THE ROLE OF METHANE IN CLIMATE CHANGE

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The Role of Methane in Climate Change, Edited by **A.G. Ishkov, Doctor of Chemical Science**

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This paper presents an analysis of the role of methane in climate change, based on various indicators used in scientific research and provides recommendations for objectively assessing the role of methane in global climate change processes.

The publication provides an analysis of the ratio of anthropogenic to natural methane emissions, an assessment of the contribution of various emission sources to total methane emissions in the atmosphere, and the increase in methane concentration in recent years.

The publication is intended for a wide range of experts and decision-makers.

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INTRODUCTION

Over the past several decades, climate change has ranked first among the globe's top environmental problems in the outlook of many countries. Recognition of the urgency of the problem of climate change and the need for collective action to prevent or at least mitigate its consequences has been confirmed by the international community with the adoption in 1992 of the United Nations Framework Convention on Climate Change (UNFCCC).

The global greenhouse effect is primarily a result of water vapor, without which life on Earth would be impossible. The adoption and entry into force of the Kyoto Protocol was a major step in the implementation of the measures envisaged by the Convention. Russia plays an important role in ensuring the successful achievement of the goals of the Convention and the Kyoto Protocol. It's worth noting that if Russia had not ratified the Kyoto Protocol, the agreement would never have entered into force.

The Earth's climate has been subject to constant fluctuations thoughout its hisotry. Among the most notable fluctuations is the cycle which transpires every one hundred thousand years – it includes both glacial periods (ice ages), when the Earth's climate is mostly colder than the present, and interglacial periods, when the climate is warmer. These cycles have natural causes; they are non-anthropogenic. According to a number of scientists, even now we are in a "transition" from one glacial period to another, but the rate of change is very gradual, on the order of 0.02°C every 100 years.

Many believe the second most potent greenhouse gas, after CO_2, is methane. Methane is a product of natural processes occurring in the biosphere, and is also released as a by-product of human industrial activity. It is necessary to assess the role of methane in global climate change, and especially methane of anthropogenic origin.

The study of the climatic changes of the last millennium using paleo-climatic data based on ice cores, tree rings, lake bed sediments and coral reefs allows researchers to reconstruct the climate of the past. Many millions of years ago, during the time of the dinosaurs, the climate was much warmer – the temperature, on average, was 7°C higher on the planet as a whole. Then the climate gradually became colder, and in the history of the Earth there were many abrupt changes (mainly cooling), which were accompanied by a mass extinction of living organisms.

The natural causes of climate change, as a systemic analysis of the problem reveals, are:

1. Variations in the Earth's orbit and angle of inclination.
2. Changes in solar activity.
3. Volcanic eruptions and changes in the quality of atmospheric aerosols.

This analysis shows that the effects of natural causes on the climate are an order of magnitude higher than anthropogenic ones. For economic and political reasons, the natural causes of climate change and natural factors that compensate for the anthropogenic impact on the climate are almost never considered. Financing for such work is not allocated.

Virtually no credible work has been done on the role of water vapor in climate change under changing conditions (ocean pollution, industrial emissions, melting of ice, etc.). In this book, an objective review of existing views on the role of methane in global climate change is given.

The IPCC estimates that the lifetime of methane in the atmosphere is 9-12 years. It is irretrievably consumed, mainly in reactions with hydroxyl (particularly in the troposphere) and atomic chlorine (mainly in the stratosphere).

In this regard, the fight against present-day methane emissions, if one takes into account the possible catastrophic consequences of climate change by the end of the century, becomes meaningless. Nevertheless, many discussions are held concerning the reduction of methane emissions, as the idea that anthropogenic emissions of methane from the oil and gas industry are easier to regulate and reduce is gaining popularity. The "treatment" of the problem is not suggested where actions are needed (where "it hurts"), but where changes can be made. The work of many scientists has substantiated arguments and alternative points of view on the problem of global warming. According to their work, a ‘small ice age’ will start between 2020 and 2030. There are concerns that the methods for estimating global temperature changes are not methodologically correct, and that global warming not only doesn’t exist, but, moreover, the globe has cooled over the past 20 years, and that the influence of natural factors (changes in the Earth's orbit, solar radiation) has been greater than anthropogenic factors.

The opinion of scientists who advocate an alternative point of view is ignored in popular publications. They don’t take into account the influences of biota on global climatic processes, those which V.I. Vernadsky addressed almost a century ago. Given increased CO_2 content and an accelerated water cycle, biomass responds with increased growth and positively influences the entire biological system of the Earth.

A heightened popular perception of the problem of global climate change influences the competition between producers of energy resources. The impact of greenhouse gases on the climate, although not a conclusively proven fact, is subject of constant discussion and political decision-making, and in recent years, so-called carbon footprints have become a subject of active discussion.

The carbon footprint includes direct and indirect greenhouse gas emissions and is usually expressed in terms of grams of carbon dioxide-equivalent (gCO_2e) per unit. This approach allows us to more objectively estimate greenhouse gas emissions for different products throughout their life cycle or in the process of obtaining the product. It permits us to objectively compare different sources of energy, including renewable and non-renewable ones, and objectively determine the "hot spots" where it is necessary to concentrate measures to reduce greenhouse gas emissions.

The experts who participated in the preparation of this analytical review do not fully agree on the problems posed by possible climate changes due to the anthropogenic emission of greenhouse gases, including methane. Nevertheless, the main conclusions of the review, in our opinion, are the most objective for this period.

Sections 1-6, 7.1, 7.2, 8, 10 and 13.1 were prepared by S.M. Semenov, I.L. Govor, and N.E. Uvarova; Section 7.3 was prepared by I.L. Karol, V.M. Ivakhov and A.A. Kiselev, Section 9 was prepared by S.A. Roginko, Section 11 was prepared by N.B. Pystina and N. A. Boyarchuk, sections 7.4, 12 and 13.2 were prepared by V.A. Grachev, K.V. Romanov and M. Kuhn. Introduction and conclusions are prepared by V.A. Grachev under the leadership of the editor of the publication, A.G. Ishkov.

1 GREENHOUSE GASES, THE MECHANISM OF HOW THEY INFLUENCE THE CLIMATE AND THEIR COMBINED EFFECTS

B In recent decades (1981 - 2010), the average annual global near-surface temperature has been about 14°C or 287 K [1]. Paleo-climatic data and global climate monitoring data gained from systematic instrumental measurements of hydrometeorological parameters indicate that this value is not constant. It has changed in both recent history and further back in time. During the 1880-2012 period, it increased by 0.85 degrees [2]. What is the reason for the change?

There are natural factors that have always influenced the flow of solar energy absorbed by the Earth's surface. These are astronomical, orbital factors: the shape of the orbit changes, it rotates in its plane, and the position of the Earth's axis relative to the plane of the earth's orbit changes. Such changes are cyclical rather than unidirectional. According to Milankovich's theory [3], such changes lead to cyclic changes in the flux of solar radiation absorbed by the Earth's surface, which is the cause of the cyclical changes in the Earth's climate (including glaciations). Despite some serious objections [4], this theory is currently the most widely accepted. The typical time scale of such phenomena is tens or hundreds of thousands of years.

There are also very short-term fluctuations in the varying degrees of solar radiation absorbed by the Earth's surface. They are caused by the fact that the luminosity of the Sun changes cyclically. For example, there is an 11-year cycle (known as the Schwabe cycle). This process affects the near-surface temperature of the Earth.

However, there are other reasons for changes in the terrestrial climate, not related to the change in the flux of solar energy reaching the Earth's surface, but related to changes in the properties of the atmosphere and the Earth's surface.

This can be illustrated in the following way: if the Earth had no atmosphere (and, for that matter, if there was no water on the Earth), then the Earth's surface would reach a flux of solar radiation averaging 341.3 W/m^2 (watts per square meter)[5]. In a state of thermodynamic equilibrium, the Earth's surface would radiate just as much. Thus, according to the Stefan-Boltzmann law, the temperature of the Earth's surface would be $287 \times (341.3/396)^{0.25} = 277$ K. The actual current radiation of the Earth's surface is 396 W м$^{-2}$, which yields a temperature that is 10 degrees higher.

The atmosphere affects the formation of the thermal environment in three ways:

- part of the flux of solar energy is scattered and redirected back into space
- part of the flux of solar energy is absorbed by the atmosphere;
- most of the infrared radiative flux of the Earth's surface and atmospheric layers is captured by the atmosphere and redirected to the Earth's surface (greenhouse effect).

Since the beginning of the industrial era (approximately 1750 AD), the content of greenhouse gases in the atmosphere has increased significantly due to human activity (except for water vapor; any increase in its volume is compensated for by the high turnover of the atmospheric water vapor cycle). [1] This has already affected the thermal dynamics of the near-surface layer. Fig. 1.1 provides information reflecting the contributions of various factors to the change in global temperature in 1951-2010 [2]. It can be seen that the contribution of greenhouse gases (green bar) is significant and close to 0.9 degrees Celsius. The actual change (black bar) is slightly less, since there are cooling factors.

In the overall effect of greenhouse gases, the contribution of methane is not dominant. The main factor, of course, is the increase in the concentration of carbon dioxide.

The existing international agreements aimed at limiting the increase in greenhouse gas concentrations in the atmosphere in order to contain global warming, the United Nations Framework Convention on Climate Change (the UNFCCC), the Kyoto Protocol, and the Paris Agreement, primarily implement measures to limit the enrichment of the atmosphere with carbon dioxide.

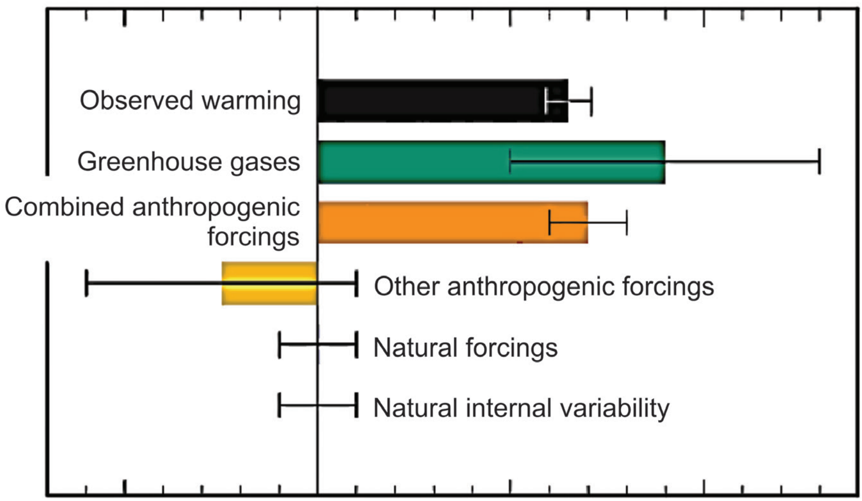

Figure 1.1. Probability Bounds (horizontal intervals) and mean values (colored rectangles) of estimates of the established contribution of various factors to the linear trend of observed global warming in 1951– 2010 (IPCC, 2014a)[2]

[1] Note. Ed.

[2] 'Observations of Warming, estimated at 0.85°C, are comparable with the observed decrease (- 0.3°C) Note. Ed.

In this context, the methane issue is already largely recognized by the world community. For example, in 2012, a new global initiative was announced to combat climate change, improve air quality and protect public health: the Climate and Clean Air Coalition. This organization conducts activity aimed at reducing the presence of so-called "short-lived climate pollutants" in the atmosphere.[3] This is the name given substances with a short lifetime in the atmosphere; about 10 years or less. In addition to methane, they include black carbon and many hydrofluorocarbons, which in general are responsible for about a third of modern global warming. Compared to CO_2, the short lifetime of such substances in the Earth's climate system contribute to the effectiveness of measures to limit their content in the atmosphere - reducing global emissions in the foreseeable future (a decade or less) will produce the desired effect.

This analytical material takes a look at the methane issue in terms of its role in current global climate change and the possibilities of limiting anthropogenic emissions into the atmosphere.

[3] The shift in focus in public discussions from long-term to short-term factors; that is, the focus, for example, on methane instead of CO_2, in fact makes it possible to demonstrate virtual emission reductions without changing the general influence of the main factor affecting the climate system (Ed.)

2 INTERNATIONAL REGULATIONS GOVERNING THE EMISSION OF GREENHOUSE GASSES

Climate change is one of the leading problems facing the modern world. Finding a solution is only possible with a high level of cooperation between countries. The main greenhouse gases are 'well-mixed' in the atmosphere. This means that limiting their content in the atmosphere is not a local problem. One country on its own, even one with a lot of territory, can't solve this problem independently by limiting greenhouse gas emissions at the national level. Despite all such restrictions, it will receive greenhouse gases from the global pool, i.e. due to emissions from other countries. Thus, the only way to solve the problem is through international cooperation.

This process can be carried out at various levels, both at the level of international associations (including the UN, OECD,[4] BRICS, Arctic Council, etc.), and at the level of partnerships between individual actors, including government and non-government organizations as well as international industrial corporations. The regulation of greenhouse gas emissions can be carried out in various ways, both in the form of stricter policies with respect to anthropogenic emissions, and by creating favorable conditions and mechanisms for introducing low-carbon technologies. At the same time, the climate initiatives adopted by these associations can have both mandatory and voluntary aspects for their participants. Russia, as a state, has decided to join such international initiatives in order to suit both its domestic and foreign policy priorities. In the following we briefly discusse the main international agreements and initiatives aimed at regulating both greenhouse gas emissions in general and methane in particular, in which Russia is taking part or intends to take part.

The main international document regulating the global anthropogenic impact on climate is the UN Framework Convention on Climate Change (UNFCCC), which was adopted on 9 May 1992, and entered into force on 21 March 1994. This agreement intends to establish the general principles of joint action to contain climate change on the planet, and its goal is thus stated [6]:

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

[4] United Nations (UN), Organization for Economic Cooperation and Development (OECD)

The overall objective of the UNFCCC is to curb the growth of anthropogenic emissions of greenhouse gases by compelling individual countries to perform within the framework of internationally agreed-upon obligations and through the organization of special protocols. It also calls for steps to be taken to increase the intensity of absorption of individual gases by terrestrial ecosystems.

Russia became a party to the UNFCCC on 28 March 1995 [7]. At present, it has been ratified by 197[5] states, which, according to the Convention, are differentiated into three main groups:

- Annex I countries: OECD members (industrialized countries), as well as countries with economies in transition (including Russia) that have made special commitments to limit emissions;
- Annex II countries (exclusively OECD members) that have undertaken special financial obligations to assist developing countries and countries with economies in transition;
- developing countries.

The supreme decision-making body of the UNFCCC, which determines the mechanisms of its operation and monitors the progress of its implementation, is the annual Conference of the Parties.

In December 1997 at the third Conference of the Parties in Kyoto, Japan, the Kyoto Protocol was adopted [8], obligating developed countries and countries with economies in transition that were parties to the Protocol (including Russia) to limit greenhouse gas emissions and provide for various financial mechanisms for this. Among the goals it set was a reduction of the total emission of greenhouse gases (including methane) by at least 5% from their 1990 levels in the period from 2008 to 2012. The document came into force on 16 February 2005.

There are 192[6] countries which are signatories to the Kyoto Protocol. After the end of the first commitment period, it was decided to implement a second such period from 1 January 2013 to 31 December 2020. Adopted at the end of 2012 in Doha, an amendment to the Kyoto Protocol [9] includes new commitments that were taken by its parties in addition to those already in existence and a second period of their operation. However, only 83 countries have ratified this document.

Russia ratified the Kyoto Protocol at the end of 2004 [10], and ensured the entry into force of the international agreement. In accordance with its instructions, Russia had to maintain average annual emissions in 2008-2012 at their 1990 level. For the second phase of the Kyoto Protocol, Russia, like many other countries, refused to assume any obligations.

At the 21st Conference of the Parties to the UNFCCC on 12 December 2015, a new climate treaty was adopted, the Paris Agreement [11]. This document was rati-

[5] Data for February 2018 from the official site of the UNFCCC, unfccc.int

[6] Data for February 2018 from the official site of the UNFCCC, unfccc.int

fied at the time by 174 countries and entered into force on 4 November 2016.

The main objective of the Paris Agreement is to strengthen global measures to combat climate change, in order to keep the increase in global temperature in this century within +2° C in relation to the pre-industrial level and even try to re-duce this figure to +1.5° C.

To this end, the participating countries determine their contributions to the achievement of the declared common goal individually and review them every five years. Unlike the Kyoto Protocol, the Paris Agreement does not provide for commitments to reduce greenhouse gas emissions, and the National Greenhouse Gas Reduction Strategies adopted by each country are pursued on a voluntary basis. Russia became a signatory to the Paris Agreement on 22 April 2016 [12 – 13], but has yet to ratify it. At present, Russia has approved a plan for the ratification of the Paris Agreement, according to which the decision to implement the agreement is slated to be made in 2019 [14].

The regulation of greenhouse gas emissions, especially their main component, carbon dioxide, faces a problem: its lifetime in the Earth's atmosphere is rather long, about 100 years. As a result, measures aimed at reducing the anthropogenic emission of CO_2, even if they are highly successful, will only produce the desired results after a few decades or later. Given this fact, the idea of reducing emissions of Short-Lived Climate Pollutants (SLCPs) such as methane, whose impact on solar radiation absorption and the climate is also significant, is currently being actively proposed, but such pollutants spend much less time in the atmosphere.

At the 38th meeting of the leaders of the Group of Eight (G8) in 2012, a fundamentally new international initiative was put forward, supported by the summit participants, including Russia: G8 Action on Energy and Climate Change. It dealt with the measurement and control of SLCPs which had an anthropogenic impact on the environment, including methane.[7]

On 16 February 2012, The United Nations Environment Program (UNEP) announced the launch of a new international initiative - the Climate and Clean Air Coalition ("the Coalition"). Its co-founders were Bangladesh, Canada, Ghana, Mexico, the United States and Sweden. The coalition operates on the basis of the "Framework Agreement for the Creation of a Coalition for Co-operative Action" [15]. This defines the work strategy and leadership of the Coalition, a high-level assembly that's held annually.

The Coalition's goal is to implement the idea of reducing the emissions of short-lived climate pollutants. This is a new step for the world community in reducing the anthropogenic impact on the climate system. In the Coalition, each country determines its priorities and the measures it intends to implement fully

[7] An objective assessment of the actual role of methane in climate change is the goal of this work. (Ed.)

voluntarily and independently. The Coalition agreement is not a legally binding document by nature, according to which countries must take certain actions or allocate certain funds. However, its arrangement is extremely straightforward and focused on practical activity.

At present, the coalition members include: 58 countries; 63 non-state associations, including 17 international organizations (including the World Bank, UNEP, the United Nations Development Program, and the OECD), as well as over 90[8] different individual organizations, both public and private. Russia has been a member of the Coalition since 2014 [15].

During the 22nd Conference of the Parties in Morocco on 14 November 2016, the Coalition submitted the Marrakech Communiqué [16] adopted at the 8th High-level Assembly. In it, it announces its intention to take measures to reduce the SLCPs and calls on all countries to take effective measures to slow the growth of climate change. Coalition partners also committed themselves to reducing methane emissions from oil and gas operations.[9] At present, Russia hasn't adopted the Marrakech Communiqué.

At the 2014 UN Climate Summit in New York, a coalition of transnational oil and gas companies announced a decision to pool their efforts with governments and international environmental organizations to reduce methane emissions. To this end, the parties of the coalition created the Oil and Gas Methane Partnership [18]. Oil and gas companies, various environmental organizations, as well as the governments of large oil and gas producing countries, including Russia, joined the initiative.

Additionally, in November 2017, the world's largest energy companies: BP, Eni, ExxonMobil, Repsol, Shell, Statoil, Total and Wintershall, established the Guidelines for reducing methane emissions in the value chain of natural gas. In March 2018, PJSC Gazprom adopted these principles.

According to the Guiding Principles, the companies have agreed to the following obligations: a constant reduction of methane emissions; increasing the efficiency of work at every step of the production of gas; increasing the accuracy of data on methane emissions; promote sound policies and regulations for methane emissions, and increase transparency.

Now in many countries, especially developed countries, there is a tendency to adopt more restrictive attitudes towards greenhouse gas emissions and increase interest in low-carbon technologies, including when implementing the principles of sustainable development and increasing energy efficiency. This process will undoubtedly affect the formation of new international initiatives and programs.

[8] Data for February 2018 from the official website of the Coalition http://ccacoalition.org

[9] This paper will assess the real contribution of methane emissions from the gas industry

3 A RETROSPECTIVE LOOK AT THE CONCENTRATION OF METHANE IN THE ATMOSPHERE

The content of methane in the atmosphere is determined by the processes leading to its entry into the air (emission) and its elimination (depletion), and depends on their variability over time. Emissions are the result of natural biochemical and geochemical processes, as well as anthropogenic ones. The removal of methane from the atmosphere (depletion) is determined by the total rate of its chemical destruction in the atmosphere and absorption by the soil (see Section 4).

Historically, the Earth's climate has never been static. Paleoclimatic studies in Antarctica, namely the drilling of Antarctic ice at Vostok Station and analysis of the obtained ice core, have made it possible to establish, to some extent, how the climate has changed throughout geological history. The results of this study were published by an international group of authors [17, 19 ± 21]. In their work, the temperature values were reconstructed over a time interval of approximately 420,000 years. The results are shown in Fig. 3.1.

As can be seen in the chart, CH_4 varies cyclically. Approximately once every hundred thousand years it reaches a minimum: approximately 350 ppb. These minima approximately correspond to the time of the great glaciations, which regularly repeat. After reaching the minimum point, the CH_4 level raises rapidly to values of 700-800 ppb within about 10,000 years, and then a gradual, albeit not even, decrease in concentration occurs. As can be seen in the figure, this is also

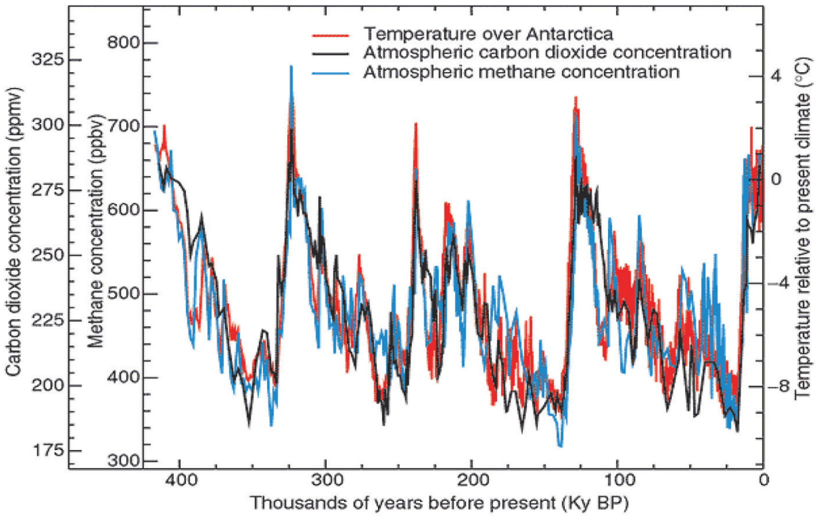

Figure 3.1. Changes in temperature and atmospheric concentrations of methane and carbon dioxide, obtained from the analysis of Antarctic ice cores, Vostok station (Barnola et al, 2003)

characteristic of the concentration of carbon dioxide (CO_2). Temperature fluctuations vary in a way reflecting the level of CO_2 in the atmosphere. According to the theory of M. Milankovich [3], temperature fluctuations can be explained by orbital factors - cyclic changes in the properties of the Earth's orbit and the position of the Earth's axis relative to the plane of the Earth's orbit. The long-term fluctuations in the concentration of methane (and carbon dioxide) that develop throughout tens or hundreds of thousands of years are a consequence of these temperature changes [3].

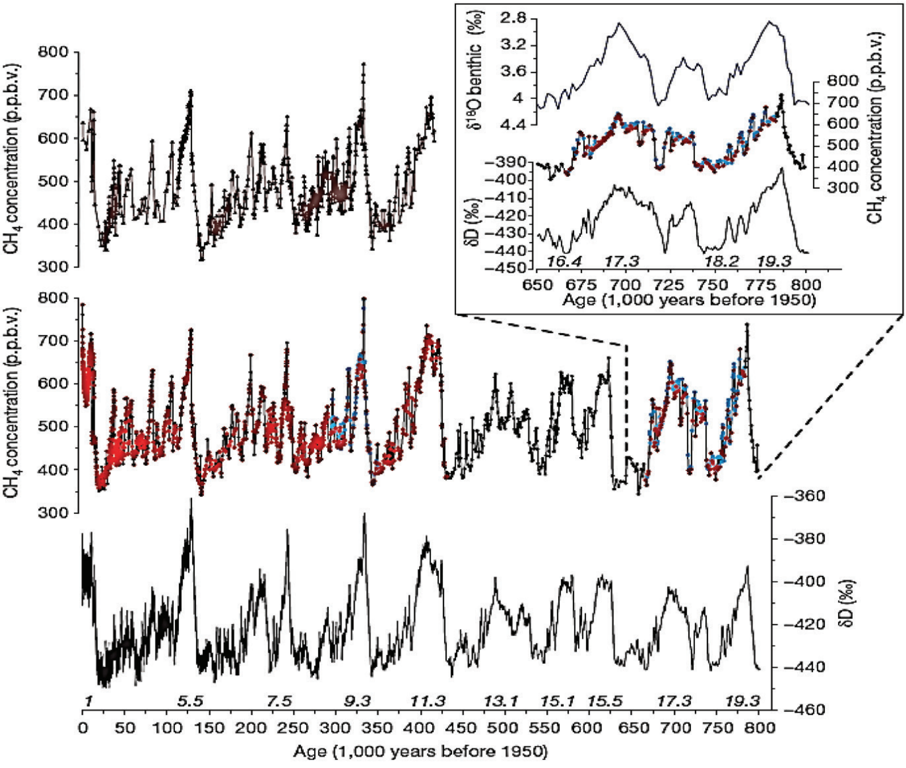

Figure 3.2. Changes in the concentration of methane in the atmosphere over the course of 800,000 years (Loulerlegue et al., 2008). The data set is for years prior to 1950 AD (the left side of the scale). The upper brown line is the methane concentration from the ice core data from Vostok station. The middle curve (the red and later black line, and the line with blue dots), according to the core data from dome "C" (black dots – already-published early data, red dots - the results of the analysis in Grenoble, blue - in Bern). The lower black curve is the deuterium content (peaks correspond to temperature rises). The box in the top right relays detailed data for the period 650-800 thousand years ago: the upper curve represents the content of deuterium in ma-rine sediments (an indicator of ocean temperature); the middle curve is the methane content in the atmosphere; the lower curve is the content of deuterium in the ice from dome "C". You can observe their clear correlation.

Paleoreconstructions have been put together so far that reflect approximately the past 800,000 years of history. An analysis of the gas composition of air bubbles from ice cores, collected in Antarctica and Greenland, have made it possible to trace the evolution of methane concentrations in the atmosphere, as well as temperature. The results are shown in Fig. 3.2 [23].

Note that the concentration of methane prior to the industrial era (conditionally, until 1750) never exceeded 800 ppb. Given that before mankind engaged in intense economic activity, humans had an insignificant effect on atmospheric differences, the observed concentration of methane was exclusively determined by natural processes [23, 24].

The concentration of CH_4, as well as the other two main "anthropogenic" greenhouse gases, CO_2 and N_2O, changes in tandem at different points throughout the globe. Fig. 3.3 relays the given values of methane at Low-Doum station in Antarctica and in Greenland since 1000 AD. These are the results of a group of researchers [25]; their corresponding publication is [26]. In Fig. 3.3 it can be seen that, first, the differences in concentrations in Antarctica and Greenland are small, and second, prior to the beginning of the industrial era, the value of the CH_4 concentration fluctuated within the range of 625-675 ppb. Beginning in around 1750, it left this range, and began to grow systematically. It reached the level of approximately 1500 ppb by the end of the 20th century.

Currently, global concentrations of methane in the near-surface layer has reached 1,800 ppb or more [27].

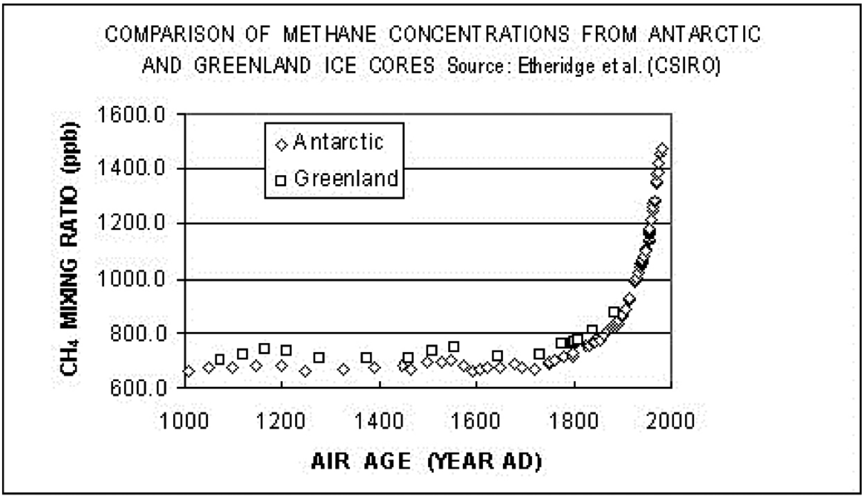

Figure 3.3. Progress of the concentration of methane in 1000 AD in Antarctica and Greenland (Etheridge et al, 2002)

4 THE GLOBAL BUDGET OF METHANE IN THE ATMOSPHERE

At any given time, the methane content in the atmosphere is determined by its emission into the atmosphere and its removal from the atmosphere. Recall that, according to paragraph 9 of Article 1 of the UNFCCC[6], "Source" means "*any process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere.*" Hereinafter, "Sink" refers to any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere.

