communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-00898-z OPEN

Delaying methane mitigation increases the risk of breaching the 2 °C warming limit

Claude-Michel Nzotungicimpaye [1,2,3✉], Alexander J. MacIsaac[1] & Kirsten Zickfeld[1]

Atmospheric methane levels are growing rapidly, raising concerns that sustained methane growth could constitute a challenge for limiting global warming to 2 °C above pre-industrial levels, even under stringent CO_2 mitigation. Here we use an Earth system model to investigate the importance of immediate versus delayed methane mitigation to comply with the 2 °C limit under a future scenario of low CO_2 emissions. Our results suggest that methane mitigation initiated before 2030, alongside stringent CO_2 mitigation, could enable to limit global warming to well below 2 °C over the next three centuries. However, delaying methane mitigation to 2040 or beyond increases the risk of breaching the 2 °C limit, with every 10-year delay resulting in an additional peak warming of ~0.1 °C. The peak warming is amplified by the carbon-climate feedback whose strength increases with delayed methane mitigation. We conclude that urgent methane mitigation is needed to increase the likelihood of achieving the 2 °C goal.

[1] Department of Geography, Simon Fraser University, Burnaby, BC, Canada. [2] Department of Geography, Planning and Environment, Concordia University, Montréal, QC, Canada. [3] Climate and Environment, St. Francis Xavier University, Antigonish, NS, Canada. ✉email: cnzotung@stfx.ca

Methane (CH_4) is a potent greenhouse gas, second only to CO_2 in the contribution to global temperature increase relative to pre-industrial levels[1]. Atmospheric CH_4 levels have grown rapidly since the year 2007[2,3]. The mean atmospheric CH_4 concentration ([CH_4]) currently exceeds 1900 parts per billion (ppb), which is >2.5 times larger than the pre-industrial average[4]. Recent trends of observed CH_4 levels are tracking future scenarios of unmitigated emissions[5,6]. For more than three decades, global CH_4 emissions have been dominated by anthropogenic sources mostly related to fossil fuel exploitation, livestock production, waste and agriculture[2,3,7]. Several studies have highlighted the importance of CH_4 mitigation for tackling climate change in the current century, in parallel with efforts to decarbonize the world economy[8–10].

A salient outcome of the 2015 Paris Agreement is the international commitment to keep global warming to well below 2 °C above pre-industrial levels, and pursue efforts to limit the mean global temperature increase to 1.5 °C above pre-industrial levels[11]. Achieving these temperate goals will require reaching net-zero CO_2 emissions alongside deep reductions in CH_4 and other non-CO_2 emissions by or around mid-century[12]. While the need for urgent CH_4 mitigation is now recognized (e.g. the Global Methane Pledge following COP26[13]), it is necessary to assess the importance of immediate versus delayed CH_4 mitigation to comply with the temperature goals in the Paris Agreement—particularly taking into account potential Earth system feedbacks. There is still limited knowledge about (i) the importance of biogeochemical feedbacks[14,15] in the context of CH_4 mitigation for achieving the Paris temperature goals[16,17], and (ii) long-term (i.e. multi-century) climate impacts of delaying or failing to mitigate CH_4 in the current century[18,19].

In this study, we use an Earth system model with an interactive CH_4 cycle to investigate the importance of immediate versus delayed CH_4 mitigation to comply with stringent warming limits in the Paris Agreement. It is important to note that: (i) currently, there are very few Earth system models driven by CH_4 emissions in their representation of the global CH_4 cycle[17,20]; and (ii) previous research applying an Earth system modeling approach to investigate CH_4 mitigation and its implication for meeting stringent temperature goals have relied on scenarios of prescribed [CH_4] without considering explicit changes in anthropogenic CH_4 emissions, potential climate-CH_4 feedbacks, and climate impacts of CH_4 mitigation beyond the 21st century[16]. We use version 2.10 of the University of Victoria Earth System Climate Model (UVic ESCM)[21], into which we implemented a simplified representation of the global CH_4 cycle—featuring simulated wetland CH_4 emissions (including CH_4 emissions from previously frozen soil carbon upon permafrost thaw)[22] and atmospheric CH_4 decay (See Methods). We validate the model against historical [CH_4] data and estimations of the global CH_4 budget in recent decades (See Supplementary Notes 1 & 2).

To assess the importance of timing for CH_4 mitigation to achieve the 2 °C temperature goal, we prescribe anthropogenic CH_4 emissions according to two Shared Socioeconomic Pathways (SSPs)[23,24]: (i) SSP1-2.6, a scenario featuring immediate CH_4 mitigation; and (ii) SSP3-7.0, a scenario without CH_4 mitigation throughout the 21st century. We design four additional scenarios of anthropogenic CH_4 emissions by assuming different initiation of CH_4 mitigation over the next few decades. These scenarios follow the SSP3-7.0 trajectory up to a specific year (2020, 2030, 2040 and 2050) and decline linearly to reach the same amount of CH_4 emissions as SSP1-2.6 in 2100, and then evolve according to the SSP1-2.6 extension beyond the 21st century (Fig. 1). These mitigation scenarios assume deep reductions in anthropogenic CH_4 emissions, corresponding to 69–78% of emission reductions between the year of peak emissions and the year 2100

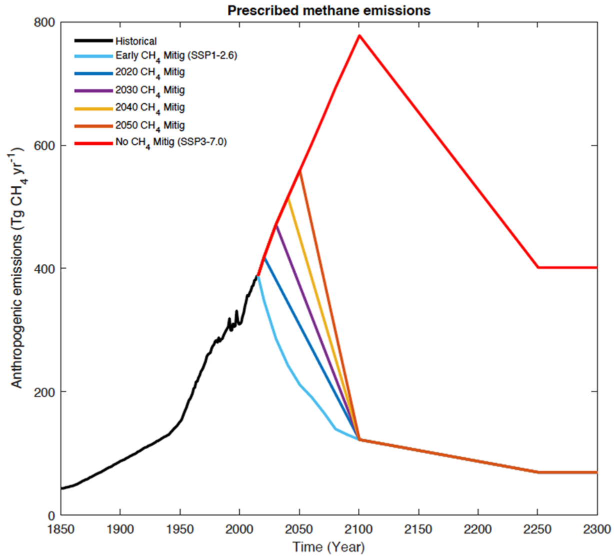

Fig. 1 Anthropogenic CH_4 emissions prescribed to the UVic ESCM in this study. Emissions in the early mitigation scenario ("Early Mitig") correspond to SSP1-2.6, whereas emissions without mitigation ("No Mitig") correspond to SSP3-7.0. Immediate and delayed mitigation scenarios follow the SSP3-7.0 CH_4 emission trajectory to the specified point in time and decline linearly to reach the same amount of CH_4 emissions as SSP1-2.6 in 2100, and evolve according to the SSP1-2.6 extension beyond the 21st century.

