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Articles

Methane emission from the Western Siberia's wetland ecosystems in 2000–2050

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The interannual variability of methane emissions from wetland ecosystems of Western Siberia in 2000–2050 has been investigated. Calculations of CH_4 emission were performed using the approach, in which the total daily methane flux is determined by the sum of positive temperatures accumulated in the soil at that time and its moisture content. Required characteristics of the soil were obtained using regional climate model RegCM4. The reanalysis NCEP-DOE AMIP-II (R2) and data of HadGEM2-ES global model for the RCP4.5 and RCP8.5 evolution scenario of the global climate system were used to define the initial and boundary conditions. It was found that for Western Siberia's wetland complexes, analyzed in this paper, the model estimates for methane emission in 2000–2013 vary from ~3.5 to ~5.5 Tg CH_4/yr. The average value of emission is 4.34 TgCH_4/yr. The rate of change of methane emission during this period is almost neutral. Growth of CH_4 emission is observed only in the areas of tundra and forest tundra. Forecast values of methane emission obtained for the period 2021–2050 for scenarios RCP4.5 and RCP8.5 ranges from 3.9 up to 7.6 Tg CH_4/yr. The average emission values are 5.0 and 5.8 Tg CH_4/yr, respectively. Trends of CH_4 emission for this period are also practically neutral.

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Keywords

CMIP5 climate evolution scenario, Reanalysis NCEP-DOE AMIP-II (R2), regional climate model RegCM4, soil temperature, volumetric moisture content

Introduction

Monitoring of the greenhouse gases content in the atmosphere and implementing measures to reduce the so-called carbon footprint are today included in the agenda of the Government of the Russian Federation and are enshrined in the form of specific tasks in the National Action Plan for

Adaptation to Climate Change, approved in December 2019, as well as in the Scientific and Technological Strategy Development of the Russian Federation, adopted in December 2016. One of the key tasks being solved within the framework of the problem is the creation of specialized territories for the implementation of measures to control climate-active gases – carbon polygons. As part of the planned work, carbon polygons will be created in almost all regions of Western Siberia, which will make this territory the largest research and educational platform in the areas of carbon balance control, environmental monitoring, establishing the behavior of the climate system of the Siberian region, etc.

The relevance of implementation of the carbon polygons project in Western Siberia is due to the presence of the largest wetland complexes, which are natural sources of the second most important greenhouse gas after carbon dioxide (CO2) – methane (CH_4) (Saunois et al. 2020). Methane affects the chemical composition of the atmosphere as well as both the radiation balance and climate of the Earth. According to the latest data the Working Group I Intergovernmental Panel on Climate Change (IPCC), the contribution of CH_4 to the increase in global air temperature is more than 20% (Canadell et al. 2021).

Latest report of the World Meteorological Organization (WMO) concluded that, since the beginning of the industrial era, the content of methane in the surface layer of the atmosphere has increased by 253% and reached a level of 1908±2 ppb in 2021 (Crotwell et al. 2022). Of particular concern is the increase in atmospheric CH_4 concentration growth rate over the last decade, equal on average 9.2 ppb/yr.

The methane content in the atmosphere is determined by the relationship between the amount of gas entering the atmosphere from the underlying surface level (sources), the volume of CH_4 absorbed by the underlying surface, and chemical losses in the atmosphere (sinks). The main channel for the sink of atmospheric methane (about 90%) is the reaction with hydroxyl radical (OH) in the troposphere. As a result of analyzing data for 2008–2017 for all types of sources and sinks, the IPCC report established an imbalance in the methane budget. The decadal mean CH_4 imbalance increased at the rate of 21 TgCH_4/yr (Canadell et al. 2021).

According to Canadell et al. (2021) the contribution of wetland complexes to methane budget are given equal to 159–199 TgCH_4/yr. The paper Zhang et al. (2023) provides estimates of global CH_4 emissions from wetlands obtained for the period 2000–2021. According to Zhang et al. (2023), in 2007–2021, global CH_4 emissions have increased by 5–6% compared to the base period 2000–2006. The growth rate of emissions during this period is 1.3-1.4 TgCH_4/year, which exceeds the estimate of 0.9 TgCH_4/year obtained by Zhang et al. (2017) in ensemble calculations within the RCP scenarios. Additionally Zhang et al. (2023) shows that in 2020 and 2021, the growth rate of emissions was maximum and was 5% higher than the trend of the previous 20-year period. The estimates obtained for 2020 and 2021 are confirmed by the results Feng et al. (2023). Both papers (Zhang et al. 2023 and Feng et al. 2023) note that the greatest changes in the growth rate of methane emissions are found for East Africa, tropical Asia and temperate Eurasia. At the same time, according to Zhang et al. (2023) there are indications that high latitude wetlands have only a moderate increase in CH_4.

The established Zhang et al. (2023) and Feng et al. (2023) increase in the content of methane in the Earth's atmosphere in 2020 and 2021 is associated with an increase in its emission, as well as a decrease in the content of the OH radical. One of the key factors influencing the concentration of hydroxyl radical OH in the atmosphere is the volume of carbon monoxide (CO) and nitrogen oxides (NOx) produced by the combustion of fossil fuels (Prather et al. 2012). To explain the increase in methane content in the atmosphere in 2020–2021, Peng et al. (2022) conducted a study on the impact of CO and NOx emission reductions caused by the COVID-19 pandemic on OH radical content. At the same time, Peng et al. (2022) note that for northern Eurasia, the spring-summer period of 2020 was extremely hot. Increased temperature conditions could provoke an increase in CH_4 emission from biogenic sources. Thus, the results of these studies confirm a strong positive feedback between anthropogenic and natural factors of methane balance, which requires more in-depth study.

