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Mitigation implications of an ice-free summer in the Arctic Ocean

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Key Points:

- Ice-free summers in the Arctic are expected to occur in the next few decades, but this process is currently not considered by integrated assessment models
- Our study shows the significant implications of Arctic sea-ice loss to mitigate global temperature to below 2°C
- This study highlights the need for a better understanding of how the rapid changes observed in the Arctic may impact our society

Supporting Information:

- Supporting Information S1

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Abstract The rapid loss of sea ice in the Arctic is one of the most striking manifestations of climate change. As sea ice melts, more open water is exposed to solar radiation, absorbing heat and generating a sea ice–albedo feedback that reinforces Arctic warming. Recent studies stress the significance of this feedback mechanism and suggest that ice-free summer conditions in the Arctic Ocean may occur faster than previously expected, even under low-emissions pathways. Here, we use an integrated assessment model to explore the implications of a potentially rapid sea ice-loss process. We consider a scenario leading to a full month free of sea ice in September 2050, followed by three potential scenarios afterward: partial recovery, stabilization, and continued loss of sea ice. We analyze how these scenarios affect the mitigation efforts to keep global temperature increase below 2°C. Our results show that sea-ice melting in the Arctic requires more stringent mitigation efforts globally. We find that global CO_2 emissions would need to reach zero levels 5–15 years earlier and that the carbon budget would need to be reduced by 20–51% to offset this additional source of warming. The extra mitigation effort would imply an 18–59% higher mitigation cost to society. Our results also show that to achieve the 1.5°C target in the presence of ice-free summers, negative emissions would be needed. This study highlights the need for a better understanding of how the rapid changes observed in the Arctic may impact our society.

1. Introduction

The rapid decline of Arctic sea-ice extent in the past few decades is one of the most evident indicators of global warming. One direct consequence of this phenomenon is the sea ice–albedo feedback (SIAF), which amplifies Arctic temperature changes. A better understanding of the processes leading to this accelerated sea-ice loss has been recognized as one of the "grand challenges" of climate science [*Kattsov et al.*, 2010] as Arctic changes are going to have profound climatic [*Liu et al.*, 2012], ecological [*Post et al.*, 2013], economic [*Gautier et al.*, 2009; *Smith and Stephenson*, 2013], and societal [*Laidler et al.*, 2008; *Newton et al.*, 2016] implications, not only for the northern regions but for the entire globe [*Lenton et al.*, 2008; *Duarte et al.*, 2012].

Since satellite data records began in 1978, Arctic sea-ice extent has been showing persistent and significant reductions across all months. Generally, this decrease has been most pronounced for the month of September, at the end of the melting season. In September 2012, when the last record minimum was registered, Arctic sea-ice extent was 3.3×10^6 km^2, equivalent to a 50% reduction compared to the sea-ice cover during the early 1980s. On average, Arctic sea-ice extent declined at a rate of 7.5% per decade in the period 1979–2001 and at 22.2% per decade within the period 2001–2015 [*ARC*, 2015]. The retreat in the extent of sea ice is part of an ongoing, more abrupt decline in ice thickness, volume, and age [*ARC*, 2015].

An *ice-free summer* (i.e., a sea-ice extension of less than one million square kilometers) in the Arctic Ocean is now projected to occur earlier than previously expected [*Stroeve et al.*, 2007, 2012]. According to the IPCC AR5, it could occur around 2040–2060 [*IPCC*, 2013] under a high-emissions scenario (i.e., RCP8.5, Table S1, Supporting Information). Other authors [*Wang and Overland*, 2012; *Overland and Wang*, 2013], who combine information from climate models with observational data, suggest that an Arctic sea ice-free summer by the 2030s is more likely. If the estimated volume of lost sea ice is used as proxy for future sea-ice extent, some authors [*Maslowski et al.*, 2012] project ice-free summers in the Arctic Ocean by 2020 or even earlier. Finally, given the vulnerability of sea ice, some authors [*Serreze et al.*, 2007] anticipate that an abrupt episode due to natural climate variability could also trigger a faster transition of sea-ice loss.

