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The interaction of Solar Radiation Modification with Earth System Tipping Elements

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Abstract. The avoidance of hitting tipping points is often considered a key benefit of Solar Radiation Modification (SRM) techniques, however, the physical science underpinning this has thus far not been comprehensively assessed. This review assesses the available evidence for the interaction of SRM with a number of earth system tipping elements in the cryosphere, the oceans, the atmosphere and the biosphere, with a particular focus on the impact of SAI. We review the scant available literature directly addressing the interaction of SRM with the tipping elements or for closely related proxies to these elements. However, given how limited this evidence is, we also identify and describe the drivers of the tipping elements, and then assess the available evidence for the impact of SRM on these. We then briefly assess whether SRM could halt or reverse tipping once feedbacks have been initiated. Finally, we suggest pathways for further research. We find that SRM mostly reduces the risk of hitting tipping points relative to same emission pathway scenarios without SRM, although this conclusion is not clear for every tipping element, and large uncertainties remain.

1 Introduction

Climate Change caused by anthropogenic greenhouse gas (GHG) emissions is increasingly recognised as a major threat to human and ecological systems (IPCC, 2023). Solar Radiation Modification (SRM) has been proposed as a set of methods that could ameliorate some of these climate risks, and is gaining salience at national (National Academies of Sciences and Medicine, 2021) and international (United Nations Environment Programme, 2023) levels. One aspect of climate change that is gaining increased

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attention are earth system tipping points (Armstrong McKay *et al.*, 2022), which are seen as potentially triggering dangerous changes increasing the risk of negative impacts of anthropogenic climate change and thus demand action to reduce the likelihood of hitting them (Lenton *et al.*, 2019). These impacts of climate change also have to be considered alongside the growing crisis of biodiversity loss, which is less widely recognised but is nonetheless dangerously pushing ecological systems towards lower biodiversity states (Legagneux *et al.*, 2018). While climate change and biodiversity loss are in themselves of great concern, their interaction is also of compelling interest, and the potential for climate change and SRM to influence tipping of ecological systems to lower biodiversity systems is also a critical issue. In the context of these growing dangers to humans and the biosphere from tipping points, SRM has been discussed (National Academies of Sciences and Medicine, 2021), although thus far, no comprehensive assessment of the impact of SRM on a variety of earth system tipping elements have been discussed. We discuss the potential for SRM to help avoid, postpone or precipitate hitting tipping points in the cryosphere, atmosphere, oceans, and biosphere, with particular attention to the impact on the drivers of tipping in these systems.

1.1 Tipping Elements

Several definitions for tipping elements in the earth system have been suggested (Lenton *et al.*, 2008; Van Nes *et al.*, 2016; Armstrong McKay *et al.*, 2022). While details differ, their common denominator is that at a critical threshold (the tipping point) a small additional change in some driver leads to qualitative changes in the system. As explicitly stated in Van Nes *et al.*, (2016) and Armstrong McKay *et al.* (2022), and described in nearly all examples in Lenton *et al.* (2008), these qualitative changes are brought about by self-accelerating changes caused by a positive feedback which drive the system to a new state. While the "state" of climate tipping elements can often be characterised by a single indicator, for example the mass of the Greenland ice sheet, this may not hold for ecological systems, which may have a variety of stable assemblages. In ecological systems, the concept of tipping elements may be somewhat different, with tipping behaviour is not only seen for large, complex systems, but also on the level of species, and events leading to species extinction can be considered a tipping point.

We use the word "driver" for the key variables external to the system that initiate the relevant changes, and "dynamics" for the self-accelerating processes that accomplish the tipping. Typically, once these processes have kicked in, they will continue even if the drivers stop to increase, or even decrease. An edge case are threshold-free feedbacks (Lenton *et al.*, 2008; Van Nes *et al.*, 2016; Armstrong McKay *et al.*, 2022), systems in which positive feedbacks play a role but are not strong enough to lead to

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run-away processes. These are commonly discussed alongside tipping elements, so some of these threshold-free feedbacks will be discussed here. For ease, when referring to the overall set of systems we are dealing with in this article, we will use the term ‘tipping element’ and only clarify that some are in fact feedbacks rather than tipping elements where it is conceptually necessary .

Changes brought about by crossing a tipping point may be completely irreversible (e.g. if species become extinct) or show hysteresis (e.g. if an icecap can regrow but only if temperature drops significantly below the tipping point for melt). However, following Masson-Delmotte et al. (2021), we do not consider hysteresis or irreversibility as necessary conditions for tipping.

Armstrong McKay *et al.* (2022) tie their tipping points to global warming thresholds. However, a tipping element may have other climate drivers, e.g. precipitation in the Amazon region, thus making the tipping point not merely global temperature related. When only greenhouse-gas-induced climate change is considered, one might assume that non-temperature drivers scale solely with GMST, which acts as proxy for the overall strength of climate change. However, if SRM is considered, other climate drivers do not necessarily scale with GMST; for example, SRM may restore GMST but fail to restore precipitation in the Amazon (Jones et al. 2018). Especially in ecological systems, non-climate or CO_2 drivers, such as human-induced deforestation, also play a key role.

Not just the value of a variable (e.g., GMST) but also the trajectory may play a role. For example, ice sheets have long response times and may only tip if the critical temperature has been exceeded for sufficiently long times (Lenton *et al.*, 2008; Armstrong McKay *et al.*, 2022). On the other hand, some tipping elements may be more susceptible to fast changes than to slow changes, even if the eventual magnitude of the change is the same (Ashwin *et al.*, 2012).

1.2 Solar Radiation Modification

While reducing and eventually eliminating (net) greenhouse gas emissions remains the only way to address the root cause of global warming, various climate intervention approaches have been suggested to complement mitigation and reduce global warming and its impacts. One set of approaches are collectively known as Solar Radiation Modification (SRM), a suite of proposed technologies aimed at increasing the earth’s albedo, reducing incoming solar radiation and thus reducing global surface temperatures (National Academies of Sciences and Medicine, 2021). While several SRM techniques have been proposed (National Academies of Sciences and Medicine, 2021), Stratospheric Aerosol Injection (SAI) is currently the best researched and the most plausible candidate to generate significant, fairly homogeneous cooling, and thus is the deployment method primarily discussed in this article.

SRM would mimic the effect of large volcanic eruptions by injecting particles or precursor gas (most commonly suggested is SO2) into the stratosphere to create a thin reflective aerosol cloud.

Even if SRM can be used to reverse Global Mean Surface Temperature (GMST) rise from increasing Greenhouse Gas concentrations (Tilmes *et al.*, 2020), it does not reverse the anthropogenic greenhouse effect, but acts through a different mechanism, i.e. reflecting sunlight. This means that SRM does not cancel the effect of increased greenhouse gas concentrations perfectly. Although modelling studies suggest that SRM might bring many relevant climate variables closer to their pre-industrial values (Irvine *et al.*, 2019), residual changes to atmospheric, oceanic and ecological systems would remain. SRM might introduce additional effects, such as changes in the balance between direct and indirect solar radiation and changes in the ozone layer (United Nations Environment Programme, 2023). SRM and its research also have a variety of social and political consequences and relevant considerations, including the risk of conflict (Bas and Mahajan, 2020), securitisation of the climate (Corry, 2017) or mitigation deterrence (McLaren, 2016)), and issues of imperialism (Surprise, 2020), democracy (Stephens *et al.*, 2021) and justice (Horton and Keith, 2016; Táíwò and Talati, 2022). We stress that the risks and potential benefits of SRM does not solely depend on its effects on climate, including tipping points, but would have to be assessed in a holistic risk assessment framework.

SRM implementation could follow many scenarios, with various background greenhouse gas trajectories, SRM approaches (SAI or alternatives), deployment sites, starting and end times, and intensities (MacMartin *et al.*, 2022), potentially including a mix of more or less coordinated regional approaches (Ricke, 2023) Unless otherwise specified, we assume a background greenhouse gas trajectory that would lead to a potentially large, multi-decade temperature overshoot, which is eventually brought under control by negative emission technologies. Against this background, SAI is used to produce a largely homogeneous cooling that limits global mean surface temperature (GMST) overshoot to a constant target, such as 1.5°C above pre-industrial, resembling (MacMartin, Ricke and Keith, 2018; Tilmes *et al.*, 2020). Unless specified, we assume all claims of the impact of SRM are relative to the same emissions pathway without SRM deployment.

1.3 Solar Radiation Modification and Tipping Elements

SRM has been considered a possible response to avoid tipping points in numerous contexts. Heyward and Rayner (2016) argue that tipping point rhetoric, as part of general ‘green millenarianism’, was a key part of early SRM advocacy. Avoiding tipping points is mentioned as a possible effect of SRM in prominent recent reports, such as National Academies of Sciences and Medicine (2021) and United Nations Environment Programme (2023), whilst Bellamy (2023) found 56.2% of people surveyed in their study slightly to strongly supported SRM as a response to tipping points. Heutel, Moreno-Cruz and Shayegh (2016) finds that in their economic model of tipping elements SRM is a part of the optimal policy alongside mitigation, where SRM mitigates the added risk that tipping elements add, whilst mitigation remains what it would be without tipping elements existing. Others have proposed emergency framings of SRM with reference to tipping points, something that both Horton (2015 and Lenton (2018) argue against. Despite this discussion, however, there has been very little assessment on the science of the interaction of SRM with tipping elements; this paper will attempt to lay some foundations to allow for fuller assessment in the future.

SRM might prevent climate and ecological systems from crossing tipping points, or it might push systems over tipping points. In ecological systems, which have many drivers and many possible states, it is also possible that both SRM and climate change without SRM would lead to hitting different tipping points within the same tipping element. The question may then not be *whether* tipping can be caused or prevented, but *which* tipping will occur under certain conditions.

To our knowledge, no systematic review of the impacts of SRM on tipping points has been conducted to date, though some studies on individual tipping elements exist. Yet while detailed research on potential SRM impact may be scarce for many tipping points, a first-order indication might be attempted by studying how SRM might affect known drivers and dynamics of a given tipping element. If the relevant drivers roughly scale with GMST, we can expect that SRM would reduce the likelihood that this tipping point is hit when compared to the same GHG concentration without SRM, although the efficacy (e.g. relative to the same temperature with avoided emissions) may be uncertain. If the key drivers are precipitation, regional climate or other factors that are not directly related to global temperature, then the effect of SRM might be harder to determine and may depend on the design of the deployment scheme.

Another difficult question is how SRM interacts with the dynamics of tipping element once the feedback processes are initiated, and whether it could reverse an ongoing or completed tipping. This is often harder to get first order indicators of, as the complexity of the feedbacks and the nature of hysteresis are generally less well understood than the initial drivers. Nonetheless, this may in particular be relevant if one considers to use SRM only as an emergency solution (Lenton, 2018). However, the lack of evidence means we will comment on this question less than the question of preventing or postponing tipping.