For Western Siberia, the obtained methane emission estimates Bohn et al. (2015) have a large uncertainty from 2.42 to 11.19 $TgCH_4$/yr. In a recent study Xi et al. (2023), conducted for the period 2000–2021 for wetland complexes and aquatic ecosystems of Western Siberia, methane emission volumes varied from 4.80±0.43 to 8.29±0.81 $TgCH_4$/yr. This paper is a continuation of a study Makushev et al. (2016a) in which preliminary estimations of the CH_4 emission from wetland complexes in Western Siberia were obtained.

Despite the significant amount of performed researches, there is great uncertainty in assessing the contributions of various sources types of methane at the global and regional levels and their temporal evolution. For example, Zhang et al. (2023) notes that for such natural sources of methane as wetlands, the existing uncertainty in climate datasets does not allow researchers to formulate an unambiguous conclusion about the impact of rising temperatures or changes in precipitation on the rate of increase in CH_4 content in wetlands. The main reasons for this uncertainty are the sparse network of observation points (Arshinov et al 2012), the spatiotemporal heterogeneity of fluxes from many natural and anthropogenic sources (Glagolev et al. 2007; Panikov 1995; Zavarzin 1995), as well as the insufficient use of the capabilities of satellite systems for monitoring of the atmosphere and underlying surface of the region.

Figure 1 shows the change in the methane mixture ratio in the upper troposphere of Western Siberia in 2002–2022, obtained from data of the Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit (AIRS) hyperspectrometer of the Aqua satellite (Aumann et al. 2003) within the framework of the approach proposed in Lagutin et al. (2012). Studies of methane content in the upper troposphere using AIRS data are carried out in two zones of Western Siberia, covering most of the region's wetland complexes and having the following boundary coordinates: zone 1 (55°–65° N, 60°–90° E); zone 2 (45°–55° N, 60°–90° E). Before the failure of the Advanced Microwave Sounding Unit (AMSU), also installed on board Aqua, in 2016, both, AIRS and AMSU, operated as a hyperspectral suite. This operation mode made it possible to reconstruct the vertical profiles of temperature and humidity of the atmosphere with ~80% coverage of the observation area by clouds. The paper Lagutin et al. (2022) proposes an approach for restoring the «all-weather» operating mode of AIRS using data from Advanced Technology Microwave Sounder (ATMS) (Weng et al. 2013) installed on the Suomi-NPP, NOAA-20 and NOAA-21 satellites, that a part of NASA's Joint Polar Satellite System (JPSS) program (Goldberg et al. 2013). The Lagutin et al. (2022) shows that the inclusion of ATMS data to processing algorithms makes it possible to obtain geophysical results that practically coincide with the original AIRS/AMSU data, and thereby continue to obtain a unique more than 20-year series of hyperspectral satellite data for carrying out climate research and analysis of the gas composition of the atmosphere.

