https://doi.org/10.5194/esd-2022-17
Preprint. Discussion started: 29 April 2022

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Deploying Solar Radiation Modification to limit warming under a current climate policy scenario results in a multi-century commitment

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Abstract. A growing body of literature investigates the effects of Solar Radiation Modification (SRM) on global and regional climates. Previous studies have mainly focused on potentials and side-effects of SRM with little attention given to potential deployment timescales. Here, we look at a scenario that fails to achieve 1.5°C-compatible mitigation and instead relies on SRM and Carbon Dioxide Removal (CDR) to avoid temperature rises above the threshold. Assuming SRM removes the incentive to increase mitigation beyond the currently pledged level of ambition, we assess SRM deployment lengths under three illustrative emission scenarios that follow current climate policy and are continued with varying assumptions about net-negative CDR (-11.5, -10 and -5 GtCO2yr-1). Under these assumptions, SRM would need to be deployed for around 245 - 315 years. We find only minor effects of SRM on the global net carbon flux decades after cessation. In total, around 976 - 1344 GtCO2 would need to be removed by CDR, much more than in so-called high-overshoot 1.5°C scenarios. Our study points towards an additional risk of SRM that so far has received limited attention: Initialization and commitment to SRM would happen under the assumption that CDR can be scaled up sufficiently to allow SRM to be phased out again. In our scenarios, SRM would come with very long legacies of deployment, implying centennial commitments of costs, risks and negative side effects of SRM and CDR combined.

1 Introduction

Current governmental climate pledges and targets including the Nationally Determined Contributions' (NDCs') ambition are estimated to lead us to a global mean warming of around 3°C (Rogelj et al., 2016). This is twice the amount of warming agreed on in the Paris Agreement of 2015 that entails pursuing efforts of limiting warming to 1.5°C at the end of the 21st century (UNFCCC, 2016). The growing concern of overshooting the Paris Agreement's long-term temperature target has led to a discussion of Solar Radiation Modification (SRM) which could in theory cool the Earth very quickly (Irvine et al., 2016). SRM

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techniques intend to artificially lower global mean surface temperature (GMT) by modifying the radiative energy budget of the atmosphere. Proposed methods include Stratospheric Aerosol Injection (SAI), Cirrus Cloud Thinning (CCT) and Marine Cloud Brightening (MCB) (Lawrence et al., 2018). Most SRM methods operate on one of the impacts of climate change, temperature, without addressing its cause: anthropogenic greenhouse gas (GHG) emissions. Without explicit emission reduction as well as removal of these climate forcers from the atmosphere longterm, i.e. through Carbon Dioxide Removal (CDR) (Fuss et al., 2018), GHG emissions commit us to millennia of elevated temperature levels. Therefore, SRM deployment needs to be combined with emission reductions and CDR if a millennial requirement of SRM induced temperature reductions is to be avoided.