This study reviews a number of key tipping elements and associated threshold free feedbacks, somewhat although not exclusively following those laid out in Armstrong McKay *et al.* (2022). There are many other potential tipping elements but we hope this study provides a preliminary analysis of the interaction of SRM with a wide class of tipping elements.

2 Cryosphere

2.1 The Greenland Ice Sheet

Collapse of the Greenland ice sheet would raise sea levels by more than 7 metres (Morlighem *et al.*, 2017) and the freshwater it will release is also expected to slow the AMOC (Sect. 3.1), affecting global heat transfer (Rahmstorf *et al.*, 2015; Böning *et al.*, 2016).

Over the past few decades, mass loss from the Greenland ice sheet has accelerated (Shepherd *et al.*, 2012) and its mass balance has become more negative (Sasgen *et al.*, 2012; IMBIE Team, 2020). This mass loss has been increasingly dominated by surface melt, which is expected to continue to be the major influence of Greenland sea level contribution over the next century (Enderlin *et al.*, 2014; Goelzer *et al.*, 2020). Surface elevation has also declined, with Chen *et al.* (2021) observing a decrease of 12cm/yr between 2010-2019, and (Yang *et al.*, 2022) seeing a 20cm/yr decrease over a similar period.

In the future, Greenland appears committed to significant mass loss. Aschwanden *et al.* (2019) find that the Greenland ice sheet could lose between 8-25% of its mass in the next 1000 years even under RCP2.6, and up to 100% under RCP8.5. The authors find that the surface-elevation feedback plays a role in the persistent mass loss from Greenland, even when temperatures are stabilised at 2500. Gregory, George and Smith (2020) see a sea level contribution of between 0.5–2.5m for the same timeframe if present day surface mass balance was maintained. Estimates for Greenland sea level contribution by 2100 range from 0.01-0.07m under RCP2.6, and 0.03 to 0.16m SL under RCP8.5 (Fox-Kemper et al, 2021). Robinson, Calov and Ganopolski (2012) find temperature thresholds of irreversible loss are between 0.8–3.2 °C due to surface elevation and albedo feedbacks, though the rate of melt depends on the temperature above the threshold. Using a different model combination, Ridley *et al.* (2010) find that the ice sheet cannot be sustained for a warming of 2°C.

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2.1.1 Drivers and Feedbacks

Controls on Greenland tipping element are strongly driven by atmospheric changes, consisting of the interlinked surface-elevation and melt-albedo feedbacks (Robinson, Calov and Ganopolski, 2012; Tedesco *et al.*, 2016). These feedbacks are closely linked to surface mass balance.

Surface mass balance describes the balance of accumulation and loss on a glacier or ice sheet's surface. Accumulation comes from snowfall, while loss is a result of melting and runoff, evaporation, and wind driven redistribution of snow (Lenaerts *et al.*, 2019). The accumulation zone represents the area of a glacier or ice sheet where mass gain is greater than mass loss, and the ablation zone, usually at lower elevations, is where mass loss is greater than mass gain. If ablation across a glacier or ice sheet outweighs accumulation, surface mass balance is negative, meaning it is losing mass overall. Total mass balance also considers mass gains and losses from ice in contact with the ocean, such as basal melt and calving.

When a glacier or ice sheet undergoes surface melting, its elevation decreases. At lower altitudes, surface air temperature rises (Notz, 2009), allowing more surface melting and a further decrease in elevation (Lenton *et al.*, 2008) At a critical threshold, this feedback mechanism could continue unabated. Alongside this, melting exposes bare ice, old ice and ground, and creates melt ponds, all of which have a lower albedo than snow. These surfaces absorb more incoming solar radiation, leading to increased heating and more melt (Notz, 2009). Both feedbacks are controlled by atmospheric temperatures, though post-glacial rebound could mitigate some surface lowering, this process would likely not occur on useful timescales to alleviate the rapid mass loss if these feedbacks were triggered (Aschwanden *et al.*, 2019). Post-glacial rebound describes the gradual rise in the Earth's crust following glacier retreat, when the burden of the overlying ice pushing it down has been removed.

2.1.2 The impacts of SRM

SRM would lower atmospheric temperatures rapidly, decreasing the amount of surface melting on the Greenland ice sheet (Irvine, Keith and Moore, 2018). Irvine *et al.* (2009) found that even partially offsetting warming (by decreasing the solar constant) in a 4 x CO2 world would be enough to slow the sea level contribution from the ice sheet and prevent collapse. Both Moore, Jevrejeva and Grinsted (2010) and Irvine (2012) found that Greenland collapse could even be reversed if SRM strategies managed to offset the radiative forcing at a fast enough rate. In contrast, Applegate and Keller (2015) see that while SRM can reduce the rate of mass loss from Greenland, it cannot completely stop it, and strong hysteresis prevents rapid regrowth when temperatures are reverted. Fettweis *et al.* (2021) also see reduced surface melt through reduction of the solar constant via G6solar compared with a high emissions scenario, in part due to a weakening of the melt-albedo feedback. However, this reduction is not enough to prevent negative mass balance being reached by the end of the century, and therefore a possible tipping point being crossed. Greenland mass loss is decreased by 15-20% due to the reduction in surface melting under the G4 GeoMIP scenario, compared with RCP4.5 (Moore *et al.*, 2019). Lee *et al.* (2023) find that SAI at 60°N is effective at reducing surface melt and runoff from the ice sheet, but impacts are not localised with cooling throughout the northern hemisphere and a southward shift of the Intertropical Convergence Zone. However, mirroring SAI in the southern hemisphere has been shown to minimize this shift (Nalam, Bala and Modak, 2018; Smith *et al.*, 2022).

SAI may also result in some sulphate deposition in southern and western Greenland (Visioni *et al.*, 2020) . This would lower the albedo and could enhance the melt-albedo feedback, though the extent to which this would be negated by the decreased in temperatures and incoming solar radiation is unknown.

2.2 The Antarctic Ice Sheet

The Antarctic ice sheet holds 58m of sea level rise (Fretwell *et al.*, 2013), therefore even small losses could incur catastrophic impacts for low lying cities and communities. Sea level contributions from Antarctica range from 0.03-0.27m under SSP1-2.6 to 0.03-0.34m under SSP5-8.5 (Fox-Kemper et al., 2021). Furthermore, substantial melting would inject large amounts of cold freshwater into the oceans, changing oceanic circulation by inhibiting Antarctic Bottom Water (AABW) formation (Rahmstorf, 2006), a key component in global heat transfer (Bronselaer *et al.*, 2018). In contrast to the Greenland ice sheet, mass loss from Antarctica is driven primarily by the ocean, which melts and thins the base of ice shelves (IMBIE Team, 2020). This reduces their buttressing capabilities, increasing ice velocities and discharge into the ocean (Alley *et al.*, 2015). Current Antarctic air temperatures mean surface melting is limited and not a major component of mass loss, but this could change in future with rising atmospheric temperatures (DeConto and Pollard, 2016).

2.2.1 Drivers and Feedbacks

Both the East and West Antarctic Ice Sheet are tipping elements which could be triggered by two major mechanisms, marine ice sheet instability (MISI) and marine ice cliff instability (MICI).

The West Antarctic Ice Sheet is grounded almost completely below sea level and many areas are situated on reverse bed slopes, meaning that here, the bedrock in the interior is more depressed than the coasts due to the weight of the overlying ice, creating topographical conditions where the bedrock slopes down inland (Weertman, 1974).

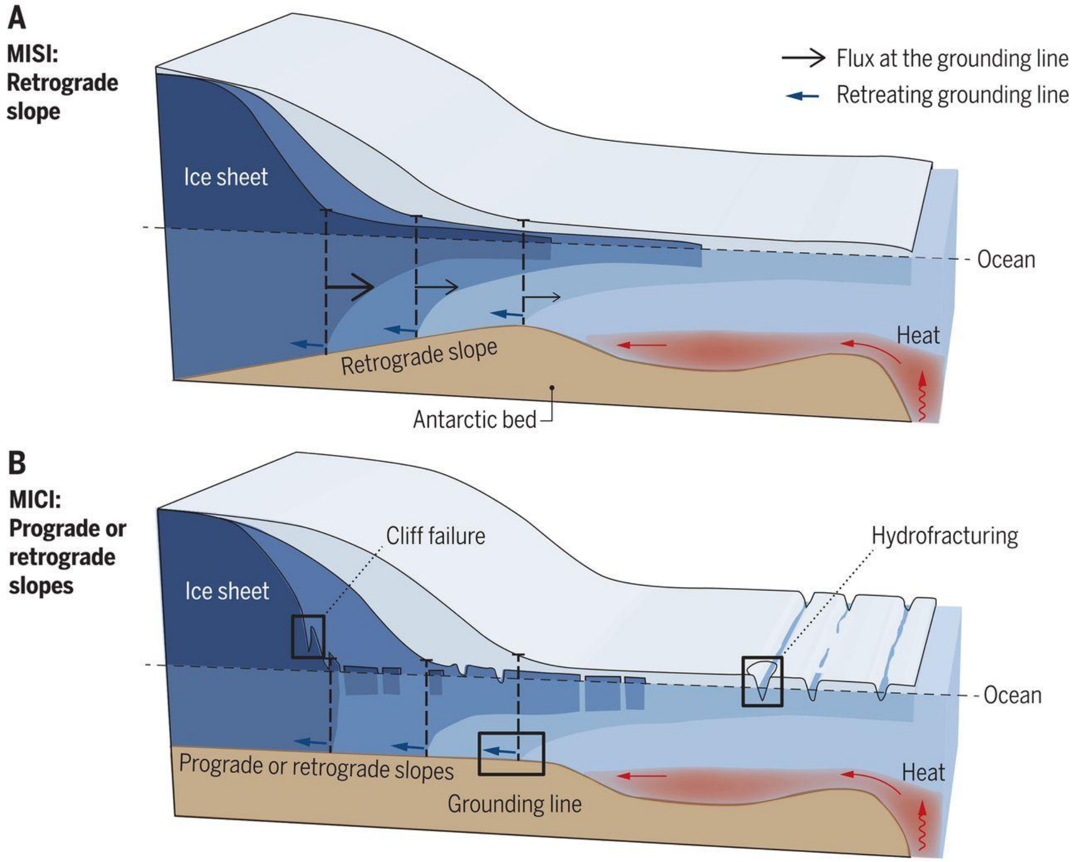

Figure 1. Schematic of marine ice sheet instability (a) and marine ice cliff instability (b). Taken from (Pattyn and Morlighem, 2020).