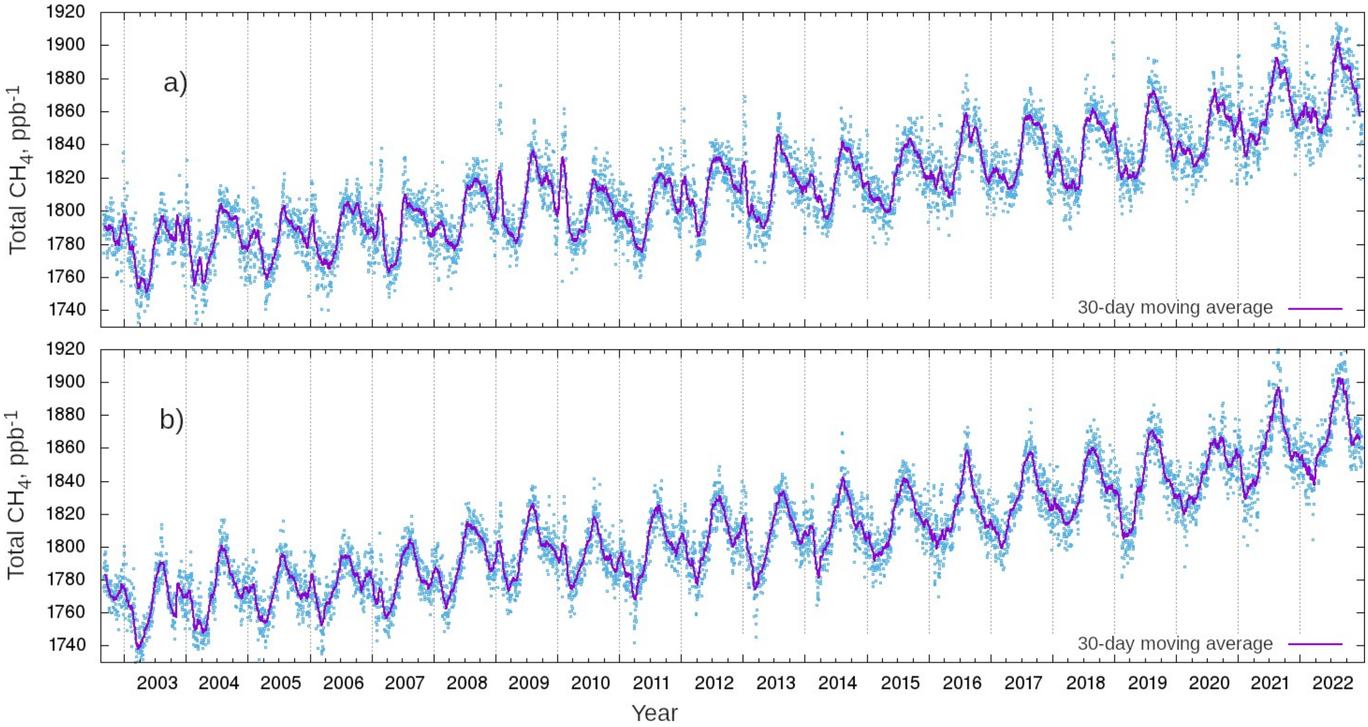

Figure 1. *Annual cycle and interannual variability of the methane mixture ratio CH4AIRS in the upper troposphere of Western Siberia according to AIRS hyperspectrometer of Aqua satellite for two study zones: a) zone 1 (55°–65° N, 60°–90° E); b) zone 2 (45°–55° N, 60°–90° E).*

AIRS/AMSU data shown in Figure 1 clearly shows an irregular trend, the presence of maximums in the annual cycle in winter and summer, as well as the presence of periods with positive and negative (for example, in 2010) rates of its increase. Under the assumption of a constant rate of atmospheric methane sink due to the reaction with the OH radical (Belan 2010; Montzka et al. 2011), the reasons for the observed variations may be changes in the rate of methane emission from the wetland complexes located in Western Siberia, changes in the amount of CH_4 entering the region's atmosphere from other territories as a result of the transfer of air masses, as well as variations in methane emissions from anthropogenic sources.

This paper explores the first reason. The main goals of the paper are to establish interannual variability and trends in methane emissions from the wetland complexes in Western Siberia in 2000–2013 and 2021–2050 within the framework of the approach Christensen and Cox (1995) using data from the regional climate model RegCM4/CLM4.5 (Pal et al. 2007; Giorgy et al. 2012), as well as comparing the obtained results with ground-based observation data.

Materials and methods

Model of methane emission from the Western Siberia's wetland complexes

Modeling of methane emissions from the wetland complexes in the region was carried out using the approach proposed in Christensen and Cox (1995). The choice of this model is due to its consideration of the main factors that determine the emission of methane by wetland ecosystems: soil temperature, vertical distribution of soil moisture content, which is a better predictor of methane flux from wetlands than the level of wetland waters, as well as methane emissions in the aerobic zone (see, for example, Christensen et al. (2003); Deppe et al. (2010); Estop-Aragones et al. (2013); Fan et al. (2014) and references therein). It was used in Denisov et al. (2010); Denisov et al. (2011); Mokhov et al. (2007) to assess methane emissions from wetland complexes in Northern Eurasia, and in Wania et al. (2013) to compare methane emission modeling programs within the framework of the international WETCHIMP project.

In the model used in the study Christensen and Cox (1995), CH_4 emission at time (day of the year) is determined by the sum of positive temperatures accumulated in the soil at that time and its moisture content. The daily methane flux $F$$CH_4$[mg$CH_4$ m-2 day-1] is described by the expression

$$F_{\mathrm{CH_4}}(t) = \sum_{i=1}^{N} H(T_i)\{2\Theta_i - 1\}\{P_i(t)\Delta z_i\}Q_{10}^{(T_i-2)/10}$$

Figure 2.

Here N is the number of soil layers in which methane emissions are calculated; – temperature (ºC) of the i-th layer thickness ΔZ_iat the moment t; Θ_i– relative moisture content of the layer (fraction of the maximum moisture content); $P_i(t)$ – methane productivity in the layer i at the moment t; Q_{10} is the temperature coefficient, and $H(T_i)$ is the Heaviside step function (1 at T_i> 0 and 0 at T_i≤ 0), which excludes frozen soil layers from consideration.

When calculating methane emissions, it was assumed that the main contribution comes from the top layer of wetland soils, the thickness of which is 120 cm. In the climate model RegCM4/CLM4.5 this zone is divided into eight layers, the lower boundaries of which are, respectively, 1.8, 4.5, 9.1, 16.6, 28.9, 49.3, 82.9 and 120.0 cm. The temperature coefficient used in the calculations varied from 2 to 2.6 in accordance with the distribution obtained in Zhou et al. (2009) (see also Kotsyurbenko et al. (2004); Riley et al. (2011); Zhu et al. (2014).

Methane productivity in each layer of moistened soil at time t, following Christensen and Cox (1995), linearly depends on the integral of positive temperature values

$$P_i(t) = \gamma \cdot \left(\alpha + \beta \int_0^t T_i(\tau) d\tau \right)$$

Figure 3.

Since α = 42.5 [mgCH_4 m-3 day-1] and β = 0.0375 [mgCH_4 m-3 day-2 ºC-1] are empirical coefficients established in Christensen and Cox (1995) based on experimental data for the tundra, a correction factor was introduced in the equation (2). This factor reflecting the ratio of the amount organic matter in the simulated cell RegCM4/CLM4.5 for other botanical-geographical areas of the region to a similar value for the tundra zone. This coefficient reflects the ratio of the amount of organic matter in the modeled cell of RegCM4/CLM4.5 for other botanical-geographical areas of the region to a similar value for the tundra zone. This coefficient was found according to the data presented in the database Sheng et al. (2004).

