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Model Estimates for Contribution of Natural and Anthropogenic CO_2 and CH_4 Emissions into the Atmosphere from the Territory of Russia, China, Canada, and the USA to Global Climate Change in the 21st Century

S. N. Denisov[a]*, A. V. Eliseev[a, b, c], and I. I. Mokhov[a, b, d]

[a]*Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences,*
Pyzhevskii per. 3, Moscow, 119017 Russia
[b]*Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow, 119991 Russia*
[c]*Kazan (Volga Region) Federal University, ul. Kremlevskaya 18, Kazan, 420008 Russia*
[d]*Moscow Institute of Physics and Technology, Institutskii per. 9, Dolgoprudny, Moscow oblast,*
141700 Russia
**e-mail: denisov@ifaran.ru*

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Abstract—Model estimates of the contribution of anthropogenic and natural fluxes of greenhouse gases from the territories of different countries to global climate change in the 21st century under different scenarios of anthropogenic forcing were obtained. Quantitative estimates were made for the effect of changes in regional climatic conditions on the intensity of the greenhouse gas exchange between the atmosphere and natural ecosystems over different time horizons in comparison with anthropogenic emissions. For Russia, China, Canada, and the United States, the CO_2 uptake by natural ecosystems in the second half of the 21st century decreases under all scenarios of anthropogenic forcing, with a weakening of the corresponding climate-stabilizing effect. At the same time, the methane emission to the atmosphere by wetlands in the analyzed regions increases significantly in the 21st century according to the model estimates. As a consequence, the cumulative effect of natural fluxes of greenhouse gases into the atmosphere for some regions may accelerate the warming.

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1. INTRODUCTION

The detailed and comprehensive analysis of changes in the carbon cycle in the terrestrial climate system and their effects on climate requires an adequate consideration of the carbon balance of forests, wetlands, and other natural ecosystems [1, 16, 18]. This is especially relevant in connection with the Paris Agreement under the United Nations Framework Convention on Climate Change (2015) concerning the problems of reducing emissions of greenhouse gases and related adaptation at the national level [9, 10].

Different parameters can be used to quantify relative and absolute contributions of emissions of different greenhouse gases into the atmosphere, as well as emissions from different regions, countries, or separate sources to climate change. They are used for evaluating various factors (for example, physical ones, such as a change in temperature or sea level) over different time horizons. The climatic effect of emissions can be assessed for a specific moment or integrated over a given time interval. The most common parameters are based on the estimate of radiative forcing [8, 34], which is used for comparing the contribution of different factors affecting the Earth's radiation budget to the change in global mean surface air temperature.

The United Nations Framework Convention on Climate Change, Kyoto Protocol, and Paris Agreement use the 100-year global warming potential (GWP) calculated as integral radiative forcing over the 100-year time horizon to determine the relative contribution of anthropogenic emissions of different greenhouse gases. At the same time, the goals of the climate policy are usually formulated as some specified temperature thresholds, the exceeding of which should be avoided: for example, the limit of the global temperature rise equal to 2 or 1.5°C as stated in the Special Report on Global Warming of 1.5°C. Such goals require the knowledge of climate sensitivity to a single radiative forcing and, hence, are not directly compatible with the metric based on the cumulative radiative forcing [35]. The global temperature change potential (GTP) is the most frequently used alternative metric [33, 34]. The GTP indicates changes in global surface air temperature over a specified time period after an emission pulse of a given gas relative to the changes resulting from a similar emission of carbon dioxide (CO_2) and, thus, takes into account the climate response along with the radiative efficiency and lifetime of the gas in the atmosphere. Such approach is much more consistent with the current goals of climatic agreements.

The present paper provides the estimates of anthropogenic and natural fluxes of carbon dioxide and methane (CH_4) for different Northern Hemisphere regions in the 21st century under different scenarios of anthropogenic forcing and their contributions to global warming.

2. THE MODEL AND NUMERICAL EXPERIMENTS

The climate model developed by the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (IAP RAS) was used [11–13]. It is a global climate model of intermediate complexity [17, 21, 26, 40]. The peculiarity of the model is that the large-scale dynamics of the atmosphere and ocean (with a scale exceeding synoptic one) is described explicitly, while synoptic processes are parameterized. The latter considerably reduces the time needed to perform numerical experiments. The model contains the module carbon cycle, in particular, the methane cycle that takes into account atmospheric emissions and absorption of CO_2 and CH_4 by different natural ecosystems [3, 4], including wetlands [7, 14]. The CO_2 emission to the atmosphere due to wildfires and deforestation [23] and the influence of different land use scenarios [22] are considered. Climate models with an interactive carbon cycle module are called the Earth system models.

The IAP RAS climate model version used in the present study has a spatial resolution of 4.5° in latitude and 6° in longitude and an integration step of 5 days. Natural CO_2 fluxes between the atmosphere and ground pools are parameterized using the temperature and humidity calculated in the model taking into account the dynamics of carbon stocks in plants and soil. Other necessary parameters are either specified as constant or vary according to scenarios. Methane emissions from wet ecosystems are interactively computed in the model and depend on the temperature and carbon content in soil. The portions of the area of model cells occupied by wetlands are specified using the time-independent mask. Other methane emissions of the natural origin are comparatively small and are specified constant.

The atmospheric module of the IAP RAS climate model does not imply a scheme of photochemical transformations of the components. Global concentrations of CO_2 and CH_4 in it are determined by the balance equations with a time step of 1 year. At the same time, the CO_2 balance is determined by annual total fluxes between the atmosphere and ground pools, by anthropogenic emissions, as well as by the exchange with the ocean depending on the global mean sea surface temperature. The concentration of CH_4 in the atmosphere is determined by total natural and anthropogenic emissions and a typical lifetime of a methane molecule. More than 90% of methane contained in the troposphere is removed by chemical reactions (mainly by the oxidation by the OH radical). In [5], the numerical simulations with the IAP RAS climate model were performed for different dependences of the methane lifetime in the atmosphere on temperature. The methane lifetime related to OH was parameterized using the coefficients of sensitivity to air temperature, CH_4 concentration in the atmosphere, emissions from fires, and scenarios of anthropogenic emissions of CO, NO_x, and volatile organic compounds (VOC) [25]:

$$\tau_{\mathrm{OH}}(t) = \tau_0 \left[1 + \sum_i s_i \frac{F_i(t) - F_{0,i}}{F_{0,i}} \right] \qquad (1)$$

where $\tau_0 = 11.2$ years; s_i is the sensitivity coefficients (see Table 1); F_i is the values of the respective parameters ($F_{0,\,i}$ is their values in 2000).

The IAP RAS model was used to hold numerical experiments for the period of 1850–2100 under different scenarios of anthropogenic forcing with a change in the concentration of greenhouse gases in the atmo-

Table 1. The sensitivity coefficients for equation (1) [24]

i	Parameter	s_i
	Chemical and climatic effects	
1	Global temperature	–3.00
2	Emission from fires	0.02
3	Concentration of CH_4	0.31
	Anthropogenic emissions	
4	NO_x	–0.14
5	CO	0.06
6	VOC	0.04

sphere, tropospheric and stratospheric volcanic aerosols, total solar radiation, and area of agricultural lands. For the period of 1850–2005, these forcings were specified in accordance to the CMIP5 Historical Simulations protocol (http://www.iiasa.ac.at/web-apps/tnt/RcpDb). For the period of 2006–2100, anthropogenic forcings were specified in accordance to the RCP 2.6, 4.5, 6.0, and 8.5 scenarios [2, 4].