This topography makes the West Antarctic Ice Sheet vulnerable to MISI, where rapid retreat and collapse could be initialised due to a destabilising of grounding lines. The grounding line represents the area where grounded ice begins floating to become an ice shelf or calves into the ocean (Pattyn, 2018). In order for a grounding line to remain stable, the upstream ice flow must be equilibrated by the downstream discharge (Thomas, 1979). If an ice shelf thins or collapses, its buttressing effect reduces and causes the grounding line to retreat downslope to deeper waters where the ice is thicker. As the flux of ice across the grounding line is related to ice thickness, this increases ice discharge and pushes the grounding line further downslope in a positive feedback that can only be reversed if buttressing increases or the bed slope reverses (Weertman, 1974; Gudmundsson, 2013)).

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Parts of the East Antarctic Ice Sheet are similarly grounded below sea level with reverse bed slopes and so are also vulnerable to MISI, such Wilkes and Aurora Basins, Totten Glacier and Wilkes Land, with the latter being the main region of mass loss in the East Antarctic Ice Sheet (Rignot *et al.*, 2019).

The major driver of MISI is ocean thermal forcing, responsible for melting the base of the ice shelves (Gudmundsson, 2013). In Antarctica, MISI is also influenced by upwelling of warmer circumpolar deep water (CDW), which can be more than 4°C warmer than the freezing point and is widely believed to be a current driver of basal melting in the Amundsen sea (Jacobs *et al.*, 2011). CDW upwelling is wind driven, though this process is poorly understood (Thoma, Jenkins and Holland, 2008; Dinniman, Klinck and Hofmann, 2012). The Southern Annular Mode has been shown to have become positive, strengthening the westerlies which could lead to more CDW upwelling (Dinniman, Klinck and Hofmann, 2012).

Ice shelves can also be weakened and made more prone to collapse by hydrofracturing. Hydrofracturing occurs when meltwater formed on the ice shelf surface flows into crevasses and deepens them due to increased water pressure or refreezing, which can increase calving (Scambos, Hulbe and Fahnestock, 2013; Pollard, DeConto and Alley, 2015) .

Observations of rapid grounding line retreat (Rignot *et al.*, 2014; Scheuchl *et al.*, 2016) and modelling studies (Favier *et al.*, 2014; Joughin, Smith and Medley, 2014) indicate that MISI may already be in motion in the Amundsen Sea Embayment driven by CDW intrusions onto the continental shelf. (Johnson and Lyman, 2020) and (Bronselaer *et al.*, 2020) both see significant ocean warming trends, with the latter observing a 3°C warming in the Southern Ocean over the past two decades. (Fox-Kemper et al., 2021) has linked mass loss in the West Antarctic Ice Sheet to MISI, and above 2°C atmospheric warming this mechanism is thought to be a key driver of mass loss and therefore possible collapse of the West Antarctic Ice Sheet and parts of the East Antarctic Ice Sheet (Golledge *et al.*, 2015; Pattyn, 2018; Garbe *et al.*, 2020; Lipscomb *et al.*, 2021).

Another, more uncertain tipping process that could push both the East and West Antarctic Ice Sheets into unstable retreat, however, is marine ice cliff instability (MICI), comprised of ice cliff failure and hydrofracturing. The MICI theory posits that ice shelves with ice cliffs taller than ~100m are theoretically unstable due to the stress of the overlying ice exceeding the ice yield strength (Bassis and Walker, 2011). Therefore, it is speculated that, if ice shelf disintegration produces cliffs of this height, a self-sustained collapse and retreat of the grounding line could be triggered (Pollard, DeConto and Alley, 2015). This process is exacerbated by hydrofracturing, which further weakens the ice. As MICI has never been observed, with only indirect palaeo evidence (e.g. Wise *et al.*, 2017), rates of collapse and

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the duration of this self-sustained collapse is uncertain, though (Pollard, DeConto and Alley, 2015) see the West Antarctic Ice Sheet collapse in decades.

MICI's drivers are similar to MISI, as both involve ice shelf disintegration and so are vulnerable to ocean thermal forcing and circulation melting the base of the ice shelf (Pritchard *et al.*, 2012). Atmospheric temperatures are also important for MICI as this influences the amount of meltwater available for crevassing on the ice sheet's surface (Pollard, DeConto and Alley, 2015). At present, surface melting is not a major process in Antarctica, but this could change in future with climate change increasing air temperatures.

As temperatures increase, ice shelf collapses are projected to become more likely (Trusel *et al.*, 2015; DeConto and Pollard, 2016). Using a model that invokes MICI processes, (DeConto and Pollard, 2016) see higher ice losses than most other studies and find under RCP4.5 there is 32cm of sea level rise, and by 2500 there is almost total West Antarctic Ice Sheet collapse. For RCP8.5, they find that Antarctica contributes 77cm by 2100 and the West Antarctic Ice Sheet collapses within 250 years. Under 2°C warming, (DeConto *et al.*, 2021) improved version of the same model projects the rate of mass loss up to 2100 as similar to present day rates, but at 3°C, this jumps by an order of magnitude, with the rate increasing again for more fossil fuel intensive scenarios.

As this mechanism is uncertain and has never directly been observed, (Fox-Kemper et al., 2021) states that there is low confidence in simulating MICI, and as such, its ability to push the East or West Antarctic Ice Sheet beyond a tipping point is uncertain.

2.2.2 The impacts of SRM

There are virtually no studies which focus on SRM's impact on the East or West Antarctic Ice Sheet, but there is evidence to suggest that SRM would cool the Antarctic (Visioni *et al.*, 2021), which would be useful in limiting ice sheet deterioration via hydrofracturing. SRM may be less effective at cooling the poles than the tropics as during the polar night where there is limited or no solar radiation, it would have no effect (McCusker, Battisti and Bitz, 2012).

McCusker, Battisti and Bitz (2015) suggest that sulphate SAI induced stratospheric heating would intensify and shift southern hemisphere surface winds poleward, increasing CDW upwelling and therefore basal melting. This finding however, may be injection strategy dependent as injection of a different aerosol may not cause the stratospheric heating observed (Keith *et al.*, 2016). In addition, the poleward shift seen from McCusker, Battisti and Bitz (2015) tropical injection location is not seen for a southern hemisphere injection where the jet shifts equatorward (Bednarz *et al.*, 2022; Goddard *et al.*,

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2023). Goddard *et al.* (2023) also find that, while the Antarctic response to SRM is strongly dependent on injection strategy, multi-latitude sulphate SAI injection that limits global warming to 0.5C above preindustrial could prevent possible collapse of much of the Antarctic ice sheet.

Due to the gap in the literature around SRM's impact on Antarctica, some studies of carbon dioxide removal (CDR) impacts are also discussed here. Though CDR experiments are not a substitute for SRM as both have different impacts on atmospheric and ocean circulation, CDR studies can be used as a useful analogy to assess reversibility questions.

Garbe *et al.* (2020) use global mean temperature to perform equilibrium experiments, and find the Antarctic ice sheet exhibits hysteresis; with regrowth occuring much more slowly than mass loss. Under their more extreme 6-9°C warming scenarios where over 70% of the ice sheet is lost, the present-day ice sheet extent does not return, even when temperatures are reverted to present day levels. DeConto *et al.* (2021) show that while implementing CDR in the first half of this century could reduce sea level rise compared to a 3°C warming scenario (in line with current policies), it cannot reverse it due to the slow response time of the ocean to thermal changes, and that sea level contributions are strongly dependent on the decade CDR is implemented.

The ocean's slow response time to climate forcings mean that even if temperatures were reverted or rapid CDR was deployed, marine ice instabilities could still be triggered. A delayed ocean response to reduced atmospheric temperatures would likely also be seen with SRM, and for sulphate SAI in particular, it is unclear how the resultant stratospheric heating will affect atmosphere and ocean circulation, and therefore also CDW upwelling. While SRM would likely be effective in reducing surface melting and hydrofracturing, it would therefore not be as effective at reducing basal melt. In addition, a reduction in atmospheric temperatures would reduce the moisture holding capabilities of the air, decreasing the amount of precipitation falling as snow on Antarctica. Mid latitude SAI itself would also dampen the hydrological cycle and suppress precipitation (Tilmes *et al.*, 2013; Irvine, Keith and Moore, 2018; Visioni *et al.*, 2021). Therefore, if SRM's effect on reducing basal melt is limited, while simultaneously decreasing the amount of snowfall accumulating on Antarctica, it is also possible that it could be more harmful than doing nothing at all, as in a warmer, non-SRM world, the resulting increase in precipitation may slightly offset some mass loss (Edwards *et al.*, 2021; Stokes *et al.*, 2022).

2.3 Mountain Glaciers

Current trends of glacier mass balance globally are negative (Fox-Kemper et al, 2021), with glacier mass loss accounting for ~20-30% of current observed sea level rise (Zemp *et al.*, 2019; Rounce *et al.*, 2023). Zemp *et al.* (2019) also show that if present rates of mass loss were sustained, Western Canada, the USA, central Europe and low latitude glaciers would all lose almost all mass by 2100. Most glaciers are not in equilibrium with the current climate and so are still responding to past temperature changes. Therefore, it is projected that they will continue to experience substantial mass loss through the 21st century, regardless of which emissions scenario is followed (Marzeion *et al.*, 2018; Zekollari, Huss and Farinotti, 2019).

2.3.1 Drivers and Feedbacks

Mountain glaciers are subject to the surface-elevation and melt-albedo feedbacks (Johnson and Rupper, 2020), which would not only raise sea levels, but also reduce the availability of fresh water for mountain communities. Rounce *et al.* (2023) see that mass loss in larger glaciated areas is linearly related to global temperature, but that smaller regions are much more sensitive to warming, leading to a non-linear relationship above 3°C (Rounce *et al.*, 2023).

2.3.2 The impacts of SRM

Glaciers occupy a wide range of climate regions. As such, each individual glacier has its own topographical and climatological conditions affecting its mass balance and it is unlikely that SRM would have a uniform effect. Reducing temperatures using SRM would be more effective for low latitude glaciers where an increased proportion of the energy flux is shortwave (Irvine, Keith and Moore, 2018). Zhao *et al.* (2017) find that although all glaciers in high mountain Asia retreat by 2069 due to their slow response times to temperature changes, SRM could still limit mass loss. Under the G3 and G4 scenarios, glacier area losses in 2089 are 47% and 59% of their 2010 areas, respectively, compared with 73% under RCP4.5.