RegCM4/CLM4.5 model and computational experiments design

The temperature T_i and relative moisture content Θ_i of each soil layer required for calculations were determined using the regional climate model RegCM4/CLM4.5 (Pal et al. 2007; Giorgy et al. 2012). The dynamic core of the model is the hydrostatic version of the mesoscale model MM5. A description of the main modules of RegCM4 and the model configuration used in the calculations are given in our previous works (Lagutin et al. 2014; Lagutin et al. 2017; Lagutin et al. 2018; Makushev et al. 2016b). To calculations of methane emissions the modeling results obtained for the region with coordinates (50°–75° N, 55°–95° E) were used. The analysis of the results was carried out only for model cells falling within the zone (55°–73°N, 60°–90°E) and containing, in accordance with the database Sheng et al. (2004), wetland complexes. The cells of the region containing wetland complexes and the proportions of wetlands in them are shown in Figure 2 on a grid with a spatial resolution of 40×40 km, adopted in the RegCM4 model.

When modeling the characteristics of the climate system, data from the NCEP- DOE AMIP-II (R2) reanalysis (Kanamitsu et al. 2002) and the HadGEM2-ES global model (Collins et al. 2011) were used to set the initial and boundary conditions for the RCP 4.5 and RCP 8.5 scenarios of possible evolution of the climate system (Moss et al. 2010).

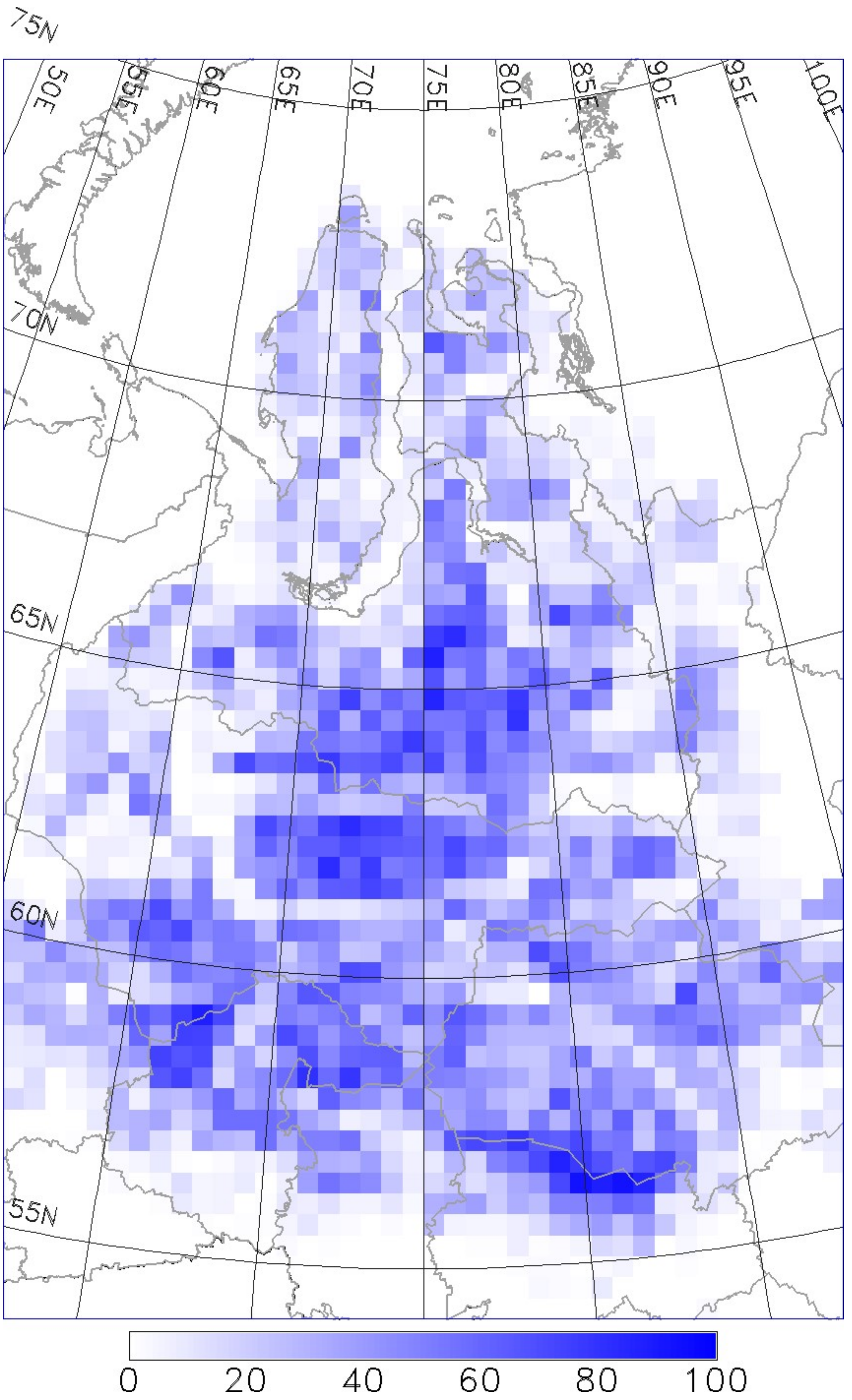
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Figure 4. ***Figure 2.*** *Wetland complexes of Western Siberia and their fractions on a 40×40 km grid of the RegCM4 model according to data from (Sheng et al. 2004).*

The quality of the RegCM4 model's reproduction of surface air temperature and anomalies of total annual precipitation intensity, as well as the annual cycle and interannual variability of outgoing long-wave radiation, was verified by the authors in a series of computational experiments presented in Lagutin et al. (2014); Lagutin et al. (2017); Lagutin et al. (2018); Makushev et al. (2016b). The main result of previous research is the conclusion about the successful use of the RegCM4 model in describing the contemporary climate of Western Siberia and the possibility of its use for modeling future climate. To verify the quality of modeling of temperature and soil moisture, additional comparisons of model results with ERA5 reanalysis data (Hersbach et al. 2020) were carried out.

