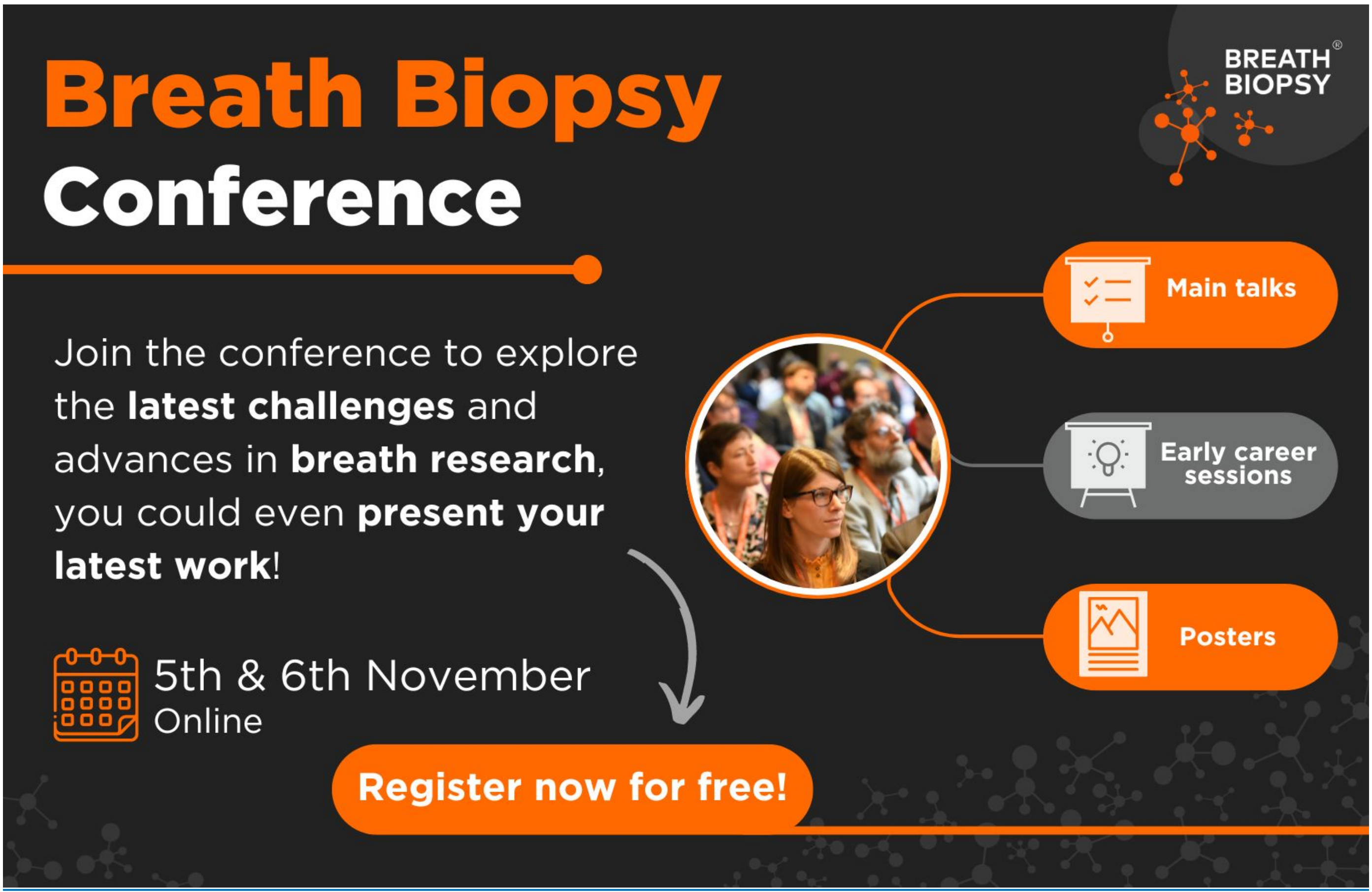
ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

How much methane removal is required to avoid overshooting 1.5 °C?

To cite this article: Chris Smith and Camilla Mathison 2024 *Environ. Res. Lett.* **19** 074044



IOP Publishing *Environ. Res. Lett.* **19** (2024) 074044 https://doi.org/10.1088/1748-9326/ad5853

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
31 January 2024

REVISED
2 May 2024

ACCEPTED FOR PUBLICATION
14 June 2024

PUBLISHED
25 June 2024

LETTER

How much methane removal is required to avoid overshooting 1.5 °C?

Chris Smith[1,2,3,*] and Camilla Mathison[1,3]

[1] School of Earth and Environment, University of Leeds, Leeds, United Kingdom
[2] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[3] Met Office Hadley Centre, Exeter, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: c.j.smith1@leeds.ac.uk

Keywords: methane removal, adaptive scenario, climate mitigation

Supplementary material for this article is available online

Abstract

Methane is the second most important anthropogenic greenhouse gas after carbon dioxide. With an atmospheric lifetime of around a decade, methane mitigation starting immediately has the potential to avoid substantial levels of additional warming by mid-century. In addition to the methane emissions reductions that are necessary to limit warming, we address the question of whether technological methane removal can provide additional benefits by avoiding global mean surface temperatures exceeding 1.5 °C above pre-industrial—the high-ambition Paris Agreement climate goal. Using an adaptive emissions methane removal routine in a simple climate model, we successfully limit peak warming to 1.5 °C for overshoots of up to around 0.3 °C. For substantially higher overshoots, methane removal alone is unable to limit warming to 1.5 °C, but in an extreme scenario could limit peak warming by an ensemble median 0.7 °C if all atmospheric methane was removed, requiring huge levels of net removal on the order of tens of petagrams cumulatively. The efficacy of methane removal depends on many emergent properties of the climate system, including climate sensitivity, aerosol forcing, and the committed warming after net zero CO_2 (zero emissions commitment). To avoid overshooting 1.5 °C in the low-overshoot, strong-mitigation SSP1-1.9 scenario, a median cumulative methane removal of 1.2 $PgCH_4$ is required, though this may be much higher if climate sensitivity is high or the zero emissions commitment is positive, and in these cases may require ongoing methane removal long after peak warming in order to stabilise warming below 1.5 °C.