As SRM is more effective at counteracting hydrological changes than temperature changes (Ricke *et al.*, 2023), while melt may be reduced, surface mass balance could be negatively affected by reduced snowfall in the accumulation zone. Idealised experiments using a reduction of the solar constant to halve the warming resulting from doubled CO2 indicate that negligible amounts of the planet would see substantially reduced precipitation compared to preindustrial (Irvine *et al.*, 2019), but precipitation changes from SRM specifically are unlikely to be uniform. (Zhao *et al.*, 2017) highlight that, for Himalayan glaciers, this precipitation decrease may be much less important compared with whether the precipitation is falling as snowfall in the accumulation zone or as rainfall, in which case SRM induced cooling might prove valuable.

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2.4 Land Ice Further Research

Currently, there are large gaps in the literature with regards to how SRM will affect land ice, particularly Antarctica. This lack of research makes it challenging to assess the robustness of any one result. For example, it is difficult to ascertain whether the sulphate SRM induced CDW upwelling found in McCusker, Battisti and Bitz (2015) is a robust outcome. Therefore, there is a need for model ensembles forced by various SRM scenarios, to include aerosols other than sulphate and methods other than SAI. As suggested in Irvine et al. (2018), the inclusion of Geo-MIP scenarios in the Ice Sheet (Nowicki *et al.*, 2016) and Glacier (Hock *et al.*, 2019) Modelling Intercomparison Projects (ISMIP and GlacierMIP, respectively) would be an important addition to the current experiments. This would improve knowledge of ice sheet and glacier response to SRM including if reversing sea level rise on useful timescales is possible. Including Geo-MIP scenarios in the next set of ISMIP and GlacierMIP experiments would also allow for comparison with SSP scenarios that have a similar forcing via GHG reduction, such as SSP2-4.5.

The GeoMIP scenarios are fairly simplistic as they prescribe only an equatorial injection and do not take into account the equator-to-pole temperature gradient. As SRM impacts the polar regions differently compared with the rest of the globe, targeted SRM injection at specific latitudes could be more effective, though it could yield different results depending on location. For example, (Bednarz *et al.*, 2022) find that a northern hemisphere SAI injection with sulphate drives a positive SAM, whereas southern hemisphere injection results in a negative SAM response. This area therefore requires more research. Running ice sheet and glacier model ensembles forced by the Geoengineering Large Ensemble project (GLENS, (Tilmes *et al.*, 2018)) simulations would aid further exploration of the effects of targeted SAI as these experiments inject at 30°N, 30°S, 15°N and 15°S. Seasonal SAI has also been shown to be more effective for Arctic sea ice than year round injection (Lee *et al.*, 2021) expanding this to land ice would be an important avenue for future research.

2.5 Sea Ice

Sea ice is frozen seawater, typically 10s of cm to several metres thick, and at any one time covers around 7% of the earth’s surface, although this coverage is decreasing at around 10% per decade (Fetterer, 2017).

Late summer Arctic sea ice extent has declined by 50% since satellite observations began in the late 1970s (Fetterer, 2017). The Arctic is expected to be seasonally ice-free by mid-century; a majority of CMIP6 models see ice-free periods during the Arctic summer by 2050 under all plausible emissions scenarios (Notz and SIMIP Community, 2020). CMIP6 models project a decline in Winter sea ice which is linear in both cumulative CO_2 and warming (Notz and SIMIP Community, 2020).

Despite substantial warming, there was a slight increasing trend in Antarctic sea ice through the observational record until around 2014 (Parkinson, 2019), likely due to natural variability (Meehl *et al.*, 2016). However, in recent years, a series of low sea-ice extents have occurred; Antarctic sea ice reached its lowest extent on record in 2022 only to be surpassed with a new record low in February 2023 (Fetterer, 2017). Projections of Antarctic sea ice response to climate change have lower confidence than for the Arctic, due to poorer model representation (Masson-Delmotte et al., 2021). CMIP6 models predict a decline over the 21st Century of 29-90% in summer and 15-50% in Winter, depending on the emissions scenario.

2.5.1 Drivers and Feedbacks

On decadal time-scales, temperature is the main control on Arctic sea ice (Notz and Stroeve, 2018). Local radiative balance at the sea-ice edge may also be an important control on Arctic sea ice extent (Notz and Stroeve, 2016), and large scale modes of atmospheric variability, such as the Arctic Oscillation, also contribute strongly to interannual variability (e.g. (Stroeve *et al.*, 2011; Mallett *et al.*, 2021). Unlike in the Arctic, almost all (>80%) of the Antarctic sea ice is seasonal, disappearing each summer. Wind patterns, modulated by large scale modes of atmospheric circulation such as the Southern Annular Mode, are a key driver of Antarctic sea ice extent on inter-annual to decadal timescales (Masson-Delmotte et al 2021)

Sea ice under global warming is subject to the ice albedo feedback (Serreze *et al.*, 2009), whereby the loss and thinning of sea ice reduces the surface albedo so increases the absorption of solar radiation, leading to additional warming, and further sea-ice loss. As a result, it has been posited that sea ice loss could be subject to tipping points (North, 1984; Merryfield, Holland & Monahan, 2008). However, there are also stabilising feedbacks. Open ocean during the polar night can rapidly vent heat to the atmosphere (e.g. (Serreze *et al.*, 2007), thin ice grows faster than thick ice (Bitz and Roe, 2004), and later forming ice has a thinner layer of insulating snow cover on entering the winter months and so can grow more quickly (Hezel et al 2012; Notz and Stroeve, 2018)

These mechanisms likely prevent tipping-point behaviour from arising for summer Arctic sea ice; GCM simulations find that arctic sea ice is expected to recover to an equilibrium state associated with large scale climate forcing within 1-2 years of complete removal (Tietsche *et al.*, 2011), and the observed time-series of summer sea-ice extent has a negative 1-year lag autocorrelation, that is, years with low summer sea-ice extent are typically followed by years with above average extent and vice versa (Notz and Stroeve, 2018). Both satellite observations (Notz and Marotzke 2012; Notz and Stroeve, 2018) and modelling studies (Tietsche *et al.*, 2011) concur that the stabilizing feedbacks outweigh the destabilizing ice-albedo feedback to mean that summer sea ice loss is not self-accelerating, such that the overall sea ice-extent is expected to remain tightly coupled to the external driver, i.e., temperature rise, throughout its decline (Stroeve and Notz, 2015). For Winter Arctic sea ice, there is a potential for abrupt areal loss at a threshold warming (Bathiany *et al.*, 2016). This is because once the arctic is seasonally ice free, sea ice coverage drops to zero wherever the ocean is too warm to form sea ice in a given year, and if warming is spatially uniform, this transition can happen rapidly over a large area at a threshold warming level (Bathiany *et al.*, 2016).

2.5.2 The impacts of SRM

There is broad agreement across models that SRM would cool both the Arctic and Antarctic (Berdahl *et al.*, 2014; Visioni *et al.*, 2021)**.** As expected given this cooling, various models have shown a reduced loss of both Arctic (Jones *et al*, 2018; Jiang *et al.*, 2019; Lee *et al.*, 2020; Lee *et al.*, 2021) and Antarctic (McCusker, Battisti and Bitz, 2015; Jiang *et al.*, 2019) sea ice under SRM. Under the GeoMIP scenarios G3 and G4, SAI delays the loss of sea ice but this is not sufficient to prevent the loss of almost all September sea ice in most models (Berdahl *et al.*, 2014). However, it is likely that this is due to insufficient cooling, and that a world at the same global mean temperature without SRM would also lose all September sea ice in these models (Duffey *et al.*, 2023).

Under equatorial or globally uniform injection, SRM likely cools the Arctic less strongly than the global mean and thus results in greater arctic amplification, and loss of Arctic sea ice at a given global mean temperature (Ridley and Blockley, 2018). This effect is reduced with greater injection in the mid and high latitudes. For example, the Geoengineering Large Ensemble simulations in CESM (Tilmes *et al.*, 2018), which use injection at multiple latitudes to hold global temperature at its 2020 value, while also controlling the meridional temperature gradient, show a 50% increase in Arctic September sea-ice extent relative to present day (Jiang *et al.*, 2019). Similarly, several studies have modelled SAI with high latitude injection and found that such strategies can effectively halt declines in Arctic sea ice under high emissions scenarios (Jackson et al., 2015; Lee *et al.*, 2021; Lee *et al.*, 2023), potentially more efficiently per unit SO_2 injection than low latitude injection strategies (Lee *et al.*, 2023).

Winter arctic sea ice is restored less effectively than summer sea ice in modelling of SRM scenarios (Berdahl *et al.*, 2014; Jiang *et al.*, 2019; Lee *et al.*, 2021; Lee *et al.*, 2023). For example, one SRM scenario sees 50% more sea-ice extent at the September minimum than the control case (at the same global mean temperature without SRM), but 8% less extent at the March maximum (Jiang *et al.*, 2019). This is linked to a general under-cooling of the polar winter by SRM, and an associated suppression of the seasonal cycle at high latitudes (Jiang *et al.*, 2019; Duffey *et al.*, 2023). However, modelling of SRM shows at least partial effectiveness at increasing winter sea ice and reducing local winter near-surface air temperatures (Berdahl *et al.*, 2014; Jiang *et al.*, 2019; Lee *et al.*, 2021; Lee *et al.*, 2023). As such, it is likely that SRM would decrease the probability of passing any potential thresholds to more abrupt winter Arctic sea-ice decline.

The literature on Antarctic sea-ice response to SRM is more limited than for the Arctic case. The modelling of volcanic eruptions suggests an asymmetric response to hemispherically symmetric aerosol forcings, with Antarctic sea ice extent increasing much more weakly than Arctic under volcanic cooling (Zanchettin *et al.*, 2014; Pauling, Bushuk and Bitz, 2021). A similar result is found in the Geoengineering Large Ensemble simulations in CESM (Tilmes *et al.*, 2018; Jiang *et al.*, 2019) find that Antarctic sea ice is less well preserved than Arctic sea ice under this SRM simulation, particularly in austral winter, with a 23% reduction in maximum extent relative to the baseline. However, while several modelling studies show only incomplete preservation of Antarctic sea ice under SRM, in all cases the absolute extent of sea ice is increased relative to the warmer world without SRM (Kravitz *et al.*, 2013; McCusker, Battisti and Bitz, 2015; Jiang *et al.*, 2019).

Sea-ice loss is expected to be reversible were temperatures to reduce (Tietsche *et al.*, 2011; Ridley, Lowe and Hewitt, 2012). As such, we would expect sufficient SRM cooling to be capable of restoring sea ice after the onset of ice-free conditions.

2.5.3 Further Research

There has been little study of the impact of SRM on Antarctic sea ice. Given the potential hemispheric asymmetry in response to aerosol forcing discussed above, and in the context of concerns over the ability of SRM to arrest Antarctic change (Section 2.2), this is an important research gap. Additionally, there has been little work, except the study of (Ridley and Blockley, 2018), quantifying the change in Arctic climate and sea ice under SRM with comparison to the expected change at the level of global warming under that SRM scenario. As such, further research is required to quantify the effectiveness of different SRM strategies for Arctic restoration (Duffey *et al.*, 2023).