Figure 3 shows the results of comparisons of the temperature and moisture content in the soil layers in depth 0–7 cm, 7–49 cm and 49–91 cm obtained using the RegCM4/CLM4.5 model with ERA5 reanalysis data for the study domain (55°–73°N, 60°–90°E). It has been established that for the territory of Western Siberia for 2000–2013 the temperature difference does not exceeds 1 ºC, basically. The volumetric moisture content bias varies from 10 to 20% depending on the layer depth and season. Note that such error in moisture content is acceptable in this class of problems.

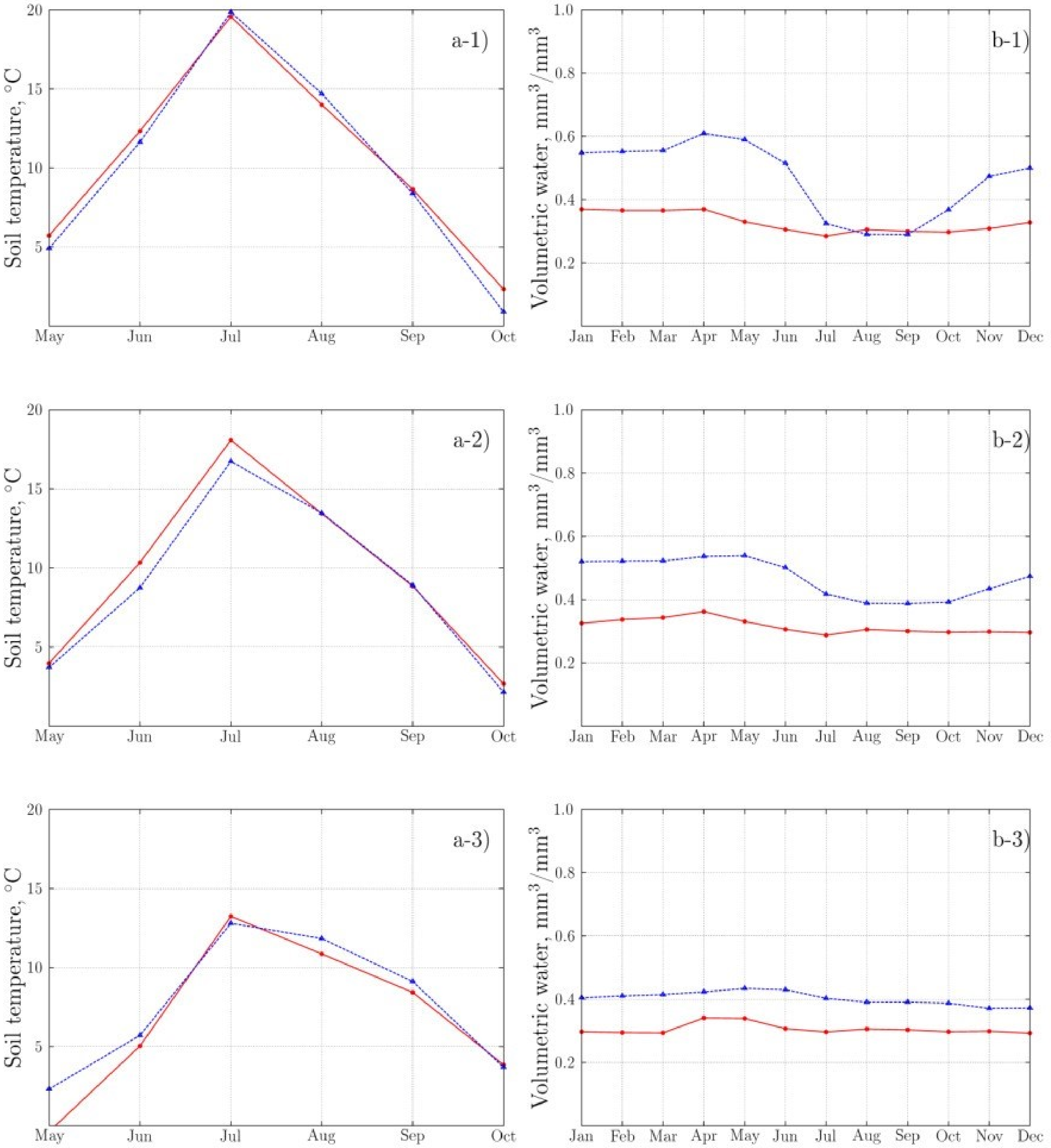

Figure 5. ***Figure 3.*** *Comparisons of ERA5 reanalysis (Hersbach et al. 2020) (solid red line) and RegCM4/CLM4.5 data (dashed blue line) for soil temperature (a) and volumetric moisture content (b) for the study domain in three ERA5 soil layers: (1) – layer 0–7 cm, (2) – layer 7–49 cm, (3) – layer 49–91 cm.*

Result

At the first stage of the research, computational experiments were carried out to test the possibility of using a modified empirical model Christensen and Cox (1995), created on the basis of experimental data for the tundra, to estimate methane emissions in the taiga zone of Western

Siberia. Calculations within the framework of model (1)–(2) were carried out for subzones of the northern, middle and southern taiga using the boundaries given in Glagolev et al. (2012), and for the territory of the Tomsk region, the wetland complexes of which are located in the subzones of the middle and southern taiga. The results of calculations of methane emissions for 1999–2010 are shown in Figure 4.