(Supplementary Table 1). CH_4 mitigation approaches that are currently achievable with existing strategies and technologies (i.e. technically feasible solutions) could– once deployed– lead to the elimination of >50% of global anthropogenic CH_4 emissions by the year 2050, with large contributions from cutting fossil fuel and solid waste emissions[25]. By design, our idealized mitigation scenarios allow us to compare the effect of immediate versus delayed CH_4 mitigation on the global climate at the end of the 21st century and beyond. We further assume that all other future anthropogenic forcings (including CO_2 emissions) evolve according to SSP1-2.6, which is a scenario aimed at limiting global warming to below 2 °C throughout the 21st century[26].

Results

Delaying CH_4 mitigation results in higher peak warming. The timing of CH_4 mitigation affects peak levels of [CH_4], [CO_2], and surface air temperature (SAT) in the future. According to our model, every 10-year delay in CH_4 mitigation increases the [CH_4] peak by 150-180 ppb (Fig. 2b). As such, delaying CH_4 mitigation to the 2040-2050 decade will increase the [CH_4] peak by 450–540 ppb relative to CH_4 mitigation initiated at or around 2020. The [CH_4] increase has a direct effect on global mean surface air temperature (SAT). For every 10-year delay in CH_4 mitigation, our model simulates an additional peak warming of ~0.1 °C (Fig. 2d). Delaying CH_4 mitigation to or around mid-century will increase the peak warming by 0.2–0.3 °C relative to a CH_4 mitigation initiated at present-day. Through feedback mechanisms operating in the Earth system (discussed below), one indirect effect of delaying CH_4 mitigation manifests with atmospheric CO_2 concentration ([CO_2]). Our model suggests that every 10-year delay in CH_4 mitigation implies an increase in the [CO_2] peak by 2-3 ppm (Fig. 2c). Consequently, delaying CH_4 mitigation to the 2040-2050 decade will increase the [CO_2] peak by 6-9 ppm relative to CH_4 mitigation at present-day. Relative to the early mitigation scenario (SSP1-2.6), delaying CH_4 mitigation to the 2040-2050 decade implies more [CH_4]

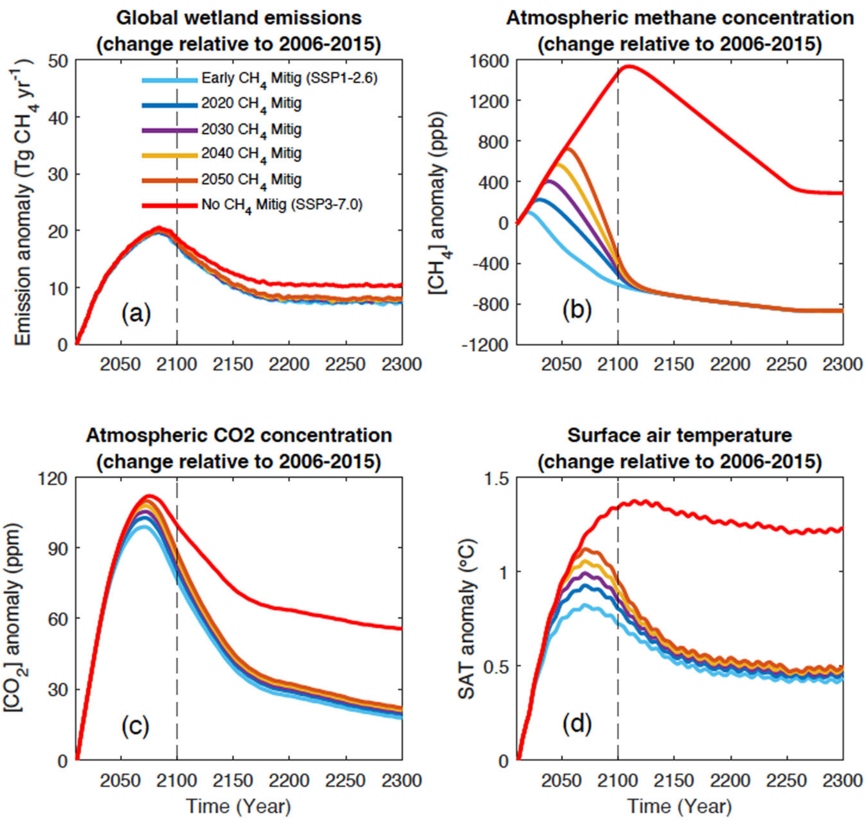

Fig. 2 Projected changes in atmospheric composition and temperature relative to present-day conditions under the mitigation scenarios explored in this study. Changes are shown for (**a**) global wetland CH_4 emissions, (**b**) atmospheric CH_4 concentration, (**c**) atmospheric CO_2 concentration, and (**d**) surface air temperature (SAT) relative to 2006-2015 for different initiation of CH_4 mitigation under the assumption that all non-CH_4 forcing agents (including CO_2) from anthropogenic sources evolve according to SSP1-2.6. The variability in the SAT curves is associated with the solar cycle.

(~200 ppb) and warming (~0.2 °C) at the year 2100 (Fig. 2b, d and Supplementary Note 3).