Currently, there are two methods for evaluating sources/sinks of greenhouse gas: bottom up and top-down.

The **bottom-up** method is essentially a way of determining total emissions into the atmosphere or removal from the atmosphere of a substance being studied by measuring output in terms of some generalized geographic or economic source or sink (i.e. a region or a sector of the economy), and is based on a measurement or evaluation and subsequent summation of values for its components. Unfortunately, this is not always a solvable task due to various reasons - the lack of detailed data, instrumental methods, etc. Therefore, the so-called "top-down" method is also used, which solves the inverse problem: a mathematical model of the process is constructed that allows one to quantify the changes in the incoming and outgoing fluxes of matter from the observed changes in concentration (which are more easily measured than inflow/outflow). Naturally, the estimates obtained depend on the type and features of the model used, and often differ markedly among different authors.

Since the flow of methane into the air is completely determined by flows from the surface, the application of the "top-down" estimate allows for the establishment of a maximum value for emissions in the region under study. The use of additional data, such as isotopic studies, allows us to judge the power of emissions from individual source classes. On a global and continental scale, such assessments are considered sufficiently reliable. The drawbacks of this approach are related to the quality of meteorological observations and models, as well as the inability to consider in detail some types of sources, especially anthropogenic ones.

When assessing bottom-up emissions, an incomplete accounting of sources can lead to errors when considering the spatio-temporal variability of the flow and the corresponding estimates. These two approaches can be applied for any time period (including for predictive estimates) both within the same region and globally.

At the same time, the 'bottom-up' values given for global methane emissions are higher, mainly because of the issue of a possible reassessment of the contribution of geological and water sources, which is still being scientifically debated. It should be noted that, unfortunately, some processes leading to CH_4 emissions remain poorly understood. Moreover, they often differ in high temporal and territorial variability and depend on many factors, which in the end can lead to significant differences in estimates.

To date, there are many individual studies, including measurements of distributed concentrations of CH_4 in the atmosphere (both terrestrial and satellite) (see Section 6.2), its in/outflow from/to various sources and sinks, paleoclimatic data (see Section 3), as well as information on the biogeochemical cycle of methane and its isotopic composition. However, only the reduction of these data to a single 'budget' of methane for the corresponding time period and comparison with the observed increase in its concentration in the atmosphere make it possible to judge the correctness of the determination of the intensity of its formation, emission into the atmosphere, and its removal from it.

Given the variety of information available, material developed by several recognized scientific groups (including the IPCC, US EPA and GCP), involved in the development and reduction of the global methane budget were selected as sources of data for this report. The data used in the report for compiling the global methane balance in modern times (from 2000) using different approaches are given in Table. 4.1. Historical data and reconstruction of CH_4 emissions are given in Tabl 4.1 and in Fig. 4.1, 6.15 and 6.16. Forecasting of its emissions for several decades ahead is considered in Section 6.3.

4.1. MAIN SOURCES OF METHANE

Chemically, methane is practically never formed within the atmosphere itself. Therefore, the atmospheric sources of CH_4 can't be taken into consideration; assume that the flow of methane into the atmosphere is completely determined by its fluxes from the earth's surface [31].

Methane which has entered the atmosphere can be [32]:

- biogenic, occurs as a result of the chemical transformation of organic matter (for example, the burning of organic matter);

- bacterial, formed as a result of the activity of methanogenic (methane producing) bacteria in the bottom sediments of bogs and other bodies of water, as well as in the stomachs of insects and animals (mainly ruminants);

- thermogenic, occurring in sedimentary rocks during their immersion to depths of 3-10 km, where organic substances undergo a chemical transformation under conditions of high temperature and pressure;

- abiogenic, occurring as the result of the chemical reactions of inorganic compounds, usually at great depths inside the Earth's mantle.

According to the results of the estimation of methane formation volumes, processes involving anaerobic methanogenic bacteria predominate among its sources, which can be expressed by the resulting formula:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The molecular hydrogen used in the course of this reaction is produced by bacteria that do not generate methane, but develop in the same medium [31].

Methane sources are usually divided into two large groups: natural (ie, natural in origin) and anthropogenic (formed as a result of human activities). Some sources may be of mixed origin.

When determining the total amount of CH_4 entering the atmosphere from each source, the estimates of different authors differ noticeably. The classification of sources and their composition also has significance and may differ among different studies. In addition, the intensity of CH_4 emissions varies with time. Thus, determining the value of emissions should be conducted during different time periods, taking into account the methods used and the coverage of sources.

The greatest spread of global estimates was noted for natural sources of CH_4, including wetlands and the Arctic seas, which are considered important for Russia. Anthropogenic sources have been studied somewhat better.

Currently, the wetlands are the dominant natural source of methane. They contribute between 25 and 32% (2000-2012 data) of all its emissions and at the same time are characterized by high temporal variability and a dependence on climatic factors (feedback from the climate).

Anthropogenic emissions account for 49 to 61% of global CH_4 emissions (data 2000-2012), according to different estimates. The methane generation related to the extraction and use of fossil fuels is 29-34%, while that of natural gas is less than 10%.

4.1.1. NATURAL SOURCES

Every year, according to various estimates, from 218 to 384 Tg of CH_4 enter the atmosphere from natural sources (Table 4.1). Among them, the most intense is the flow of CH_4 from the surface of wetlands, which accounts for 80%.

The main natural sources of methane are the following [32, 33]:

- *Wetlands (including swamps and thermokarst).* Moistened soils containing a large amount of organic matter which create anaerobic conditions that promote the activity of methanogenic bacteria are a significant source of methane. Of these, the most powerful sources of this gas are bogs (especially tropical ones), since they are characterized by a high degree of bioproductivity. Methane can be released from such soils by molecular diffusion, by means of bubbles and through plants.

- *Surface water objects (including lakes and rivers).* Methane formation in freshwater reservoirs occurs in bottom sediments in the same way as it does in boggy (humidified) areas. The most active source of methane is considered to be lakes, while in comparison with mires their bio-productivity is about 10 times lower.

- *Fires*. During an inferno methane is formed as a result of the incomplete combustion of biological material. The main contribution to the emission of methane is caused by fires in savannas and tropical forests.

- *Ruminants*. Animals, especially ruminants, are a fairly intense source of methane release, due to the bacterial fermentation process occurring in their gastrointestinal tracts.

- *Insects*. Methane can be released as a result of the digestion processes of terrestrial insects, capable of the deep biochemical processing of cellulose. Importantly, they include termites.

- *Seas and Oceans.* The source of methane emissions in the seas and oceans is both bottom sediments (mostly on the ocean shelf and in shallow bays), and a water column. There are various theories of the mechanism of such emissions, but in general they are considered to be due to the anaerobic bacterial decomposition of organic matter. In addition, methane emissions from geological sources under the sea bottom and methane hydrates can enter the ocean.

It should be noted that wetlands, lakes, fires and animals can be elements of both a natural system and an economic one.

In addition to the usual sources of methane, there are also permanent sources of methane emissions. There are also natural reservoirs which contain a large amount of this gas, but do not release noticeable emissions into the atmosphere under normal conditions. However, they can react to methane emissions if new conditions arise, such as via climate change.

These sources include [31 – 33]:

- *Ancient Permafrost.* Permafrost contains both pre-existing methane (in air bubbles frozen in ice) and organic substances. Methane is contained both in the frozen ground and in pockets mixed with air, as well as in the form of methane hydrates (see below). Its content in the frozen permafrost averages 2.3 mg/ kg [32]. Such frozen terrain also contains a large amount of dead organic matter capable of serving as material for the formation of methane-creating bacteria at both positive and negative temperatures.

- *Methane hydrates.* Methane hydrates are solid chemical clathrate compounds of methane with water, which are stable only in a certain range of low temperatures and high pressures. One cubic meter of methane hydrate contains the equivalent of about 164 m^3 of ordinary gaseous methane. While Methane gas hydrates have been found on the continents, most of the deposits are located on the ocean shelf.

- *Deposits of gas and oil.* Natural gas containing methane is usually divided into three groups: natural gas from purely gas deposits, gas from gas-condensate deposits and associated petroleum gas. Methane is then dissolved in gas fluids or oil under pressure at great depths. The greatest amount of such methane (up to 90-97%) is contained in the gas of gas deposits, occurring mainly up to depths of 1,500 m. Methane emission from such sources can naturally occur due to diffusion and jet processes.

- *Coal deposits.* Methane formation in sedimentary rocks occurs through the pyrolysis of organic substances under high pressure, as well as high temperature conditions during the formation of coal. Methane is contained in coal in various forms, including in the form of solutions, in a free state, and also in adsorbed form. It is also found in the rocks accompanying the coal seams.

- *Other deep geological sources of methane.* The release of methane from terrestrial rocks can also occur due to a variety of geochemical processes: volcanic activity; mud volcanism; the separation of mineral and geothermal springs, together with waters; in the form of seeps from the Earth's mantle; or in the form of jet streams along faults of the earth's crust. The release of methane is activated in areas with high seismic activity.

The change in natural landscapes and ecosystems due to human activities leads to a change in the flow of methane from these sources. In addition, an increase in the temperature of the planet will affect the increase in CH_4 emissions, since a change in temperature by one degree changes the intensity of its release in microbiological processes by about 10% [32].

4.1.2. ANTHROPOGENIC SOURCES

According to various estimates, every year, from 319 to 352 Tg of CH_4 enter the atmosphere from anthropogenic sources. (data for 2000-2012). The distribution of these sources by volume of methane emissions and by year is given in Table. 4.1.

The results obtained by the US Environmental Protection Agency (Table 4.1, [35]) are used as an additional source of data on anthropogenic methane emissions in the scientific literature and in this report. Various predictive models of CH_4 emissions up to 2030 are based on this work, both for assessing climate change and for justifying the application of various techniques for reducing emission and their financial evaluation (see Sections 6.4 and 9, [34]).

In general, anthropogenic methane emissions in each country vary significantly over time and depend on such basic factors as the number of inhabitants, the level of development of the economy and individual technologies. Anthropogenic sources can be classified according to relevant sectors of the economy: energy, industrial processes, agriculture and waste. It should be taken into account that the composition of sources attributable to each sector and their classification by industry may differ slightly among authors, which may lead to additional differences in the final data.

Currently, the most significant components of anthropogenic methane emissions are domestic animals - up to 30% of anthropogenic emissions, as well as the production and processing of oil and gas - about 23%.

The main anthropogenic sources of methane are the following [28, 32, 35]:

- *Pets*, Just like wild animals, domestic animals, especially ruminants, are sources of methane formed during digestion.

- *Rice fields*. Rice fields are an intense source of methane, since they are covered with water for a considerable time, which creates favorable conditions for the development of anaerobic methanogenic bacteria. It is believed that methane enters the atmosphere mainly through plants, since without rice plants, similarly treated fields yield a flow of methane that is 1/50 as much.

- *Waste*. Dumped waste is a notable source of methane, since it contains a lot of moist organic material, and inside it anaerobic conditions are created that promote the formation of methane with the participation of bacteria. When using composting techniques, including when handling manure, a significant amount of methane is also released. The amount of methane released decreases with the use of special technologies for methane capture and utilization.

- *Wastewater*. Treatment of industrial and domestic wastewater in biological treatment plants or settling tanks, where there are anaerobic conditions for the development of methanogenic bacteria, leads to methane emissions. The amount of methane released decreases with the use of special technologies for methane capture and utilization.

- *Coal Industry*. When coal is extracted from the fields, methane enters the atmosphere as directly emitted during coal mining, as well as methane from the degassing of coal seams, as well as methane from mines, where mining is stopped. The amount of methane released can be reduced by using special technologies for its extraction and utilization.

- *Burning biomass and fuel*. In the event of the incomplete combustion of organic substances, methane is emitted both when fuel is used, and when burning agricultural residues and other organic wastes. Its main global source is in Africa, where it is widely practiced to burn straw when preparing soil for a new crop.

The extraction, processing, transportation, storage and distribution of natural gas and oil can be accompanied by methane emissions. The sources of methane in this case are the leaks of equipment and the technological need for gas venting during the course of repairs, start-ups and stops of equipment at production sites, etc. The amount of methane released decreases with the application of measures to prevent leaks and related petroleum gas utilization techniques.

Historical reconstruction of past global anthropogenic emissions of CH_4 was performed in [36] for the period of time 1860-1994. Estimates were made for the following sources: the incineration of associated and process gas, the gas supply, coal mining, burning of biomass, livestock, rice and waste disposal.

Table 4.1

Methane emissions from anthropogenic sources, Мт(CH_4) (EPA, 2012) for 1990 and 2005 (bottom-up) and prognosis for 2030 ('Business as Usual' scenario)

Source category/Year	1990	2005	2030
Energy, total *including:*	105,1	118,4	166,2
Extraction and processing of oil and gas	60,9	73,5	100,6
Coal Mining	25,2	24,8	37,3
Fossil Fuel Combustion	10,5	10,7	17,3
Burning of Biomass	8,4	9,4	11,0
Industrial production	0,4	0,4	0,3
Agriculture, total *Including:*	142,1	144,5	166,9
Ruminants	84,0	90,2	110,5
Rice growing	22,9	23,9	24,3
Treatment of manure	11,1	10,4	12,0
Burning grass in the savanna, agricultural and resi-dues, emissions from arable land	24,1	20,0	20,0
Waste, total Including:	51,0	61,2	75,4
Solid waste disposal	33,6	37,8	45,7
Waste water treatment	16,8	22,7	29,0
Other waste treatment methods	0,6	0,7	0,7
Total:	**298,5**	**324,6**	**408,8**

4.2. METHANE REMOVAL

Methane removal from the atmosphere occurs naturally through chemical (in the atmosphere) and biochemical (soil) processes. Precipitation plays practically no role in the removal of CH_4 from the atmosphere, due to its low solubility in water.

CH_4 molecules are quite stable in the atmosphere; they do not possess a high degree of reactivity and interact only with a few very active substances - hydroxyl OH molecules, as well as with chlorine atoms Cl and excited O (^1D) oxygen atoms. The destruction of methane during the reaction with free OH radicals occurs mainly in the troposphere. During its diffusion, methane enters the stratosphere and is destroyed there by a variety of chemical and photochemical processes. When molecules of methane are absorbed from the air by soil microorganisms, they are destroyed biochemically. This process mainly occurs in dry soils of forests and steppes [28, 32, 35].

The main methane drainage mechanism is its chemical reaction with the hydroxyl radical OH, which eliminates approximately 90% of all incoming emissions from the atmosphere annually, or 9% of its total contemporary atmospheric content [28]. These processes are discussed in more detail in Section 16.

The application of technologies for capturing and utilizing CH_4 from anthropogenic sources, as well as some cases of its extraction from natural reservoirs for further use, can be considered as anthropogenic "removal"; however, the volume of such processes is small.

4.3. SUMMARY OF THE MODERN METHANE BUDGET

The intensity ratio between methane inflow and outflow determine its possibility of accumulating in the atmosphere, and as a result – its concentration and its growth, as well as the total amount of methane in the atmosphere (see Table 4.3, Sections 3 and 6.2.).

The data given corresponds to the observed increase in the global content of methane in the atmosphere, since its release into the atmosphere exceeds its re-moval. It is believed that climate-related fluctuations in CH_4 emissions from natural wetlands are the main factor responsible for the observed global interannual variability in CH_4 emissions. In this respect, a certain but less significant role is played by biomass that burns during those years, in which extensive fires were observed [28].

Despite the previously described difficulties in obtaining data on the components of the global methane budget, [37] there is a very high degree of certainty that the increase in CH_4 in the atmosphere since the beginning of the industrial era has hitherto been the result of human activities.

Table 4.2

Global methane budget in 2011, bottom-up (Saunois at al., 2016)

Category	Unit	Value
Total content of CH_4 in the atmosphere	CH_4 Mt	4954±10
Atmospheric removal	CH_4 Mt/year	542±56
Atmospheric growth	CH_4 Mt/year	14±3
All sources of methane, including:	CH_4 Mt/year	556±56
Anthropogenic	CH_4 Mt/year	354±45
Natural	CH_4 Mt/year	202±35

5 ESTIMATING THE "LIFETIME" OF METHANE IN THE ATMOSPHERE AND THE FACTORS THAT DETERMINE IT

Methane enters the atmosphere mainly from the Earth's surface, where its natural and anthropogenic sources are located. This gas is much lighter than air, and it tends to move from the near-surface layer to the upper layers of the atmosphere, a process which is sped up by convection. In the stratosphere, CH_4 "dies" through a series of chemical and photochemical reactions, i.e. there, it is irretrievably removed from the atmosphere.

This 'fate' agrees with the character of its vertical 'distribution' in the atmosphere. A typical distribution – the American 'Standard Atmosphere' [38] – is shown in Fig. 5.1. In the troposphere, up to an altitude of approximately 10 km, the concentration of CH_4, expressed by the volume mixing ratio (VMR),[10] changes little. The processes leading to the elimination of methane in the troposphere are much slower than vertical physical mixing. In the tropopause, in the stratosphere and above, the ratio of these velocities is different, which is manifested in a noticeable decrease in its content (VMR) with altitude.

The removal of CH^4 from the atmosphere is mostly a chemical process, dominated by reactions with hydroxyl radicals (OH), atomic chlorine (Cl), and excited atomic $O(^1D)$. We present the corresponding reactions [32, 40]:

$$OH + CH_4 \rightarrow H_2O + CH_3;$$

$$OH + CH_4 \rightarrow H_2O + CH_3;$$

$$Cl + CH_4 \rightarrow HCl + CH_3;$$

$$O(^1D) + CH_4 \rightarrow OH + CH_3$$

$$(\text{или } O(^1D) + CH_4 \rightarrow CH_3OH;\ O(^1D) + CH_4 \rightarrow CH_2O + H_2)$$

During the course of chemical reactions with hydroxyl radicals (OH) approximately 90% of the total volume of methane is removed from the atmosphere [41 – 43].

The basic source of *hydroxyl radicals* (OH) in the Earth's atmosphere is the interaction of excited oxygen atoms $O(^1D)$ and water:

$$O(^1D) + H_2O \rightarrow 2OH$$

Excited oxygen atoms $O(^1D)$ are formed during ozone photodissociation:

$$O_3 + h\nu\ (\lambda \leqslant 310\ \text{нм}) \rightarrow O(^1D) + O_2$$

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[10] The mixture for atmospheric gases is most commonly expressed as a volume ratio (parts per hundred - %), pro mil (parts per thousand - ‰), parts per million - ppm, parts per billion – ppb, parts per trillion - ppt

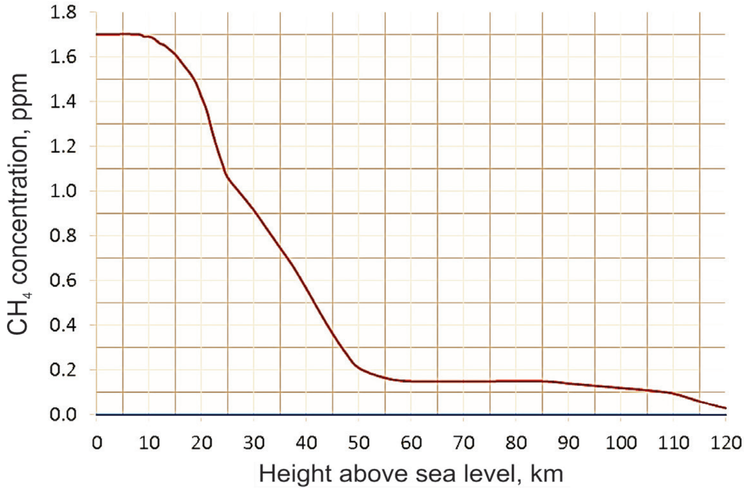

Figure 5.1. Typical vertical distribution of methane content:
Y axis - concentration of CH_4 (ppm); X axis - altitude above sea level, km
(U. S. Standard Atmosphere, 1976)[11]

If this reaction requires a sufficiently intense inflow of ultraviolet or stronger radiation, as well as a sufficient concentration of ozone, of which there is more in the upper atmosphere, then the previous reaction requires the presence of water vapor, the content of which decreases with altitude. The combination of the effect of these two differently directed factors leads to the fact that the OH content in the upper atmosphere is higher.

Fig. 5.2 graphs the concentration of hydroxyl radicals in the atmosphere according to height above sea level, corresponding to the American standard atmosphere [38][12] . These figures correpond to 45° NW.

The destruction of methane in reactions with atomic chlorine (Cl) occurs mainly at altitudes above 35 km. In the creation of varying levels of atomic chlorine Cl in the atmosphere, the role of its precursors of anthropogenic origin is great [44]. These are chlorofluorocarbons (CFCs), also known as freon. These substances are used as refrigerants in refrigeration systems and in aerosol spray manufacturing. When hit with ultraviolet light or stronger radiation, CFCs dissociate with Chlorine atoms, which enter the atmosphere. For example,

$$CF_2Cl_2 + h\nu\ (\lambda \leqslant 214\ \text{нм}) \rightarrow CF_2Cl + Cl;$$

$$CFCl_3 + h\nu\ (\lambda \leqslant 214\ \text{нм}) \rightarrow CFCl_2 + Cl.$$

[11] In Fig. 5.1, the period should be interpreted as a decimal separator.

[12] http://www.digitaldutch.com/atmoscalc/; http://www.spectralcalc.com/

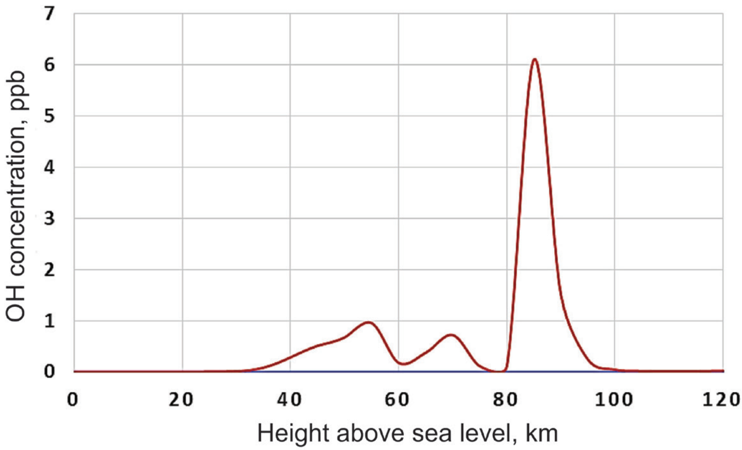

Figure 5.2. Typical vertical distribution of hydroxyl-radical content:
the Y-axis is OH concentration (ppb); the X-axis is height in kilometers above sea level
(U. S. Standard At-mosphere, 1976)

Atomic chlorine can appear in the atmosphere and for natural reasons. For example, seawater, volcanic activity and forest fires can be sources of CH_3Cl emissions. This substance can split into CH_3 and Cl.

The combination of soil absorption to the elimination of atmospheric methane is limited.

All these processes determine the lifetime of methane in the atmosphere. According to varying contemporary estimates, this is 8 – 12 years [31], 8-15 years [40], 9.1 ± 0.9 years [45], 8-10 years [29], or 9.3 ± 0.9 years [46]. According to a synthesis assessment of the Intergovernmental Panel on Climate Change (IPCC), it is 12.4 years (IPCC, 2013).

Methane is considered a greenhouse gas (its "greenhouse" effect per unit of increase in the content in the atmosphere exceeds that of carbon dioxide, see section 7). However, the processes of removing CH_4 from the atmosphere in turn depend on the climate. It was shown [40] that the lifetime of methane in the atmosphere decreased from 1900 to 2005, due to the warming of the climate by about 3%. According to research [46] a larger reduction value for the period 1980-2000 is given: 4.3 ± 1.9%. This could have contributed to some slowdown in atmospheric methane content growth between the end of the 20th century and the beginning of the 21st century. (a slowdown has been observed between the late 1990s and 2007).

6 MECHANISMS OF METHANE INFLUENCE ON CLIMATE CHANGE

6.1. THE BASICS

The main source of energy in the Earth's system[13] is the Sun. Its radiation fluxes reach the upper boundary of the planet's atmosphere and further penetrate through them to the Earth's surface. This flux of solar radiation to the Earth averages 341.3 Watt м$^{-2}$ on the upper boundary of the atmosphere (conditionally, at an altitude of 200 km). Part of the solar radiation flux is reflected back into space by the atmosphere and the earth's surface, while approximately 70% is absorbed. The average geothermal heat flux through the earth's surface is equal to 0.06 Watt м$^{-2}$, i.e. four orders of magnitude less.

The spectral distribution of the flux of solar radiation at the upper boundary of the atmosphere is shown in Fig. 6.1. Visible light is part of this flow. The monochromatic components of this radiation have a wavelength of 0.4 – 0.7 µm.

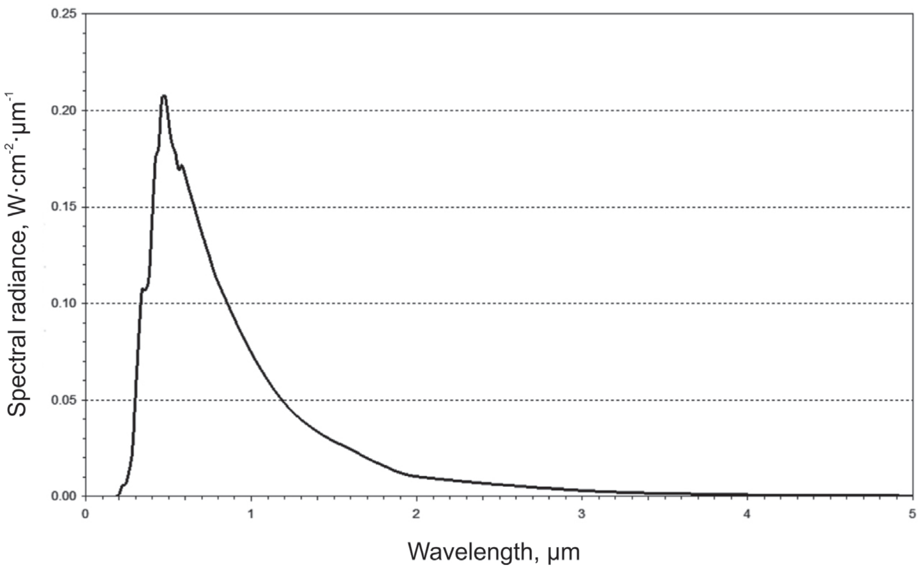

Figure 6.1. Solar radiation distribution (spectral density) on the top boundary of the atmosphere by wavelength [47]

[13] "The Earth's system", means the totality of all objects in the atmosphere, on the earth's surface and in the terrestrial stratum and their interaction, including through the exchange of mass and energy

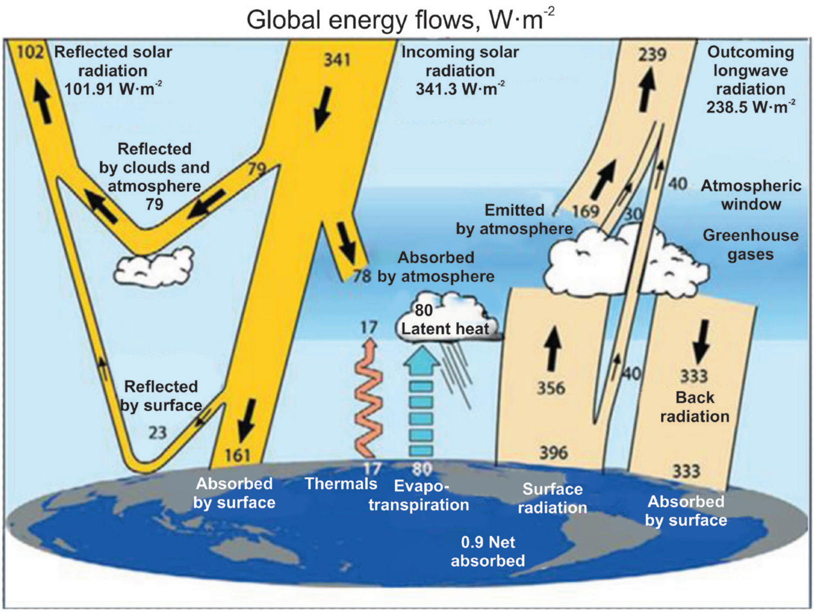

Figure 6.2. Global energy flows (W m⁻²) in the "atmosphere + the Earth's surface" system (Trenberth, Fasullo, Kiehl, 2009)

Fig. 6.2 shows the current global energy budget at work in the Earth's system [48].