Achieving the Paris Agreement's target of 1.5°C assumes stringent mitigation with large near-term emission reductions as shown in the 1.5°C-compatible pathways of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR1.5) (Rogelj et al., 2018). It has been discussed that, in the absence of this strong near-term mitigation, SRM could be a tool to avoid overshooting 1.5°C and the impacts the exceedance would entail, while emission reductions and CDR are sufficiently scaled up until SRM is no longer needed to artificially lower GMT (Allen et al., 2018; Buck et al., 2020; Neuber & Ott, 2020). This 'buying-time'-approach, although criticized for relying on uncertain promises of SRM and CDR and increasing the risk of 'climate debt' (Asayama & Hulme, 2019), currently remains the dominant framing of SRM deployment (Neuber & Ott, 2020). Surprisingly little analysis, however, has been done on the timescales this type of SRM deployment would entail. Tilmes et al. (2016) analysed climate impacts of pathways whose temperature peaks at 3°C by the end of the 21st century and use CDR and SRM to limit temperature increase to 2.5°C and 2°C. Having a focus on climate impacts in their study, they show the duration of SRM deployment in their scenarios without discussing its implications. Similarly, MacMartin et al. (2018) looked at an experimental setup where mitigation, CDR and SRM are used as a strategy to meet the 1.5°C-goal from a 'business-as-usual' starting point. Both, Tilmes et al. (2016) and MacMartin et al. (2018), did not explicitly discuss the time this type of SRM deployment would entail and include very high rates of CDR that exceed sustainability criteria identified in the literature (Coninck et al., 2018; Fuss et al., 2018; Smith et al., 2015). Here, we take a different approach to MacMartin et al. (2018) by not evaluating mitigation, CDR and SRM as independent additive components to achieve a certain temperature outcome but rather by regarding plausible scenarios that arise from considering these options in conjunction. Specifically, we assume that the availability of SRM affects mitigation ambition and that after SRM initialization there is no incentive to increase ambition beyond the currently pledged targets. It is of course impossible to know how emissions would evolve under SRM. Some scholars argue that SRM could be deployed to do 'peak-shaving' under already ambitious mitigation scenarios (Coninck et al., 2018), while others fear it could undermine mitigation ambition even further (Baatz, 2016; Pierrehumbert, 2019) and present a 'moral hazard' risk (Keith, 2000; McLaren, 2016; Bellamy et al., 2016; Burns et al., 2016; Merk et al., 2016; Moreno-Cruz, 2015; Wibeck et al., 2015). In this study, we take a neutral position in this

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context and assume that current climate pledges until the end of the 21st century are implemented despite SRM, but not increased.

One key risk of SRM is the so-called 'termination shock', a rapid warming response to a sudden stop of SRM deployment (Parker & Irvine, 2018). We assume that such shocks are to be avoided and that plausible scenarios of SRM would need to seek a gradual deployment phase-out. Such a phase-out requires CDR to bring GHG concentrations back to a level where SRM can be stopped without any termination shock or temperature increases above a safe threshold. To bring the world on such a trajectory, we assume that GHG emissions go to zero after 2100 and net-negative through continued mitigation and large-scale CDR. SRM is used to keep GMT increase at 1.5°C, while mitigation measures and CDR capacity are sufficiently implemented to significantly reduce GHG concentration in the atmosphere. A simple climate model, the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) version 6 (Meinshausen et al., 2011), is used to simulate the global temperature response to GHG emissions and SRM.

While many methods for CDR (Fuss et al., 2018) and SRM (Boucher et al., 2013; Lawrence et al., 2018) exist, this study does not differentiate between these specific technological approaches as our results are independent of the specific SRM and CDR engineering techniques or their effects on one another. Furthermore, this paper does not address issues of technical feasibility or environmental side effects of SRM or CDR, of which there are many (Hubert, 2017). Neither does it propose potential implementation strategies and designs or questions relating to economic, political or ethical concerns of either one of them. With this contribution, we aim to provide a conceptual framework for further exploring SRM deployment length in the context of scenarios that use the technology as a temporary measure.

2 Methods

As the underlying scenario, we use the Climate Action Tracker global emissions pathway in line with the 'unconditional pledges and targets that governments have made, including Nationally Determined Contributions (NDCs)' (Gütschow et al., 2018; CAT, 2020). We employ this pathway because we assume no incentives to increase mitigation ambition under SRM deployment. This data is used for all major GHGs from 2000 until 2100 with an overall peak emission value of 55.7 GtCO2eqyr-1 in 2031. To be able to estimate potential SRM timescales we extend the pathway until 2500 via linear extrapolation of the last 20 years of the 21st century. This extrapolation is continued until emission values of the single gases arrive at respective minimum levels of the gases in the marker scenario SSP1-1.9 (Meinshausen et al., 2020) (Fig.1a). We

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assume that these levels represent values to which emissions of gases can realistically be reduced. The minimum emission value for a specific gas is held constant from then onwards.

