THE GREENHOUSE GAS METHANE (CH_4): SOURCES AND SINKS, THE IMPACT OF POPULATION GROWTH, POSSIBLE INTERVENTIONS

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Foreword

The research carried out at IIASA approaches the highly complex issue of population–development–environment interactions simultaneously at three different levels: (1) By carrying out comprehensive in-depth case studies (such as the recently completed Mauritius study) that try to consider all relevant factors for one specific place in the world and try to more fully understand the real mechanisms at work. (2) Through global-level studies that consider population change in relation to one specific environmental aspect (e.g., CO_2 emissions or land use). (3) By defining and calculating alternative population scenarios that take into account any possible environmental feedback into the population and may serve as input to more comprehensive global change scenarios.

This paper by Gerhard Heilig is a good example of the second approach, i.e., global-level studies of population that take into account one specific environmental issue, namely the changes in atmospheric methane concentrations. The author provides us with a very welcome and comprehensive survey of the dynamics of this important greenhouse gas which is often neglected in the study of human impacts of possible global warming; he not only estimates the effect of alternative scenarios of population growth on global methane emissions but also points toward options for stabilizing its atmospheric concentration.

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The Greenhouse Gas Methane (CH_4): Sources and Sinks, the Impact of Population Growth, Possible Interventions

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Methane (CH4) is one of the trace gases in the atmosphere that is considered to play a major role in what is called the "greenhouse effect." There are six major sources of atmospheric methane: emission from anaerobic decomposition in (1) natural wetlands; (2) paddy rice fields; (3) emission from livestock production systems (including intrinsic fermentation and animal waste); (4) biomass burning (including forest fires, charcoal combustion, and firewood burning); (5) anaerobic decomposition of organic waste in landfills; and (6) fossil methane emission during the exploration and transport of fossil fuels. Obviously, human activities play a major role in increasing methane emissions from most of these sources. Especially the worldwide expansion of paddy rice cultivation, livestock production and fossil fuel exploration have increased the methane concentration in the atmosphere. Several data sets help estimate atmospheric methane concentration up to 160,000 years back. Major sources and sinks of present-day methane emission and their relative contribution to the global methane balance demonstrate great uncertainties in the identification and quantification of individual sources and sinks. Most recent methane projections of the Intergovernmental Panel on Climate Change (IPCC) for 2025 and 2100 are discussed and used to estimate the contribution of population growth to future methane emission. Finally the paper discusses options and restrictions of reducing anthropogenic methane emissions to the atmosphere.

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INTRODUCTION

Methane (CH4) is one of the trace gases in the atmosphere that is considered to play a major role in what is called the "greenhouse effect." Despite its still extremely minute concentration (around 1.7 ppmv) this radiatively and chemically reactive gas has been accumulating in the atmosphere at the rate of about 1% per year. Today the methane concentration is about double that in the preindustrial era and two to six times higher than during the first emergence of homo sapiens.

The role of methane in the chemistry of the atmosphere is complex and still not fully understood. In principle methane is oxidized by photochemical reactions to carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O) and CH_2O, thereby consuming the hydroxyl radical (OH) (Cicerone & Oremland, 1988). This destructive reaction with OH is the biggest sink of methane in the atmosphere. The reaction involves a set of several other trace gases, including ozone (O_3). Atmospheric methane affects the earth's radiative balance in several ways: Its oxidation produces other important greenhouse gases (such as CO_2 and water vapor); it directly contributes to global warming through its infrared absorption spectrum; and it controls the lifetime of many other gases of climatic importance, such as ozone (O_3).

EVIDENCE FOR AN INCREASE IN ATMOSPHERIC METHANE CONCENTRATION

There is abundant evidence that the concentration of atmospheric methane is rising rapidly. In 1978 a systematic sampling program of atmospheric CH_4 was started. Global monthly averages are derived from seven specially selected monitoring sites in Alaska, Tasmania, Samoa, Oregon, Hawaii and Antarctica; in addition, 25 sampling sites around the world collect monthly data on CH_4 concentration (see Figure 1).

Our knowledge about concentrations of atmospheric CH_4 before 1978 is based on ice cores drilled from the inland ice of Antarctica and Greenland. Air bubbles, trapped in ice cores, were analyzed using the flame ionization technique and gas chromatography (Barnola et al., 1987). The depth from where the ice was recovered corresponds to its age. Until now there have been four major investigation programs of ice cores to study past levels of atmospheric trace gases (Boden et al., 1990):

—the Soviet Antarctic Expedition at Vostok (East Antarctica) (Barnola et al., 1987; Raynaud et al., 1988);
—the investigation of the U.S. Cold Regions Research and Engineering

Laboratory at Byrd Station, Antarctica (Neftel et al., 1982; Stauffer et al., 1988);

—the Greenland Ice Sheet Program—an international collaboration between the United States, Denmark, and Switzerland—at Dye 3 station in Greenland (Dansgaard et al., 1982); and

—the joint drilling by the Polar Ice Coring Office (Nebraska) and the Physics Institute at the University of Bern at Siple Station, Antarctica (Neftel et al., 1985).

On the basis of these investigations it was estimated that the level of CH_4 increased from 0.34 ppmv some 160,000 years ago to 1.3 ppmv in 1955. Since then it further grew to 1.7 ppmv in 1988. For details see Tables 1 and 2. As Figure 1 demonstrates there was great variation in CH_4 levels during prehistoric times. However, there is no evidence that the atmospheric concentration of methane ever reached half the level of today. In fact, during ten thousands of years the CH_4 level in the atmosphere was less than 25% of today.

The presence of radiatively active gases—such as methane—in the

FIGURE 1. Annual atmospheric CH_4 concentrations during the past 160,000 years (derived from ice cores and the NOAA/CMDL flask sampling network). Sources: Boden et al., 1991, pp. 205-321; Khalil and Rasmussen, 1982.

