LETTER

The value of early methane mitigation in preserving Arctic summer sea ice

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Abstract

A growing body of literature has identified methane mitigation as a key component of limiting the rate and extent of global warming. However, little is known about how methane mitigation can benefit other critical aspects of the climate system. This study explores the value of early methane mitigation in addition to carbon dioxide mitigation in helping avert an approaching and concerning climate event: the near-complete loss of Arctic summer sea ice. While drastic cuts in carbon dioxide emissions will ultimately control the fate of Arctic summer sea ice, we show that simultaneous early deployment of feasible methane mitigation measures is essential to avoiding the loss of Arctic summer sea ice this century. In fact, the benefit of combined methane and carbon dioxide mitigation on reducing the likelihood of a seasonally ice-free Arctic can be greater than the simple sum of benefits from two independent greenhouse gas policies. The extent to which methane mitigation can help preserve Arctic summer sea ice depends on the implementation timeline. The benefit of methane mitigation is maximized when all technically feasible measures are implemented within this decade, and it decreases with each decade of delay in implementation due to its influence on end-of-century temperature. A key insight is that methane mitigation substantially lowers the risk of losing Arctic summer sea ice across varying levels of concomitant carbon dioxide mitigation. This analysis provides further evidence of the value of early methane mitigation and the need to consider its benefits beyond reduced global temperature and improved air quality.

1. Introduction

Methane emissions are the second largest contributor—following carbon dioxide (CO2)—to today’s global warming due to human activities and are responsible for a quarter of today’s radiative forcing from warming pollutants (Myhre et al 2013, Ocko et al 2018, Forster et al 2021). Not only is methane mitigation therefore a crucial component in limiting future warming, but it is especially important in limiting near-term warming due to its relatively short atmospheric lifetime (around a decade relative to potentially hundreds of years to millennia for CO2; Solomon et al 2010).

Several studies have quantified the global temperature impacts of methane and its mitigation (e.g. Shoemaker et al 2013, Shindell et al 2017, Xu and Ramanathan 2017, Collins et al 2018, Ocko et al 2021). However, there has been limited exploration of the climate benefits of methane mitigation beyond temperature impacts. While it is reasonable to assume that limiting the rise in global temperature would benefit other aspects of the climate system, such as reducing the risks and extent of ice melt, sea level rise, and extreme events, our understanding of these benefits remains largely indirect. A few studies have investigated the role of short-lived climate pollutants on global mean sea level rise (Hu et al 2013, Sterner et al 2014, Zickfeld et al 2017), but the use of simplified emissions scenarios requires further translation to use in policy applications. Therefore, in order to assess climate benefits of methane mitigation beyond temperature using policy relevant scenarios, we explore how deployment of all currently available...
methane mitigation measures affects the risk of the near-complete loss of Arctic summer sea ice (referred to as ‘summer sea ice’ hereafter).

Studies show that based on the current trend of global warming, the Arctic could become seasonally ice free (defined as September sea ice extent falling below 1 M km$^2$ annually) in the foreseeable future (e.g. Wang and Overland 2009, Massonnet et al 2012, Notz and SIMIP Community 2020, Peng et al 2020, Senfleben et al 2020, Wei et al 2020, Árthun et al 2021, Bonan et al 2021, Diebold and Rudebusch 2021). Recent estimates with statistical and global climate models (GCMs) predict that the first ice-free September could occur as early as the 2030s (Peng et al 2020, Diebold and Rudebusch 2021, Docquier and Koenigk 2021, Wang et al 2021). The global mean temperature at which the Arctic is expected to have sustained ice-free summers often ranges around 2 °C–3 °C above the pre-industrial (1850–1900) level, albeit with large uncertainty (Mahlstein and Knutti 2012, Jahn 2018, Niederdrenk and Notz 2018, Sigmond et al 2018, IPCC 2019, Notz and SIMIP Community 2020). This critical temperature was once considered the ‘tipping point’ of Arctic sea ice, which denotes the critical threshold of a climate ‘tipping element’ where a little perturbation would bring the system to a new state (Lenton et al 2008, Lenton and Williams 2013, Schellnhuber et al 2016). However, the majority of evidence since then shows that the melting of summer sea ice is directly linked to local temperatures, is spatially uneven, reversible with cooling, and does not exhibit true tipping behavior (e.g. Notz 2009, Armour et al 2011, Ridley et al 2012, Li et al 2013, Wagner and Eisenman 2015, Kopp et al 2016, Árthun et al 2021). Ice-free Septembers could occur intermittently before the Arctic becomes seasonally ice free in summer. The recent sixth assessment report from the Intergovernmental Panel on Climate Change (IPCC) also concludes that the loss of summer sea ice will not be abrupt on decadal and longer timescales and will be reversible if forcing reverses, therefore not considered a ‘climate tipping element’ (Lee et al 2021). Nonetheless, the collective evidence suggests that sustained ice-free summers are likely to occur this century with continued warming (Lee et al 2021).