For fossil-CO2 we continue the linear reduction until respective maximum levels of net-negative CO2 emissions (realized through large-scale CDR) are reached. We assess three different maximum CDR levels: -11.5 GtCO2yr-1, which equals CDR deployment in the SSP1-1.9 scenario, -10 GtCO2yr-1 and -5 GtCO2yr-1. The respective scenarios will be called 'CDR -11.5', 'CDR -10' and 'CDR -5'. All three magnitudes of CDR are in or slightly above the range of maximum potential by 2050 (Coninck et al., 2018; Fuss et al., 2018). However, given the substantial remaining GHG emissions implied by the unchanged ambition under SRM, the maximum net-negative potentials will only be reached in the 22nd century. The beginning of CDR deployment is not defined. However, we start our differentiation between the three different removal rates only in the year when the respective minimum value is reached, which inherently is earlier for CDR -5 than for CDR -11.5. We argue that scaling up to -11.5 GtCO2yr-1 would require more time. CDR is assessed from 2152 onwards, the year when fossil-CO2 values become negative. However, this does not preclude CDR deployment prior to 2152. We acknowledge that forecasting technology this far in the future is highly speculative and this analysis is by no means intended to be a realistic representation of SRM and CDR pathways. CDR is discontinued abruptly in the year when median total radiative forcing levels from a MAGICC6 simulation fed with the newly designed emission pathways arrive at 2.2 Wm-2 in a simulation run without SRM (Fig. 1a, c). Although a phase-out of CDR at the end would be more likely, this would not fundamentally change the main message of our study. After termination of CDR deployment, fossil-CO2 emissions remain at 0 GtCO2yr-1. Emission values prior to 2000 are from MAGICC's historical database.

In our scenarios, SRM initialization is determined by the year where GMT increase exceeds 1.5°C (2034). The termination criterion of SRM equals that of CDR (total radiative forcing = 2.2 Wm-2). Perturbation of solar irradiance is used to mimic the effects of SRM on temperature. The unmodified solar irradiance in the MAGICC6 setup consists of observed solar irradiance until 2009 and is held constant from then onwards at 0.12 Wm-2.

All global climate model simulations are conducted with the simple climate emulator MAGICC6, commonly used in several leading IAMs and in the IPCC. The model includes a simplified terrestrial and ocean carbon cycle model (Meinshausen et al., 2011, 2009). We apply a probabilistic setup with an ensemble of 600 runs derived by a Markov-Chain Monte-Carlo approach and provide estimates for the ensemble median as well as indicating the 66% (likely) uncertainty range in brackets. The range depicts the Equilibrium Climate Sensitivity uncertainty of the IPCC Fifth's Assessment Report (Rogelj et al., 2012, 2014) and the C4MIP carbon cycle ranges (Friedlingstein et al., 2014) and therefore offers good coverage of climate system and model uncertainty. Being a reduced-complexity model, MAGICC6 has its caveats and constraints related to the physical and spatial resolution of relevant climate and carbon cycle processes. Nevertheless, MAGICC6 has been used successfully in many

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instances to analyze long-term perspectives (Meinshausen et al., 2011, 2020; Nauels et al., 2017). Therefore, we consider it also appropriate for this type of exploration of hypothetical SRM deployment length.

3 Results

Without SRM deployment, but under the emission scenario where additional mitigation does not happen, GMT would overshoot 1.5°C in the year 2034 (2027 - 2043) and reach a peak temperature of 3°C in the mid 22nd century (2154) (66% range 2154: 2.4 – 4.0 °C) (Fig. 1b). The magnitude of SRM deployment is decided by the yearly amount of total radiative forcing that exceeds the 2.2 Wm-2 threshold, which was determined to lead to a pathway that does not exceed 1.5°C. This 'excess' radiative forcing, represented by the gray area in Fig. 1c, is subtracted from solar irradiance (Fig. 1c, 2a), i.e. total radiative forcing above 2.2 Wm-2 is subtracted from 0.12 Wm-2, the unmodified solar irradiance, in every year during SRM deployment. In order to achieve the desired 1.5°C limit as precisely as possible throughout the phase of SRM deployment, an adjustment of this calculated modified solar irradiance is necessary. The calculated initial reduction in solar irradiance is relaxed over the time when the geoengineered temperature drops below 1.48°C. This is the case under all three scenarios starting in 2151 (Fig. 2, dashed lines). CDR deployment length is changed accordingly to end five years after the adjusted SRM end date.