1. Introduction

On an emissions basis, methane contributes a best estimate 0.5 °C to present-day global warming, being the second largest anthropogenic contributor to historical warming behind carbon dioxide [1, 2]. Methane has a relatively short atmospheric lifetime of around a decade. Therefore, unlike many other greenhouse gases with longer lifetimes, reducing net emissions of methane can substantially reduce its radiative forcing, and hence its climate impact, in the short-to-medium term. Methane's short lifetime, and large contribution to warming which includes its indirect effects on ozone formation and stratospheric water vapour, both potent greenhouse gases, make its reduction a critical pillar of limiting peak warming within the goals of the Paris Agreement [3].

In recognition of methane's importance, over 150 countries have now signed the Global Methane Pledge [4], first announced at COP26 in Glasgow in 2021, to reduce CH_4 emissions by 30% in 2030 relative to 2020 levels. Alongside climate benefits, reducing methane concentrations has well documented co-benefits for air quality due to the reduction in surface ozone, owing to methane's role in ozone formation [5]. However, recent years have seen an increase in the atmospheric growth rate of methane [6], which is likely a combination of increasing emissions and bio-physical feedbacks [7].

The net input of methane into the atmosphere can be reduced either by avoiding the emission entirely, or by oxidising emitted or ambient methane to CO_2. In many cases, emissions avoidance can be revenue neutral, such as preventing leaks from oil and gas infrastructure [8]. If methane release is difficult to avoid but concentrated in a small region at levels greater than the ambient level, such as a wastewater treatment plant or dairy farm, localised methane oxidation could prevent a large fraction of methane emissions being dispersed into the atmosphere [9]. As a mole of CO_2 has a much lower radiative efficiency than a mole of CH_4 [10], oxidation to CO_2 results in a substantially smaller radiative forcing and climate warming impact. Methane oxidation methods include enhancement of natural hydroxyl and chlorine sinks, photocatalysis in solar updraft towers, zeolite catalyst in direct air capture devices, and methanotrophic bacteria [11].

Methane emissions reduction through avoidance or point-source oxidation, if successfully implemented and extended to all anthropogenic sources of methane emissions, provides a lower bound of net methane emissions of zero. Eliminating all methane emissions through oxidation to CO_2 is at present unlikely considering the disperse nature of many sectors, including food production [9, 12]. Additionally, it is easier to avoid emitting methane in the first place than to emit first and remove later, and strong action on methane mitigation should take priority over technological oxidation or removal. Assuming zero methane emissions was possible, methane concentrations would relax back towards pre-industrial levels of around 700 ppb over several decades. Emergent research is exploring actively removing methane from the atmosphere *in-situ* [13–15] in its well-mixed state far from emissions sources. One proposed, yet untested, method of *in-situ* methane removal is adding iron particles to ship emissions with the aim of creating additional chlorine and hydroxyl radicals from seawater, speeding up the natural reaction of methane decomposition in the atmosphere [16]. With a substantial scale-up, *in-situ* removal could allow for methane emissions to technically be net negative, such that more methane is removed per year by an artificially enhanced sink than is emitted by human activities (whether oxidised at source or not). If net negative methane emissions were sustained for long enough, methane concentrations could theoretically fall below pre-industrial levels. Methane removal would be subject to several technical, economic, moral and governance challenges, including whether the energy investment in methane removal would generate additional CO_2 that offsets any gain [17]. Nevertheless, we set aside these issues in this article, instead focusing on a climate-centred analysis of methane removal's geophysical potential.

Owing to its near-term impacts, enhanced methane mitigation or removal could be used for 'peak-shaving': avoiding overshooting a temperature threshold such as the 1.5 °C Paris Agreement high-ambition goal while implementing a rapid CO_2 decarbonization pathway. Avoiding a temperature overshoot may reduce the severity of negative climate impacts such as extreme weather events and human heat stress, reduce the risks of triggering tipping elements in the Earth system such as ice sheet destabilisation, Amazon rainforest dieback, and further methane release from thawing permafrost and clathrates [18], while reducing the impacts of slower-process Earth system risks such as sea-level rise.

Previous work has investigated the potential for avoided warming using methane migitation or removal in idealised [9, 19], reduced-complexity [20, 21] and Earth System models [15, 22]. In this paper we extend the reduced-complexity model approach framed on the question of how much methane removal would be required to avoid an overshoot of 1.5 °C, using an ensemble of runs from a reduced-complexity climate model calibrated on existing Earth System models and constrained using observations.

2. Method

2.1. Emissions scenarios

We use three global emissions scenarios that exhibit various degrees and durations of overshooting 1.5 °C above pre-industrial. These are the Shared Socioeconomic Pathways (SSPs) SSP1-1.9 and SSP5-3.4-overshoot [23], and the Illustrative Mitigation Pathway (IMP) from the IPCC Working Group 3 (WG3) report [24] with high levels of negative CO_2 emissions (IMP-Neg) [25].