The cumulative effect of anthropogenic and natural fluxes of CO_2 and CH_4 on the change in surface temperature since 1990 was evaluated using the cumulative temperature potential CT based on GTP, which was modified for considering changing background conditions.

3. CUMULATIVE TEMPERATURE POTENTIAL

The global temperature potential of gas x is the ratio of its absolute potential to that of CO_2:

$$\mathrm{GTP}_x(H) = \frac{P_x^{(a)}}{P_{\mathrm{CO}_2}^{(a)}} \tag{2}$$

where the absolute potential of the global temperature change $P^{(a)}$ is the change in the global mean surface temperature at the time moment $t = H$ in response to the emission pulse of 1 kg of gas x at the time moment $t = 0$. It is usually written as the convolution of radiative forcing with the core of the climatic response R_T :

$$P_x^{(a)}(H) = \int_0^H RF_x(t)R_T(H - t)dt \tag{3}$$

where RF_x is the radiative forcing caused by the emission pulse of gas x; R_T is the climatic response shifted in time (until the considered time horizon).

The expression for calculating $RF_x(t)$ can be written as the product of the radiative efficiency of gas x (A_x) by the function of the pulse response of its concentration to the emission at the time moment $t = 0$ ($IRF_x(t)$). It should be noted that both A_x and IRF_x and, hence, $P^{(a)}$ are determined for the gas emission pulse under constant background conditions, while it is necessary to evaluate the impact of emission scenarios in changing conditions in the 21st century.

For changing background conditions, $P^{(a)}$ can be rewritten as the sum of integrals for every year:

$$P_x^{(a)*}(T_0, T_H) = \sum_{k=T_0+1}^{T_H} \int_{k-1}^{k} RF_{x,k}(t)R_T(T_H - T_0 - t)dt \tag{4}$$

where T_0 is the year of emission; $T_H = T_0 + H$. The value of $RF_{x,k}$ can be calculated assuming that all necessary parameters are constant for each specific year k but can vary from year to year.

For continuous emissions that started at the time moment T_0, the total effect from the source of gas x specified by the emission scenario $E_x(t)$ at the time moment T_H can be written as the cumulative temperature potential:

$$CT_x(T_0, T_H) = \sum_{t=T_0}^{T_H-1} E_x(t)P_x^{(a)*}(t, T_H). \tag{5}$$

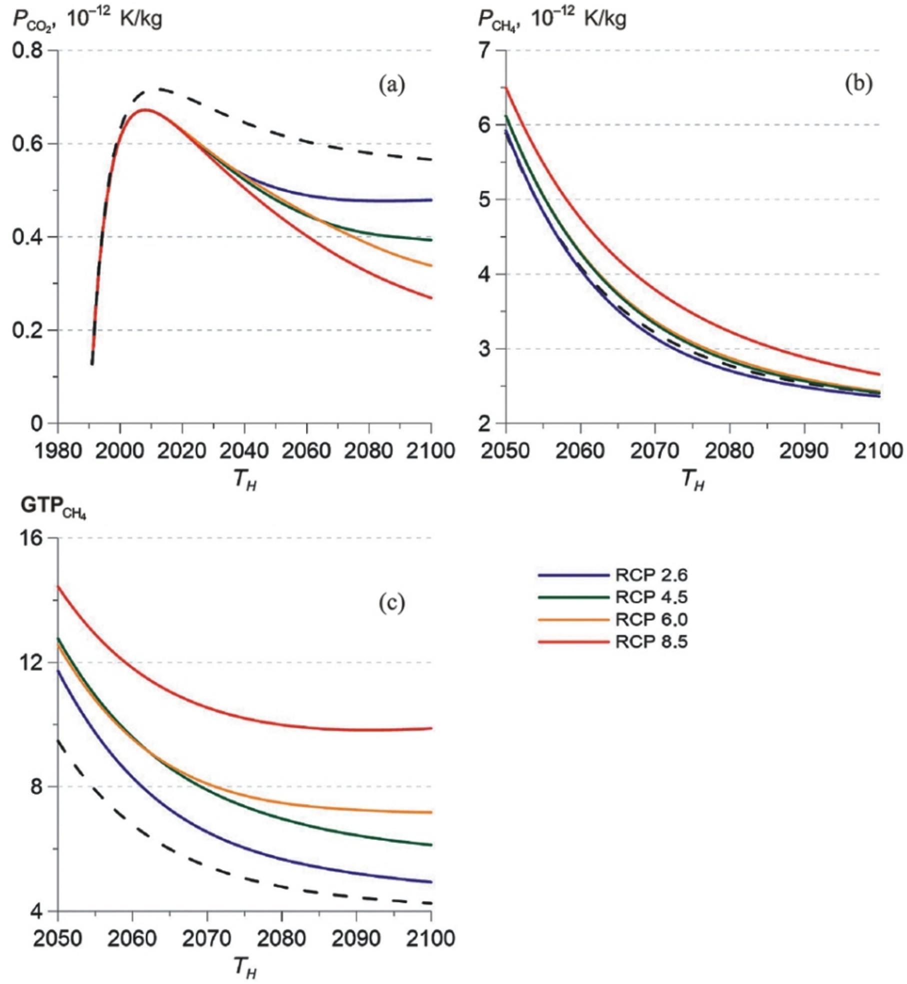

Fig. 1. The absolute potential of global surface air temperature change $P^{(a)}$ (the dotted line) and $P^{(a)*}$ (the solid lines) for the horizon [1990; T_H] for (a) the CO_2 emission pulse and (b) methane, as well as (c) corresponding relative potentials (GTP) of methane.

Figure 1a presents the values of the absolute potentials $P^{(a)}$ and $P^{(a)*}$ of carbon dioxide for the time period from 1990 to the year of T_H (hereinafter, [1990; T_H]), which were obtained as a result of model experiments with the IAP RAS climate model. As mentioned above, *RF* for $P^{(a)}$ is calculated assuming that background conditions at the time moment T_0 remain unchangeable throughout the interval [T_0; T_H], while for $P^{(a)*}$, the changes in RF resulting from changes in background conditions are taken into account. Therefore, for the time periods exceeding 10–15 years, $P^{(a)*}$ and $P^{(a)}$ can differ significantly. For the most aggressive anthropogenic scenario RCP 8.5 (with the greatest change in background conditions), $P^{(a)}$ is more than twice higher than $P^{(a)*}$ for CO_2 released in 1990 over the 100-year time horizon.

The potentials $P^{(a)}$ and $P^{(a)*}$ for methane calculated for the interval [1990; T_H] (Fig. 1b) differ much smaller for all analyzed scenarios. For RCP 8.5, the maximum discrepancy reaches 20% for the time horizon of about 80 years and does not exceed 6% for the other scenarios. Nevertheless, if $P^{(a)}$ is substituted by $P^{(a)*}$ when calculating the relative potential of the global temperature change (GTP) for methane (Fig. 1c), its values for greater time intervals can be 2–2.5 times higher. For example, GTP for methane emitted in 1990 over the 100-year time horizon computed using $P^{(a)}$ is equal to 4.1 (which corresponds to the IPCC Fifth Assessment Report), and taking into account changes in background conditions, it can be equal to 5–10 depending on the anthropogenic forcing scenario (Fig. 1c).