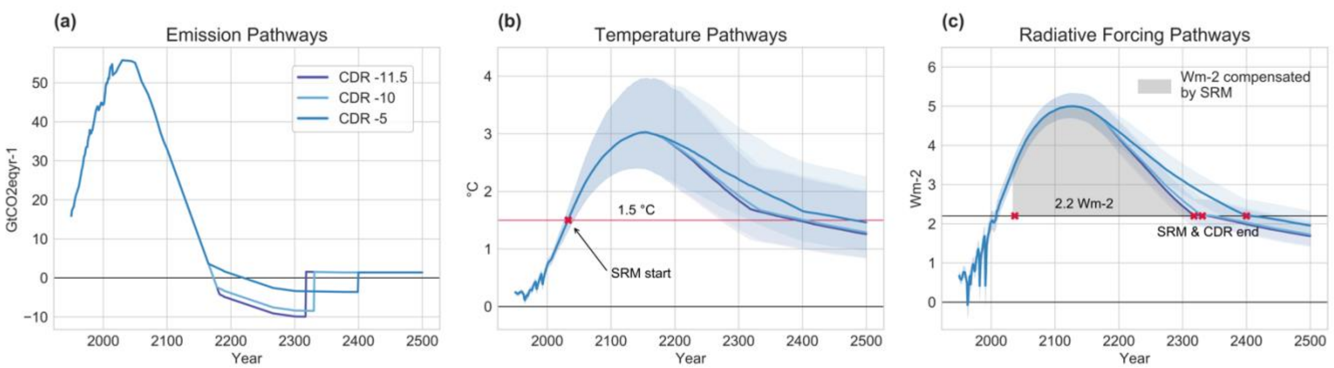

Figure 1: Scenario design. b) and c) are explicitly without SRM; ranges represent 66% uncertainty range a) GHG emission scenarios that differ in the amount of CDR b) corresponding temperature pathways; red crosses indicate the overshoot of 1.5°C GMT increase and the start of SRM c) corresponding radiative forcing pathways; gray shaded area represents amount of radiative forcing that is subtracted from solar irradiance; red crosses indicate the start of SRM and the end year of SRM and CDR

For the presented experimental setup, our results indicate that several centuries of SRM deployment in combination with other mitigation approaches would be necessary to keep warming at 1.5°C. More specifically we determine a length of 245 (218 - 271) years of SRM for the -11.5 CDR scenario, 253 (225 - 282) years and 315 (270 - 363) years for -10 CDR and -5 CDR respectively (Fig. 3). In the peak deployment year in this study (2125), SRM removes a maximum amount of 2.80 Wm-2.

Some modeling studies suggest that even higher amounts of radiative forcing could be compensated in theory (Kleinschmitt et al., 2018; Niemeier & Timmreck, 2015; Niemeier & Schmidt, 2017).