A comparison of the obtained in our study data with the results of Glagolev and Shnyrev (2008) showed that the average values of methane emissions for these zones 3.95 and 0.94 TgCH_4/yr are in good agreement with ground-based observation data 3.95 and 0.67 Tg CH_4/yr.

The comparison results presented above led the authors to the conclusion that it is possible to use the approach Christensen and Cox (1995), in which the total daily methane output is determined by the sum of positive temperature values accumulated in the soil at that time and its moisture content, and the RegCM4/CLM4.5 data for modeling methane emission from the wetland complexes of Western Siberia.

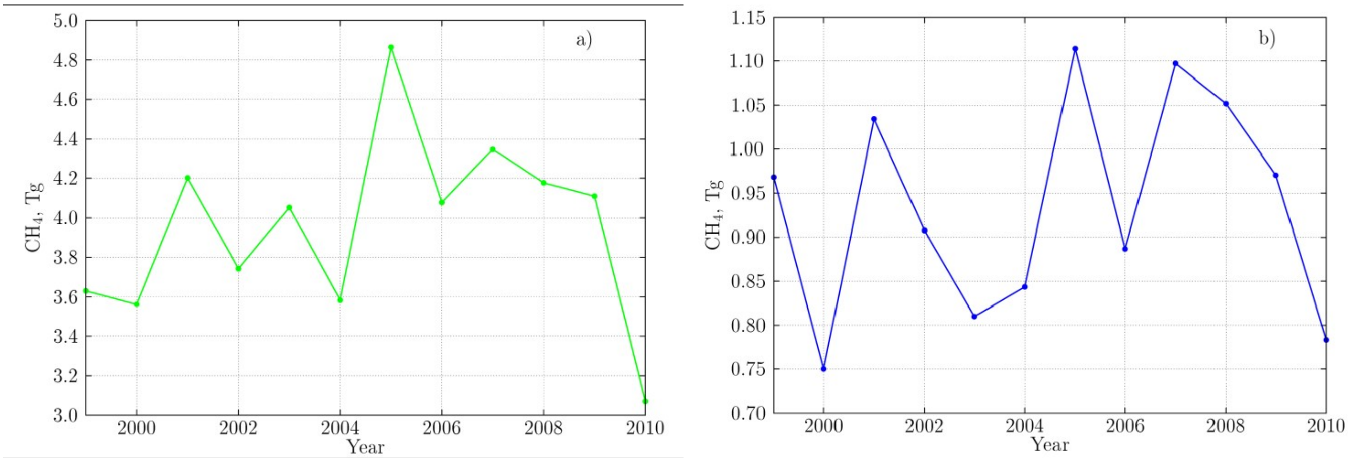

Figure 6. ***Figure 4.*** *Methane emissions from the wetland complexes in Western Siberia in 1999–2010 according to the results of the RegCM4/CLM4.5 model: a) taiga zone; b) the territory of the Tomsk region.*

Results of calculations of CH_4 emissions from the wetland complexes of Western Siberia for the period 2000–2050 are shown in Figure 5. Analysis of these data leads to the following conclusions.

1. It has been established that for the wetland ecosystems of Western Siberia for 2000–2013 model estimates of methane emissions vary from ~3.57 to 5.52 Tg/ yr. The rate of change in methane emissions during this period is practically neutral, the average emission value is 4.34 Tg/yr. An increase in CH_4 emissions is observed only in the tundra and forest-tundra zones.

2. Obtained in this work for 2000–2013 the average methane emission estimate of 4.34 Tg/year is in good agreement with the result of 3.91 ± 1.29 Tg/yr (Glagolev et al. 2011). Established in work for 2003–2009 the average emission of 4.6 Tg/yr is slightly higher than the result of 3.0±1.4 Tg/yr, which was obtained in Kim et al. (2011) for the same period.

3. The range of changes in the predicted values of methane emissions for the RCP 4.5 and RCP 8.5 scenarios, shown in Figure 5 for 2021–2050, is larger and varies from 3.9 to 7.6 Tg/yr. The average emission values are 5.0 and 5.8 Tg/yr, respectively. CH_4 emission trends during this period are also practically zero. This is due to the fact that the increase in temperature is compensated by a decrease in soil moisture content.