2.6 Permafrost

Permafrost is perennially frozen soil which stores around 1500 GtC in the form of organic matter, roughly twice as much carbon as is found in the atmosphere (Meredith *et al.*, 2019). As the earth warms, permafrost thaws and subsequent decomposition of thawed organic matter releases CO_2 and methane, further warming the planet. As such, permafrost thaw is a positive feedback on global temperature, known as the permafrost carbon feedback. The permafrost carbon feedback is estimated to add–roughly 0.05 °C per °C to global temperature increase (Schuur *et al.*, 2015). The strength of the permafrost carbon feedback depends, not only on the reduction in permafrost, but also on the proportion of carbon emissions released as CO_2 versus methane, and on the degree of offsetting by increased plant biomass in current permafrost regions (Wang *et al.*, 2023).

Permafrost has warmed globally by 0.3°C over the last 20 years (Biskaborn *et al.*, 2019). Over the 21st century, greenhouse gas emissions from thawing permafrost are expected to be similar in magnitude to those of a medium sized industrial country, with estimates from ESMs putting emissions at order of magnitude 10 $GtCO_2e$ per °C global warming by 2100 (Masson-Delmotte *et al.*, 2021). For a rapid decarbonisation scenario limiting warming to under 2°C by 2100, permafrost GHG emissions are expected to use up perhaps 10% of the remaining emissions budget (MacDougall *et al.*, 2015; Comyn-Platt *et al.*, 2018; Gasser *et al.*, 2018).

2.6.1 Drivers and Feedbacks

Gradual permafrost thaw occurs due to vertical thickening of the active layer in response to warming at rates of centimetres per decade (Grosse et al., 2011; Turetsky et al., 2020) However, locally, permafrost is also subject to abrupt thaw, which refers to thaw occurring on rapid timescales of days to several years due to the physical collapse of the surface caused by ice melt (Turetsky et al., 2020). Such abrupt thaw may increase the strength of the permafrost carbon feedback substantially relative to that modelled in ESMs. For example, Turetsky et al. (2020) report an increase in estimated permafrost carbon release by 40% and an increase in global warming potential by 100% when abrupt thaw is taken into account in addition to gradual thaw by active layer thickening.

Soil temperature is the fundamental control on permafrost thaw, and this in turn is principally controlled by annual mean near-surface air temperature (Chadburn et al., 2017; Burke, Zhang and Krinner, 2020). Earth system models predict an approximately linear decline in permafrost area with air temperature increase over the current permafrost regions (Slater and Lawrence, 2013). Various other factors also impact soil temperature however, including vegetation cover, precipitation type and amount, and

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wildfire (Grosse et al., 2011). For example, summer rainfall fluxes sensible heat into the soil, increasing thaw (Douglas, Turetsky and Koven, 2020), and snow cover over winter insulates the soil, increasing its annual mean temperature (Zhang, Osterkamp and Stamnes, 1997).

Armstrong McKay et al. (2022) suggest with low confidence a potential threshold behaviour at >4°C global warming or 9°C of local warming for near-synchronous and rapid thaw of large areas of permafrost, particularly Yedoma deposits (Strauss et al., 2017), driven by an additional local positive feedback on thawing due to heat production from microbial metabolism. The self-accelerating permafrost thaw driven by this additional feedback is driven in part by large local rates of warming (Luke and Cox, 2011). If such a threshold exists, Armstrong McKay et al. (2022) estimate that passing it might lead to a pulse of one-off GHG emissions over 10-300 years equivalent to a rise in global mean temperature of 0.2-0.4 °C.

Considering the total land carbon feedback, rather than just the permafrost carbon feedback, the increase in net primary productivity in current permafrost regions will offset at least some of the loss of permafrost carbon over this century (Schuur et al., 2022). Some simulations even show the permafrost regions as net carbon sinks under warming, due to warming and CO_2 fertilization increasing the productivity of vegetation (McGuire et al., 2018)

2.6.2 The impacts of SRM

There is good inter-model agreement that SRM would reduce mean annual air temperature over the permafrost regions (Berdahl *et al.*, 2014; Visioni *et al.*, 2021), so we expect it to reduce permafrost thaw relative to warming scenarios without SRM. Modelling studies support this expectation; only a handful of modelling studies have assessed the permafrost response to SRM, but all find reduced loss of permafrost carbon with deployment of SRM (Jiang *et al.*, 2019; Lee *et al.*, 2019, 2023; Chen, Liu and Moore, 2020; Chen *et al.*, 2023; Liu, Moore and Chen, 2023).

The inter-model spread in permafrost projections is large and can be larger than the difference between SRM and non-SRM scenarios (Chen, Liu and Moore, 2020), so the single model assessments need to be treated with caution. Three studies have assessed the permafrost response to SRM in a multi-model context using the GeoMIP simulations (Chen, Liu and Moore, 2020; Chen *et al.*, 2023; Liu, Moore and Chen, 2023). These studies show that SRM avoids a large fraction of the permafrost loss projected under warming scenarios without SRM. For example, using equatorial SAI to bring global temperatures in line with a medium emissions scenario (SSP2-4.5) under a high emissions scenario (SSP5-8.5) is modelled to mitigate most (>80%) of the extra permafrost carbon loss associated with the high emissions scenario (Chen *et al.*, 2023).

However, SRM strategies typically restore permafrost somewhat less effectively than global mean temperature, because they see residual warming in the permafrost regions (Chen, Liu and Moore, 2020; Chen *et al.*, 2023). It is likely that SRM strategies targeted at restoring polar climate, by injecting more aerosols outside of the tropics, could largely avoid this effect. For example, almost all the 21st century permafrost loss under the high emissions scenario RCP8.5 is avoided under an SAI scenario which modifies injections to target the equator to pole gradient, as well as global mean temperature (Jiang *et al.*, 2019)

While there has been no modelling study assessing the potential for SRM to avert the widespread and rapid decline envisioned under the permafrost 'collapse' scenario of Amstrong-McKay *et al.* (2022), the fundamental driver of this tipping behaviour is surface temperature, and as such, we expect that reducing local temperatures using SRM would reduce the likelihood of this scenario. However, as it is driven by internal heat production, it seems unlikely that SRM could substantially help once tipping in this 'collapse' scenario had begun, were the near-synchronous onset across a large part of the permafrost regions, assumed by Amstrong-McKay et al. (2022), to take place.

Emissions from thawed permafrost are irreversible on centennial timescales (Schaefer *et al.*, 2014; Schuur *et al.*, 2022). SRM would not be able to reverse the increased atmospheric GHG concentrations once permafrost thawing had occurred.

2.6.3 Further Research

Greater understanding is required of the degree and cause of under-cooling of Northern Hemisphere high latitudes under SRM, and the dependence of such under-cooling on the injection strategy. This would facilitate quantification of the expected permafrost carbon feedback under different SRM strategies. Additionally, the broader study of the high latitude land carbon feedback under SRM would benefit from the attention of scientists from a range of backgrounds, including soil science and ecology, to quantify the impact of simultaneous changes in temperature, hydrology and CO_2 concentration expected under SRM (Jiang *et al.*, 2019; Lee *et al.*, 2019; Lee *et al.*, 2023; Chen, Liu and Moore, 2020; Chen *et al.*, 2023; Liu, Moore and Chen, 2023).

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2.7 Methane Hydrates

Marine methane hydrates are methane trapped in water ice in sea floor sediments. These hydrates contain a large amount (1000s of GtC) of methane and are vulnerable to melt over millenia given several degrees of ocean warming, and so represent a positive climate feedback that may have contributed to past warming events on geological timescales (Archer, Buffett and Brovkin, 2009). However, globally significant methane emissions from hydrates on decadal or centennial timescales are very unlikely (Masson-Delmotte *et al.*, 2021; Schuur *et al.*, 2022). There is no expected threshold warming level associated with methane hydrates as a whole and thus they are typically considered a threshold-free feedback rather than tipping element (Armstrong McKay *et al.*, 2022) and at moderate warming levels (e.g. 2°C) they likely exert a negligible impact on surface temperature (Wang *et al.*, 2023).

2.7.1 The impacts of SRM

There is no literature which we are aware of which evaluates the impact of SRM on methane hydrates. The reduction in surface temperature under SRM, if maintained over very long timescales, might be expected to reduce ocean-floor temperatures and thus the rate of melt. However in the curve-flattening scenarios without SRM (i.e. an overshoot scenario), the overshoot may not be long enough (MacMartin *et al.*, 2018) for its impacts to be felt by the methane hydrates in the deep ocean (Ruppel and Kessler 2016), meaning SRM may have little benefit over such scenarios. Moreover, there is no consensus yet amongst models on the large-scale ocean circulation response to SRM (Fasullo and Richter, 2023).

3. Oceans

This section treats three possible tipping elements, all part of the Atlantic (and Southern Ocean) circulation (see Figure 2): The Atlantic Meridional Overturning Circulation (AMOC; Figure 2 part 1-4), deep convection in the north Atlantic Subpolar Gyre (Figure 2 part 3), and Antarctic Bottom Water formation (Figure 2 part 5-6).

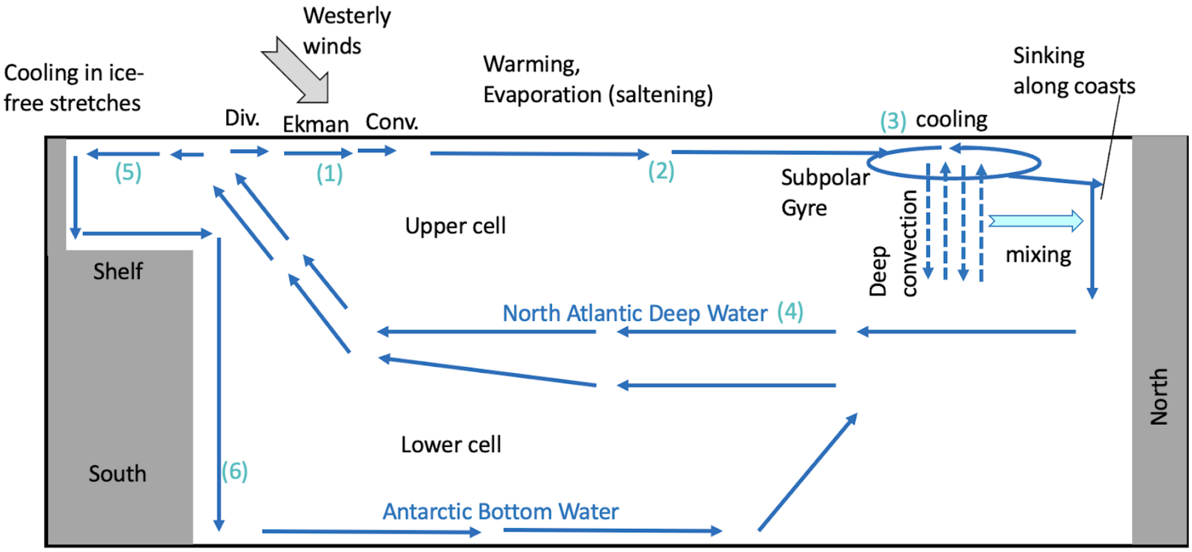

Figure 2. Schematic of the Atlantic circulation. (1) Westerly winds around 40°S drive a northward Ekman transport, causing divergence to the South and enabling the upwelling of North Atlantic Deep water. (2) To the north, water moves northwards, warming and saltening (through evaporation). (3) In the subpolar gyre, water moves counterclockwise, aided by the cold core of the gyre and thermal wind effects. Winter cooling drives deep convection, thereby cooling the water inside the gyre over great depths. Cold water mixed into coastal currents (e.g. along Greenland) helps to drive sinking there. (4) The resulting North Atlantic Deep Water returns to the South. (5) Very dense Antarctic Bottom Water is formed in sea-ice-free stretches around Antarctica, where water is exposed to cold air. (6) It sinks along the shelf edge and feeds the lower circulation cell.