Solar radiation heats the Earth's surface and, to a much lesser extent, the atmosphere. Like any body, the Earth and Sun both radiate energy. But the temperature values on the Earth's surface and in the atmospheric layers are low (about 300 K or less) in comparison with the temperature on the surface of the Sun (about 6,000 K). Therefore, the Earth's surface and atmospheric layers radiate at a completely different wavelength - the infrared range. Fig. 6.3 shows the calculated spectral distribution of the radiation of the Earth's surface, which averages 288.15 K.

As can be seen from 6.2, the atmosphere releases only about 10% of the infrared radiation from the planet's surface into space. The rest is absorbed by the atmospheric layers at varying altitudes. These layers emit "up and down" almost entirely in the infrared range. In total, out of a range of 396 W m^{-2} emitted from the Earth's surface, 333 W m^{-2} is redirected by the atmosphere back to the earth's surface. These properties of the terrestrial atmosphere create the "greenhouse" effect, so that the thermal conditions in the near-surface layer are quite comfortable. Let us explain the "greenhouse effect" using a simple illustrative example.

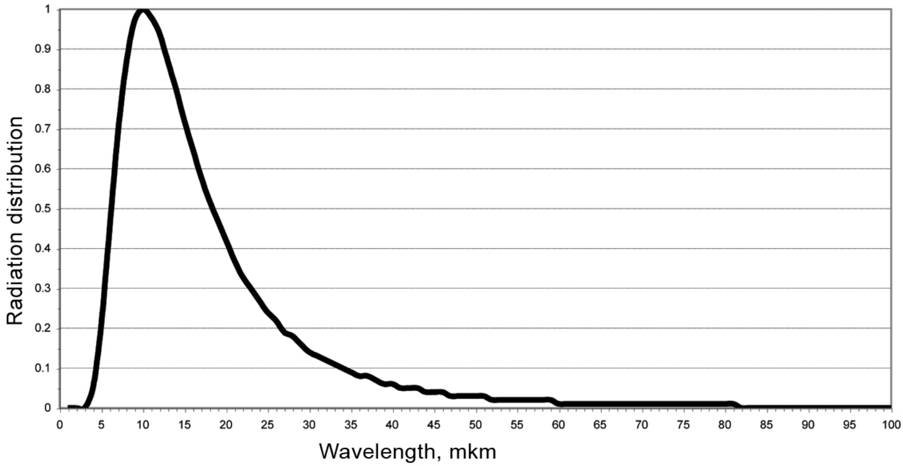

Figure 6.3. Calculated distribution of blackbody radiation by wavelength at a surface temperature of 288.15 K (Earth) in spectrums with a maximum spectral density[14]

Fig. 6.4 shows radiation streams of two types: shortwave (solar, conventionally with a wavelength of $\lambda < 3$ μm) and long-wave, infrared (the radiation of the Earth's surface and atmospheric layers, conditionally with a wavelength of $\lambda \geqslant 3$ μm). It is believed that only short-wave radiation comes from the Sun, and that terrestrial radiation is all long-wave radiation.

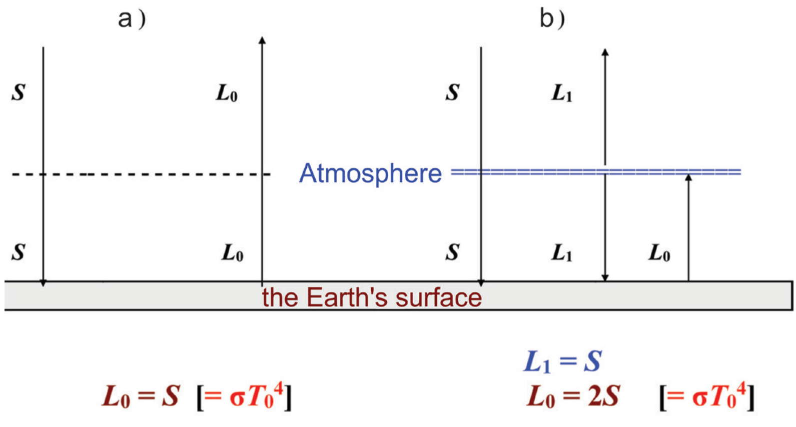

Figure 6.4. An illustration of the radiation model of the greenhouse effect: the terrestrial surface (земная поверхность) completely absorbs all fluxes of solar radiation S, and the atmosphere (атмосфера) is transparent for solar, short-wave radiation L_0, but completely opaque for terrestrial, long-wave radiation L_1. In the presence of such an atmosphere, the equilibrium temperature of the earth's surface is greater than that established in the absence of an atmosphere.

In the left panel, a) the atmosphere is absent. The stream of solar energy S, unhindered, reaches the Earth's surface and is completely absorbed by it. It heats the Earth's surface to a temperature T_0, at which the flux of long-wave radiation of the earth's surface is $L_0 = \sigma T_0^4$ (the Stefan-Boltzmann law) becomes equal to the flux S, i.e. for radiation equilibrium, $S = \sigma T_0^4$.

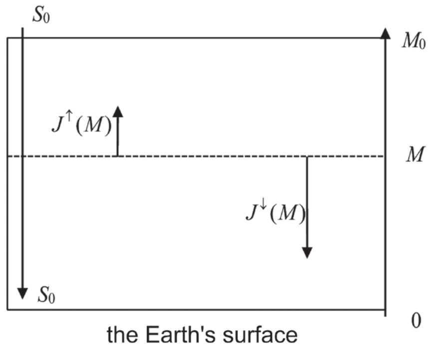

Figure 6.5. Illustrative radiation model in which a horizontally homogeneous atmosphere has a continuous vertical distribution; symbols are explained in the text; the Earth's surface

The ascending and descending currents of long-wave radiation at "altitude" M are partially absorbed by the atmospheric layer with a mass of dM (w(M) is the aborbtion coefficient). This process describes the first part of the two equations below, on the right-hand side. In a state of equilibrium, the absorbed energy is radiated upwards and downwards equally. This is described by the second part of the equations.

$$\frac{dJ^{\downarrow}(M)}{d(-M)} = -w(M)J^{\downarrow}(M) + 0.5w(M)(J^{\downarrow}(M) + J^{\uparrow}(M)),$$

$$\frac{dJ^{\uparrow}(M)}{dM} = -w(M)J^{\uparrow}(M) + 0.5w(M)(J^{\downarrow}(M) + J^{\uparrow}(M)).$$

Wherein $S_0 + J^{\downarrow}(M) = J^{\uparrow}(M)$ represents the equilibrium condition for the fluxes of radiant energy at "height" M (i.e. at lower attitudes, the atmosphere does not heat up or cool), and $J^{\downarrow}(M_0) = 0$, long-wave radiation does not come to the earth's atmosphere from outside. This system of equations has the following solutions:

$$J^{\uparrow}(M) = S_0(1 + 0.5\int_M^{M_0} w(x)dx); \qquad J^{\downarrow}(M) = 0.5S_0 \int_M^{M_0} w(x)dx.$$

The ascending flux of longwave radiation depends on the "height" M and the average (weighted average by mass) of the absorption coefficient W(M) times the height from M to M_0 as follows:

$$J^{\uparrow}(M) = S_0(1 + 0.5\int_{M}^{M_0} w(x)dx) = S_0(1 + 0.5(M_0 - M)W(M)).$$

In the given model, at the outermost boundary of the atmosphere ($M = M_0$) the flow $J\uparrow(M)$ is always equal to S_0 – the Earth's system as a whole does not heat up and does not cool.

In the simplest case, when the absorption coefficient w does not depend on the "height" (W = w = const), the flux $J\uparrow(M)$ increases linearly with the mass of the overlying layer of the atmosphere. As the average absorption coefficient increases, this gradient becomes steeper – see Figure 6.6.

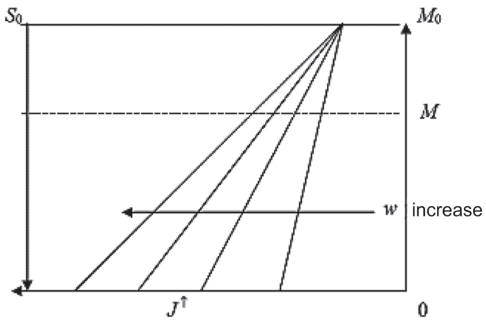

Figure 6.6. The change in the ascending flux of longwave radiation as a function of the "height" M and the absorption coefficient w; increase

Fig. 6.6 illustrates the enhancement of the greenhouse effect, which becomes more "thick" when greenhouse gasses including methane are distributed throughout the atmosphere at varying altitudes, after enrichment, the value of the absorption coefficient increases and the surface temperature increases. Since the greenhouse substances introduced by man into the atmosphere constitute a small proportion of the total, the total mass of the atmospheric column M_0 in the calculation was assumed to be unchanged.

Methane's enhancement of the absorption of infrared radiation by atmospheric layers follows from the fact that methane has a pronounced ability to absorb radiation in the 6.3 – 8.3 micron range (Fig. 6.7), and radiation in this range comprises an appreciable share of the total radiation flux of the earth's surface (Fig. 6.3).

The estimates presented in Fig. 6.7 were obtained from the 2008 edition of the HITRAN [51] molecular spectroscopic database.[14]

[14] Data from the experiments http//www.spectralcalc.com

In such experiments, the flow of monochromatic radiation I_0 is directed to a transparent container containing a certain amount of the gas to be examined, and then the outgoing stream I is measured. The absorption coefficient is estimated using a value proportional to [−ln(I / I_0)]. Normally, the valuation is performed by dividing this value by the thickness of the container (in the direction of the beam) and the concentration of the gas being examined. The values of the absorption coefficient for methane in Fig. 6.7 were given in relative units. In calculating the results of the experiements, the pressure value was set at 1,013.25 hPa, the absolute temperature was set at 288.15 K, the concentration of methane in the tank was 0.01 ppm, and the thickness of the container (in the direction of the beam) was 0.1 cm.

We note that methane demonstrated pronounced absorption in some parts of the spectrum: close to 1.7 μm, 2.2 μm, and 3.3 μm. However, the fraction of this radiation in the total radiation flux of the earth's surface is relatively small (Fig. 6.3).

Fig. 6.8 [48] shows the results of calculating the radiation-equilibrium temperature of the earth's surface for various methane concentrations (X-axis = ppm) where the volume composition of the atmosphere, with respect to other components, corresponds to what it was in 1970. Zero on the Y-axis corresponds to a temperature equal to the average for 1970. As can be seen in Figure 6.8, methane plays a role in the formation of the radiation-equilibrium temperature of the Earth's surface, in the concentration range from 0 to order of magnitude more than contemporary values, but this contribution does not exceed 1°C.

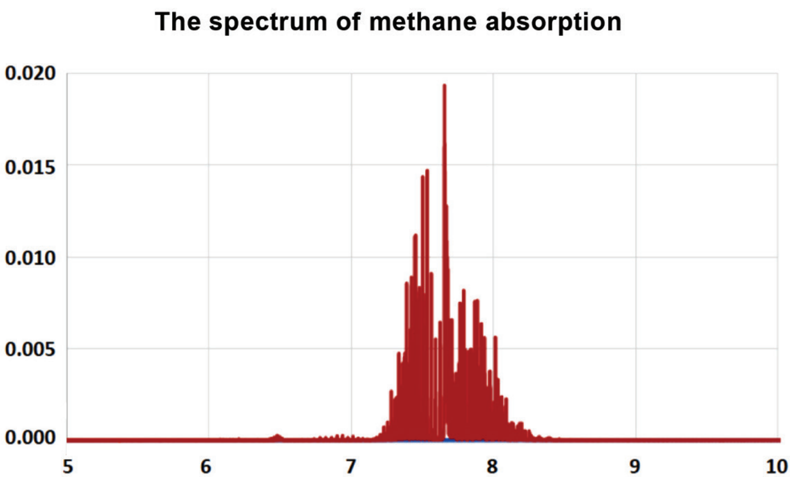

Figure 6.7. The spectrum of methane absorption in the 6.3 – 8.3 micron wavelength range: wavelength (μm) is shown along the X-axis; the Y-axis shows the absorption coefficient (relative units)

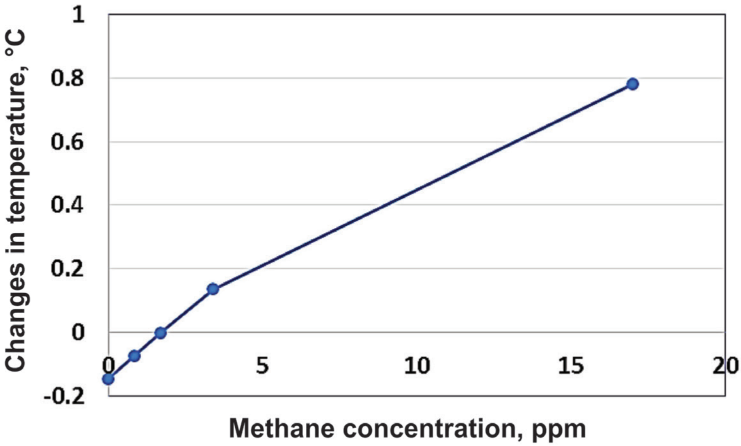

Figure 6.8. Changes in radiation-average equilibrium surface temperature (vertical axis, ° C) in response to changes in methane concentration (horizontal axis, ppm) while the atmospheric composition of the other components remain unchanged and correspond to their 1970 values. The calculated radiation-equilibrium temperature for 1970 is set as zero on the Y-axis.

We note that the estimates presented in Fig. 6.8, were obtained within the framework of the radiation model. Accounting for other non-radiation factors can change these estimates. Such factors include the possible activation of convective heat outflow from the earth's surface upward and induced warming - enrichment of the atmosphere with water vapor and other greenhouse gases. For example, an increase in methane content increases the concentration of another greenhouse gas, ozone, in both the troposphere and stratosphere [31 – 41]. However, although the result of the combined effect of all these factors on temperature is not yet clear, their effect is in many cases multidirectional.

6.2. EVALUATION OF THE CURRENT CONCENTRATION OF METHANE IN THE ATMOSPHERE AND ITS CHANGES DURING THE INDUSTRIAL ERA

As was noted earlier (see Section 4.2), the concentration of methane in the atmosphere as a whole depends on the ratio between the rate of its emission into the atmosphere and its removal. The observed values of these concentrations differ from season to season and by latitude (Fig. 6.9).

It must be underscored beforehand that the development of average annual concentrations of methane in the near-surface layer (and also in the Troposphere, because of the very limited change in its content at this altitude, as expressed in the volume mixing ratio) is similar despite varying background conditions.[15] Fig. 6.9 shows the change in methane concentration (ppb) at very distant points on the planet where the monitoring stations are located, and where systematic measure-ments are beeing made [52, 82]. They are located in Ireland, in the USA (Oregon / California), the Barbados, American Samoa, and Tasmania[17] (Table 6.1). The measurements are carried out within the framework of the AGAGE project (Advanced Global Atmospheric Gases Experiment), which is conducted with the support of the National Aeronautics and Space Administration of the United States (NASA, USA).

Table 6.1

Coordinates of several monitoring stations of the AGAGE project

Country or territory	Name of monitoring station	Latitude	Longitude
Tasmania, Australia	Cape Grim	41° S	145° E
Ireland	Adrigole/ Mace Head	52° / 53° N	10° W
Oregon/California, USA	Cape Meares / Trinidad Head	45°/ 41° N	124° W
Barbados	Ragged Point	13° N	59° W
American Samoa	Cape Matatula	14° S	171° W

Fig. 6.9, which depicts the background concentrations of methane, shows that:

- Concentrations in the Northern Hemisphere slightly exceed (by 100-200 ppb) values observed in the Southern Hemisphere;

- 2000–2007 reflect a pause in the growth of methane in the atmosphere – the concentrations were stable.

The first can be explained by the fact that the main natural and anthropogenic sources of methane are on land, and the ocean outflow is relatively small (see Table 4.1). Since in the Northern Hemisphere, the proportion of the Earth's surface that isn’t covered by water is greater than in the Southern Hemisphere, its generation of methane is slightly higher.

[15] Background conditions are characterized by the fact that the level of gas content ob-served there is not formed under the influence of a certain local source, but is determined by the processes of global transport and mixing in the atmosphere

[16] http://agage.eas.gatech.edu/

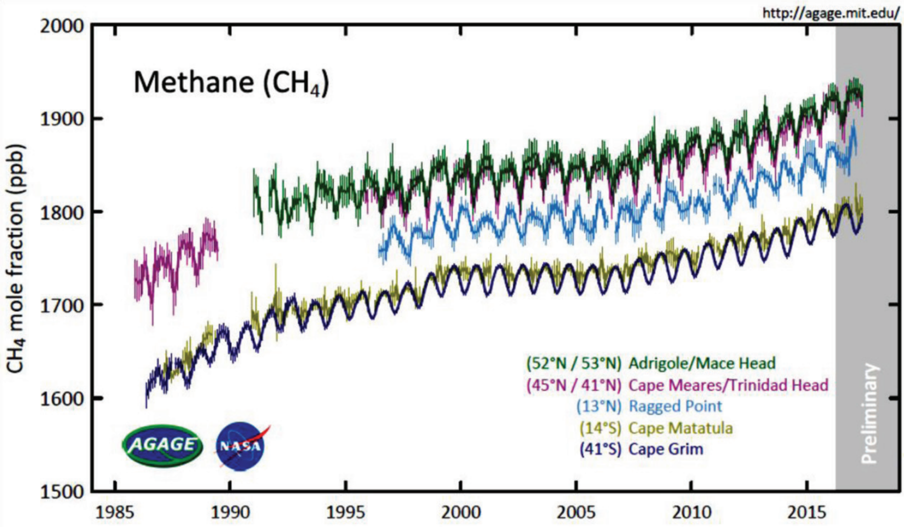

Figure 6.9. The current change in average monthly methane concentrations (ppb), according to the AGAGE project (Prinn et al., 2000, 2016): measurements recorded in Ireland, the US (Oregon/California), the Barbados, American Samoa, and in Tasmania; data from the AGAGE project (http://agage.eas.gatech.edu/)

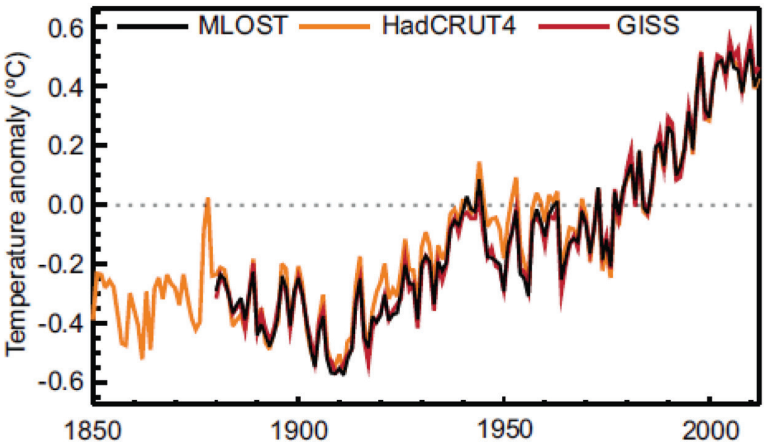

Figure 6.10. The change in the mean global temperature (three different series of observational data are depicted - MLOST, HadCRUT4 and GISS) in the near-surface layer in 1850-2012, relative to the average for the years 1961-1990. (IPCC, 2013, p. 193)

The stability of global methane levels in 2000-2007 can be explained by the presence of a feedback loop between the temperature and the processes of generation and elimination of methane. During this period, the global temperature growth rate significantly decreased; even a certain period of non-directional variability occurred (Fig. 6.10). However, after 2007, the proportion of methane in the atmosphere resumed growing (Fig. 6.11).

Fig. 6.12 shows the growth rate of the methane content in the atmosphere between 1984 and 2014, according to background measurements [27]. From the mid-1980s through 1991, the concentration of methane increased by more than 10 ppb per year. Then, for about a decade, growth slowed and was no more than 3 ppb per year. Between 2000 and 2007, the methane concentration in the atmosphere stabilized. However, since 2007, it has started to grow again; through 2013 its growth rate was about 5.7 ppb per year.

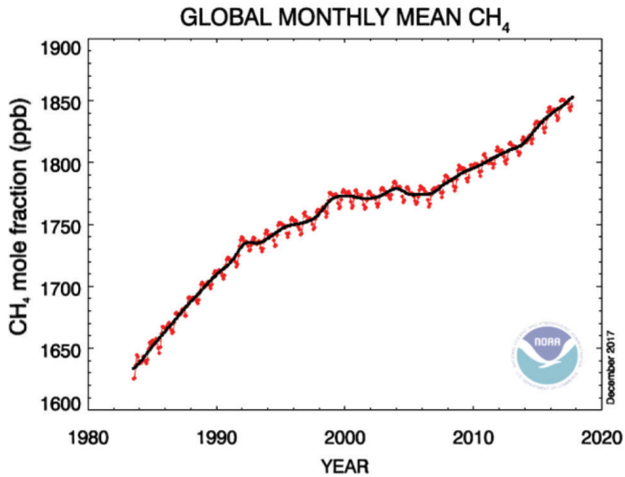

Figure 6.11. Change in the average monthly global concentration of CH_4 in the near-surface layer (Dlugokencky, NOAA/ESRL) (www.esrl.noaa.gov/gmd/ccgg/trends_ch4/; Nisbet et al., 2016)

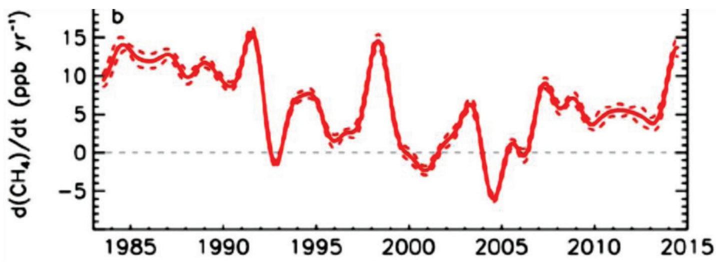

Figure 6.12. Rate of growth in the methane content of the atmosphere, 1984-2014. (Nisbet, 2016)

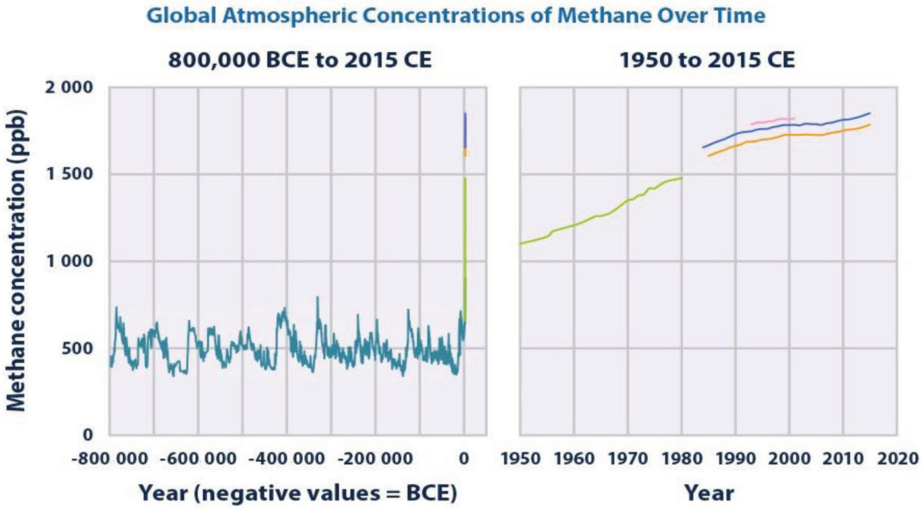

Figure 6.13. Natural fluctuations in the global concentration of methane in the last 800,000 years and its growth in the industrial era (https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases)

Fig. 6.13 shows the global concentrations of methane over the last 800,000 years. This information is provided by the US Environmental Protection Agency[17] and is the result of paleo-reconstructions using various ice cores, as well as instrumental background measurements. The figure shows that in the last 800,000 years, excluding the industrial era (conventionally - since 1750), methane concentrations varied between 300 - 800 ppb (see the left panel in Figure 6.13). In the industrial era, there was an increase in concentration, which by now has reached 1,800 ppb and surpassed this level. Thus, the increase in methane concentration was more than 250% (see also Section 3). Recall that the increase in the concentration of carbon dioxide for the relevant period was only about 40%.

Fig. 6.14 presents the progress in industrial period (from 1750 till today) of global average concentrations of the three main anthropogenic greenhouse gases: carbon dioxide CO_2, methane (CH_4), and nitrous oxide (N_2O). The figure shows that methane demonstrates the most significant relative increase.

There is a very high degree of certainty that this increase in the atmosphere's methane content during the industrial period occurred as a result of economic activity (see Sections 3 and 4.1, 4.3). According to IPCC estimates [53], approximately

[17] https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases

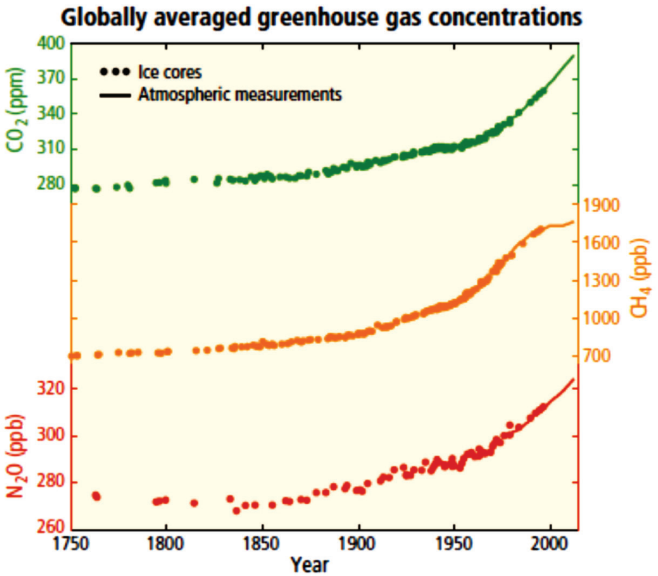

Figure 6.14. Global concentrations of carbon dioxide CO_2 (in green), methane CH_4 (in origin) and nitrous oxide N_2O (in red) – ice core reconstruction data and instrumental measurements (IPCC, 2014)

48-65% of modern global methane emissions in 1990 – 2009 were anthropogenic in origin (or 47-61% in 2000-2013, according to different authors, presented in this report in section 4).

6.3. EXISTING APPROACHES TO MODELING AND FORECASTING OF METHANE EMISSIONS AND CONCENTRATION

In order to forecast future concentrations of atmospheric methane, it's first necessary to estimate:

- The scale of its global release into the atmosphere, and
- The processes of its removal from the atmosphere.

Both components are difficult to forecast because of varying uncertainties (see Section 4).

Naturally-occurring emissions are subject to the influence of climatic conditions. In assessing them, generally speaking, it is necessary to take into account feedback from the climate. If the climate becomes warmer and more humid, the natural emission of methane from the Earth's surface increases. This phenomen can lead to an increase in the concentration of methane in the atmosphere. This has happened repeatedly during the last million years (Fig. 3.1).

Global anthropogenic emissions are associated with economic activities, and with global economic development. To make predictions of economic devel-opment, literally in terms of the climate, decades in advance, is not realistic.

For all these reasons, the rate of emissions and future concentrations of methane can be described only in the framework of some model concepts of the processes of its emission into the atmosphere and removal from the atmosphere. The basis for describing future global emissions is the so-called world development scenarios. Here is the definition of the term "scenario" which is given by the IPCC in the Fifth Assessment Report in the contribution of Working Group I[18] (IPCC, 2013, Glossary): *"A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships."*

Scenarios can have different time horizons – they can be short-to medium-term (up to 2030) or long-term (beyond 2030). They may differ in their approach to long-term modeling (optimization and simulation models), the degree of detail of the processes which result in methane emissions, and in terms of the flexibility of measures used to control the emissions.[19] The scenarios assume a wide range of parameters that determine the dynamics of methane emissions.

The characteristics of such scenarios include demographic and economic parameters (population, energy prices, hydrocarbon production, etc.), measures to control emissions and the consequences of their use in various sectors of the economy, as well as the introduction of new technology [53-55]. Due to objective reasons (the processes of anthropogenic methane emissions have not fully been understood yet, and are subject to being influenced by many factors that change over time), reliably establishing the parameters of future socio-economic development is not possible. As a result, a series of possible scenarios is drawn up, ranging from 'worst-case' to 'best-case' [53 - 56].

Often, modeling and forecasting are performed separately for each sector of the economy, or for each region, followed by a summary of the results [57, 58].