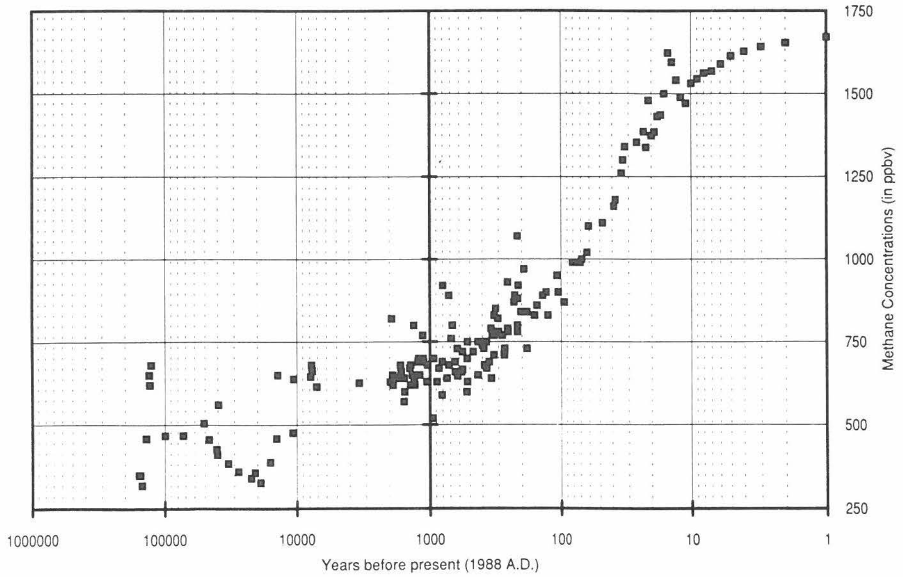


TABLE 1

Sources and Sinks of Atmospheric Methane: Various Estimates (in Teragrams per Years)

	(1)	(2)	(3)	IPCC: 1990 (4)	IPCC: 1990 (5)	IPCC: 1992 (6)	IPCC: 1992 (7)
Natural Sources							
Total: Natural Systems: a) – e)	*36.1*	100-300	—	*175*	*116-445*	*155*	*116-300*
a) Wetlands	36.1	—	110	115	100-200	115	100-200
b) Termites	—	—	—	40	10-100	20	10-50
c) Ocean	—	—	—	10	5-20	10	5-20
d) Freshwater	—	—	—	5	1-25	5	1-25
e) CH_4 Hydrate	—	—	—	5	0-100	5	0-5
Anthropogenic Sources							
Fossil Gas Total: a) + b)	80.2	*55-95*	—	*80*	*44-100*	100	70-120
a) Coal mining	—	30-50	—	35	19-50		
b) Natural gas & pet. industry	—	25-45	—	45	25-50		
Paddy Rice Fields	98.4	60-170	100	110	25-170	60	20-150
Animals Total: a) + b)	104.7	*95-135*	75.8	*80*	65-100	*105*	*85-130*
a) Enteric fermentation in animals	—	75-100	—	80	65-100	80	65-100
b) Animal wastes	—	20-35	—	—	—	25	20-30
Domestic Sewage Treatment	—	—	—	—	—	25	—
Landfills	35.7	30-70	—	40	20-70	30	20-70
Biomass Burning	—	50-100	—	40	20-80	40	20-80
Total Emission	355.1		500	525	290-965	515	331-875
Sinks							
Reaction with OH	—	—	—	500	400-600	470	420-520
Removal by Soils	—	—	—	30	15-45	30	15-45
Atmospheric Increase	—	—	—	44	40-48	32	28-37

Sources:
(1) Stockholm Environment Institute, 1991.
(2) Hogan et al., 1991.
(3) Lerner et al., 1988; Matthews et al., 1991; Matthews and Fung, 1987.
(4) Houghton et al., 1990, p. 20: best estimate.
(5) Houghton et al., 1990, p. 20: range of estimates.
(6) Houghton et al., 1992, p. 35: best estimate.
(7) Houghton et al., 1992, p. 35: range of best estimates.
Italics: Totals by Heilig
– no data available

TABLE 2

Historical Trends in Selected Methane-Related Agricultural Actvities

	POPULATION		RICE (PADDY)				CATTLE		SLAUGHTERED MEAT (Beef & Veal)			
			Area Harvested		Production				Slaughtered		Producton	
				Average		Average		Average		Average		Average
	Total (mill.)	Annual Growth (%)	Total (mill.)	Annual Growth (%)	Heads Total (1000)	Annual Growth (%)	Heads Total (1000)	Annual Growth (%)	Heads Total (1000)	Annual Growth (%)	Total (1000)	Annual Growth (%)
1961	3,020*		115,484		215,813		944,875		167,981		27,250	
1961-70		2.0		1.6		4.3		1.5		2.2		3.6
1970	3,698		133,130		316,676		1,084,388		204,786		37,819	
1970-80		1.8		0.8		2.3		1.2		0.8		1.5
1980	4,448		144,429		399,201		1,219,793		220,924		43,878	
1980-90		1.7		0.1		2.6		0.5		0.9		1.5
1990	5,292		145,776		518,508		1,279,257		241,283		51,152	

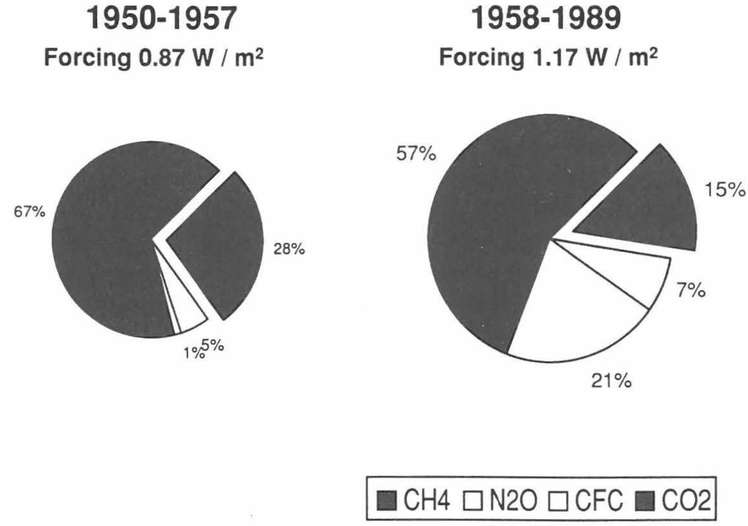
*1960
Source: FAO, 1991c; annual growth rates calculated by author.

Earth's atmosphere is a precondition of life. By trapping long-wave radiation emitted from the earth's surface they raise the global *mean* surface temperature by some 30 K to about 15° C (Mitchell, 1989). Otherwise, it would be around −18° C, which would prevent life as we know it. The most important greenhouse gas is water vapor. According to estimates by John Mitchell (1989) it is about twice as important for greenhouse heating as CO_2, and 60 times as important as methane. Methane, however, is one of the trace gases which has substantially increased its atmospheric concentration since the Industrial Revolution and thus contributed to the enhancing of the greenhouse effect. Presently methane is considered the third most important trace gas responsible for the *increase* in radiative heating of the atmosphere—after carbon dioxide and the CFCs (Houghton et al., 1990; Rosswall, 1991). Some scientists have estimated that a doubling of present atmospheric methane levels would lead—everything else being equal—to a warming of some 0.61 W/m (Smil, 1987, p. 271).