Figure 2a demonstrates the values of the absolute potentials $P^{(a)}$ and $P^{(a)*}$ for CO_2 on the 20-year interval. The absolute potential of CO_2 under all scenarios except RCP 2.6 decreases during the 21st century, its value for the most aggressive RCP 8.5 scenario decreases more than twice. This is associated with an increase in atmospheric CO_2. Under the RCP 2.6 scenario, the CO_2 concentration in the atmosphere in the

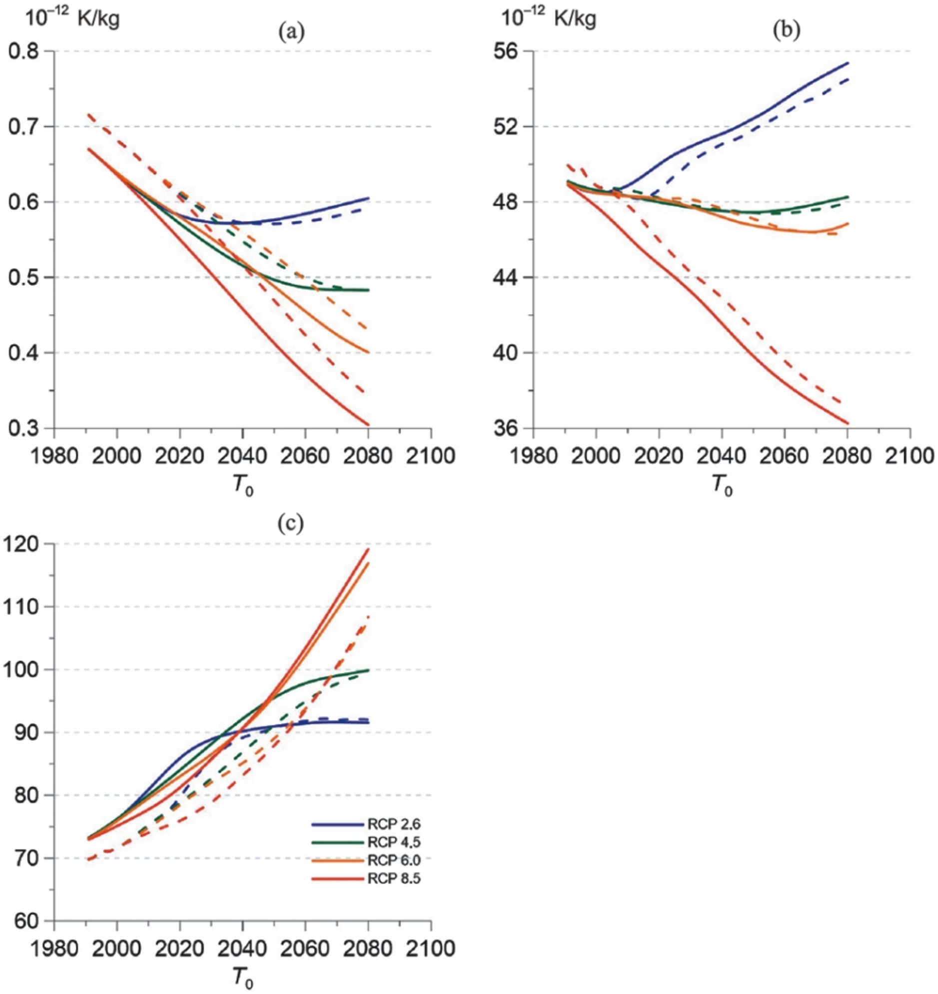

Fig. 2. The absolute potential of global surface air temperature change on the 20-year interval for the emission pulses of (a) CO_2 and (b) CH_4 at the time moment T_0 under changing background conditions (the solid lines) and constant (the dotted lines) background conditions fixed at the moment of emission, as well as (c) the relative potential of CH_4 on the interval $[T_0, T_0 + 20]$.

second half of the 21st century starts decreasing. Therefore, the decrease in the potential changes into its growth. Although the rather short 20-year interval after the emission is considered, the consideration of changes in background conditions affects a change in the potential by the value up to 15%.

The values of $P^{(a)}$ and $P^{(a)*}$ for methane emissions in the 20-year interval vary in a similar way (Fig. 2b). In this case, the slow decrease in the potentials changes into the increase already in the first half of the 21st century for the RCP 2.6 and in the second half of the century for the RCP 4.5 and 6.0. The consideration of changes in background conditions for the 20-year period makes a smaller contribution to the methane potential, which does not exceed 3%.

A more rapid decrease in the absolute potentials $P^{(a)}$ and $P^{(a)*}$ for CO_2 leads to an increase in the relative potential on the 20-year interval for the methane GTP in the 21st century. It grows from 70 to 92–108 if changes in background conditions are not considered and from 73 to 91–119 if they are considered. In general, it may be stated that the values of the analyzed potentials are shifted in time approximately by a half of the analyzed time interval (7–13 years depending on the potential and anthropogenic forcing scenario) if changing background conditions are neglected.

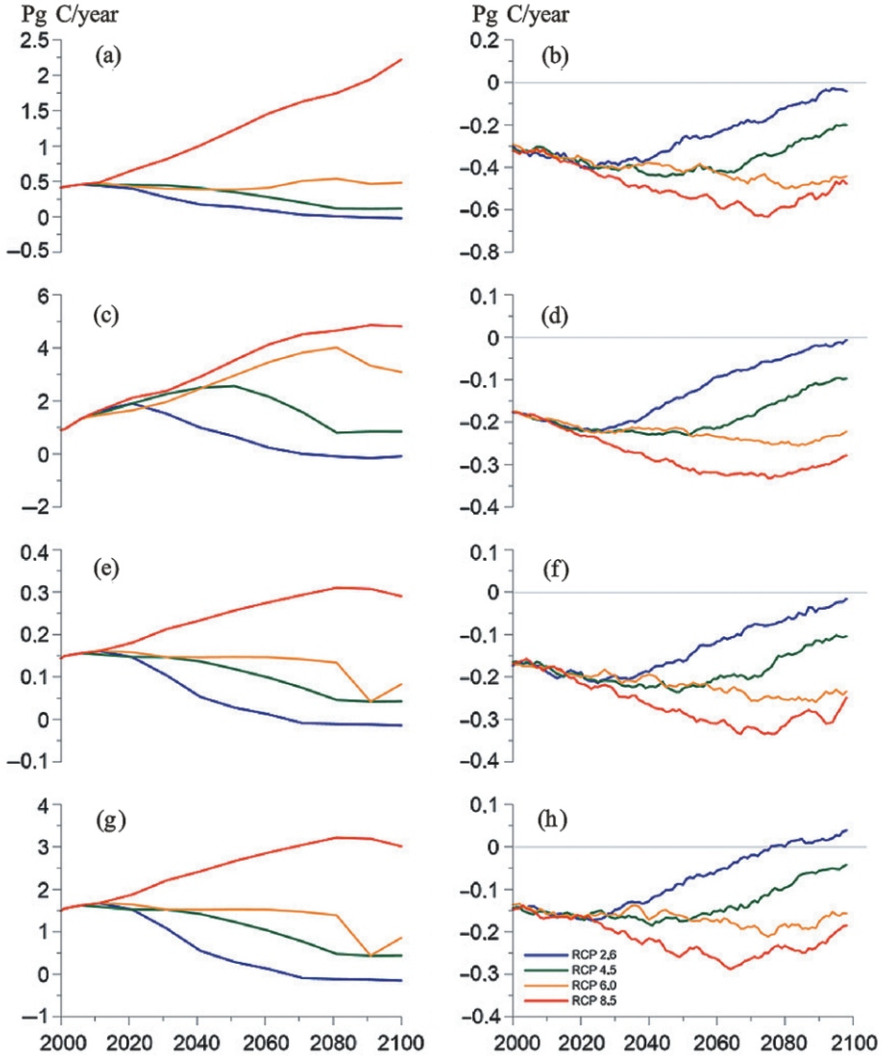

Fig. 3. (a, c, e, g) Anthropogenic and (b, d, f, h) natural CO_2 fluxes from the territory of (a, b) Russia, (c, d) China, (e, f) Canada, and (g, h) the USA.