The consequences of summer sea ice loss have raised considerable concern in the climate science and policy communities. First, loss of sea ice means replacing the highly reflective ice with dark ocean waters that absorb far more sunlight, leading to even further warming in the Arctic region—the so-called ice-albedo feedback (Budyko 1969, Sellers 1969) that has been verified by satellite observations (Pistone et al 2014). Second, the lack of sea ice would disturb polar ecosystems, as many animals such as polar bears and walruses depend on sea ice to feed, socialize, and reproduce (Durner et al 2009, Cherry et al 2013, Molnár et al 2020). Third, an open ocean in the Arctic could lead to dramatically increased shipping in the region with its associated impacts (Wei et al 2020), and potentially with other geopolitical implications. Given that Arctic warming is suggested to alter mid-latitude weather patterns such as stalling extreme weather events that put agriculture at risk (Francis and Vavrus 2012, Cohen et al 2014), additional warming may exacerbate weather impacts with concomitant social disruption. Further, additional Arctic warming may accelerate the thawing of permafrost, which could release even more greenhouse gases and is irreversible for centuries, though the size of this feedback remains uncertain (Schaefer et al 2011, Chadburn et al 2017, Lee et al 2021).

However, loss of summer sea ice is not inevitable, and it can still be preserved if society curbs emissions of greenhouse gases and limits global temperature rise. The maximum extent of global warming ultimately relies on emissions of CO$_2$, and therefore net zero CO$_2$ emissions must be achieved in order to stabilize the climate (IPCC 2018). However, methane emissions also play an important role in climate change, and especially in the near-term (Naik et al 2021, Ocko et al 2021, UNEP and CCAC 2021). Studies show that the feasibility of achieving global temperature targets would be greatly reduced without methane mitigation due to its influence on the allowable carbon budget (Rogelj et al 2015, Collins et al 2018). A recent analysis suggests that methane may contribute nearly 1 °C of additional future warming in 2100 in the absence of mitigation, yet, half of anthropogenic methane emissions are currently mitigable with existing strategies (Ocko et al 2021). Immediate and rapid deployment of these feasible methane mitigation measures under a strong methane policy would avoid considerable warming in both the near- and long-term.

In this study, we build upon Ocko et al (2021), expanding the analysis of the impact of methane mitigation on temperature benefits to those on summer sea ice. We quantify the impact of strong methane policy (defined as deploying all available methane mitigation technologies) on reducing the risk of surpassing current estimates of the temperature at which the Arctic may become seasonally ice free. We also consider several emissions mitigation timelines for methane and CO$_2$ to assess the importance of early action on preserving summer sea ice and the sensitivity of methane's role to different CO$_2$ trajectories.

2. Methods

To assess how methane mitigation may impact the likelihood of a seasonally ice-free Arctic, we combine estimates of global mean temperature responses to varying emissions scenarios with estimates of global mean temperatures (‘thresholds’) at which summer sea ice would disappear.
2.1. Emissions scenarios

We develop four main emissions scenarios from 2020 to 2200: current policy, net zero CO₂ emissions, strong methane action, and combined CO₂ and methane action. The current policy case is constructed from multiple data sources (text S1 and figure S1 available online at stacks.iop.org/ERL/17/044001/mmedia), and can be considered as middle-of-the-road among various existing future scenarios with minimal climate action and results in around 4 °C of warming by end of century (figure S1(a)). For CO₂ mitigation, we focus on net zero CO₂ pathways in which no further CO₂ are being added to the atmosphere through human activities beyond what can be removed by human intervention. Net zero CO₂ is chosen given recent convergence around the need for mid-century net zero CO₂ emissions to stabilize the climate and achieve the Paris Agreement temperature goals (IPCC 2018), and as many countries and businesses around the world have pledged to reach ‘net zero’ around mid-century (Levin et al 2020). For methane mitigation, we apply a 55% reduction from the current policy baseline (figure S2), which is considered achievable within 10 years with existing technologies (Ocko et al 2021). Note that we do not consider other constraints such as behavioral changes and socio-economic factors. We focus on CO₂ and methane mitigation given that other greenhouse gases and black carbon emissions play a limited role over the investigated timeframe (figure S3). In addition, the benefit of black carbon mitigation may be somewhat offset by concurrent mitigation of co-emitted cooling pollutants (Stohl et al 2015, Harmsen et al 2020). However, this assumption is not intended to downplay the role of black carbon emissions in contributing to climate change, especially over the short term.

For each of the three mitigation scenarios, we develop several pathways that encompass different mitigation magnitudes and implementation timelines, including nine CO₂ mitigation pathways, 18 methane mitigation pathways, and some combinations of the two (figure S2 and text S1). Global mean temperature responses to all emissions pathways are simulated by the reduced-complexity climate model Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) version 6 (Meinshausen et al 2011a). See text S2 for more details. All global mean temperatures presented in this paper are relative to the pre-industrial (1850–1900) level.

