Model estimates for climatic effects of anthropogenic GHG emission scenarios in the 21st century

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Abstract. To estimate the climatic effects of anthropogenic CO₂ and CH₄ emission scenarios we performed numerical experiments using IAP RAS CM global climate model. Emissions pathways of 5 RCP (Representative Concentration Pathways) regions were used as evaluated scenarios. It is shown that the anthropogenic contribution of CO₂ to global surface temperature change starts to decrease in the second half of the century only for RCP 2.6 and only for ASIA, OECD and REF emission scenarios. The rest of the CO₂ emission scenarios contribute to an increase in the global surface temperature of the atmosphere throughout the 21st century. The growth of the compensatory effect of natural CO₂ fluxes generally slows down by the end of the 21st century. Impact of anthropogenic methane emissions on climate stabilizes in the 21st century for all scenarios under RCP 2.6, 4.5 and 6.0. The estimates of GHG climatic cost equal up to 24 mK per PgC for CO₂ and up to 0.9 mK per Tg for CH₄. Methane is shown to have at least 40 times stronger impact on global surface temperature per molecule than CO₂.

1. Introduction

Various indicators can be used to quantify the relative and absolute contribution to climate change of emissions of different greenhouse gases, as well as emissions from different regions, countries or individual sources. The climatic effect of emissions can be estimated for a specific time instant or integrated over a given time interval. The most common indicators are based on the radiative forcing (RF) [1], which is used to compare the contribution to changes in global mean surface temperature of various factors affecting the Earth's radiative budget.

For this purpose, the UN Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement use global warming potentials (GWP) of various GHG’s, calculated as the integral of radiative forcing on a defined time horizon divided by the same integral of reference gas, normally CO₂. At the same time, targets for climate policy are usually formulated as some given temperature thresholds to be avoided. Because of inherent inertia of the climate system, such goals are partly incompatible with a metric based on cumulative radiative forcing [2]. The most used of the alternative metrics is the global temperature change potential (GTP) [1,3]. The GTP indicator reflects changes in global temperature at a selected time interval after a pulse release of a selected gas relative to changes resulting from a similar CO₂ release, and thus accounts for climate response along with radiative efficiency and atmospheric lifetime of the gas.
In this paper, the cumulative influence of the anthropogenic CO$_2$ and CH$_4$ emission scenarios to the surface air temperature changes in the 21$^{st}$ century is estimated using the cumulative temperature potential CT [4] based on GTP, which was modified to account for changing background conditions.

2. Methods and data
To estimate the climatic effects of anthropogenic CO$_2$ and CH$_4$ emission scenarios we performed numerical experiments using IAP RAS CM global climate model [5-7]. Thus, the necessary background parameters for calculating the cumulative temperature potential of CO$_2$ and CH$_4$ emissions were obtained. The range of possible anthropogenic GHG emission scenarios from various sources was obtained by rescaling the anthropogenic emission scenarios for different regions of the Earth according to the RCP (Representative Concentration Pathways) data.

2.1. Model and Setup of Numerical Experiments
The IAP RAS CM belongs to the class of the global climate models of intermediate complexity [8,9]. A specific feature of the model is that the large-scale atmospheric and oceanic dynamics (with a scale exceeding the synoptic) are described explicitly, whereas the synoptic processes are parameterized. The latter makes it possible to substantially reduce the time required for model simulations. The model contains modules of the carbon cycle, including partly interactive methane cycle, and a module for calculation of emissions from deforestation and from natural fires [10,11].

Using the IAP RAS CM, we performed numerical experiments for 1765–2100 with scenarios of anthropogenic impacts on climate due to changes in the content of greenhouse gases in the atmosphere, tropospheric and stratospheric volcanic sulfate aerosols, changes in the total solar irradiance, and changes in the area of agricultural lands. For 1700–2005, these forcings were given in accordance with the “Historical Simulations” of the CMIP5 project (http://www.iiasa.ac.at/web-apps/nt/RcpDb). For 2006–2100, the anthropogenic forcings were given prescribed in accordance with the anthropogenic impact scenarios RCP 2.6, 4.5, 6.0 and 8.5 of the CMIP5 project. The numerical experiments described in this study are similar to those conducted earlier with the IAP RAS CM [4,12].

2.2. Cumulative Temperature Potential
Global Temperature Potential of gas x is the ratio of its absolute potential to absolute potential of CO$_2$:

$$GTP_x(H) = \frac{P_x^{(a)}}{P_{CO2}^{(a)}}$$  \hspace{1cm} (1)

where the Absolute Global Temperature change Potential ($P^{(a)}$) is the change in global mean surface temperature at time $H$ in response to a 1 kg pulse emission of gas $x$ at time $t = 0$ [13]. It is often written as a convolution of the radiative forcing with the climatic response kernel $R_T$:

$$P_x^{(a)}(H) = \int_0^H RF_x(t) R_T(H - t) dt,$$

where $RF_x$ is the radiative forcing due to a pulse emission of a gas $x$, and $R_T$ is the temporally displaced climate response to a unit forcing.