All three scenarios show some level of overshoot behaviour, in the sense that they reach a peak warming that exceeds 1.5 °C before 2100 (figure 1(a)). Using our model calibration (section 2.2), SSP1-1.9 has median peak warming of 1.56 °C relative to pre-industrial and is classified as Category 1 (C1) '1.5 °C low or no overshoot' scenario in IPCC AR6 WG3 [24]. Despite a small overshoot, C1 scenarios are deemed compatible with the 1.5 °C Paris Agreement long-term temperature goal [24].

IMP-Neg reaches a peak warming of 1.77 °C before declining back below 1.5 °C after 2100 and is compatible with a 'well-below 2 °C' goal of the Paris Agreement and classified as a C3 scenario in IPCC AR6 WG3. As defined in [24], this means that the scenario has a 67% or greater likelihood of remaining below 2 °C. IMP-Neg has a large temperature overshoot, in which peak warming is reversed by implementing large amounts of carbon dioxide removal. Despite not falling back below 1.5 °C before 2100, it

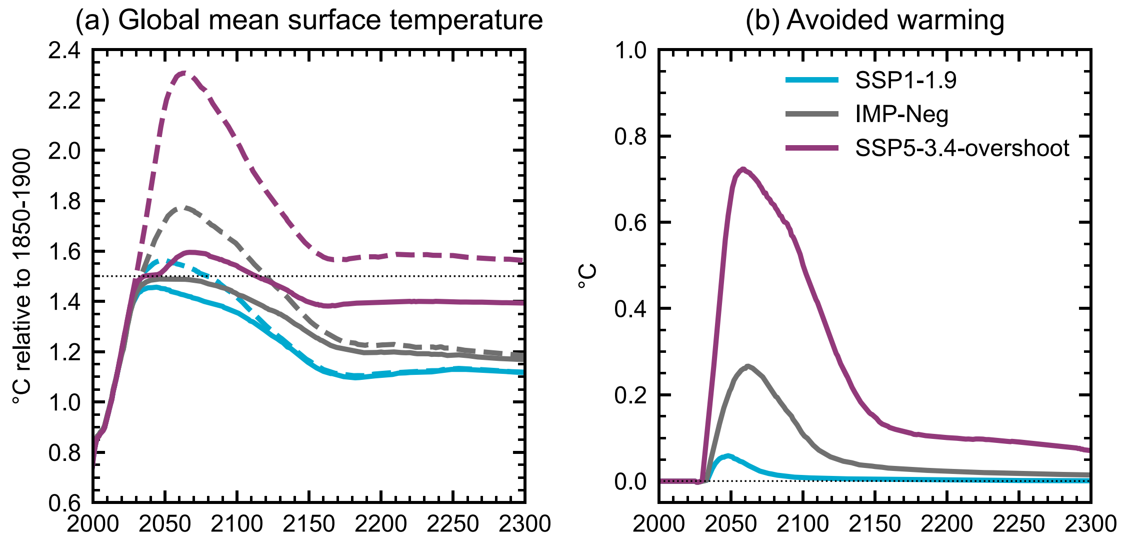


Figure 1. (a) Global mean surface temperature anomaly projections for the SSP1-1.9 (blue), IMP-Neg (grey) and SSP5-3.4 (purple) scenarios, without (dashed) and with (solid) methane removal. (b) Avoided warming due to methane removal, calculated as the median difference between the ensembles without and with methane removal in each scenario. Shown are ensemble medians; for uncertainties see supplementary figure 2.

shares a lot of characteristics with so-called '1.5 °C high overshoot' (C2) scenarios. SSP5-3.4-overshoot is not a 1.5 °C or 2 °C compatible scenario in the Paris Agreement sense, but is chosen as it is engineered to have a large temperature overshoot [23], peaking at around 2.3 °C in the 2060 s and declining back to 1.6 °C around 2150.

We run scenarios to 2300 to determine the long-term overshoot response. SSP1-1.9 and SSP5-3.4-overshoot emissions pathways are part of the Reduced Complexity Model Intercomparison Project scenarios [26, 27], and their extensions to 2300 already exist. For IMP-Neg, we use the emissions scenario prepared for the IPCC AR6 WG3 [24, 28], and extend it based on the logic of [29] for post-2100 timeframes.

2.2. Climate model

We use an 841 member ensemble of the Finite-amplitude Impulse Response (FaIR) simple climate model (v2.1.3) [30], using calibration v1.4.0 [31]. FaIR is a simple climate model that determines atmospheric concentrations of greenhouse gases from their emissions, radiative forcing of greenhouse gases and other anthropogenic forcers from their concentrations and emissions, and global mean surface temperature projections from radiative forcing using a three-layer energy balance model. FaIR contains modules that emulate the carbon cycle and carbon cycle feedbacks, and atmospheric chemistry including aerosol and ozone formation from methane and impacts on methane's atmospheric lifetime. The forcing from the oxidation of methane to water vapour in the stratosphere is also included. One chemical effect that is not included in FaIR is the oxidation of CH_4 to CO_2, where the newly-generated CO_2 molecule contributes a small level of radiative forcing. The omission of methane oxidation was found to contribute an uncertainty of 3 ppm in CO_2 concentrations in 2100 in RCP8.5, much smaller than the spread in projections due to carbon cycle feedbacks, and on a forcing basis likely to be much smaller than indirect effects that are included such as on ozone formation and oxidation to stratospheric water vapour.

v2.1 of FaIR includes a new variable methane lifetime module. This parameterises the tropospheric hydroxyl radical (OH) sink from emissions of nitrogen oxides (NOx), volatile organic compounds (VOCs) and carbon monoxide (CO), concentrations of CH_4, N_2O and halocarbons, and global mean surface temperature anomaly. The sensitivities of methane lifetime to each factor are found from a least-squares curve fit that maps methane emissions to concentrations over the 1750–2022 period with the bounds for each parameter being the range from chemistry-enabled Earth system models [32, 33]. The correspondence of modelled to observed methane concentrations is good and demonstrated in supplementary figure 1(a). The methane lifetime is 10.3 yr in 1850, increasing steadily to 11.0 yr in the 1960s before dropping rapidly to 9.4 yr in the 2010s (supplementary figure 1(b)) owing to a rapid increase in NOx emissions and steady rate of warming increase, both effects acting to increase available OH in the troposphere [2]. The methane lifetime reported by FaIR is a whole atmosphere 'burden' lifetime rather than a 'perturbation' lifetime [34].