The decline in [CH_4] in response to CH_4 mitigation depends on the balance between CH_4 sources and sinks (Supplementary Fig. 1). CH_4 sources are dominated by anthropogenic CH_4 emissions (Fig. 1 and S1a), whereas CH_4 sinks in our model are proportional to the atmospheric CH_4 burden (Methods and Supplementary Fig. 1b, c). A delayed CH_4 mitigation results in a higher atmospheric CH_4 burden and [CH_4] than for an early mitigation, which implies a lag in the decline of CH_4 sinks and [CH_4] for the delayed mitigation in comparison to the early mitigation. Implications of this lag are most noticeable towards the end of the 21st century: while total CH_4 emissions converge in 2100 for all mitigation scenarios, the atmospheric CH_4 burden around the year 2100 remains high for delayed CH_4 mitigation relative to early CH_4 mitigation owing to a lag in CH_4 sinks (Supplementary Fig. 2). Overall, relative to the early CH_4 mitigation (SSP1-2.6), simulated CH_4 sinks in 2100 are ~65 Tg CH_4 yr^{-1} higher for CH_4 mitigation delayed to 2040-2050 (See Supplementary Note 4).

The peak warming is amplified by biogeochemical feedbacks. In our model simulations, SAT changes are influenced by biogeochemical feedbacks in addition to the timing of CH_4 mitigation. In particular, we find that the feedback of SAT changes on the atmospheric CO_2 concentration (referred to as the carbon-climate feedback) contributes to increasing peak SAT differences between early and delayed CH_4 mitigation. While we prescribe the same anthropogenic CO_2 emissions in all our model simulations (See Methods), atmospheric CO_2 levels are projected to be higher for delayed CH_4 mitigation scenarios than for early CH_4 mitigation scenarios (Fig. 2c). In comparison to early CH_4 mitigation, delayed CH_4 mitigation results in high [CH_4] levels that lead to high SAT levels. Enhanced global warming results in high [CO_2] levels, which in turn contribute to increase the SAT differences between early and delayed CH_4 mitigation scenarios. Such feedbacks between SAT and [CO_2] involve the response of natural CO_2 sinks to global warming and climate change. For instance, increased SAT enhances the release of CO_2 through soil respiration and weakens the uptake of atmospheric CO_2 by oceans through the solubility pump, resulting in enhanced [CO_2] and an amplification of global warming[14]. Overall, we deduce that the carbon-climate feedback amplifies the SAT response in late versus early CH_4 mitigation scenarios (Fig. 2d and Fig. 3). To quantify the contribution of the carbon-climate feedback to additional peak warming from delayed CH_4 mitigation, we performed additional model simulations with prescribed CO_2 concentration from the early mitigation scenario (i.e. Early CH_4 Mitig SSP1-2.6). These model simulations suppress the warming signal from delayed CH_4 mitigation that is due to the carbon-climate feedback, and their difference with our standard model simulations allows to quantify the magnitude of the feedback. According to our results, the contribution of the carbon-climate feedback to the peak warming increases for every 10-year delay in CH_4 mitigation (Fig. 3). The peak warming attributable to the feedback ranges from ~0.03 °C for CH_4 mitigation initiated in 2020 to ~0.06 °C for CH_4 mitigation initiated in 2050 (Fig. 3).

In contrast, we do not detect a strong feedback between global warming and wetland CH_4 emissions in our model simulations–despite changes in precipitation patterns and wetland areal extents between the different mitigation scenarios explored in this study (Supplementary Fig. 3). Differences in projected wetland CH_4

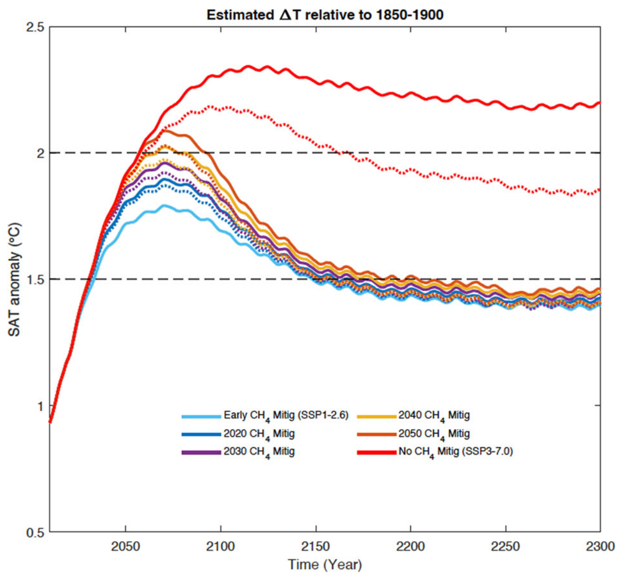

Fig. 3 Projected changes in air temperature relative to the pre-industrial era under the mitigation scenarios explored in this study. Changes are shown for global mean surface air temperature (SAT) relative to 1850–1900 for different initiation of CH_4 mitigation under the assumption that non-CH_4 forcing agents evolve according to SSP1-2.6. An estimate of 0.97 °C is considered for the global warming level in the 2006-2015 decade relative to the 1850–1900 period[29]. The variability in the SAT curves is associated with the solar cycle. Given that the observed historical warming level for the 2006-2015 decade relative to the 1850–1900 period is associated with an uncertainty of ±0.12 °C[29], we provide a version of this figure with the uncertainty range in the supplementary information (Supplementary Fig. 5). The dashed lines correspond to model simulations with prescribed CO_2 concentration from the Early CH_4 Mitig (SSP1-2.6) scenario, which imply climate projections without the carbon-climate feedback. The difference between dashed and continuous lines of the same color illustrates the magnitude of the carbon-climate feedback.

emissions between early and delayed CH_4 mitigation scenarios do not exceed 1 Tg CH_4 yr^{-1} for more than two centuries (Fig. 2a), which translates into a negligible fraction of [CH_4] and SAT differences between these mitigation scenarios. We conclude that the importance of the feedback between wetland CH_4 emissions and climate change is small under the low CO_2 emission scenarios explored in this study.

Timing of CH_4 mitigation and stringent warming limits. Determining the historical warming level is a critical aspect for assessing the implications of future climate projections on global warming limits in the Paris Agreement[27,28]. Our model simulates a global warming level of 1.1 °C for the 2006-2015 decade relative to the 1850–1900 period, whereas the recent Sixth Assessment Report (AR6) by the IPCC provides an estimate of 0.97 °C for the global warming level over the same decade relative to the same baseline period[29]. Hence, for this study, we adopt the above IPCC estimate to project future global warming levels associated with different scenarios of CH_4 mitigation (Fig. 3).