2.2. Likelihood of seasonally ice-free Arctic

To determine the probability of a seasonally ice-free Arctic for each emissions pathway, we use a distribution of temperature thresholds that represent the range of global mean temperatures above which Arctic sea ice extent could fall below 1 M km² every summer—which is considered ‘nearly sea ice-free’ (Wang and Overland 2009). This temperature distribution has a mean of 2.45 °C and a 68% confidence interval of 2.2 °C–2.7 °C relative to the pre-industrial level (figure S4) following Iseri et al (2018). The mean value of the distribution is derived from a subset of Coupled Model Intercomparison Project (CMIP) 5 models that represents present-day sea ice conditions reasonably well and projects ice-free summer conditions to occur during 2041–2060 under the representative concentration pathway (RCP) 8.5 scenario (Massonnet et al 2012). This subset of models project ice-free summer to occur above 2.44 °C global mean temperature increase on average with a range of 1.9 °C–3.1 °C. A Gaussian distribution is then applied to represent the uncertainties of summer sea ice temperature thresholds. It is important to note that this distribution is a simplified assumption of the probability density of certain temperature thresholds which remains difficult to constrain (Stroeve and Notz 2015, Notz and SIMIP Community 2020, Senfleben et al 2020).

We use the joint kernel density estimation (KDE; figure S4) method to estimate the likelihood of a seasonally ice-free Arctic over time for each emissions pathway. Joint KDE, also known as joint probability density function, is commonly used to characterize the relationship between non-parametric distributions by indicating the likelihood of two events occurring at the same time. In this case, the two events are ‘global mean temperature reaches X degrees’ and ‘summer sea ice temperature threshold is Y degrees’. Once the probability of any X and Y occurring at the same time is determined (shown in figure S4(c)), one could integrate the density function in the domain where X is larger than Y (area below the diagonal line in figure S4(c)) to determine the total probability of global mean temperature exceeding summer sea ice temperature threshold. For each resulting temperature trajectory in our analysis, we use joint KDE to calculate the probability of exceeding the temperature threshold of summer sea ice every decade through 2100 (figure S4(d)). The level of likelihood is defined according to the IPCC uncertainty guidance—unlikely (0%–33%), as likely as not (33%–66%), likely (66%–100%), very likely (90%–100%) and virtually certain (99%–100%) (Mastrandrea et al 2010).

2.3. Uncertainties

The uncertainties of the risk estimates for summer sea ice mainly come from three sources: emission scenarios (including mitigation magnitude and timeline), MAGICC simulations of global temperature outcomes, and the response of summer sea ice to certain levels of temperature increase.

The uncertainty of future emission scenarios is analyzed by applying various pathways to each mitigation scenario (section 2.1 and text S1). We do not attempt to represent all the numerous possible emission scenarios the world could pursue, rather
a reasonable range of scenarios that are aligned with climate policy discussions and/or technological feasibility.

The uncertainty of global temperature simulations comes from both the physical understanding of the climate system (often reflected in climate sensitivity) and the approach of utilizing a reduced-complexity climate model. MAGICC is one of many reduced-complexity climate models that are widely used to rapidly reproduce the global aggregated characteristics of complex GCMs (Meinshausen et al. 2011a), and its performance has been evaluated by previous studies (Meinshausen et al. 2011b, Ocko et al. 2018; see text S2 for more details). To address the uncertainty of climate sensitivity, we conduct a 190 member ensemble simulation with parameterizations that mimic more complex GCMs and carbon cycle models. The range of temperature outcomes for any given year would reflect inter-model differences in their climate response to anthropogenic emissions, which is then incorporated into the joint probability calculations. However, we note that MAGICC does not simulate unforced variability (i.e. internal variability) of GCMs which could further broaden the range of temperature outcomes in any given year and affect the risk estimate for summer sea ice. It also does not include any spatial variations in radiative forcing or temperature response, thus the spatial variations of summer sea ice are not discussed in this study.

The uncertainty of summer sea ice response to certain levels of temperature increase is represented by varying the distribution of summer sea ice temperature threshold. Current estimations of when the Arctic will become nearly ice-free in summer will reflect inter-model differences in their climate response to anthropogenic emissions, and the spatial variations of summer sea ice are not discussed in this study.

3. Results and discussion

With existing climate policy, we find that global mean temperature will likely exceed the summer sea ice temperature threshold soon after 2060 with \(\sim 2.8 \, ^\circ\text{C}\) temperature increase above pre-industrial level (2052–2070 and 2.5 \(\sim 3.1 \, ^\circ\text{C}\) considering temperature threshold uncertainties), and with more than a 95\% chance by 2100 with \(\sim 4 \, ^\circ\text{C}\) temperature increase (figure 1). This projection appears conservative compared to estimates by GCMs and statistical methods, which put the critical temperature close to 2 \(^\circ\text{C}\) and the ice-free date before mid-century under high emission scenarios (Overland and Wang 2013, Notz and Stroeve 2018, Peng et al. 2018, Notz and SIMIP Community 2020, Bonan et al. 2021, Diebold and Rudebusch 2021, Wang et al. 2021), although some of them investigate the first ice-free year that would occur before sustained ice-free summers. The current climate policy scenario also has slightly lower emissions compared to a typical high emission scenario such as RCP8.5, resulting in a later ice-free date.

To date, the largest collective effort to curb global emissions of climate pollutants has been through the Paris Agreement, adopted in 2015 with the goal of limiting temperature rise to well below 2 \(^\circ\text{C}\) (United Nations/Framework Convention on Climate Change 2015). While nearly all countries in the world set emissions reduction goals for 2030 as their nationally determined contributions (NDCs) to the Paris Agreement, many studies have pointed out that current pledges—extended throughout this century—are not sufficient to achieve the agreed upon temperature target (Rogelj et al. 2016, Sanderson et al. 2016, Iyer et al. 2017). We find that this is also true in the context of preserving summer sea ice; if the NDCs are achieved in 2030 and extended to 2100 with a similar reduction rate, there is still likely to be a seasonally ice-free Arctic by 2100 (figure S1(b)).