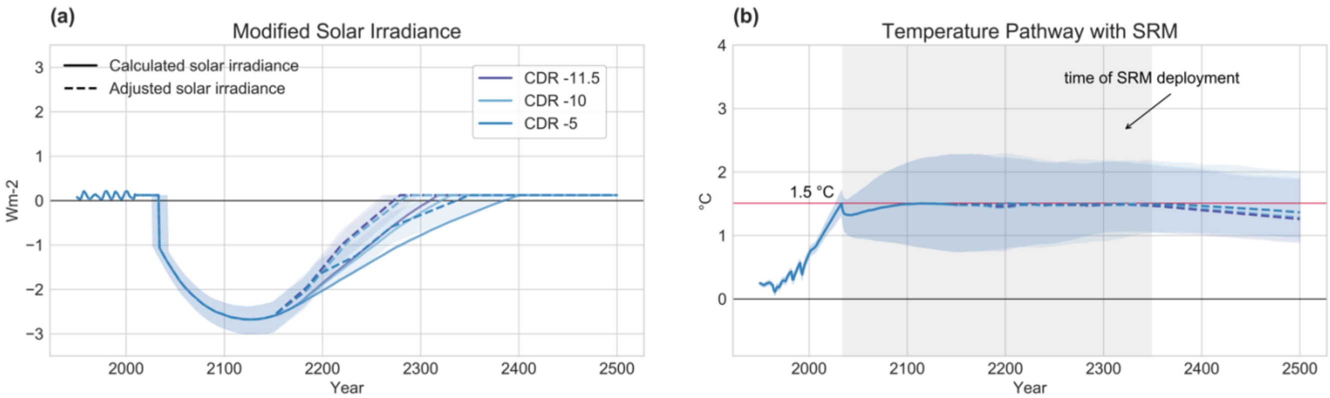

Figure 2: SRM deployment a) SRM implementation with solar irradiance as proxy; calculated (solid lines) and adjusted (dashed lines) modified solar irradiance with 66% ranges for adjusted pathways b) temperature pathway with adjusted SRM. Ranges illustrate 66% uncertainty range; gray shaded area represents SRM deployment years of CDR -5

While the specific start date of CDR deployment remains open in this analysis, CDR is continued until 2284 for CDR -11.5, 2292 for CDR -10 and 2354 for CDR -5. Quantifying from the point of zero fossil-CO_2 emissions, CDR cumulatively removes 1344 $GtCO_2$ (CDR -11.5), 1266 $GtCO_2$ (CDR -10) and 976 $GtCO_2$ (CDR -5), much more than in so-called high-overshoot 1.5°C pathways (Rogelj et al., 2018).

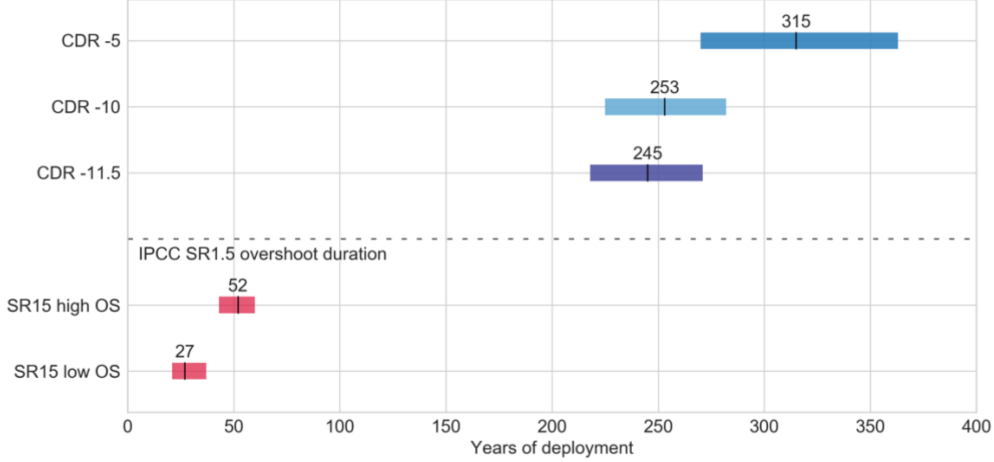

Figure 3: Length of SRM deployment. Tick and number indicate median length of deployment for each scenario; bar represents 66% uncertainty range. Red bars are median overshoot duration of the high (high OS) and low (low OS) overshoot 1.5°C IAM scenarios in the IPCC SR1.5 (Rogelj et al., 2018)