4. RESULTS

4.1. *Natural and Anthropogenic Fluxes of CO_2 and CH_4*

Anthropogenic emissions for Russia were computed using the RCP family scenarios for the REF region (the countries of Eastern Europe and the former USSR, http://www.iiasa.ac.at/web-apps/tnt/RcpDb) with the corresponding scaling of emissions from the territory of Russia at the moment of transition from the Historical Simulations scenario to the RCP scenarios (2000 for methane and 2005 for carbon dioxide). Anthropogenic emissions from the territory of China and North America were calculated in a similar way in accordance to the RCP scenarios for the ASIA and OECD regions, respectively. It should be noted that according to available data (https://databank.worldbank.org/data/source/world-development-indicators), anthropogenic emissions of CH_4 from the territory of Russia at the beginning of the 21st century are close to the most aggressive anthropogenic scenario RCP 8.5.

The resulting estimates of modern natural CO_2 fluxes for Russia (Fig. 3b) are in good agreement with the estimates [20] for process models (see Table 2) and the estimates from [39]. The CO_2 uptake by terrestrial ecosystems under all analyzed scenarios increases at the beginning of the 21st century. Then, for all considered scenarios, the absorption maximum is reached, which is equal to 0.4–0.6 Pg C/year. After that, it starts decreasing. The more aggressive the anthropogenic forcing scenario is, the later it happens.

Table 2. Natural CO_2 fluxes at the beginning of the 21st century

Data	CO_2 fluxes, Pg C/year			
	Russia	Canada	USA	China
IAP RAS model*	–0.31	–0.17	–0.14	–0.18
[36]		–0.15	–0.34	
[24]**		–0.24/–0.12/–0.04	–0.69/–0.36/–0.3	
[39]***	–0.32	–0.32		
[29]**				–0.35/–0.17/–0.18
[28]			–0.3...–0.58	
[20]****	–0.65/–0.56/–0.76/–0.2			
[37]				–0.26
[38]			–0.64	

* The present study, the mean for 1995–2005; ** inverse models/process models/inventory-based estimates; *** only Arctic tundra, 1990–2100; the estimate of –0.32 is total for Russia and Canada (i.e., for entire Arctic tundra); **** inverse models/eddy covariance method/inventory-based estimates/process models.

According to model estimates, natural emissions of methane from the territory of Russia (Fig. 4b) increase by the end of the 21st century by 10–200%, depending on the anthropogenic forcing scenario. Under all scenarios except the RCP 8.5, in the second half of the 21st century their value reaches the values of anthropogenic emissions of methane from the territory of Russia (Fig. 4a).

The resulting estimates of modern natural fluxes of CO_2 for China are generally consistent with the estimates [29, 37]. The CO_2 flux from the terrestrial ecosystems of China to the atmosphere changes in the 21st century similarly to the fluxes from the territory of Russia (and all other analyzed regions) (Fig. 3). The maximum uptake in the 21st century is 0.2–0.35 Pg C/year. It should be noted that the values of natural fluxes of greenhouse gases for China according to calculations make up 5–20% of respective anthropogenic emissions. Therefore, the contribution of China to the global temperature change is determined by anthropogenic forcing.

Natural emissions of methane from the territory of China (Fig. 4d) according to calculations will increase in the 21st century more slowly than in Russia. Only for the most aggressive anthropogenic scenario, the increase exceeds 50% by the end of the century.

The CO_2 uptake by the terrestrial ecosystems in North America is ~0.3 Pg C/year at the beginning of the 21st century, increases up to 0.4–0.6 Pg C/year during the century depending on the anthropogenic forcing scenario, and then starts decreasing (Figs. 3e, 3f, 3g, and 3h). The resulting estimates of modern natural CO_2 fluxes are consistent with the data [24, 36] for the territory of Canada. At the same time, the absorption of CO_2 by terrestrial ecosystems in the USA is slightly underestimated as compared both with the same data and with [28, 38]. According to calculations, natural emissions of methane from the territory of North America in the 21st century exceed the emissions from Russia by about two times but increase a bit more slowly (by 20–100% depending on the scenario). Nevertheless, they begin to exceed respective anthropogenic emissions for all scenarios except the RCP 8.5 in the second half of the 21st century. It should be noted that the main source of anthropogenic emissions of greenhouse gases in North America is the territory of the USA. The contribution of terrestrial ecosystems in the USA and Canada to the CO_2 uptake is close to each other, and the main source of natural methane emissions is the territory of Canada (Fig. 4f).

4.2. Cumulative Temperature Potential and Its Changes

Figure 5 presents the results of calculating the cumulative potential CT on the interval [1990; T_H] separately for emissions of carbon dioxide and methane in Russia, China, Canada, and the USA with the horizon T_H corresponding to 2030, 2060, and 2090. It should be noted that the anthropogenic cumulative potential (Table 3) decreases in the second half of the 21st century under the RCP 2.6 scenario (the anthropogenic potential of Russia also decreases under the RCP 4.5) and increases under the most intensive anthropogenic forcing scenarios. The anthropogenic potential of Russia decreases mainly due to the reduction of anthropogenic emissions of CH_4, while the contribution of the decrease in the emission of CH_4 and CO_2 is comparable for the other regions. For anthropogenic CO_2 emissions from China, there is a clear ef-