However, its overall contribution to the global greenhouse effect has changed during the past decades. While the *growth rates* in atmospheric concentration of many greenhouse gases (particularly CO_2 and the CFCs) increased during the last decade, those of methane declined. Hansen et al. (1990) estimated that during the 1950s CH_4 contributed some 28% to the overall greenhouse heating effect; in the 1980s its contribution declined to some 15%, while the CFCs and N_2O markedly increased their importance (see Figure 2).

Recent data indicate that the growth rate of the atmospheric methane concentration declined since 1984 from some 1.3% to 0.75% per year in 1989 (Houghton et al., 1992). (See also Appendix Table A2.) If these data are valid, it would pose a serious problem on contemporary theories of methane emission and atmospheric chemistry, since there is no convincing explanation for the decline. There are at least three possible explanations: First, it could be a reduction of methane emission from natural sources, such as natural wetlands. The shrinking of wetlands through hydrological construction and drainage is well documented for Africa (Howard-Williams & Thompson, 1985) and South America. Land reclamation is not the only factor that might change the size and distribution of wetlands. It is also possible that natural conditions, such as changing patterns in precipitation and river discharges, have altered the wetlands. Second, the slowdown in atmospheric methane concentrations could be a consequence of rising abundance of the tropospheric hydroxyl radical (OH), which is the major sink of atmospheric methane. Many experts consider this the most likely cause for declining growth rates in CH_4 concentration. And third, we cannot exclude the possibility that the emission from anthropogenic

FIGURE 2. Contribution from greenhouse gases to the changes in radiative forcing: 1950-1957 and 1958-1989. Source: Houghton et al., 1990.



sources declined (even if this is not very likely). For example, leakages and venting of methane during fossil fuel exploration might have been reduced since the large-scale commercial use of natural gas.

The recent trends in atmospheric methane concentration indicate that much research needs to be done before we can be sure about the basic facts of the global methane balance. This is even more obvious when we study available data on methane emission by various sources.

SOURCES OF METHANE EMISSION

According to the available literature there are six major sources of methane emission:

(1) anaerobic decomposition of vegetation in natural wetlands (Matthews & Fung, 1987; Baker-Blocker et al., 1977),
(2) emissions from livestock production systems which include enteric fermentation in animals (Lerner et al., 1988; Crutzen et al., 1986) and methane release from animal waste,
(3) natural (fossil) gas losses during fossil fuel exploration, processing and

distribution (coal mining, natural gas, petrochemical industry) (Quay et al., 1991),
(4) anaerobic decomposition in paddy rice fields (Conrad & Rothfuss, 1991; Khalil et al., 1991; Aselmann & Crutzen, 1989),
(5) biomass burning (including forest and savanna fires, burning of agricultural waste, charcoal production, and firewood combustion) (Delmas et al., 1991; Andreae, 1991),
(6) anaerobic decomposition of waste in landfills (Bingemer & Crutzen, 1987).

In addition some minor sources are discussed in the literature, such as the methane production of termites (Seiler, 1984), emissions from the oceans and freshwater, and emissions from CH_4 hydrate destabilization.

The sources can be grouped into anthropogenic (2) (3) (5) (6) and natural (1) (4) sources. It is also possible to distinguish bacterial (so-called "biogenic") (1) (2) (4) (6) from nonbacterial (pyrogenic) (3) (5) methane. Bacterial methane is considered to contribute some 80% (plus/minus 10%) of the total CH_4 emission; nonbacterial methane is believed to contribute 20% (plus/minus 10%). Nonbacterial methane results from thermal alteration of buried organic matter or incomplete combustion of biomass and fossil fuels (Quay et al., 1991). According to the 1992 "best estimate" of the CPCC committee, the contribution of the six major sources of atmospheric methane is as follows: wetlands (22%), enteric fermentation in animals and animal wastes (20%), coal mining, natural gas and petrochemical industry (19%), flooded rice fields (12%), biomass burning (8%), and landfills (6%).

The quantitative details of the global methane balance are highly uncertain. Not even the total annual flux of methane into the atmosphere is precisely quantified. A few years ago Sheppard put the total annual methane emission at 1.21 billion tonnes (i.e., 1210 Tg) (Smil, 1987), while more recent estimates have estimated a contribution of 300 to 700 Tg per year (Lerner et al., 1988). In 1990 the Intergovernmental Panel on Climate Change (IPCC) calculated a total annual methane emission of 525 Tg; in 1992 the IPCC published its most recent estimate of 515 Tg. These IPCC 1992 numbers, however, might give a false impression of accuracy. If one took the highest estimates in each emission category, the total methane emission would be 875 Tg per year; if one would stick to the lowest estimates it would be merely 358 Tg (Houghton et al., 1992).

There is even greater uncertainty about the contribution of each individual source to the global methane budget. Consider the case of paddy rice fields: In 1990 the IPCC estimated a total annual methane emission of 110 Tg from this source; in 1992 the committee published a "best estimate" of 60 Tg. But the range of uncertainty is high: in 1990 the IPCC considered estimates from 25 to 170 Tg per year to be scientifically sound; in 1992 it published a range of 20 to 150 Tg. In other words, if we take the highest estimates from 1990 (170 Tg) and the lowest from 1992 (20 Tg) one could think that paddy rice fields have abruptly switched from *major* to *minor* sources of global methane, or the other way around, with the two other limits (1990: 25 Tg and 1992: 150 Tg). According to the IPCC committee, natural systems (wetlands, termites, ocean, freshwater, and CH_4 hydrate) emit some 155 Tg/yr of methane to the atmosphere—but it could also be twice as much or only half of it according to other serious estimates (see Table 1). The contribution of biomass burning is also highly uncertain: IPCC's best estimate is 40 Tg/yr of methane, but serious estimates range between 20 and 80 Tg per year.

These discrepancies are not only a matter of scientific debate, but of political confrontation. If phytomass decay and biomass burning are considered major sources of methane emission, it would be mostly the third world which could be blamed for the global methane problem There we have vast paddy rice fields and widespread "slash and burn" agriculture, large-scale charcoal production and firewood consumption (Malingreau & Tucker, 1988). However, if methane ventilation during exploration of fossil fuels, and anaerobic decomposition in land fills and domestic sewage systems are considered major sources of global methane emission, the industrialized North would be in the dock—with its excessive waste production and high fossil fuel consumption.