Due to the inertia of the climate system, sea-ice loss during the first half of the century is not expected to be strongly dependent on the emissions scenario [*Overland et al*., 2014]. Therefore, it turns out that an Arctic sea ice-free summer is also possible under low-emissions pathways [*Mahlstein and Knutti*, 2012]. Within the Coupled Model Intercomparison Project 5 (CMIP5), this is the case for 15% of the simulations run through 2100 under a 2°C scenario [*Notz*, 2015]. The results of these models show that the trends of sea-ice loss until 2050 are indeed very similar for high- and low-emissions scenarios [*Hezel et al*., 2014].

A direct consequence of sea ice-free conditions is the occurrence of the SIAF, which refers to the process when sea ice (with high albedo/reflectivity) melts, and more open water (with low albedo) is exposed to solar radiation, therefore absorbing more energy and generating a self-reinforcing warming mechanism. Although this is not the only feedback mechanism associated to sea-ice loss, it has been identified to have a central role in recent Arctic temperature amplification [*Screen and Simmonds*, 2010]. Various studies have estimated the change in albedo due to sea-ice melting [*Riihelä et al*., 2013], and some have estimated the impact on regional or global radiative forcing. *Flanner et al*. [2011] estimated the global annually averaged radiative forcing caused by the sea-ice loss in the Arctic between 1979 and 2008 to be around 0.11 W m^{-2}. *Hudson* [2011] calculated that a complete removal of Arctic sea ice would result in an annual forcing of about 0.7 W m^{-2} and that "a more realistic sea-ice-free summer scenario," with no sea ice for one month in September, would result in an annual forcing of about 0.29 W m^{-2}.

Here, we study the implications of mitigating climate change to below 2°C levels in the presence of the SIAF. This feedback is not incorporated explicitly into integrated assessment models [*Stern*, 2016; *Knutti and Hegerl*, 2008], and therefore, its direct implications have not been addressed yet. We study the consequences of a sea ice-free month in September, as described by *Hudson* [2011], assuming that it may occur by 2050. Given the current trends, this scenario seems plausible. Finally, based on the current debate about a potential recovery of Arctic sea ice in a low-carbon scenario, we consider three different sea ice scenarios afterward: partial recovery, stabilization, and continued sea-ice loss.

2. Model and Scenarios

2.1. Integrated Assessment Model

We use the Dynamic Integrated Climate–Economy model (DICE version 2013R), which is an integrated assessment model that has been used in the analysis of the implications of different climate policies and pathways [*Nordhaus*, 1992; *Moore and Diaz*, 2015; *González-Eguino and Neumann*, 2016]. In our study, an optimal control rate for fossil fuel and industrial CO_2 emissions is sought that maximizes the net present value of cumulative economic welfare from 2010 to 2100, subject to a constraint on global temperature change. In this approach, economic welfare corresponds to net welfare, i.e., the damage from climate change and the mitigation costs have already been deducted. More information on the DICE model can be found in the model documentation [*Nordhaus and Sztorc*, 2013].

2.2. SIAF Scenarios

Given the high uncertainty related to projections of Arctic sea-ice melting, we characterize three scenarios of SIAF, represented by changes in radiative forcing. The scenarios explore the implications of a transition toward an entire month free of sea ice in the Arctic Ocean in September 2050, with three different developments thereafter: stabilization, partial recovery, and continued loss (no recovery) of sea ice. We estimate the additional efforts required to maintain global mean temperature change to below 2°C (called *2°C* Scenario). We compare these three SIAF scenarios with a baseline mitigation scenario that does not account for SIAF (Figure 1).

The scenarios are summarized as follows:

1. *2°C*: This is the baseline mitigation scenario. It assumes no change in global radiative forcing from Arctic sea-ice loss. This scenario introduces the constraint that global mean temperature change should be below 2°C in 2100 but allowing for overshooting. To be consistent with RCP scenarios from literature [*van Vuuren et al*., 2011; *IIASA*, 2016], we consider that the exogenous radiative forcing from non-CO_2 factors increases from 0.25 to 0.4 W m^{-2} and that land use emissions are reduced progressively to zero by 2100, which are the values associated to the RCP2.6 Scenario.