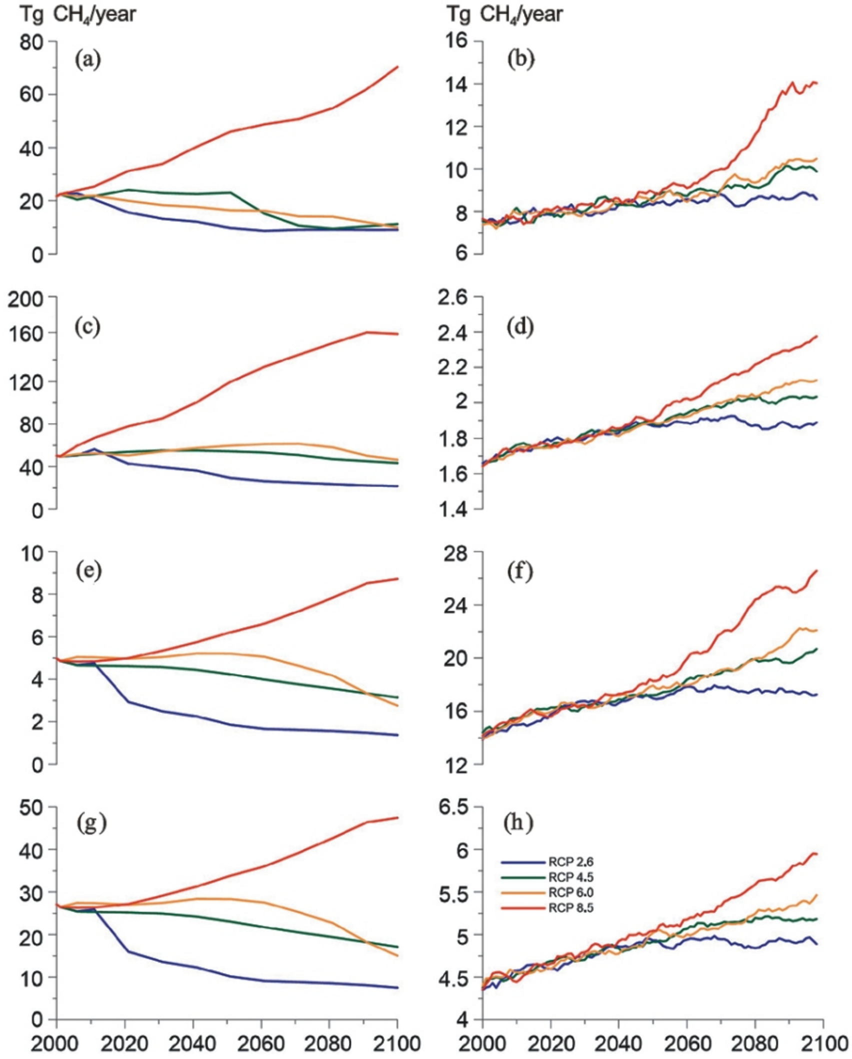

Fig. 4. The same as in Fig. 3 for CH_4 fluxes.

fect of considering changes in background conditions: although the CO_2 emissions under the RCP 8.5 scenario throughout the 21st century are greater than under the RCP 6.0 (a figure is not presented), their total effect on climate by the end of the century is weaker due to the higher global concentrations of atmospheric CO_2 (and, hence, due to the lower forcing). Thus, according to the estimates for the analyzed scenarios, only the RCP 2.6 leads to the stabilization of anthropogenic forcing on the global air temperature in the 21st century. At the same time, the stabilizing contribution of natural fluxes of greenhouse gases from terrestrial ecosystems in the 21st century increases for Russia, China, and the USA under all analyzed scenarios and poorly varies for Canada.

For Russia, natural fluxes of greenhouse gases make a significant contribution to the total changes in the global surface temperature. Their stabilizing effect on climate exceeds the total stabilizing natural effect of the other regions. For China and the USA, natural emissions are insignificant as compared to anthropogenic ones. For the United States, according to calculations, anthropogenic CO_2 emissions are a dominating factor of climate forcing, compared to it, the effect of other greenhouse gas fluxes is insignificant. For Canada, according to the estimates, the main factors of climate forcing are the natural fluxes of CH_4 and CO_2, which are comparable in value but are opposite in direction. Anthropogenic greenhouse gas fluxes are less significant.

In general, the total contribution of anthropogenic and natural fluxes of CH_4 and CO_2 to the changes in global surface air temperature from 1990 to the end of the 21st century depending on the anthropogenic forcing scenario is 0.03–0.17 K for Russia, 0.18–0.54 K for China, 0.03–0.04 K for Canada, and 0.14–0.32 K for the USA. At the same time, the total climate effect of the analyzed greenhouse gas fluxes stops growing

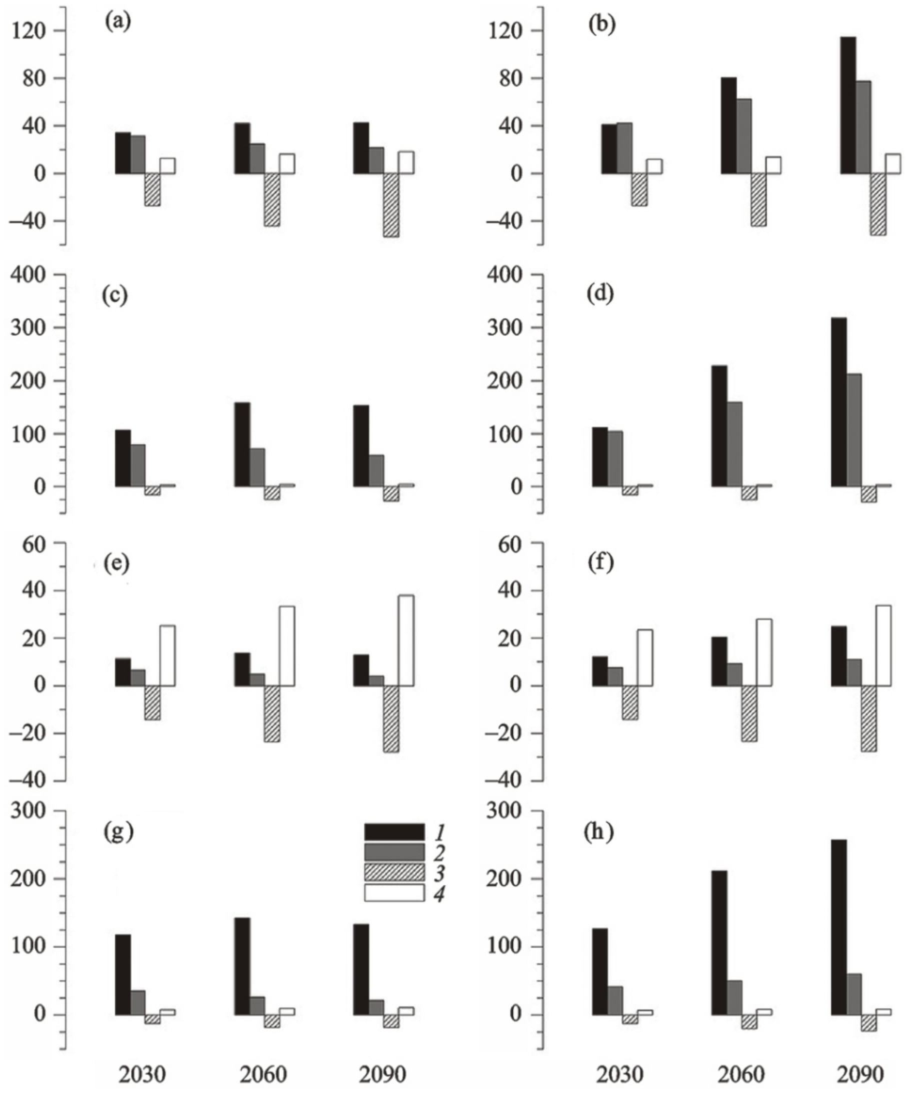

Fig. 5. The cumulative potential (mK) of (*1*, *2*) anthropogenic and (*3*, *4*) natural fluxes of (*1*, *3*) CO_2 and (*2*, *4*) CH_4 for the time intervals [1990; 2030], [1990; 2060], and [1990; 2090] from the territory of (a, b) Russia, (c, d) China, (e, f) Canada, and (g, h) the USA for (a, c, e, g) the RCP 2.6 and (b, d, f, h) RCP 8.5 scenarios.

by the end of the 21st century under all scenarios except the RCP 8.5 for Russia, only under the RCP 2.6 for China, and under the RCP 2.6 and 6.0 for North America.

