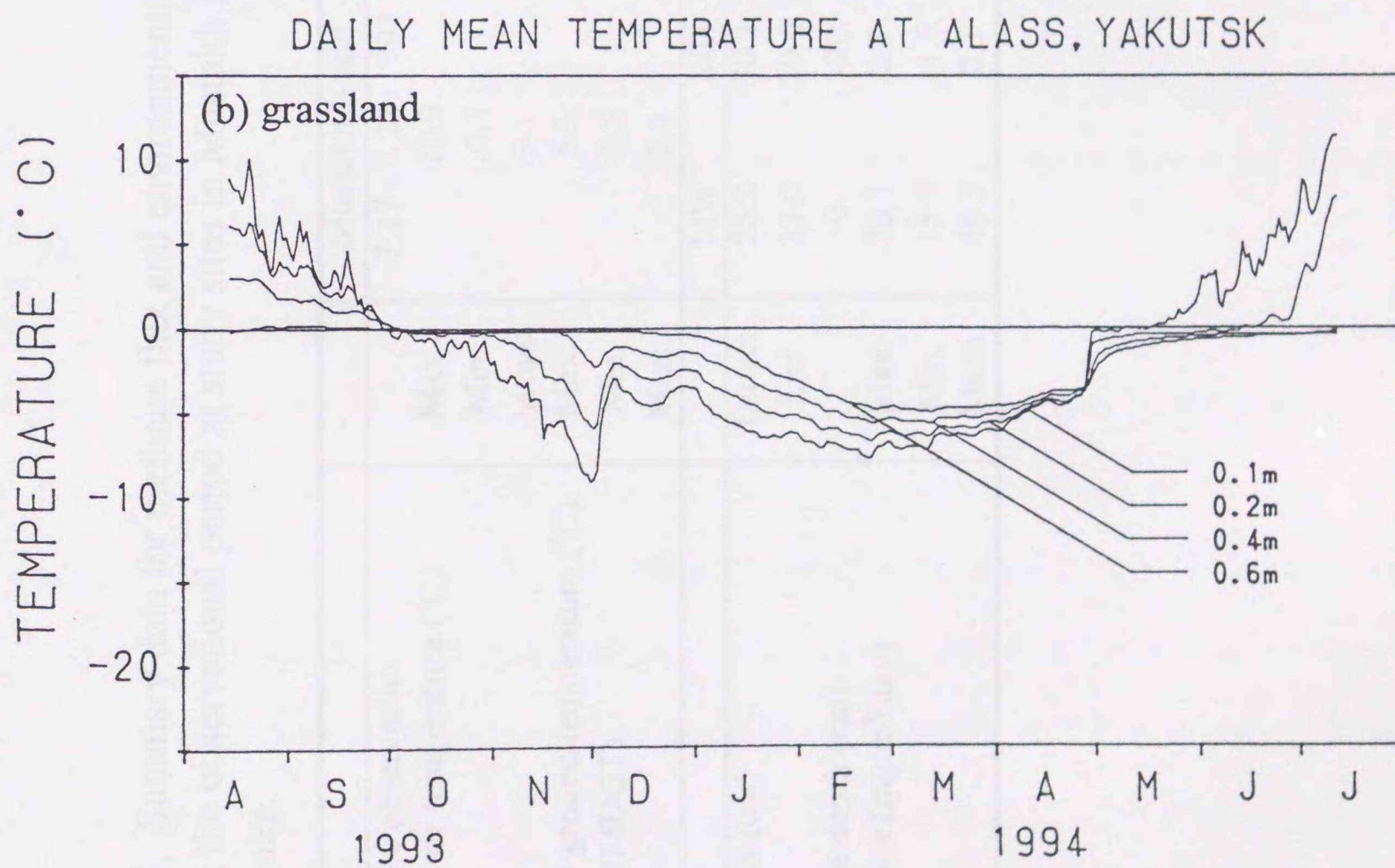


Figure 4-13. Annual variation of ground temperatures at (a) wetland and (b) grassland of allass KY, from August, 1993 to July, 1994.

Table 4-4. Summary data for methane flux and environmental variables during the observational period at study sites in Mustakh Island and Fairbanks.

		Mustakh Island	Fairbanks			
Period of the observation		7.27 - 8.28. 1993	5.03 - 5.20. 1993			
Mean daily air temperature (°C)	Max.	10.9	14.7			
	Min.	-0.3	2.9			
	Mean	3.1	7.8			
	Max.	5.3	5.5			
	Min.	0.5	1.2			
Mean daily ground temperature (°C) (MDGT)	Mean	2.3	2.9			
		MW	MD	FW1	FW2	FD1
Thaw depth (cm)	Outset	25.2	30.1	17.0	20.0	10.0
	End	33.0	39.0	41.0	45.5	22.0
Water table depth (cm)		0	-20	10	14	-7
Methane flux (mg/m ² /day)	Max.	76.3	2.3	36.24	93.84	3.6
	Min.	15.9	-1.5	2.88	3.36	-0.48
	Mean	46.3	0.3	14.88	28.08	0.91

Island and Fairbanks, although the latitudes and observational seasons were different from each other. Thus the observations in Mustakh Island and Fairbanks were made under the similar physical, especially thermal, conditions. The values of methane fluxes were obtained on the order of 10^1 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$] from wet sites (MW, FW1, and FW2) and nearly zero from dry sites (MD, FD1, and FD2). From these results, the soil moisture condition near ground surface is a important factor controlling the methane emission.

Compared with the tundra wetlands, the methane flux from alasses in taiga region were considerably large. These large fluxes are probably related to the high air temperature and deep thaw layer during the observational period. The annual methane emission is expected to be large, since the emission season (thaw season) is longer in this region than the tundra region. Therefore, it is necessary to observe time-series methane flux at permanent sites, including various environmental types, in order to estimate the methane emission from whole alasses.

Monthly mean and annual mean ground temperatures are calculated from the results of automated measurements in Kalakhari Island, Mustakh Island and Alass KY near Yakutsk (Table 4-5). At the tundra wetlands, the annual mean values of ground temperature at all depths ranged from -11°C to -12°C . The monthly mean ground surface temperatures rose above 0°C for 4 months and methane was emitted during this period. The ground temperatures at Yakutsk were fairly higher than those at tundra wetlands, especially in winter. These winter ground temperatures were also higher than those expected from air temperature (shown in Figure 3-3). This is probably due to snow accumulation and thermal inertia of lake. Because the ground temperature affect the methanogen activity, it is

Table 4-5. Summary of the ground temperatures measured in Siberia, from 1992 to 1994.

(a) Kalakhari Island		1993												Annual mean
Level	1992	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	
Air (1.5m)		5.3	-0.4	-13.6	-28.1	-25.3	-28.5	-27.4	-23.7	-17.2	-5.7	3.7	8.2	-12.7
Surface		3.9	0.6	-5.6	-21.7	-22.8	-25.2	-27.0	-23.4	-17.6	-5.7	3.1	5.9	-11.3
20 cm		1.5	0.5	-3.0	-19.0	-21.3	-23.3	-26.1	-22.7	-18.2	-7.9	-0.6	2.1	-11.5
50 cm		-0.4	-0.1	-1.5	-16.0	-19.6	-21.4	-24.9	-22.0	-18.5	-9.9	-2.5	-0.6	-11.5

		1994												Annual mean
Level	1993	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	
Air (1.5m)		6.3	1.6	-10.9	-23.8	-33.6	-33.4	-29.8	-25.0	-20.7	-4.7	3.2	9.2	-13.5
Surface		5.2	1.1	-3.7	-19.6	-30.0	-31.1							
20 cm		2.6	0.8	-1.3	-16.9	-27.7	-29.4	-28.4						
50 cm		0.0	0.0	-0.2	-13.6	-24.7	-27.3							

(b) Mustakh Island		1994												Annual mean
Level	1993	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	
Surface		5.8	1.3	-2.6	-15.5	-23.6	-27.8	-27.2	-24.4	-21.7	-7.4	5.6	8.7	-10.7
10 cm		3.7	1.0	-1.6	-14.3	-25.5	-27.1	-26.7	-24.1	-21.6	-8.5	1.8	5.2	-11.5
20 cm		1.4	0.4	-0.9	-13.1	-24.3	-26.3	-26.3	-23.8	-21.6	-9.5	-0.7	1.8	-11.9
30 cm		-0.2	-0.1	-0.8	-12.2	-23.4	-25.7	-25.9	-23.6	-21.6	-10.3	-1.7	-0.2	-12.1
40 cm		-0.6	-0.5	-0.9	-11.3	-22.4	-25.0	-25.5	-23.3	-21.5	-11.1	-2.4	-0.9	-12.1
50 cm		-1.0	-0.8	-1.0	-10.5	-21.4	-24.3	-24.9	-23.0	-21.3	-11.6	-3.0	-1.4	-12.0
60 cm		-1.6	-1.3	-1.4	-9.9	-20.7	-23.8	-24.7	-22.9	-21.4	-12.5	-4.0	-2.2	-12.2

Table 4-5. (continued)

Level	1994												Annual mean
	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	
10 cm	*9	4.5	0.0	-1.6	-2.5	-3.5	-3.6	-3.0	-1.7	0.3	6.1	**10.9	-0.5
20 cm	*7.9	4.4	0.4	-0.6	-1.6	-2.6	-3.0	-2.5	-1.6	-0.4	2.2	**6.8	-0.5
40 cm	*6.1	4.2	1.3	0.4	0.1	-0.7	-1.3	-1.3	-0.8	0.0	0.2	**0.6	0.2
60 cm	*3.3	3.0	1.0	0.2	-0.2	-0.3	-0.5	-0.8	-0.8	-0.4	-0.4	**0.3	0.1

(d) Grassland of Alass KY (Yakutsk)

Level	1994												Annual mean
	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	
10 cm	*6.8	3.0	-0.9	-4.5	-4.6	-5.7	-7.1	-6.7	-4.7	0.2	3.8	**8.8	-2.7
20 cm	*4.9	2.2	-0.3	-2.4	-3.1	-4.3	-6.1	-6.1	-4.5	-0.5	0.1	**4.8	-2.5
40 cm	*2.6	1.2	-0.1	-0.4	-1.5	-2.9	-5.1	-5.5	-4.3	-0.9	-0.4	**0.3	-2.0
60 cm	*0.1	0.1	-0.2	-0.2	-0.3	-1.7	-4.2	-4.9	-4.1	-1.2	-0.6	**0.4	-1.7

* indicates the mean value from August 15 to 31

** indicates the mean value from July 1 to 12

important to monitor the ground temperature profiles in a whole year. In next chapter, annual methane emission is estimated using these annual variations of ground temperatures.

Comparison with previous studies

Table 4-6 summarizes the results of recent observations, including this study, of methane flux in high-latitude wetlands ($> 60^{\circ}\text{N}$). All the observations shown in Table 4-6 were performed in the Alaskan permafrost area, except for those in Sweden by Svensson and Rosswall (1984). The data of Table 4-6 were classified based on the soil moisture conditions at measurement sites: (1) water surface where there is no vegetation, (2) waterlogged and wet sites, and (3) moist and dry sites. The range of methane fluxes obtained in previous works and the value of my results in Siberian tundra wetlands and alasses in Taiga region are schematized in Figure 4-14. The values of fluxes mainly depend on moisture conditions: the largest fluxes were obtained at the waterlogged or wet sites, while the moist or dry sites has the smallest fluxes. The results of this study coincide with this feature. The fluxes at the Siberian tundra wetlands are smaller than the previous results because the observational sites were located at higher latitude than those of the previous research. On the contrary, the fluxes at the alasses were fairly larger than the range of previous fluxes due to higher summer air temperature. Therefore, the alasses around Yakutsk are important as the source of atmospheric methane.