Depending on the effectiveness of the proposed measures to reduce greenhouse gas emissions, particularly methane, in various sectors of the economy, we can identify the main classes of scenarios, which reflect different models of economic development [56, 58, 59]]:

• **BASE.** A base scenario is artificial. Its purpose is to show the potential for energy savings through the transition to new technology. It is obvious that with the renewal of fixed assets and expansion of production, investments will be directed

[18] Note that both Working Group II and IPCC Working Group III adhered to the same definition

[19] http://institutiones.com/strategies/2521-zatraty-vygody-realizacii-strategij-nizkouglerodnogo-razvitiya-rossii.html

to the most modern available technology, which is more effective, as represented by the 'BAU' scenario.

• **Business-as-Usual (BAU).** This scenario does not provide for additional measures being taken by sectors of the economy to reduce emissions, except those already being implemented at the time the forecasts are made. BAU is a minimum cost scenario. It is often used to build a baseline for emissions estimates in assessing opportunities for reducing emissions.

• **Alternate scenarios**. Implyes the implementation of special measures aimed at limiting methane emissions. Accordingly, the forecasts made by those among this group will characteristically offer among the most optimistic results.

Separately, it is worth highlighting the long-term scenarios of possible socio-economic development developed by the IPCC. The IPCC scenarios are intended not so much to be used to study the dynamics of greenhouse gas emissions, but as to be used in an integrated assessment of future possible climate changes. In this regard, IPCC scenarios are more complex and take into account a wider set of input parameters than those presented above [53, 55, 60].

In order to take into account the uncertainties associated with global social and economic development in the future, the IPCC facilitated the development by the world scientific community of a group of scenarios and an assessment of the corresponding trajectories of anthropogenic emissions of climatically active substances, primarily greenhouse gases.

The first family of long-term scenarios for socio-economic development (IS 92) that included projections of anthropogenic greenhouse gas emissions, including methane, was developed by the international scientific community and summarized by the IPCC in 1992 [61, 62].[20] These six scenarios were based on a wide range of assumptions regarding the values of a number of social, economic and environmental parameters that affect greenhouse gas emissions, including methane. These scenarios did not include measures aside from the existing ones. The assumptions that were laid out in these scenarios, for the most part, were taken from the publications of specialized international organizations. Some of them resembled the SA 90 scenarios which were used in the preparation of the IPCC First Assessment Report [63].

In the IS92 scenarios, the world's population is projected to grow to 11.3 billion by 2100, with an average growth of 2.3% per year for the 21st century. They assume that both traditional and renewable energy sources will be used. These scenarios were widely used in the Second Assessment Report of the IPCC (see summary: [64]).

[20] http://sedac.ipcc-data.org/ddc/is92/

The Special Report on Emission Scenarios (SRES) was published by the IPCC in 2000. It included four main narrative storylines in which the future world was described in four essential different ways (main storylines). These four main storylines gave birth to four categories of scenarios: A1, A2, B1 и B2. We will describe them briefly [60].

A1. The main storyline and scenarios from within this family include rapid economic growth, the rapid introduction of efficient new technologies, as well as a global population which grows until the middle of the 21st century and subsequently declines. Its main features and developments include: the rapprochement of the different regions of the world, a significant reduction in interregional differences in per capita income, the strengthening of cultural and social interactions, and the creation of new opportunities.Scenarios within this family are divided into three groups, which differ according to energy use: A1FI - intensive use of fossil fuels, A1T - intensive use of other fuels, A1B – the balanced use of all fuels.

A2. The main storyline and scenarios from within this family describe a very heterogeneous world. Regions (and countries) are guided by their own strengths, and seek to preserve local characteristics. The fertility rates of the world's different regions converge very slowly, so the global population continues to grow. Economic development is mainly regionally-oriented, and the growth in per capita income and technological changes are more fragmented than in the other families of scenarios.

B1. The main storyline and scenarios of this family describe the same changing world with the same population dynamics as the storyline of the A1 scenario family. However, it assumes rapid changes in the economic structure in favor of a service and information-based economy, while material consumption reduces amid the introduction of clean and resource-efficent technologies. The emphasis is on global solutions to economic and social problems, maintaining the environment, and sustainability, including measures to promote global equality (among regions and countries). At the same time, new initiatives in the field of climate regulation are not expected.

B2. The main storyline and scenarios of this family describe a world in which the emphasis is on local decisions pertaining to the sustainability of the economy, social sphere and the environment. The global population increases steadily, albeit at a lower rate than for A2. The pace of economic development is moderate. Technological change will be slower and more diverse than for the main storylines of families B1 and A1. Although the scenarios of this family are also focused on protecting the environment and social justice, they are guided in this respect at the regional level.

On the basis of these qualitative, verbal descriptions of the future of the world, six groups of specialists in the field of mathematical modeling have developed about forty scenarios that provide different trajectories for the emissions of climate-active substances into the atmosphere. The developers believe that all these scenarios are equally valid.

These are the so-called "illustrative scenarios". These include marker scenarios, reflecting the main features of the four groups of scenarios A1B, A2, B1 and B2, as well as two additional groups for the A1FI and A1T groups. It should be noted that the term "illustrative" here should not be perceived as "artificial." On the contrary, illustrative scenarios quantify the very essence of those assumptions that were made when verbally describing the main "story lines" of the corresponding groups of scenarios.

If each of these scenarios were weighed, of course, subjectively, along with the probability of its implementation, they could be used to construct a probabilistic forecast of the climate of the 21st century. However, no specific probabilities are available. Therefore, according to the spread of emission estimates, and after the model is recalculed appropriately, climate concentrations, estimates can not be interpreted in probabilistic terms, or used to create a reliable forecast.

The SRES scenarios were used in the preparation of the IPCC Third and Fourth Assessment Reports, which were issued in 2001 and 2007, respectively.

During the preparation of the IPCC Fifth Assessment Report (2009-2014), the world scientific community developed new scenarios for socio-economic development, called representative concentrations pathways (RCP) [53, 55]. There is a family of four scenarios: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. They are marked (with the numbers at the end of the scenario symbol) by changes in radiative forcing, which can exist by 2100 compared to pre-industrial values (+2.6, +4.5, +6.0 and + 8.5 W/m^2 respectively) [53, 65].

The impossibility of developinga long-term (100 years or more) socio-economic development forecast (in the literal sense of the term) and, as a consequence, the trajectories of emissions of climatically active substances, led to the introduction of the term "prospective assessment" or "projection." In essence, this is a conditional forecast, i.e. a forecast under certain accepted conditions, under a certain scenario of future conditions, within which the forecasted variable changes. Various projections for the 21st century release of global anthropogenic methane emissions into the atmosphere and the corresponding consequences for methane levels will be discussed in the next section.

6.4. METHANE EMISSION AND CONCENTRATION SCENARIOS

In Fig. 6.15 retrospective anthropogenic methane emissions estimations are presented for the period 1990-2005, as well as projected emissions estimatesfor the subsequent years through 2030, in increments of 5 years. The estimates are prepared by the US Environmental Protection Agency (EPA) using business-as-usual (BAU) scenarios. This scenario is relatively short-term for the purposes of forecasting climate change, but its detailed development in terms of the contribution of individual anthropogenic sources allows us to consider the application of various measures to reduce emissions from them, see Section 9.

From the figure, it is clear that emissions after 2005 have been increasing almost evenly, at a constant rate. In 2030 they reached a value of 408 Tg. In this case, Russia's contribution to the average for the entire period is nowhere more than 8%. In the following Fig. 6.16 the contributions of various sectors of the economy to these emissions are presented.

According to the data shown in Fig. 6.16, in 2030 the main economic sectors contributing to the global anthropogenic release of methane will be agriculture (intestinal fermentation and rice cultivation), waste (solid waste and waste water) and energy (mainly in the oil and gas sector and the coal sector). At that point, according to this prospective assessment, the contributions of the economic sectors to methane emissions will remain practically unchanged relative to their current values; they will amount to 39.0%, 39.6% and 21.4%, respectively, for the energy, agriculture and waste sectors.

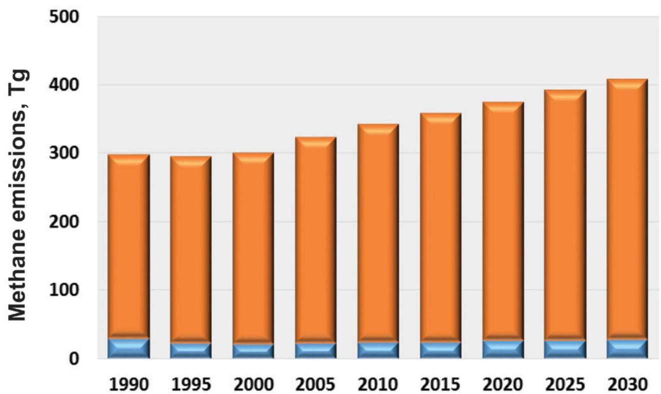

Figure 6.15. Estimates of global anthropogenic methane emissions in Tg CH_4 (in orange) until 2030 including those of the Russian Federation (in blue).
This diagram is compiled with data from the US Environmental Protection Agency (EPA, 2012)

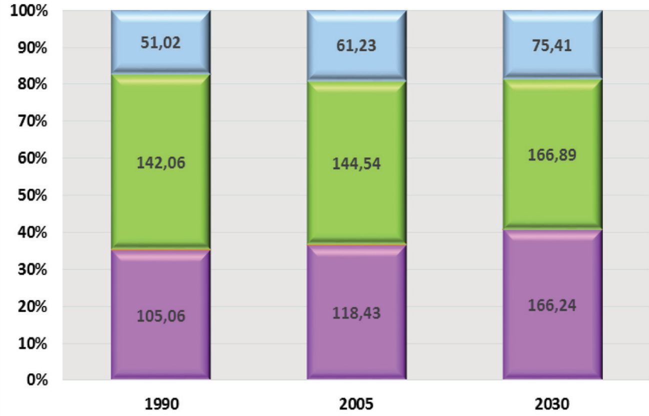

Figure 6.16. Global anthropogenic methane emissions (Tg CH_4) in 1990, 2005 and 2030, with details on the main sectors of the economy that generate them. Deposits are shown in three colors representing sources of emissions: energy (blue), agriculture (green), and waste (purple). The diagram is compiled from data from the US Environmental Protection Agency. (EPA, 2012)

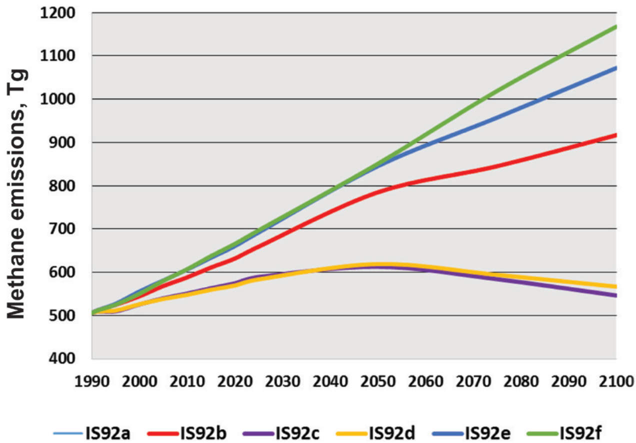

Figure 6.17. Global anthropogenic methane emissions (MT CH_4) through the year 2100, built on the basis of scenarios from the IS92 family of models. Compiled with the relevant data (Leggett J. et al, 1992; Pepper et al, 1992)

Global anthropogenic methane emissions, corresponding to the six IS92 family of scenarios, are described in [61, 62], and are shown in Fig. 6.17. Relevant data are available at http://sedac.ipcc-data.org/ddc/is92/. As seen in the figure, the IS 92 includes two "worst" scenarios for methane (IS92e and IS92f) and two "best" scenarios (IS92c and IS92d). The highest methane emissions at the end of this century correspond to the IS92e scenario, which, among other assumptions, combines moderate population growth, high economic growth, high availability of fossil fuels and the possible abandonment of nuclear energy. Methane emissions in this scenario will exceed 1,100 Tg CH_4 by the end of the 21st century.

For scenarios IS92c and IS92d, it is assumed that the population grows in the first part of the century, but that by the middle of the 21st century, economic growth has tapered off and there are serious limitations on the supply of fossil fuels. At the same time, anthropogenic methane emissions in the middle of the 21st century will for some time exceed the level of 600 MT CH_4 per year, but will be generally lower than this level.

Separately, it is worth highlighting the "intermediate" scenario IS92a, which is widely used up to the present moment for comparison with the results of more modern models in terms of standards. IS92a assumes that the global population will grow to 11.3 billion by 2100, that average economic growth between 1990 and 2100 will total 2.3% per year, and that both traditional and renewable energy sources will be used [53, 55, 61]. In this scenario, methane emissions will exceed 900 Мт CH_4 annually by 2100.

The trajectories of methane emissions shown in Fig. 6.18, correspond (with the exception of IS92a) to the scenarios presented in the IPCC Special Report on Emission Scenarios [60]. The best-case scenarios reflect an increase in emissions up to the middle of the century followed by a subsequent decline. Under the worst-case scenarios, methane emissions increase throughout the 1990-2100 time-frame.

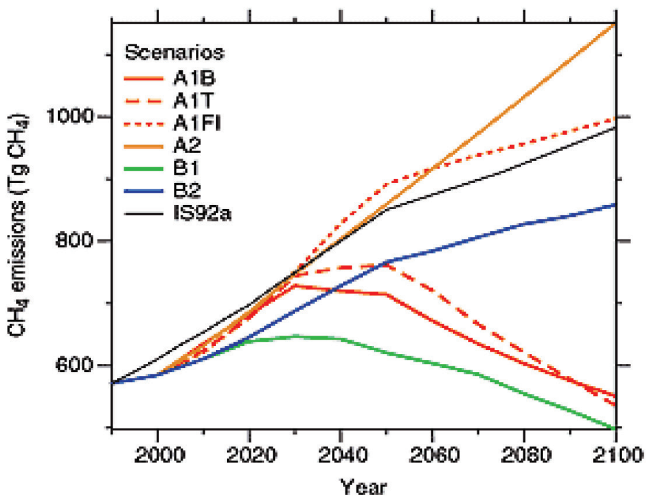

Figure 6.18. Global anthropogenic methane emissions (MT CH_4) in 1990-2100, according to the Special Report on Emission Scenarios (IPCC, 2000)

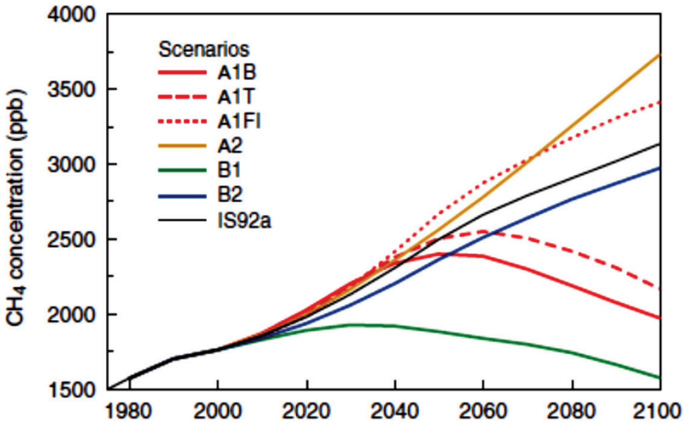

Figure 6.19. Global anthropogenic methane emissions (MT CH_4) in 1990-2100, according to the Special Report on Emission Scenarios (IPCC, 2000)

The spread of the estimates in Fig. 6.18 is sufficiently large. By 2100, emissions corresponding to different scenarios may differ by several times or even more than an order of magnitude. Such significant differences in emission trajectories inevitably cause a significant divergence in concentration trajectories, especially at the end of the period under review, in 2100, which in turn lead to significant diffeences in estimates of the future climate.

Fig. 6.19 shows the corresponding trajectories of atmospheric concentrations of CH_4. Note that even given the most severe A2 scenario from the SRES family, the global methane concentration by the end of the 21st century (about 3,750 ppb) will only be slightly more than double the current atmospheric concentration (about 1,800 ppb).

The Fifth Assessment Report of the UN IPCC, which was published in 2013-2014, summarized the relevant assessments made under the RCP family of scenarios.The results of estimating global anthropogenic emissions, corresponding to these scenarios, are shown in Fig. 6.20, and the corresponding course of global atmospheric methane concentrations is shown in Fig. 6.21.

As can be seen from Fig. 6.20, which reflects RCP scenarios, global anthropogenic emissions are slightly more moderate than projected by earlier scenarios. The best-case scenario, RCP 2.6, projects a smooth decrease in the emission of methane over the course of the given period of time, to about 150 Tg CH_4 by 2100. The worst-case scenario, RCP 8.5, however, projects methane emissions to grow to a level of 900 Tg CH_4 by the end of the century. The other two RCP family scenarios, (RCP 4.5 and RCP 6.0) provide an intermediate perspective. However, they still show a reduction in global anthropogenic methane emissions by 2100, albeit at a slower rate than in the best-case scenario.

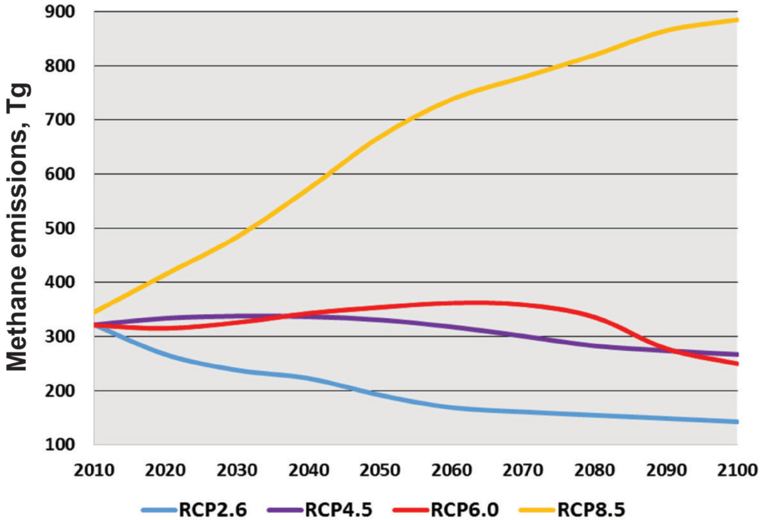

Figure 6.20. Global anthropogenic methane emissions, according to the RCP family of scenarios. Prepared using data from the study (Kirtman eta al, 2013; IPCC, 2013)

The process of change in the global atmospheric methane concentration, shown for different RCP scenarios in Fig. 6.21, also assumes more moderate growth compared to SRES scenarios (see Figure 6.19). In three of the four scenarios, the methane concentration begins to decline in the 21st century, not reaching a level of 2,250 ppb.

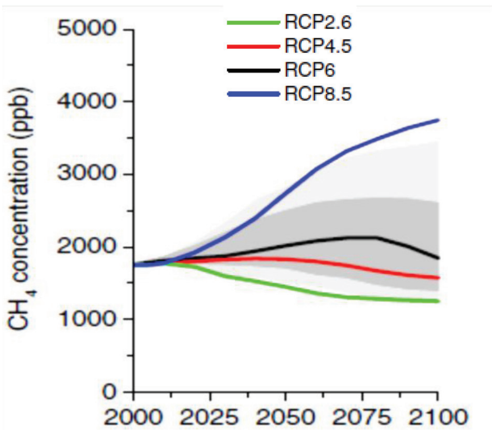

Figure 6.21. Progress of global atmospheric concentration of CH_4 (ppb) in the 21st century under RCP scenarios (Clarke et al, 2010; van Vuuren et al, 2011)

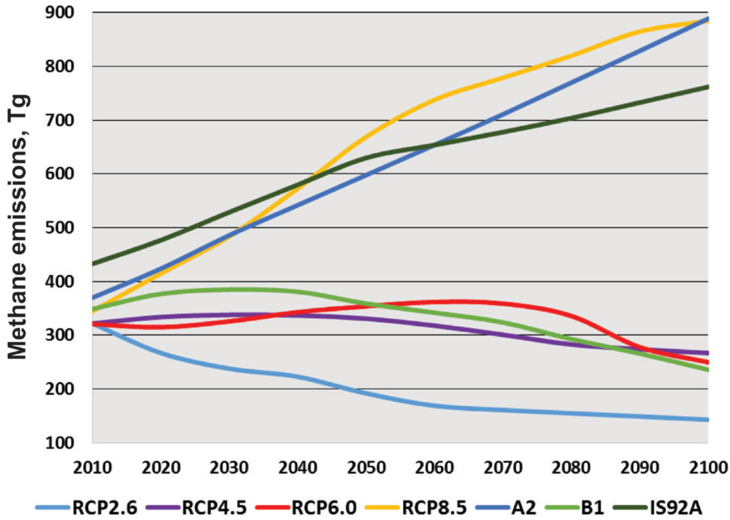

Figure 6.22. Comparison of global anthropogenic methane emissions in 2010- 2100, under the different families of scenarios, according to IPCC data (IPCC, 2013)

Fig. 6.22 shows projections of global anthropogenic methane emissions under a number of scenarios for all three families - IS 92, SRES and RCP, to illustrate the degree of coherence [53, 55].

It should also be noted that global anthropogenic methane emissions in the context of the BAU scenario, developed by the US EPA (discussed at the beginning of this section), are comparable to the values in the worst-case scenarios projected in different families IS92a, B1, RCP 8.5 - and significantly exceeds the intermediate variants of the forward-looking estimates for the RCP scenario family.

7 INDICATORS REFLECTING THE INFLUENCE OF METHANE ON THE INTENSITY OF THE GREENHOUSE EFFECT

7.1. GLOBAL WARMING POTENTIAL

To characterize the disturbance of energy flows in the system "atmosphere + the Earth's surface," particularly disturbances due to changes in the gas composition of the atmosphere, the term "radiative forcing" (RF) is often used. It is defined as follows [64]: *"Radiative forcing on the 'troposphere-Earth's surface' system (due, for example, to a change in the concentration of any greenhouse gas) is the change in net flux (W/m²) of radiant energy at the height of the tropopause after the establishment of a new thermodynamic equilibrium in the stratosphere, despite undisturbed temperature distribution in the 'troposphere - Earth's surface' subsystem."*

This means that the thermodynamic equilibrium in the stratosphere is established much faster than in the "troposphere-Earth's surface" system, which includes the lowest stratum of the atmosphere as well as the surface. Higher up, in the stratosphere, energy is spread very rapidly through radiation, absorption and reradiation. However, lower down, in the troposphere, the mechanisms involved are rather slow; they include convection and advection in the troposphere and the ocean, are also involved in the energy transfer process. In the above definition, mean global energy fluxes upwards and downwards are implied.

In carrying out model calculations, changes in the mean global surface temperature ΔT in response to a predetermined radiative forcing ΔF with radiation-convective models have been found to be approximately proportional:

$$\Delta T = \lambda \, \Delta F,$$

Which is why the proportionality coefficient $\lambda \approx 0.5$ °K / (W/m²) depends little on the cause of the change ΔF [69]. This proportionality factor is called "climate sensitivity." It is in this connection that the concept of radiative forcing has become widespread in applied research, related to the contribution of various atmospheric gases and other substances to the possible anthropogenic enhancement of the greenhouse effect.

To quantify the ability of a substance to produce radiative forcing on the "troposphere + Earth's surface" system, the concept of "global warming potential" (GWP) is used. Absolute global warming potential (AGWP) is defined as the total radiative forcing, which during a certain period of time TH (time horizon) causes the instantaneous release of 1 kg of a trace substance; at the beginning of this period:

$$AGWP = \int_0^{TH} aQ(t)dt.$$

Here t is time, elapsed since the emission; $Q(t)$ is the amount of the trace substance in the atmosphere, still remaining at time t; and a is radiative efficiency, (Wt м$^{-2}$ kg^{-1}).

In the sense of this definition, the absolute potential of global warming for a given substance depends on its radiation efficiency and the rate of its depletion from the atmosphere (in the sense of first-order kinetics, on its lifetime in the atmosphere).

The global warming potential of a substance (GWP) and the time horizon are defined as the ratio of the absolute value of the global warming potential of a substance AGWP to that of a reference substance, AGWPr :

$$GWP = \frac{AGWP}{AGWP_r}.$$

Thus, for the reference substance, GWP = 1 for any time horizon choice for the impact assessment. As a reference substance, CO_2 is usually adopted; therefore, GWP is a dimensionless quantity.

The most recent estimates of the lifetime, radiative efficiency and global warming potentials for various greenhouse gases are given in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [70]. In Table 7.1 we provide some of this information for carbon dioxide, methane and nitrous oxide. At the same time, the global warming potential is given for two time horizons, 20 and 100 years.

GWP[21] coefficients are used, in particular, to compare the emissions of greenhouse gases other than CO_2 to CO_2. The corresponding unit by which the GHG is measured in terms of CO_2 radiative forcing is called CO_2-equivalent, abbreviated as CO_{2E}. For example, (see Table 7.1) **1 Мт CH_4 = 28 Мт CO_{2E}**. These values show that the radiation consequences of the release of a mass unit (for example, 1 ton) in terms of CO_2. In the index for the conversion of methane to CO_2, it's rated 25 (in other words, 25 Мт CO_{2E}) according to the COP 19 decision made in Warsaw on the basis of the second-to-last IPCC report (the decisions of the UNFCCC slightly lag the recommendations of the IPCC).

[21] The default time horizon is 100 years, unless otherwise specified.

Table 7.1

Lifetime, radiative efficiency and global warming potential for carbon dioxide, methane and nitrous oxide for a time horizon of 20 and 100 years (Myhre et al, 2013)

Name	Chem. formula	Life span, years	Radiation effect, W/м² ppb⁻¹	AGWP, (20-year horizon) W/м² year kg⁻¹	GWP (20-year horizon)	AGWP, (100-year horizon) W/м² year kg⁻¹	GWP (100-year horizon)
Carbon dioxide	CO²	-	$1,37 \cdot 10^{-05}$	$2,49 \cdot 10^{-14}$	1	$9,17 \cdot 10^{-14}$	1
Methane	CH_4	**12,4**	$\mathbf{3,63 \cdot 10^{-04}}$	$\mathbf{2,09 \cdot 10^{-12}}$	**84**	$\mathbf{2,61 \cdot 10^{-12}}$	**28**
Nitrous Oxide	N_2O	121	$3,00 \cdot 10^{-03}$	$6,58 \cdot 10^{-12}$	264	$2,43 \cdot 10^{-11}$	265

7.2. GLOBAL TEMPERATURE CHANGE POTENTIAL

Global Temperature change Potential (GTP) is a metric that, by design is intended to play a large role in applied impact assessments compared to GWP [71].

Absolute Global Temperature change Potential (AGTP) is defined as *"change in the average global temperature at a given time t in response to a one-time emission of a unit amount of matter into the atmosphere at any point in time* ***s***[22]*."*

In addition to global warming potential, two characteristics are considered for every greenhouse gas:

- absolute Global Temperature change Potential (AGTP) – see above definition

- the corresponding relative value, Global Temperature change Potential (GTP), which is the ratio of AGTP for the substance in question to its value for the reference substance, which is usually carbon dioxide:

$$GTP = AGTP / AGTP_r$$

While AGWP (and GWP) evaluates the consequence of the release of a certain amount of a trace substance for a certain time interval [0, TH], i.e. its total effect on radiative forcing throughout the time interval, AGTP (and GTP) only esti-mates the consequence for temperature at the final time TH.

[22] The moment emission s can precede the moment of time t for which the assessment is preformed, or coincide with it.

Like GWP, the GTP metric is designed to obtain estimates of the emissions of various greenhouse gases in terms of CO_2-equivalent. As in the case of GWP, the corresponding weighting coefficients essentially depend on the time horizon used, as for the the time elapsed from the moment of ejection to the moment for which the effect is estimated.

Subsequently, work was perfomed [72] and a modification of the concept of GTP, oriented to use for estimating continuous emissions, was proposed. If it's assumed that emissions are linear, AGTP is convenient for estimating the change in global temperature $\Delta T(t)$ in time for a given scenario of global emissions of $E_i(t)$ greenhouse substances:

$$\Delta T(t) = \sum_i \int_0^t E_i(s)\, AGTP_i(t-s) ds.$$

Here i is the number of the greenhouse gas, **t** is the current time, **s** is the moment of emission [73 – 75]. In Table 7.2, estimates of the global temperature change potential are given for carbon dioxide, methane and nitrous oxide for different time horizons.