2. *2°C_SIAF_Stabilization*: This scenario assumes a linear increase in the radiative forcing due to SIAF from 0.11 W m^{-2} in 2010 to 0.29 W m^{-2} in 2050. The value of 0.29 W m^{-2} is associated with an Arctic sea ice-free September as estimated by *Hudson* [2011]. From 2050 onwards, the Arctic sea-ice cover is assumed to remain stable at 0.29 W m^{-2} until 2100. This stabilization scenario is consistent with current model predictions of sea-ice loss under a low carbon scenario and by 2100 [*Hezel et al*., 2014].
3. *2°C_SIAF_Recovery*: This scenario matches *2°C_SIAF_Stabilization* up to 2050 followed by a partial recovery of the Arctic sea-ice cover thereafter. Here, we consider that recovery takes place at half the speed of loss occurred during the period 1980–2010, leading to a change in radiative forcing of 0.19 W m^{-2} in 2100 (Figure 1). This recovery process is consistent with some recent studies, which suggest that Arctic sea-ice loss could be reversible and recover quite quickly in a cooling climate [*Notz*, 2009; *Serreze*, 2011; *Tietsche et al*., 2011].
4. *2°C_SIAF_No-Recovery*: This scenario also matches *2°C_SIAF_Stabilization* up to 2050. However, in this case, sea-ice loss continues during the second half of the century with a change in radiative forcing reaching 0.51 W m^{-2} by 2100. This scenario is consistent with some studies that contemplate the existence of a threshold or "tipping point" in the process of Arctic sea-ice loss [*Holland et al*., 2006; *Wadhams*, 2012].

3. Results and Discussion

For all four scenarios, the optimal CO_2 emissions mitigation effort to reach the 2°C target by 2100 is computed (Figure 2a). We assume that emissions reduction starts in 2020. The results indicate that fossil fuel and industrial CO_2 emissions need to reach zero (corresponding to an emissions control rate of 1) by 2065 in the scenario without SIAF (2°C scenario). However, in the presence of SIAF, the mitigation effort would need to be more stringent, and emissions would have to be zero between 5 and 15 years earlier, depending on the scenario.

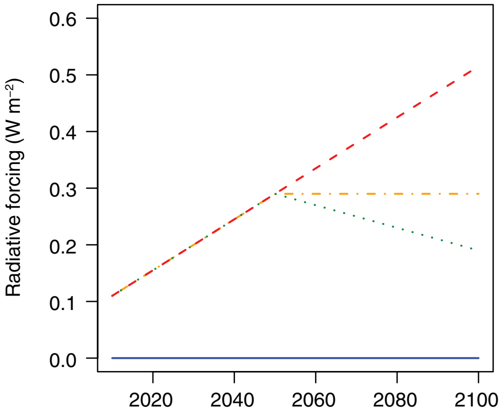

Figure 1. Changes in radiative forcing from Arctic sea ice–albedo feedback (SIAF) for each scenario (W m^{-2}). The forcings of all scenarios (but the baseline) increase from 0.11 W m^{-2} in 2010 to 0.29 W m^{-2} in 2050, which is the radiative forcing proposed by *Hudson* [2011] for an Arctic September free of sea ice under the action of the SIAF mechanism. The yellow line (dash-dotted) describes a stabilization process after 2050 (*2°C_SIAF_Stabilization*). The green line (dotted) describes a partial recovery process (*2°C_SIAF_Recovery*), and the red line (dashed) assumes a continued loss of sea ice (*2°C_SIAF_No-Recovery*). The blue line (solid) at zero radiative forcing refers to the baseline scenario without SIAF mechanism (*2°C*).

We analyze the implications of SIAF in terms of the carbon budget available for limiting temperature increases to 2°C (Figure 2b). According to the DICE model, the CO_2 budget from 2015 onward (in a 2°C scenario) is 1122 gigatons of CO_2 ($GtCO_2$), which is consistent with the range estimated by the IPCC-AR5 [*IPCC*, 2014b] and the most recent literature [*Rogelj et al*., 2016]. In the presence of SIAF, the carbon budget ends up being significantly lower, lying between 660 and 862 $GtCO_2$, depending on the scenario. The carbon budget is one of the clearest indicators that the small window of opportunity for achieving the 2°C goal is reduced considerably in the presence of Arctic sea-ice loss.