PROBLEMS OF ESTIMATING GLOBAL METHANE EMISSION

While there is not much doubt that the atmospheric methane concentration has been rising since the beginning of the industrial era, much disagreement still exists—as we have seen—on the relative weight of the various sources. Why is it so difficult to validate the estimates?

(1) Anaerobic decomposition in natural wetlands is probably more important than any other single source of atmospheric methane. Unfortunately, less than one would expect is known about their size, type, and geographical distribution. Many wetlands occur in remote and poorly surveyed regions, such as Northern Canada, Siberia, or the Amazon river basins. Another difficulty is the seasonal inundation and drying of small and scattered wetlands in the tropics. The most serious problem, however, is the broad range of wetland-vegetation, which largely determines the specific methane emission rate. Matthews et al. (1991) have identified 28

different types of natural wetlands, from low-organic nonforested swamps in the tropics to organic-rich forested bogs in the northern hemisphere. Their chemistry, plant species, morphology, vegetation physiognomy and average temperature are responsible for enormous variances in methane emission.

(2) There are reasonably good statistics on the size and distribution of wet rice areas. Some 75 to 80% of the global rice area is harvested from flooded fields. However, the specific rates of methane emission from paddy rice fields vary substantially according to rice plant variety, temperature, fertilizer input, method of cultivation, soil type and season (Lindau et al., 1990). Methane emissions from Chinese rice fields, for instance, were "found to be 4-10 times higher than emission rates from rice fields in the United States and Europe" (Khalil et al., 1991). At present estimates of specific methane emission rates from paddy rice fields are based on a limited number of test-sites, which can hardly be representative for the global wet-rice agriculture.

(3) The animal population of the world is difficult to assess. While statistics are available on the size of the domestic livestock, much less is known about the wild herbivorous fauna, including (water) buffalo, nondairy cattle, camels, caribou, elks, etc. In addition, not much is known about their specific methane emission rates. They certainly vary between different kinds of animals; but they might also vary greatly with their fodder and living conditions. Methane emission from animal waste is also difficult to assess: It varies with the treatment method of the manure and with the climate.

(4) Methane emission from the combustion of biomass can be quantified by making an inventory of all kinds of biomass burnings, including fires in forests and savannas, the combustion of fuelwood, charcoal, and the burning of agricultural wastes. By multiplying the biomass with specific methane emission rates, one will get an estimate of the net addition to the global methane balance. Obviously the amount of methane emission highly depends on the type of biomaterial burned. Delmas et al. (1991) have demonstrated CH_4 emission factors of 1.65 (in gram per kg dry matter) for savanna plant burning, 6.94 for forest fires, 5.42 for firewood burning, and 21 for charcoal production.

(5) Methane release from landfills can be calculated by estimating the number and size of municipal solid waste deposits, the proportion of degradable organic matter in the waste, and its specific methane emission rate during degradation. Obviously, all three parameters are difficult to assess, since they vary with the dominant type of organic waste and with environmental conditions (temperature, moisture, etc.) of the deposit. In addition, a significant proportion of the methane produced in the waste is

oxidized in the cover soil of the landfill before it can emit to the atmosphere. Unfortunately the oxidative capacity varies with the type and thickness of the soil cover. There is also the problem of uncontrolled waste deposits in many parts of the third world. No statistics are available on their size, location, and waste content. On the other hand some highly developed countries have started to recover methane from landfills. It is unclear, however, whether the emission rates from these landfills could be used to calibrate the worldwide estimates. The practice is restricted to a small number of deposits in the northern hemisphere with a certain mixture of waste, specific environmental conditions and waste treatment practices.

(6) Methane is also released to the atmosphere through coal mine ventilation; small amounts are also believed to degas from coal during transport. Methane also leaks from pipelines and wells of oil and natural gas (a major component of which is fossil methane). There is also methane leakage in the processing of fossil fuels by the petrochemical industry. It is somewhat surprising that the statistical data for these sources are so poor (or nonexistent). Gas ventilation from coal mines around the world is a technically controlled process, well known for many decades. The quantities of gas extracted from the mines should be known quite precisely—if not only for safety reasons. In some cases mine gas is used (and sold in large quantities) for generating energy. It is hard to understand why the petrochemical industry is not able or willing to precisely quantify methane venting and leakages.

(7) A few years ago there was a vigorous debate on the contribution of termites to the global methane budget. It was estimated that these insects could emit up to 100 Tg per year—which would have been much more than what is now considered the emission from paddy rice fields. Based on recent studies (Khalil et al., 1990) the annual emission from termites was scaled down to some 20 Tg (see Table 1). However, as everyone can understand, it is extremely difficult to estimate methane emission of termites—no one has ever counted these animals or will be able to do so.

(8) Under certain conditions water can freeze around smaller gas molecules (such as methane, propane, carbon dioxide and others), building a cage-like structure. This material is called gas clathrate (or "hydrate") (Sloan, 1991). When the clathrates melt, the captured gas can emit to the atmosphere. Methane emission due to release of old CH_4 from hydrate destabilization is currently considered a minor source (0-5 Tg). Gas clathrates can be found in deep oceans and in the Siberian permafrost (MacDonald, 1989). Not much is known about the size and distribution of these reserves, but according to some estimates the resources could be gigantic. Conservative estimates indicate that "there is perhaps twice as much en-

ergy in hydrated form as in all other hydrocarbon sources combined" (Sloan, 1991). There is the extreme speculation that if the reserves of natural methane hydrates would melt (due to extreme global warming, for instance) the earth's atmosphere could change dramatically—becoming a Jupiter-like CH_4 atmosphere, which, however, is contradicted by the fact that the atmosphere was not changed permanently during the "warm periods" in earth's history.

PROJECTIONS OF GLOBAL METHANE EMISSION

There are three types of uncertainties in projecting future trends of global methane emission: First, there is a lack of scientific knowledge concerning the identification and quantification of current methane sources, sinks, and chemical mechanisms in the atmosphere. Second, there are uncertainties associated with possible technological advances, such as improvements in paddy rice production, livestock management, domestic sewage treatment, or waste recycling. Third, it is extremely difficult (if not impossible) to predict changes in human behavior, such as life style change, social restructuring, economic reform, and political revolution.

If anthropogenic methane sources would grow in proportion to population, one could use population projections to estimate future trends in methane emission. Unfortunately, things are more complicated. Consider the following examples:

—Between 1980 and 1990 the worldwide paddy rice area (which is a major source of atmospheric methane) stagnated at an average annual growth rate of 0.09%, while the population increased by 1.74% per year and rice production grew by 2.61% annually (see Table 2). This was possible because paddy rice areas doubled their productivity. In 1961 about 115,484 million hectares were needed to produce 215,813 million tons of rice; today only 145,776 million hectares are required to grow 518,508 million tons. If this trend continues, future methane emission from paddy rice areas would increase only slightly or even decline, despite rapid population growth and a substantial increase in rice production.