According to our model simulations, the 2 °C temperature goal can be achieved through rapid and deep cuts in anthropogenic CH_4 emissions along with stringent CO_2 mitigation. Our results suggest that global warming relative to the pre-industrial period (1850–1900) could be limited to well below 2 °C throughout the 21st century if global-scale CH_4 mitigation is initiated before 2030 while all other anthropogenic emissions evolve according to SSP1-2.6 (Fig. 3). However, if CH_4 mitigation is delayed to 2040, our results suggest that the 2 °C warming target will be overshot for at least two decades in the 21st century (Fig. 3), with longer mitigation delays implying longer overshoot periods of the 2 °C threshold. As expected with SSP1-2.6, all our considered CH_4 mitigation scenarios imply a breaching of the 1.5 °C limit relative to the 1850–1900 levels (Fig. 3).

Timing of CH_4 mitigation and its implications beyond the 21st century. The timing of CH_4 mitigation over the next three decades has implications beyond the 21st century. While anthropogenic CH_4 emissions prescribed to our model converge by the year 2100 for all considered scenarios other than SSP3-7.0 (Fig. 1), atmospheric [CH_4] levels for delayed and early CH_4 mitigation scenarios converge in the first half of the 22nd century (Fig. 2b). However, SAT differences between our mitigation scenarios persist for more than two centuries in the future (Fig. 2d), owing partly to the carbon-climate feedback (Fig. 2c and Fig. 3) as well as inertia in the climate system. These results suggest that, although CH_4 stays in the atmosphere for only about a decade, delaying CH_4 mitigation by 10–30 years will have an impact on global warming over many centuries.

The timing of CH_4 mitigation has long-term implications for achieving the temperature goals in the Paris Agreement. When implemented alongside CO_2 mitigation, rapid and deep reductions in CH_4 emissions will provide long-term benefits with regards to lowering global warming levels. According to our model simulations, initiating CH_4 mitigation before 2050 will increase the likelihood of limiting global warming to 1.5 °C in the long run—from the second half of the 22nd century onwards, after an overshoot in the first half of the 21st century (Fig. 3). However, even under the assumption of net-zero CO_2 emissions by mid-century, an eventual failure to mitigate CH_4 in the current century will raise global warming to >2 °C above pre-industrial levels throughout the 21st century and beyond (Fig. 3). We conclude that rapid CH_4 mitigation efforts will provide a long-term safeguard for the temperature goals in the Paris Agreement, whereas a failure to mitigate CH_4 within the next few decades will constitute a serious challenge for achieving the 2 °C warming limit.

Discussion

Previous studies have demonstrated that deep reductions in CH_4 emissions alongside stringent CO_2 mitigation by mid-century are needed to limit global warming to below 2 °C above pre-industrial levels, in agreement with our results[18,19,30,31]. Our study presents two additional findings: (i) the importance of biogeochemical feedbacks in the context of CH_4 mitigation to achieve stringent temperature limits, and (ii) long-term climate impacts of a delay or failure to mitigate CH_4 in the current century. Our study shows that the carbon-climate feedback amplifies the SAT response for delayed versus early CH_4 mitigation. In particular, our results suggest that the strength of the carbon-climate feedback increases for every 10-year delay in CH_4 mitigation (Fig. 3). The simulated contribution from the carbon-climate feedback to the peak warming ranges from ~0.03 °C to ~0.06 °C for CH_4 mitigation initiated in 2020 and 2050, respectively. Given that the UVic ESCM has a relatively high carbon-climate feedback parameter compared to most other ESMs[32] and a TCRE (transient climate response to cumulative emissions) value close to the CMIP6 ensemble mean[14,21], we infer that our estimated warming from the carbon-climate feedback lies in the upper 50-percentile of what the CMIP6 ESM ensemble would simulate in the context of this study. With regards to climate-CH_4 feedbacks, our model simulations suggest a negligible contribution from wetland CH_4 emissions to temperature change for every 10-year delay CH_4

mitigation in a low CO_2 emission scenario. However, we do not rule out the potential for a strong climate-CH_4 feedback involving wetlands, wildfires, and atmospheric CH_4 oxidation[15]—which would imply a potential underestimation of the contribution from the climate-CH_4 feedback to the additional peak warming under delayed CH_4 mitigation.

Despite that CH_4 stays in the atmosphere for only about 10 years, delaying CH_4 mitigation by 2-3 decades will have an impact on global warming over many centuries (Fig. 2d and Fig. 3). Such a delayed CH_4 mitigation may result in other long-term impacts such as a persistent sea-level rise over many centuries[33]. On the contrary, early CH_4 mitigation reduces the risk of losing the summer sea-ice across the Arctic Ocean[34]. A failure to mitigate CH_4 in the current century implies a high risk for global warming to exceed the 2 °C warming limit for more than two centuries even under net-zero CO_2 emissions by 2050 (Fig. 3). Such an overshoot of the 2 °C threshold has the potential to increase the risk for record-breaking climate extremes[35] and tipping elements in the Earth's climate system such as the dieback of the Amazon rainforest as well as the melting of the Greenland and West Antarctic Ice Sheets[36].

While mitigation research and efforts generally focus on achieving net-zero CO_2 emissions by 2050[12,19], it is becoming more clear that rapid reductions of both CO_2 and CH_4 emissions are crucial for holding global warming to well below 2 °C above pre-industrial levels[37]. To pave the way for CH_4 mitigation in the context of meeting the temperature goals in the Paris Agreement, there is a growing number of studies on: (i) understanding processes and reasons behind changes in [CH_4] trends in recent decades[2,5], (ii) constraining the global CH_4 budget[2,38], and (iii) developing strategies for reducing anthropogenic CH_4 emissions[39] as well as technologies for atmospheric CH_4 removal[40]. Research suggests that many anthropogenic sources of CH_4 can be reduced cost-efficiently[19,25,39,41], and that the priority for deep emission cuts should be in the energy, industry and transport sectors without neglecting the high potential from the waste and agricultural sectors[6,7,19,30,31,39]. If deployed rapidly, readily available measures for large-scale CH_4 mitigation by sector can contribute to slowdown global warming[18]. In addition to the Global Methane Pledge by >100 countries representing 70% of the global economy[13], multilateral partnerships already exist to support large-scale CH_4 mitigation (e.g. the Climate and Clean Air Coalition as well as the Global Methane Initiative[42–45]). Given that atmospheric CH_4 is a precursor to ground-level ozone (O_3)—an air pollutant with negative impacts on human health and crop yields, CH_4 mitigation offers the opportunity of simultaneously tackling climate change and improving air quality, global health, as well as food security[17,46,47].