3.1. The role of methane action in preserving Arctic summer sea ice

Our analysis shows that methane mitigation can play a major role in reducing the likelihood of a seasonally ice-free Arctic. Neither CO\(_2\) nor methane mitigation alone is enough to preserve summer sea ice through this century, let alone beyond, but combined they can lower the likelihood of losing summer sea ice to below 30\% by the end of the century and even through 2200, a level which is characterized as unlikely. This can be done without relying on a large amount of negative emissions.

If global CO\(_2\) emissions were to peak today and reach net zero in 2050—the goal of many climate policies focused on not exceeding 1.5 \(^\circ\text{C}\) level of long-term warming—we find that the likelihood of an ice-free Arctic summer would be 50\%, as likely as not, by 2100 (figure 1; blue lines) and 69\%, likely, by 2200. 
Figure 1. (a) Global mean temperature change (°C) relative to pre-industrial levels (1850–1900) under different emission scenarios: (red) current policy, (orange) fast methane mitigation only, (blue) net zero CO$_2$ by 2050 only, and (green) net zero CO$_2$ and fast methane mitigation combined. Shading indicates one standard deviation of temperature projections from 190 ensemble members. (b) Likelihood of seasonally ice-free Arctic under corresponding emission scenarios in (a) and two additional scenarios where methane mitigation is delayed for 20 and 40 years, respectively. Vertical bars on the right-hand side indicate the range of likelihood outcomes calculated with two other summer sea ice temperature threshold distributions (see section 2.3 for details). (c) Likelihood of seasonally ice-free Arctic as a function of global mean temperature change (°C) derived from the scenarios in (a). Lines with markers are based on the central distribution of summer sea ice temperature threshold (figure S4(b)) and lines without markers are based on two other distributions (see section 2.3 for details). Markers denote each decade from 2000 to 2100. Red shading in (b) and (c) indicates the probability ranges that are defined as unlikely (<33%), as likely as not (33%–66%), very likely (66%–100%), and virtually certain (99%–100%) (Mastrandrea et al 2010).
(figure S5). If sustained net negative CO$_2$ emissions are achieved after reaching net zero, the likelihood of an ice-free Arctic summer will further decrease depending on the scale of negative emissions (figure S5). For example, achieving $-10$Gt ($-20$Gt) of CO$_2$ emissions per year from 2060 onwards would lead to a 39% (26%) likelihood of an ice-free Arctic summer by 2200. However, achieving these amounts of negative CO$_2$ emissions depends on the large-scale deployment of technologies that are not yet scalable. This means that while preserving summer sea ice is possible with strong CO$_2$ policies alone, it is far from certain in the absence of reductions in emissions of other major greenhouse gases (most prominently methane). While strong CO$_2$ policies are likely to have the effect of reducing emissions of other pollutants, this is not guaranteed; for example, carbon capture and storage solutions for fossil fuel systems will not reduce methane emissions from fossil fuel supply chains; several major methane sources are not related to energy use (e.g. agriculture and waste); and the energy transition from coal to natural gas and potentially biogas (i.e. methane from fermentation of organic matter) complicates matters further.

The continued risk of losing summer sea ice despite dramatic cuts in CO$_2$ is primarily due to the major role that methane plays in current and future warming (Naik et al 2021). Methane emissions are projected to nearly double by the end of the century compared to today’s level in the absence of mitigation measures, with the majority of the emissions emanating from the livestock, oil and gas, and landfill sectors as populations grow (Högglund-Isaksson et al 2020, Ocko et al 2021; figure 2(a)). These emissions may contribute to nearly 1 °C increase in global mean temperature by 2100 (Ocko et al 2021), which would increase the risk of losing summer sea ice. Ocko et al show that half of the anticipated methane emissions can be reduced with existing technologies, which can lead to a 30% decrease in near-term warming rate and avoid more than half a degree Centigrade of warming by 2100 (Ocko et al 2021). While methane mitigation alone cannot prevent a seasonally ice-free Arctic (figure 1; orange lines), a combination of strong methane and CO$_2$ policies (all technically feasible methane mitigation measures implemented by 2030 and net zero CO$_2$ by 2050) can reduce the likelihood of an ice-free Arctic summer by 2100 to as low as 19%, and thus unlikely (figure 1; green lines). Through 2200, the likelihood would remain below 30%; thus unlikely to be ice free (figure S5). Note that the extent to which methane mitigation can help preserve summer sea ice is dependent on the magnitude of the mitigation (figure S6), and therefore the potential benefit could be reduced if not all feasible measures were implemented or it could grow as technologies improve.