5. CONCLUSIONS

According to the results of the present study, the consideration of changes in climatic conditions in the model highly affects the ratio of natural sources and sinks of greenhouse gases and their effect on the climate system, especially for large time horizons under the most aggressive anthropogenic forcing scenarios. The quantitative model estimates were obtained for the contribution of anthropogenic and natural fluxes of greenhouse gases from the territory of Russia, China, Canada, and the USA to global climate change in the 21st century under different anthropogenic forcing scenarios. For the regions of Eurasia and North America, the model simulations revealed a decrease in the CO_2 uptake by natural ecosystems in the second half of the 21st century, with a weakening of the corresponding climate-stabilizing effect under the analyzed anthropogenic forcing scenarios. At the same time, according to the model estimates, the methane emission to the atmosphere by wetland ecosystems significantly grows in the 21st century.

It should be noted that the authors' estimates did not take into account some processes: the release of methane and nitrogen dioxide from wildfires [30]; the release of CO_2 and CH_4 from the permafrost thaw as

Table 3. The anthropogenic and natural cumulative potential (mK) for the interval [1990, T_H]

Country	T_H	RCP 2.6			RCP 4.5			RCP 6.0			RCP 8.5		
		E_a	E_n	CT	E_a	E_n	CT	E_a	E_n	CT	E_a	E_n	CT
Russia	2030	65	–14	51	73	–14	59	70	–14	56	83	–15	68
	2050	68	–24	44	88	–25	63	81	–24	57	123	–26	97
	2075	65	–32	33	87	–35	52	87	–33	54	169	–35	134
	2100	64	–35	29	80	–41	39	91	–38	53	208	–34	174
China	2030	185	–13	172	192	–13	179	185	–13	172	215	–13	202
	2050	226	–19	207	283	–19	264	276	–19	257	329	–20	309
	2075	222	–22	200	356	–25	331	395	–24	371	466	–25	441
	2100	205	–23	182	373	–28	345	472	–27	445	565	–26	539
Canada	2030	18	11	29	19	11	30	20	11	31	20	9	29
	2050	19	10	29	23	9	32	25	9	34	27	6	33
	2075	18	10	28	25	6	31	29	7	36	33	4	37
	2100	16	11	27	26	7	33	27	8	35	37	8	45
USA	2030	153	–5	148	160	–5	155	167	–5	162	168	–6	162
	2050	170	–8	162	203	–9	192	218	–9	209	235	–10	225
	2075	162	–9	153	225	–12	213	250	–12	238	293	–14	279
	2100	150	–7	143	230	–13	217	244	–14	230	330	–15	315

E_a is anthropogenic emission; E_n is natural emission.

a result of climate warming [32]; the release of CH_4 and N_2O from inland reservoirs [15, 19]; the release of N_2O from terrestrial ecosystems [36]. According to the estimates, wildfires lead to the global emission of 15 3 Tg of methane and 0.9 3 Tg of nitrogen dioxide per year to the atmosphere (along with aerosol particles, carbon dioxide, and carbon monoxide), and the contribution of the Russian regions makes up ~10% [6]. These values are comparatively small (see Fig. 3), but in case of their consideration, individual regions may become a source of greenhouse gases and stop being their sink. There is high uncertainty in the estimates of the greenhouse gas release from inland reservoirs [19], which may be substantial when determining how much specific regions are sinks or sources of greenhouse gases.

The quantitative estimates obtained in the present study can be updated by considering the effect of CO_2 and CH_4 release from the soil to the atmosphere during the permafrost thaw at subpolar latitudes, from which the “old” (formed in the last interglacial periods and not decomposed due to cold conditions) carbon substrate under the RCP 8.5 scenario in the 21st century can release up to 174 Pg C of carbon as CO_2 and CH_4 according to [32] and up to 240 Pg C as carbon dioxide and 5300 Tg as methane according to [16]. In addition, the formation of thermokarst lakes during the permafrost thaw in terrestrial regions favors the development of lake taliks, which also contributed to the release of these greenhouse gases to the atmosphere: according to the available estimates, this may lead to the release of up to 50 Tg CH_4 to the atmosphere in the 21st century under the RCP scenarios, with the greatest contribution in the first half of the century [31]. It should also be noted that the response of the characteristics of the terrestrial carbon and methane cycles on climate change depends on the interaction with the nitrogen cycle [27, 32].

When making strategic decisions in connection with climate change, it should be taken into account that the role of natural fluxes of greenhouse gases from terrestrial ecosystems to the atmosphere varies depending on the time horizon of planning. According to the model results, climate change influences the estimated contribution of different greenhouse gases to the temperature variations and their ratio. For example, under the RCP 2.6 scenario for climatic conditions of the second half of the 21st century ($T_0 > 2050$), natural fluxes of greenhouse gases in the analyzed regions will totally accelerate climate warming.