$P^{(a)}$ is determined for a pulse gas emission under constant background conditions, while the assessment of impact of emission scenarios under changing conditions is required. For changing background conditions $P^{(a)}$ can be written as sum of integrals for each year:

$$P_x^{(a)}(T_0, T_H) = \sum_{k=0}^{H} RF_{x,k}(T_0 + 1) R_T(T_H - T_0 - k)dt,$$

where $T_0$ is the year of emission and $T_H = T_0 + H$. $RF_{x,k}$ can be achieved in assumption of all necessary changing parameters being step functions, constant for each particular year $k$.

For sustained emissions started at time $T_0$, the cumulative effect of the source of gas $x$ at time $T_H$ can be written as cumulative temperature potential:
It represents the total expected global surface temperature change at time $T_H$ caused by the source emitting since time $T_0$.

2.3. Evaluated GHG emission scenarios
Cumulative impact on climate was estimated for anthropogenic emissions of CO$_2$ and CH$_4$ calculated according to the corresponding RCP scenarios from the ASIA (Eastern Asia), MAF (Middle Asia and Africa), LAM (Latin America), OECD (Organization for Economic Co-operation and Development, Western Europe, North America, Australia, Japan) and REF (former USSR, Eastern Europe) regions (http://www.iiasa.ac.at/web-apps/tnt/RcpDb). These emissions pathways are consistent with certain socio-economic assumptions and represent the wide range of possible changes in future anthropogenic GHG emissions. They were linearly rescaled to 1 TgC for CO$_2$ and 1 Tg for CH$_4$ in the year 2000 for each region (figure 1). Further the emissions from the specific region will be referred to by corresponding region name and the scenarios used to drive the IAP RAS model will be referred to by the RCP pathway (e.g., OECD 4.5 designates rescaled RCP 4.5 scenario from OECD region).

For comparison, similar estimates were made for natural GHG emissions from the same regions. For this purpose, the values of carbon dioxide and methane fluxes from terrestrial ecosystems obtained by interactive calculations with the IAP RAS model for the same regions were linearly rescaled using the corresponding values of anthropogenic emissions. Thus, the proportions of natural and anthropogenic scenarios of greenhouse gas fluxes were preserved.

3. Results
Figure 2 shows the values of the cumulative CT potential since the year 2000 separately for carbon dioxide and methane emissions from ASIA, LAM, MAF, OECD and REF regions. It is noted that although CO$_2$ emissions for RCP 2.6 and 4.5 are declining in the 21$^{st}$ century, the anthropogenic CT of CO$_2$ starts to decrease in the second half of the century only for ASIA, OECD and REF 2.6 (scenarios with negative emission value in the end of the 21$^{st}$ century). Other regions contribute to an increase in the global surface temperature of the atmosphere, and the OECD region is closest to stabilizing its impact. For the methane emission scenarios, the situation is more encouraging. The contribution to the growth of the surface temperature (as well as the emissions themselves) stabilizes and begins to decrease under all RCPs except 8.5 (and for the LAM scenario even in this case).
For anthropogenic CO$_2$ emissions from ASIA, it is possible to see the effect of accounting for changes in the background conditions (P(a)* instead of P(a)): although throughout the entire 21st century the ASIA 8.5 CO$_2$ emissions are higher than ASIA 6.0, due to the higher CO$_2$ concentration in the atmosphere (and thus a lower forcing) their total impact on the climate by the end of the century is lower.

**Figure 2.** Cumulative potential [mK] of anthropogenic CO$_2$ (left) and CH$_4$ (right) emissions.

**Figure 3.** Rescaled natural fluxes of CO$_2$ (left) from the RCP regions and their cumulative temperature potential [mK] (right).

For comparison, similar estimates were made for rescaled natural emissions of carbon dioxide and methane. CO$_2$ uptake (figure 3) by terrestrial ecosystems for all scenarios and regions considered increases at the beginning of the 21st century. Further in the first (RCP 2.6 and 4.5) or in the second (RCP 6.0 and 8.5) half of the 21st the maximum absorption is reached after which carbon dioxide uptake begins to decrease, and even switches to emission for LAM and MAF 2.6. Natural CO$_2$ fluxes
range from -60% and -90% to 20% and 10% of anthropogenic emissions, respectively, under scenarios RCP 2.6 and 8.5. Accordingly, they are close to full compensation of anthropogenic emissions only in the second half of the 21st century for the ASIA, OECD and REF regions under RCP 2.6 and for the REF region under RCP 4.5. This can also be observed by the CT value (figure 3) of natural CO₂ fluxes. It is closest to the compensation of anthropogenic emissions effect only for the REF region under the RCP 2.6 scenario. Moreover, due to the reduction of CO₂ uptake, the growth of the temperature potential of its natural fluxes slows down by the end of the 21st century, and for some scenarios is replaced by a reduction.