The benefit of combined methane and CO$_2$ policies on summer sea ice (80% lower likelihood compared to current climate policy) is much greater than the simple sum of benefits from two single gas policies (57% lower likelihood: 50% from net zero CO$_2$ and 7% from strong methane policy), even though the global mean temperature benefits are linearly additive between the two. This is because the probability of losing summer sea ice is more sensitive to global mean temperature change when it is close to the temperature threshold of summer sea ice. Combined mitigation lowers the global mean temperature to below 2 °C on average, which has little overlap with the summer sea ice temperature threshold, while CO$_2$ or methane only mitigation can only lower global temperature to around 2.5 °C and 3.5 °C, respectively. This amplifying effect of combined mitigation actions remains robust across varying summer sea ice temperature thresholds (figure 1(b); vertical bars). Therefore, multiple mitigation actions tend to amplify the benefit of each other in lowering the probability of losing summer sea ice. This insight highlights the need to consider climate impacts beyond temperature when evaluating the benefit of emissions mitigation policies, because the overall climate benefit is not necessarily proportional to global mean temperature.

3.2. The importance of early methane action

The benefits of methane mitigation in lowering the risk of losing summer sea ice are also dependent on when mitigation measures are deployed (figure 2). Each decade of delay in implementing a strong methane policy would reduce the benefits of such policy on reducing the risk of losing summer sea ice.

To examine how the timeline of methane mitigation affects the risk of losing summer sea ice, we analyze two sets of emissions scenarios with different timelines for starting and achieving a 55% reduction in anthropogenic methane emissions below the reference scenario: ‘slow mitigation’ and ‘delayed mitigation’ (figure 2). The methane mitigations are added on top of achieving net zero CO$_2$ emissions by 2050. The slow mitigation scenarios begin implementing methane mitigation measures in 2020 and reach 55% reduction relative to the reference scenario in 10–80 years (figure 2(a)). The delayed mitigation scenarios start implementation between 2020 and 2080 and reach 55% reduction within a decade (figure 2(c)). These scenarios are illustrative of a wide diversity of plausible pathways to achieving a 55% cut in anthropogenic methane emissions, with varying start dates and implementation rates.

The slow mitigation scenarios show similar probability of losing summer sea ice throughout the century (figure 2(b)), while the delayed mitigation scenarios show higher probability of losing summer sea ice each decade the implementation is delayed (figure 2(d)). This indicates that the benefit of methane mitigation is more sensitive to the implementation start year than the implementation rate. This is likely due to the shifting of the center
Figure 2. (a)–(c) Global methane emissions (million metric tons; MMT) with (green) various mitigation timelines compared to the (red) current policy baseline. Methane mitigation starts in 2020 and reaches 55% below baseline in different decades (2030 at the earliest and 2090 at the latest) in (a). Methane mitigation starts in different decades (2020 at the earliest and 2080 at the latest) and reaches 55% below baseline a decade after in (c). All pathways in (a)–(c) reach the same amount of methane emissions once 55% below baseline is achieved. (b)–(d) Likelihood of seasonally ice-free Arctic with (blue) net zero CO$_2$ by 2050 only and (green) combined CO$_2$ and methane action. The timelines of methane mitigation correspond to those in (a)–(c).

of the joint probability distribution with temperature change (figure S7). Early methane mitigation, regardless of implementation rate, reduces methane emissions immediately and rapidly slows the rate of warming, which ultimately results in a lower end-of-century temperature compared to delayed methane mitigation. Therefore, the chances of global mean temperature exceeding the summer sea ice temperature threshold stays small throughout the century. This is indicated as the peak density of the joint probability pattern stays further away from the integration domain (under the diagonal line), so that the integrated probability is small and less sensitive to changes in global mean temperature due to different implementation rates (figures S7(b) and (c)). On the other hand, delayed action results in a higher end-of-century temperature that shifts the peak density of the joint probability pattern closer to the integration domain, thus the integrated probability is small and less sensitive to the changes in global mean temperature due to different implementation start dates (figure S7(d)). The greater importance of early implementation date than fast implementation rate is also evident with other levels of concomitant CO$_2$ mitigation (figure S8).

A key result is that if mitigation begins in 2020, the rate of implementing methane mitigation has a small influence on the likelihood of a seasonally ice-free Arctic throughout the century. In other words, immediate mitigation of methane emissions allows us to achieve a 55% methane emissions reduction over several decades and still retain most of the benefit in reducing the probability of losing summer sea ice. However, slower implementation of early mitigation would lead to a faster rise in global mean temperature (Ocko et al 2021), which could affect the temporal evolution of summer sea ice conditions, as sea ice extent is directly linked to global mean temperature (Notz and Stroeve 2018). It could also worsen other climate impacts in the near-term such as ocean warming and extreme weather events (IPCC 2019, Fischer et al 2021).

Further, there are benefits of early methane action irrespective of the ultimate CO$_2$ mitigation timeline (figure 3). Figure 3 shows the probabilities of having a seasonally ice-free Arctic by 2100 under net zero CO$_2$ pathways with various implementation timelines (blue markers) and in combination with fast deployment of strong methane mitigation (green markers). Two groups of CO$_2$ emissions scenarios are included: one group peaks today and reaches net zero between 2050 and 2080; the other group peaks in 10–30 years from now and reaches net zero three decades after peaking (figure 3(b)). The end-of-century
probability of losing summer sea ice under these CO₂ emissions scenarios ranges from 49% to 83% and increases with slowed or delayed CO₂ mitigation (figure 3(a)). The risk of losing summer sea ice is linearly correlated with the cumulative CO₂ emissions prior to net zero being achieved (figure S9).