Table 7.2

The potential for global temperature changes of carbon dioxide, methane and nitrous oxide for 20, 50 and 100-year time horizons (Myhre et al, 2013)

Name	Chemical Formula	AGTP (20-year horizon) K kg^{-1}	GTP (20-year horizon)	AGTP (50-year horizon) K kg^{-1}	GTP (50-year horizon)	AGTP (100-year horizon) K kg^{-1}	GTP (100-year horizon)
Carbon Dioxide	CO_2	$6{,}84 \cdot 10^{-16}$	1	$6{,}17 \cdot 10^{-16}$	1	$5{,}47 \cdot 10^{-16}$	1
Methane	$\mathbf{CH_4}$	$\mathbf{4{,}62 \cdot 10^{-14}}$	**67**	$\mathbf{8{,}69 \cdot 10^{-15}}$	**14**	$\mathbf{2{,}34 \cdot 10^{-15}}$	**4**
Nitrous Oxide	N_2O	$1{,}89 \cdot 10^{-13}$	277	$1{,}74 \cdot 10^{-13}$	282	$1{,}28 \cdot 10^{-13}$	234

7.3. METEOROLOGICAL ASSESSMENT, RADIATIVE FORCING AND RELATED RESEARCH[24]

Mauna Loa Observatory in Hawaii has conducted the longest series of observations of the atmospheric concentration of methane, which continue to this day. These observations were started in the early 1980's. From 1983 to 2016, the concentration of CH_4 increased by more than 240 parts per billion, from 1,639.23 ppb to 1,870.71 billion ppb (the average values for May are given). The average inter-annual concentration growth rate was 7.3 ppb. These observations are conducted by means of an analysis of air samples taken in special jars on a gas chromatograph. Along with gas chromatography, methods of intra-cavity laser spectroscopy are widely used to measure methane concentration.

The main indicators, which assess the dynamics of changes in the concentration of methane in the atmosphere, are the trend and seasonal course. The trend reflects the nature of long-term changes and indicates how rapidly the concentration decreases or increases. The seasonal course, as the name implies, shows a change in the concentration of CH_4 due to the change in the seasons of the year. In the northern hemisphere, the methane content in the atmosphere reaches its maximum in the winter months, the minimum in the summer. In the southern hemisphere, the opposite is true. At the same time, the amplitude of the seasonal course in the Northern Hemisphere is almost twice as large as in the Southern hemisphere.

Fig. 7.1 shows a temporal variation in the concentration of methane of three stations located in different latitudinal zones: the South Pole subequatorial belt (station Mauna Loa) and Arctic (Alert station).

The change, over time, in the concentration of atmospheric methane at the South Pole exhibits pronounced seasonal fluctuations without any drastic changes, which is due to the remoteness of methane sources and the well-mixed air. Moving from the South Pole to the North, the overall level of concentration and the amplitude of the seasonal fluctuations increase, and are affected by the proximity of continental natural and anthropogenic sources of CH_4.

Fig. 7.2 shows the spatial-temporal dynamics of the change in the methane concentration for the entire globe, obtained from observed data.

After reliable estimates of methane emissions have been obtained, there is a basis for forecasting emissions. This is a complex process requiring a complex approach that takes into account many factors: the efficiency of energy consumption, the influence of changes in the climate system, forecasts for natural gas and other

[23] The moment emission **s** can precede the moment of time **t** for which the assessment is preformed, or coincide with it.

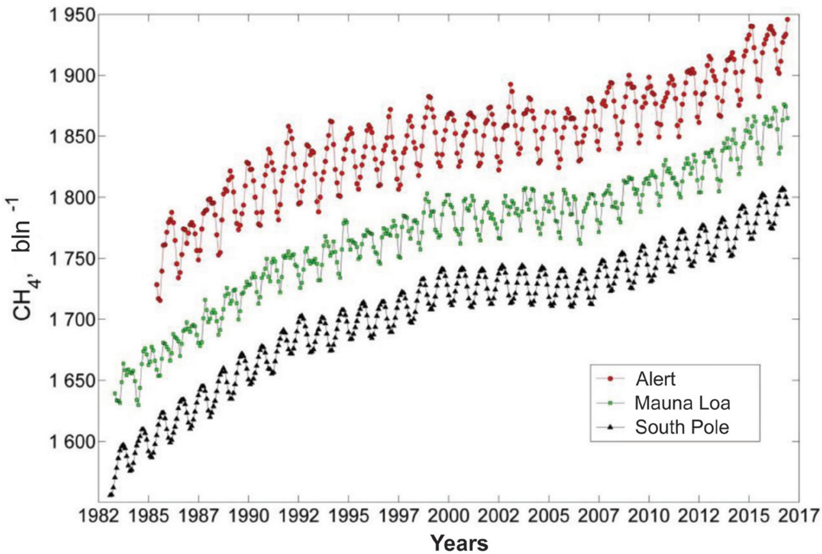

Figure 7.1. The time variation of the atmospheric concentration of methane from the data of stations located in different latitudinal zones. Graphs created with data from the WDCGG (World Data Center for Greenhouse Gases)

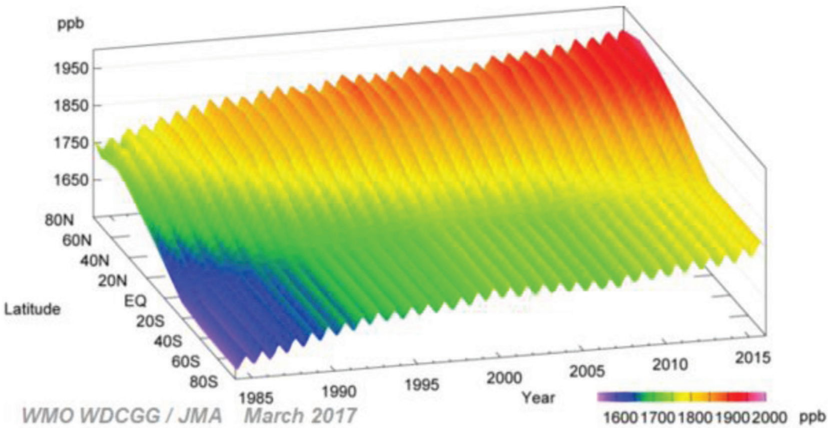

Figure 7.2. The change of the atmospheric concentration of methane over time, constructed from the average monthly observation data, at 20° latitudinal intervals (graph taken from the WDCGG web site)

fossil fuels, the appearance of new technology, expected results from measures taken to reduce emissions, etc.

To determine the numerical value for global warming potential, you can use another metric, namely Radiative Forcing (RF). This metric isn't just useful in estimating the contribution of individual greenhouse gases to global warming; it can also be applied to a wider range of factors. For example, it can help assess the impact on the Earth's climate of a large volcanic eruption or a change in the flux of solar radiation.

According to the accepted definition, **radiative forcing** is the difference between the solar radiation balances: taking into account any factors *F(t1)* and not taking into account any factors *F(t2):*

$$RF = F(t_2) - F(t_1); \quad F = I^{\uparrow}(h) - I^{\downarrow}(h) + S^{\uparrow}(h) - S^{\downarrow}(h)$$

where $I^{\uparrow}(h), I^{\downarrow}(h)$ signifies upward and downward fluxes of ultraviolet (solar) radiation, $S^{\uparrow}(h), S^{\downarrow}(h)$ signifies upward and downward fluxes of infrared (long-wave) radiation, ***F*** is the total effective flow at level ***h***. Either the upper boundary of the Earth's atmosphere or the surface can be set as level ***h***, but it's usually the tropopause (it will be considered as such heretofore in the text). **Radiative forcing is the difference between the total effective fluxes at two points in time, t_1 and t_2. In this case, the first time *(t_1)* corresponds to the "unperturbed" state of the climate system, including the atmosphere, and the second *(t_2)* - the moment when the "disturbing" event (for example, a volcanic eruption or the doubling of the atmospheric concentration of CO_2) has already taken place.** In other words, there is always some balance at the tropopause level between incoming and outgoing radiation. **Radiative forcing shows how much the balance will change when a "disturbance" is introduced in comparison with the "unperturbed" state of the climate system.** Essentially, radiative forcing is an analog of widely-used partial derivative in mathematics.

Initially, the calculation of radiative forcing was carried out using parametric formulas (IPCC, 1990), particularly for CO_2 and CH_4:

$$RF = 6,3 \ln (C/C_0);$$

$$RF = 0,036 (\sqrt{M} - \sqrt{M_0}) \times (f(M,N_0) - f(M_0,N_0)),$$

$$f(M,N) = 0,47 \ln [1 + 2,01 \times 10^{-5} (MN)^{0,75} + 5,31 \times 10^{-15} M (MN)^{1,52}].$$

where C is the concentration of CO_2 in parts per million, *M* and *N are the concentration of* CH_4 and N_2O in parts per billion by volume (ppbv). The index "0" corresponds to the "unperturbed" state (at the moment of time t_1), and the concentration without an index corresponds to t_2. Later on, when complex climate models are developed that include both radiation and chemical components, the Radiative Forcing calculations are performed directly, following the above definition. However, since each model constructed that way has its own peculiarities (and its drawbacks), when analyzing the results obtained with their help, both the "best" value and the scatter of values throughout the ensemble of the models used are indicated.

Speaking about the current values of Radiative Forcing caused by the increase in the content of CO_2 and CH_4 in the atmosphere, as a rule, they refer to (IPCC, 2013): **1.66 ± 0.17** and **0.48 ± 0.05** W/m², respectively (in this case, the effect of increasing atmospheric concentrations of carbon dioxide and methane in 1750-2011 is considered). But this is only the tip of the iceberg. The fact is that the values given above represent exclusively the response radiation fluxes directly associated with the increase in the content of CO_2 and CH_4 in the atmosphere (so-called Direct Radiative Forcing). If in the case of carbon dioxide, direct radiative forcing generally objectively reflect developing situation (since CO_2 is photochemically passive in the atmosphere), the methane is involved in proceeding atmospheric photochemical processes and thereby affects what will be the content of other component s atmospheric air (including greenhouse gases). The most significant effect is on ozone and water vapor.

As is known, the destruction of the ozone layer occurs in catalytic cycles, in which OH, NO, Cl and Br atoms, metals, etc. (shown as X) act as catalysts (the sum of each pair of catalytic reactions is indicated below the line):

$$O + XO \rightarrow X + O_2$$

$$O_3 + X \rightarrow XO + O_2$$

$$\overline{\qquad O + O_3 \rightarrow 2\ O_2. \qquad}$$

Thus, the concentration of ozone, which is a greenhouse gas, directly depends on the content of the above catalysts in the atmosphere. In turn, some of these cata-lysts react with methane:

$$OH + CH_4 \rightarrow CH_3 + H_2O$$

$$O(^1D) + CH_4 \rightarrow CH_3 + OH$$

$$\rightarrow CH_2O + H_2$$

$$Cl + CH_4 \rightarrow CH_3 + HCl$$

As a result of these reactions, their content in the atmosphere decreases, which reduces the ozone-depleting potential of the corresponding cycle and contributes to the conservation of the ozone layer.

At the same time, due to these reactions, methane molecules are destroyed, which eventually leads in the stratosphere to the formation of water vapor molecules. Taking into account the volume of water vapor thus created in the atmosphere, this basically leads to a common greenhouse effect. There end up being two changes in influence. First, the methane content is reduced and, consequently, its direct forcing is reduced, but indirect forcing appears, mainly through the increase in the influence of water vapor. However, of course, the concentration of H_2O in the atmosphere is practically left unchanged, and consequently, although **indirect CH_4 forcing** affects the final picture, the fact that CH_4 conversion increases the amount of water vapor does not lead to an increase in the influence of greenhouse gases on the climate.

The importance of the reaction of methane with hydroxyl must be pointed out because the extremely active hydroxyl radical is one of the main "purifiers" of the atmosphere, quantitatively determining the gas composition of the atmosphere. As a consequence, the evolution of methane content in the atmosphere affects other greenhouse gases, albeit to a lesser extent than ozone and stratospheric water vapor.

It is impossible to consider the issue of estimating the Radiative Forcing of methane (and other greenhouse gases) finally resolved. Even now, there are publications aimed at clarifying the methods of its calculation. For example, an article recently appeared authored by one of the initiators of the introduction of this metric, K. Shine, which points to the need for a more accurate account of the absorption of shortwave radiation by molecules of carbon dioxide, methane and nitrous oxide, including the effects of the mutual overlapping of absorption bands by these gases [89]. Based on the results of their calculations, such accounting leads to an increase in the value of the Radiation Forcing of methane of approximately 25%.

Thus, it is necessary to consider the contribution of each greenhouse gas, taking into account its influence on other greenhouse gases, without forgetting that the main greenhouse gas is H_2O.

7.4. INFLUENCE OF CLOUDS AND AEROSOLS ON CLIMATE CHANGE

Taking into account the interaction of methane with other substances in the atmosphere and its role in the formation of water vapor in the stratosphere, it seems appropriate to consider the influence of water vapor and aerosols in radiative forcing. A lot of research work has been devoted to this issue.

Let's consider some of it [90,91]. Water vapor and the clouds it forms are a serious factor affecting the Earth's climate. The literature [90], which is a continuation of Ginzburg's works [92,93], presents the results of calculations of hemispherical fluxes reflected and transmitted by the atmosphere of solar radiation and radiant heat flow, on the basis of simple optical models of a cloudless and a cloudy atmosphere. To solve the problem, the delta-Eddington method is used, which may be applied to a wide range of changes in the optical thickness of the atmosphere. The spectral values of extra-atmospheric radiation are considered in several literature sources. The calculation was made for albedo values of 0, 0.5, 0.9 and for spectral values corresponding to a sandy surface. Four values of the zenith angle of the sun were considered: 0°, 30°, 40° and 60°.

When compared with the experimental data, the corresponding solar angle values were used. The obtained values are compared with data from the spectral measurements of aircraft of hemispherical fluxes of solar radiation. It is shown that the simple optical models applied lead to real values reflecting radiation characteristics, and the accepted calculation method ensures that the result is sufficiently accurate. The estimates of the instantaneous local radiative forcing of atmospheric aerosols and clouds for three models of aerosol content and cloud layer models , considered in (Ginzburg et al, 2016). The dependence of solar radiation characteristics on the optical thickness of the atmosphere for four values of solar zenith angles, two albedo values for the albedo of the underlying surface (0 and 0.9) and two values of the survival probability of the quantum of 0.999 and 0.750 are analyzed. It is discovered that these dependences are significantly different for the models of the atmosphere being considered, which clearly reflect the influence of the optical parameters of the atmosphere and the surface on the transformation of solar radiation fluxes.

The comparison of model calculations with aircraft measurements of hemispherical fluxes of solar radiation [94] shows a good fit for fluxes and radiant tributaries in a cloudless and cloudy atmosphere, which makes it possible to use simple models of a homogeneous atmosphere to obtain radiation characteristics. The calculation of Radiative Forcing in a cloudy atmosphere requires more complex, multi-layer models, consisting of at least two layers, which is evident from the difference and the significance and sign of the results. It is especially necessary to emphasize the great influence of the process of absorption of solar radiation in a cloudy atmosphere, in which atmospheric aerosols play a decisive role; this must be carefully taken into account during modeling. A two-layered cloudy atmosphere model provides positive forcing, even in the absence of aerosols, due to gas absorption, which is stronger for scattering light in the clouds. We note the value of the optical thickness $\tau = 4$, which is in some sense a threshold: the dependence of the radiation characteristics on the optical thickness varies sharply upon transition from a less optically thick atmosphere to a more optically thick one. This is due to the fact that it is for these values of τ that the role of multiple scattering in the formation of the radiation field increases sharply, which was shown in [95]. The obtained results demonstrate that the simple optical models used provide an adequate consideration of the influence of the most important factors on the variability of solar radiation in the atmosphere. The work was carried out within the framework of the Federal Target Program "Research and Development in Priority Areas for the Development of the Russian Science and Technology System for 2014-2020" (Agreement No. 14.586.21.0023, unique identifier of the RFMEFI58615X0023 project) and using the Environmental Safety Observatory at St. Petersburg State University Research Park.

These studies confirm the position that "the main greenhouse gas is water vapor." The fact that the concentration of water vapor remains almost unchanged may be explained by the fact that their turnover varies from 7 to 10 days: the concentration increases and precipitation falls out. This is a natural mechanism of climate regulation.

A serious influence on the climate can be caused by aerosols, the source of which can be **volcanic eruptions** [91].

In order to reliably estimate the possible changes in the Earth's climate, it is necessary to ensure that the main factors determining the radiative heat exchange in the atmosphere are sufficiently accurately taken into account in climate models. In cloudless conditions, an important component of the atmosphere that forms the radiation regime of the atmosphere along with absorbing atmospheric gases is aerosol. When taking into account the aerosol attenuation in calculations of radiation flows in the 0.2 μm to 5.0 μм wavelength range of solar radiation, it is necessary to know the optical parameters of the aerosol: the optical thickness τ, the single-scattering albedo > 0, and the scattering asymmetry factor **g**. The optical parameters of the aerosol can be determined from direct measurements of spectral transparency, and also reconstructed from radiation measurements. A quantity called aerosol radiative forcing (ARF) is used to quantify the effect of aerosol on the radiation balance at the Earth's surface and at the upper boundary of the atmosphere. The short-wave ARF, which is analyzed in this paper, is defined as the difference between the solar radiation balances calculated with and without aerosol absorption and scattering. The balance is determined at each level of the atmosphere as the difference between incoming and reflected flows.

Aerosol optical thickness is the main parameter defining the degree of aerosol influence on the solar radiation flux. To quantify the turbidity of the atmosphere due to aerosol particles, the optical thickness of the aerosol at a wavelength of 550 nm is traditionally used, which, in the absence of spectral transparency measurements, can be reconstructed from actinometric measurements of integrated solar flows. However, knowledge of this parameter alone is insufficient to determine the effect of tropospheric aerosols on the surface air temperature and climate [97-100]. Depending on the magnitude of the single scattering albedo, aerosol particles can heat or cool the Earth's surface. With the creation of devices designed for radiation measurements in several narrow intervals of the solar spectrum, it became possible to determine all three aerosol optical parameters at several wavelengths. The method is used by AERONET, a network of solar photometers which observes the specified parameters at four wavelengths: 440, 670, 870 and 1,020 nm. The AERONET network includes several hundred stations located in different regions throughout the world. Note that the satellite measurements are limited to the 550 nm spectrum, and their measurements are subject to frequent errors, due to the influence of the clouds and the underlying surface. Ground measurements and model calculations are therefore necessary for the determination of the remaining parameters.

The paper [91] presents comprehensive data from systematic measurements taken in cloudless conditions at the Zvenigorod Scientific Station (55°42' N, 36°46' E) of the A.M. Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (ZSS IAP RAS). The data were obtained in spring-summer 2004 and in the summer of 2005 and are used to determine the values of the shortwave radiative forcing of the background aerosol. The background aerosol at the ZSS has a typical optical thickness of 0.04-0.30 at a solar radiation wavelength of 550 nm. It more significantly affects the flux of solar radiation, than, for example, smoke aerosol, the radiation properties of which have been investigated. Nevertheless, the study of background aerosol is of great scientific interest, because due to its constant presence in the troposphere, it has a significant effect on the radiation balance of the atmosphere and the surface.

As a result, in this work [91] calculations of the flow of solar radiation at the surface and aerosol radiative forcing were carried out for cloudless periods of observation at the ZSS in the summer of 2004 and 2005. Five models of optical aerosol parameters were used: a standard model of continental aerosol, a semi-empirical model obtained from the measured data, and three models derived from scattering theory calculations, based on the average size distribution of aerosol particles recovered from aureole measurements. A study of the sensitivity of the flow and forcing to the choice of the aerosol model showed that the relative error associated with the choice of the model is small with respect to the downward flow flux (<5%) and reaches 120% in aerosol forcing at the upper boundary of the atmosphere. The magnitude of the aerosol radiative forcing at the upper boundary of the atmosphere varies from -15 to -2 W/m², according to our calculations. The availability of data on the values of the single scattering albedo and the scattering asymmetry factor at 550 nm for each observation period, and the consideration of these parameters in radiation calculations, make it possible to significantly refine the value of the aerosol radiative forcing, in comparison with the use of the mean values of these parameters for all periods being calculated.

An even more accurate determination of the amount of aerosol radiative forcing is possible only if data are available on the distribution of aerosol particles by size and their chemical composition for the particular situation analyzed. As a result of the sensitivity study used for the radiation calculations, two models of background aerosol optical parameters are proposed: a semi-empirical model and an average model obtained from calculations based on scattering theory. Both models use values from the single-scattering albedo and the asymmetry factor at a wavelength of 550 nm, reconstructed from the measurements for each observation period.

These studies have confirmed that volcanic eruptions which have happened for millions of years have a significant impact on the climate and life of people on Earth.

The 2010 eruption of Eyjafjallajökull volcano in Iceland, left air traffic in Europe at a standstill for several days, even though related emissions totalled only 0.01 km³.

For comparison:

- The eruption of Krakatoa volcano in Indonesia – 20 km³ (1883),

- The eruption of Tambora volcano in Indonesia – 150 km³ (1815) - the largest eruption in the history of human civilization, significantly changed the climate on the planet: in Germany and Canada in the summer of 1816, snow fell and thousands of people died from hunger and epidemics.

- The eruption of the Huaynaputina volcano in Peru - 30 km³ (1600) - led to a cold snap and crop failures in Northern Europe, and is likely to also have contributed to the onset of the Time of Troubles in Russia.

Millennia ago there were four terrifying eruptions:

- New Zealand's Taupo volcano – 1,170 km³ (26,500 years ago) - coincided with the beginning of a global cooling period, which lasted about 2,000 years. Although the connection between these events has not yet been proven.

- Toba volcano in Indonesia – 2,800 km³ (74,000 years ago) - The largest eruption in the last few million years caused the mass extinction of animals and plants around the world due to climate change.

- Yellowstone volcano in the USA – 1,000 km³ (640,000 years ago) - the last super-eruption in the Yellowstone Caldera.

- Siberian Traps volcano - 5 million km³ (250 million years ago) - formed as a result of the emergence of a superplume on the surface. Emissions of lava and ash covered an area of 2-7 million km². The eruption lasted a million years: about 90% of life on Earth was destroyed.

8 THE CLIMATIC ROLE OF ANTHROPOGENIC METHANE EMISSIONS IN COMPARISON WITH OTHER GREENHOUSE GASES

The average global concentration of methane in the near-surface atmosphere in the year 1750 has been estimated at 722 ± 25 ppb [26, 76]. By the year 2011, this figure had reached 1,803 ± 2 ppb [77].

During the period of 1750-2011, the radiative forcing of methane was 0.48 ± 0.05 W/m², and the total radiative forcing of all well-mixing gases was 2.83 [2.54 – 3.12] W/m² [70].

Thus, currently, methane accounts for about 17% of the total radiative forcing related to the anthropogenic increase in the contents of well-mixing GHG (greenhouse gases) in the atmosphere. Fig. 8.1 shows the values of radiative forcing of CO_2, CH_4, N_2O and other well-mixing GHG in 1850-2011. Methane is currently the second most powerful gas after CO_2 in terms of radiative forcing[24].

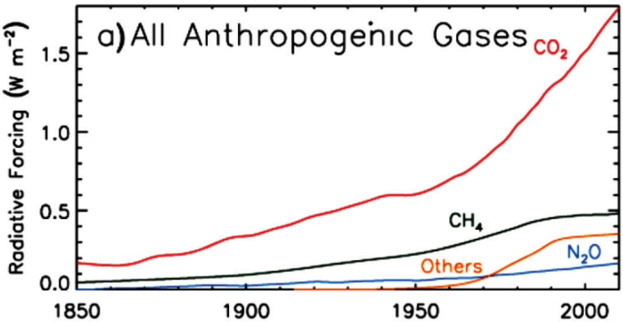

Figure 8.1. The radiative forcing of carbon dioxide, methane, nitrogen monoxide, and other well-mixing gases in the years 1850-2011. (Myhre et al, 2013, p. 677)

Fig. 8.2 shows the radiative forcing in the 21st century related to the anthropogenic emissions of carbon dioxide, methane, nitrogen monoxide, ozone, and other GHGs and aerosols since the beginning of industrial era [78]. The calculations were made under the conditions of four RCP scenarios for the year 2100. The top diagram shows absolute values, the bottom diagram shows relative values as a percentage of the total radiative forcing.

Note that the contemporary contribution of methane is estimated at approx. 23%, which is somewhat higher than the given estimation of 17%. However, this is explained, among other factors, by different base numbers: in the estimation above, the base number did not include the aerosols, which have a cooling effect.

[24] Water vapor not taken into account (editor's note.)

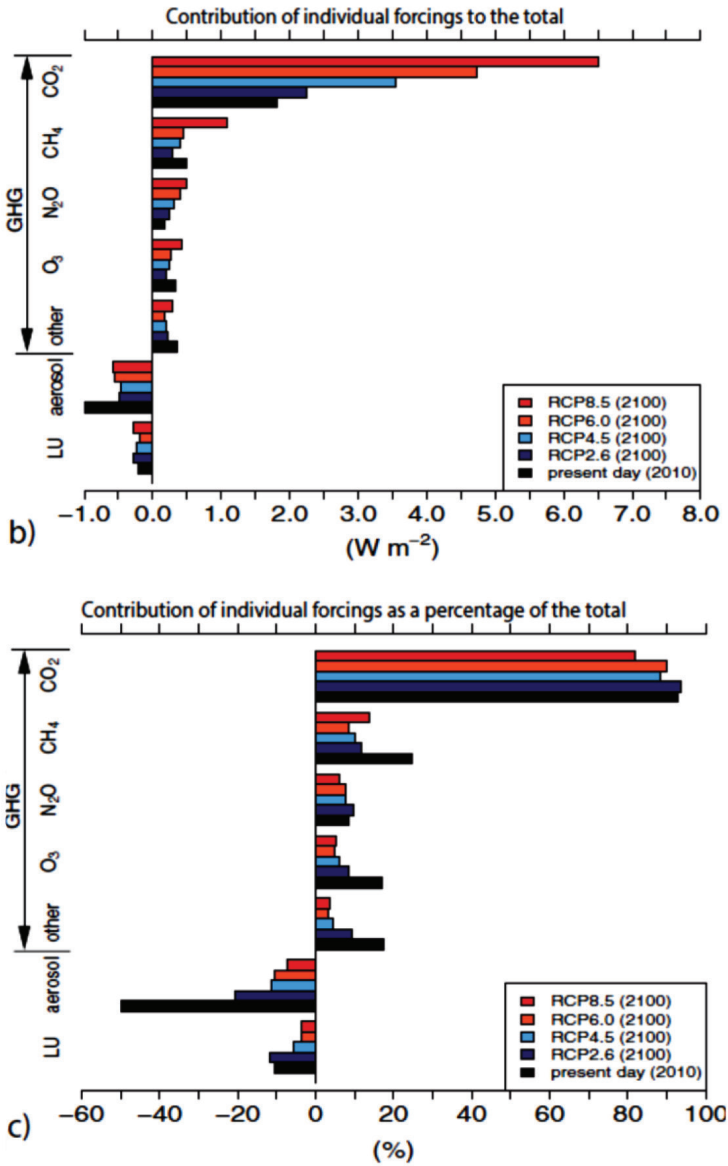

Figure 8.2. The contributions of various greenhouse gasses – CO_2, CH_4, N_2O, O_3, other GHGs and aerosols – in the total radiative forcing (since the beginning of the industrial era) in the year 2100 under the conditions of four RCP scenarios, and in 2010: top diagram – absolute values, bottom diagram – % (Meinshausen, 2011; Collins et al, 2013, p. 1046)

In any case, the estimations for the year 2100 demonstrate that in relative units, the role of methane in the future will not increase – it will remain approximately at the level of the early 21st century or somewhat lower.

For a tentative estimation of the contribution of CH_4 to the increase in global temperature in the 21st century, one can use the approximate proportionality between this increase and the radiative forcing.

As a conclusion to this section, let us give the changes in average temperature of the near-surface atmosphere (Table 8.1) expected under the conditions of various RCP scenarios. Assuming that the change in temperature is proportional to the radiative forcing ($\Delta T = \lambda\ \Delta F$, Section 7.1), and taking into account the estimations of methane contribution to the radiative forcing in the late 21st century under the conditions of RCP scenarios, one can arrive at the conclusion that the methane contribution to the change in global temperature is within 1°C.[25]

Table 8.1

Anomaly ΔT of average temperature (°C) in relation to the average level during 1986–2005 under the conditions of RCP scenarios – both globally and for some geographic regions (Collins et al, 2013, p. 1055). A cross-model standard deviation σ is given, and an interval (in brackets) corresponding to the 90% confidence interval (5%, 95%) for a normal distribution.