The 841-member ensemble is constrained from a prior of 1.6 million members that are calibrated to the responses of CMIP6 Earth System models for their temperature response to forcing, carbon cycle feedbacks, aerosol and ozone radiative forcing

[31]. The sampled ensemble members forming the prior distributions also include the assessed uncertainty in methane radiative forcing of ±20% around its best estimate [35]. The constrained ensemble is selected to ensure consistency with the observed record of global mean surface temperature change from 1850–2022 including its uncertainty, and the correspondence to the historical warming record is demonstrated in supplementary figure 1(c). In addition to historical warming, the posterior is reweighted to fit eight distributions of assessed and observed climate metrics (equilibrium climate sensitivity (ECS); transient climate response (TCR); direct, indirect and total aerosol forcing; surface temperature anomaly in 2003–2022 relative to 1850–1900; CO_2 concentrations in 2022; and time integrated Earth energy uptake increase in 2020 relative to 1971). The ECS, TCR and aerosol constraints are from IPCC AR6 WG1 [35] and other constraints from the Indicators of Global Climate Change (IGCC) project which updates the IPCC assessments to 2022 [6]. The sampling and constraining procedure is described in [31].

2.3. Adaptive methane removal algorithm

The three scenarios are first run from 1750 until the end of 2022 which defines our historical period (even though the scenarios diverge in 2015). We follow IPCC AR6 WG3 logic, updated for the IGCC assessment of warming through 2022, which anchors historical warming to be 1.03 °C for 2003–2022 relative to 1850–1900. From 2023 onwards, FaIR is run one year at a time with an adaptive methane removal algorithm [36]. For each scenario and each of the 841 ensemble members, the global mean surface temperature anomaly is checked each year to determine if it exceeds 1.5 °C above 1850–1900 (or more precisely, 0.47 °C above 2003–2022). If 1.5 °C is exceeded, 20 $TgCH_4$ is removed from that scenario and ensemble member in the current year, and the year re-run with the lower emissions. This is repeated until either the year-end temperature is reduced below 1.5 °C or the atmospheric methane concentrations are reduced below 50 ppb. When either the temperature goal has been reached or concentration lower bound has been hit, the model steps forward to the next year and the process is repeated. A sensitivity analysis with a 10 $TgCH_4$ removal step showed almost identical results.

The 50 ppb lower concentration limit was chosen to avoid FaIR attempting to run with negative atmospheric concentrations of methane (impossible in both real and model world). Stabilizing methane concentrations at 50 ppb is likely far lower than what could be achieved using available methane removal technologies, and again we demonstrate only the geophysical potential for methane removal. For context, pre-industrial methane concentration was around 700 ppb, and has not been lower than 320 ppb over the last 156 000 years [37].

3. Results

3.1. Global mean surface temperature

Figure 1(a) shows global mean surface temperature projections from the three scenarios. Methane removal can successfully avoid overshooting 1.5 °C in the SSP1-1.9 and IMP-Neg scenarios in the respective ensemble medians, but not in every ensemble member (supplementary figure 2). Methane removal cannot avoid exceeding 1.5 °C in the SSP5-3.4-overshoot ensemble median. The maximal atmospheric capacity for removal is exhausted as evidenced by the inflection point in the warming trajectory around 2050. Supplementary figure 3 shows that concentrations hit the 50 ppb floor in the median of the SSP5-3.4-overshoot ensemble in around 2050.

Figure 1(b) shows the difference between temperatures projected in the adaptive methane removal scenarios compared to the no-removal scenarios. Methane removal successfully offsets up to 0.3 °C of peak warming in the lower overshoot scenarios. Although warming cannot be kept below 1.5 °C in SSP5-3.4-overshoot, methane removal reduces peak warming by over 0.7 °C, and this peak shaving has the effect of keeping global mean temperature around 0.1 °C below the no-removal scenario (in the ensemble median). The lower bound of avoided warming from methane removal in both SSP1-1.9 and IMP-Neg is zero (supplementary figure 2(b)), indicating that a favourable climate configuration (for example, ECS on the low side of the IPCC assessment) could render methane removal unnecessary to meet 1.5 °C. However, these scenarios could both also exceed 1.5 °C by a large amount if ECS is high, necessitating large amounts of methane-removal-driven cooling (supplementary figure 2(b)).

3.2. Required removal rates

The annual gross CH_4 removal required in each scenario is shown in figure 2(a). The median level of methane removal required in SSP1-1.9 is 60 Tg CH_4 yr^{-1} (around 15% of current anthropogenic emissions). Indeed, the median CH_4 emissions in SSP1-1.9 and IMP-Neg remain net positive at all times, showing that 1.5 °C could theoretically be achieved in these scenarios with very aggressive methane mitigation combined with breakthrough technologies to oxidise most residual emissions at source [9]. As seen in figure 2(a), the time dependence of methane removal determined from the adaptive scenarios is without reference to any assumptions around feasibility, and require very rapid rates of methane deployment technologies in the very near future, starting around 2030. Methane removal would be required to a greater extent in SSP5-3.4-overshoot, could not limit peak warming below 1.5 °C, and requires methane emissions to go net negative requiring *in-situ* removal methods.