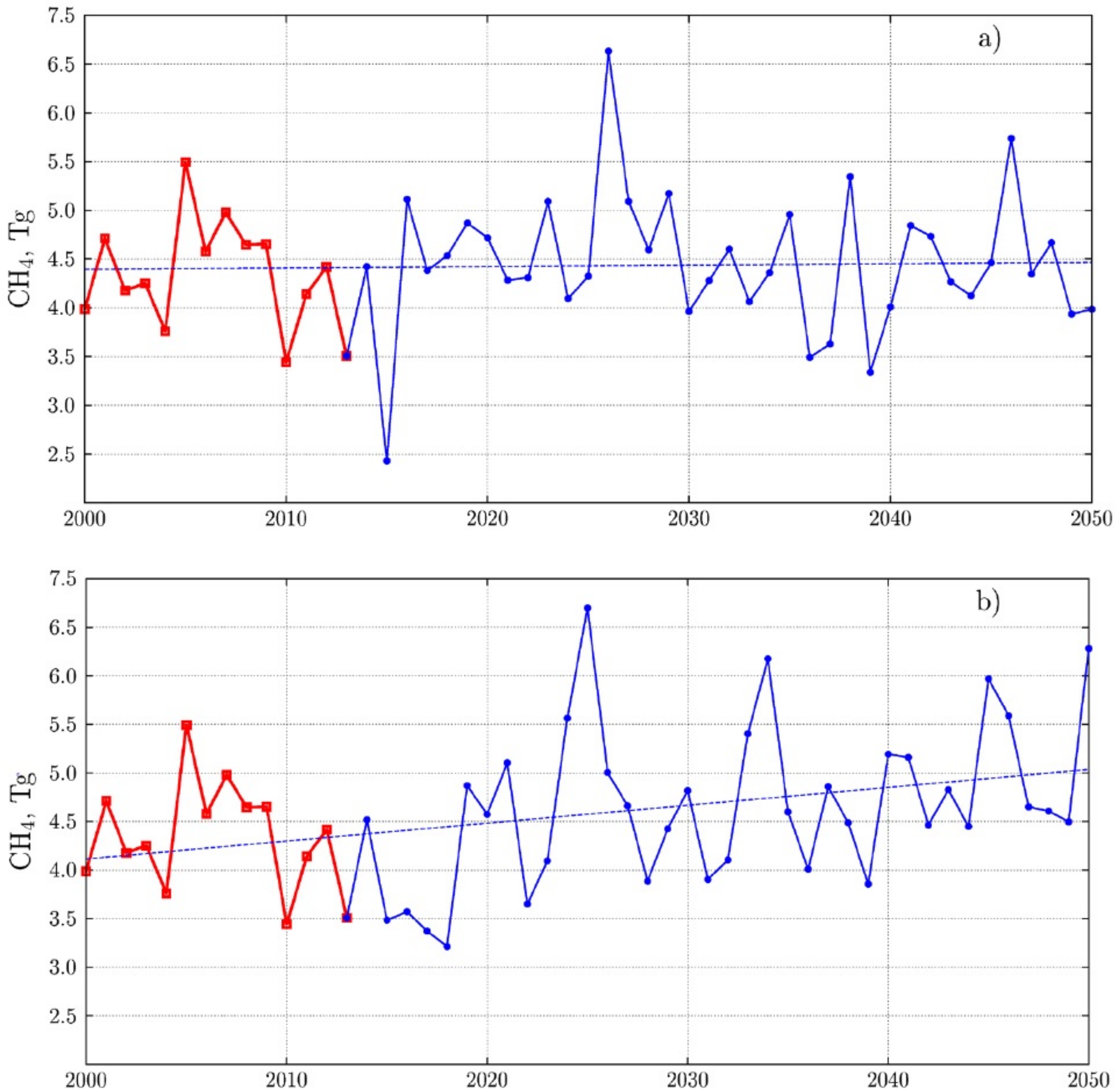

Figure 7. ***Figure 5.*** *Annual methane emission from wetland complexes of Western Siberia obtained using the RegCM4/CLM4.5 data. The initial and lateral boundary conditions for the period 2000–2013 (bold red line) are provided by the NCEP-DOE AMIP-II (R2) (Kanamitsu et al. 2002) reanalysis and for the period 2013–2050 (bold blue line) according to the global model HadGEM2-ES (Collins et al. 2011) for RCP 4.5 (a) and RCP 8.5 (b) scenarios. Dashed blue lines are the growth rate of methane emission.*

Discussion

Western Siberia is the largest region on the planet covering ~2.9 M km^2 within 62°– 89°E and 53°–73°N (Xi et al. 2023), containing the highest latitude wetland system. The area of wetlands and aquatic systems of the region accounts for approximately 27% of the total global one. According to contemporary estimates, the wetland complexes of Western Siberia contain about 40% peat deposits over the world (see Xi et al. (2023) and references in it). These deposits, partly located in the permafrost zone, contain significant amounts of organic carbon (about 70 Pg C). With a warming climate and thawing soil, large amounts of soil carbon can be released in permafrost zones. Fast degradation of this carbon will, in turn, lead to the release of methane into the atmosphere.

Lakes and open water bodies are the second largest source of methane after wetlands (Kyzivat et al. 2022). According to Peregon et al. (2009), the area of aquatic ecosystems in the region, such as lakes, is ~0.081 million km2.

In a recent study, Xi et al. (2023) obtained quantitative estimates of methane emissions from wetland complexes and aquatic ecosystems in Western Siberia. In the calculations, the authors used two biogeochemical models of methane emission from wetland complexes and three data sets with information about aquatic ecosystems to set initial conditions (for details, see (Xi et al. 2023). In the figure 6, by blue dots and a line shown the results of modeling the total methane emissions from wetland complexes and aquatic system obtained Xi et al. (2023) using data sets MF (Matthews and Fung 1987) for wetlands and GSW (Pekel et al. 2016) for aquatic ecosystems.

The results of our studies obtained within RegCM4/CLM4.5 model for 2000- 2021 are generally consistent with the conclusions of Xi et al. (2023). Red points and line on Figure 6 are the total methane emission from wetland and aquatic system. The contribution of wetland complexes for RCP 4.5 and RCP 8.5 scenarios is shown in Figure 6. To take into account the contribution of aquatic system, the results Xi et al. (2023) obtained using the GSW data set were used.