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REFERENCES

1. *Second Roshydromet Assessment Report on Climate Change and Its Consequences in the Russian Federation* (Roshydromet, Moscow, 2014) [in Russian].
2. S. N. Denisov, A. V. Eliseev, and I. I. Mokhov, “Contribution of Natural and Anthropogenic Emissions of CO_2 and CH_4 to the Atmosphere from the Territory of Russia to Global Climate Changes in the Twenty-first Century,” Dokl. Akad. Nauk, No. 1, **488** (2019) [Dokl. Earth Sci., No. 1, **488** (2019)].
3. S. N. Denisov, A. V. Eliseev, and I. I. Mokhov, “Climate Change in IAP RAS Global Model Taking Account of Interaction with Methane Cycle under Anthropogenic Scenarios of RCP Family,” Meteorol. Gidrol., No. 11 (2013) [Russ. Meteorol. Hydrol., No. 11, **38** (2013)].
4. S. N. Denisov, A. V. Eliseev, I. I. Mokhov, and M. M. Arzhanov, “Model Estimates of Global and Regional Atmospheric Methane Emissions of Wetland Ecosystems,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 5, **51** (2015) [Izv., Atmos. Oceanic Phys., No. 5, **51** (2015)].
5. A. V. Dzyuba, A. V. Eliseev, and I. I. Mokhov, “Estimates of Changes in the Rate of Methane Sink from the Atmosphere under Climate Warming,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 3, **48** (2012) [Izv., Atmos. Oceanic Phys., No. 3, **48** (2012)].
6. A. V. Eliseev and A. V. Vasil’eva, “Wildfires: Observational Data and Modeling,” Fundamental’naya i Prikladnaya Klimatologiya, No. 3 (2020) [in Russian].
7. A. V. Eliseev, I. I. Mokhov, M. M. Arzhanov, P. F. Demchenko, and S. N. Denisov, “Interaction of the Methane Cycle and Processes in Wetland Ecosystems in a Climate Model of Intermediate Complexity,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 2, **44** (2008) [Izv., Atmos. Oceanic Phys., No. 2, **44** (2008)].
8. I. L. Karol’, A. A. Kiselev, and V. A. Frol’kis, “Indices of the Factors that Form Climate Changes of Different Scales,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 4, **47** (2011) [Izv., Atmos. Oceanic Phys., No. 4, **47** (2011)].
9. I. I. Mokhov, “Climate Change: Causes, Risks, Consequences, and Problems of Adaptation and Regulation,” Vestnik Akad. Nauk, No. 1, **92** (2022) [Her. Russ. Acad. Sci., No. 1, **92** (2022)].
10. I. I. Mokhov, “Russian Climate Research in 2015–2018,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 4, **56** (2020) [Izv., Atmos. Oceanic Phys., No. 4, **56** (2020)].
11. I. I. Mokhov, P. F. Demchenko, A. V. Eliseev, V. Ch. Khon, and D. V. Khvorost’yanov, “Estimation of Global and Regional Climate Changes during the 19th–21st Centuries on the Basis of the IAP RAS Model with Consideration for Anthropogenic Forcing,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 5, **38** (2002) [Izv., Atmos. Oceanic Phys., No. 5, **38** (2002)].
12. I. I. Mokhov and A. V. Eliseev, “Modeling of Global Climate Variations in the 20th–23rd Centuries with New RCP Scenarios of Anthropogenic Forcing,” Dokl. Akad. Nauk, No. 6, **443** (2012) [Dokl. Earth Sci., No. 2, **443** (2012)].
13. I. I. Mokhov, A. V. Eliseev, P. F. Demchenko, V. Ch. Khon, M. G. Akperov, M. M. Arzhanov, A. A. Karpenko, V. A. Tikhonov, A. V. Chernokulsky, and E. V. Sigaeva, “Climate Changes and Their Assessment Based on the IAP RAS Global Model Simulations,” Dokl. Akad. Nauk, No. 2, **402** (2005) [Dokl. Earth Sci., No. 4, **402** (2005)].
14. I. I. Mokhov, A. V. Eliseev, and S. N. Denisov, “Model Diagnostics of Variations in Methane Emissions by Wetlands in the Second Half of the 20th Century Based on Reanalysis Data,” Dokl. Akad. Nauk, No. 2, **417** (2007) [Dokl. Earth Sci., No. 8, **417** (2007)].
15. V. M. Stepanenko, E. E. Machul’skaya, M. V. Glagolev, and V. N. Lykossov, “Numerical Modeling of Methane Emissions from Lakes in the Permafrost Zone,” Izv. Akad. Nauk, Fiz. Atmos. Okeana, No. 2, **47** (2011) [Izv., Atmos. Oceanic Phys., No. 2, **47** (2011)].
16. J. G. Canadell, P. M. S. Monteiro, M. H. Costa, L. Cotrim da Cunha, P. M. Cox, A. V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P. K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, “Global Carbon and Other Biogeochemical Cycles and Feedbacks,” in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Ed. by V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Pean, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekci, R. Yu, and B. Zhou (Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA, 2021).
17. M. Claussen, L. A. Mysak, A. J. Weaver, M. Crucifix, T. Fichefet, M. Loutre, S. Weber, J. Alcamo, V. A. Alexeev, A. Berger, R. Calov, A. Ganopolski, H. Goosse, G. Lohmann, F. Lunkeit, I. I. Mokhov, V. Petoukhov, P. Stone, and Z. Wang, “Earth System Models of Intermediate Complexity: Closing the Gap in the Spectrum of Climate System Models,” Climate Dynamics, **18** (2002).
18. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Ed. by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. Midgley, L. Alexander, N. Bindoff, F. Breon, J. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J. Gregory, D. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. K. Kanikicharla, P. Lemke, J. Marotzke, V. Masson-Delmotte, G. Meehl, I. Mokhov, S. Piao, Q. Dahe,

V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L. Talley, D. Vaughan, S. Xie, M. Allen, O. Boucher, D. Chambers, J. Christensen, P. Ciais, P. Clark, M. Collins, J. Comiso, V. Menezes, R. Feely, T. Fichefet, A. Fiore, G. Flato, J. Fuglestvedt, G. Hegerl, P. Hezel, G. Johnson, G. Kaser, V. Kattsov, J. Kennedy, A. K. Tank, C. le Quere, G. Myhre, T. Osborn, A. Payne, J. Perlwitz, S. Power, M. Prather, S. Rintoul, J. Rogelj, T. F. Stocker, M. Rusticucci, M. Schulz, J. Sedlacek, P. Stott, R. Sutton, P. Thorne, and D. Wuebbles (Cambridge Univ. Press, Cambridge, New York, 2013).