Limitations of this study include uncertainties in the areal extent and dynamics of natural wetlands, as well as in the wide array of physical, biological, and chemical controls on CH_4 production and oxidation which determine the response of wetland CH_4 emissions to climate change[48]. Despite its simplicity, our wetland CH_4 model is capable of reproducing present-day wetland CH_4 emissions based on soil moisture, carbon, and temperature simulated by the UVic ESCM[22] (Supplementary Table 2). Additional limitations of this study are associated with: (i) static CH_4 emissions from non-wetland natural sources, and (ii) a constant lifetime for atmospheric CH_4 as part of the parameterization for atmospheric CH_4 decay. Natural CH_4 emissions from non-wetland sources (such as termites, lakes, wildfires, geologic seeps, marine hydrates) are not represented in the UVic ESCM and are held fixed in our model simulations (See Methods). Processes governing the future evolution of these natural CH_4 sources are poorly understood[2,49].

The consideration of a constant lifetime for atmospheric CH_4 is a simplified assumption made in this study as part of initial steps to represent the atmospheric CH_4 decay and the global CH_4 cycle in the UVic ESCM (See Methods and Supplementary Note 5). In reality, the atmospheric CH_4 lifetime varies by a few months to a few years mostly due to changes in atmospheric chemistry associated with CH_4 sinks[50], and this variation in the CH_4 lifetime has been invoked to explain past changes in the growth rates of atmospheric CH_4 levels[3,50]. Variations in the atmospheric CH_4 lifetime are mainly regulated by a chemical feedback involving the oxidation of CH_4 by the OH radical[3,50], a process not simulated by our model. This feedback mechanism is such that increasing [CH_4] (e.g. under delayed CH_4 mitigation) reduces the abundance of the OH radical, which further increases [CH_4] and raises the global warming level. Therefore, one consequence of our assumption of a constant lifetime for atmospheric CH_4 is a potential underestimation of the [CH_4] peak in delayed mitigation scenarios. However, our main result that delaying CH_4 mitigation increases the risk of breaching the 2 °C warming limit is not considerably affected by the use of different values for the atmospheric CH_4 lifetime in the range of published estimates (i.e. 7–11 years)[2] (Supplementary Fig. 4).

By design, this study makes a fundamental assumption with regards to future emission scenarios: effective mitigation of CO_2, other non-CH_4 greenhouse gases (GHGs), as well as aerosols, except for CH_4. This assumption is such that future emissions of non-CH_4 GHGs (including CO_2) and aerosols decline by mid-century according to a scenario consistent with limiting global warming to 2 °C by 2100 (i.e. SSP1-2.6), while anthropogenic CH_4 emissions continue to increase throughout the next three decades and beyond (i.e. SSP3-7.0). While we acknowledge the importance of aerosols and other non-CO_2 forcing agents in the context of climate mitigation to achieve the temperature goals in the Paris Agreement[16,51], our future scenarios focus on CH_4 mitigation to investigate recent concerns raised about sustained [CH_4] growth since 2007 and the associated potential challenge for achieving the 2 °C warming limit even under stringent CO_2 mitigation by mid-century[5,38].

Our study suggests that aggressive reductions of anthropogenic CO_2 emissions without CH_4 mitigation could push the Earth system beyond the 2 °C warming limit above pre-industrial levels for more than two centuries in the future. Initiating large-scale CH_4 mitigation in the current decade, along with stringent CO_2 mitigation, can allow to achieve the temperature goals in the Paris Agreement. However, delaying CH_4 mitigation to the next decade or beyond will increase the risk of breaching the 2 °C warming limit. According to our model simulations, every 10-year delay in CH_4 mitigation will result in an additional peak warming of about 0.1 °C. Consequences of such an increased peak warming over time and breaching the 2 °C warming limit are widespread, including an increased risk for an Arctic Ocean without sea ice in the summer[34], record-breaking climate extremes[35], the dieback of the Amazon rainforest[36], the disintegration of major ice sheets[36], persistent sea-level rise over multiple centuries[33], and several other global and regional impacts of increasing global warming levels on natural and socio-economic systems[52,53]. Considering that [CH_4] has been rising steadily since 2007 in line with unmitigated emission scenarios[5,6], we highlight the importance of immediate cuts in anthropogenic CH_4 emissions globally, along with stringent CO_2 mitigation, in order to increase the likelihood of keeping global warming to well below 2 °C above pre-industrial levels. Actions associated with the Global Methane Pledge[13] launched at COP26 in November 2021 should not be delayed, because every year of delayed CH_4 mitigation implies additional global warming.

Methods

Model description. We use the University of Victoria Earth System Climate (UVic ESCM) for our simulations. The UVic ESCM consists of a 2-D (vertically-integrated) energy-moisture balance model for the atmosphere coupled to a comprehensive 3-D ocean general circulation model (OGCM) with marine biogeochemistry, a thermodynamic sea ice model, and a land surface model with dynamic vegetation as well terrestrial carbon fluxes (in the form of CO_2)[54,55]. In this study, we use a version of the EMIC based on UVic ESCM 2.10[21] which features a multi-layer ground structure (i.e. 14 ground layers of unequal thicknesses extending down to a depth of 250 m) that is capable of simulating permafrost freeze-thaw processes as well as permafrost CO_2 fluxes (i.e. CO_2 release and uptake)[56]. Furthermore, the version of the UVic ESCM used in this study simulates the spatial and temporal dynamics of wetlands[57]. In particular, sub-grid scale wetlands are identified in the EMIC following a TOPMODEL approach for global models[58]. The areal extent of wetlands varies in response to changes in soil hydrology (soil moisture content, runoff, surface inundation, etc.), which is affected by changes in precipitation, evapo-transpiration, temperature, vegetation—among many other atmospheric and terrestrial processes. In this study, we use a modified version of UVic ESCM 2.10 into which we incorporated a simplified representation of the global CH_4 cycle (See next sections).