CO_2 concentration in the atmosphere is one of the control variables proposed to evaluate the status of the planetary boundary of climate change [*Steffen et al*., 2015]. In the presence of SIAF, the CO_2 concentration in the atmosphere would have to peak earlier and be lower during the entire century (Figure 2c). The peak in CO_2 concentrations would decrease from 476 parts per million (ppm) to 447–459 ppm and be below current values (400 ppm) by the end of the century.

Given the strong current connection between emissions and economic activities, decarbonization efforts inevitably affect the global economy. A primary source of information on multidecadal costs of mitigation stems from integrated models such as the one used in this study [*IPCC*, 2014a]. A relevant economic

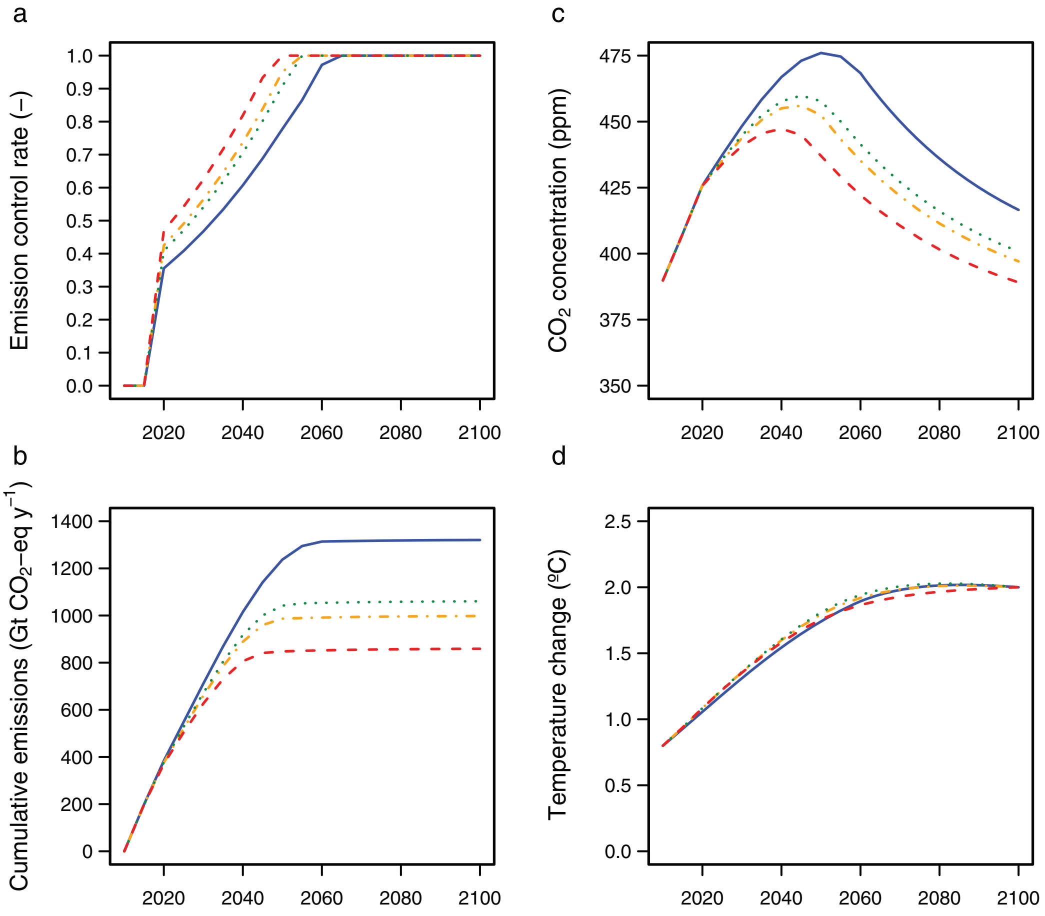

Figure 2. Climate change control implications. (a) Control rate (percentage of emissions reduction with respect to baseline) for fossil fuel and industrial CO_2 emissions. (b) Cumulative fossil fuel and industrial CO_2 emissions. (c) CO_2 concentration in the atmosphere. (d) Temperature change. The blue line (solid) at zero radiative forcing refers to the baseline scenario without SIAF mechanism (*2°C*). The yellow line (dash-dotted) describes a stabilization process after 2050 (*2°C_SIAF_Stabilization*). The green line (dotted) describes a partial recovery process (*2°C_SIAF_Recovery*,) and the red line (dashed) assumes a continued loss of sea ice (*2°C_SIAF_No-Recovery*).