When strong methane mitigation (figure 3(c); 55% below baseline by 2030) is deployed in addition to these net zero CO₂ emissions scenarios, the end-of-century probabilities of losing summer sea ice are consistently reduced by 24%–30% (figure 3(a)). We also test the sensitivity of the added benefit of strong methane policy to two other summer sea ice temperature thresholds (described in section 2.3). The results show that strong methane policy brings substantial reductions to the probability of losing summer sea ice across various timelines of net zero CO₂ emissions and different choices of temperature thresholds (vertical bars in figure 3(a)). It also shows the value of early CO₂ action given that less CO₂ is emitted in pathways where net zero is achieved in earlier decades.

**4. Conclusions**

Our analysis of the risk of losing summer sea ice under varying emission scenarios reveals the critical role of early methane mitigation, which is currently considered to have mostly near-term benefits related to temperature and air quality (Ocko et al. 2021, UNEP and CCAC 2021). Achieving net zero CO₂ emissions by 2050 alone is likely not enough to avoid the disappearance of summer sea ice (figure 4). However, when combined with early action to reduce methane emissions, it becomes unlikely to have a seasonally ice-free Arctic this century and potentially even longer. If methane action is delayed, the risk of losing summer sea ice increases, and there are consistent benefits from early methane action independent of net zero CO₂ timelines. By combining net zero CO₂ with fast methane mitigation, the benefit of preserving summer sea ice is maximized beyond the simple sum of two independent greenhouse gas policies.

The strong influence of methane mitigation in preserving summer sea ice results from both the continued role that methane plays in future warming and the sensitivity of summer sea ice to further increases in global temperature. This makes the imminent and near-complete loss of summer sea ice likely as the Earth continues to warm in the absence of methane emissions mitigation. Given the potential for methane mitigation to lower anticipated end-of-century warming by half a degree Centigrade, it is not surprising that it can also make a substantial contribution to preserving summer sea ice (Jahn 2018, Scren 2018). However, it is unexpected that early methane action would play a more important role in
reducing the likelihood of losing summer sea ice as compared to a fast implementation rate of methane mitigation.

Our results are in contrast to previous studies that suggest that we can get the same long-term benefits of methane mitigation whether we act now or later, because methane only has an atmospheric lifetime of around a decade and therefore does not accumulate in the atmosphere in the long-term (Bowerman et al 2013, Pierrehumbert 2014). While the influence of methane mitigation timeline on the long-term temperature outcome is indeed small, our analysis shows that the mitigation timeline is important when considering the risk of losing Arctic summer sea ice. Our study adds to a growing literature outlining the myriad long-term benefits of methane mitigation, as well as the importance of early action (Hu et al 2013, Zickfeld et al 2017, Ocko et al 2021).

Our methods have some limitations that could benefit from future research. For instance, our approach does not simulate how methane emissions and mitigations could affect the temporal and spatial evolution of summer sea ice conditions that are important for local ecosystem and social impacts. Furthermore, since the temperature outcome and risk of losing summer sea ice are calculated in two separate steps, our method does not include feedback between melting ice and temperature, which could in turn affect the risk of losing summer sea ice. A more comprehensive modeling approach using fully coupled GCMs could bring additional insights into the physical linkage between methane emissions and the Arctic sea ice system, and investigate any potential nonlinear effects. We note that while the model and statistical methods used in the study represent a highly simplified configuration of the sea ice system and how it interacts with anthropogenic emissions, the quantification of risk in a seasonally ice-free Arctic provides important new insights into the value of methane mitigation that can be further validated by GCMs. Methane mitigation is an important complement to stringent CO₂ mitigation, and the many benefits of early action are increasingly clear.

**Data availability statement**

The data that support the findings of this study are openly available at the following URL/DOI: [https://github.com/TSun-climdyn/Data_for_Sun-et-al.](https://github.com/TSun-climdyn/Data_for_Sun-et-al.).

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References

Armour K C, Eisenman I, Blanchard-Wrigglesworth E, McCusker K E and Bitz C M 2011 The reversibility of sea ice loss in a state-of-the-art climate model Geophys. Res. Lett. 38 L16703

Árthun M, Oonheim I H, Dírr J and Eldevik T 2021 The seasonal and regional transition to an ice-free Arctic Geophys. Res. Lett. 48 e2020GL090825

Bonan D B, Schneider T, Eisenman I and Wills R C J 2021 Constraining the seasonal onset of seasonally ice-free Arctic using a simple model Geophys. Res. Lett. 48 e2021GL094309

Bowerman N H A, Frame D J, Huntingford C, Lowe J A, Årthun M, Onarheim I H, Dörr J and Eldevik T 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 (Cambridge: Cambridge University Press) p 204

Budyko M I 1969 The effect of solar radiation variations on the climate of the Earth Tellus 21 611–9

Chadburn S E, Burke E J, Cox P M, Friedlingstein P, Hugelius G and Westermann S 2017 An observation-based constraint on permafrost loss as a function of global warming Nat. Clim. Change 7 340–4