—Meat production, the second most important source of anthropogenic methane in the atmosphere, also became more efficient during past decades: In 1961 some 168 million animals had to be raised and slaughtered to produce 27 million tons of meat (beef and veal). By 1991 the meat production had nearly doubled (51 million tons), but the number of slaughtered animals only increased to 241 million. Since 1961 population growth rates were consistently higher than the increase in the total number of cattle (see Table 2). Between 1980 and 1990, for example, the number of cattle nearly stagnated (at an average annual growth rate of 0.48%) while the population increased by 1.74% annually and the world-wide production of beef and veal grew by 1.53% per year.

—Projections of future trends in agricultural land use and food production, which are based on detailed FAO food demand projections, also reject a simple proportional relationship between population growth and methane emission. In 1988 the FAO published an assessment of world food and agricultural prospects to the year 2000 (Alexandratos, 1988). According to this study the paddy rice area of 93 developing countries would only increase from 105 million hectares in 1982/84 to 120 million hectares in the year 2000. This would be equivalent to an annual growth rate of just 0.8%. The FAO also estimated that livestock numbers in these 93 developing countries would increase between 1.0% (cattle and buffalo) and 2.8% (poultry) annually. This would be a significant slow-down as compared to the period from 1961-63 to 1983-85 when average annual growth rates ranged between 1.2% and 4.3%, respectively.

—And finally we have estimates of future trends in deforestation, which is a source of methane emission due to associated biomass burning. In its most recent tropical forest assessment, the Food and Agricultural Organization estimated that, on average, 16.9 million hectares of tropical forests were cleared annually from 1981 to 1990 (FAO, 1991a, 1991b). Clearing rates increased from 13.2 million hectares in 1980 to 20.8 million hectares in 1990. In its 1992 greenhouse gas scenarios the IPCC assumes that between 1990 and 2025 on average between 12.0 (scenario IS92d) and 20.7 (scenario IS92f) million hectares will be cleared annually. Between 2025 and 2100 the average area cleared per year is predicted to range from only 3.1 (scenario IS92d) to 12.8 (scenario IS92f). For obvious reasons deforestation rates will decline; and consequently there will be a reduction in methane emission from this source.

These trends indicate that a decline in per capita methane emission during the next decades is very likely. The critical question is whether, and to what extent, the decline will be offset by population growth.

The Intergovernmental Panel on Climate Change (IPCC) has only recently published a projection of greenhouse gases, including CH_4. The panel defined five scenarios which combine various assumptions on population growth, economic activity, energy efficiency and technological advances. There were also several assumptions on future trends in deforestation (Houghton et al., 1992). In addition three different demographic projections were used: the 1991 World Bank projection, the United Nations medium/low variant, and the UN medium/high variant longterm projections. Table 3 gives the total population for 2025 and 2100, as well as average annual growth rates that were used in the calculation of the scenarios.

By 2100 global annual methane emission is projected to range between 546 Tg (scenario IS92c) and 1,168 Tg (scenario IS92f). In scenario IS92c current emissions would only slightly increase from 506 Tg to 589 Tg in 2025 at an annual growth rate of 0.43%. By 2100 the annual methane emission would decline to 546 Tg. This would be equivalent to a near stagnation of methane emission during the next century at average annual growth rates of 0.07% (for 1990-2100). However, according to the more pessimistic IPCC scenario IS92f the global methane budget could be severely set off balance: In this scenario the committee expects annual methane emission to more than double by 2100. Average annual growth rates of methane emission would only lightly decline from 0.91% (for the period between 1990 to 2025) to 0.69 (between 2025 to 2100) (see Table 3).

An interesting result of the IPCC calculation is the minor change in projected annual methane emission for the next decades, as compared to the enormous range of uncertainty in the base data. Serious estimates of the global annual methane emission for 1990 range between 358 and 825 Tg (see Table 1); the high estimate is some 2.3 times higher than the low estimate. On the other hand IPCC's projection scenarios for the year 2025 (based on the average estimate of 506 Tg in 1990) range between 584 and 697 Tg; they differ by a factor of only 1.2 (see Table 3). This gives the impression that estimates of global methane emission become more precise when projected into the future. Of course, one could use both the high and the low (rather than the "best") estimate of current methane emission estimates; but then the exercise would become rather meaningless. It would produce absurd predictions, ranging from negligible to gigantic annual emissions.

The fact that predicted changes in methane emission by the year 2025 are well within the range of uncertainty of current quantification, explains why all projections have to be used with extreme care. It also explains why it is probably more important to validate current emission rates than to develop highly sophisticated projection models.

CONTRIBUTION OF POPULATION GROWTH TO METHANE EMISSION

Future trends in global methane emission are a product of two factors: (1) population growth and (2) average per capita emission rates—which

TABLE 3

Selected Results of 1992 IPCC Greenhouse Gas Scenarios: Global Methane (CH_4) Emission

	POPULATION						METHANE EMISSION									
	World Bank		UN Medium/Low		UN Medium/High		Scenario IS92a/b		Scenario IS92c		Scenario IS92d		Scenario IS92e		Scenario IS92f	
	Total (mill.)	Average Annual Growth (%)	Total (mill.)	Average Annual Growth (%)	Total (mill.)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)
1990	5,297		5,262		5,327		506		506		506		506		506	
1990-2025		1.4		1.0		1.6		0.8		0.4		0.4		0.9		0.9
2025	8,504		7,591		9,444		659		589		584		692		697	
2025-2100		0.4		−0.2		0.8		0.4		−0.1		0.0		0.6		0.7
2100	11,300		6,415		17,592		917		546		567		1,072		1,168	
1990-2100		0.7		0.2		1.1		0.5		0.1		0.1		0.7		0.8

Scenarios IS92a/b and IS92e are based on the World Bank 1991 population projection; scenarios IS92c and IS92d are based on the UN medium/low case projection; and scenario IS92f is based on the UN medium/high case population projection. For details of scenario assumptions see: Houghton et al., 1992, Table A3.6, p. 80. Compiled from: Houghton et al., 1992; and UN, 1991.

represent the combined net-effect of technological advances and expansion of anthropogenic methane sources due to life style changes. We have used a simple decomposition method for quantifying the contribution of population growth to the global methane balance, based on the IPCC methane projections.