3.1 Atlantic Meridional Overturning Circulation (AMOC)

The upper branch of the Atlantic Meridional Overturning Circulation (AMOC) transports salty, warm water towards the subpolar North Atlantic, where it sinks and returns to the south as so-called North Atlantic Deep Water. In order to sink, this water must be sufficiently dense compared with the deeper water. If the surface water in the North Atlantic becomes warmer or fresher, this inhibits sinking. North-Atlantic sinking is at least partly compensated by water rising in the Southern Ocean, due to an interplay of Ekman-driven upwelling and eddy flow (Marshall and Speer, 2012). It is debated whether overall AMOC strength is determined by the Northern sinking or the Southern Ocean processes (Johnson *et al.*, 2019) .

AMOC generally weakens in coupled climate models under climate change. (Weijer *et al.*, 2020)) find that AMOC declines: for newer models (CMIP6) by 24% between present-day and 2100 for the weak forcing scenario SSP1-2.6 and 39% for the strong forcing scenario SSP5-8.5. For older models (CMIP5), the decline is 21% for RCP2.6 and 36% for RCP8.5. Until 2060, there is only a weak difference among forcing scenarios in CMIP6. In none of the CMIP6 model in (Weijer *et al.*, 2020) does the AMOC strength drop to (near) zero by 2100. Few models show hardly any weakening.

Tipping – as opposed to merely weakening – requires that AMOC has a stable “off-state”, in which strong buoyancy forcing in the North Atlantic reduces surface density and prevents sinking. Starting with (Stommel, 1961), the possible presence of an off-state has been debated. However, it is uncertain whether AMOC can actually tip. Paleo evidence suggests AMOC has undergone rapid transitions (Lynch-Stieglitz, 2017), hinting at bi-stability. While conceptual or reduced-complexity ocean models show hysteresis under North Atlantic freshwater forcing (purple and green paths in fig. 3a), such experiments are prohibitively computationally expensive in state-of-the-art coupled models. Instead, modellers use hosing experiments, where large amounts of freshwater are dumped in the North Atlantic, to determine whether AMOC shuts down. Such experiments cannot distinguish a stable off-state from a prolonged, yet temporary shut-down (Gent, 2018; Rind *et al.*, 2018). Jackson *et al.* (2022) present multi-model experiments with unrealistically strong hosing. After hosing stops, AMOC does not recover in about half of these models, namely those in which AMOC had weakened below 5Sv.

It has been suggested that AMOC in CMIP models may be too stable to produce AMOC tipping, because AMOC-related freshwater import into the Atlantic at 34°S (called M_{ov} or F_{OT}) is positive, whereas it is negative in observations; the rationale being that if AMOC imports salt (exports freshwater, $M_{ov}<0$), AMOC weakening would lead to freshening and further AMOC weakening, ultimately shutting AMOC down (Rahmstorf, 1996). However, the ability of M_{ov} to diagnose AMOC stability is still under debate (Gent, 2018; Jackson *et al.*, 2022).

To summarise, it is uncertain whether AMOC has an off-state under current conditions. AMOC does not need to actually tip in order to generate climate impacts. A prolonged quasi-stable shutdown or strong reduction in AMOC strength without complete shutdown could have severe climate impacts even without actual tipping (fig. 3d).

3.1.1 Drivers and Feedbacks

Global warming could reduce North Atlantic surface water density (and hence weaken and potentially tip AMOC) through heat flux or freshwater flux, i.e. changes in precipitation minus evaporation or meltwater flux from Greenland melting. In addition, climate change might influence the position or strength of the westerly winds in the Southern Ocean, potentially affecting AMOC’s upwelling branch.

However, changes in eddy fluxes might (partly) compensate the change in westerlies (Marshall and Speer, 2012).

Gregory *et al.* (2016) found that for forcings derived from doubling CO2 gradually over 70 years (1pctCO2), only heat flux changes lead to significant AMOC weakening, whereas freshwater flux other than ice sheet runoff has no significant impact. However, a recent preprint (Madan *et al.*, 2023) suggests that for instantaneous CO2 quadrupling in CMIP6, freshwater forcing from sea ice melt weakens AMOC. Liu, Fedorov and Sévellec (2019) also suggested that changes in sea ice cover may impact AMOC through changes in freshwater input (freezing, advection and melting of ice floes) and heat flux (e.g., shielding ocean water from atmospheric influences). Using an intermediate complexity model, Golledge *et al.* (2019) found that freshwater fluxes from Greenland (and Antarctica) derived from ice sheet models under RCP8.5 forcing might weaken AMOC by 3-4Sv. Atmospheric circulation changes, e.g. North Atlantic Oscillation (NAO), may also affect AMOC, for example by introducing heat flux anomalies (Delworth 2016).

It is uncertain if tipping into an off-state can be reached with climate forcings that can be reached under global warming. If so, buoyancy forcing, either from heat flux changes or freshwater changes, is likely the key driver, as is the case for AMOC weakening.

WHilst the classic view is that a gradual change in forcing would eventually tip AMOC (fig. 3a), random fluctuations in buoyancy forcing might push AMOC into the off-state even if the tipping point is not reached ("noise-induced tipping", fig. 3b, (Ditlevsen and Johnsen, 2010)). In addition, it has been suggested that fast changes in the buoyancy forcing may lead to rate-induced tipping (fig. 3c, (Lohmann and Ditlevsen, 2021)).

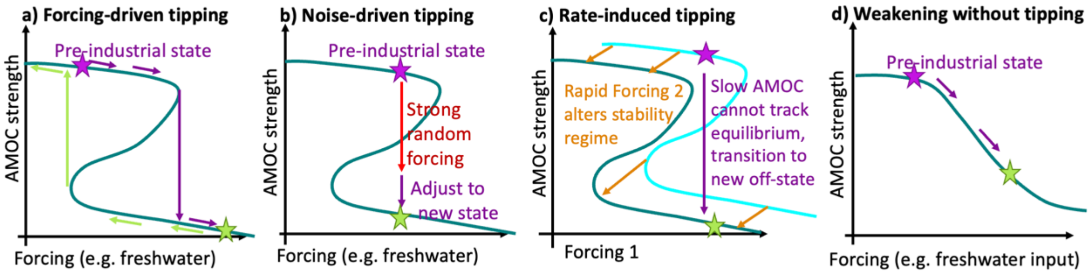

Figure 3: Mechanisms for potential AMOC tipping (or weakening).

3.1.2 The impacts of SRM

Intuitively, assuming AMOC tipping can occur, one would expect SRM to help prevent the transgression of the AMOC tipping point, because it would reduce surface heat flux (short-wave radiation) in the North Atlantic (as shown for tropospheric aerosol, Hassan 2021) and slow down Greenland melting and sea ice melting (Sects. 2.1 and 2.5), hence freshwater input.

Xie *et al.* (2022) used several SRM scenarios and climate models from GeoMIP (Kravitz *et al.*, 2011). The SRM methods used include SAI, solar dimming, increasing ocean albedo (a rough proxy for MCB or for placing reflective foam on the water), and increasing cloud droplet number concentration (a simple representation of MCB), and the strength varies from a modest reduction to complete elimination of greenhouse-gas-induced warming. They found that in all cases, SRM reduces GHG-induced AMOC weakening. If global mean surface temperature change is fully compensated, AMOC is not fully but nearly restored in the multi-model mean, with solar dimming performing slightly better and MCB slightly worse than SAI. Using the CESM2-WACCM model, (Tilmes *et al.*, 2020) found that if SRM is used to cool RCP8.5 forcing back to 1.5 degrees, AMOC weakening is roughly halved compared to RCP8.5 forcing without SRM compared to year 2020. In a previous model version, AMOC weakening was even overcompensated by SRM, leading to AMOC strengthening (Fasullo *et al.*, 2018; Tilmes *et al.*, 2018).

As mentioned, climate models do not simulate AMOC tipping under RCP forcing until 2100 (Weijer 2020), although some do for extreme hosing (Jackson 2022) or warming (Hu et al., 2013). This may be an artefact of overly stable models, but it also means it is hard to directly simulate the effect of SRM on AMOC tipping. However, as SRM reduces AMOC weakening, it seems plausible that it can prevent or postpone AMOC tipping, as both are driven by the same buoyancy forcing.

The presence of potential rate dependency of the AMOC tipping (Lohmann and Ditlevsen, 2021) may imply that strategies where SRM is used to reduce the rate of warming before being phased out may reduce the risk of tipping the AMOC. However, it also implies that termination shock may increase the risk of tipping compared to the same temperature rise without SRM. However, rate-dependent AMOC tipping remains uncertain, and the lack of quantitative constraints on this makes it difficult to suggest how important these two SRM scenarios could be at affecting the risk of tipping.

If AMOC is prone to rate-dependent tipping, SRM might reduce this risk by reducing warming rates, if deployed such as to slow down global warming. However, if rate-induced AMOC tipping is possible, a

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sudden termination of SRM could lead to higher rates of change and increase tipping risks. It is unclear whether SRM would affect the amplitude of buoyancy forcing noise, which is one factor determining the risk of noise-induced tipping. However, SAI may influence how close AMOC is to the tipping point, which also the susceptibility to noise-induced tipping.