Region	Scenario			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Global: 2046–2065	1,0 ± 0,3 [0,4, 1,6]	1,4 ± 0,3 [0,9, 2,0]	1,3 ± 0,3 [0,8, 1,8]	2,0 ± 0,4 [1,4, 2,6]
2081–2100	1,0 ± 0,4 [0,3, 1,7]	1,8 ± 0,5 [1,1, 2,6]	2,2 ± 0,5 [1,4, 3,1]	3,7 ± 0,7 [2,6, 4,8]
Land: 2081–2100	1,2 ± 0,6 [0,3, 2,2]	2,4 ± 0,6 [1,3, 3,4]	3,0 ± 0,7 [1,8, 4,1]	4,8 ± 0,9 [3,4, 6,2]
Ocean: 2081–2100	0,8 ± 0,4 [0,2, 1,4]	1,5 ± 0,4 [0,9, 2,2]	1,9 ± 0.4 [1,1, 2,6]	3,1 ± 0,6 [2,1, 4,0]
Tropics: 2081–2100	0,9 ± 0,3 [0,3, 1,4]	1,6 ± 0,4 [0,9, 2,3]	2,0 ± 0,4 [1,3, 2,7]	3,3 ± 0,6 [2,2, 4,4]
Arctic: 2081–2100	2,2 ± 1,7 [-0,5, 5,0]	4,2 ± 1,6 [1,6, 6,9]	5,2 ± 1,9 [2,1, 8,3]	8,3 ± 1,9 [5,2, 11,4]

[25] Estimation by S.M. Semenov, I.L. Govor, N.E. Uvarova for NIIPE under the contract DP-MDK-2017-01 dated 18.05.2017. (editor's note)

9 AN ALTERNATIVE VIEW TO THE CLIMATE CHANGE PROBLEM[26]

In spite of the impression created by the global media that there is a wide consensus among the world's scientific community on anthropogenic global warming taking place on Earth, an analysis of current views of scientists from different countries shows a dramatic diversity of opinions on the issue. This mostly results from the objectivity that still remains in several scientific schools and demands that any problem be realized in all its complexity; and the complexity of the global climate problem is rightly viewed as a highly critical one. According to many scientists, humankind today does not have the means to adequately address the issue and to forecast the global climate in any meaningful way; the same models that are used for this are characterized as simplistic, or even as the ones that adjust the problem to fit the solution. The hyped "consensus" regarding the global warming and its causes is described by those holding alternative views as "forced", and its media coverage as one-sided [96 – 121].

The range of opinions in the global scientific community covers the following issues of climate change trends, which is characterized as global cooling, not warming, by some scientists.

Among other reasons, it is attributed to the decreasing solar activity. Here is an opinion of Valentina Zharkova, a professor at Northumbria University, England: "Solar activity is currently very low, and the Sun's magnetic field is greatly decreased. This means that cosmic rays destroy our clouds in the troposphere, open up the atmosphere, and decrease the temperature. Apart from snow, there are new, very unusual polar lights in North America and Europe — their color is quite unique. This suggests that the particles' origin is cosmic rays, not the sun. Therefore, we believe this to be a beginning of the global solar minimum, which will last 30 years."

Yelena Popova, a leading researcher at the Institute of Physics of the Earth of the Russian Academy of Sciences, has arrived at the same uncomfortable conclusion: "In general, solar activity is a regular, cyclical process. Every 11 years, the number of spots increases, then decreases again. Our calculations have shown that the next three cycles of solar activity will have smaller amplitude than the previous ones. On a schematic diagram, the next cycle is lower. That is, its amplitude will be lower, then even lower, and then the solar activity will rise." [96]

History has already seen periods of low solar activity. The most well-known one is the Maunder Minimum, which began in 1645 and lasted over half a century.

[26] The work performed by S.A. Roginko for NIIPE under the contract DP-MDK-2018/04 dated 10.04.2018.

The rivers Thames and Danube were used for sledding, and the frozen Moscow River served as fairgrounds, half a year long. The phenomenon was discovered by Edward Walter Maunder, an English astronomer (1851—1928), as he studied solar observation archives. According to Maunder's calculations, as few as around 50 sunspots were observed during that period, instead of the usual 40-50 thousand.

Maunder's results were later confirmed by the analysis of Carbon-14 content, as well as some other isotopes, e.g. Beryllium-10, in ice and trees. This analysis has allowed the identification of 18 minimums of solar activity during the last 8,000 years, including the Spörer Minimum (1450—1540) and the Dalton Minimum (1790—1820). Also, some data suggest that during the Maunder Minimum, a fall in the intensity of polar lights and the speed of Sun's rotation were observed [97].

The Maunder Minimum coincides in time with the coldest phase of global climate cooling observed between the 14th and 19th centuries (the so called Little Ice Age).

Although the period during the Maunder Minimum was much longer – it lasted six solar cycles. The next, contemporary period that is expected, will be much shorter – three cycles only. Therefore, no large-scale cataclysms as in the 17th century are forecast, but there definitely will be a decrease in temperature.

A more pessimistic forecast regarding the probable outcome of the new Little Ice Age is given by John L. Casey, an American climatologist and NASA employee. With several colleagues, he presented a report to the heads of the world's leading governments and the UN, clearly stating that there is a danger for the humankind. According to Casey, "We will soon face dark and cold days and nights and, as a consequence – crop failures and mass starvation." The proof of radical climate shifts, in Casey's opinion, are the very weather anomalies today, which are misrepresented by many politicians and experts as the results of global warming. All these consequences will become tangible within the nearest 30 years, he claims [96].

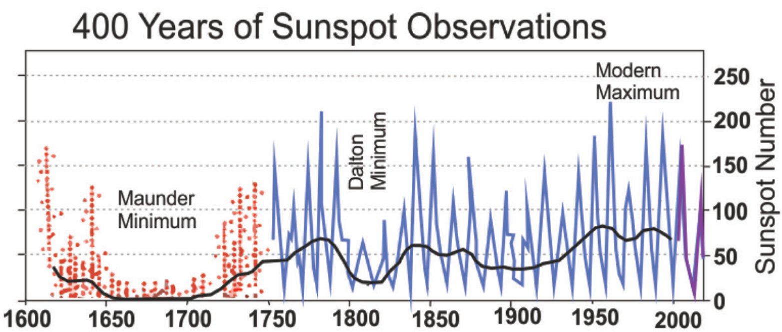

Figure 9.1. Solar activity during the period of Maunder Minimum.
Source:2 (https://en.wikipedia.org/wiki/Maunder_Minimum)

One of the proofs he offers of this hypothesis are the data on permafrost in Greenland published in January 2018 refuting the hype statements regarding the "melting Greenland" made by the global warming theory adherents. According to the group of scientists headed by Professor Bo Elberling – Director of the Center for Permafrost (CENPERM) at the University of Copenhagen, the temperature of permafrost areas in Greenland haven't increased during the last 15 years – instead, temperatures fell sharply. Bo Elberling justly maintains that with a 15-year span, only weather changes can be monitored, not climatic changes, but even these data seriously contradict the propaganda material that frighten legislators, leaders and laypeople alike with a temperature increase every year [98].

THE NATURE OF CLIMATIC CHANGES, WHERE NATURAL CYCLIC FACTORS ARE PREDOMINANT

One such factor is precession (circular rotation of the Earth's axis in relation to its inclination toward the Sun), discovered over two thousand years ago by the ancient Egyptian astronomers.

As the Earth rotates around its axis, it slows down its movement (the decel-

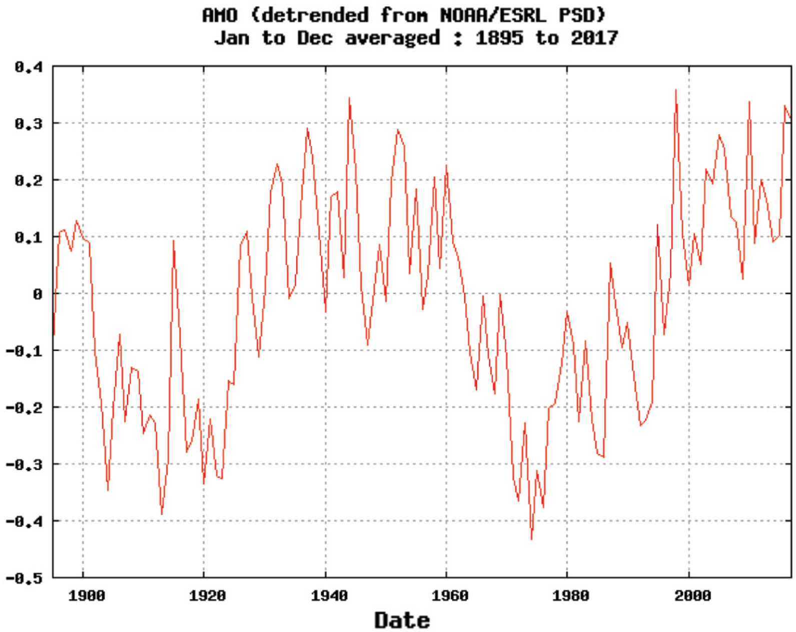

Figure 9.2. Temperature changes in the permafrost areas of Greenland (1900 – 2017). Source: [99] (http://sciencenordic.com/greenland%E2%80%99s-recent-temperature-drop-does-not-disprove-global-warming)

eration is variable, approx. 0.1 - 1 second per one thousand years). As its rotation slows down, the Earth swings like a humming top, alternately exposing its different sides to the Sun. That was why the ancient Greeks called the inclination of sun rays to the Earth's surface "climate" [99].

Durign the Earth's precession, its axis makes a full turn (360°) every 25,920 years (1° every 72 years). The angle of Earth's axis deviation (from a conventional center) as the planet swings is 23° 27'. This corresponds to the distance from Sweden to Cyprus on the globe. The angle between the maximum and minimum inclination of Earth to the Sun in precession is twice as much: 46° 54'. This approximately corresponds to the distance from the polar circle to Africa. So when the Earth exposes the northern Scandinavian shores to the Sun (instead of the African shore, as it is today), the Scandinavian countries will be as hot as Central Africa.

The ancient Egyptians and Greeks called the full circle of 25,920 years of the planet's precession and swinging the Great Year (Platonic Year), with all its global climate changes. Thus, the precession affects the climate changes on Earth in the only important, global, and cyclical way.

Geological data suggest that ice periods on Earth were repeated many times, with the last ice age ending around 10-12 thousand years ago. At that time, the glaciers in the northern hemisphere sometimes reached the latitudes of modern cities including Kiev, Berlin, and London. Scandinavia, the Baltics, Canada, and Siberia were buried under hundreds of meters of ice and snow. In some places, the ice was as thick as in today's Antarctic. Because a large mass of Earth's water was concentrated in the ices of northern continents, covering vast spaces of Eurasia and America, the world ocean level was 100-200 m below its current level.

The attempts to forecast future climatic changes on the basis of this trend suggest that with the precession movement of our planet, peak heat in the northern hemisphere has not been crossed yet. The peak heat may be expected after 1,000-3,000 years from now. Until then, various combinations of cooling and warming periods are possible. According to Vladimir Melnikov – an academician of the Russian Academy of Sciences and Head of the Cryosophy Department at University of Tyumen – the Earth is currently experiencing a transition between states. We are near the end of an interglacial period, 10 thousand years into it, and about 1 thousand years remains until the new ice age, i.e. the planet is currently on its way to cooling.

This opinion is partly shared by Victor Osipov – a scientific director of the Institute of Environmental Geoscience of the Russian Academy of Sciences. In his opinion, "one can only judge about the climate changes by looking at trends. And the current trend – a Holocene one (Holocene is the Quaternary epoch following Pleistocene and ongoing during the last 12 thousand years), which has been developing during the last 8,000 years – this is a trend of the Earth's temperature decreasing, but against the background of decrease during the last 150 years, we have

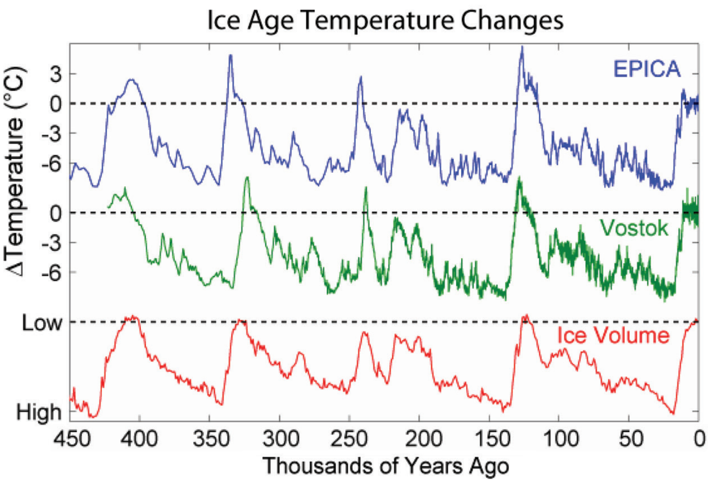

Figure 9.3. Temperature cycles during the last 450 thousand years (according to the data from ice analysis in Antarctic expeditions). Source: [102]

a rapid temperature increase: 0.02° every ten years. This hasn't happened before. There is an assumption that this is related to technogenesis and the man-made impact on the climatic system. That is why the temperature is currently increasing, but the centuries-long cooling trend remains"[103].

One of the new hypotheses on climate trends is the hypothesis of global dimming published in 1985 by Atsumu Ohmura, a scientist at the Swiss Federal Institute of Technology. This phenomenon, discovered by Ohmura in his research, is a decrease in the level of sunlight every decade. According to the results of his research, the level of sunlight reaching the Earth's surface has decreased by over 10% during the last three decades. The research was continued by other specialists, and currently the scientific literature presents several other works published on the issue, all of them identifying a decrease in the light level. The decrease in sunlight level was noted in Ireland, Arctic, Antarctic, and Japan.

The Royal Meteorological Institute of Belgium announced the December 2017 as the darkest month since 1887, when the observations began. During this month, only 10.5 hours of visible sun at the meteorological station of Uccle were recorded.

In the northern France, only 26 hours of sunlight were recorded in December 2017, and even less in January 2018. The French meteorological service (Météo-France) recorded only 2.7 hours of sunshine between January 1 and 13 in Lille, the largest city in the region, which was considered an anomaly by meteorologists and recorded as a "unique event", because the average indicator for this city in January is 61.4 hours.

The dimming became an acknowledged global issue in 2001, when Shabtai Cohen, an Israeli scientist, and his colleagues from the Volcani Center in Bet-Dagan gathered all the available proofs together and made the conclusions confirming the validity of this theory [104].

The generalized form of interconnection between the climate and sun radiation was first formulated in the so-called Milankovitch cycles (named after Milutin Milankovitch, a Serbian astrophysicist). The Milankovitch cycles reflect the oscillations in the amount of sunlight and solar radiation reaching the Earth throughout large spans of time. To a large extent, the Milankovitch cycles explain the natural climatic changes taking place on Earth, and play a major role in climatology and paleoclimatology, mostly in studying the problems of global warming and greenhouse effect. However, because of the complex processes of interaction between different factors, and because of the feedback, a full identification of climate changes with the fluctuations in solar energy received by Earth is not justified and cannot serve as a sufficiently accurate model to reconstruct the past and future climatic processes.

The Milankovitch cycles describe the periodic deviations of insolation in hemispheres from the average value throughout a large time span, ranging from 5 to 10 percent. The reason of these deviations from the average intensity of solar radiation on Earth is the following effects:

• The lunisolar precession (mentioned above): a rotation of the Earth's axis with the period of 25,920 years, resulting in changes in the seasonal amplitude of solar flux intensity in the northern and southern hemispheres of the Earth;

• Long-period oscillations (the so-called multi-century oscillations) of the angle of Earth's axis inclination to its orbital place with a period of 41,000 years, caused by impacts of other planets;

• Long-period oscillations of the eccentricity of Earth's orbit with a period of 93,000 years.

• A shift of the perihelion of Earth's orbit and an ascending node of the orbit with the periods of 10 and 26 thousand years, correspondingly [105].

• Because these effects are periodic with non-repeated periods, very long epochs regularly occur when they have a cumulative impact by strengthening each other. The Milankovitch cycles are usually used for explaining the climatic optimum in Holocene (the optimum lasted from circa 9000 to 5000 B.C., during this period, the temperature was much higher than in the present).

One more type of natural cyclical oscillations affecting the climate, accord-ing to the scientists, are the Dansgaard-Oeschger oscillations. These are sharp climate changes during the last ice age, 23 in total, according to the materials of Greenland core samples. They are named after the scientists who were the first ones to use ice

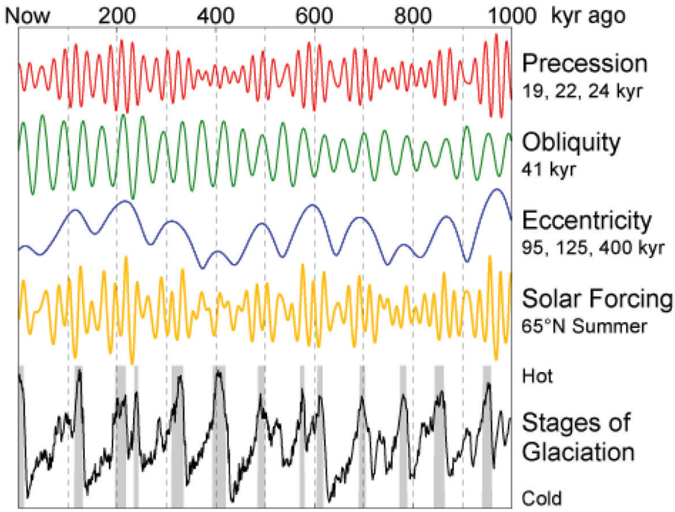

Figure 9.4. The effects contributing to the Milankovitch cycles in time Source: [106]

core samples to study paleoclimate and to notice the traces of sharp temperature changes in them.

In the northern hemisphere, the Dansgaard-Oeschger oscillations are manifested as a fast (within decades) warming followed by a gradual cooling (centuries-long). The temperature difference during an oscillation in Greenland reached 15 degrees Celsius (according to other sources, 7-8 degrees). In the southern hemisphere, the warming is slower, and the amplitude of oscillations is less significant. Although the temperature variations in Greenland and Antarctic are vastly different, a correlation is observed between the times of sharp temperature oscillations in Greenland and a temperature gradient in Antarctic: the change in Greenland usually occurred at the end of a gradual temperature change in Antarctic.

The Dansgaard-Oeschger oscillations follow a 1,470-year cycle, which, in turn, consists of 87-year and 210-year cycles. The latest materials of ice cores for the last 50 thousand years show deviations of approx. 12% (2% for the last five oscillations). At the same time, the oscillations in older parts of the core do not show regular cycles.

Similar 1,500-year climate oscillations during Holocene are called Bond cycles [107].

THE CORRECTNESS OF DESCRIPTION OF CLIMATE CHANGES, OF CLIMATE SIMULATION METHODOLOGY, AND OF BASELINE DATA.

The so-called medieval climate optimum became a subject of heated debate: between the 9th and 15th centuries, it caused a noticeable population growth and agricultural production throughout Europe, which resulted from expansion of agricultural lands and an increase in the quality of crops. The warm (compared to our days) climate helped the growing agricultural nations spread to peripheral, poorly developed regions such as northern Norway (where grain crops have been grown up to the polar circle). The warm climate allowed Vikings to permanently settle in Iceland (the year 870) and Greenland (starting 986; in the 15th century, the settlements were abandoned). The chronicles mention winemaking in East Prussia, Pomerania, and even southern Scotland at the time.

However, the politicization of climate change problem forced the senior executives at IPCC to switch in the late 1990s from the acknowledgment of the optimum to its actual denial, because the fact that the humankind successfully survived throughout several centuries with the temperatures much higher than the current ones was in contradiction with the task of intimidating the people today with the impending warming. To this end, the earlier reconstructions of IPCC (see the red line in the figure below) were substituted by other versions that ignored the historical evidence of high temperature (see the blue and black line ibid.).

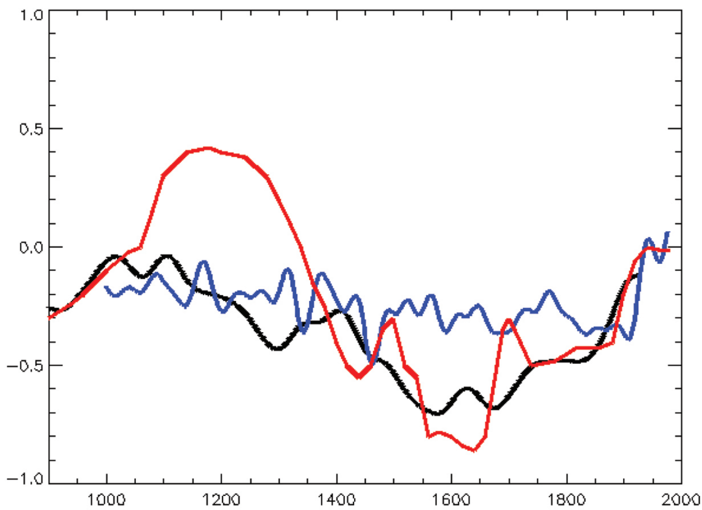

Figure 9.5. The early and late scenarios of global temperature, IPCC. Source: [108]

A classical product of such historical reconstruction adjusted to fit the desired answer was the notorious "hockey stick" graph made by Michael Mann, an American climatologist. In the graph, the temperature during the last 1,000 years is clearly shown as some flat scale serving as a background for a zoom in the latest 50-100 years. The Climategate scandal has revealed the true motives of the IPCC's board members, who consciously misrepresented the baseline data in order to prove an unprecedented nature of the warming of recent decades. According to some researchers who examined the climatic model of M. Mann, this model shows a steady increase of the indicator by the end of period for any row of random numbers used as source data [108].

The correspondence of IPCC experts copied during the Climategate by unknown hackers from the servers of the Climatic Research Unit, University of East Anglia, confirms that a biased, alarmist approach was used in their work, the actual data was ignored, and an open desire to manipulate the global community's opinion was predominant. It has been revealed that these experts:

- misrepresented the data and willingly distorted the contents of temperature baseline data for various points on the globe received from a network of meteorological stations;

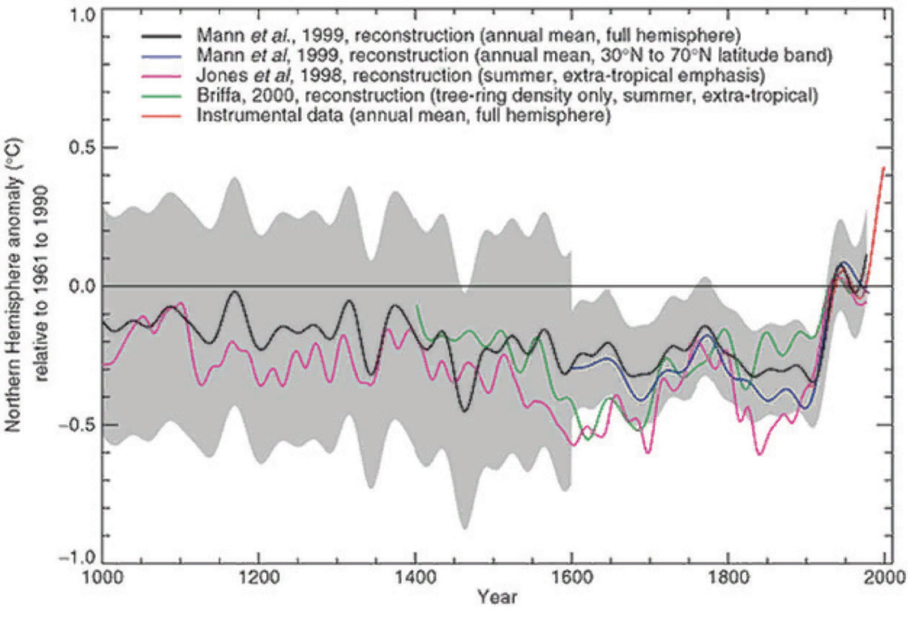

Fig. 9.6. The "hockey stick" graph according to M. Mann, P. Jones, and other IPCC experts. Source: [109]

- selected (to adjust the task to a predefined answer) the so-called correction factors arbitrarily to be used for simulating temperature processes on the planet;

- omitted the actual data on temperature processes on the planet and refused to provide them to independent researchers;

- stigmatized the representatives of alternative scientific schools indiscriminately, blocked their attempts to present the results of their research in scientific publications.

The correspondence between the authors of the Fourth Assessment Report of the IPCC – the one that received a Nobel prize – raises serious suspicions. Here is a quote from a letter by Phil Jones, Director of the Climatic Research Unit, to Michael Mann, his US colleague: "Mike, Can you delete any emails you may have had with Keith re AR4?" Jones writes to Caspar Ammann and Eugene Wahl, his British colleagues, during the preparation of this report: "Try and change the Received date! Don't give those skeptics something to amuse themselves with." Michael Mann calls to his colleagues to boycott the Climate Research journal – the one that doubted the anthropogenic causes of warming: "Perhaps we should encourage our colleagues in the climate research community to no longer submit to, or cite papers in, this journal." Special care is taken by Mr. Jones for the source data to not get into the public's hands (e.g. such independent researchers as Stephen McIntyre and Ross McKitrick, called "the two MMs" in the email): "The two MMs have been after the CRU station data for years. If they ever hear there is a Freedom of Information Act now in the UK, I think I'll delete the file rather than send to anyone."

Note that some climatologists were unable to face the current problems. For instance, Mike Hulme of the same University of East Anglia stated as follows regarding the Climategate: "This event might signal a crack that allows for processes of re-structuring scientific knowledge about climate change. It is possible that some areas of climate science have become sclerotic. It is possible that climate science has become too partisan, too centralized. The tribalism that some of the leaked emails display is something more usually associated with social organization within primitive cultures; it is not attractive when we find it at work inside science" [110].

American scientists Richard Lindzen, Stephen McIntyre, Ross McKitrick, and others voice suspicions regarding the trustworthiness of baseline data on the warming in recent decades. Many ask the question: what were the points where the data were gathered? In the 19th century, meteorological stations were mostly based in large cities; until today, many stations are still there. The megapolises have grown considerably during the last 200 years, the volumes of heat emissions in their territory grew hundreds of times because of the industry, vehicles, heating, etc. Today, every large city is a huge thermal spot, where the average annual temperature is 5-10 degrees higher than in their suburbs. It is not hard to see how random are the numbers in global temperature calculations where the data from large city stations were used.

The real picture of data gathering points revealed by American activists shows that many thermometers included in the official grid of national climate change data sources are attached to the walls next to such sources of heat emissions as refrigerators, ACs, windows, and concrete slabs. All of this aggravates the already present effect of an urban heat spot and makes the data distortion unavoidable. The research carried out in 2009 when 650 volunteers inspected 860 thermometers out of 1,221 total land-based thermometers included in the monitoring grid of the National Oceanic and Atmospheric Administration, USA (NOAA) has shown that out of this amount, 89% do not meet the official requirements because they were placed next to artificial heat sources [111].

At the level of global network of temperature data, things are not much better. Out of 1,079 stations in the global network, 80% are either within city agglomerations, or in airports (where plenty of artificial heat sources are also present). Moreover, the amount of stations in the network, which was almost 6,000 in the 1980s, has fallen drastically. Which stations were taken out, and which ones remained? Among the surviving stations, the share of stations in large cities and airports has sharply increased, as well as of the stations in the latitudes where the warming effect is more pronounced. Also, the share of high altitude stations has decreased, and the share of sea level stations has increased. According to the Institute for Economic Analysis, out of more than 400 meteorological stations in the Rosgidromet system, only 12 were included in the global source grid – the ones located mostly in major cities and/or showing the highest temperature growth [112].

But the "care" about the "proper" source data did not stop there. There are also the technologies for adjusting the source data on the pretext of relocating the thermometers, and on other grounds. Such adjustments, according to some American experts, provided almost the entire increase in temperature officially declared in the US during 1930–1990. Besides, there is a practice of revising the sources data in approximately 10 years after they are received – it is not hard to guess the trend of such revisions.

In the end, the data can be hidden from the public, violating all the laws on free access to information, and even destroyed – this has also happened. For example, representatives of the Climatic Research Unit, University of East Anglia, had to admit under pressure from media, that the direct measurement data, on whose basis the global warming graphs were built, were destroyed. The information that had been gathered and stored since early 20th century was deleted, according to the university employees, in late 1980s, when the climatology laboratory was relocated to a new building. They admitted that "the data were stored on old media – film, videotapes, and others, and when the laboratory was moved to another building, the boxes with archive documents and tapes were simply burned. No one was capable of transferring these data to new formats."

The atmosphere of intolerance to those express alternative opinions, created by alarmist climatologists, forces many dissenting ones to only voice their views after their career is over. For example, Dr. Joanne Simpson, one of the world's top meteorologists, said when she retired that she was finally free to speak frankly about the global warming and state that "as a scientist I remain skeptical." She had been silent, fearing personal attacks. Dr. Simpson pioneered computer simulation, and she notes that the computer models are still not good enough to predict weather, much less can they predict global climatic trends scientifically.

Dr. Fred Singer, the first director of the US Weather Satellite Service, and Dr. Frederick Seitz, a physicist, former president of Rockefeller University and the National Academy of Sciences, maintained that the computer models used doubtful input data and made the allowances that defined the answers about the nature and the trends of global warming that the scientists expected to have [112].

Among the scientists who are skeptical to different extents to the so-called "climate consensus" are Nobel Prize laureates, fellows of the Royal Society, academicians from different countries, and professors of leading universities. A tentative system of their views follows[27].