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With regard to the carbon cycle response, we find a stronger land carbon uptake during periods of strong SRM deployment and high atmospheric CO_2 concentrations that is largest in the 22nd century compared to a non-SRM scenario (Fig. 4). Ocean carbon uptake, however, would be weakened. At the time of cessation around the year 2300, the difference between a SRM and no-SRM scenario are still of the order of 60 GtC but will equilibrate over time to around 10 GtC in 2500. We note a difference between land and ocean carbon fluxes. While the land sink is enhanced under the SRM scenario compared to no SRM, this effect weakens over time as CDR is deployed and CO_2 concentrations drop. To the contrary, a somewhat weaker ocean sink remains over time, possibly as the result of lower atmospheric CO_2 concentrations. Assessing the robustness of the land and ocean carbon cycle responses in more complex models resolving the biogeochemistry of land and ocean in full detail would be required to further substantiate these findings (Cao, 2018).

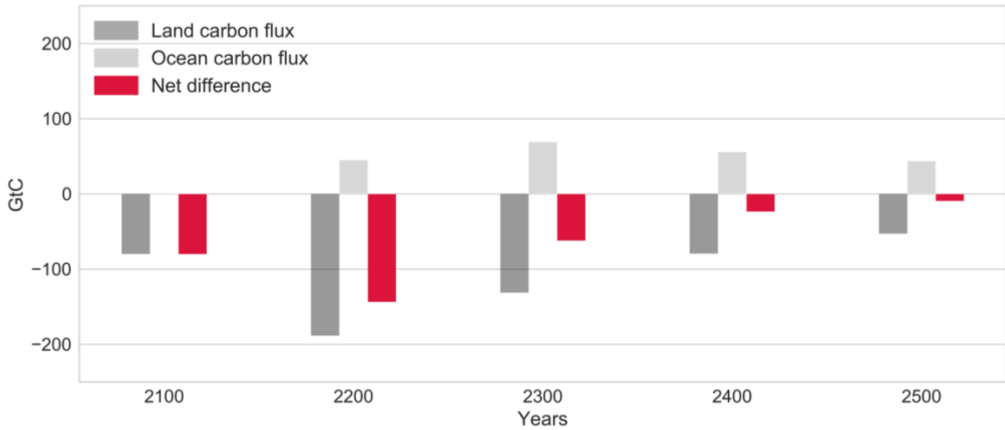

Figure 4: Temporal evolution of the difference in carbon fluxes without SRM vs. with SRM (negative values imply higher carbon fluxes in case of SRM). Cumulative carbon fluxes since 1765 are shown based on the MAGICC6 default carbon cycle setting. Values correspond to CDR -11.5; negative values indicate more cumulative GtC taken up in the SRM scenario versus no-SRM scenario.

4 Discussion

In the current literature, SRM is dominantly framed in the context of a stopgap measure (Asayama & Hulme, 2019; Buck et al., 2020; Neuber & Ott, 2020). Here, our study focusses on the question what timeframe this temporary deployment would entail. We determine time lengths of SRM deployment of 245 - 315 years, which would indicate a multi-century commitment to SRM, even when combined with high levels of CDR. Of course, this is conditional on the assumption that SRM removes the incentive to increase mitigation beyond the currently pledged targets. But for reasons outlined above we consider both, more or less mitigation ambition, plausible as a result of SRM deployment. Our middle-of-the-road emissions pathway provides a starting point for exploring these interlinkages. Different assumptions about future GHG emissions and CDR availability would alter the outcome considerably. Nevertheless, despite being based on slightly different framings, the timescales of SRM deployment in our study largely confirm the results by MacMartin et al. (2018) and Tilmes et al. (2016).

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These timeframes are much longer than the required CDR deployment in GHG emission reduction pathways for limiting warming to 1.5°C in 2100 after a high or low overshoot assessed in the IPCC SR1.5 (Fig. 3) (Rogelj et al., 2018). Therefore, even if society was able to continue moving towards a zero-emission lifestyle after SRM and CDR are deployed, presuming SRM and CDR work as desired and can be developed to this potential, future generations would be bound to engage with these technologies and all their risks and costs for several centuries.