19. B. R. Deemer, J. A. Harrison, S. Li, J. Beaulieu, T. DelSontro, N. Barros, J. F. Bezerra-Neto, S. Powers, M. D. dos Santos, and J. Vonk, "Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis," BioScience, No. 11, **66** (2016).
20. A. J. Dolman, A. Shvidenko, D. Schepaschenko, P. Ciais, N. Tchebakova, T. Chen, M. Molen, L. Marchesini, T. Maximov, S. Maksyutov, and E. Schulze, "An Estimate of the Terrestrial Carbon Budget of Russia Using Inventory-based, Eddy Covariance and Inversion Methods," Biogeosci., **9** (2012).
21. M. Eby, A. J. Weaver, K. Alexander, K. Zickfeld, A. Abe-Ouchi, A. Cimatoribus, E. Crespin, S. Drijfhout, N. Edwards, A. Eliseev, G. Feulner, T. Fichefet, C. Forest, H. Goosse, P. Holden, F. Joos, M. Kawamiya, D. Kicklighter, H. Kienert, K. Matsumoto, I. Mokhov, E. Monier, S. Olsen, J. O. Pedersen, M. Perrette, G. Philippon-Berthier, A. Ridgwell, A. Schlosser, T. S. V. Deimling, G. Shaffer, R. S. Smith, R. Spahni, A. Sokolov, M. Steinacher, K. Tachiiri, K. Tokos, M. Yoshimori, N. Zeng, and F. Zhao, "Historical and Idealized Climate Model Experiments: An EMIC Intercomparison," Clim. Past., No. 3, **9** (2013).
22. A. V. Eliseev and I. I. Mokhov, "Uncertainty of Climate Response to Natural and Anthropogenic Forcings due to Different Land Use Scenarios," Adv. Atmos. Sci., No. 5, **28** (2011).
23. A. V. Eliseev, I. I. Mokhov, and A. V. Chernokulsky, "An Ensemble Approach to Simulate CO_2 Emissions from Natural Fires," Biogeosci., No. 12, **11** (2014).
24. D. J. Hayes, D. P. Turner, G. Stinson, A. David McGuire, Y. Wei, T. O. West, L. S. Heath, B. de Jong, B. G. McCon- key, R. A. Birdsey, W. A. Kurz, A. R. Jacobson, D. N. Huntzinger, Y. Pan, W. Mac Post, and R. B. Cook, "Reconciling Estimates of the Contemporary North American Carbon Balance among Terrestrial Biosphere Models, Atmospheric Inversions, and a New Approach for Estimating Net Ecosystem Exchange from Inventory-based Data," Glob. Change Biol., No. 4, **18** (2012).
25. C. D. Holmes, M. J. Prather, O. A. Sovde, and G. Myhre, "Future Methane, Hydroxyl, and Their Uncertainties: Key Climate and Emission Parameters for Future Predictions," Atmos. Chem. Phys., **13** (2013).
26. A. H. MacDougall, T. L. Frolicher, C. D. Jones, J. Rogelj, H. Matthews, K. Zickfeld, V. Arora, N. J. Barrett, V. Brovkin, F. A. Burger, M. Eby, A. Eliseev, T. Hajima, P. Holden, A. Jeltsch-Thommes, C. Koven, N. Mengis, L. Menviel, M. Michou, I. Mokhov, A. Oka, J. Schwinger, R. Seferian, G. Shaffer, A. Sokolov, K. Tachiiri, J. Tjiputra, A. Wiltshire, and T. Ziehn, "Is There Warming in the Pipeline? A Multi-model Analysis of the Zero Emissions Commitment from CO_2," Biogeosci., No. 11, **17** (2020).
27. G. Myhre, D. Shindell, F.-M. Breon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, "Anthropogenic and Natural Radiative Forcing," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley (Cambridge Univ. Press, Cambridge, UK and New York, NY, USA, 2013).
28. S. W. Pacala, G. C. Hurtt, D. Baker, P. Peylin, R. Houghton, R. Birdsey, L. Heath, E. Sundquist, R. Stallard, P. Ciais, P. Moorcroft, J. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E. Holland, M. Gloor, M. Harmon, S. Fan, J. Sarmiento, C. Goodale, D. Schimel, and C. Field, "Consistent Land- and Atmosphere-based U.S. Carbon Sink Estimates," Science, No. 5525, **292** (2001).
29. S. Piao, J. Fang, P. Ciais, P. Peylin, Y. Huang, S. Sitch, and T. Wang, "The Carbon Balance of Terrestrial Ecosystems in China," Nature, **458** (2009).
30. M. Saunois, A. R. Stavert, B. Poulter, P. Bousquet, J. Canadell, R. Jackson, P. Raymond, E. Dlugokencky, S. Houweling, P. Patra, P. Ciais, V. Arora, D. Bastviken, P. Bergamaschi, D. Blake, G. Brailsford, L. Bruhwiler, K. Carlson, M. Carrol, S. Castaldi, N. Chandra, C. Crevoisier, P. Crill, K. Covey, C. Curry, G. Etiope, C. Frankenberg, N. Gedney, M. Hegglin, L. Hoglund-Isaksson, G. Hugelius, M. Ishizawa, A. Ito, G. Janssens-Maenhout, K. Jensen, F. Joos, T. Kleinen, P. Krummel, R. Langenfelds, G. Laruelle, L. Liu, T. Machida, S. Maksyutov, K. McDonald, J. McNorton, P. Miller, J. Melton, I. Morino, J. Muller, F. Murguia-Flores, V. Naik, Y. Niwa, S. Noce, S. O'Doherty, R. Parker, C. Peng, S. Peng, G. Peters, C. Prigent, R. Prinn, M. Ramonet, P. Regnier, W. Riley, J. Rosentreter, A. Segers, I. Simpson, H. Shi, S. J. Smith, L. P. Steele, B. Thornton, H. Tian, Y. Tohjima, F. Tubiello, A. Tsuruta, N. Viovy, A. Voulgarakis, T. S. Weber, M. van Weele, G. R. van der Werf, R. Weiss, D. Worthy, D. Wunch, Y. Yin, Y. Yoshida, W. Zhang, Z. Zhang, Y. Zhao, B.-Y. Zheng, Q. Zhu, Q. Zhu, and Q. Zhuang, "The Global Methane Budget 2000–2017," Earth Syst. Sci. Data, No. 3, **12** (2020).
31. T. S. V. Deimling, G. Grosse, J. Strauss, L. Schirrmeister, A. Morgenstern, S. Schaphoff, M. Meinshausen, and J. Boike, "Observation-based Modelling of Permafrost Carbon Fluxes with Accounting for Deep Carbon Deposits and Thermokarst Activity," Biogeosci., No. 11, **12** (2015).

32. E. A. G. Schuur, A. D. McGuire, C. Schadel, G. Grosse, J. Harden, D. Hayes, G. Hugelius, C. Koven, P. Kuhry, D. Lawrence, S. Natali, D. Olefeldt, V. Romanovsky, K. Schaefer, M. Turetsky, C. Treat, and J. Vonk, “Climate Change and the Permafrost Carbon Feedback,” Nature, No. 7546, **520** (2015).
33. K. P. Shine, T. K. Berntsen, J. S. Fuglestvedt, R. B. Skeie, and N. Stuber, “Comparing the Climate Effect of Emissions of Short- and Long-lived Climate Agents,” Phil. Tran. Roy. Soc. A, **365** (2007).
34. K. P. Shine, J. S. Fuglestvedt, K. Hailemariam, and N. Stuber, “Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases,” Climate Change, No. 3, **68** (2005).
35. S. M. Smith, J. A. Lowe, N. H. A. Bowerman, L. K. Gohar, C. Huntingford, and M. R. Allen, “Equivalence of Greenhouse-gas Emissions for Peak Temperature Limits,” Nature Climate Change, **2** (2012).
36. H. Tian, G. Chen, C. Lu, X. Xu, W. Ren, B. Zhang, K. Banger, B. Tao, S. Pan, M. Liu, C. Zhang, L. Bruhwiler, and S. Wofsy, “Global Methane and Nitrous Oxide Emissions from Terrestrial Ecosystems due to Multiple Environmental Changes,” Ecosyst. Health Sustain, **1** (2015).
37. H. Tian, X. Xu, C. Lu, M. Liu, W. Ren, G. Chen, J. Melillo, and J. Liu, “Net Exchanges of CO_2, CH_4, and N_2O between China’s Terrestrial Ecosystems and the Atmosphere and Their Contributions to Global Climate Warming,” J. Geophys. Res. Biogeosci., **116** (2011).
38. J. Xiao, Q. Zhuang, B. E. Law, D. Baldocchi, J. Chen, A. Richardson, J. Melillo, K. Davis, D. Hollinger, S. Wharton, R. Oren, A. Noormets, M. Fischer, S. Verma, D. Cook, G. Sun, S. McNulty, S. Wofsy, P. Bolstad, S. Burns, P. Curtis, B. Drake, M. Falk, D. Foster, L. Gu, J. Hadley, G. Katul, M. Litvak, S. Ma, T. Martin, R. Matamala, T. Meyers, R. Monson, J. W. Munger, W. Oechel, U. Paw, H. Schmid, R. Scott, G. Starr, A. Suyker, and M. Torn, “Assessing Net Ecosystem Carbon Exchange of US Terrestrial Ecosystems by Integrating Eddy Covariance Flux Measurements and Satellite Observations,” Agr. Forest Meteorol., No. 1, **151** (2011).
39. W. Zhang, C. Jansson, P. A. Miller, B. Smith, and P. Samuelsson, “Biogeophysical Feedbacks Enhance the Arctic Terrestrial Carbon Sink in Regional Earth System Dynamics,” Biogeosci., **11** (2014).
40. K. Zickfeld, M. Eby, A. J. Weaver, K. Alexander, E. Crespin, N. Edwards, A. Eliseev, G. Feulner, T. Fichefet, C. Forest, P. Friedlingstein, H. Goosse, P. Holden, F. Joos, M. Kawamiya, D. Kicklighter, H. Kienert, K. Matsumoto, I. Mokhov, E. Monier, S. Olsen, J. O. Pedersen, M. Perrette, G. Philippon-Berthier, A. Ridgwell, A. Schlosser, T. S. V. Deimling, G. Shaffer, G. Shaffer, A. Sokolov, R. Spahni, M. Steinacher, K. Tachiiri, K. Tokos, M. Yoshimori, N. Zeng, and F. Zhao, “Long-term Climate Change Commitment and Reversibility: An EMIC Intercomparison,” J. Climate, No. 16, **26** (2013).