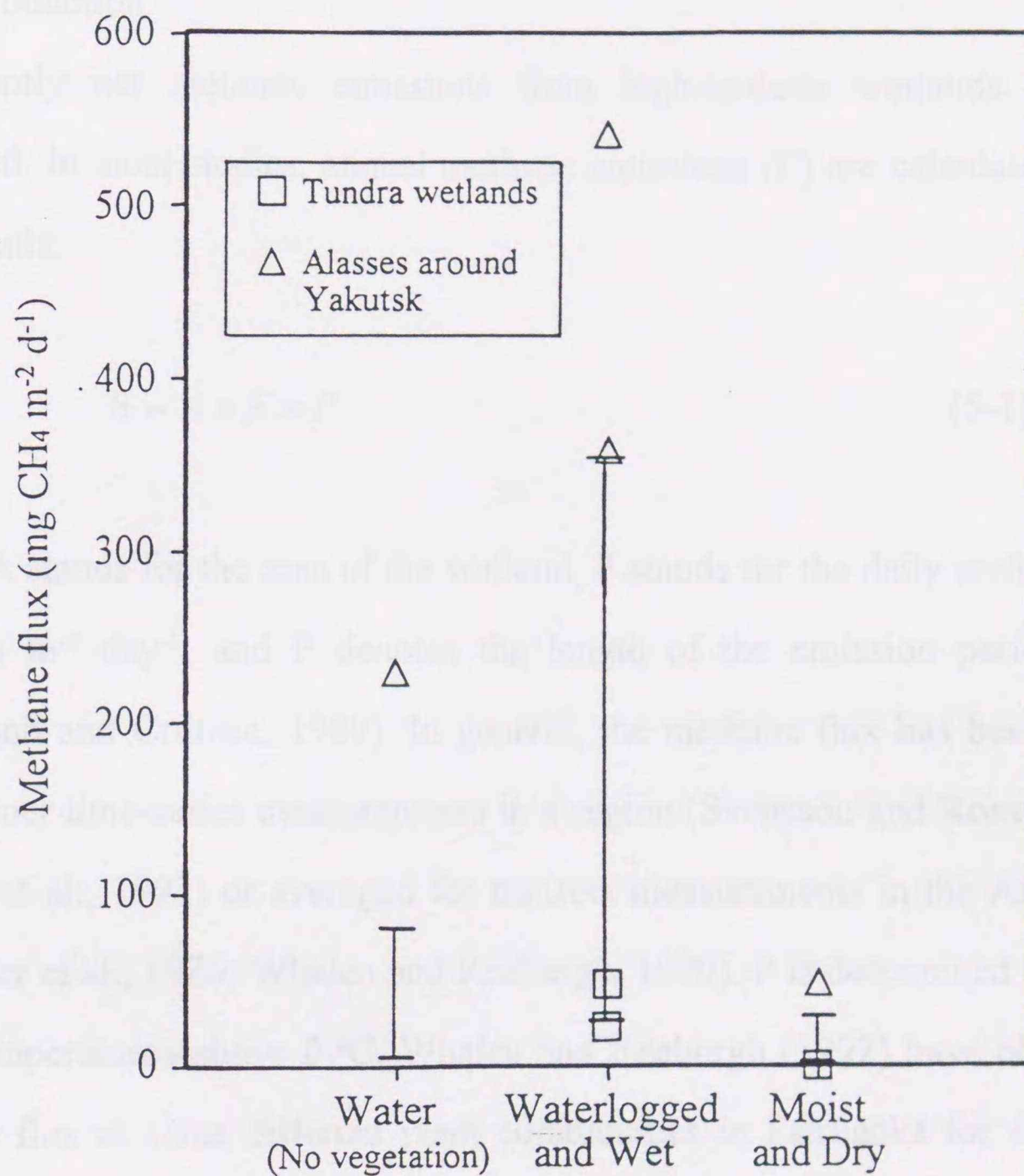
Table 4-6. Summary of previous measurements of methane flux in high latitude wetlands (> 60°N).

Reference	Location	Period	Study type	Habitat	CH ₄ flux (mg /m ² /day)
Svensson and Rosswall (1984)	Sweden 68.4°N	Jun.-Sep. 1974	summer flux time series at permanent sites	ombrotrophic communities	1.1
				hummock	3.0
				between hummocks	16.5
				shallow depression	25.9
				deeper depression	58.2
Sebacher et al. (1986)	Alaska 63-71°N	August 1984	flux transect, Arctic and boreal regions	intermediate ombro- minerotrophic communities	360.3
				minerotrophic communities	
				moist tundra	4.9
				waterlogged tundra	119
				wet tussock tundra	40
Whalen and Reeburgh (1990)	Alaska 66.5-70.2°N	Jul.-Aug. 1987	flux transect, Alaskan Pipeline Haul Road	alpine fen	289
				boreal marsh	106
				wet tundra	90
				low brush-muskeg bog	45
				moist tundra	31
Bartlett et al. (1992)	Alaska 60.8°N	Jul.-Aug. 1988	summer flux time series at permanent sites	freshwater tundra	21
				spruce forest	4.6
				alpine tundra	0.6
				upland tundra	2.3
				wet meadow tundra	144
				aquatic vegetation	89
				water (small lakes)	77
				water (large lakes)	3.8

Table 4-6. (continued)

Fan et al. (1992)	Alaska 65.1°N	Jul.-Aug. 1988	summer flux time series at permanent sites	dry tundra wet meadow tundra lake	11 29 57
Morrissey and Livingston (1992)	Alaska 60.5-70.5°N	August 1987	flux transect, Alaskan Arctic tundra	tussock tundra wet meadow open water emerging vegetation of lake	3.9 105.4 3.1 79.3
Whalen and Reeburgh (1992)	Alaska 64.9°N	all year 1987-1990	annual flux time series at permanent sites	tussock carex moss intertussock depression	59* 127.9* 11* 11.6*
This study	Siberia 72.0°N	July 1992	flux transect, Siberian Arctic tundra	tussock tundra mossy tundra	22.3 8.6
This study	Siberia 71.5°N	Jul.-Aug. 1993	summer flux time series at permanent sites	tussock tundra mossy tundra	46.3 0.3
This study	Alaska 64.9°N	May 1993	spring flux time series at permanent sites	carex moss	21.5 0.5
This study	Siberia 62.0°N	August 1993	flux transect, Siberian Alass	water floating plant wet sedge grassland	231.0 359.4 538.0 47.8

* means 4-years average



I : Previous works:

Svensson and Rosswall (1984)
 Sebacher et al. (1986)
 Whalen and Reeburgh (1990, 1992)
 Bartlett et al. (1992)
 Fan et al. (1992)
 Morrissey and Livingston (1992)

Figure 4-14. The average methane fluxes of Siberian tundra wetlands and alases around Yakutsk, and the range of methane flux observed previously at high latitude wetland (from Table 4-4).

5. Estimation of annual methane emission from Siberian tundra wetlands

5-1. Introduction

Recently net methane emissions from high-latitude wetlands have been estimated. In most studies, annual methane emissions (E) are calculated by using the formula:

$$E = A \times F \times P \quad (5-1)$$

Where A stands for the area of the wetland, F stands for the daily methane flux in $\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$, and P denotes the length of the emission period in days (Aselmann and Crutzen, 1989). In general, the methane flux has been averaged for summer time-series measurements in a region (Svensson and Rosswall, 1984; Bartlett et al., 1992) or averaged for transect measurements in the Arctic region (Sebacher et al., 1986; Whalen and Reeburgh, 1990). P is determined by monthly mean temperatures above 0°C . Whalen and Reeburgh (1992) have observed the methane flux at some different plant communities in Fairbanks for 4 years and obtained the seasonal change of the flux. However, they estimated the annual methane emission using the observed annual fluxes and fraction of each plant community for total tundra wetland area, disregarding the spatial distributions of methane flux due to the difference of physical conditions. Thus, both or either of seasonal and spatial variabilities of the methane flux have not been considered in the most previous estimations of methane emissions.

In this study, in order to estimate annual methane emission taking the seasonal and spatial variabilities of the methane flux into consideration, the daily methane

flux from the tundra wetlands is attempted to express a function of available physical factors. The procedure is given below:

(1) On the basis of the time-series observations in Mustakh Island and Fairbanks, the daily methane flux is expressed as a function of a certain physical factor of the environment.

(2) The seasonal and spatial variations of the physical environmental factor are computed using a numerical model.

(3) The annual methane flux is calculated based on (1) and (2), and the annual methane emission is estimated by multiplying this sum by the area of the wetland.

5-2. Relationship between methane emission and active layer conditions

As mentioned in Section 2-4-2, the ground temperature and moisture affect the microbiological processes and the emission of methane from the ground surface to the atmosphere. A variety of relationships between the methane flux and the air or ground temperature have been reported (Svensson and Rosswall, 1984; Crill et al., 1988a; Moore and Knowles, 1990; Bartlett et al., 1992; Morrissey and Livingston, 1992). The relationship between the flux and groundwater level or soil moisture content have also been shown in some transect studies (Svensson, 1980; Sebacher et al., 1986; Harris et al., 1988). In addition to the ground temperature and moisture, the thaw depth is an especially important factor in the tundra wetland because methanogens start to produce methane when soil temperature rises above 0 °C.

The results of the observations indicated the following effects of soil moisture to methane emission; methane was released from the ground surface to the air at the waterlogged and wet sites where the water table stood at, or above the ground

surface. In contrast, there was little emission of methane at the moist and dry sites where the water table was below 3 cm deep. Therefore, the existence of water on the ground surface is a principal factor for the methane emission. The water table depth showed little seasonal change at the tundra region where the active layer is shallower than 50 cm. Thus, the effect of soil moisture can be regarded as an extent of inundation area.

In this study, a parameter "centimeter-degrees" is introduced as the factor controlling the methane flux from waterlogged and wet places in the tundra wetland. This parameter was defined as a product of thaw depth and daily mean temperature averaged within a thaw layer (MDGT). This parameter was also proposed by Whalen and Reeburgh (1992). The centimeter-degrees is schematically represented by an area of the shaded portion in Figure 5-1. It accounts for the integration of net microbial activity over a thaw layer. Hence, it is a significantly reasonable index of methane emission from the tundra wetland. Additionally, the centimeter-degrees is a generally available parameter, because the air temperature is globally and continuously observed at a large number of points, and the thaw depth can be calculated using the air temperature.

Single correlation coefficients between the methane flux and the physical factors of an active layer such as MDGT, thaw depth and centimeter-degrees at the sites of Mustakh Island and Fairbanks are presented in Table 5-1. Statistical correlation between the water table depth and the methane flux was not recorded because the depths of water table were stable during the observational period at every sites. Table 5-1 indicates that Methane fluxes at the MW and FW sites were significantly correlated with the centimeter-degrees. At the FW site, the correlation coefficient between the thaw depth and the flux was also high because

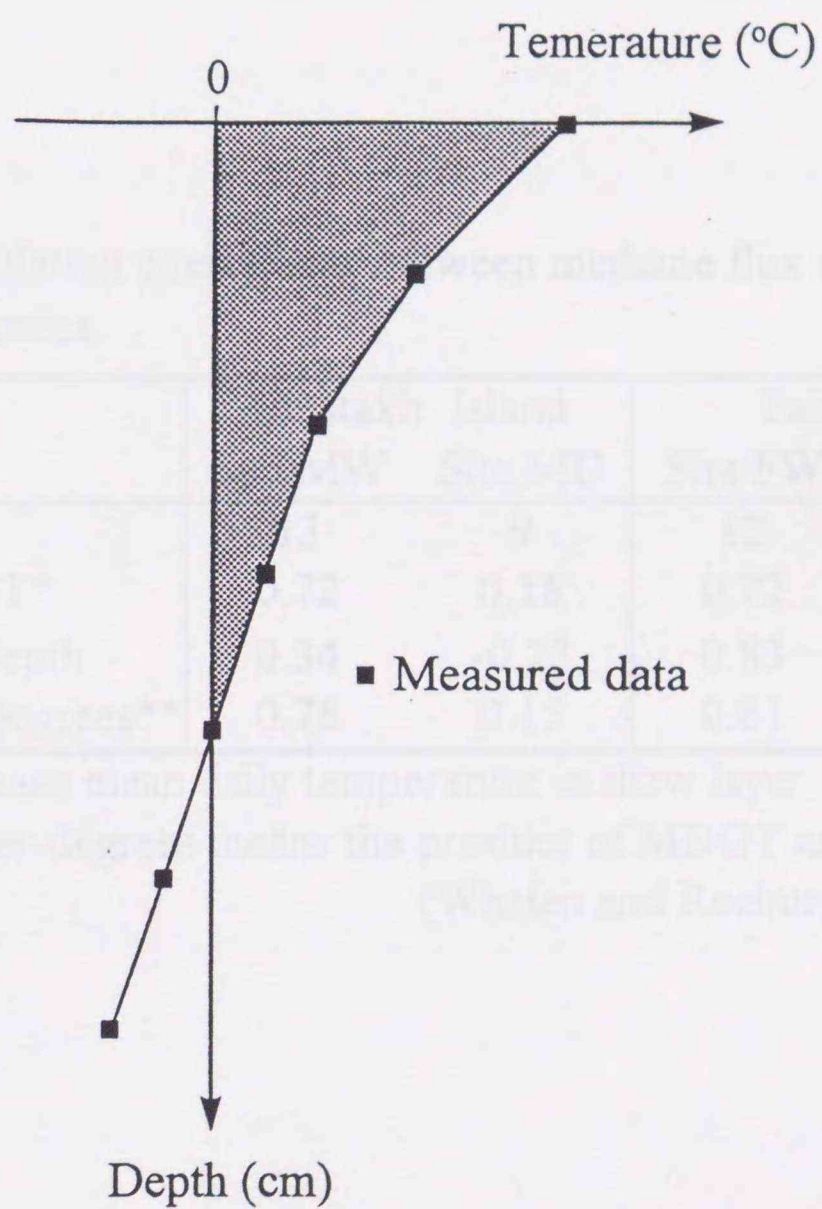


Figure 5-1. Scheme of the centimeter-degrees, which is defined as a product of thaw depth and mean daily ground temperature by Whalen and Reeburgh (1992). Squares represent measured temperature at every 10 cm deep.

the thaw of frozen soil progressed rapidly. On the other hand, at the MW and FD sites distinctive correlation was not obtained. Whalen and Reeburgh (1992) have also reported the high correlation between the methane flux and the centimeter-degrees.

In this study, the methane flux from the wet sites is expressed as a linear function of the centimeter-degrees. Figure 5-2 shows the relationship between the centimeter-degrees and the methane fluxes at the sites of MW and FW. The solid and broken lines represent regression lines obtained by a least square method. The expressions of these lines are yielded by the following equations:

Table 5-1. Correlation coefficients between methane flux and subsurface thermal properties.