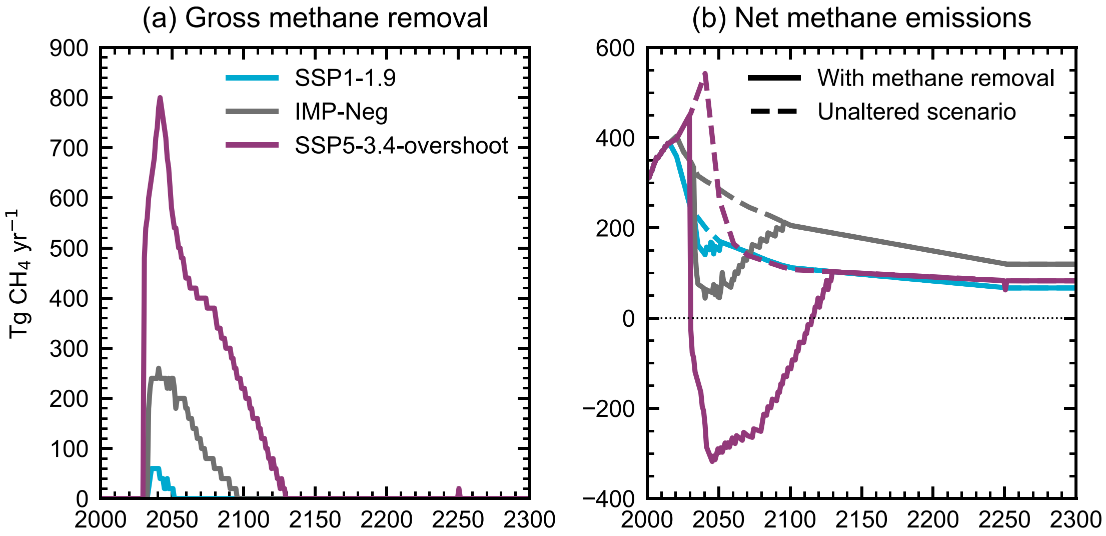


Figure 2. (a) Gross methane removal in the ensemble medians in the three adaptive methane removal scenarios. For other quantiles refer to supplementary figure 3. (b) Net methane emissions in the adaptive scenarios (ensemble medians, solid lines) and scenarios before methane removal (dashed lines).

Figure 2 shows the median removal required, which masks substantial uncertainty from the state of the climate system. Supplementary figure 4 shows the quantiles of required gross methane removal. In all three scenarios, there is a risk that methane removal would need to be continuously deployed far into the future to stabilise temperatures under 1.5 °C in more than 10% of SSP1-1.9 ensemble members and more than 20% of IMP-Neg and SSP5-3.4-overshoot ensemble members. The risks of continued reliance on peak-shaving methods have been discussed previously in the context of solar radiation management [38], which is an appropriate analogy. Furthermore, the deployment rates required in the near future could be unrealistically large to keep warming under 1.5 °C as evidenced by the large spike before 2030.

3.3. Required cumulative removal

The median cumulative removal required between 2023 and 2300 in SSP1-1.9 is 1.2 PgCH$_4$, the equivalent of around 3 years' of current emissions. However, the uncertainty in climate, explored in section 3.5, could mean that substantially higher levels of cumulative removals are required: up to 87 PgCH$_4$ in SSP1-1.9 to bring a pathway that overshoots 1.5 °C back below this level. Across the three scenarios, cumulative removals of up to 103 PgCH$_4$ may be required to avoid overshoot of 1.5 °C.

As methane's atmospheric lifetime is relatively short, active removal methods are merely accelerating a process that would have happened anyway: chemical decomposition in the atmosphere with an *e*-folding time of around a decade. Thus, the benefit of the removal of one unit of methane decays over time, and a cumulative methane removal metric is ideally adjusted to account for its lifetime to determine an 'effective' cumulative removal [15]. However, we determine that to first order in figure 3 that gross cumulative methane removal required between 2023 and 2300 is a function of peak warming before removal. In figure 3 ensemble members in which peak warming can be limited to 1.5 °C using methane removal are shown in solid circles, and those where the atmospheric concentration minimum of 50 ppb is reached before temperatures can be reduced below 1.5 °C are shown in hollow circles.

It can be seen that the level of required methane removal increases approximately linearly with peak warming in the adjusted ensemble member. We use an ordinary least squares regression to predict cumulative required removal for ensemble members where peak warming is successfully limited to 1.5 °C:

$$R_{\mathrm{CH}_4} = \begin{cases} 0 & T_{\mathrm{peak}} \leqslant 1.5 \\ a + bT_{\mathrm{peak}} & T_{\mathrm{peak}} > 1.5 \end{cases} \tag{1}$$

where T_{peak} is peak warming and R_{CH_4} is cumulative methane removal. The best fit coefficients to equation (1) for the three scenarios are given in table 1.

It may seem counter-intuitive that *less* methane removal (lower *b* coefficient) would be required in SSP5-3.4-overshoot than in the lower warming scenarios. However, as the relationship is fit only for ensemble members that successfully limit peak warming, only the lowest warming ensemble members, typically those with lower climate sensitivity (section 3.5), contribute to the regression calculation.