Wetland CH_4 emissions. Wetland CH_4 emissions are simulated in the UVic ESCM following a recent model development[22]. Wetland CH_4 emissions are calculated as the balance between microbial production and oxidation of CH_4 in the soil column. CH_4 production is calculated in each soil layer as a function of moisture content, carbon content, temperature, and the relative depth from the soil surface. In this approach, soil moisture (i.e. water saturation) represents potential anoxic conditions. Soil carbon represents organic matter that may be accessed by methanogens. Soil temperature allows to estimate potential changes in methanogenic activity, whereas the relative depth from the soil surface allows to represent the net effect of depth-dependent controls on CH_4 production that are unresolved by the UVic ESCM (e.g. the quality of organic matter and the distribution of methanogens in the soil). CH_4 production is assumed to not take place in dry soil layers (i.e soil layers unsaturated with water) as well as in frozen soil layers. CH_4 oxidation is calculated for the entire soil column as a fraction of the amount of CH_4 produced in the soil column. The oxidized CH_4 fraction is determined based on an estimated oxic zone depth, which represents the prevalence of methanotrophs in the soil. This fraction increases as the oxic zone deepens. By design, our model simulates wetland CH_4 emissions associated with CH_4 production across the globe (including CH_4 emissions from previously frozen soil carbon upon permafrost thaw)[22].

Atmospheric CH_4 and associated radiative forcing. A simple one-box model is used to simulate the evolution of the atmospheric CH_4 burden (B) with time as the balance between total CH_4 emissions (E) and total CH_4 sinks (S). The box model is defined as $\frac{dB}{dt} = (E - S)$, where $E = E_a + E_w + E_n$ represents the sum of prescribed anthropogenic CH_4 emissions (E_a), simulated wetland CH_4 emissions (E_w), as well as natural CH_4 emissions from non-wetland sources (E_n) such as termites, wild ruminants, wildfires, lakes, rivers, geologic seeps, and marine hydrates. Given that the UVic ESCM does not incorporate these non-wetland natural sources and in the absence of dataset for CH_4 emissions from these sources, we assume that non-wetland natural CH_4 emissions remain constant in time at 45 Tg C yr^{-1} (equivalent to 60 Tg CH_4 yr^{-1}). This value is in the range of estimated total CH_4 emissions from non-wetland natural sources over the last four decades[2,3] as well as pre-industrial periods[59]. Sinks of atmospheric CH_4 are aggregated into a single term (S) calculated as $S = B\,(1 - \exp(-\frac{1}{\tau_{CH4}}))$, where τ_{CH4} is the atmospheric CH_4 lifetime assumed to be 9.3 years[2]. Similar estimates for the atmospheric CH_4 lifetime have been reported for the pre-industrial era (9.5 ± 1.3 years) and present-day (9.1 ± 0.9 years)[60]. At each time step, $[CH_4]$ is determined based on the atmospheric CH_4 burden (B) by using a factor equivalent to ~2.8 Tg CH_4/ppb. Radiative forcing associated with changes in $[CH_4]$ is calculated using the formulation in ref. [61] and is accounted separately from the aggregated forcing of other non-CO_2 GHGs that is prescribed to the UVic ESCM in its standard configuration[21].

Non-CH_4 radiative forcing agents. To drive the UVic ESCM over the 1850–2300 period (1850–2014 for the historical simulation and 2015-2300 for future projections), we use CMIP6 data for non-CH_4 natural and anthropogenic radiative forcing agents[23,62–64]. For natural forcing agents (volcanic and solar), we use volcanic radiative forcing anomalies spanning the historical period (1850–2014)[64] and solar constant data prescribed to 2300[63]. For anthropogenic forcing agents, we (i) use CMIP6 data for the historical simulation, and (ii) assume that all non-CH_4 GHGs (including CO_2) as well as aerosols evolve according to a scenario consistent with limiting global warming to 2 °C throughout the future (i.e. SSP1-2.6). Specifically, we prescribe CO_2 emissions from fossil fuels as defined in the SSP1-2.6 scenario and their long-term extension[23,24]. The SSP1-2.6 scenario features strong reductions in CO_2 emissions as well as negative CO_2 emissions (i.e. artificial removal of atmospheric CO_2) in the second half of the 21st century[65]. Furthermore, we prescribe gridded land-use change (LUC) data according to SSP1-2.6[66] and the UVic ESCM internally calculates corresponding LUC CO_2 emissions. The radiative forcing of CO_2 is calculated within the UVic ESCM following the formulation from ref. [61]. Radiative forcing values of other non-CH_4 GHGs are calculated externally using concentration data and their extension[23], which are then summed up into an aggregated forcing that is prescribed to the UVic ESCM. For anthropogenic sulfate aerosols, we prescribe SSP1-2.6 gridded aerosol optical depth (AOD) data to the UVic ESCM[67,68] and the model uses this data to internally calculate the associated radiative forcing. While forcing data for CO_2 and other non-CH_4 GHGs extend to 2300[23], forcing data for LUC and sulfate aerosols are prescribed to 2100 and their radiative forcing are held fixed at their 2100 values in our climate simulations.

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The model outputs analyzed in this study are archived at https://doi.org/10.20383/102.0748[69].

Code availability

The code for the University of Victoria Earth System Climate Model (UVic ESCM) used in this study is available at https://doi.org/10.5281/zenodo.7999745[70].