	Mustakh Island		Fairbanks	
	Site MW	Site MD	Site FW	Site FD
n	13	9	12	10
MDGT*	0.72	0.18	0.72	0.31
Thaw depth	0.34	-0.23	0.83	0.27
Centimeter-degrees**	0.78	0.15	0.81	0.25

* MDGT means mean daily temperature in thaw layer

** Centimeter-degrees means the product of MDGT and thaw depth
(Whalen and Reeburgh, 1992)

the thaw of frozen soil progressed rapidly. On the other hand, at the MD and FD sites distinctive correlation was not obtained. Whalen and Reeburgh (1992) have also reported the high correlation between the methane flux and the centimeter-degrees.

In this study, the methane flux from the wet sites is expressed as a linear function of the centimeter-degrees. Figure 5-2 shows the relationship between the centimeter-degrees and the methane fluxes at the sites of MW and FW. The solid and broken lines represent regression lines obtained by a least square method. The expressions of these lines are yielded by the following equations:

$$\text{MW site: } F = 0.45 \times \text{CD} + 2.37 \quad (5-2)$$

$$\text{FW site: } F = 0.17 \times \text{CD} - 1.78 \quad (5-3)$$

Where F represents the daily methane flux in $\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ and CD denotes the centimeter-degrees in $^{\circ}\text{C} \cdot \text{cm}$. This relationship might be applicable when the thaw depth is less than a certain critical value. When the thaw layer is deeper than the critical depth methane emission is probably limited by a lack of transport pathway from deep level of soil to air, and by a lack of organic substrate for methanogenesis. It is necessary to clarify the critical depth. The regression coefficient of the MW site is approximately three times larger than that of the FW site. This difference depends on the different conditions of vegetation, substrate quality, pH and other unknown factors. It is, however, important that the methane flux could be calculated by the linear function of the centimeter-degrees in both sites, although the slope is different from each other. In the following section the

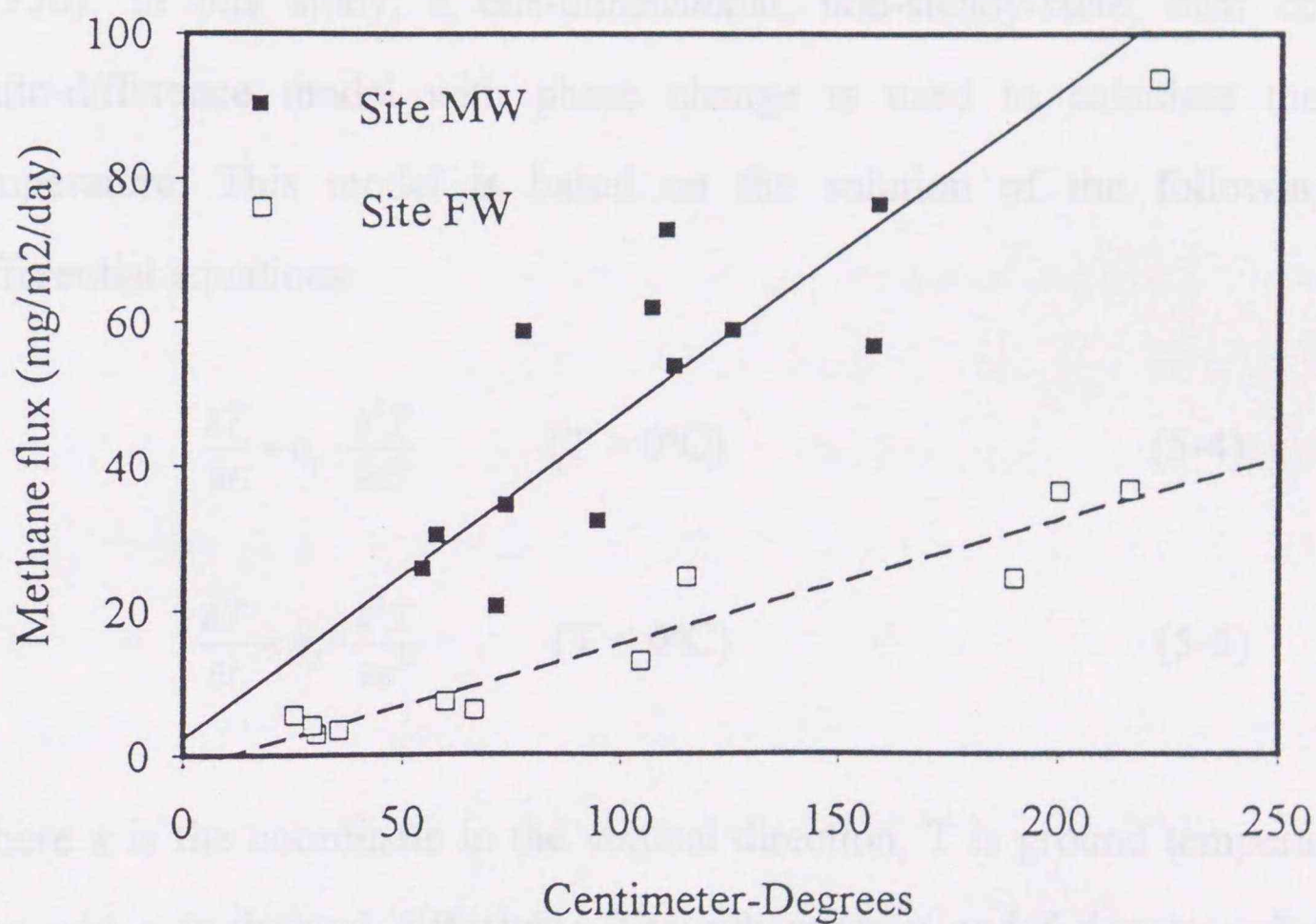


Figure 5-2. The relationship between centimeter-degrees and methane fluxes at MW and FW sites.

annual methane fluxes from Siberian tundra wetlands are estimated using the (5-2) equation, assuming that Mustakh Island is a representative site of the Siberian tundra wetlands.

5-3. Estimation of ground temperature profile and active layer thickness

5-3-1. One-dimensional thermal conduction model

Ground temperature profile and active layer thickness are obtained using heat conduction models with phase change (Kane et al., 1991; Nakayama et al., 1993b). In this study, a one-dimensional, non-steady-state, heat conduction, finite-difference model with phase change is used to calculate the ground temperature. This model is based on the solution of the following partial differential equations:

$$\frac{\partial T}{\partial t} = a_u \cdot \frac{\partial^2 T}{\partial x^2} \quad (T > 0^\circ\text{C}) \quad (5-4)$$

$$\frac{\partial T}{\partial t} = a_f \cdot \frac{\partial^2 T}{\partial x^2} \quad (T < 0^\circ\text{C}) \quad (5-5)$$

Where x is the coordinate in the vertical direction, T is ground temperature, t is time and a is thermal diffusivity. The subscripts u and f denote unfrozen and frozen state, respectively. These equations are nondimensionalized and solved numerically using an implicit finite difference technique. Using subscripts (n) on the function T to denote the space coordinate and superscripts (p) on T to denote the time coordinate, nondimensionalized temperature T is approximated as:

$$T_n^{p+1} \approx \frac{\Delta t}{(\Delta x)^2} \cdot (T_{n+1}^{p+1} + T_{n-1}^{p+1} - 2T_n^{p+1}) + T_n^p \quad (5-6)$$

Where Δt is the time step which is one day and Δx is the grid spacing which is 10 cm. The latent heat with phase change is incorporated using an apparent heat capacity method. The latent heat is substituted for an apparent heat capacity with equivalent amounts when freezing temperature stands within a given temperature range.

The following parameters are required for the numerical simulation. The first is properties of the sediments, such as thermal conductivity, volumetric heat capacity and volumetric water content. The structure of sediment layer is assumed to be uniform over Siberian tundra wetland and the properties are given in Table 5-2. The upper layer consists of peat and the middle layer is a mixture of silt and peat. The lower layer is assumed to consist of ice. This assumption is proper because the ice complexes, which are a special type of massive ice in permafrost, are well developed in the Siberian tundra area. The thermal conductivities of the upper two layers for both thaw and frozen conditions were calculated using the decrements with depth of daily fluctuations of ground temperatures and the densities of the sediments. The ground temperatures at several depths and the densities were measured automatically during a whole year on Kalakhari Island and Mustakh Island. The volumetric water contents of each layer were also measured on Kalakhari Island in summer of 1992. The volumetric heat capacities were calculated using the volumetric water contents and the specific heat of the sediment and water. The specific heat of the dry sediment is assumed to be $0.2 \text{ [cal g}^{-1} \text{ K}^{-1}]$. And, that of water is given as $1.0 \text{ [cal g}^{-1} \text{ K}^{-1}]$ above 0°C and $0.5 \text{ [cal g}^{-1} \text{ K}^{-1}]$ below 0°C .

The second required parameter is the upper and lower boundary conditions.

The condition of the upper boundary which is the ground surface is given as annual fluctuation of mean daily ground surface temperature. The lower boundary is at a depth of 10 m below the surface and its condition is assumed to be a constant temperature which is equal to mean January ground surface temperature. The annual variation of daily mean ground surface temperature is given in the following sinusoidal form and is applicable to the place where the ground temperature has not been measured, in addition to the measured one.

Table 5-2. Soil properties in Siberian tundra wetland.

Depth (cm)	Material	Volumetric water content	Thermal conductivity (cal/cm/sec/K)		Volumetric heat capacity (cal/cm ³)	
			frozen	unfrozen	frozen	unfrozen
0 - 20 cm	peat	0.8	0.0039	0.0013	0.35	0.70
20 - 50 cm	silt & peat	0.7	0.0030	0.0013	0.30	0.60
50 - 1000 cm	ice	1	0.0053	0.0014	0.50	1.00

where T_s is the mean daily ground surface temperature, T_m is the mean daily ground surface temperature in the month of maximum ground surface temperature, T_{min} is the minimum ground surface temperature, T_{max} is the maximum ground surface temperature, T_0 is the ground surface temperature at the time of maximum ground surface temperature, P is the phase difference. From the ground temperature profile can be estimated once the ground surface and annual range of ground surface temperature are obtained.

5-3-2. Simulation of ground temperature profile in Khatanga Island

In order to verify the accuracy of the solution, simulated ground temperatures at depths of 20 and 50 cm were compared with measured ones on Khatanga Island in 1993. At first, the annual variation of measured ground surface temperature shown in Figure 5-2 was set as the upper boundary condition. The results of calculations and the measured temperature from June to September are shown in Figure 5-3. The simulated variation of temperature at 20 and 50 cm

The condition of the upper boundary which is the ground surface is given as annual fluctuation of mean daily ground surface temperature. The lower boundary is at a depth of 10 m below the surface and its condition is assumed to be a constant temperature which is equal to mean annual ground surface temperature. The annual variation of daily mean ground surface temperature is given in the following sinusoidal form to be applicable to the place where the ground temperature has not been measured, in addition to the measured one:

$$ST(n) = AMP \times \sin(2n\pi / 365 + PH) + MAST \quad (5-7)$$

Where ST stands for the daily mean ground surface temperature and n is an elapsed day. AMP represents the amplitude of annual variation which is defined as a difference between the maximum and minimum of mean monthly ground surface temperature. MAST represents annual mean ground surface temperature and PH is a phase difference. Thus the ground temperature profile can be estimated once the annual mean and annual range of ground surface temperature are obtained.