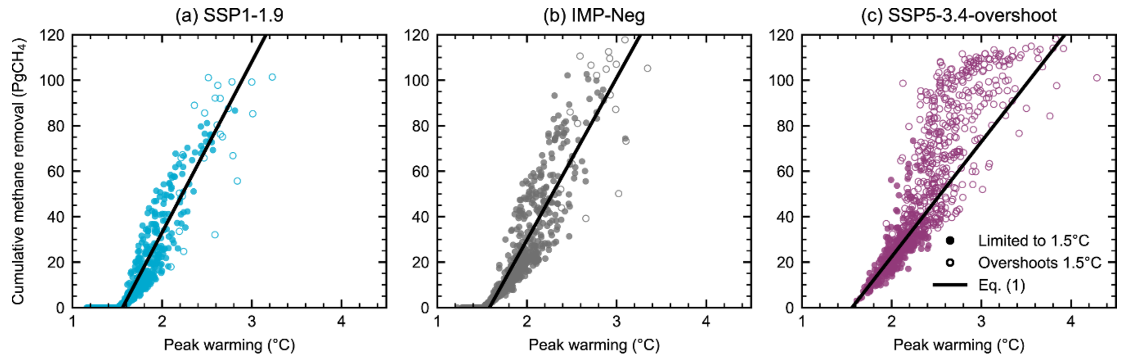


Figure 3. Cumulative methane removal required in order to limit peak warming to 1.5 °C, depending on peak warming in the adjusted projection, in (a) SSP1-1.9; (b) IMP-Neg and (c) SSP5-3.4-overshoot. Filled circles relate to ensemble members where peak warming is limited to less than 1.5 °C. Hollow circles are ensemble members where peak warming cannot be limited to 1.5 °C. The black line shows the ordinary least squares linear regression to solid circles where peak warming exceeds 1.5 °C.

Table 1. Best fit coefficients for predicting the level of required cumulative methane removal to limit peak warming to below 1.5 °C from the relationship in equation (1), for ensemble members in which peak warming of 1.5 °C is successfully avoided using methane removal alone. For context, current global anthropogenic methane emissions are around 0.4 $\mathrm{PgCH_4\ yr^{-1}}$.

Scenario	a [$\mathrm{PgCH_4}$]	b [$\mathrm{PgCH_4\ K^{-1}}$]
SSP1-1.9	−117	75
IMP-Neg	−113	71
SSP5-3.4-overshoot	−79	51

3.4. Atmospheric chemistry and radiative forcing

Methane's atmospheric burden lifetime is reduced in all three scenarios, though most strikingly in SSP5-3.4-overshoot which is reduced from a median lifetime of 9.7 yr to 6.4 yr in 2050 (supplementary figure 5(a)). The reduction in methane concentration in each scenario is due to the self-feedback in methane lifetime [34], which far outweighs the opposing effect of a slightly reduced warming. Methane and ozone radiative forcing is also reduced in all three ensemble members (supplementary figures 5(b) and (c)). Methane radiative forcing is at its most negative when SSP5-3.4-overshoot hits 50 ppb, at a floor of around $-0.6\ \mathrm{W\ m^{-2}}$.

3.5. What dictates uncertainties in required cumulative removal?

The level of cumulative methane removal required can also be expressed in terms of emergent properties of the climate system. Figure 4 shows the relationship between the ECS, a standard climate metric defined as the long-term equilibrium warming from the forcing equivalent of a doubled atmospheric $\mathrm{CO_2}$ concentration, and cumulative required methane removal in the three scenarios. In these instances, ECS is calculated from the properties of the impulse-response climate model component of FaIR (see [30] for details). For SSP5-3.4-overshoot, ECS is a very good predictor of the cumulative methane removal. As a higher forcing scenario than IMP-Neg and SSP1-1.9, ECS is more influential in determining peak and long-term warming than in the lower scenarios. Conversely, the present-day aerosol forcing can be used as a predictor of required cumulative methane removal (supplementary figure 6) due to its strong anti-correlation with ECS in historically-consistent climate projections [39].

Another metric that dictates the cumulative methane removal is the zero emissions commitment (ZEC) to net zero $\mathrm{CO_2}$ emissions. If ZEC is positive, there is residual warming after net zero, such that net negative $\mathrm{CO_2}$ emissions would be required to stabilise warming. If the $\mathrm{CO_2}$ emissions pathway is prescribed, as in the three scenarios presented, then a positive ZEC requires non-$\mathrm{CO_2}$ forcing to be reduced further in order to stabilise warming: in this case, the mechanism that we have available is further methane removal. We run idealised experiments in FaIR using the esm-1000PgC-bell experiment [40] to determine the ZEC 50 years after net zero $\mathrm{CO_2}$. We indeed find that there is a positive correlation between the ZEC and the required level of cumulative methane removal (supplementary figure 7).

4. Discussion

We present a geophysical assessment of the potential for methane removal to avoid overshooting of 1.5 °C warming using a calibrated, constrained ensemble of the FaIR simple climate model. Generally, methane removal or oxidation could be an option for limiting small, temporary temperature overshoots of up to around 0.3 °C. The required level of cumulative methane removal scales roughly with peak warming, though it likely that the costs to remove methane would scale faster than linearly as its concentration becomes more dilute in the atmosphere at increasingly high levels of removal.

Reducing methane concentration below pre-industrial levels of around 700 ppb would be

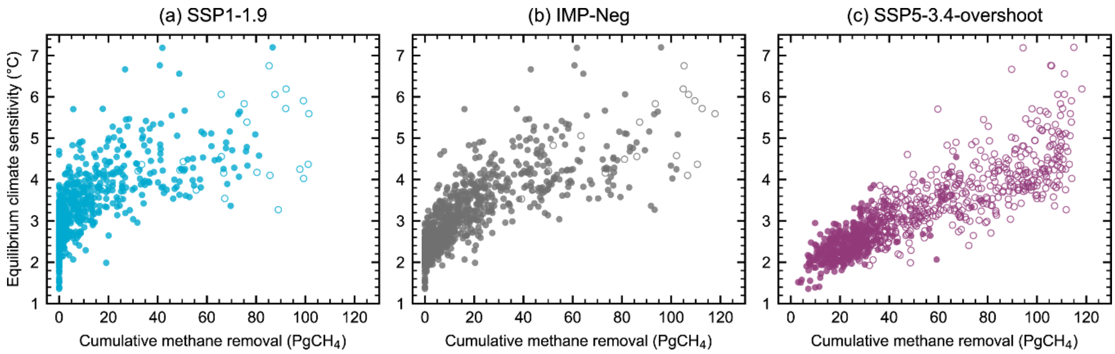


Figure 4. Relationship between cumulative methane removal required to limit global mean surface temperature to 1.5 °C in all three scenarios and equilibrium climate sensitivity (ECS). Solid points are ensemble members in which peak warming is successfully limited to 1.5 °C.