During peak deployment SRM reduces a maximum amount of 2.80 Wm^{-2} per year. While Stratospheric Sulfur Injection is currently thought to be the most feasible and effective option of SRM (NRC, 2015), estimates from modeling studies (e.g. Kleinschmitt et al., 2018; Niemeier & Timmreck, 2015; Niemeier & Schmidt, 2017) on total maximum potential of Stratospheric Sulfur Injections vary strongly, depending on physical representations in the models and implementation strategies. Nevertheless, while even larger reductions in radiative forcing than in this study might be possible in theory, it is questionable whether the negative side effects of very large SRM deployments could be managed, considering the already remarkable implications for much smaller deployments than implemented in this study (e.g. Tilmes et al., 2016; Jones et al., 2018; Robock et al., 2008; Zarnetske et al., 2021).

The main concern with CDR is the magnitude of yearly removal to which it can be scaled up. To contextualize, a yearly removal of 11.5 $GtCO_2$ equates to about a third of today's yearly fossil CO_2 emissions (Friedlingstein et al., 2019) and would be an industrial effort by itself. There is a broad discussion in current literature on negative side effects and sustainability concerns with CDR in mitigation scenarios (Brack & King, 2020; Fuss et al., 2018; Smith et al., 2015) as well as the question of equity in the allocation of CDR burden (Fyson et al., 2020). These recognized environmental and social concerns of CDR are at least as applicable for pathways where CDR is combined with SRM and engagement needs to be sustained for centuries compared to decades due to the replacement of additional mitigation by SRM and CDR. Major concerns are the considerable land, water and financial requirements and constraints in long-term storage of removed CO_2 that increase for higher yearly removal rates. Different expectations about these limitations lead to a wide array of estimated potentials. Our study entails optimistic assumptions regarding the magnitude of future CDR over many decades, as they are at the upper end of estimates in current literature (Coninck et al., 2018; Fuss et al., 2018). Especially biophysical models point towards a smaller removal potential (Fuss et al., 2018; Smith et al., 2015). In terms of geological storage, the total required CO_2 removal in these scenarios is in range of suggested practical storage capacity (Dooley, 2013). It has to be noted that, although we quantify the amount of $GtCO_2$ removed by CDR from the moment of zero fossil-CO_2 emissions onwards, the actual start of CDR deployment is not defined and deployment prior to reaching zero fossil-CO_2 is not categorically excluded from this analysis and the results.

There are many uncertainties and risks discussed in relation to SRM (Lawrence et al., 2018). Our study showcases that there is an additional risk that commences as soon as it is deployed: if SRM is started to keep warming at a certain level it is done under the assumption that it will be possible to deploy CDR at the scale required to be able to stop SRM again. Whether or not this is indeed feasible is an open question. Our research highlights the substantial dependencies of SRM and CDR deployment which imply side-effects, risks, costs and uncertainties of both, SRM and CDR.

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Some scholars have claimed that SRM could be understood as a carbon dioxide removal technology by enhancing the carbon sink (Keith et al., 2017). However, the underlying analysis was limited to the 21st century and quantifies the effect during high levels of SRM deployment. Our data, too, suggests that carbon uptake is larger during and just around the end of SRM deployment, giving the potentially false impression that SRM could be an effective tool in limiting the concentration of CO_2 in the atmosphere. However, when looking at a longer timeframe including some decades after SRM cessation our data shows that the cumulative difference in carbon uptake is negligible (Fig. 4). While our results carry substantial uncertainties due to the large simplifications in the MAGICC6 carbon cycle and are not directly comparable to the Keith et al. (2017) paper, other studies too suggest that carbon uptake is counterbalanced in the years following SRM cessation (Lee et al., 2020; Plazzotta et al., 2019; Tjiputra et al., 2016) and the effect of additional carbon uptake during SRM deployment is only minor (Lee et al., 2020; Proctor et al., 2018; Sonntag et al., 2018). The effects of SRM on the carbon cycle differ for the type and location of SRM, the underlying CO_2 concentration and model used and require further investigation to draw more decisive conclusions (Cao, 2018; Dagon & Schrag, 2019; Lee et al., 2020; Muri et al., 2018). Because SRM can only be considered a temporary solution, termination of it should be inevitable and assessment of fluxes after the cessation of SRM is necessary. Therefore, the conclusion of SRM as a CDR technology does not hold for assessments that do not cover the whole life cycle of SRM. In fact, analyzing SRM over the whole timeframe instead of considering only moments of deployment does not just clarify that SRM cannot be considered CDR, but highlights the necessity to account for the whole deployment length also when undertaking assessments of cost-effectiveness or risks of SRM, for example.