indicator is the CO_2 price, which quantifies the marginal costs of mitigation, that is, the cost per additional unit of CO_2 reduction. The extra warming from SIAF requires more stringent mitigation efforts, and to achieve these, a higher carbon price is needed as cheaper mitigation options are progressively exhausted. In the presence of SIAF, the price of CO_2 must be higher, both now and in the future (Figure 3a). In 2020, the global carbon price in the mitigation scenario without SIAF is estimated at US$34 per ton of CO_2 (\$ tCO_2^{-1}). However, if we consider the SIAF effect, the price of CO_2 increases by 38–89%. The DICE model explicitly includes a backstop technology, which refers to a future technology that can eventually replace all fossil fuels at an initially “high” cost (350 \$ tCO_2^{-1} in 2010), declining over time due to technological progress. This explains the decreasing CO_2 price in all scenarios during the second half of the century (Figure 3a). The global CO_2 price reported here assumes full participation of all countries and well-functioning markets in all sectors. Therefore, it provides a benchmark for the *lowest cost* under these idealized implementation conditions.

In addition to the CO_2 price, we estimate the evolution of the mitigation cost in the period 2010–2100. The presence of SIAF would increase the present value of mitigation cost from US$8 trillion to a range between US$9.7 trillion and US$11.5 trillion. Although these extra costs are significant and can vary depending on the discount rates used [*Stern*, 2008; *Nordhaus*, 2007], they are relatively low when compared to the projected global economic growth during the century, with the estimated economic benefits that the Arctic provides to our economy in terms of regulation of the climate system [*Euskirchen et al*., 2013] or with our own estimations of the future extra damages from SIAF in a no climate policy scenario (see Supplementary

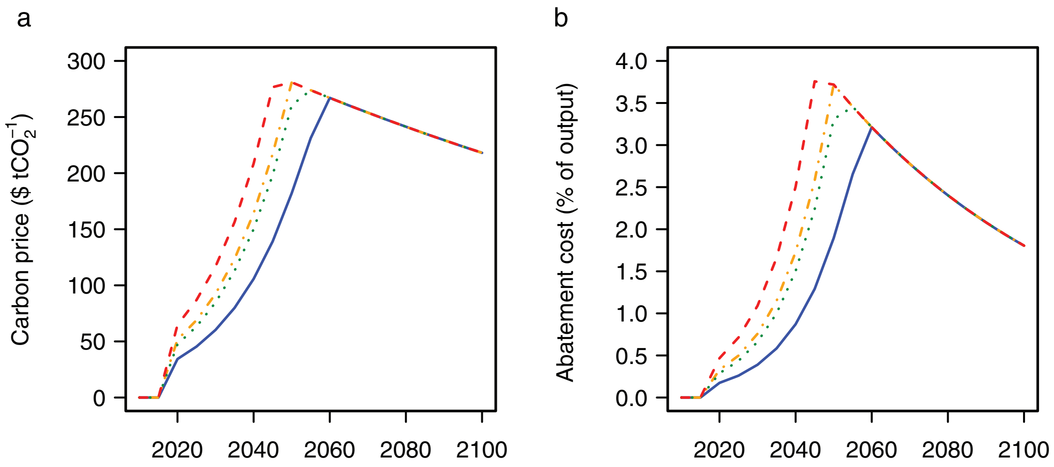

Figure 3. Economic implications. (a) Carbon price. (b) Abatement cost (percentage of output). The yellow line (dash-dotted) describes a stabilization process after 2050 (*2°C_SIAF_Stabilization*). The blue line (solid) at zero radiative forcing refers to the baseline scenario without SIAF mechanism (*2°C*). The green line (dotted) describes a partial recovery process (*2°C_SIAF_Recovery*,) and the red line (dashed) assumes a continued loss of sea ice (*2°C_SIAF_No-Recovery*).