—First we calculated average per capita emission rates according to the five IPCC scenarios (see Table 4). In 2025 they will range between 73.8 (IS92f) and 81.4 kg per person (IS92e). By 2100 the average per capita methane emission could decline to 66.4 kg (IS92f) or increase to 94.9 kg (IS92e) according to scenario.

—In a second step we calculated total methane emission by assuming constant 1990 population, but projected per capita methane emission rates. According to the IPCC scenario IS92f total methane emission was projected to reach 697 Tg in 2025. However, at constant 1990 population, the emission would be only 393 Tg. In other words, population growth would increase the global methane balance by 230%. In 2025 the contribution of population growth to global methane emission ranges from 44 to 77%. In 2100 the demographic component could reach 230% or decline to 22%—according to scenario (see Table 5).

However, this simple method of calculating the contribution of population growth to future methane emission is not without problems. Future population growth will mainly occur in the third world, while per capita methane emission rates might be highest in the more developed countries. In this case it would be necessary to disaggregate and to calculate the contribution of population growth separately for more and less developed regions. The contribution of population growth to methane emissions on the regional level would be very different from the global average. This is typical for CO_2 emissions, for instance, where extremely low per capita rates in third world countries have to be combined with very high rates of population growth, while very low population growth occurs in regions with extremely high per capita emission of carbon dioxide.

There is, in fact, an interhemispheric difference in atmospheric methane concentrations which suggests that methane sources are not distributed equally around the globe. The concentration is significantly lower at the equator and across the entire southern hemisphere. There seem to be significant methane sources in the high northern latitudes (50° to 80° north)—probably natural wetlands and sources associated with oil and natural gas wells and coal mines (Yavitt, 1992). These emissions could be associated with industrialized countries.

On the other hand the *largest* methane sources seem to be located between 30° and 40° north where we also find many developing countries.

TABLE 4

Projected Methane Emission, Projected Population, and Per Capita Methane Emission Between 1990 and 2100 According to the 1992 IPCC Greenhouse Gas Scenarios

	Scenarios IS92 a/b			Scenario IS92 c			Scenario IS92 d			Scenario IS92 e			Scenario IS92 f		
	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Capita Emiss. (kg)	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Capita Emiss. (kg)	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Capita Emiss. (kg)	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Capita Emiss. (kg)	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Capita Emiss. (kg)
1990	506	5,297	96	506	5,262	96	506	5,262	96	506	5,297	96	506	5,327	95
2025	659	8,504	78	589	7,591	78	584	7,591	77	692	8,504	81	697	9,444	74
2100	917	11,300	81	546	6,415	85	567	6,415	88	1,072	11,300	95	1,168	17,592	66

Scenarios IS92a/b and IS92e are based on the World Bank 1991 population projection; scenarios IS92c and IS92d are based on the UN medium/low case projection; and scenario IS92f is based on the UN medium/high case population projection. For details of IPCC scenario assumptions see: Houghton et al., 1992, Table A3.6, p. 80.

TABLE 5

Estimated Contribution of Population Growth to the Increase in CH_4 Emission Between 1990 and 2100 According to the 1992 IPCC Greenhouse Gas Scenarios

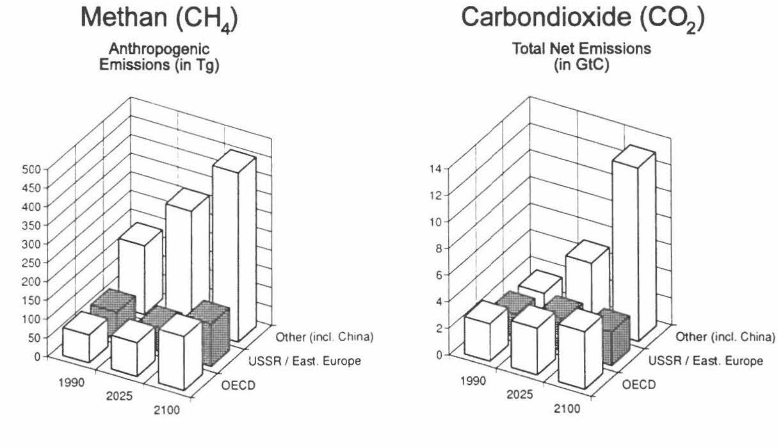
	Scenarios IS92 a/b			Scenario IS92 c			Scenario IS92 d			Scenario IS92 e			Scenario IS92 f		
	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)
1990	506	—	—	506	—	—	506	—	—	506	—	—	506	—	—
2025	659	410	60	589	408	44	584	405	44	692	431	61	697	393	77
2100	917	430	113	546	448	22	567	465	22	1,072	503	113	1,168	354	230

Scenarios IS92a/b and IS92e are based on the World Bank 1991 population projection; scenarios IS92c and IS92d are based on the UN medium/low case projection; and scenario IS92f is based on the UN medium/high case population projection. For details of IPCC scenario assumptions see: Houghton et al., 1992, Table A3.6, p. 80.

Contrary to carbon dioxide, methane is not primarily emitted from the production and consumption sectors of affluent societies. It could rather be called the "poor man's greenhouse gas," since major sources of atmospheric methane are in developing countries with high population growth. China and India, for instance, account for 52% of the world's harvest area of paddy rice; India, Africa and Latin America are home to large numbers of cattle. There are developing countries with large natural wetlands, such as the Congo or Brazil; and biomass burning, such as forest fires, fuelwood burning and charcoal production is typical for the African savannas and Latin American forest areas.

Currently, the OECD (which includes all major industrial countries), plus the former USSR and Eastern Europe are estimated to be responsible for 144 Tg emission of CH_4—which is equivalent to just 44% of the *anthropogenic* emissions. China, the other centrally planned economies in Asia, and all other (developing) countries account for 56% of anthropogenic methane emissions. According to the IPCC 92 ISA92a scenario, the OECD plus the former USSR and Eastern Europe will contribute only 33% to the worldwide anthropogenic methane emission in 2025. Two-thirds will be from developing countries (see Figure 3 and 4).