It is difficult to understand to what extent SRM could restore the AMOC once tipping has begun, as no model simulations exist. If AMOC shows hysteresis, very strong SRM might be required to restore AMOC, and this forcing may have to be applied for many decades, with potentially detrimental consequences. (Schwinger *et al.*, 2022) demonstrate this by simulating the effect of instantaneous Carbon Dioxide Removal, and hence instant cooling, on a a weakened (i.e. not even tippied) AMOC. AMOC recovered, but during the transition period, the North Atlantic region was severely overcooled, as the cooling effect of CDR already manifested itself, while AMOC was still weak.Pflüger et al., 2023 likewise find North Atlantic overcooling due to prolonged AMOC weakening under a delayed-SRM scenario. Attempts to restore a fully tipped AMOC might lead to even more severe and extended overcooling.

3.1.3 Further Research

Ongoing efforts of the AMOC research community may help to better understand AMOC instability and its susceptibility to SRM. Improving climate models may reduce biases, in particular potentially excessive AMOC stability, and hopefully eventually enable us to directly simulate SRM's impact on AMOC tipping. Meanwhile, qualitative insights on SRM's effect on potential AMOC tipping might be gained by using simulations with extreme forcings (warming and/or freshwater) which actually tip AMOC, and investigate whether SRM can postpone or revert tipping.

Another research avenue could be to chart more systematically the impact of SRM on AMOC drivers, including in the South. This requires disentangling the direct effect of SRM forcing from AMOC feedbacks (Hassan et al, 2021). Impacts on drivers likely depend on the SRM method (e.g. SAI or alternatives) and strategy (e.g. timing, intensity and location of injection points. Note that even if AMOC does not tip, a significant prolonged weakening may already have severe consequences, making SRM's impact on AMOC weakening a worthy research subject even in absence of tipping.

3.2 Sub-Polar Gyre

There are indications that deep convection in the subpolar gyre (SPG) in the North Atlantic may collapse without full AMOC collapse. Sgubin *et al.* (2017) find that 7 CMIP5 models (17.5% of the models) exhibit an abrupt cooling in the SPG in one or more RCP simulation, without full AMOC collapse. Rather, a local collapse of deep convection took place. When considering only models with

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realistic background stratification in the SPG, 50% of the remaining models exhibit abrupt cooling. Similarly, Swingedouw *et al.* (2021) find that 4 CMIP6 models show abrupt cooling in SSP1.26 and/or SSP2.45 simulations. They conjecture that SPG collapse also occurs in SSP5.85 scenarios but remains undetected because global warming masks their cooling criterion. In CMIP6, the models with abrupt cooling are among those with most realistic background stratification.

3.2.1 Drivers and Feedbacks

The studies, leaning on Born and Stocker (2014), suggest the following mechanism for SPG collapse. First, the SPG gradually freshens due to enhanced precipitation and runoff caused by intensified hydrological cycle under global warming; meltwater from Greenland could provide additional freshening, and surface warming might further reduce surface density. Once threshold stratification is reached, deep convection is strongly reduced in the (western) SPG, preventing winter cooling and further reducing the density in the interior of the gyre. Less dense water in the interior of SPG means weaker gyre circulation because of thermal wind effects; this in turn leads to reduced salt import from tropics and hence additional freshening.

SPG collapse can occur without AMOC collapse, but the two may influence each other. Deep convection in the SPG increases the water density, because convection ensures deeper water layers to be cooled in winter and because it strengthens the gyre circulation and thus saltwater import from the tropics. Eddy mixing with the coastal boundary currents brings water from the interior of the SPG to the coast, where sinking (as opposed to convection, i.e. mixing) can take place thanks to friction breaking geostrophic balance (Katsman *et al.*, 2018; Sayol, Dijkstra and Katsman, 2019). Hence SPG weakening may contribute to AMOC weakening or tipping, although AMOC may be (partially) sustained if deep convection in the Nordic seas remains intact (Sgubin *et al.*, 2017). Conversely, AMOC weakening might reduce salt import into the SPG and initialise its weakening or tipping.

3.2.2: The impacts of SRM

Pflüger *et al.*, 2023 show that in CESM2, the SPG collapses under an RCP8.5 scenario, but deep convection is preserved in the eastern part of the SPG if SRM is used to stabilise GMST at 1.5ºC above pre-industrial. We conjecture that SRM might at least partially counteract SPG collapse by reducing or reverting buoyancy forcing in the subpolar North Atlantic. The drivers are similar to those discussed in Sect. 3.1, although the exact impacts of these drivers will differ.

To our knowledge, no study has explicitly simulated SPG recovery due to SRM. Plüger et al., when cooling an RCP8.5 scenario down to 1.5ºC from 2080 using SAI, find that SPG convection remains in the collapsed state except for one year, but that surface density continues to increase, suggesting a possible recovery after 2100.

3.2.3: Further Research

Fundamental research on SPG tipping may help to improve our understanding of the dynamics and the impact of various drivers. As some climate models do simulate SPG tipping, targeted experiments could be performed in these models, e.g. applying SRM some time before the tipping to test SRM's preventative potential, and after the tipping, to assess reversibility. As with AMOC, different SRM strategies may have different effects, hence a range of scenarios should be tested.

3.3 Antarctic Bottom Water

Antarctic Bottom Water (AABW) is a very cold and moderately salty water mass that forms around Antarctica by ocean heat loss (especially in ice-free areas, where water is exposed to very cold katabatic winds from Antarctica). It sinks to great depth, filling the abyssal ocean and constituting the lower branch of the lower Atlantic circulation cell. (Fig. 2, (5)).

Armstrong McKay *et al.* (2022) list a cessation or strong reduction of AABW formation as a potential Global tipping element, because it could affect the global ocean circulation. Antarctic Bottom Water Collapse is likely to stabilise the AMOC due to the 'bipolar ocean see-saw' effect (Lago and England, 2019) adapted an ocean model to represent freshwater inflow from Antarctic ice melt following the assumptions of (DeConto and Pollard, 2016) as an extreme case. They found that under meltwater inflow representing RCP4.5 and RCP8.5 scenarios, AABW shuts down within 50 years, while it is significantly reduced under RCP2.6. As most models do not represent ice melt, (Armstrong McKay *et al.*, 2022) categorise the effect only as "potential" tipping element. (Fox-Kemper *et al.*, 2021) assigns medium confidence to the prediction that the lower circulation cell in the Atlantic will decrease through the 21st century as a result of Antarctic ice sheet melt, but does not predict a tipping point or complete shut-down.

3.3.1: Drivers and Feedbacks

The mechanism is related to freshening of surface water by the melting of the Antarctic Ice Sheet which prevents sinking (Fox-Kemper *et al.*,2021). Whilst the exact origins of this freshening is uncertain, it has been projected that in the Atlantic this freshening is due the melting of the Larsen Ice Sheet and in the Indo-Pacific the melt of the West Antarctic Ice Sheet (Zhou *et al.*, 2023). Other effects of climate change, in particular wind stress forcing, might also affect AABW formation and at least partly counteract the effect of ice melt (Dias *et al.*, 2021).

Wind variability driven by teleconnections may introduce interannual to interdecadal variability driving AABW volume reduction by reducing sea-ice divergence in the Weddell Sea, which may also at least partly explain current trends (Zhou *et al.*, 2023). These wind trends are also consistent with that expected under climate change, so it is possible these are also part of a larger trend.

3.3.2: The impacts of SRM

To our knowledge, no dedicated studies exist on the effect of SRM on AABW tipping. We conjecture that SRM’s effectiveness to mitigate AABW tipping depends on its ability to counter Antarctic ice melt, both from land and sea ice (Sects. 2.2 and 2.5). SRM’s influence on secondary drivers, including Antarctic wind changes through teleconnections, may modify the outcome and is hard to predict; we currently do not have modelling of the impact of SRM on these winds, and thus a judgement heere is impossible to make. We also have no evidence as to whether SRM could reverse AABW tipping.

3.2.3: Further Research

Better understanding how and whether AABW can tip will be key. Given the dependence on Antarctic Ice Melt, as well as its relation with the AMOC, understanding the impact of SRM on both of those tipping elements is also important. Finally, understanding the impact of SRM on Antarctic Winds and the teleconnections that drive them may also be important if these prove to be influential in driving long-term trends of AABW formation.

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4: Atmosphere

4.1: Marine Stratocumulus Cloud

Marine stratocumulus clouds are low-altitude clouds that form primarily in the sub-tropics, covering approximately 20% of the low-latitude ocean or 6.5% of the Earth's surface. Due to their location, high albedo and low-altitude they produce a very substantial local forcing of up to -100 Wm^{-2} (Klein and Hartmann, 1993). Recent work has shown that these clouds exhibit multiple equilibrium states and that at sufficiently high Sea-Surface Temperatures (SST) or CO_2 concentrations they can transition from a cloudy to a non-cloudy state (Bellon and Geoffroy, 2016; Schneider, Kaul and Pressel, 2019; Salazar and Tziperman, 2023). The break-up of these cloud decks would be associated with substantial local and global temperature increases, with Schneider, Kaul and Pressel (2019) predicting a 10 °C warming within the affected domain and an enormous 8 °C global warming in response. As the feedbacks associated with this warming make it more difficult for these clouds to form, this transition would exhibit substantial hysteresis requiring CO_2 concentrations to be brought far below the original threshold for the cloud decks to reform (Schneider, Kaul and Pressel, 2019; Salazar and Tziperman, 2023).

4.1.1: Drivers and Feedbacks

Unlike most types of clouds, the convection that produces marine stratocumulus clouds originates at the cloud-top and is driven by longwave radiative cooling (Turton and Nicholls, 1987). If this longwave cooling is sufficiently strong, air parcels from the cloud top descend all the way to the ocean surface producing a well-mixed boundary layer that connects the cloud layer with its moisture source (Schneider, Kaul and Pressel, 2019). These cloud decks will break up if this longwave cooling weakens to such an extent that the descending air parcels can no longer reach the ocean surface (Salazar & Tziperman, 2023). This can occur if the longwave emissivity of the overlying atmospheric layer increases sufficiently, i.e., if Greenhouse Gas (GHG) concentrations or water vapour content rise sufficiently (Schneider, Kaul and Pressel, 2019). It can also occur if too much of the warm, dry air from the overlying inversion layer is mixed into the cloud as this would dehydrate the cloud, reducing its emissivity and hence the longwave cooling that sustains it (Bretherton and Wyant, 1997).

Using a cloud-resolving Large Eddy Simulation of a patch of marine stratocumulus coupled to a tropical atmospheric column model, Schneider et al. (2019) found that if CO_2 concentrations rose above 1200 ppm there was a sudden transition from a cloudy to a non-cloudy state. This transition was associated with a 10 °C warming within this domain and an ~8 °C global warming, as such they found that CO_2 concentrations needed to be brought back below 300 ppm for the system to return to the cloudy state. Salazar and Tziperman (2023) reproduced this hysteresis in an idealized mixed layer cloud model, finding multiple equilibria between 500 and 1750 ppm.