Natural methane emissions from wetlands at the beginning of the 21st century is estimated to range from 10% for the ASIA region to 100% for the LAM region of corresponding anthropogenic emissions. During the century, they increase due to the growth of the atmospheric temperature. The strongest increase occurs in the OECD and REF regions under the RCP 8.5 scenario where emissions are calculated to double by the end of the century, while in other regions the growth equals 10-20%. This is due to the fact that in boreal latitudes not only temperature increases faster than average, but also the duration of the warm season increases. Cumulative temperature potential of natural methane emissions by the end of the 21st century equals 22-144% of the potential of the corresponding anthropogenic emissions for RCP 2.6 scenario and 4-50% for RCP 8.5.

We can also try to compare the "climatic cost" of different scenarios of greenhouse gas emissions. As can be seen from figure 1, the regional emissions differ significantly. It is possible that approximately the same amount of total greenhouse gas emissions during the 21st century is achieved in different ways (as, for example, in the ASIA and MAF 2.6 scenarios for CO₂ and OECD and REF 4.5 for CH₄). The difference in the calculated response of the surface temperature of the atmosphere can be observed as well (figure 2). Figure 4 shows the value of the "climatic cost" of the emission scenarios obtained by dividing the climate response by the total emissions of the corresponding greenhouse gases by a given moment. The smaller this value, the smaller the temperature increase per unit of emissions. Despite the aforementioned significant differences in both the emission scenarios themselves and their cumulative temperature potential, the resulting climatic cost differs slightly between the scenarios (deviations do not exceed 10%) for both CO₂ and CH₄. Thus, it depends more on total amount of gas emitted over the given period than on specific pathway of such emissions.

For both greenhouse gases generally by the end of the century, the emission climatic cost begins to decline, although the reasons for this are different. The decline in CO₂ emission cost is mainly due to
an increase in its concentration and a corresponding decrease in RF. Therefore, it falls most rapidly at RCP 8.5, when the concentration rises most rapidly. The decrease in the climatic cost of methane, in turn, is associated with its short (about 10 years) lifetime in the atmosphere. In this case, only recent emissions affect the temperature growth, and the climatic cost decreases as the considered period increases.

In addition, it is also possible to compare the relative contributions of methane and CO$_2$ to changes in global surface temperature under the considered scenarios. Table 1 shows the ratio of the climatic cost of total methane emissions over different periods beginning in 2000 to the climatic cost of CO$_2$ emissions (in the same units, for example, kgCO$_2$ per kgCH$_4$). The resulting dimensionless value is similar in purpose to GWP and GTP. It is shown that on time horizon of less than a century under expected scenarios of greenhouse gas emissions, methane is at least 40 times more efficient than CO$_2$. For the most aggressive anthropogenic scenario RCP 8.5 this value exceeds 90 throughout the 21st century. Although this value can be substantially reduced if earlier emissions are taken into account, such an approach reflects the real relationship between the climate impacts of CO$_2$ and CH$_4$ emissions on a 50–100-year planning horizon. The 100-year GWP, while conceptually incompatible with current climate policy goals, is much closer in magnitude to the values obtained than the 100-year GTP [13]. Thus, in the case of switching to the use of GTP in a multi-gas policy, it is worth choosing a much shorter time horizon for methane.

| Scenario | 2020 | 2040 | 2060 | 2080 | 2100 |
|----------|------|------|------|------|------|
| RCP 2.6  | 143±3| 102±5| 73±7 | 55±5 | 45±3 |
| RCP 4.5  | 140±4| 108±3| 88±3 | 70±7 | 57±8 |
| RCP 6.0  | 138±4| 105±4| 88±7 | 80±8 | 68±7 |
| RCP 8.5  | 137±3| 110±3| 98±5 | 94±5 | 93±5 |

4. Conclusions

According to the results obtained, the anthropogenic contribution of CO$_2$ to global surface temperature change starts to decrease in the second half of the century only for RCP 2.6 and only for ASIA, OECD and REF. The rest of the CO$_2$ emission scenarios contribute to an increase in the global surface temperature of the atmosphere throughout the 21st century. At the same time, the growth of the compensatory effect of natural CO$_2$ fluxes slows down by the end of the 21st century, and for some scenarios is replaced by a reduction. Impact of anthropogenic methane emissions on climate stabilizes in the 21st century for all regions under RCP 2.6, 4.5, and 6.0. The results obtained for the REF region can be considered applicable to Russia as well, since it represents a significant share of the region in terms of both area and anthropogenic emissions.

Accounting for changes in climatic conditions can influence the impact indicators of various greenhouse gas emissions on the climate system, especially over large time horizons under the most aggressive scenarios of anthropogenic impact. The more intensive the anthropogenic impact on the climate, the smaller the efficiency of contemporary CO$_2$ emissions is. At the same time, the relative role of contemporary methane emissions increases.

It is shown, that efficiency of anthropogenic GHG emission scenario impact is weakly dependent on specific emission pathway. The key role is played by the total amount of gas emissions for a given period.

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