necessary to avoid larger overshoots. It is not evaluated whether this level of methane concentration would be achievable in practice. Nevertheless, reductions below pre-industrial concentrations could not be achieved with point-source oxidation alone and would require *in-situ* removal. The side-effects of adding large volumes of iron particles to increase the marine atmosphere hydroxyl and chlorine sink could be substantial and deleterious with results only available from a single Earth System model to date [22], and more research on the atmospheric chemistry and air quality effects is needed. Although not evaluated, as methane becomes more and more dilute in the atmosphere, the costs of removal will increase, and the question of whether this is cost-effective relative to conventional mitigation (simply reducing positive emissions of methane along with other greenhouse gases and short-lived climate forcers) is appropriate to ask. Figure 2 shows that the required rates of scaling up of methane removal technology would be very rapid, particularly in the higher overshoot scenarios, and any realistic peak shaving scenario would need to phase in methane removal more gradually.

Another consideration is the simplified radiative forcing relationship used in FaIR, having its origins in [29, 41]. In [41], the range of validity for the CH_4 radiative forcing relationship is 340–3500 ppb. The formula in [29] used in FaIR is an improved functional fit to the data of [41]. It is not evaluated whether the approximate square-root law for radiative forcing of methane holds below 340 ppb to concentrations as low as 50 ppb. This is less of an issue for the results provided for SSP1-1.9 and IMP-Neg, where the majority of ensemble members do not reach such low atmospheric concentrations, but results for SSP5-3.4-overshoot should be interpreted with this caveat in mind.

Finally, emissions of species that affect methane lifetimes have not been altered and follow their parent scenarios. Additional benefits, in terms of reduced methane lifetime and further reductions in ozone forcing, could be obtained by contemporaneous action on VOC and CO emissions, whereas reducing NOx emissions would be beneficial for ozone and air quality but lengthen methane lifetime [32].

In summary, there is geophysical potential for methane oxidation or technological methane removal as part of a portfolio of climate mitigation technologies to limit peak warming, but would only be worthwhile as part of a long-term strategy to limit global mean surface temperature increase. Methane removal is not a silver bullet, and not a substitute for rapid reductions to net zero (or net negative) CO_2, which remain the surest way to achieve the Paris Agreement long-term temperature goals.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.11099512 [42].

Acknowledgments

C S was supported by a NERC/IIASA Collaborative Research Fellowship (NE/T009381/1) and the European Commission under the Horizon Europe Climate, Energy and Mobility program project WorldTrans (101081661). C S and C M were supported by the Met Office Hadley Centre Climate Programme funded by DSIT.

ORCID iDs

Chris Smith https://orcid.org/0000-0003-0599-4633
Camilla Mathison https://orcid.org/0000-0002-6269-4605

References

[1] Smith C J and Gasser T 2022 Modeling the non-CO_2 contribution to climate change *One Earth* **5** 1330–5

[2] Szopa S *et al* 2021 Short-lived climate forcers *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 V Masson-Delmotte *et al* (Cambridge University Press) ch 6

[3] IPCC 2021 Summary for policymakers *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 V Masson-Delmotte *et al* (Cambridge University Press)

[4] European Commission 2021 *Joint EU-US Press Release on the Global Methane Pledge* (available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_4785) (Accessed 26 January 2024)

[5] Turnock S T, Reddington C L, West J J and O'Connor F M 2023 The air pollution human health burden in different future scenarios that involve the mitigation of near-term climate forcers, climate and land-use *GeoHealth* **7** e2023GH000812

[6] Forster P M *et al* 2023 Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence *Earth Syst. Sci. Data* **15** 2295–327

[7] Nisbet E G 2023 New hope for methane reduction *Science* **382** 1093

[8] IEA 2023 *Global Methane Tracker 2023* (available at: www.iea.org/reports/global-methane-tracker-2023)

[9] Abernethy S, Kessler M I and Jackson R B 2023 Assessing the potential benefits of methane oxidation technologies using a concentration-based framework *Environ. Res. Lett.* **18** 094064

[10] Smith C *et al* 2021 The Earth's energy budget, climate feedbacks and climate sensitivity supplementary material *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 V Masson-Delmotte *et al* (Cambridge University Press) ch 7.SM (available at: www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07_Supplementary_Material.pdf)

[11] Ming T, Li W, Yuan Q, Davies P, de Richter R, Peng C, Deng Q, Yuan Y, Caillol S and Zhou N 2022 Perspectives on removal of atmospheric methane *Adv. Appl. Energy* **5** 100085

[12] Jackson R B *et al* 2021 Atmospheric methane removal: a research agenda *Phil. Trans. R. Soc.* A **379** 20200454

[13] Jackson R B, Solomon E I, Canadell J G, Cargnello M and Field C B 2019 Methane removal and atmospheric restoration *Nat. Sustain.* **2** 436–8

[14] Boucher O and Folberth G A 2010 New directions: atmospheric methane removal as a way to mitigate climate change? *Atmos. Environ.* **44** 3343–5