5-3-2. Simulation of ground temperature profile at Kalakhari Island

In order to verify the accuracy of the solution, simulated ground temperatures at depths of 20 and 50 cm were compared with measured ones on Kalakhari Island in 1993. At first, the annual variation of measured ground surface temperature shown in Figure 4-5 was used as the upper boundary condition. The results of calculations and the measured temperatures from June to September are shown in Figure 5-3. The simulated variations of temperature at 20 and 50 cm

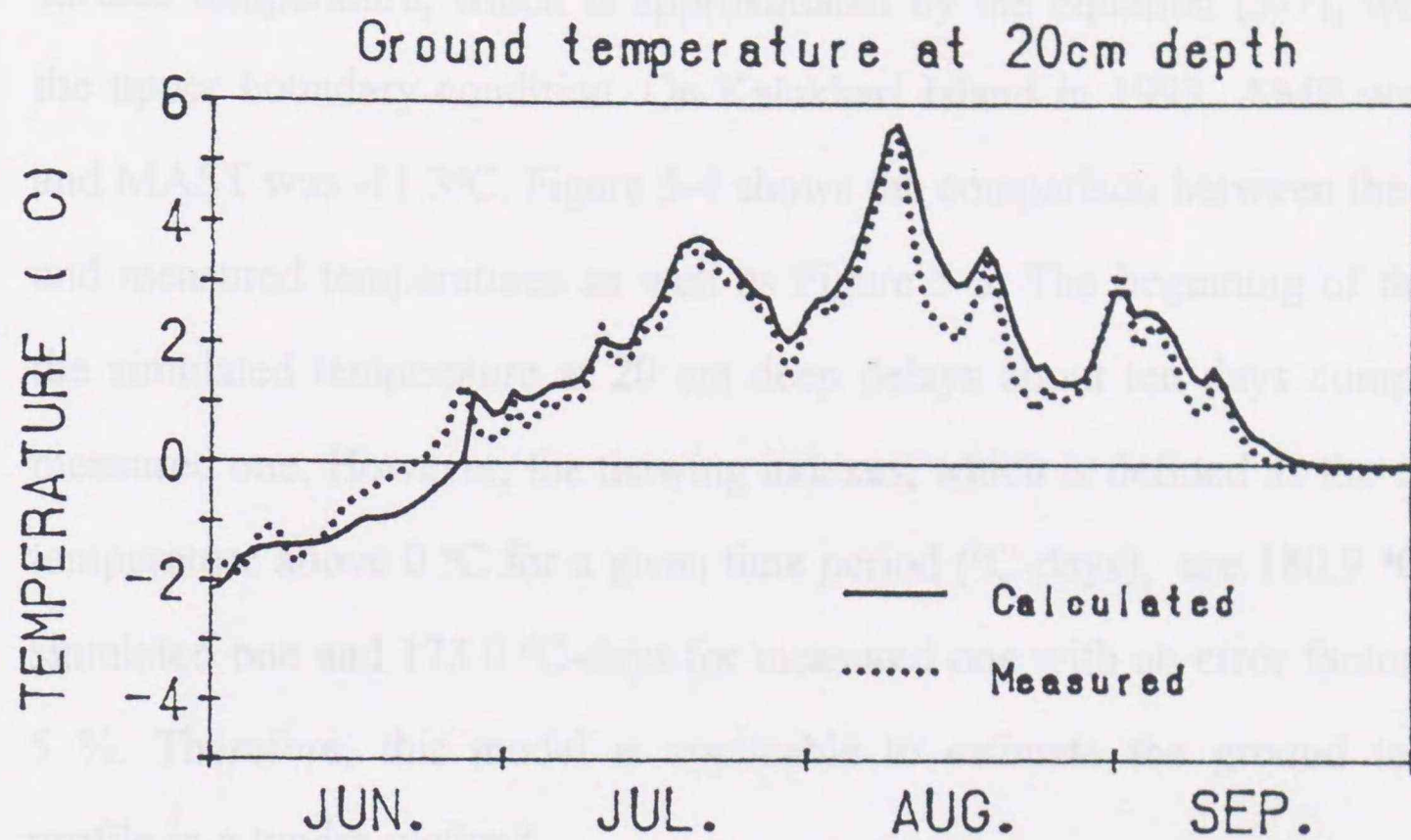
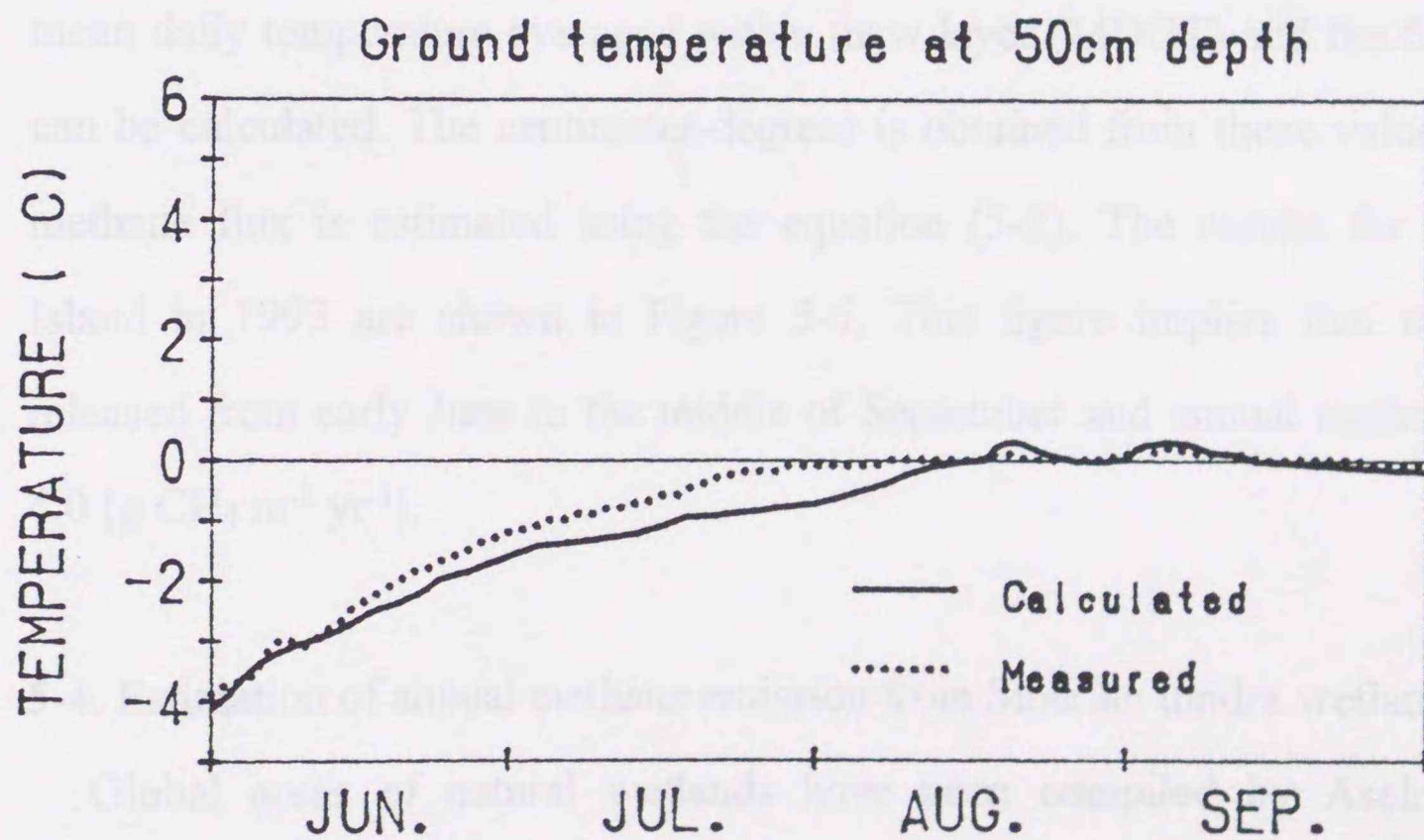


Figure 5-3. Comparison between simulated and measured temperature at depths of 20 and 50cm on Kalakhari Island, 1993. Measured ground surface temperature was used as the upper boundary condition.

deep coincide with measured ones. The beginning and the end of thaw period at the 20 cm depth are also well simulated. Secondly, the variation of ground surface temperature, which is approximated by the equation (5-7), was used as the upper boundary condition. On Kalakhari Island in 1993, AMP was 18.0 °C and MAST was -11.3°C. Figure 5-4 shows the comparison between the simulated and measured temperatures as well as Figure 5-3. The beginning of the thaw of the simulated temperature at 20 cm deep delays about ten days compared with measured one. However, the thawing indexes, which is defined as the cumulative temperature above 0 °C for a given time period (°C-days), are 180.9 °C-days for simulated one and 173.0 °C-days for measured one with an error factor less than 5 %. Therefore, this model is applicable to estimate the ground temperature profile in a tundra wetland.

Using the simulated ground temperature profile at depths of every 10 cm, the mean daily temperature averaged within thaw layer (MDGT) and the thaw depth can be calculated. The centimeter-degrees is obtained from these values and the methane flux is estimated using the equation (5-2). The results for Kalakhari Island in 1993 are shown in Figure 5-5. This figure implies that methane is released from early June to the middle of September and annual methane flux is 4.0 [g CH₄ m⁻² yr⁻¹].

5-4. Estimation of annual methane emission from Siberian tundra wetlands

Global areas of natural wetlands have been compiled by Aselmann and Crutzen (1989) and Matthews and Fung (1987). Aselmann and Crutzen (1989) reported the distribution and percentages of natural wetlands on a 2.5° latitude by 5.0° longitude grid system. Using this information and the vegetation map of the

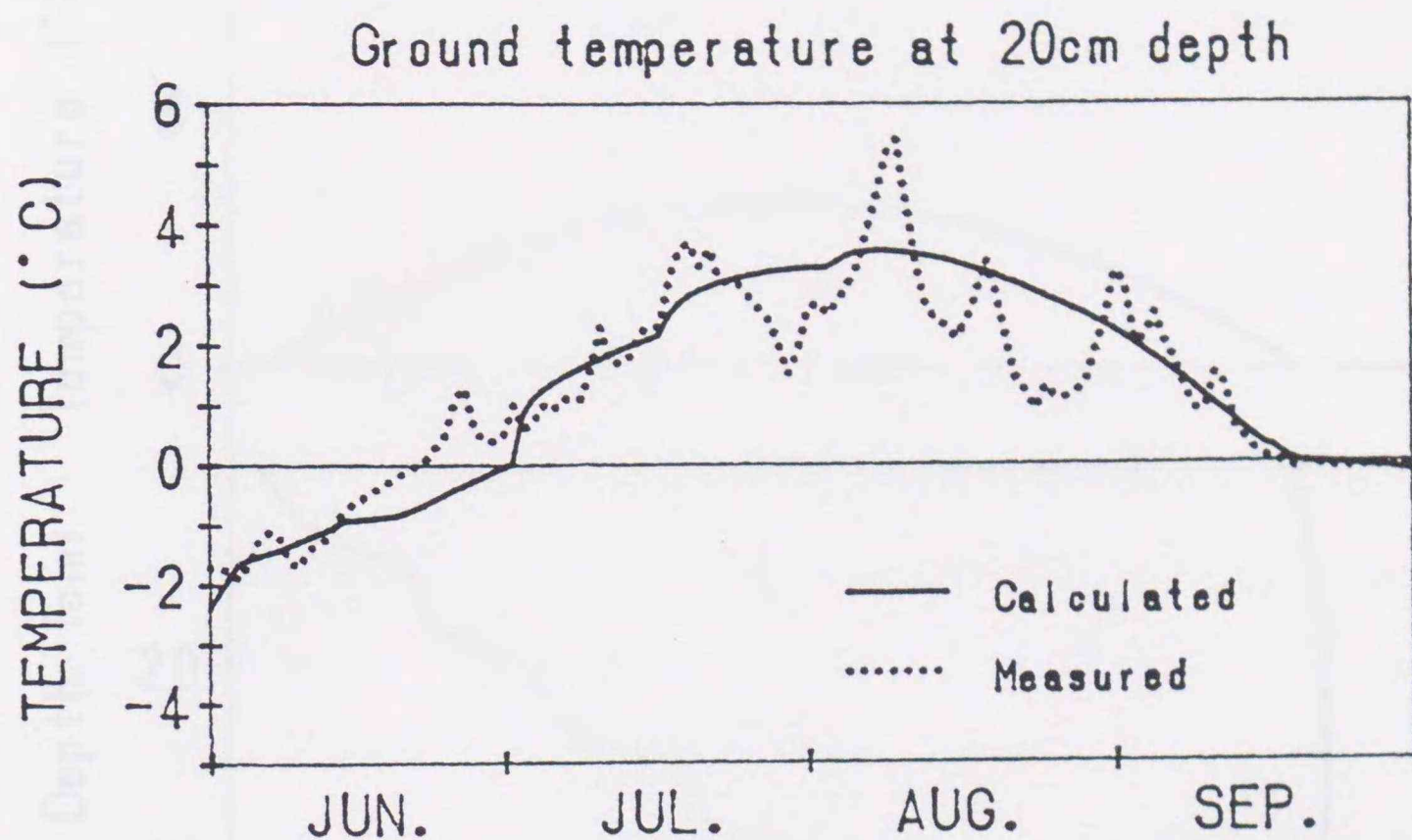
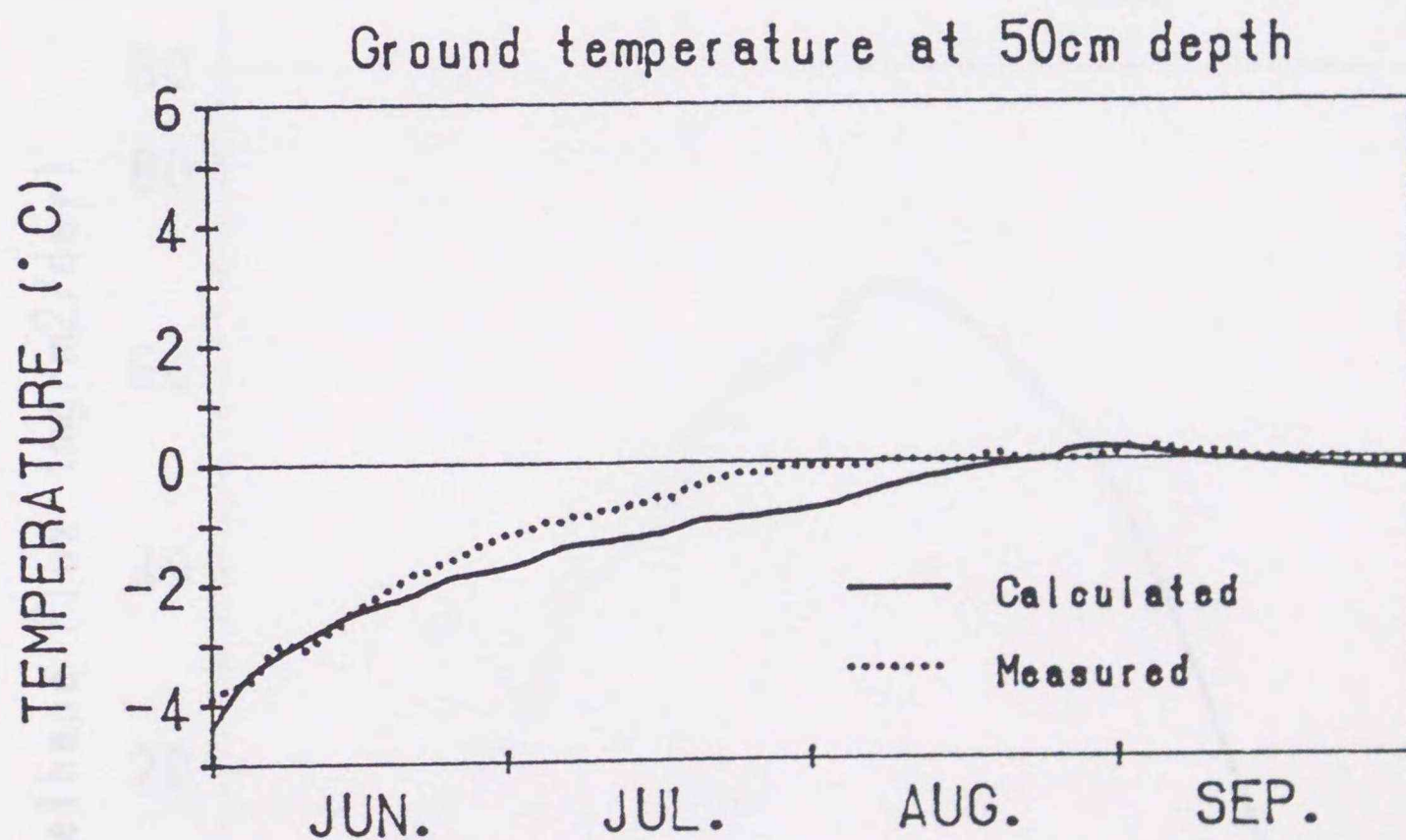