Received: 4 July 2022; Accepted: 16 June 2023;
Published online: 12 July 2023

References

1. Forster, P. et al. In *Climate Change 2021: The Physical Science Basis* (eds. Colman, R., Matthews, D. H. & Ramaswamy, V.) Ch. 7 (Cambridge University Press, 2021).
2. Saunois, M. et al. The global methane budget 2000–2017. *Earth Syst. Sci. Data* **12**, 1561–1623 (2020).
3. Kirschke, S. et al. Three decades of global methane sources and sinks. *Nat. Geosci.* **6**, 813–823 (2013).
4. Dlugokencky, E. *Global Methane Monthly Means*. https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/ (2022).
5. Nisbet, E. G. et al. Very strong atmospheric methane growth in the 4 years 2014–2017: implications for the Paris agreement. *Global Biogeochem. Cycles* **33**, 318–342 (2019).
6. Saunois, M., Jackson, R. B., Bousquet, P. & Canadell, J. G. The growing role of methane in anthropogenic climate change. *Environ. Res. Lett.* **11**, 120207 (2016).
7. Jackson, R. B. et al. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. *Environ. Res. Lett.* **15**, 071002 (2020).
8. Ramanathan, V. & Xu, Y. The Copenhagen accord for limiting global warming: criteria, constraints, and available avenues. *Proc. Natl. Acad. Sci. USA*. **107**, 8055–8062 (2010).
9. Weaver, A. J. Toward the second commitment period of the Kyoto protocol. *Science* **332**, 795–796 (2011).
10. Shoemaker, J. K., Schrag, J. P., Molina, M. J. & Ramanathan, V. What role for short-lived climate pollutants in mitigation policy? *Science* **342**, 1323–1324 (2013).
11. UNFCCC. *The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement*. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf (2015).
12. IPCC. *Global Warming of 1.5 °C*. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf (2018).
13. European Commission. *Launch by United States, the European Union, and Partners of the Global Methane Pledge to Keep 1.5 °C Within Reach*. https://ec.europa.eu/commission/presscorner/detail/en/statement_21_5766 (2021).
14. Arora, V. K. et al. Carbon-concentration and carbon-climate feedbacks in CMIP6 models and their comparison to CMIP5 models. *Biogeosciences* **17**, 4173–4222 (2020).
15. Cheng, C. H. & Redfern, S. A. T. Impact of interannual and multidecadal trends on methane-climate feedbacks and sensitivity. *Nat. Commun.* **13**, 1–11 (2022).
16. Jones, A., Haywood, J. M. & Jones, C. D. Can reducing black carbon and methane below RCP2.6 levels keep global warming below 1.5 °C? *Atmos. Sci. Lett.* **19**, 1–5 (2018).
17. Staniaszek, Z. et al. The role of future anthropogenic methane emissions in air quality and climate. *npj Clim. Atmos. Sci.* **5**, 1–8 (2022).
18. Ocko, I. B. et al. Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. *Environ. Res. Lett.* **16**, 054042 (2021).