Conclusion

The paper presents the results of study of the interannual variability of methane emissions from wetland ecosystems of Western Siberia in 2000–2050. The contribution of wetland complexes to the total CH_4 emission was obtained within the framework of the emission model Christensen and Cox (1995). In this model the total daily methane flux is determined by the sum of positive temperatures accumulated in the soil and the soil moisture content. Characteristics of the soil were obtained using regional climate model RegCM4/CLM4.5 (Pal et al. 2007; Giorgy et al. 2012). The information basis of the study is the results of the reanalysis NCEP-DOE AMIP-II (R2) (Kanamitsu et al. 2002) obtained for 2000–2013. HadGEM2-ES global model forecast data (Collins et al. 2011) within the RCP4.5 and RCP8.5 scenarios of possible evolution of the global climate system were used for 2013–2050.

It is shown that our results are in good agreement with ERA5 reanalysis data (Hersbach et al. 2020), as well as the results of studies of methane emissions from wetland complexes and aquatic system of Western Siberia published in the papers by other authors (Glagolev et al. 2011; Xi et al. 2023; Zhang et al. 2023; Feng et al. 2023).

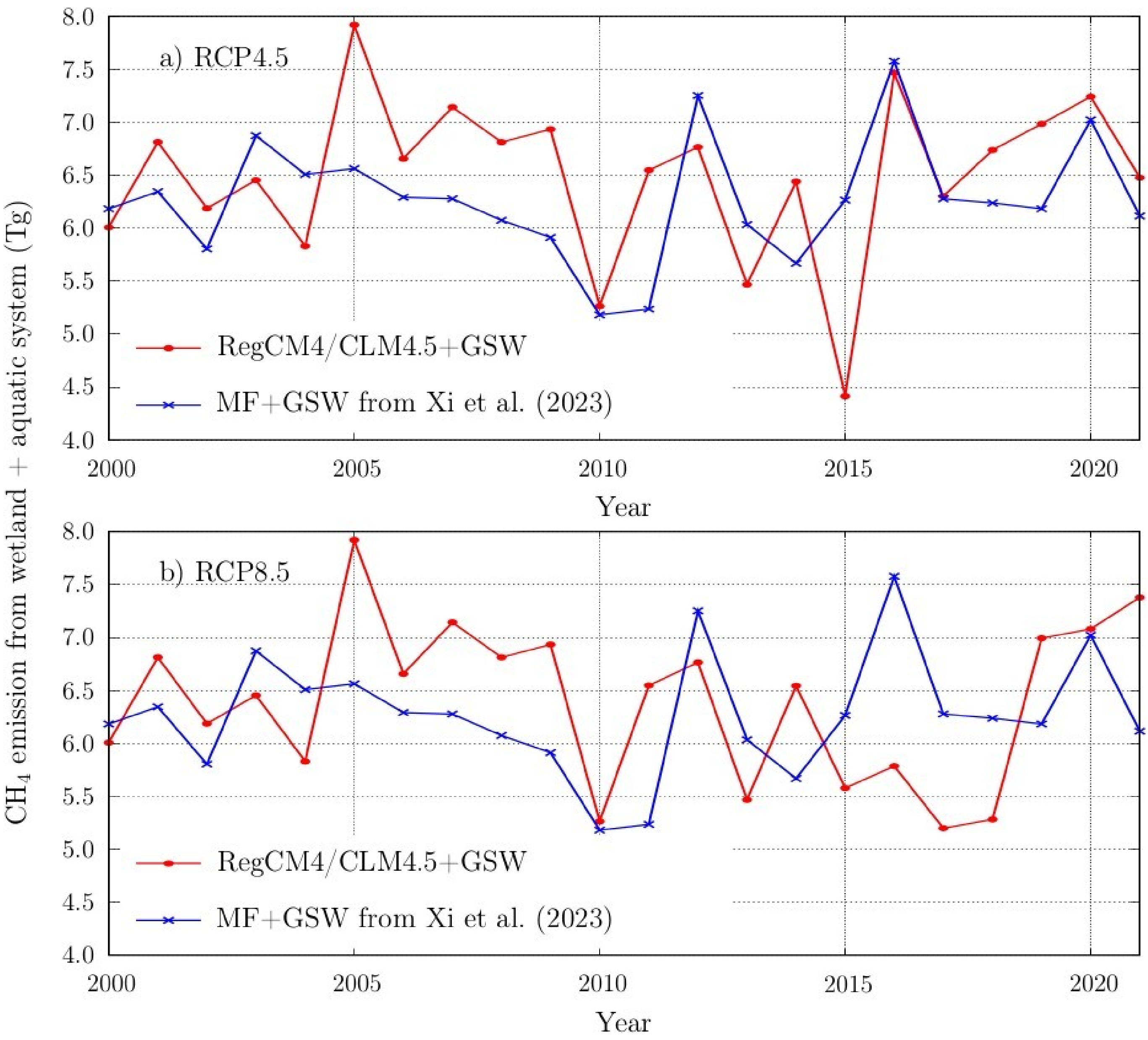

Figure 8. ***Figure 6.*** *Total methane emission from wetland and aquatic system of the Western Siberia region from 2000 to 2021 for RCP 4.5 (a) and RCP 8.5 (b) scenarios. Blue points and line are results of Xi et al. (2023), red points and line are our results obtained within RegCM4/ CLM4.5 model for 2000–2021.*

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