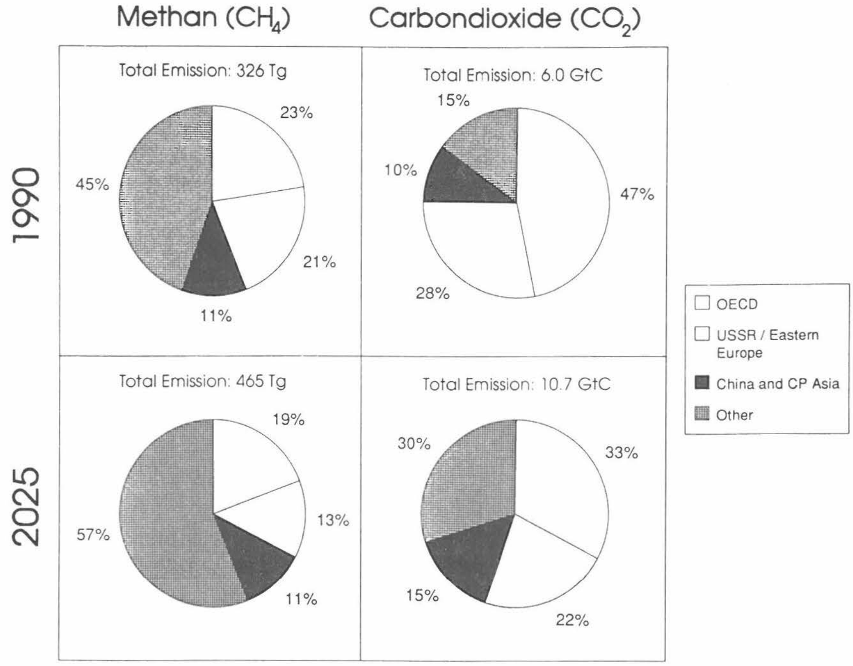
FIGURE 3. Anthropogenic emissions of CH_4 and net emissions of CO_2 by region (according to IPCC scenario IS92a). Source: Houghton et al., 1992.



OECD countries include: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Sweden, Switzerland, Turkey, United Kingdom,United States, Yogoslavia

Source: IPCC, 1992, p.81

FIGURE 4. Anthropogenic CH_4 emissions and net emissions of CO_2: contribution of selected regions in percent (according to IPCC scenario IS92a). Source: Houghton et al., 1992.



While the precise geographic distribution of methane sources is still highly uncertain, one can at least assume a fairly homogenous distribution among countries with high and low population growth. In any case, however, methane sources are geographically much more balanced than the sources of carbon dioxide emission. Therefore it is acceptable to use *global* estimates for calculating the contribution of population growth to future methane emission.

OPTIONS, CONSTRAINTS, AND RISKS FOR REDUCING METHANE EMISSION

In its recent report the Intergovernmental Panel on Climate Change (IPCC) concluded that global methane emissions would have to be reduced by only 15-20% to stop the rise of its atmospheric concentration (Houghton et al., 1992). This should be an easy target to reach if current mitigation estimates are correct. For instance, a United States/Japan IPCC working group recently found that most methane emissions could be reduced by between 30 and 90%. Several options are being discussed on how to reduce methane emissions to the atmosphere:

(1) a modification of farming techniques in paddy rice agriculture;
(2) a reduction of livestock and the processing of manure (bio-gas production);
(3) the implementation of better technologies for reducing fuelwood burning and charcoal production;
(4) the prevention of forest and savannah fires;
(5) the reduction of methane losses in the petrochemical industry, as well as the reduction of methane ventilation from coal mines and methane degassing from coal during transport;
(6) the draining of natural wetlands; and
(7) the prevention of methane emission from landfills.

The above mentioned IPCC expert group found that methane emissions from animal waste and sewage systems could be reduced by up to 80% in the near future (before 1995). This would also partly be possible with relatively simple technologies. Primarily by stopping the waste of fuelwood, one could decrease methane emission from biomass burning by between 20 and 80%. CH_4 emission from ruminants could be reduced by up to 75% and even emissions from flooded rice fields could decline by up to 30%. The range of methane emissions from rice paddies is enormous: It can be as low as 8 $gm^{-2}yr^{-1}$ (gram per square meter per year) as measured in Thailand or as high as 170 $gm^{-2}yr^{-1}$ as documented for the TuZu Szechuan Province in China. A number of soil and water factors influence methane emission from paddy rice fields, but we also know that emission varies significantly with cultivation methods. A change in the agricultural practices, such as *not* putting straw into the flooded field, can dramatically reduce methane emission.

While the potential for reduction of anthropogenic methane emission is clearly documented we should not underestimate economic and social **constrants** that might prevent implementation of these measures. There are, for instance, limits to the reduction of methane emission from livestock. In the arid rangelands of Africa and Asia—where a substantial proportion of the world livestock is located—the population has few alternatives for sustenance: Cattle ranging across vast areas (a practice which makes it nearly impossible to reduce methane emission from enteric fermentation and animal wastes) may be the only sustainable system of food production in these areas. One could also question the willingness of people in Northern America and Europe to modify their animal protein-rich diets which could, in principle, reduce the livestock (and thus methane emission) in these regions. On the contrary—it is quite likely that we will observe a trend to meat based diets in Asia and Latin America ("Hamburger Revolution") which would lift methane emission from livestock to soaringly high levels. In China, for instance, the meat supply grew *tenfold* between 1961 and 1989 (from 3.8 kg per person per year to 25.6 kg) and has reached a level that is now half as high as in Europe during the 1950s. Worldwide, the meat supply per capita has increased from 22.9 to 31.7 kg per capita between 1961 and 1990 (FAO, 1992).

There are also apparent **environmental risks** which might prevent mitigation measures. For instance, a conversion of natural wetlands into agricultural land, which could reduce the methane emission from this natural source, would also destroy the innate biological richness of these ecosystems. Tropical wetlands, such as the Pantanal floodplain in southcentral Brazil, are refuges for several endangered species. The drainage of wetlands and conversion into intensively farmed areas have already led to some of the most-decimated habitats, such as the Tule marshes in the Central Valley of the United States of America. The conversion of natural wetlands could also affect watershed dynamics and increase the risk of flooding downstream. Agricultural modernization, as well, could trigger a broad range of environmental degradation—including soil erosion, ground water pollution, and salinization.

CONCLUSION

(1) Methane (CH_4) is a powerful greenhouse gas. It affects the Earth's radiative balance by being oxidized to CO_2. It is also important for the atmospheric chemistry since it controls the abundance of ozone (O_3) and the hydroxyl radical (OH) (which in turn affects the lifetime of other greenhouse gases, such as the CFCs). According to IPCC estimates, methane contributed some 15% to the changes in radiative forcing from 1980 to 1990.

(2) The concentration of methane in the atmosphere is still extremely minute (around 1.7 ppmv); but the gas has been accumulating in the atmosphere at the rate of around 1% per year. Today the methane concentration is about double that in the preindustrial era (of some 0.8 ppmv).

(3) During the 1980s the growth rate of atmospheric methane concentration has slowed down—from 1.3% per year in the late 1970s to some 0.75% in 1989. There is no generally accepted explanation for this decline.