THE LEADING SCIENTISTS DENYING THE CORRECTNESS OF IPCC CLIMATE MODELS

Freeman Dyson, a fellow of the Royal Society (UK)

Ivar Giaever, Nobel laureate in physics (1973)

Richard Lindzen, MIT Professor Emeritus of Meteorology, member of the National Academy of Sciences (USA)

Ross McKitrick, a professor of economics at the University of Guelph

Patrick Moore, former President of Greenpeace Canada

Harrison Schmitt, American geologist, an Apollo 17 astronaut, former U.S. senator

THE LEADING SCIENTISTS MAINTAINING THAT THE GLOBAL WARMING RESULTS MOSTLY FROM NATURAL CAUSES

Sallie Baliunas, a retired astrophysicist, Harvard University

Vincent Courtillot, a member of the French Academy of Sciences

William Happer, professor of physics, emeritus, at Princeton University

[27] The work performed by S.A. Roginko for NIIPE under the contract DP-MDK-2018/04 dated 10.04.2018.

Kary Mullis, Nobel laureate in chemistry, 1993

Ole Humlum, a professor at the University of Oslo

Wibjörn Karlén, professor emeritus at Stockholm University

Nir Shaviv, a professor at the Hebrew University of Jerusalem

Roy Spencer, a meteorologist, a principal research scientist at the University of Alabama

THE LEADING SCIENTISTS MAINTAINING THAT THE REASONS FOR GLOBAL WARMING ARE UNDETERMINED

Claude Allègre, professor emeritus at the Institute of Geophysics in Paris

Pål Brekke, an astrophysicist, Senior Advisor at the Norwegian Space Centre

John Christy, Distinguished Professor of Atmospheric Science, Director of the Earth System Science Center at the University of Alabama, former co-author of several IPCC reports

Petr Chýlek, a researcher at Los Alamos National Laboratory

Stanley Goldenberg, a meteorologist at NOAA (National Oceanic and Atmospheric Administration), USA

Antonino Zichichi, professor emeritus at the University of Bologna, President of the World Federation of Scientists

Shortly before Donald Trump was elected president, on September 12, 2016, thousands of scientists published a letter of protest against spurious theories of global warming, which became a sensation. A letter against the politicization of the warming problem was signed by 31,000 scientists, including 9,000 holders of Ph.D and higher degrees. The scientists protest against the primitive concepts of anthropogenic warming, hydrocarbon taxes, and restrictions to economic growth.

10 POSSIBILITIES FOR REDUCING ATMOSPHERIC METHANE EMISSIONS FROM ANTHROPOGENIC SOURCES

The potential for reducing atmospheric methane is determined both by our technological capacity for doing so, as well as economic indicators regarding the technology. The regulation of methane emissions is determined by national legislation. In most post-Soviet countries, methane is not only associated with greenhouse gases, it is considered a pollutant as well, and therefore emissions face stringent regulation, control and monitoring. Estimates of past global anthropogenic emissions of greenhouse gases and different emission scenarios in the 21st century show that unless special measures are taken, methane emissions over time can increase (Table 4-2 and Section 6). Possible measures which could mitigate methane emissions include:

- increasing energy efficiency and reducing the resource intensity of the economy, which will lead to a reduction in emissions from the sources of CH_4 associated with these resources (for example, hydrocarbon fossil fuels or waste);

- capturing (collecting) methane (at landfills, at the preparatory stages of coal mining, etc.);

- using of special technology and activities that reduce methane emissions in currently existing processes.

The last of these points will be considered in more detail, in light of the information provided in the following sources [2, 34, 80, 81]. The assessment methodology used to obtain this data was based (excluding agriculture) on methane emissions from anthropogenic sources up to the year 2030 was based on the Business-as-Usual projections (Section 6.4) compiled by the US Environmental Protection Agency [35].

The analysis investigated the application of various technological approaches to reducing CH_4 emissions in each sector, and their aggregate final effect in comparison with the previously-calculated forecasts for 2030 (Table 9.1). In addition, for each of these approaches and a combined approach incorporating all of them, the cost of their implementation was assessed and the so-called average "break-even carbon price" calculated in dollars[28] per 1 tCO_2e[29] , when the cost of emissions (or benefits) and the cost of reducing emissions coincide.

Anthropogenic sources of methane emissions are quite diverse (see Tables 4.1 and 4.2). Accordingly, the ways and means of reducing the possibility of CH_4 emissions for them are different. Furthermore, the only sectors considered are those in which a high potential for methane emission reduction has been noted, which can

[28] Hereinafter 'dollar' refers to USD.

[29] Calculations (EPA, 2013) used a global warming potential of 21 for methane, i.e. 1 metric ton of CO_{2E} equals about 0.05 metric tons of CH_4

be realized at a relatively low cost [34, 81]. The technically achievable potential for reducing CH_4 emissions and the costs of its implementation for different industries are shown in Table 9.1.

Table 10.1

Total reduction potential of methane emissions in % of emissions calculated for 2030 (baseline), depending on the carbon price (GMI, 2015; EPA, 2013)

Sector	Cost per metric ton of CO_2e, US dollars*					Emissions in 2030, Megatons CH_4	Total reduction potential (at any cost)
	0	15	30	45	60		
Oil and Gas	35%	42%	44%	45%	47%	101	58%
Coal Mining	10%	56%	59%	59%	59%	37	60%
Agriculture	0%	3%	10%	13%	15%	18	28%
Household Waste	12%	26%	31%	32%	32%	46	61%
Wastewater	1%	3%	5%	7%	8%	29	36%

Note:
* - During calculations, a GWP of 21 was used for methane, i.e. 1 metric ton of CO_2e equals about 0.05 metric tons of CH_4

Agriculture (manure management). The total reduction potential of this sector is 28% of the base level of 2030. The cost of reducing emissions by 3% or 10% is \$15 or \$30 per tCO_2e, respectively. However, in this sector, the use of more expensive measures (costing upwards of \$60 per tCO_2e) does not provide significant additional benefits in reducing emissions, since it only provides an additional 5% reduction in emissions.

Oil and gas industry.[30] This sector offers implementable opportunities to reduce methane emissions; it's possible to reduce emissions by 35% using cost-effective interventions. The global potential for emission reductions in the sector could reach 44 and 49 Tg CH_4 by 2020 and 2030, respectively (representing 58% of total emissions in the Business-as-Usual emission scenario for each year). Almost 70% of this potential can be achieved at carbon prices below \$5. In addition, more

[30] Given the different methodological approaches to estimating emissions, the reduction potential is also assessed by experts in different ways (Ed.)

than 61% of the reduction (30 metric tons of CH_4 by 2030) is economically viable at current energy prices, i.e. practically does not require additional costs.

An increase in cost per tCO_2e from 15 to 60 US dollars would allow for an additional 5% reduction in methane emissions. However, the elimination of the remaining 11% to obtain the maximum reduction value would require expenditures exceding \$60 per tCO_2e. The method for estimating these costs for reducing methane emissions was documented by US EPA Natural Gas STAR. The results of calculations of the financial feasibility of applying different technologies for reducing methane emissions in different countries and regions and their effect are given in Table. 10.2.

Table 10.2

The potential of individual countries and regions to reduce CH_4 emissions (in megatons) in the oil and gas sector at different carbon prices in 2030

Country (region)/ Break even price (\$/metric ton CO_2e)*											
	–10	**–5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 producing countries											
Iraq	33	34	35	4	38	39	39	41	41	43	5
Kuwait	18	2	22	23	23	24	24	24	26	28	35
Russia	18	18	66	88	9	90	98	98	105	111	127
USA	38	4	40	44	44	47	47	47	50	52	67
Uzbekistan	5	5	17	23	23	23	25	25	28	28	33
Remaining regions											
Africa	55	6	59	62	65	65	67	68	7	71	85
Central and South America	15	16	16	16	17	17	18	18	18	19	24
Middle East	21	25	25	26	28	28	28	29	29	30	37
Europa	1	1	8	8	8	8	1	9	9	9	12
Eurasia	11	11	20	2	25	25	27	3	29	31	37
Asia	19	27	28	30	33	3	34	35	36	37	43
Country (region)/ Break-even price (\$/metric ton CO_2e)*											
	–10	**–5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
North America	14	2	19	20	21	21	21	22	22	23	28
Total	253	276	355	401	413	421	437	442	462	48	58

* Calculations (EPA, 2013) used a global warming potential of 21 for methane, i.e. 1 metric ton of CO_2E equals about 0.05 metric tons of CH_4

Coal mining industry. The total reduction potential in this sector (for underground coal mining) is approximately 60% of total annual emissions in 2030. The maximum potential for reducing emissions in the coal mining sector is 19 Tg CH_4 and 22 Tg CH_4 in 2020 and 2030, respectively.

Over 56% of all possible emission reductions (almost the total possible reduction potential) in this industry can be achieved if up to 15 dollars is spent per $tCO_{2}e$. However, as funds are spent beyond that point, there are few additional opportunities for reduction. In addition, a reduction of approximately 4 Tg CH_4 is cost-effective at current (2018) projected energy prices (i.e., without additional costs).

Household waste. The global potential for reducing methane emissions in the municipal solid waste disposal sector is approximately 28 Tg CH_4 per year by 2030, or 61% of baseline emissions. In this industry, a reduction of more than 25% can be achieved for $15 per $tCO_{2}e$ or less. Furthermore, as the cost of eliminating greenhouse gases increases, the effectiveness of spending on emissions reductions will decrease (with a 100% increase in costs per $tCO_{2}e$ from $30 to $60), emissions will be reduced by 1%. However, at a cost of over $60 per $tCO_{2}e$, it is possible to achieve an additional 29% reduction in emissions. Also, there are approximately 3 to 4 Tg of CH_4 reductions that are cost effective at current energy prices.

Wastewater. The total reduction potential of methane emissions in the wastewater treatment sector is 36% of the baseline emissions of 2030, which equals 10 Tg CH_4. The cost of measures to reduce methane emissions in this industry limit the extent to which they are addressed, such emissions can only be cut by 5% at a price of $30 per $tCO_{2}e$. At a cost of $ 60 per $tCO_{2}e$, you can raise this figure to 8%. In this sector, only 1% of emission reductions can be achieved at no additional cost.

All these estimates for different sectors of the economy are based on a forecast, where the described in the emission reduction technologies were absent in the 2015 to 2020 period, the total CH_4 emissions from manure management, wastewater treatment and waste management will increase by approximately 6%, and emissions from the coal and oil and gas industries will increase by 14 and 10%, respectively (see Table 10.1).

In general, for all these sectors, it's possible to reduce methane emissions by approximately 45 Tg CH_4 from the projected Business-as-Usual emission level of 2030 without additional financial costs. If $ 60 per $tCO_{2}e$ is spent, the aggregate reduction in methane can be doubled, which is more than 70% of the possible reduction across all of these five sectors. A brief description of the proposed technology and approaches to reducing methane emissions are given in Table. 10.3.

It should be noted that at present the development of the necessary measures to limit and control methane emissions, including the use of special technologies for reducing emissions, is carried out by government organizations and scientific institutions, as well as directly by companies involved in production.

Their implementation can be carried out both at the national level and at the level of individual companies or industry associations, and include both voluntary and mandatory measures, as well as be economically stimulated by incentives at different levels. It should be noted that the difference between CH_4 and other GHGs is that it is included in some countries (including Russia) with air pollutants that are already part of the existing monitoring and emission reduction system. It also is different in that it offers additional economic benefits if it is re-used, as a valuable fuel resource or chemical raw material.

Many of the current options for reducing methane emissions are associated with obtaining additional benefits. Some technologies for reducing emissions include its regeneration and use as a fuel for both electricity generation and transport.

In addition, methane is the main element in natural gas, so its collection and utilization provides another valuable and environmentally friendly (with combustion) energy carrier. Moreover, methane may be recycled in agriculture and used while processing manure, and landfill methane has been used as a renewable energy source.

The production of energy from this CH_4 makes it possible to abandon the use of other energy carriers with a high degree of CO_2 emissions and other pollutants such as wood, coal and oil. In addition, the collection and removal of methane from coal mines can also improve industrial safety, as this reduces the risk of explosions.

To familiarize with existing possibilities for reducing CH_4 emissions and proposed courses of action in the future, it appreads advisable to address both developers and associations (including international ones) that explore the effectiveness of their use and promote their application throughout the world (GMI, CCAC, WRI, UNECE, Natural Gas STAR[31]). Alternativly additional information is in general provided in reports published by gas companies, such as PJSC Gazprom, Statoil (Eqinor), etc.

[31] According to [83]

Table 10.3

Main opportunities for reducing CH_4 emissions in various sectors (GMI, 2015)

Sources of Methane	Emissions reduction technology
Oil and gas CH_4 emissions occur during normal operation, routine maintenance and the malfunctioning of systems in the oil and gas industries, both during production and during the transportation and refining of oil and gas	- Implementation of monitoring systems and implementation of programs to repair equipment in order to reduce emissions or gas leaks. - Modernization of technology and equipment to reduce or completely eliminate emissions or gas leaks; - Optimization of maintenance and equipment upgrades for the more accurate measurement and control of methane emissions or associated parameters. - The use of methane collection systems and the utilization of methane, including in associated petroleum gas.
Coal mines Methane is released from existing and abandoned underground coal mines and open quarries during coal mining, as well as during its processing, storage and transportation.	- Degassing of coal seams (by drilling wells to collect methane during mining operations) followed by the further utilization or use of methane. - Utilization of low concentrations of methane in the emissions of ventilation plants for the production of heat by oxidizing, for the purpose of generating electricity or other needs.
Household waste Isolation of CH_4 in the process of decomposition of organic waste under the anaerobic conditions that are typical for waste disposal sites	- Biogas recovery using a number of wells and pipelines that collect and deliver it to the disposal sites by incineration (including for electricity) or for fuel or other needs.
Manure management. (Agriculture) CH_4 is released by the decomposition of manure or manure stored or processed in systems that promote the creation of an anaerobic environment (ie, when stored in sedimentation tanks, ponds, tanks or pits).	- Collection of biogas produced in closed anaerobic sedimentation tanks for its further utilization or use. - Use of methane tanks composting organic waste in an anoxic environment and emitting methane, which is suitable for collection and further use.
Wastewater CH_4 is released during the decomposition of organic wastewater under anaerobic conditions	Application: - Methane tanks for sludge treatment (introduction or re-furbishing of existing aerobic treatment systems). - Biogas capture systems at existing open anaerobic sedimentation tanks. - New centralized aerobic wastewater treatment systems or closed sedimentation tanks. - Establish systems for catching and burning biogas for its utilization, including obtaining electricity or heat.

11 THE GAS INDUSTRY AS A SOURCE OF METHANE EMISSIONS INTO THE ATMOSPHERE

Natural gas plays a key role in the world economy.

The main product of the gas industry, natural gas (CH_4), is the most environmentally friendly fossil fuel, and is a valuable source of chemical raw materials. Natural gas is composed of methane (80-99%), ethane (1-5%), propane, butane and other gaseous substances.

Methane, the main component of natural gas, is considered a greenhouse gas (GHG). In this regard, the management of emissions in the gas industry has become the focus of attention of the world community in light of efforts to resolve the global problem of climate change, despite their comparatively modest contribution to the total amount of emissions from anthropogenic sources.

Several studies have recently been conducted to assess global emissions from the oil and gas sector. A comparison of these estimates is presented in the World Energy Forecast of the International Energy Agency.

It should be noted that the share of methane emissions from the gas industry are insignificant in comparison with other sources.

For comparison, methane emissions in the gas industry are relatively small: the European Environment Agency (EEA) reported that in 2015 methane emissions from gas operations accounted for 5% of total methane emissions in the EU, equivalent to 0.6% of total GHG emissions in the EU. In the EU countries, the two

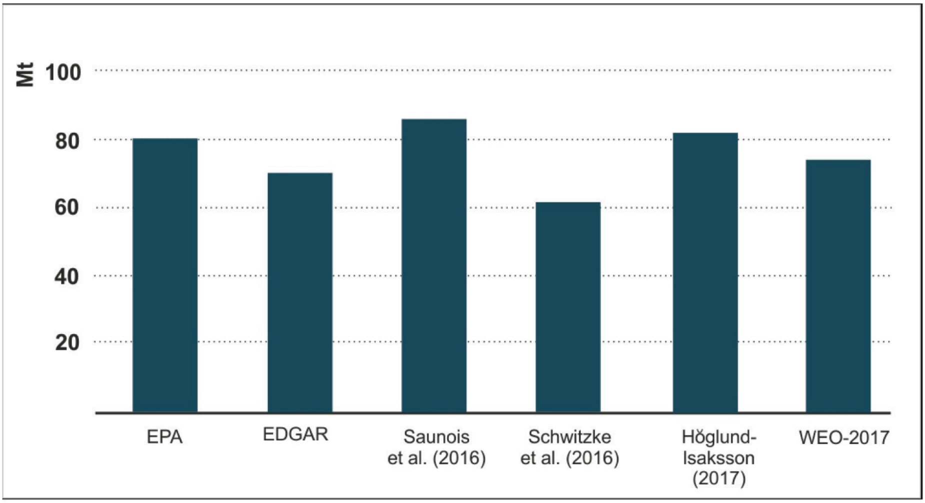

Figure 11.1. Comparison of recent estimates of global methane emissions from the oil and gas industry (International Energy Agency, World Energy Outlook 2017)

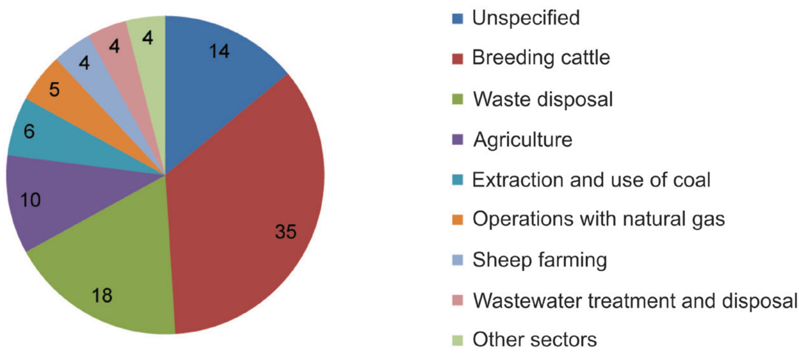

Fig. 11.2. Share of key categories of methane emission sources for the EU 28 and Iceland, 2015, %. (Annual European Union greenhouse gas inventory 1990–2015 and inventory report 2017)

major sources of methane emissions are: livestock (domestic fermentation) and wastewater treatment and landfills (Figure 11.2). Together, they accounted for 53% of methane emissions in 2015.

The main activities in the gas industry are: geological exploration, production, transportation, storage, processing and distribution of natural gas.

The ways of producing natural gas changed with the development of technology. Today, the most common way of extracting natural gas (so-called traditional gas) is to drill wells to a depth of 1,000 meters or more. Preliminary geological exploration of the terrain is carried out, allowing specialists to find and estimate the volumes of gas deposits. In the extraction of shale gas, the hydraulic fracturing of dense gas-bearing layers is used - water is pumped into the drilled cavity, which displaces the gas and takes its place. This method has serious drawbacks, principally because of the effect it has on the environment. The gas can't be collected in full; only part of it comes to the surface. The other part possibly seep into alternative areas and allegations of groundwater contaminations were raised.

The gas industry is specific in terms of methane emissions because the natural gas it generates is consumed during the course of production, due to its own uses. Technologically-driven and unavoidable losses of methane in operations to maintain the required operating parameters of the gas industry predominantly determine the volumes of its emissions into the atmosphere.

Depending on the technology and use in the gas industry, the level of methane emissions depends on the level of efficiency. According to the estimates of the International Energy Agency, on average, methane emissions amount to 1.7% of the total volume of natural gas throughout the entire production chain.

Potential sources of methane emissions during the life cycle of natural gas, from the well to the consumer, are presented in large form in Table 11.1.

Table 11.1

The main potential sources of methane emissions in the life cycle of natural gas

Step	Source	Example
Exploration	Drilling and foundation funding	Uncaptured gas emits into the atmosphere
	Well development	Gas evolution during well development
Extraction	Burning (unplanned)	Unburned methane
	Liquid pumping	Potential of gas released during pumping
	Bleeding	Bleeding from equipment during repairs and technological operations
	Fugitive emissions	Leaks from equipment
Recycle	Burning (unplanned)	Unburned methane
	Use of fuel	Unburned methane
	Fugitive emissions and bleeding	Leakage and bleeding from equipment
Pipeline trans-porta-tion, underground storage, distribution	Use of fuel	Unburned methane
	Bleeding	Gas is released during pumping
	Fugitive emissions	Leaks from equipment
Using	Leaks and methane "breakthrough"	Unburned methane in gas engines, domestic and industrial gas appliances

The reasons for methane emissions are: the technical use of the gas during processing (including during repairs), standard gas losses, fugitive emissions and accidents.

The main component of gas consumption for technical needs related to its production, transportation, processing, storage and distribution companies, the so-called technical losses of gas, consists of gas consumption for fuel and other technical needs (planned emissions into the atmosphere) and losses due to leaks (unplanned emissions into the atmosphere).

To determine the level of emissions, companies use inventories to qurntify their sources. The methods by which natural gas (methane) emissions are monitored at gas industry facilities can be divided into contact and remote (laser and infrared methane detectors, airborne-based instruments that search for methane leaks from the air at a great distance, stationary automated laser systems for continuous monitoring of methane leaks on the territory of compressor stations). These include specific methods: organoleptic, acoustic, bio-indicative, and settlement prediction.

There is also a balanced method (included among the calculation methods), which takes into account the volume of gas at the input and output from the system. The preferred method is based on a search with instruments and the measurement of losses of methane due to leaks, which allows for the correct assessment of where methane leaks occur and for their volume to be measured.

Given that methane emissions constitute a factual loss of a marketable product, gas companies are introducing mitigation measures and best practices to further reduce methane emissions. For example, in the European Union between 1990 and 2015, as a result of the efforts made by the gas industry, methane emissions from gas operations decreased by 46%.

The Technical Association of the European Gas Industry (Marcogaz) conducted an analysis of methane emissions from gas producers' main activities. According to Marcogaz, methane losses (as a share of gas sales) occur:

when transporting gas: 0.05%,

during the underground storage of gas: 0.01%,

during gas distribution: 0.1-0.2%.

The best global practices in preventing and reducing methane emissions employed at Gazprom PJSC are as follows:

• Using energy-saving technologies during the scheduled maintenance at production sites – e.g. gas bypassing from a deactivated circuit of compressor area or a linear section of trunk gas pipeline to adjacent areas in operation; using mobile compressor stations; pumping out any remaining gas from deactivated pipeline sections to be used internally; etc.

• Repairing defective pipes with polymer composite materials;

• using pressurized tie-in technologies and replacing defective pipeline sections with threaded fiberglass sleeves during gas pipeline maintenance;

• replacing the valves and installing split couplings without interrupting gas deliveries;

• using dry gas seals in compressor shafts;

• introducing the configurations to blow out dust traps at compressor and gas distribution stations without venting gas to the ambient air;

• carrying out gas dynamic research and geophysical surveys in wells without venting natural gas to the ambient air, by using telemetry;

• replacing the valves without killing the wells;

• utilizing flash gas by capturing and recovering it;

• optimizing the operation of production facilities;

• using electrically driven compressors;

• the implementation of monitoring programs for fugitive methane emissions and the use of modern equipment and leak detection facilities; and many other activities.

Due to the implementation of this set of measures, losses of natural gas in the Unified Gas Supply System of Russia in 2009-2017 were reduced by over 58.3 percent.

Over the years, the gas industry has been working to reduce methane emissions through both mandatory (regulation and taxazion) and voluntary programs: the Global Methane Initiative, Natural Gas Star, the Climate and Oil and Gas Initiative, etc.

In addition to joint initiatives, the world's leading gas companies have their own individual programs to reduce methane emissions. The world's leading energy companies BP, Eni, ExxonMobil, Repsol, Shell, Statoil, Total, Wintershall and Gazprom announced their commitments by signing the Guiding Principles on Reducing Methane Emissions across the Natural Gas Value Chain.

12 THE CARBON FOOTPRINT OF NATURAL GAS AND ITS ROLE IN THE DE-CARBONIZATION OF ENERGY

Climate considerations are becoming increasingly important for the energy sector. One of the key indicators on the energy market is what's called a "carbon footprint" (greenhouse gas emissions across the entire production chain).

Natural gas is among the types of energy resources that are crucial in the transition to a low-carbon economy. Using it for the production of electricity instead of coal leads to 40-50% reductions in the emission of carbon dioxide (CO_2), even taking methane emissions (CH_4) into account in evaluating, despite the respective technological processes. At the same time, CO_2 emissions can be further reduced through the introduction of innovative new technologies, such as switching to methane-hydrogen fuel. The gasification of regions, and transitioning electricity generation and the transport sector to natural gas positively affects air quality, since methane combustion is characterized by low NOx emissions and practically no sulfur dioxide (SO_2), eliminating particulate emissions.

It should be noted that the gas industry has already made a significant contribution to reducing the carbon intensity of the global economy. The replacement of coal in electric power generation with natural gas and petroleum products in transportation is a fast and cost-effective way to ensure a low-carbon future.

The gas industry is now paying increasing attention to the problems of reducing its own carbon footprint. Reducing energy consumption (Fig. 12.1) with increasing pressure in the main gas pipelines while transporting gas provides a significant reduction in greenhouse gas emissions.

For example, the use of the northern export corridor for the supply of Russian gas to the European Union provides for a significant reduction in the carbon footprint of gas.

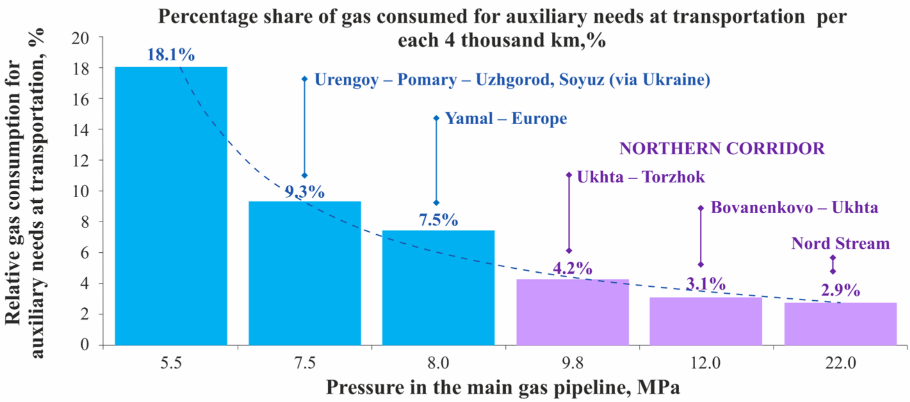

Figure 12.1. The energy efficiency of new Russian export gas flows

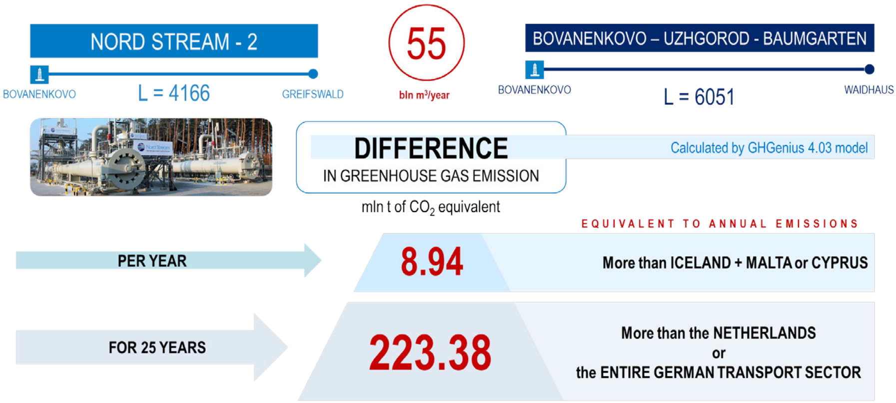

Figure 12.2. comparison of export corridors for the transportation of Russian natural gas to Western European countries

It should also be noted that pipeline deliveries in the EU have a smaller carbon footprint than LNG supplies due to significant emissions which result from liquefaction. Figure 12.3 compares the specific greenhouse gas emissions for gas deliveries to Central Europe from Qatar, the United States and Russia.

In recent years, the gas industry has become a driver of low-carbon development, ensuring the sustainability of the energy supply, including byk leveling the unevenness of renewable energy. Natural gas remains a stepping-out point for the development of hydrogen energy. Experts predict that the gas industry will continue to provide consumers with low-carbon energy for sustainable development in the future.