Cherry S G, Derøeche A E, Thiemann G W and Lunn N J 2013 Migration phenology and seasonal fidelity of an Arctic marine predator in relation to sea ice dynamics J. Anim. Ecol. 82 912–21

Cohen J et al 2014 Recent Arctic amplification and extreme mid-latitude weather Nat. Geosci. 7 627–37

Collins W J et al 2018 Increased importance of methane reduction for a 1.5 °C target Environ. Res. Lett. 13 054003

Diebold F X and Rudebusch G D 2021 Probability assessments of an ice-free Arctic: comparing statistical and climate model projections J. Econom. (https://doi.org/10.1016/j.jeconom.2020.12.007)

Docquier D and Koenigk T 2021 Observation-based selection of Diebold F X and Rudebusch G D 2021 Probability assessments of an ice-free Arctic: comparing statistical and climate model projections J. Econom. (https://doi.org/10.1016/j.jeconom.2020.12.007)

Durner G M et al 2009 Predicting 21st-century polar bear habitat distribution from global climate models Ecol. Monogr. 79 25–58

Fischer E M, Sippel S and Knutti R 2021 Increasing probability of record-shattering climate extremes Nat. Clim. Change 11 689–95

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: Cambridge University Press) p 204

Francis J A and Vavrus S J 2012 Evidence linking Arctic amplification to extreme weather in mid-latitudes: Arctic links to mid-latitude weather Geophys. Res. Lett. 39 L06801

Guarino M-V et al 2020 Sea-ice-free Arctic during the last interglacial supports fast future loss Nat. Clim. Change 10 926–32

Harmsen M J H M, van Dorst P, van Vuuren D P, van den Berg M, Dingenen R V and Klimont Z 2020 Co-benefits of black carbon mitigation for climate and air quality Clim. Change 163 1519–38

Höglund-Isaksson L, Gmez-Sanabria A, Klimont Z, Rafaj P and Schyp W 2020 Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe results from the GAINS model Environ. Res. Commun. 2 025004

Hu A, Xu Y, Tebaldi C, Washington W M and Ramanathan V 2013 Mitigation of short-lived climate pollutants slows sea-level rise Nat. Clim. Change 3 730

IPCC 2019 IPCC Special Report on the Oceans and Cryosphere in a Changing Climate ed H-O Pörtner et al (Cambridge: Cambridge University Press)

IPCC 2018 Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty ed V Masson-Delmotte et al (Cambridge: Cambridge University Press)

Iseri Y, Yoshihata K, Kiguchi M, Tawatari R, Kanae S and Oki T 2018 Towards the incorporation of tipping elements in global climate risk management: probability and potential impacts of passing a threshold Sustain. Sci. 13 315–28

Iyer G, Ledca C, Clarke L, Edmonds J, McJeon H, Kyle P and Williams J H 2017 Measuring progress from nationally determined contributions to mid-century strategies Nat. Clim. Change 7 671–4

Jahn A 2018 Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming Nat. Clim. Change 8 409–13

Kopp R E, Shwom R L, Wagner G and Yuan J 2016 Tipping elements and climate–economic shocks: pathways toward integrated assessment Earth’s Future 4 346–72

Lee J Y et al 2021 Future global climate: scenario-based projections and near-term information 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: Cambridge University Press) p 195

Lenton T M, Held H, Kriegler E, Hall J W, Lucht W, Rahmstorf S and Schellnhuber H J 2008 Tipping elements in the Earth’s climate system Proc. Natl Acad. Sci. 105 1786–93

Lenton T M and Williams H T P 2013 On the origin of planetary-scale tipping points Trends Ecol. Evol. 28 380–2

Levin K, Rich D, Ross K, Fransen T and Elliott C 2020 Designing and communicating net-zero targets (Washington, DC: Working Paper, World Resources Institute) (available at: www.wri.org/design-net-zero)

Li C, Notz D, Tietzsch S and Marotzke J 2013 The transient versus the equilibrium response of sea ice to global warming J. Clim. 26 5624–36

Mahlstein I and Knutti R 2012 Arctic sea ice predicted to disappear near 2 °C global warming above present J. Geophys. Res. Atmos. 117 D06104

Massonnet F, Fichefet T, Goesse H, Bitz C M, Philippin-Berthier G, Holland M M and Barriat P-Y 2012 Constraining projections of summer Arctic sea ice Cryosphere 6 1383–94

Mastrandrea M D et al 2010 Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties (Intergovernmental Panel on Climate Change (IPCC))

Meinshausen M, Raper S C B and Wigley T M L 2011a Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—part 1: model description and calibration Atmos. Chem. Phys. 11 1417–56

Meinshausen M, Wigley T M L and Raper S C B 2011b Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—Part 2: Applications Atmos. Chem. Phys. 11 1457–71

Molnár P K, Bitz C M, Holland M M, Kay J E, Fenek S R and Amstrup S C 2020 Fasting season length sets temporal limits for global polar bear persistence Nat. Clim. Change 10 732–83

Myhre G et al 2013 Anthropicogenic 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, D Qin, G-K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press) pp 659–740

Naik V 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: Cambridge University Press) p 162

Niederdrenk A L and Notz D 2018 Arctic sea ice in a 1.5 °C warmer world Geophys. Res. Lett. 45 1963–71