Figure 5-4. Comparison between simulated and measured temperature at depths of 20 and 50 cm on Kalakhari Island, 1993. Approximated ground surface temperature by sine curve was used as the upper boundary condition.

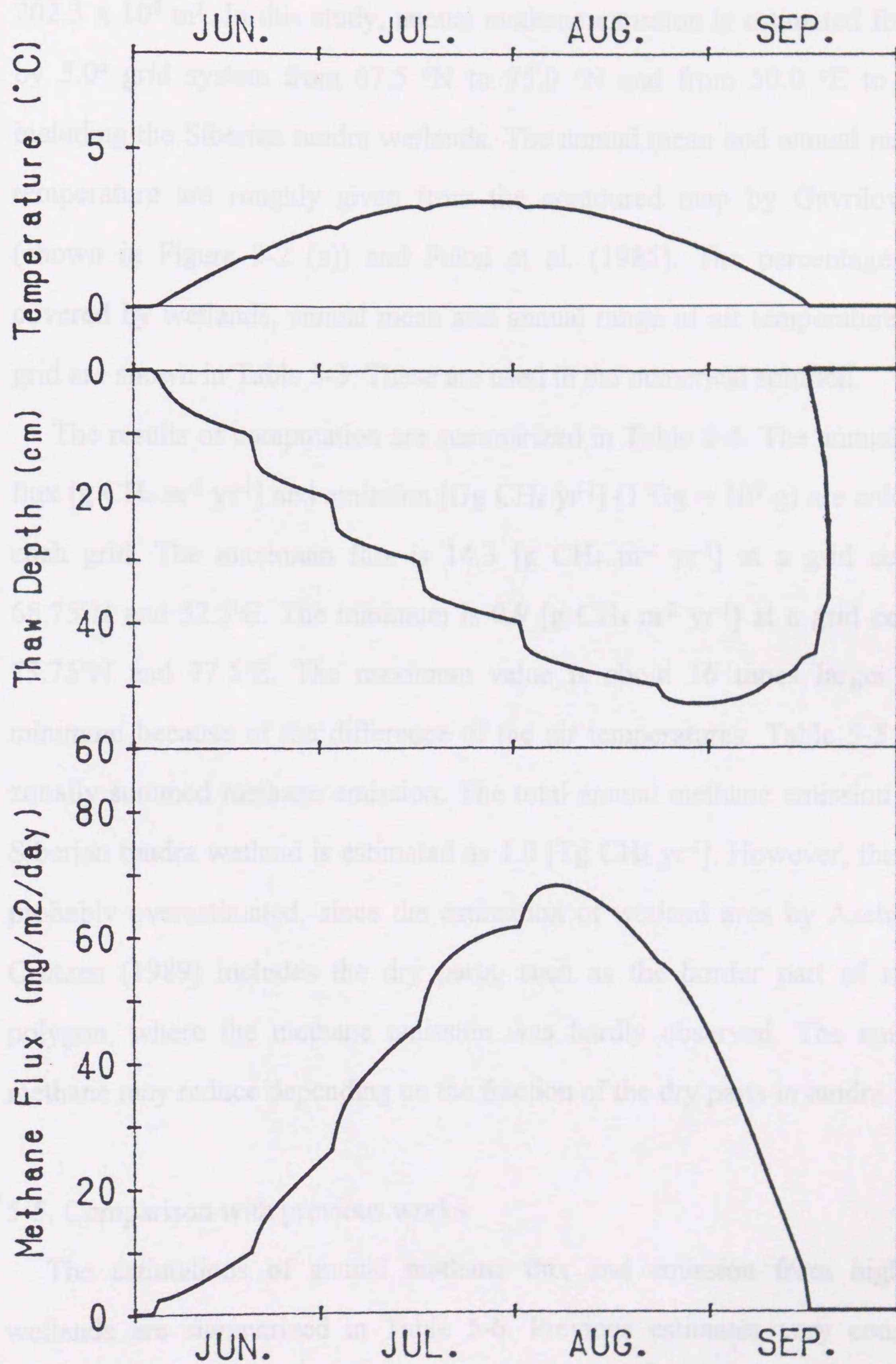


Figure 5-5. Simulation of MDGT (upper), thaw depth (middle) and methane emission (lower) on Kalakhari Island, 1993.

Siberian region (Figure 3-4), the area of Siberian tundra wetland is estimated as $202.3 \times 10^9 \text{ m}^2$. In this study, annual methane emission is estimated for the 2.5° by 5.0° grid system from 67.5°N to 75.0°N and from 50.0°E to 180.0°E , including the Siberian tundra wetlands. The annual mean and annual range of air temperature are roughly given from the contoured map by Gavrilova (1981) (shown in Figure 3-2 (a)) and Fukui et al. (1985). The percentages of area covered by wetlands, annual mean and annual range of air temperature for each grid are shown in Table 5-3. These are used in the numerical solution.

The results of computation are summarized in Table 5-4. The annual methane flux [$\text{g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$] and emission [$\text{Gg CH}_4 \text{ yr}^{-1}$] ($1 \text{ Gg} = 10^9 \text{ g}$) are calculated at each grid. The maximum flux is $14.3 [\text{g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}]$ at a grid centered at 68.75°N and 52.5°E . The minimum is $0.9 [\text{g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}]$ at a grid centered at 73.75°N and 77.5°E . The maximum value is about 16 times larger than the minimum because of the difference of the air temperatures. Table 5-5 indicates zonally summed methane emission. The total annual methane emission from the Siberian tundra wetland is estimated as $1.0 [\text{Tg CH}_4 \text{ yr}^{-1}]$. However, this value is probably overestimated, since the estimation of wetland area by Aselmann and Crutzen (1989) includes the dry parts, such as the border part of ice-wedge polygon, where the methane emission was hardly observed. The emission of methane may reduce depending on the fraction of the dry parts in tundra wetland.

5-5. Comparison with previous works

The estimations of annual methane flux and emission from high-latitude wetlands are summarized in Table 5-6. Previous estimates vary considerably, they generally center between 20 and 40 [$\text{Tg CH}_4 \text{ yr}^{-1}$]. These can account for

Table 5-3. Distribution of tundra wetland, annual mean and annual range of air temperature for the 2.5° latitude by 5.0° longitude grids, including Siberian tundra wetland.

[illegible]

Annual flux of methane ($\text{g/m}^2/\text{yr}$)	
Area of wetland (10^4m^2)	
Annual emission of methane (Gg/yr)	

	50.0	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0	125.0	130.0	135.0	140.0	145.0	150.0	155.0	160.0	165.0	170.0	175.0
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
	55.0	60.0	65.0	70.0	75.0	80.0	85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0	125.0	130.0	135.0	140.0	145.0	150.0	155.0	160.0	165.0	170.0	175.0	
75.0				1.7		0.9		2.2	2.6	2.1	1.3	1.6		2.0	2.9											
1	-	-	-	1.0	-	1.0	-	1.0	1.0	7.8	1.0	2.9	-	2.9	1.9	9.7	-	-	-	-	-	-	-	-	-	
72.5				1.7		0.9		2.2	2.6	16.4	1.3	4.6		5.8	3.8	28.1										
72.5				3.7	3.5	4.0	4.5		5.0	4.2	3.6					3.6	2.0	2.5	2.0	2.5	2.9					
1	-	-	-	2.2	4.7	5.8	2.2	-	5.8	1.1	1.1	-	-	-	-	1.1	12.3	12.3	13.5	5.8	12.3	-	-	-	-	
70.0				8.1	16.5	23.2	9.9		29.0	4.6	4.0				4.0	24.6	30.8	27.0	14.5	35.7						
70.0	14.3	11.7	11.1	10.3	10.6	9.9	9.9	11.9																		
1	3.8	5.0	3.8	1.3	1.3	3.8	2.5	1.3	-	-	-	-	-	-	-	-	-	6.3	13.9	21.3	3.6	5.5	4.2	2.7	2.3	
67.5	54.3	58.5	42.2	13.4	13.8	37.6	24.8	15.5																		

Table 5-5. Summary of zonally estimates of methane emission in Siberian tundra wetlands.

Latitude (degree N)	Area of wetland (10^9m^2)	Annual methane emission (Tg / yr)
75.0 - 72.5	30.2	0.1
72.5 - 70.0	80.2	0.2
70.0 - 67.5	91.9	0.7
Total	202.3	1.0

Table 5-6. Summary of methane emission estimates from high-latitude wetlands

Reference	Annual Methane Flux (mg/m ² /yr) (Daily flux x Period)	Annual Methane Emission from Tundra wetlands (Tg) (Area : 10 ⁹ m ²)
This study	0.9 (73.75°N, 77.5°E) 14.3 (68.75°N, 52.5°E)	1.0 (202: Siberian tundra wetland))
Sebacher et al. (1986)	11.2 (112 mg/m ² /d x 100 days)	45.0 - 106.0 (4000 - 9500)
Matthews and Fung (1987)	*20.0 (200 mg/m ² /d x 100 days)	2.7 (128)
Whalen and Reeburgh (1990)	5.2 (52 mg/m ² /d x 100 days)	38.0 (7340)
Fan et al. (1992)	3.0 (25 mg/m ² /d x 120 days)	22.0 (7300)
Bartlett et al. (1992)	12.0 (wet tundra) (100 mg/m ² /d x 120 days) 0.7 (dry/moist tundra) (5.8 mg/m ² /d x 120 days)	10.9 (7340)
Whalen and Reeburgh (1988)	**8.0 (Eriophorum) **5.0 (Carex) **0.5 (Moss) **0.6 (Interussock)	19.3 - 32.7 (7340)

* literature emission rates

** based on the observations throughout the year

about 17 to 35 % of global methane emissions from wetlands. My estimated value as $1.0 \text{ [Tg CH}_4 \text{ yr}^{-1}]$ is much smaller than those in the previous researches. The difference might be noted that my estimation was made only in the Siberia and the previous ones were made on a global scale. Since the values of annual methane flux in this study, ranging from 0.9 to $14.3 \text{ [g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}]$, are comparable with those in the previous studies, the difference of the estimations is caused by the difference of tundra wetland area used for the estimations.

The definition of "tundra wetland" was differently used among researchers. The tundra wetland is regarded as the inundated treeless terrain in this study. According to this definition, the tundra is distributed only in Arctic region. Fairbanks and Yukon-Kuskokwim delta, where the observations were made by Whalen and Reeburgh (1988, 1992) and Bartlett et al., (1992), are not the tundra but the coniferous forest region. Matthews (1983) calculated that the global area of tundra wetland is $7340 \times 10^9 \text{ m}^2$. Although the area of global tundra estimated by Matthews (1983) also incorporates various types of tundra, the estimation was based only on vegetation and disregarded soil moisture conditions. This area was used as the area of tundra wetland in some studies (Sebacher et al., 1986; Whalen and Reeburgh, 1990; Fan et al., 1992). Global wetland area has been compiled to be about 5300 to $5700 \times 10^9 \text{ m}^2$ (Matthews and Fung, 1987; Aselmann and Crutzen, 1989) and tundra wetland area has been estimated $596 \times 10^9 \text{ m}^2$ (Chappellaz et al., 1993b), hence the methane emission from tundra wetland, in the strict sense, must be smaller than those estimated previously.