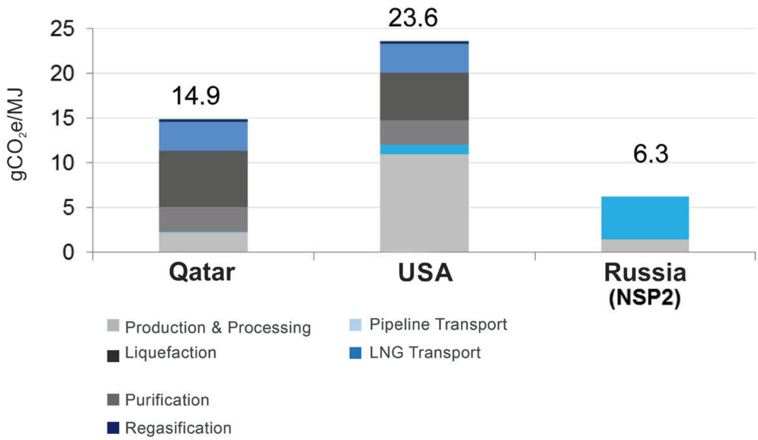

Figure 12.3. Emissions of greenhouse gases in the supply of natural gas to central Europe (Think-step research)

13 THE ROLE OF METHANE IN GLOBAL CLIMATE CHANGE

An adequate assessment of the role of methane in climate change is critical for making scientifically sound policy decisions, including in the area of global energy development. In order to carry out an objective analysis of data and existing methods, this book presents both traditional approaches and alternative assessments that have a scientific basis, but have not been widely disseminated among the public for various reasons.

13.1. ASSESSMENT OF THE ROLE OF METHANE IN THE THEORY OF CLIMTE WARMING[32]

In the 20th century, the scale of the anthropogenic impact on the Earth's climate system became global. The development of the world economy, especially in the second half of the twentieth century, led to a significant enrichment of the atmosphere with greenhouse gases (carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O, etc.) due to their emissions into the atmosphere during economic activity. The enrichment of the atmosphere with greenhouse gases enhances the natural greenhouse effect, which leads to warming in the near-surface layer of the atmosphere and to other climate changes. Between 1880 and 2012, the average global temperature increased 0.85°C, and most of this warming was due to the anthropogenic enhancement of the greenhouse effect.

This warming is uneven: the heating of land is more active in comparison with the oceans; and some parts of the land, in turn, are heated more than average. The warming, as a consequence, affects natural and social systems, as well as public health, which has prompted public concern in many countries, including in the scientific community and among policymakers. In particular, it is alarming that experts estimate that by the end of the 21st century, global warming is expected to increase by several degrees compared to the level at the end of the 20th century, depending on how the world economy develops and implements measures to contain global greenhouse gas emissions.

Among the three main greenhouse gases, CO_2, CH_4 and N_2O, if each were equal in terms of emission, the most influence on the climate system would be that of nitrous oxide N_2O, followed by methane CH_4, and lastly carbon dioxide CO_2. N_2O, then CH_4, then CO_2 would have the most influence on average temperatures of the non-surface layer of the atmosphere if the concentration of these greenhouse gasses was increased over a long period of time (if they were equal in terms of the volume ratio of the mixture, in ppm terms). However, in absolute terms, the key

[32] S.M. Semyenov, I.L. Gobor, N.G. Uvarova for NIIPE according to contract ДП-МДК-2017-01 of 18.05.2017. (Red.)

GHG is CO_2, and is likely to remain so in the 21st century, because the increase in the volumes of its global emissions by far exceeds those of other gases.

Carbon dioxide played a crucial role in both the existing greenhouse warming and that expected during the 21st century. Methane plays a smaller role. From 1750 until 2011, the key greenhouse gasses had the following radiative impact on the Earth's climatic system: CO_2 1.82 (1.63 – 2.01) W/m², CH_4 0.48 ± 0.05 W/m², N_2O 0.17 ± 0.03 W/m². During the same period, the total radiative impact of all greenhouse gasses was 2.83 (2.54 - 3.12) W/m². Here, the contribution of methane is 17%.

The contemporary natural global emissions of methane are about 347 Tg CH_4/year[33] , including 63% from swamps. Its main sources are: swamps, various bodies of water (lakes, rivers, seas, and oceans), fires, fermentation of fodder in the stomachs of ruminant wild animals and insects, the thawing of permafrost, methane hydrates, hydrocarbon deposits, and some other deep geological sources.

The contemporary anthropogenic methane emissions are estimated at 331 Tg CH_4/year[34] (according to other estimates, 325 Tg CH_4/year), which is about half of its total emission into the atmosphere. The main sources of these emissions are: rice fields, ruminant farm animals (27% of the total anthropogenic emissions), the oil & gas industry (23%), solid waste and wastewater, coal mine methane, biomass burning, and fuel burning. Russia's contribution to anthropogenic CH_4 emissions was about 8%.

Note that many processes resulting in both natural and anthropogenic CH_4 emissions are still poorly understood and depend on multiple factors, which may bring about significant discrepancies between the estimations made by different authors and in different years.

According to estimations, the life cycle of methane in the atmosphere is 12.4 years.[35] It is irreversibly used up, mostly in reactions with hydroxyl (mostly in the troposphere) and atomic chlorine (mostly in the stratosphere). There is practically no discharge of methane to the Earth from the atmosphere. There is no feasible possibility of accelerating the discharge of methane from the atmosphere.

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[33] IPCC data for 2000-2009, bottom-up assessment

[34] IPCC data for 2000-2009, bottom-up assessment

[35] Recently, a decrease of methane's life cycle in the atmosphere has been observed, in connection with an increase of the hydroxyl radical (OH), which destroys methane, in the atmosphere, and, as a result, an intensification in the CH_4 discharge [Prather M.J., Holmes C.D., Hsu J. Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry // Geophysical Research Letters. 2012. V.39. L09803. doi:10.1029/2012GL051440], [Kiselev A. A., Karol I.L. Modeling of the long-term tropospheric trends of hydroxyl radical for the Northern Hemisphere // Atmospheric Environment. 2000. V.34. P.5271—5282] (Ed.)

This short life cycle of CH_4 (in comparison with carbon dioxide) has recently been attracting the attention of researchers attempting to resolve the problem of regulating GHG emissions, because measures taken to reduce the anthropogenic emissions of methane will impact its content in the atmosphere as early as within one or two decades. As such measures are developed, it should not be overlooked that the main reason for contemporary global warming is carbon dioxide, and methane's role is noticeable but minor.

13.2. A COMPLEX ANALYSIS OF THE ROLE OF METHANE IN CLIMATE CHANGE

Methane is an important organic substance in the atmosphere [148, 149]. Its discovery in the atmosphere, in 1947, was relatively recent [144]. Its concentration is small, stabilizing at 1.75 ppm. For comparison's sake, the concentration of CO_2 in the atmosphere is 400 ppm.

The impact of methane should be viewed on the basis of the total GHG balance. In the opinion of many, methane is second to carbon dioxide among the GHGs. However, water vapor is methodologically excluded from the estimation, although it is evident that the main GHG is H_2O. The contribution of H_2O to the greenhouse effect is estimated at 36–72%, CO_2 at 9–26%, and CH_4 at 4–9% [158–162], i.e. **the balance of water, together with the energy balance, is the intrinsic factor of global climate stability**. Water vapor is a natural regulator of the atmospheric processes. Around 12–14 thousand km³ are involved in the hydrological cycle (1/2 of the amount of water in the Lake Baikal); 45 cycles occur annually. Their duration is 7–10 days. Precipitation and evaporation are essentially equal (577 thousand km³ per year).

In the atmosphere, methane appears mostly in near-surface layer, in the troposphere, 11–15 km wide. The concentration of methane poorly depends on the height in the interval from the Earth's surface to the tropopause, which is conditioned by a high speed of vertical mixing within 0–12 km (1 month) as compared to the life cycle of methane in the atmosphere [148]. The historical concentration of methane in the atmosphere has been determined by a study of the ice cover at Vostok Station in Antarctica. This study has shown that the concentration during the last 150,000 years fluctuated with a period of 20,000 years, which has proven the natural cause of these fluctuations.

The total methane content in the atmosphere is about 5 bln metric tons; the yearly changes assessed at 592–785 mln tons are practically equal to the emissions (542–852 mln t). The analysis of methane generating sources shows that the biggest source are swamps (21%), while the second biggest are rice fields (20%), which are essentially man-made swamps. If these sources of methane are eliminated, the world's food security, however, becomes jeopardized. The applies to the emissions from ruminant of domestic animals (cows) (15% of the total methane emissions).

The UN report states that the fast-growing herds of farm animals are the biggest threat for climate, forests, and wildlife. Animal farming produces 18% of GHG — higher than the automobiles, aircraft, and other vehicles combined. The burning of fuel to produce fertilizers necessary to grow fodder, produce meat, and deliver it to consumers (and the destrucktion of vegetation for pastures) is responsible for 9% of the total carbon dioxide emissions [151].

Other methane sources include: biomass burning (10%), coal mines and waste sites (7%). Methane hydrates, which are often "blamed" for methane emissions, only contribute 1%. The methane of coal mines (7%) is not only connected to considerable human casualties, but also increases the carbon footprint via the use of coal for energy generation.

According to the assessment reports of IPCC [158-162], the total emissions of methane from natural and anthropogenic sources are shown in Table 13.1.

Table 13.1

Sources of methane emission into the atmosphere, millions tons/year

Natural emissions		**Anthropogenic emissions**	
Sources	millions tons/year	Sources	millions tons/year
Swamps	217	Ruminant animals	89
Ocean	54	Waste	75
Lakes and rivers	40	Oil & gas industry (including biofuel)	50
Wild animals	15		
Termites	11	Rice fields	36
Hydrates	6	Biomass burning	35
Fires	3	Other	46
Permafrost	1		
Natural emissions		**Anthropogenic emissions**	
Total, mln t/year	**347**	**Total, mln t/year**	**331**
Total, %	**57,9%**	**Total, %**	**45,1%**

The contribution of anthropogenic methane emissions to the total GHG emissions and the contribution of the oil & gas industry are presented in Fig. 13.1.

American climatologists have carried out an experimental assessment of methane's greenhouse effect, based on field measurements, for the first time. While the previous assessments of methane's greenhouse activities were based on calculations and laboratory experiments, the recent research has successfully connected the radiative heating of the near-surface atmosphere layers with the dynamics of

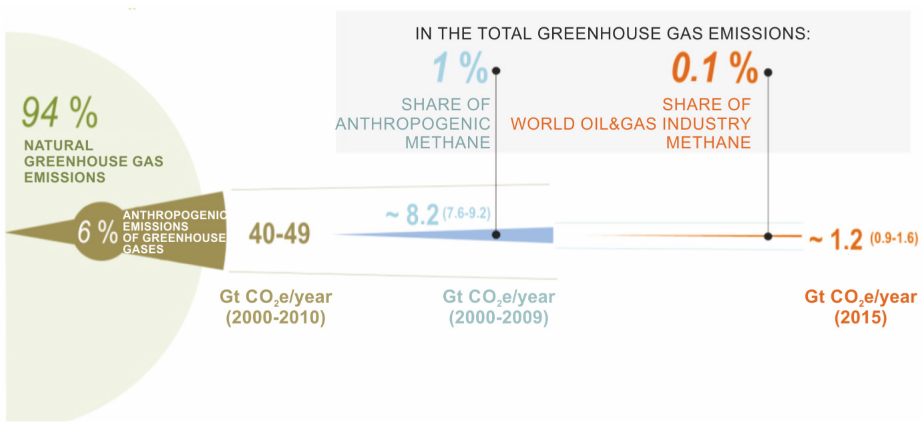

Figure 13.1. Contribution of methane emissions in the gas industry to total GHG emissions
Source: The Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013

methane concentration, as a direct result of spectrometric measurements in the atmosphere. The authors state that the methane concentration in the atmosphere remained at an approximately constant level from 1995 until 2006, after which it began to increase. As of today, no final explanation for these methane concentration dynamics has been put forward [164].

The American climatologists, headed by Daniel Feldman from Lawrence Berkeley National Laboratory, carried out a study connecting the dynamics of car-bon dioxide concentration in the atmosphere with the radiative heating of the at-mosphere — the difference between the energy of solar radiation coming to the Earth and the energy of radiation leaving Earth. At the observatory in the south of the Great Plains, independent measurements of methane concentrations in the near-surface atmosphere and its radiative effect, which was calculated with the use of spectrometer radiometers, were carried out, as well, from 2002 until 2013. To avoid potential cloud interference, the measurements of radiative heating were made during cloudless weather.

The scientists note that in spite of the large error of methane concentration measurements, they have confirmed the previous data on the dynamics of methane concentration during the last 20 years: before 2006, the gas concentration remained at an approximately constant level (about 1,880 parts per billion of methane by volume), after which its steadily increased, at an average rate of approx. 7.5 parts per billion by volume per year. The scientists note that the obtained data could have been influenced by the water vapor contained in the atmosphere, so in the future, for a higher accuracy of assessment of the individual contributions of the two gases, additional research has to be carried out. However, even the recently available measurement results connect the data on methane concentration to its greenhouse effect directly, by means of field measurements. Before these recent measurments with new connections were made, all such assessments were either made theoretically, or as part of laboratory experiments.

The dynamics of change in the atmospheric concentration of methane, referred to above and in the Fifth Assessment Report [157 – 162], is shown in Fig. 13.2. An increase in concentration is sometimes followed by a decrease in concentration.

If the concentration of methane in the atmosphere does not increase, this means that the rate of methane entering the atmosphere is equal to the rate of its release.

Methane is eliminated from the atmosphere, mainly in reaction with the OH radical:

$$OH + CH_4 = H_2O + CH_3$$

The mechanism of change of concentration probably has its own natural character similar to the mechanism and regulation of water vapor.

In the study [163] "Global biogeochemical cycles of increasing methane content in the atmosphere: growth in 2007 - 2014 and isotopic shifts" by fifteen influential institutions in the United Kingdom, the United States, New Zealand, Canada, South Africa and other countries showed that the globally averaged molar fraction of methane in the atmosphere increased from 2007 to 2013 by 5.7 ± 1.2 parts per billion per year. At the same time, the indicator $\delta^{13}C_{CH4}$ (the ratio of carbon isotopes $^{13}C/^{12}C$ in methane) has shifted to significantly more negative values since 2007. An extreme value of growth, 12.5 ± 0.4 ppb/year, was recorded in 2014; a further shift towards more negative values was observed in most latitudes. The isotope evidence presented here indicates that the most significant increase in methane is due to a significant increase in biogenic methane emissions, especially in the tropics, for example, due to the expansion of tropical wetland areas in years with abnormally high rainfall or in connection with an increase in the number of sources of methane emissions from agriculture, such as ruminants and rice fields. Similar

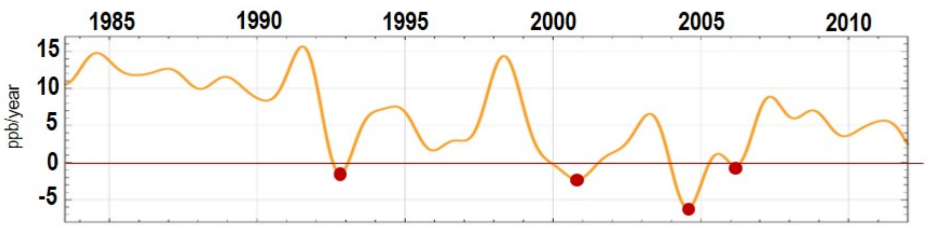

Fig. 13.2. Dynamics of growth / decrease of methane concentration in the atmosphere

changes in the rate of methane removal from the atmosphere in reactions with the OH radical were not observed in other tracers from the chemical composition of the atmosphere and, as it seems, they do not explain short-term fluctuations in the methane concentration. However, there is a possibility of an increase in emissions from fossil fuel combustion; however, a steady shift to depleted ^{13}C isotope and its significant inter-annual variability, as well as an increase in methane's share in the tropical regions and the Southern Hemisphere after 2007, both of these facts show that emissions from fossil combustion did not become the main reason for the growth of methane concentration.

Although emissions from fossil fuels, are part of the overall methane budget decline, the data [163] can not exclude an increase in absolute emissions, especially if the source gas was isotopically highly depleted in ^{13}C. However, based on both latitude analysis and isotopic constraints, as causes of methane growth, **Siberian gas was excluded** , and emissions from other sources of fossil fuels such as Chinese coal, hydrofracturing in the US, or most LNG, are generally more enriched with in ^{13}C and, as such, also do not correspond to isotopic constraints.

Methane is a short-lived greenhouse gas (8 to 12 years). At the same time, the focus on reducing emissions of short-lived greenhouse gases has no impact on the long-term trend of the Earth's changing climate system, which is determined by long-lived greenhouse gases (CO_2), so special attention to methane is more politically motivated to demonstrate "light" and fast, but virtual and ineffective "measures" to reduce greenhouse gas emissions.

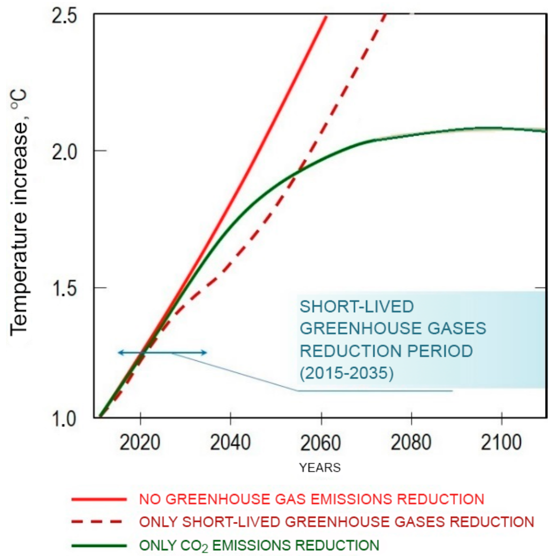

Fig. 13.3. Contribution of CO_2 and short-lived greenhouse gases to global temperature retention

It should be noted that according to the 5th IPCC Assessment Report:

- there is no single system of indicators to accurately compare all the effects of different emissions, all metrics have limitations and uncertainties;
- until the publication of the 4th IPCC Assessment Report, Global Warming Potential (GWP) was the most common metric indicator;
- **Global Temperature Change Potential (GTP) is now increasing** in popularity; it is based on the change in the mean global surface temperature at a selected point in time, and also with respect to the change caused by the reference CO_2 gas;
- measures to limit anthropogenic methane emissions at the lowest layer of the atmosphere with ozone are defined as a "win-win situation": they can lead to both cooling and climate warming.

A comparison of the methods for assessing the greenhouse effect of GWP and GTP is shown in Fig. 13.4.

The key indicator is the conversion factor for methane emissions (the main component of natural gas) into CO_2-equivalent.

According to the guidelines for the formation of national inventories approved by the Conference of the Parties to the Framework Convention on Climate Change No. 24 / CP.19, the calculations apply the Global Warming Potential (GWP) for a 100-year period. For methane, this value is 25 (the comparison factor with the base greenhouse gas, carbon dioxide). The 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (hereinafter referred to as IPCC) proposes to increase the methane potential in this methodology for calculating a carbon footprint of 34.

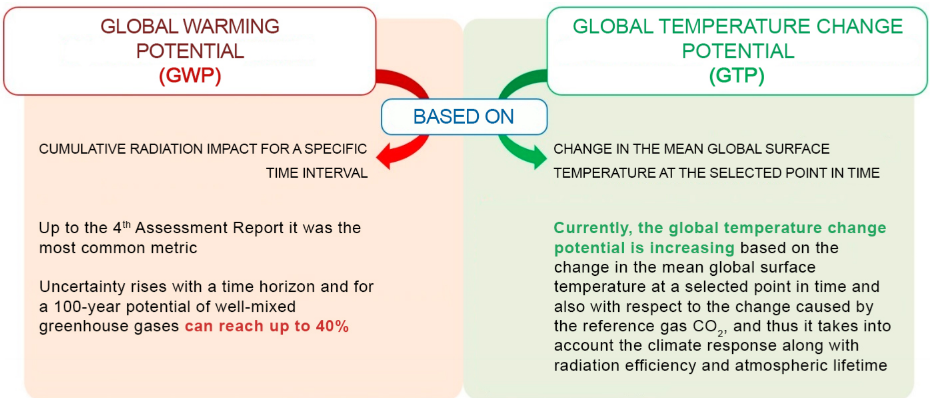

Fig. 13.4. Comparison of methods for assessing the greenhouse effect of a substance
Source: 5th Assessment Report
Interstate Panel on Climate Change, 2013

From one IPCC report to the next, the proposed conversion factors for methane emissions into CO_2-equivalent have constantly been changing. The evolution of the coefficients is shown in Fig. 13.5.

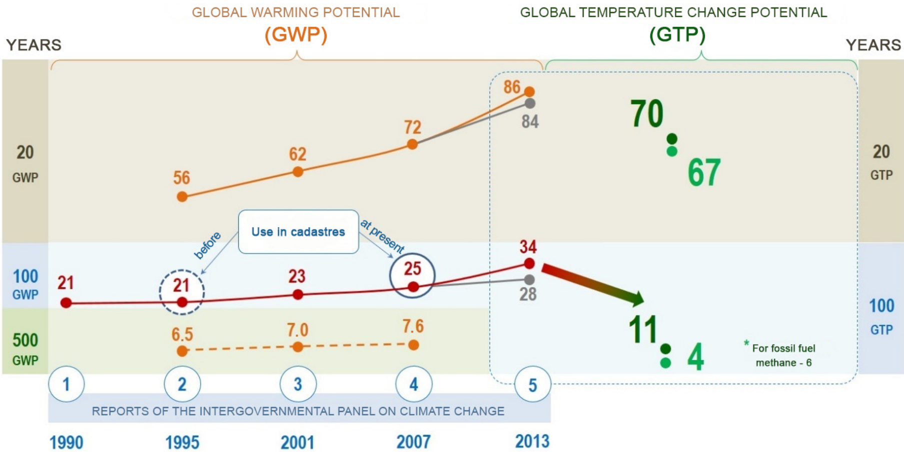

Fig. 13.5. Methodical approaches to assess the role of methane in climate change

The new Global Temperature Change Potential is based on a change in the mean global surface temperature at a selected point in time. In other words, this indicator tries to answer the question: what will the temperature change in year X be in response to the radiation impact of certain greenhouse gas emissions? Simply put, **the global temperature change potential** is much better suited to the goal-setting policy as is being promoted in the Paris Climate Agreement.

If Global Temperature Potential is used, methane has a 4 to 11x greater effect than CO_2, which is much lower than in the Global Warming Potential (28-34 times).

Due to the significant difference (3-7 times) in assessing the impact of methane on climate in the IPCC methodologies, additional studies of the climate system are required. For example, often the works ignore not only the natural causes of climate change, but also factors that compensate for the natural anthropogenic impact on the climate. With the increase in temperature, evaporation of H_2O increases, cloudiness increases, and the albedo of the Earth increases, which compensates for anthropogenic influence.

A reasonable approach to the analysis of these processes is very important for solving global environmental problems [154]. The role of methane in the climate system must be considered, together with other natural and anthropogenic processes [157], and the contribution of each element of the system must be objectively assessed.

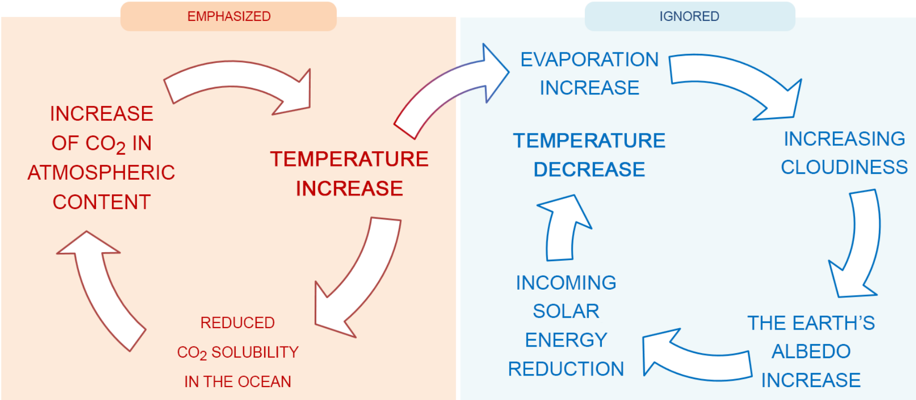

Fig. 13.6. Noosphere balance of the climate

GENERAL CONCLUSIONS

1. The impact of anthropogenic emissions on the Earth's climate system attracted attention in the second half of the 20th century. The prevailing view is that the development of the world economy has led to the signif-icant enrichment of the atmosphere with greenhouse gases (CO_2, etc.), which enhances the greenhouse effect and leads to warming in the near-surface layer of the atmosphere and to other climate changes. Between 1880 and 2012, the world's average temperature increased by about 0.85°C.

Many contend that by the end of the 21st century, global warming is expected to increase the world's average temperature by several degrees in comparison with the end of the 20th century, depending on global economic development and on the implementation of measures to contain global greenhouse gas emissions.

A number of international agreements are aimed at solving this problem, notably: the United Nations Framework Convention on Climate Change, the Kyoto Protocol and the Paris Climate Agreement (2015). At the same time, the notion of "global climate change" is often replaced by the term "global warming." An objective assessment indicates that climate change is cyclical, and throughout Earth's history, there have been periods of global warming and cooling.

2. In absolute terms, the most important greenhouse gas is CO_2, because the growth in its global emissions far exceeds the growth in emissions of other gases. Carbon dioxide plays the key role in the greenhouse effect that's already occurred, and may play that role during the 21st century. Methane is of lesser importance due to its smaller concentration, but the increase in its global concentration in the atmosphere is noticeable. From 1750 to 2011, the main greenhouse gases had the following radiative forcing on the Earth's climate system: CO_2 accounted for 1.82 (± 0.2), CH_4 is responsible for 0.48 ± 0.05 W/m², and N_2O accounts for 0.17 ± 0.03 W/m². Over the same period, the total radiative forcing of all greenhouse gases was 2.83 (2.54 - 3.12) W/m²; Of which Methane accounts for 17%.

3. An estimation of the radiation forcing of methane is the difference in the solar radiation balances, whether or not other factors are taken into account, whether they're natural (aerosol emissions during volcanic eruptions, changes in solar activity, etc.) or anthropogenic. It allows us to make the following observations:

- Methane plays a role in the photochemical processes taking place in the atmosphere and thus influences the content of other components of air in the atmosphere (including greenhouse gases), while carbon dioxide is photo-chemically passive in the atmosphere;
- this phenomenon leads to a twofold effect. First, the methane content is reduced and, consequently, its direct forcing is reduced. Indirect forcing appears, mainly through an increase in the influence of water vapor. Taking into account that the

concentration of H_2O in the atmosphere is practically unchanged, the indirect forcing of CH_4 does not affect the final picture. That is, increasing the amount of water vapor breaking down CH_4 does not lead to an increase in the influence of greenhouse gases on the climate.

4. The most common viewpoint is that modern natural global methane emissions total 347 (238-484) Tg CH_4 / year. Its main sources are: wetlands (63%), various water bodies (lakes, rivers, seas and oceans), fires, the fermentation of food in the stomach of ruminants and insects, thawing permafrost, methane hydrates, and other deep geological sources.
Take into account that industrial emissions of methane reached a total of 558 (540-568) million tons. The annual elimination of methane as chemical processes in the atmosphere is 548 (529-555) million tons, which is a difference of 10 million tons, which is 0.2% of the total mass of methane in the atmosphere (about 5 trillion tons).

5. According to experts, the lifetime of methane in the atmosphere is 8-12 years. It is irretrievably consumed mainly in reactions with hydroxyl (mainly in the troposphere) and atomic chlorine (mainly in the stratosphere). Due to its short lifetime compared with carbon dioxide, CH_4 has recently attracted increased attention from those seeking to solve the problems that are controlling the greenhouse gas emissions. However, the focus on reducing the emissions of short-lived greenhouse gases (methane) in fact has no impact on the long-term trend of changing the Earth's climate system, which is determined by long-lived greenhouse gases (CO_2), so special attention to methane is more a politically motivated action for demonstrating "light" and fast, but virtual and inconclusive "measures" to reduce greenhouse gas emissions.

6. An analysis of the dynamics of the change in the concentration of methane in the atmosphere shows that the emission of methane are approximately equal to its removal from the atmosphere. This process occurs naturally and is similar in this respect to the regulation of the heat balance through the water vapor circulation cycle.

7. A comparison of the methods recommended by the Intergovernmental Panel on Climate Change to assess the effect of various substances on the climate system demonstrates the lack of a unified system of indicators for an accurate comparison of all effects. Estimating the role of methane in existing GWP (Global Warming Potential) and GTP (Global Temperature Change Potential) is different, but in general, it shows that methane plays a minor role in the climate change pro-

cess. The conversion factor of methane emissions into CO_2-equivalent decreases from 28 to 4 in the transition from the Global Warming Potential to the Global Temperature Change Potential, which is more relevant to the objectives of the UNCCC Paris Agreement.

8. The analysis of the carbon footprint shows that methane emissions from the world's oil and gas industry represent 0.1% of global greenhouse gas emissions, including the 0.004% share of the Russian gas sector. This suggests that methane emissions from the oil and gas industry have had a little impact on the climate.

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