In this analysis, we use SRM for the prevention of overshooting the 1.5°C-target and the global society would only be committed to SRM under the stated conditions of the analysis. Possible avenues for prior phase-outs have been discussed in MacMartin et al. (2018), Keith & MacMartin (2015) and Parker & Irvine (2018). However, these avenues would violate the 1.5°C-target and, as suggested by Parker & Irvine (2018), the phase-out of the amount of Wm^{-2} compensated in our study, would require about 50-75 years to avoid a termination shock. Therefore, even if SRM was, due to technical and or environmental considerations, phased out earlier, the phase-out itself would be a multi-decadal undertaking and does not change the fact that large-scale SRM implies a long-term commitment.

It is important to highlight that even if global temperature was stabilized with the help of SRM, this will not provide a solution with respect to regional impacts (Jones et al., 2018) and other impacts of high GHG concentration levels such as ocean acidification (Tjiputra et al., 2016). In our study, however, we do not aim to provide a comprehensive analysis of impacts or side-effects of such a climate intervention nor do we provide a likely or desirable implementation strategy but rather explore a concept to determine hypothetical SRM deployment lengths.

5 **Conclusions**

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In this study, we have looked at the timescales of SRM deployment in scenarios where SRM replaces stringent mitigation to limit warming to 1.5°C. SRM is applied to hold GMT increase at 1.5°C above pre-industrial levels while emissions are cut and CDR is scaled up until SRM could be safely phased out. We assume that under SRM there is no incentive to increase mitigation beyond the currently pledged level, established as the moral hazard argument (Keith, 2000; McLaren, 2016). Our study points towards an additional risk of SRM that – so far – has received limited attention: Initialization and commitment to SRM happens under the assumption that CDR can indeed be scaled up sufficiently to be able to phase out SRM again. Whether this is possible remains an open question. Our results show that, even in prospect of high CDR and the continuation of current climate targets despite SRM, we would commit ourselves to 245 - 315 years of SRM deployment to hold warming to 1.5°C. About 976 - 1344 $GtCO_2$ would be removed with CDR over the deployment phase. In the year of peak deployment, SRM compensates 2.80 Wm^{-2}. While these results cannot be seen as an accurate representation of possible future deployment and its feasibility remains an open question, they nevertheless point to a multi-century commitment to SRM and CDR, even for deployment at the upper end of currently estimated maximum potentials. We find only minor long-term impacts on the net global carbon flux a few decades after SRM cessation, suggesting no lasting effect of SRM on atmospheric CO_2 fluxes. All these aspects require further analysis but the fundamental dependency of SRM on CDR holds and our work illustrates that. This study provides a conceptual approach for further model experiments that could enable us to better understand the timescales SRM deployment would entail.

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Code and data availability statement

The code and data are available at http://doi.org/10.5281/zenodo.4316695 (Baur, 2021). The current policy emission pathway (2000-2100) is available upon request from https://climateactiontracker.org.

Author Contribution

SB, AN and CFS designed the experiments and SB carried them out. SB prepared the manuscript with contributions from all authors.

Ethics Declaration

The authors declare that they have no conflict of interest.

Acknowledgments

Funding was provided by the European Union's Horizon 2020 Research and Innovation Programme under grant nos. 820829 (CONSTRAIN) and the German Federal Ministry of Education and Research (01LN1711A).

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