Table 1. Sensitivity Analysis of Timing for a Sea Ice-Free Arctic.[a]

	Radiative Forcing 2050/2100 (W m^{-2})	Carbon Budget From 2015 (GtCO$_2$) and Reduction With Respect to *2°C*		Mitigation Cost 2010–2100 (Trillions of 2005US$) and Reduction With Respect to *2°C*	
2°C	0/0	1122		8.0	
2°C _Recovery					
2060	0.25/0.15	896	−20.1%	9.4	18.5%
2050	0.29/0.19	862	−23.2%	9.7	22.3%
2040	0.35/0.25	794	−29.2%	10.3	28.8%
2°C_Stabilization					
2060	0.25/0.25	834	−25.7%	9.9	24.7%
2050	0.29/0.29	799	−28.7%	10.2	28.6%
2040	0.35/0.35	732	−34.7%	10.8	35.6%
2°C_No-Recovery					
2060	0.25/0.43	722	−35.6%	10.9	36.8%
2050	0.29/0.52	660	−41.1%	11.5	44.7%
2040	0.35/0.65	549	−51.0%	12.7	59.5%

[a] The table shows the results of alternative timing of a full month free of Artic sea ice between 2040 and 2060. A linear trend is set in order to achieve a radiative forcing of 0.29 W m^{-2} by that date, as in Figure 1. In all scenarios, after 2050, a recovery/stabilization/no-recovery trend is applied to the value achieved in 2050, as the first column shows. The table presents results of carbon budgets for 2015 onwards (GtCO$_2$) and present values of mitigation costs between 2010 and 2100 (trillions of 2005US$).

Material). The mitigation cost as a percentage of the economic output (Figure 3b) is below 1% in the short run and up to 3.7% at the maximum point (mid-century) of the worst-case scenario.

4. Sensitivity Analysis

A key issue in studies of Arctic sea-ice loss is the date at which the sea ice-free condition may occur. Predictions from different models and projections vary greatly so that there is much uncertainty in relation to this timing. Table 1 shows the results of a sensitivity analysis of the date for a full month free of sea ice in the Arctic between 2040 and 2060. The changes in radiative forcing depicted in Figure 1 is modified, assuming a linear trend that would reach a radiative forcing of 0.29 W m^{-2} in 2040 or 2060. After 2050, the same rates

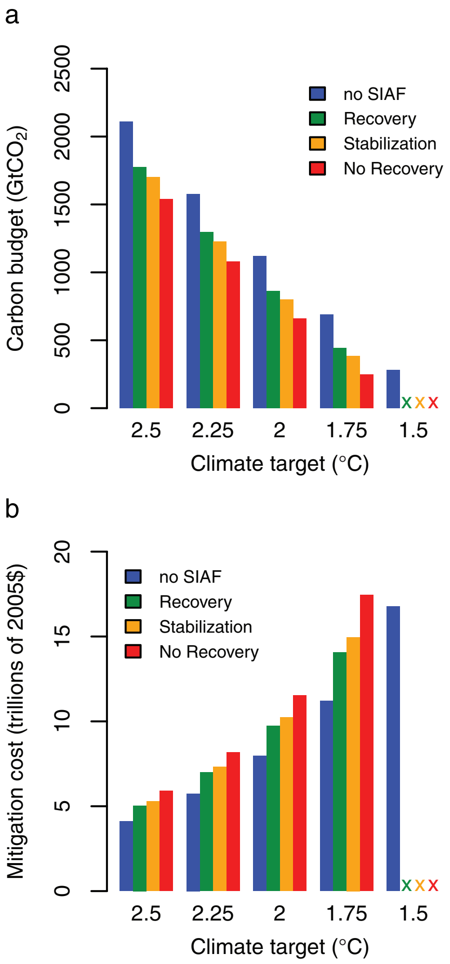

Figure 4. Sensitivity analysis on climate targets. The figure presents the implications for climate targets between 1.5°C and 2.5°C in the context of SIAF. The figure presents results of (a) carbon budget for 2015 onwards (GtCO$_2$) and (b) present value of mitigation costs between 2010 and 2100 (trillions of 2005US$). According to the DICE model, the 1.5°C target is not attainable ("X") if the SIAF is considered.

from the three SIAF scenarios are applied. The results show that the earlier the date of the first sea ice-free month occurs, the lower the carbon budget becomes. In the worst case situation of one month free of Arctic sea ice by 2040 without recovery, the carbon budget would have to be reduced from 1122 to 549 GtCO$_2$, implying a 51% reduction. Similarly, in that situation, the mitigation cost would increase from US$8 trillion to US$12.7 trillion.