6. Estimation of methane emission change induced by a climatic change

The methane flux from the tundra wetland is determined by the ground temperature and the thaw depth. The thaw depth also depends on the summer ground temperatures. Therefore, the warming of air temperature, especially in summer, might cause an increase of methane emission from the tundra wetlands. In this chapter, the increase of annual methane flux on the tundra wetland due to a future possible warming is estimated on Kalakhari Island.

6-1. Prediction of future climatic warming

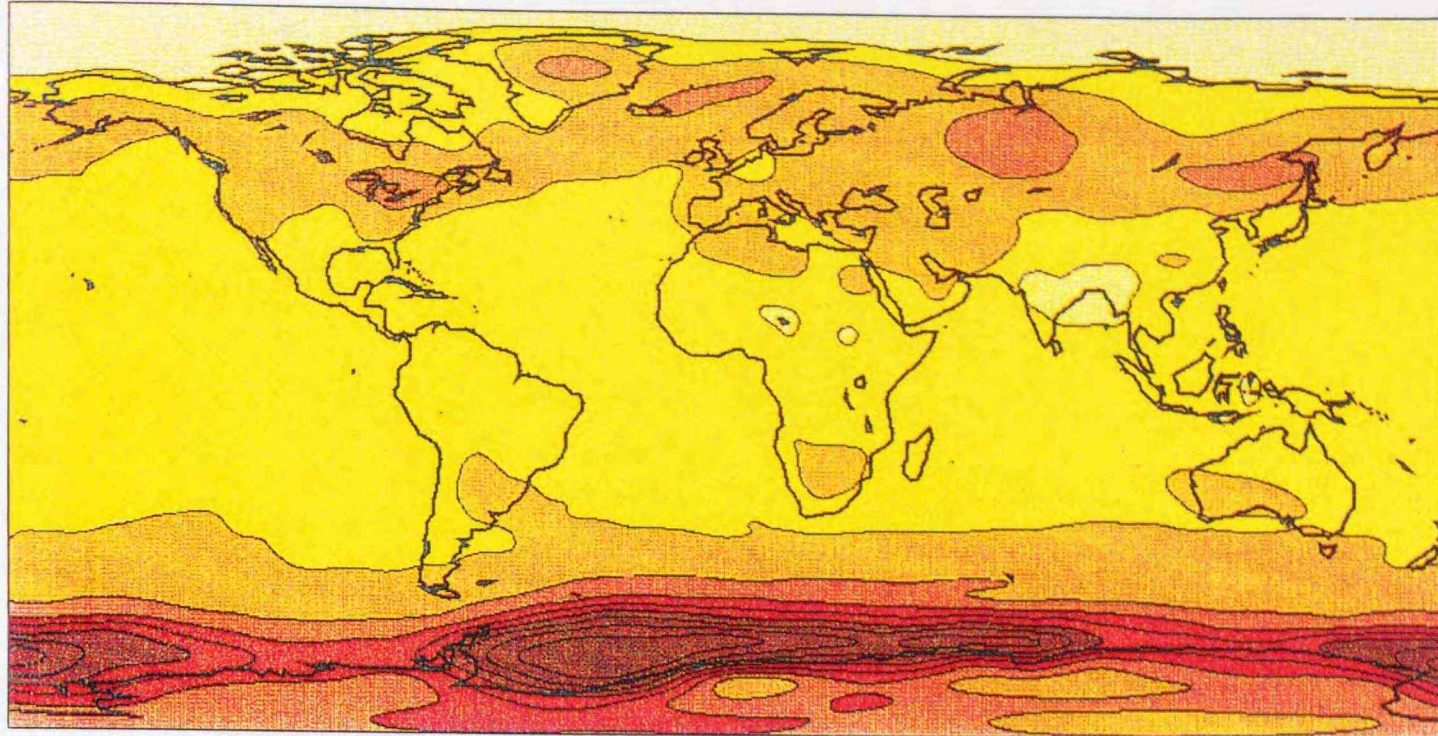
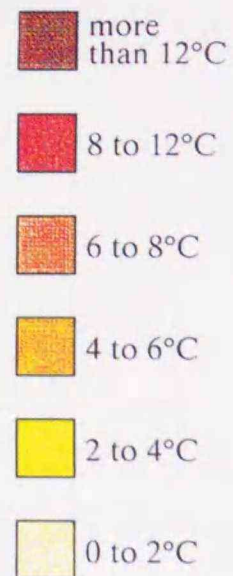
Magnitudes of future warming that may result from increase of concentrations of CO₂ and other greenhouse gases in the atmosphere have been predicted using GCMs (General Circulation Models) by a lot of research groups (e.g. Manabe and Stouffer, 1980; Hansen et al., 1984; Washington and Mheel, 1984; Mitchell et al., 1989; Stouffer et al., 1989; Manabe et al., 1992). In general, two type of simulations have been carried out to predict future climatic change: one is an equilibrium experiment and the other is a time-dependent experiment. The equilibrium experiment uses atmosphere-ocean mixed layer model and ignores both the deep ocean and changes in ocean circulation (Cubasch and Cess, 1990). Thus this is easier and requires less computer time than time-dependent simulations. However, as long as greenhouse gas concentrations continue to increase, climate will not reach at an equilibrium state. Thus, equilibrium simulation is not applicable in direct manner as forecasts (Mitchell et al., 1990).

Most equilibrium experiments consider the effect of doubling the concentration of atmospheric CO₂, since the effect of increases in other trace

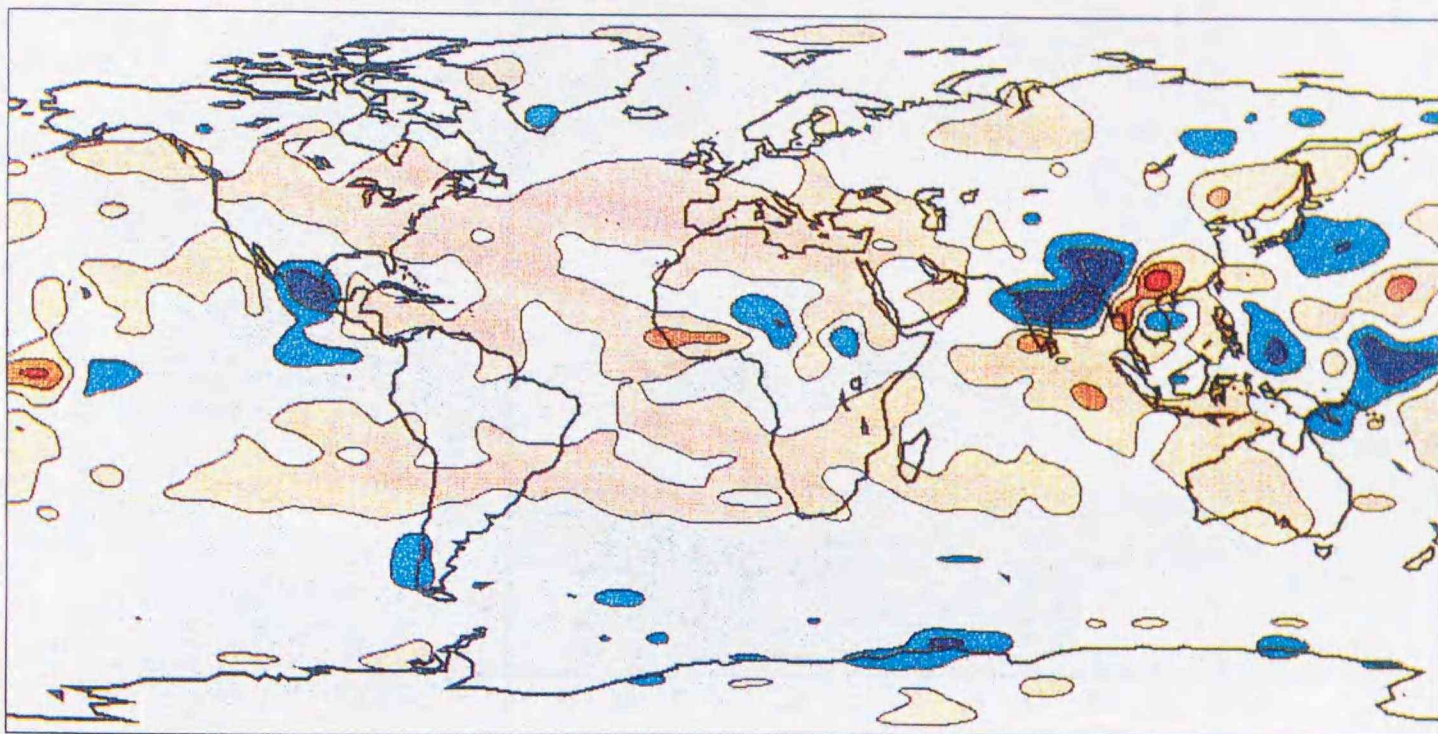
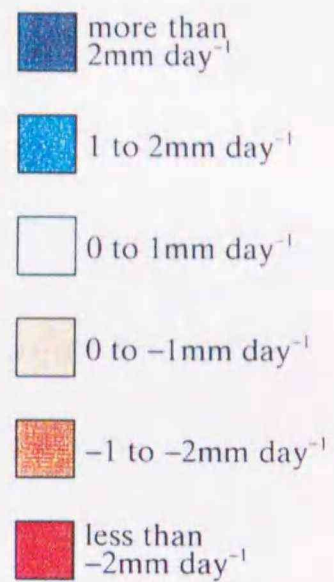
gases can be calculated in terms of an effective CO₂ increase. All models show substantial changes in climate when equivalent CO₂ concentrations are doubled, even though the changes vary from model to model on a sub-continental scale. Figure 6-1 shows changes in surface air temperature, precipitation, and soil moisture due to equivalent CO₂ doubling for the months of June-July-August. The estimates come from the Geophysical Fluids Dynamics Laboratory (Mitchell et al., 1990). In the Arctic region of Siberia, air temperature is estimated to rise higher by 2 to 4 °C than present value, while it is predicted that there will be little changes in precipitation and soil moisture. The zonally averaged increase in surface air temperature due to equivalent CO₂ doubling is shown in Figure 6-2 (Hansen et al., 1984). At 70 °N, which is close to the latitude of Tiksi, the air temperature is estimated to rise higher than the present temperature by 8 °C in winter and by 2 °C in summer.

Time-dependent response of climate to a gradual increase in greenhouse gases concentrations is computed using a coupled ocean-atmosphere general circulation model with full ocean dynamics. These simulations have now been done by a small number of researchers using coarse resolution models for a 100 year long duration. Their results indicate that the global rise in temperature with a steadily increase of equivalent CO₂ concentration of 1% per year, is an approximately constant fraction of the equilibrium rise caused by the instantaneous increasing of greenhouse gases. Figure 6-3 shows the simulated increase in global averaged temperature for the CO₂ increase of 1 % per year. The time-dependent response of surface air temperature to a doubling of CO₂ is about 60 % of the current equilibrium value. The regional patterns of temperature and precipitation change generally resemble those of an equilibrium simulation of an atmospheric model,

(e) JJA $2\times\text{CO}_2 - 1\times\text{CO}_2$ surface air temperature: GFHI



(e) JJA $2\times\text{CO}_2 - 1\times\text{CO}_2$ precipitation: GFHI



(e) JJA $2\times\text{CO}_2 - 1\times\text{CO}_2$ soil moisture: GFHI

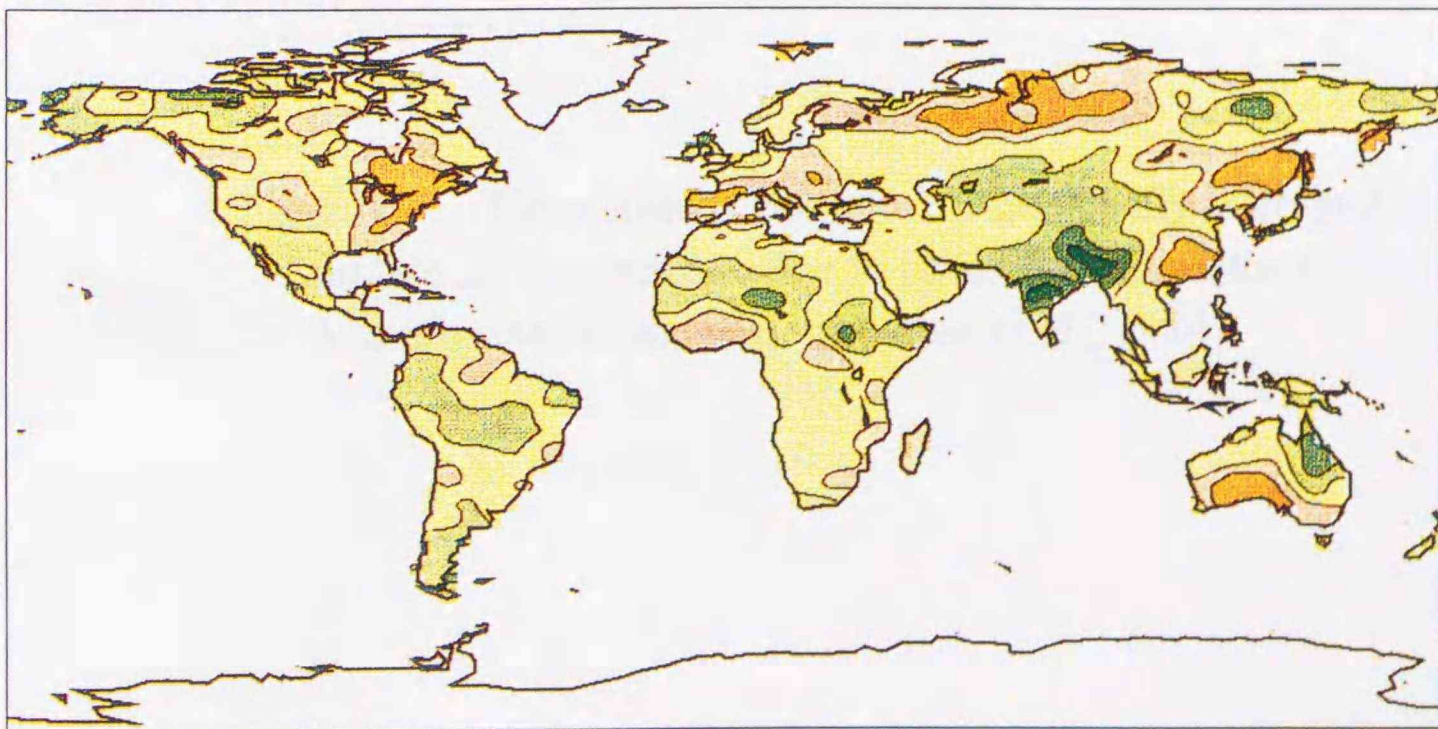
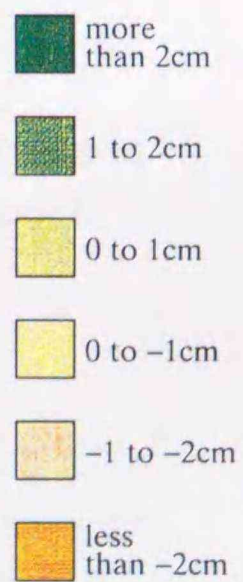


Figure 6-1. Change in surface air temperature (upper), precipitation (middle) and soil moisture (lower) due to doubling CO_2 , for months June-July-August. (Mitchell et al., 1990).