[15] Abernethy S, O'Connor F M, Jones C D and Jackson R B 2021 Methane removal and the proportional reductions in surface temperature and ozone *Phil. Trans. R. Soc.* A **379** 20210104

[16] van Herpen M M J W *et al* 2023 Photocatalytic chlorine atom production on mineral dust–sea spray aerosols over the North Atlantic *Proc. Natl Acad. Sci.* **120** e2303974120

[17] Nisbet-Jones P B R, Fernandez J M, Fisher R E, France J L, Lowry D, Waltham D A, Woolley Maisch C A and Nisbet E G 2022 Is the destruction or removal of atmospheric methane a worthwhile option? *Phil. Trans. R. Soc.* A **380** 20210108

[18] Wunderling N, Winkelmann R, Rockström J, Loriani S, Armstrong McKay D I, Ritchie P D L, Sakschewski B and Donges J F 2023 Global warming overshoots increase risks of climate tipping cascades in a network model *Nat. Clim. Change* **13** 75–82

[19] Cael B B and Goodwin P A 2023 Global methane pledge versus carbon dioxide emission reduction *Environ. Res. Lett.* **18** 104015

[20] Ocko I B, Sun T, Shindell D, Oppenheimer M, Hristov A N, Pacala S W, Mauzerall D L, Xu Y and Hamburg S P 2021 Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming *Environ. Res. Lett.* **16** 054042

[21] Harmsen M *et al* 2020 The role of methane in future climate strategies: mitigation potentials and climate impacts *Clim. Change* **163** 1409–25

[22] Li Q *et al* 2023 Global environmental implications of atmospheric methane removal through chlorine-mediated chemistry-climate interactions *Nat. Commun.* **14** 4045

[23] O'Neill B C *et al* 2016 The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6 *Geosci. Model Dev.* **9** 3461–82

[24] Riahi K *et al* 2022 Mitigation pathways compatible with long-term goals *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed P R Shukla *et al* (Cambridge University Press)

[25] Riahi K *et al* 2021 Cost and attainability of meeting stringent climate targets without overshoot *Nat. Clim. Change* **11** 1063–9

[26] Nicholls Z R J *et al* 2020 Reduced complexity model intercomparison project phase 1: introduction and evaluation of global-mean temperature response *Geosci. Model Dev.* **13** 5175–90

[27] Nicholls Z and Lewis J 2021 Reduced Complexity Model Intercomparison Project (RCMIP) protocol, version v5.1.0 (Zenodo) (https://doi.org/10.5281/zenodo.4589756)

[28] Kikstra J S *et al* 2022 The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures *Geosci. Model Dev.* **15** 9075–109

[29] Meinshausen M *et al* 2020 The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500 *Geosci. Model Dev.* **13** 3571–605

[30] Leach N J, Jenkins S, Nicholls Z, Smith C J, Lynch J, Cain M, Walsh T, Wu B, Tsutsui J and Allen M R 2021 FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration *Geosci. Model Dev.* **14** 3007–36

[31] Smith C, Cummins D P, Fredriksen H-B, Nicholls Z, Meinshausen M, Allen M, Jenkins S, Leach N, Mathison C and Partanen A-I 2024 fair-calibrate v1.4.1: calibration, constraining and validation of the FaIR simple climate model for reliable future climate projections *EGUsphere Preprint* https://doi.org/10.5194/egusphere-2024-708 (Posted online 11 April 2024, accessed 27 April 2024)

[32] Thornhill G D *et al* 2021 Effective radiative forcing from emissions of reactive gases and aerosols—a multi-model comparison *Atmos. Chem. Phys.* **21** 853–74

[33] Thornhill G D *et al* 2021 Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models *Atmos. Chem. Phys.* **21** 1105–26

[34] Myhre G *et al* 2013 Anthropogenic and natural radiative forcing *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 T F Stocker *et al* (Cambridge University Press) ch 8, pp 659–740

[35] Forster P *et al* 2021 The Earth's energy budget, climate feedbacks and climate sensitivity *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 V Masson-Delmotte *et al* (Cambridge University Press)

[36] Terhaar J, Frölicher T L, Aschwanden M T, Friedlingstein P and Joos F 2022 Adaptive emission reduction approach to reach any global warming target *Nat. Clim. Change* **12** 1136–42

[37] Köhler P, Nehrbass-Ahles C, Schmitt J, Stocker T F and Fischer H 2017 A 156 kyr smoothed history of the

atmospheric greenhouse gases CO_2, CH_4 and N_2O and their radiative forcing *Earth Syst. Sci. Data* **9** 363–87

[38] Baur S, Nauels A, Nicholls Z, Sanderson B M and Schleussner C-F 2023 The deployment length of solar radiation modification: an interplay of mitigation, net-negative emissions and climate uncertainty *Earth Syst. Dyn.* **14** 367–81

[39] Smith C J, Al Khourdajie A, Yang P and Folini D 2023 Climate uncertainty impacts on optimal mitigation pathways and social cost of carbon *Environ. Res. Lett.* **18** 094024

[40] MacDougall A H *et al* 2020 Is there warming in the pipeline? A multi-model analysis of the zero emissions commitment from co_2 *Biogeosciences* **17** 2987–3016

[41] Etminan M, Myhre G, Highwood E J and Shine K P 2016 Radiative forcing of carbon dioxide, methane and nitrous oxide: a significant revision of the methane radiative forcing *Geophys. Res. Lett.* **43** 12614–23

[42] Smith C and Mathison C 2024 How much methane removal is required to avoid overshooting 1.5 °C? *Zenodo* (https://doi.org/10.5281/zenodo.11099512)