(4) About two-thirds of the global methane emission to the atmosphere is man-made. Fossil gas leakage from coal mines and oil wells, rice cultivation on flooded fields, livestock production systems, and biomass burning are the four most important anthropogenic sources of atmospheric methane.

(5) The increase of methane in the atmosphere is not inexorable. With appropriate technical and organizational measures the global methane emission could be stabilized. For example, burning methane from coal mines and oil wells in power generators—instead of just blowing it into the air—would not only reduce the direct emission, but also save other sources of energy. With clever agricultural practices methane emissions from flooded rice fields could be minimized; methane emission from animal wastes could be reduced by treatment in biogas generation plants. We could also reduce leakage from natural gas pipelines and distribution networks. We could promote landfill gas collection.

(6) While there is technical potential for reducing methane emission we also face constraints and risks. There is a worldwide trend to animal-based food which makes it quite unlikely that we could achieve a significant reduction of livestock-related methane emission. For environmental reasons, we must also refrain from draining natural wetlands (which are the largest natural source of atmospheric methane). This measure would not only destroy the biodiversity of these ecosystems, but also affect the balance of related watershed systems.

(7) Methane losses in the petrochemical industry, methane ventilation from coal mines and methane degassing from coal during transport, however, can be reduced substantially. The emission from these sources is primarily due to technological inefficiency, which in turn depends on the lack of investment capital and know-how, lousy maintenance of equipment, poor monitoring of production processes, and—rather simply—a lack of "good-will" among those responsible. It is well documented that simple and cost-efficient measures could substantially reduce methane emission from these sources. Even if population growth (and spreading industrialization) were to require an increase in fossil fuel exploration, the total methane emission from these sources could decline in absolute terms with better technology and intelligent process design.

8) Contrary to carbon dioxide, methane is not primarily emitted from the production and consumption sectors of affluent societies. Significant sources of atmospheric methane are in developing countries, where high population growth is projected for the next decades. According to the most recent IPCC projections, the anthropogenic emission of methane to the atmosphere would stagnate or even decline, if population had stabilized at its 1990 level. Through its link to food production, third world population

growth is a key factor of future methane emission. By the year 2025 (third world) population growth could increase methane emission by between 22 and 230%, as compared to a constant 1990 population.

(9) Methane is an attractive target for controlling the greenhouse effect. First, there would be a fast response to emission cutbacks, since the gas has the relatively short lifetime in the atmosphere of only some 11 years. Second, it would require the reduction of only 15-20% of total methane emission to stop the atmospheric increase of this greenhouse gas Only recently it was estimated that reductions in methane emission "would be 20-60 times more effective in reducing the potential warming of the earth's atmosphere over the next century than reductions in CO_2 emissions" (Hogan et al., 1991; Yavitt, 1992). Even very modest measures, such as cutting natural gas leakage in half, would be sufficient to stabilize the current CH_4 concentration in the atmosphere.

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APPENDIX

TABLE A1

Atmospheric Methane from Ice Cores: Selected Measurements

Year	CH_4-Concentration in ppmv	Range of Successive Measurements	Source
1956	1.34	0.08	4b
1955	1.30	0.07	4a
1954	1.26	0.08	4b
1950	1.18	0.07	4a
1949	1.16	0.08	4b
1940	1.11	0.07	4a
1927	1.10	0.07	4b
1925	1.02	0.06	4a
1919	1.00	0.07	4a
1917	0.99	0.06	4b
1907	0.99	0.06	4b
1893	0.87	0.07	4a
1882	0.90	0.08	4a
1861	0.83	0.07	4a
1857	0.90	0.06	4b
1849	0.89	0.08	4a
1934	0.86	0.07	4a
1827	0.83	0.06	4b
1818	0.95	0.06	4b
1804	0.73	0.08	4a
1804	0.84	0.06	4b
1771	0.78	0.09	4a
1771	0.80	0.06	4b
Years Before Present			
550	0.667	0.025	2
600	0.647	0.025	2
3,400	0.627	0.025	3
7,100	0.615	0.025	2
7,700	0.663	0.030	3
7,800	0.680	0.027	3
7,900	0.645	0.037	3
10,600	0.638	0.025	2
10,800	0.477	0.025	3
14,000	0.650	0.032	3
14,300	0.460	0.025	2
16,000	0.389	0.032	3

TABLE A1 *(Continued)*

Year	CH_4-Concentration in ppmv	Range of Successive Measurements	Source
19,000	0.327	0.030	3
21,000	0.358	0.041	3
22,400	0.341	0.027	2
27,900	0.360	0.025	2
33,500	0.385	0.025	2
39,800	0.561	0.031	3
40,500	0.411	0.032	3
41,000	0.427	0.033	3
46,600	0.457	0.027	2
51,100	0.505	0.031	2
73,000	0.468	0.025	3
100,000	0.468	0.025	3
127,800	0.68	0.04	1
131,100	0.62	0.02	1
132,400	0.65	0.04	1
138,800	0.46	0.03	1
149,100	0.32	0.03	1
153,600	0.35	0.01	1
157,300	0.35	0.04	1

Sources:
1 Soviet Antarctic Expedition at Vostok
2 U.S. Cold Regions Research and Engineering Laboratory at Byrd Station
3 Greenland Ice Sheet Program
4a Polar Ice Coring Office (Nebraska) and the Physics Institute at the University of Bern at Siple Station: dry extraction
4b Polar Ice Coring Office (Nebraska) and the Physics Institute at the University of Bern at Siple Station: vacuum melt extraction

TABLE A2

Atmospheric Methane: Global Averages

Year	CH_4-Concentration in ppmv (1)	CH_4-Concentration in ppmv (2)
1962		1.354
1965		1.386
1966		1.338
1967		1.480
1968		1.373
1969		1.385
1970		1.431
1971		1.436
1972		1.500
1973		1.624
1974		1.596
1975		1.541
1976		1.490
1977		1.471
1978		1.531
1979		1.545
1980	1.562*	1.554
1981	1.568	1.569
1982	1.590	1.591
1983	1.614	1.615
1984	1.627	1.629
1985	1.642	1.643
1986	1.654	1.656
1987	1.672	1.673
1988	1.683**	1.697

Sources:
(1) The global average is based on 7 sampling sites: Barrow (Alaska, USA); Cape Grim (Tasmania, Australia); Cape Kumukahi (Hawaii, USA); Cape Matatula (American Samoa); Cape Meares (Oregon, USA); Mauna Loa (Hawaii, USA); South Pole (Antarctica) (Boden et al., 1990, pp. 144-145).
(2) Data 1962-1978: Khalil and Rasmussen, 1982.
* August-December 1980
** January-September 1988