Notz D 2009 The future of ice sheets and sea ice: between reversible retreat and unstoppable loss Proc. Natl Acad. Sci. 106 20390–5

Notz D and SIMIP Community 2020 Arctic sea ice in CMIP6 Geophys. Res. Lett. 47 e2020GL086749

Notz D and Stroeve J 2018 The Trajectory Towards a Seasonally Ice-Free Arctic Ocean Curr. Clim. Change Rep. 4 407–16

Ocko I B, Naik V and Paynter D 2018 Rapid and reliable assessment of methane impacts on climate Atmos. Chem. Phys. 18 15555–68

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. 15 054042

Overland J E and Wang M 2013 When will the summer Arctic be nearly sea ice free? Geophys. Res. Lett. 40 2097–101

Peng G, Matthews J L, Wang M, Vose R and Sun L 2020 What do global climate models tell us about future Arctic sea ice coverage changes? Climate 8 15

Peng G, Matthews J and Yu J 2018 Sensitivity analysis of Arctic sea ice extent trends and statistical projections using satellite data Remote Sens. 10 230

Pierrehumbert R T 2014 Short-lived climate pollution Annu. Rev. Earth Planet. Sci. 42 341–79

Pistone K, Eisenman I and Ramanathan V 2014 Observational determination of albedo decrease caused by vanishing Arctic sea ice Proc. Natl Acad. Sci. 111 3322–6

Ridley J K, Lowe J A and Hewitt H T 2012 How reversible is sea ice loss? Cryosphere 6 193–8

Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkel H, Schaeffer R, Sha F, Riahi K and Meij恩hausen M 2016 Paris Agreement climate proposals need a boost to keep warming well below 2 °C Nature 534 631–9

Rogelj J, Meinshausen M, Schaeffer M, Knutti R and Riahi K 2015 Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming Environ. Res. Lett. 10 075001

Sanderson B M, O’Neill B C and Tebaldi C 2016 What would it take to achieve the Paris temperature targets? Geophys. Res. Lett. 43 7133–42

Schaefer K, Zhang T, Bruhwiler L and Barrett A P 2011 Amount and timing of permafrost carbon release in response to climate warming: amount and timing of permafrost carbon release Tellus B 63 165–80

Schellnhuber H J, Rahmstorf S and Winkelmann R 2016 Why the right climate target was agreed in Paris Nat. Clim. Change 6 649–53

Screen J A 2018 Arctic sea ice at 1.5 and 2 °C Nat. Clim. Change 8 362–3

Sellers W D 1969 A global climatic model based on the energy balance of the Earth-atmosphere system J. Appl. Meteorol. 8 392–400

Senfleben D, Lauer A and Karpechko A 2020 Constraining uncertainties in CMIP5 projections of September Arctic sea ice extent with observations J. Clim. 33 1487–503

Shindell D, Borgford-Parnell N, Brauer M, Haines A, Kuylenstierna J C I, Leonard S A, Ramanathan V, Ravishankara A, Amann M and Srivastava L 2017 A climate policy pathway for near- and long-term benefits Science 356 493–4

Shoemaker J K, Schrag D P, Molina M J and Ramanathan V 2013 What role for short-lived climate pollutants in mitigation policy? Science 342 1323–4

Sigmund M, FYfe J C and Swart N C 2018 Ice-free Arctic projections under the Paris Agreement Nat. Clim. Change 8 404–8

Solomon S, Daniel J S, Sanford T J, Murphy D M, Plattner G-K, Knutti R and Friedlingstein P 2010 Persistence of climate changes due to a range of greenhouse gases Proc. Natl Acad. Sci. 107 18354–9

Stenner E, Johansson D J A and Azar C 2014 Emission metrics and sea level rise Clim. Change 127 335–51

Stohl A et al 2015 Evaluating the climate and air quality impacts of short-lived pollutants Atmos. Chem. Phys. 15 10529–66

Stroeve J and Notz D 2015 Insights on past and future sea-ice evolution from combining observations and models Glob. Planet. Change 135 119–32

UNEP and CCAC 2021 Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions (Nairobi: United Nations Environment Programme)

United Nations/Framework Convention on Climate Change 2015 Adoption of the Paris Agreement (Paris: United Nations) 21st Conference of the Parties

Wagner T J W and Eisenman I 2015 How climate model complexity influences sea ice stability J. Clim. 28 3998–4014

Wang B, Zhou X, Ding Q and Liu J 2021 Increasing confidence in projecting the Arctic ice-free year with emergent constraints Environ. Res. Lett. 16 094016

Wang M and Overland J E 2009 A sea ice free summer Arctic within 30 years? Geophys. Res. Lett. 36 L07502

Wei T, Yan Q, Qi W, Ding M and Wang C 2020 Projections of Arctic sea ice conditions and shipping routes in the twenty-first century using CMIP6 forcing scenarios Environ. Res. Lett. 15 104079

Xu Y and Ramanathan V 2017 Well below 2 °C: mitigation strategies for avoiding dangerous to catastrophic climate changes Proc. Natl Acad. Sci. 114 10315–23

Zickfeld K, Solomon S and Gilford D M 2017 Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases Proc. Natl Acad. Sci. 114 657–62