Another important issue is the climate target selected. We further assess the sensitivity of the mitigation effort toward climate targets ranging from 1.5°C to 2.5°C in 2100 (Figure 4). The results show that the carbon budget in a scenario without SIAF is 2112 GtCO$_2$ for a 2.5°C target and 282 GtCO$_2$ for the 1.5°C target. According to the DICE model, the 1.5°C target is not attainable for any of our SIAF scenarios. This implies that the only way to achieve this target in the presence of SIAF would be through "negative emissions," i.e., extraction of CO$_2$ from the atmosphere, an option that it is not represented in the DICE model. Mitigation costs increase with the level of climate target stringency. The result for mitigation costs show that in a scenario without SIAF, the cost would be US$4.1 trillion for a 2.5°C target and US$11.2 trillion for a 1.75°C target. In the presence of SIAF, the cost for reaching the 1.75°C target would increase to a value in the range between US$14 trillion and US$17.4 trillion.

Finally, we do not include other sources of uncertainty in the sensitivity analysis of this section, as discussed by *Hudson* [2011] (e.g., changes in cloud cover) or the remaining uncertainties in the current levels of radiative forcing from SIAF. For example, *Pistone et al*. [2014] doubled the current estimations for SIAF of *Flanner et al*. [2011] and *Hudson* [2011] used here. Moreover, our study only captures the SIAF forcing effect quantified by *Hudson* [2011], whereas other authors, such as *Caldeira and Cvijanovic* [2014], estimate that if all other feedbacks were also considered, a full year free of Arctic sea ice could produce a net radiative global forcing as large as 3 W m^{-2}.

5. Conclusions

Arctic sea ice is a key indicator of global climate change because of its sensitivity to warming and its role in amplifying climate change through the SIAF. However, this feedback has not been captured in to integrated assessment models, and therefore, its direct implications have not been addressed. Moreover, recent trends in sea-ice extent and volume in the Arctic show greater and faster losses than generally obtained from physical models. Although there is much uncertainty about the timing of the first sea ice-free summer in the Arctic, it is imperative to study this phenomenon now, even if in stylized form [*Lenton and Ciscar*, 2012], in order to better understand its implications and guide further research and current decision making. This is especially important if abrupt losses of Arctic sea ice—such as those of 2007 and 2012—become a recurrent phenomenon in the coming years.

Our study reveals the significant consequences of rapid Artic sea-ice loss for keeping climate change to low levels. The sooner the sea ice-free condition occurs, the more difficult it will be to control climate change, especially if sea-ice recovery does not occur. Emission reduction efforts should increase significantly beyond what is currently assumed in mitigation scenarios that do not include Arctic sea-ice loss. For this to happen, existing energy infrastructures would have to be replaced quicker, and policy instruments that could make such improvements feasible would need to be adopted earlier. Therefore, the already difficult task of achieving the targets of the Paris Agreement may become even more challenging. Our results show that the only way in our scenarios to achieve the 1.5°C target in the presence of SIAF would be through negative emissions, which imply more risks and uncertainties for the future [*Rogelj et al*., 2015; *Hansen et al*., 2016]. The implications of Arctic sea ice-free conditions for the decarbonization pathways of the global economy are severe.

Our current scenarios of SIAF (represented through changes in radiative forcing) should be complemented in the future by considering scenarios of sea-ice loss derived directly from physical models. In addition to the SIAF addressed in this study, other related feedbacks occurring in the Arctic should also be considered. A better understanding of the socioeconomic implications of the rapid environmental changes occurring in the Arctic also requires a more intensive collaboration between the integrated assessment community and climate scientists.

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