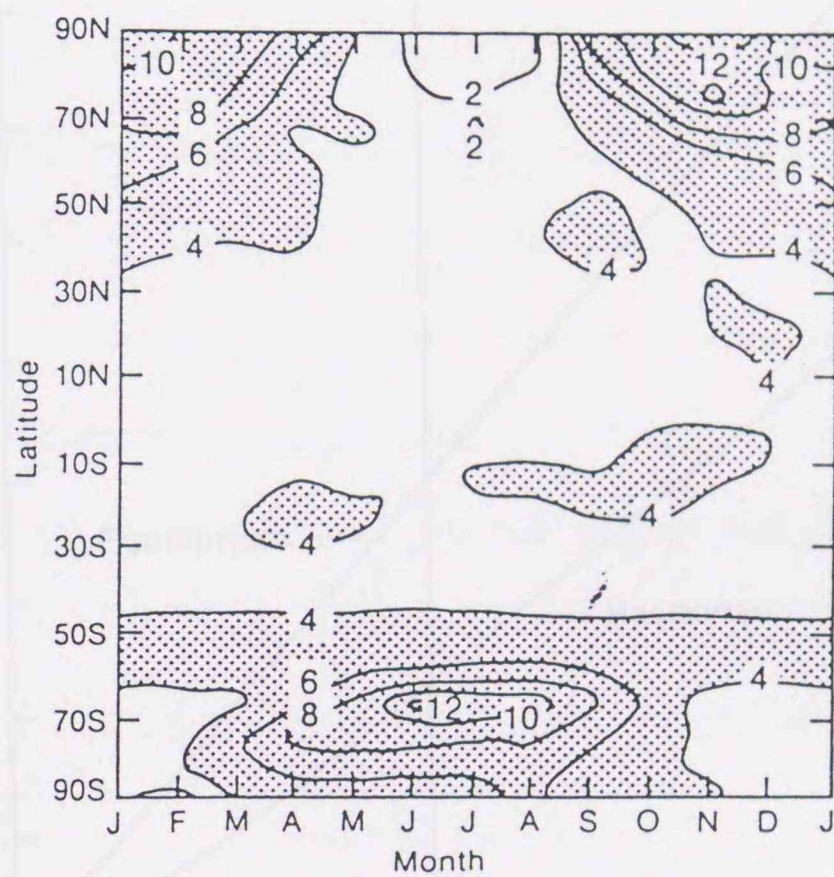


Figure 6-2. Time-latitude diagram of the zonally averaged increase in surface air temperature due to doubling CO₂ in the GISS model. Warming >4 °C stippled. (Hansen et al., 1984).

though uniformly reduced in magnitude (Bretherton et al., 1990).

6-2 Evolution of change of methane emissions caused by climate warming

6-2-1 Equilibrium climate change

At first, the equilibrium change of methane flux caused by CO_2 doubling is

estimated for Kakkai Island. On the basis of the prediction shown in Figure 6-1

and 6-2, it is assumed that on Kakkai Island (TTT) precipitation and soil

moisture do not change and ground surface and air temperature increases by 2°C

in summer and by 0.5°C in winter under the assumption of the doubling of

equivalent CO_2 concentration. Then increase of summer temperature result in

an increase of annual mean temperature of 1.25°C and reduction of amplitude of

annual variation by 1.5°C . Ground temperature profile is simulated using

a sine curve with 13.0°C of AMP and 10°C of TTT (equation (3-7)) since

the present TTT is 14.0°C and 11.3°C , respectively, on Kakkai

Island.

Figure 6-3 shows the MDTT, the depth and methane flux results from the

calculation. The time period shown by the x-axis is month and the y-axis

depth becomes that 20 cm deeper than the present conditions shown in Figure

3-5. The annual methane flux results in $3.9 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$ and becomes more

than twice of the present value.

Figure 6-3. The change in surface air temperature for a linear increase in greenhouse gas forcing, with an equivalent CO_2 doubling time of 70 years. (bretherton et al., 1990).

In the next step, the time-dependent increase of methane flux with a constant

change induced by a global increase of atmospheric CO_2 is estimated. If the

equivalent CO_2 concentration increases at a rate of 1% per year, the

though uniformly reduced in magnitude (Bretherton et al., 1990).

6-2. Evaluation of change of methane emission caused by climatic warming

6-2-1. Equilibrium climatic change

At first, the equilibrium change of methane flux caused by CO₂ doubling is estimated for Kalakhari Island. On the basis of the prediction shown in Figure 6-1 and 6-2, it is assumed that on Kalakhari Island (72°N), precipitation and soil moisture do not change and ground surface and air temperature increases by 2 °C in summer and by 8 °C in winter, under the assumption of the doubling of equivalent CO₂ concentration. These increases of seasonal temperature result in an increase of annual mean temperature by 5 °C and an reduction of amplitude of annual variation by 3 °C. Thus, the ground temperature profile is simulated using a sine curve with 15.0 °C of AMP and -6.3 °C of MAST (equation (5-7)) since the present AMP and MAST is 18.0 °C and -11.3 °C, respectively, on Kalakhari Island.

Figure 6-4 shows the MDGT, thaw depth and methane flux results from the calculation. The thaw period becomes longer by about one month and the thaw depth becomes about 20 cm deeper than the present conditions shown in Figure 5-5. The annual methane flux results in 8.9 [g CH₄ m⁻² yr⁻¹] and becomes more than twice as large as the present flux.

6-2-2. Time-dependent climatic change

In the next step, the time-dependent increase of methane flux with a climatic change induced by a gradual increase of atmospheric CO₂ is estimated. If the equivalent CO₂ concentrations increase at a rate of 1 % per year, the

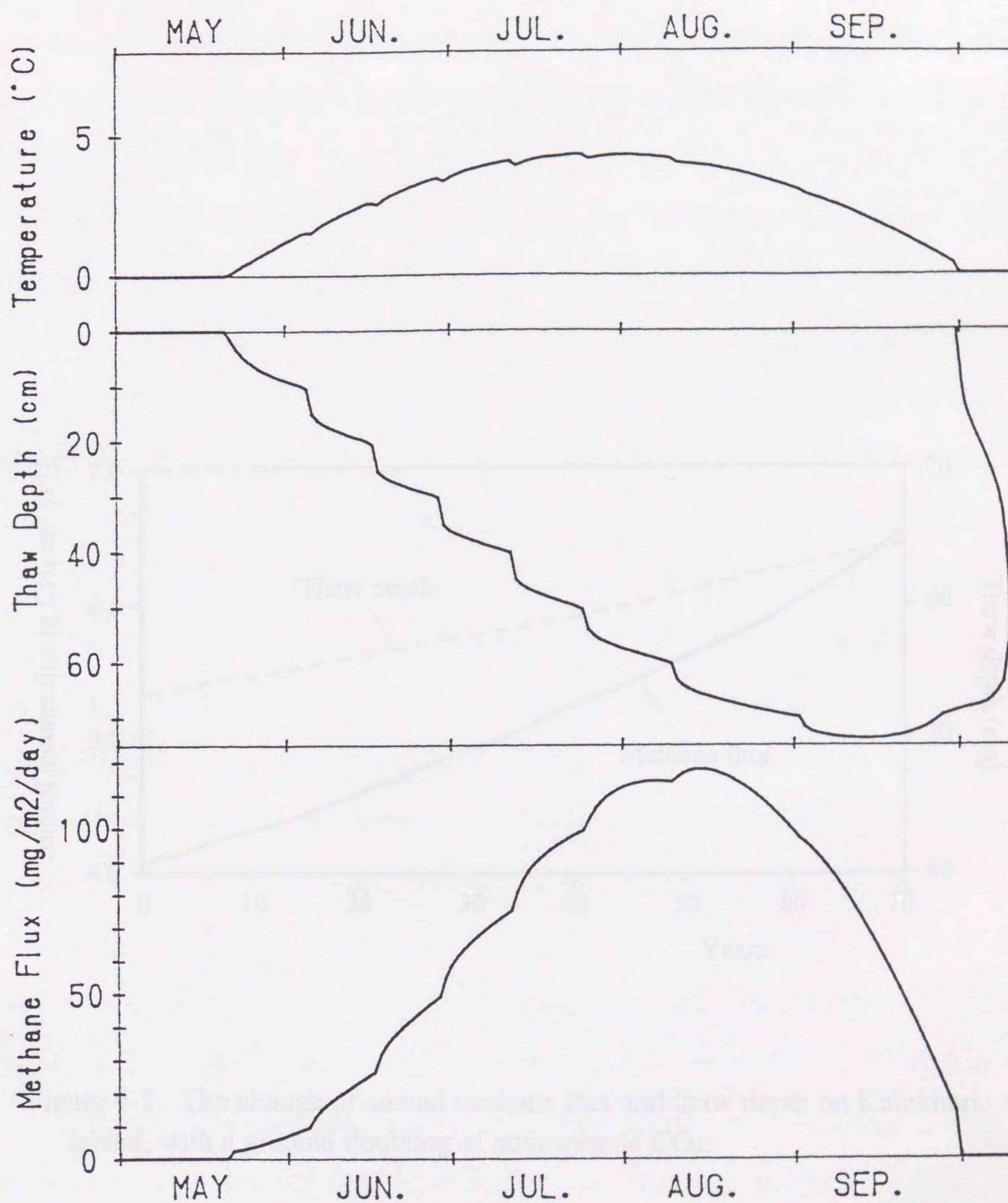


Figure 6-4. Simulation of MDGT (upper), thaw depth (middle) and methane emission (lower) on Kalakhari Island, when equivalent CO_2 concentrations are doubled.