19. Harmsen, M. et al. The role of methane in future climate strategies: mitigation potentials and climate impacts. *Clim. Change* https://doi.org/10.1007/s10584-019-02437-2 (2019).
20. Abernethy, S., O'Connor, F. M., Jones, C. D. & Jackson, R. B. Methane removal and the proportional reductions in surface temperature and ozone. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **379**, 20210104 (2021).
21. Mengis, N. et al. Evaluation of the University of Victoria Earth System Climate Model version 2.10 (UVic ESCM 2.10). *Geosci. Model Dev.* **13**, 4183–4204 (2020).
22. Nzotungicimpaye, C.-M. et al. WETMETH 1.0: a new wetland methane model for implementation in Earth system models. *Geosci. Model Dev.* **14**, 6215–6240 (2021).
23. Meinshausen, M. et al. The SSP greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**, 3571–3605 (2019).
24. Nicholls, Z. R. J. et al. Reduced complexity model intercomparison project phase 1: protocol, results and initial observations. *Geosci. Model Dev.* **13**, 5175–5190 (2020).
25. Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P. & Schöpp, W. Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the gains model. *Environ. Res. Commun.* **2**, 1–21 (2020).
26. O'Neill, B. C. et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.* **42**, 169–180 (2017).
27. Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J. & Séférian, R. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* **571**, 335–342 (2019).
28. Tokarska, K. B. et al. Recommended temperature metrics for carbon budget estimates, model evaluation and climate policy. *Nat. Geosci.* **12**, 964–971 (2019).
29. Gulev, S. K. et al. 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* (eds. Osborn, T. J. & Zarrin, A.) Ch. 2 (Cambridge University Press, 2021).
30. Gernaat, D. E. H. J. et al. Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Glob. Environ. Chang.* **33**, 142–153 (2015).
31. Rogelj, J. et al. Mitigation pathways compatible with 1.5 °C in the context of sustainable development. in *Global Warming of 1.5 °C.* (eds Flato, G.) 93–174 (IPCC, 2018).
32. Chimuka, V., Nzotungicimpaye, C.-M. & Zickfeld, K. Quantifying Land Carbon Cycle Feedbacks Under Negative CO2 Emissions. *Biogeosciences* https://doi.org/10.5194/bg-2022-168 (2023).
33. Zickfeld, K., Solomon, S. & Gilford, D. M. Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. *Proc. Natl. Acad. Sci. USA.* **114**, 657–662 (2016).
34. Sun, T., Ocko, I. B. & Hamburg, S. P. The value of early methane mitigation in preserving Arctic summer sea ice. *Environ. Res. Lett.* **17**, 1–11 (2022).
35. Fischer, E. M., Sippel, S. & Knutti, R. Increasing probability of record-shattering climate extremes. *Nat. Clim. Chang.* **11**, 689–695 (2021).
36. Wunderling, N. et al. Global warming overshoots increase risks of climate tipping cascades in a network model. *Nat. Clim. Chang.* https://doi.org/10.1038/s41558-022-01545-9 (2022).
37. Sun, T., Ocko, I. B., Sturcken, E. & Hamburg, S. P. Path to net zero is critical to climate outcome. *Sci. Rep.* **11**, 1–10 (2021).
38. Ganesan, A. L. et al. Advancing scientific understanding of the global methane budget in support of the Paris Agreement. *Global Biogeochem. Cycles* **33**, 1475–1512 (2019).
39. Nisbet, E. G. et al. Methane mitigation: methods to reduce emissions, on the path to the Paris Agreement. *Rev. Geophys.* https://doi.org/10.1029/2019RG000675 (2020).
40. Jackson, R. B. et al. Atmospheric methane removal: a research agenda. *Philos. Trans. R. Soc. A* **379**, 1–17 (2021).
41. Höglund-Isaksson, L. Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs. *Atmos. Chem. Phys.* **12**, 9079–9096 (2012).
42. Unger, C., Mar, K. A. & Gürtler, K. A club's contribution to global climate governance: the case of the Climate and Clean Air Coalition. *Palgrave Commun.* **6**, 1–10 (2020).
43. Pekkarinen, V. Going beyond CO2: Strengthening action on global methane emissions under the UN climate regime. *Rev. Eur. Comp. Int. Environ. Law* **29**, 464–478 (2020).
44. Leonard, L. Tackling climate change in the Global South: an analysis of the Global Methane Initiative multilateral partnership. *J. Soc. Dev. Sci.* **5**, 168–175 (2014).
45. Haines, A. et al. Short-lived climate pollutant mitigation and the Sustainable Development Goals. *Nat. Clim. Change* **7**, 863–869 (2017).
46. Anenberg, S. C. et al. Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls. *Environ. Health Perspect.* **120**, 831–839 (2012).
47. Shindell, D. et al. Simultaneously mitigating near-term climate change and improving human health and food security. *Sci.* **335**, 183–188 (2012).
48. Bridgham, S. D., Cadillo-Quiroz, H., Keller, J. K. & Zhuang, Q. Methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. *Glob. Chang. Biol.* **19**, 1325–1346 (2013).
49. Dean, J. F. et al. Methane feedbacks to the global climate system in a warmer world. *Rev. Geophys.* **56**, 207–250 (2018).
50. Schaefer, H. On the causes and consequences of recent trends in atmospheric methane. *Curr. Clim. Chang. Rep.* **5**, 259–274 (2019).
51. Dreyfus, G. B., Xu, Y., Shindell, D. T., Zaelke, D. & Ramanathan, V. Mitigating climate disruption in time: a self-consistent approach for avoiding both near-term and long-term global warming. *Proc. Natl. Acad. Sci. USA* **119**, 1–8 (2022).
52. Warren, R., Price, J., Fischlin, A., de la Nava Santos, S. & Midgley, G. Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. *Clim. Change* **106**, 141–177 (2011).
53. Arnell, N. W., Lowe, J. A., Challinor, A. J. & Osborn, T. J. Global and regional impacts of climate change at different levels of global temperature increase. *Clim. Change* **155**, 377–391 (2019).
54. Weaver, A. J. et al. The UVic Earth System Climate Model: model description, climatology, and applications to past, present and future climates. *Atmos. Ocean* **39**, 361–428 (2001).
55. Eby, M. et al. Lifetime of anthropogenic climate change: Millennial time scales of potential CO2 and surface temperature perturbations. *J. Clim.* **22**, 2501–2511 (2009).
56. MacDougall, A. H. & Knutti, R. Projecting the release of carbon from permafrost soils using a perturbed parameter ensemble modelling approach. *Biogeosciences* **13**, 2123–2136 (2016).
57. Avis, C. A., Weaver, A. J. & Meissner, K. J. Reduction in areal extent of high-latitude wetlands in response to permafrost thaw. *Nat. Geosci.* **4**, 444–448 (2011).
58. Gedney, N. & Cox, P. M. The sensitivity of global climate model simulations to the representation of soil moisture heterogeneity. *J. Hydrometeorol.* **4**, 1265–1275 (2003).
59. Houweling, S., Dentener, F. & Lelieveld, J. Simulation of preindustrial atmospheric methane to constrain the global source strength of natural wetlands. *J. Geophys. Res. Atmos.* **105**, 17243–17255 (2000).
60. Prather, M. J., Holmes, C. D. & Hsu, J. Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry. *Geophys. Res. Lett.* **39**, L09803 (2012).
61. Etminan, M., Myhre, G., Highwood, E. J. & Shine, K. P. Radiative forcing of carbon dioxide, methane, and nitrous oxide: a significant revision of the methane radiative forcing. *Geophys. Res. Lett.* **43**, 12614–12623 (2016).
62. Meinshausen, M. et al. Historical greenhouse gas concentrations for climate modelling (CMIP6). *Geosci. Model Dev.* **10**, 2057–2116 (2017).
63. Matthes, K. et al. Solar forcing for CMIP6 (v3.2). *Geosci. Model Dev.* **10**, 2247–2302 (2017).
64. Schmidt, A. et al. Volcanic radiative forcing from 1979 to 2015. *J. Geophys. Res. Atmos.* **123**, 12491–12508 (2018).
65. Gidden, M. J. et al. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: A dataset of harmonized emissions trajectories through the end of the century. *Geosci. Model Dev.* **12**, 1443–1475 (2019).
66. Lawrence, D. M. et al. The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design. *Geosci. Model Dev.* **9**, 2973–2998 (2016).
67. Fiedler, S. et al. First forcing estimates from the future CMIP6 scenarios of anthropogenic aerosol optical properties and an associated Twomey effect. *Geosci. Model Dev.* **12**, 989–1007 (2019).
68. Stevens, B. et al. MACv2-SP: A parameterization of anthropogenic aerosol optical properties and an associated Twomey effect for use in CMIP6. *Geosci. Model Dev.* **10**, 433–452 (2017).
69. Nzotungicimpaye, C.-M. Earth system model simulations highlighting the need for methane mitigation to comply with the 2 °C global warming limit. *Fed. Res. Data Repos.* https://doi.org/10.20383/102.0748 (2023).
70. Nzotungicimpaye, C.-M., MacIsaac, A. & Zickfeld, K. An Earth system climate model used to investigate the importance of urgent methane mitigation for limiting global warming to 2 °C above pre-industrial levels. *Zenodo* https://doi.org/10.5281/zenodo.7999745 (2023).

Acknowledgements

K.Z. and C.-M.N. acknowledge support from the Natural Sciences and Engineering Research Council (NSERC) Discovery Grant Program. This research was enabled by computing resources provided by the Digital Research Alliance of Canada.

Author contributions

C.-M.N. conceived the study and designed the model experiments, with contributions from K.Z.. C.-M.N. implemented the representation of the global CH_4 cycle in the UVic ESCM, with contributions from AJM on the atmospheric CH_4 module. C.-M.N. performed the model simulations, model validation, as well as the analysis and interpretation of results. K.Z. contributed to the interpretation of results. C.-M.N. wrote the manuscript and all authors provided critical feedback that helped shape its final version.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-00898-z.

Correspondence and requests for materials should be addressed to Claude-Michel Nzotungicimpaye.

Peer review information *Communications Earth & Environment* thanks the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Sagar Parajuli and Joe Aslin.