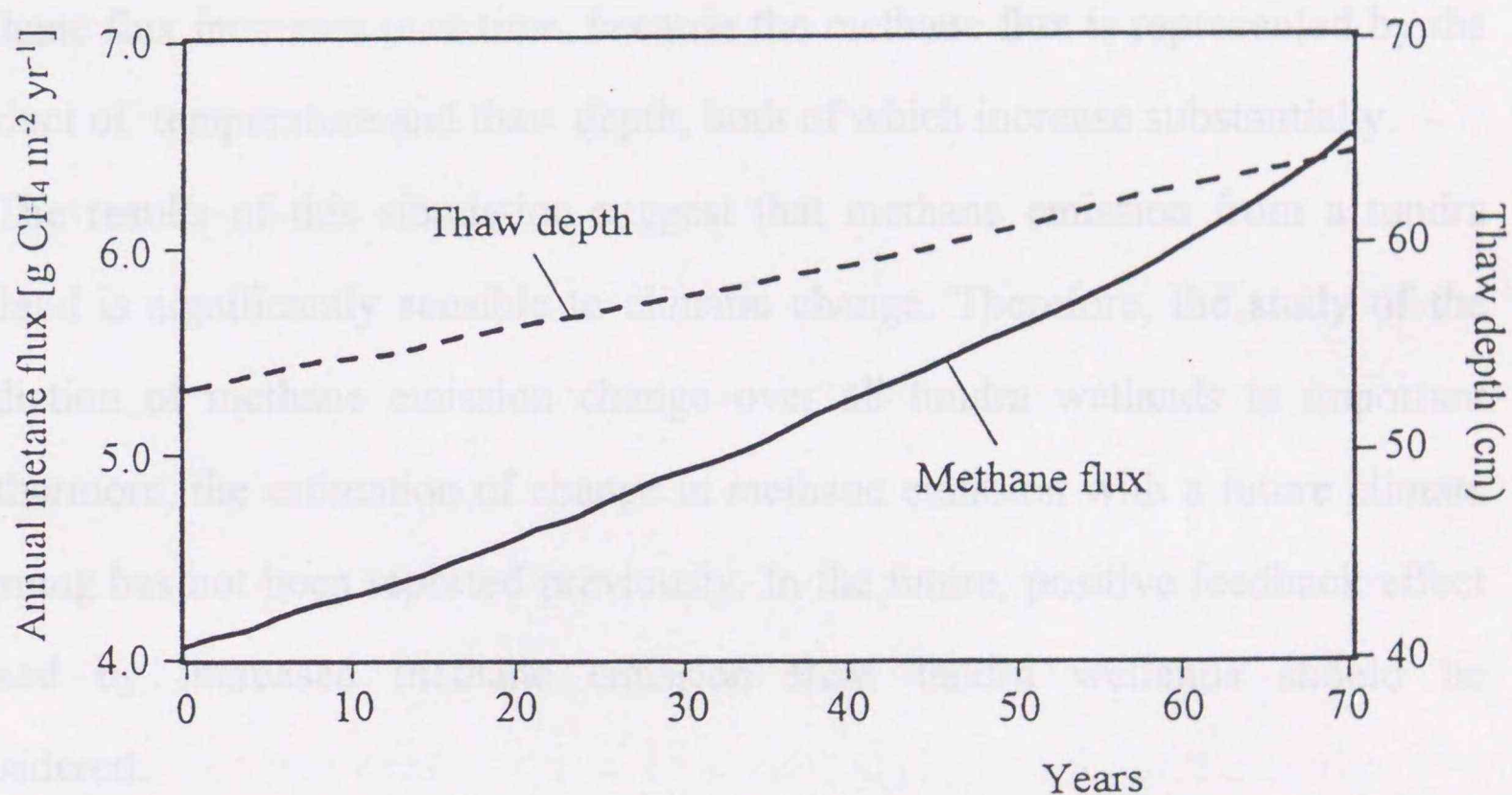


Figure 6-5. The change of annual methane flux and thaw depth on Kalakhari Island, with a gradual doubling of atmospheric CO₂.

concentration arrives twice as large as that of the present after 70 years. In this study, assuming the magnitude of warming is 60 % of equilibrium value when CO₂ concentrations are doubled (after 70 years) and the warming is linear, the AMP and MAST are varied linearly from 18.0 °C to 16.2 °C and -11.3 °C to -8.3 °C during the 70 years.

The variation of thaw depth and annual methane flux are shown in Figure 6-5. The thaw depth increases linearly from 53.2 to 64.5 cm. The annual methane flux is estimated to increase by 2.4 [g CH₄ m⁻² yr⁻¹] (from 4.1 to 6.5 [g CH₄ m⁻² yr⁻¹]) and corresponds to about 60 % of the present value. The increasing of the methane flux increases over time, because the methane flux is represented by the product of temperature and thaw depth, both of which increase substantially.

The results of this simulation suggest that methane emission from a tundra wetland is significantly sensible to climatic change. Therefore, the study of the prediction of methane emission change over all tundra wetlands is important. Furthermore, the estimation of change in methane emission with a future climate warming has not been reported previously. In the future, positive feedback effect caused by increased methane emission from tundra wetlands should be considered.

In this simulation, it was assumed that no changes occur in soil moisture in the process of CO₂ doubling. However, the soil moisture is one of the most critical factors affecting methane production in wetland environments. The change of soil moisture also causes the change of wetland areas. Thus, the accurate prediction of the change of soil moisture is required in order to estimate the increase of methane emission from tundra wetlands caused by a future climate warming.

7. Conclusions

This study aims to clarify the importance of natural wetlands in the permafrost area, where the methane is released from a thawed layer, as the source of atmospheric methane. For this purpose, first, the present author carried out the field observations of methane flux and other environmental factors in Siberian tundra area and alasses in taiga region. Secondly, on the basis of these results, she estimated the annual methane emission from the Siberian tundra wetlands, taking accounts of the seasonal and spatial variations of methane flux. Furthermore, the change of methane flux from the tundra wetland, possibly induced by future climate warming, was estimated. The conclusions of this study are summarized in following statements.

(1) The observations were carried out at three places in Siberian tundra wetlands and six alasses in taiga region around Yakutsk, in the summers of 1992 and 1993. The methane flux measurements were made at a forested bog in Fairbanks, Alaska, in May of 1993, in order to compare with Siberia as results. In the Siberian tundra wetlands, the high methane flux values were obtained from waterlogged and wet sites as the order of 10^1 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$]. On the other hand, it was not released from dry and moist sites. Mean daily ground temperature varied between 0.5 and 5.3 °C and the time-series variation of methane flux exhibited a similar trend to the ground temperature. The methane fluxes at forested bog in Fairbanks were in the order of 10^1 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$] at waterlogged sites and almost zero at moist sites as well as Mustakh Island. Flux values in both the tundra wetlands in Siberia and the bog in Fairbanks tend to coincide with to each other, implying the similarity of the controlling factors such

as mean daily ground temperature and thaw depth.

At alasses around Yakutsk, the environments in an alass were classified into four types based on the vegetation, soil moisture and micro topography. Methane fluxes were measured at several sites of each environmental type. Methane fluxes from alasses were yielded on the order of 10^2 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$] from the sites of water surface, floating-plant and wetland. They were yielded on the order of 10^1 [$\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$] from rather dry grasslands. The magnitudes of methane flux were significantly larger than previously observed ones in high-latitude wetlands. Therefore, the alasses in the taiga region of east Siberia is considered to be important source of methane.

(2) The present author introduced the "centimeter-degrees", which is defined as the product of thaw depth and mean daily temperature within a thaw layer, as a parameter determining the daily methane flux. This factor was also proposed by Whalen and Reeburgh (1992). This parameter accounts for the integration of net microbial activity over thaw layer, therefore it is a significantly reasonable index of methane emission from a tundra wetland. The linear relationship between methane flux from wet sites and centimeter-degrees was performed with a high correlation coefficient both in Mustakh Island and Fairbanks.

(3) The one-dimensional heat conduction model with phase change was used for calculating the seasonal variation of centimeter-degrees. The centimeter-degrees were calculated at each of the 2.5° latitude by 5.0° longitude grids, including Siberian tundra regions. On the basis of the calculated centimeter-degrees, the linear function expressed by the equation (5-2), and the area of the wetland (Aselmann and Crutzen, 1989), the annual methane emissions were estimated at each grid. The values of fluxes were different from each grid to the

other, ranging from 0.9 to 14.3 [g CH₄ m⁻² yr⁻¹]. These values are comparable with previous estimated ones in a tundra wetland. The annual methane emission from the Siberian tundra wetlands was estimated as 1.0 [Tg yr⁻¹], which is much smaller than previously estimated ones. Mainly, it is because that "tundra wetland" is differently defined in this study than in previous ones. Most researchers have assumed the tundra vegetation area or whole wetland on permafrost area as a tundra wetland. This assumption results in overestimation of the area of tundra wetlands.

(4) The increase of methane flux due to equivalent CO₂ doubling was estimated for Kalakhari Island. The increase of the annual methane flux is estimated to rise from the present 4.1 to 6.5 [g CH₄ m⁻² yr⁻¹] after 70 years. This is under the assumption of a gradual doubling of equivalent CO₂ concentrations (1% per year). This increase corresponds to about 60 % of present amount of emission. The results of this simulation suggest that the increase of methane emission from tundra wetland is significantly sensible to climate warming.

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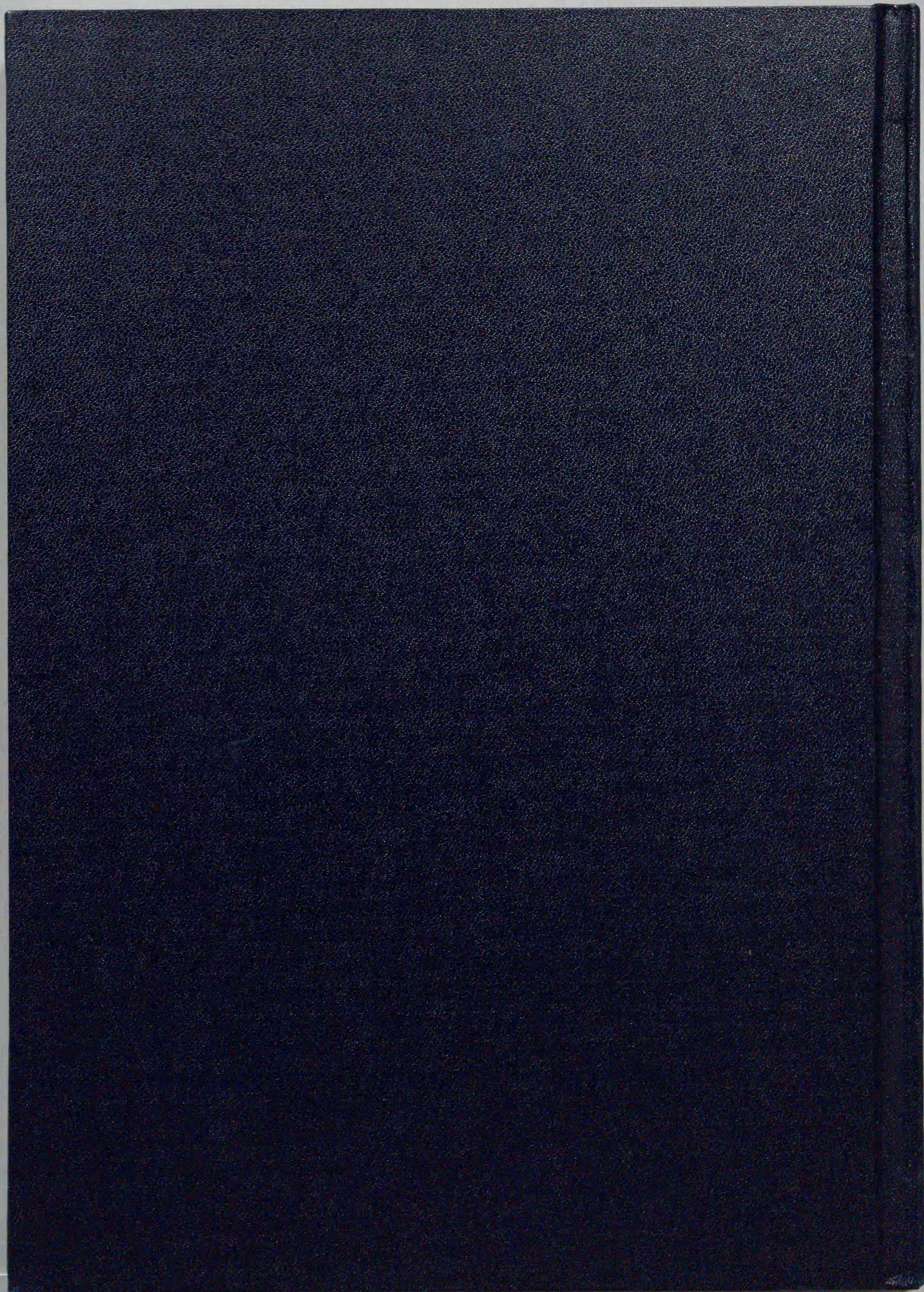
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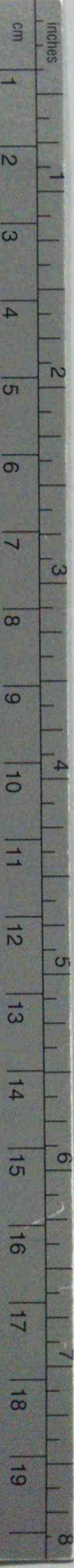
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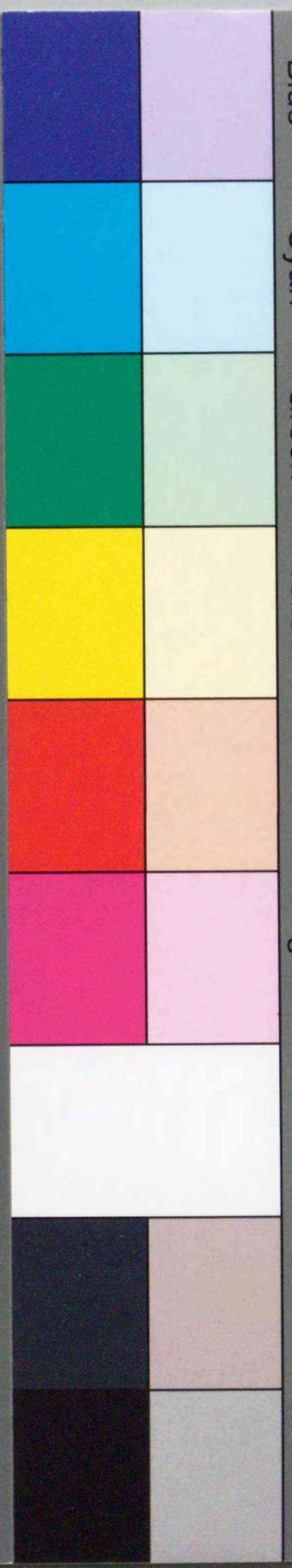




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