4.1.2: The impact of SRM

In a follow-up study, Schneider, Kaul and Pressel (2020) found that whilst reducing insolation to offset some of the warming from elevated CO_2 concentrations did not eliminate this hysteresis, the critical threshold for marine stratocumulus break-up is raised from >1200 ppm in their CO_2-only runs to >1700 ppm. The increase in global temperatures is reduced from ~8 °C to ~5 °C, though CO_2 concentrations must still be brought below 300 ppm to restore the clouds.

However, the reduction in insolation that they imposed in their simulations only offset roughly half of the warming from their elevated CO_2 concentrations. While simulations by the Geoengineering Model Intercomparison Project (GeoMIP) found that a reduction of between 1.75 and 2.5% was needed to offset each doubling of CO_2 concentrations (Kravitz *et al.*, 2013), Schneider, Kaul and Pressel (2020) applied only a 3.7 Wm^{-2} reduction for every doubling of CO_2 to the 471 Wm^{-2} of incoming sunlight in their sub-tropical domain, i.e., a 0.8% reduction. As warming increases the latent heat flux from the surface that leads to greater cloud-top turbulence and the dehydration of the clouds, and it leads to increased water vapour in the overlying inversion layer, the residual warming in these SRM simulations substantially weakens the longwave cooling that sustains the clouds. This may suggest that if Schneider, Kaul and Pressel (2020) had reduced incoming sunlight sufficiently to eliminate the residual warming in their simulations they would have found a much higher critical CO_2 threshold in their SRM case.

Some support for this conclusion on the effects of this residual warming can be found in the sensitivity tests of Salazar and Tziperman (2023). In one case (in Figure 4, row 2 in Salazar and Tziperman (2023)) they eliminate the water vapour feedback, associated with higher temperatures , finding that the critical CO_2 threshold for marine stratocumulus collapse is more than doubled from 1750 to >4000 ppm. However, in this case they still have elevated sea surface temperatures, and so a greater latent heat flux from the surface than would be the case if SRM fully offset the warming.

While SRM would not address the reduction in longwave cooling caused by elevated GHG concentrations, it would be effective in lowering temperatures, reducing the water vapour feedback and the increase in turbulence caused by increased latent heat flux from a warmer ocean surface. As such SRM would substantially raise the critical CO_2 threshold for marine stratocumulus from a very high CO_2 concentration to an extremely high CO_2 concentration.

4.1.3: Further Research

To date there has been very little research into this potential tipping point, as such further research in a wider range of models is needed to determine whether it is a robust feature of marine stratocumulus decks. As the CO2 concentrations and temperatures required to produce this tipping point may have occurred at certain points in the past, e.g., the Paleocene-Eocene Thermal Maxima (Schneider, Kaul and Pressel, 2019), future research could address whether observations and model simulations of this period are consistent with this potential tipping point.

To assess SRM's potential to address this tipping point more fully, a wider range of SRM simulations than those in Schneider, Kaul and Pressel (2020) could be conducted. For SAI, such simulations should include the effects not present in sun-dimming experiments, such as stratospheric heating, and should cover a range of scenarios with different levels of GHG forcing where SAI offsets all warming. Studies assessing MCB's potential to address this tipping point would also be particularly worthwhile as MCB would directly modify marine stratocumulus clouds, changing the cloud microphysics in ways which may affect the threshold for collapse.

5: Biosphere

5.1: The Impact of SRM on ecological systems in general

Tipping points in ecology can refer to complete system changes either in the dominant plant species, in the life forms or functional types of the plants (e.g. from trees to grasses), to large changes in the organisms present (diverse native species community to monocultures of an invasive species), or in the physical structure of an environment (wetland or aquatic to dry land, deep soil to eroded rock substrate). Moreover, they don't solely refer to such changes at the system level, but also in the extinction of individual species. Such changes may be driven by self-sustaining drivers and positive feedbacks, or to sudden or persistent drivers without positive feedbacks.

Little research has been undertaken to understand how complex ecological systems would respond to SRM interventions. Although no direct evidence exists, we can project possible outcomes based on our understanding of observed responses of ecological systems to climate and climate change, extrapolating to the results of the extensive climate modelling efforts for some SRM approaches. Information from comparisons of the same system at different times in the deep and recent past, and from comparing systems exposed to different environmental conditions can mimic some of the simulated changes imposed by SRM. Ecological systems have experienced tipping points at many stages of Earth's history (e.g (Setty *et al.*, 2023), and a great deal is known about the climatic and other factors driving those tipping points. Changes often happened over very long periods of time, but sudden cataclysmic events like the Chicxulub impact were instantaneous tipping points that forced total system changes in marine and terrestrial environments.

There is a rich ecological literature on the topic of alternative stable states (e.g., (Holling, 1973; Beisner and Haydon, 2003; Thompson *et al.*, 2021), including both mathematical theory and experimental or observational studies of specific systems that can help identify drivers that can tip systems to alternative states.

Ecological systems are typically driven over tipping points by a complex series of drivers rather than single dominant drivers, and SRM is likely to change many environmental factors affecting these systems. Determinants of species diversity and other properties of ecological systems include climate, soils and anthropogenic factors (Liang *et al.*, 2022), and it is likely that drivers of ecological tipping points also include climate change phenomena manifested at the local scale as well as anthropogenic disturbances and their interactions. Ecological systems that tip are often more local or regional than those of other aspects of the earth system, and the greater uncertainty of knowledge of climate impacts at this scale can make understanding the impacts of particular climatic changes even harder. Moreover, thus far, anthropogenic non-climatic factors, chiefly land-use change, has been the key driver of biodiversity loss, and factors such as harvest and exploitation(eg hunting and fishing) further make these systems more susceptible to tipping. The reality is that we are already witnessing profound and irreversible changes –systems forced over tipping points–in many ecological systems at many spatial scales in response to multiple driving elements occurring both rapidly and gradually.

The clearest clues as to whether SRM can prevent ecological tipping points lies in its central role of reducing warming (albeit with regional uncertainties), and thus those ecological systems that suffer most from the direct impact of increased temperatures might potentially benefit from SRM-induced cooling and evade heat-propelled tipping points that would otherwise happen under unabated planetary warming. However, responses such as species distributions, interactions (e.g. pollination), and ecosystem processes such as productivity may be more affected by more organism-focused temperature related factors. These may include extreme heat, which is generally reduced by SRM (Kuswanto *et al.*, 2022), a loss of extreme cooling and increase in nighttime temperatures, which are reduced substantially, but not fully, compared to same-temperature mitigation scenarios by SRM (Zarnetske *et al.*, 2021) as well as other factors for which we have very limited evidence for the impact of SRM on, such as the duration of growing seasons, the duration of continuous freezing temperatures, seasonality of precipitation relative to temperatures. Some factors affected by temperature may drive ecological effects in opposite directions as well; for example cooling may suppress photosynthesis due to a drop in productivity or increase it if the suppression of heat stress is more significant (Zarnetske *et al.*, 2021). Thus even for the factor where we best understand the climatic effects of SRM, the effects on ecological systems remain challenging to predict.

SRM would influence many other aspects of climate beyond temperatures, most importantly precipitation. Changes to the hydrological cycle under SRM are central to plant productivity, growth, survival and reproduction and the spatio-temporal extent of these changes may be key in determining the overall impact of SRM on ecological tipping elements. However, large uncertainties in the simulated hydrological consequences of different SRM schemes preclude a simple answer as to whether a SRM scheme would alleviate or exacerbate hydrological-related drivers of tipping. Targeted efforts to examine individual ecological systems for their observed and modelled responses to changes in hydrological variables relative to predicted changes resulting from SRM schemes are critical before we can predict thresholds for hydrological changes that can drive tipping.

SRM scenarios would also affect other factors in novel ways when compared to climate change. Whilst temperatures would be kept artificially low, CO_2 levels will still rise, which have profound impacts on terrestrial and marine ecosystems (Zarnetske *et al.*, 2021) . Moreover, the diffuse to direct light ratio would be possibly enhanced under SRM, potentially enhancing photosynthesis (Xia *et al.*, 2016). In addition, the interaction between climate change and human disturbance makes ecological resilience or vulnerability challenging to predict, and thus the role of SRM for tipping points in a particular ecological system also strongly depends on current and future influences from human activities. Finally, tipping points of an ecological system depend on multiple drivers of climatic factors as well as interactions of multiple elements within the system. Microbial communities, insects, pollinators etc. are important elements that support or disrupt healthy functioning of forests and biodiversity. Although these elements are not fully covered in this review, they deserve far more research because their responses to climate change and potentially to SRM are likely key to understanding future fates and

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tipping likelihood of many ecological systems under SRM. A holistic and systematic approach is required to analyse the internal dynamics and resilience of ecological systems and their sensitivity or robustness as a whole to external forcings of multiple climatic drivers for the assessment of potential effects of SRM on potential tipping points.

In general, temperatures would be reduced in all cases of SRM, but there are many other factors that are sensitive to the exact configuration of the deployment scheme of SRM. Changes in SRM scenarios may profoundly impact ecosystems, due to the sensitivity to different affected variables. SRM could cause permanent, irreversible changes in ecological systems regardless of whether it was halted or continued and whether its effect was beneficial or deleterious to current ecological systems. Whilst SRM can be easily reversed, for example, by stopping stratospheric injections, it is not obvious that the effects of SRM on ecological systems are reversible ecologically. This depends first on how long the injections had been occurring, and when they were stopped; if SRM were to continue for decades but CO2 continued to increase, it is well established that the termination effects on ecological systems (Ito, 2017; Trisos *et al.*, 2018) would be so disruptive that tipping points would almost certainly be precipitated for many ecological systems. Less obvious is whether and how the nature of the specific SRM scenario affects whether the resulting changes are irreversible; we know already from modelling that some scenarios might cause irreversible changes even in the short term (e.g. severe drought or inundation resulting from changes to the movement of the Hadley cells (Smyth, Russotto and Storelvmo, 2017; Cheng *et al.*, 2022).

5.2: Dipterocarp Forests

Dipterocarp forests are astoundingly diverse systems in southeast Asia, including Borneo, peninsular Malaysia, and parts of Indonesia and Sumatra. These forests have faced both climate threats and land use change. Factors that force their transformation to other systems and failure to persist and regenerate can be considered to precipitate tipping points. Enormous trees belonging to the plant family Dipterocarpaceae dominate these forests, with dozens of genera and hundreds of species, and many other families of plants and animals coexist in these forests, including orangutans and other primates, bats, birds and others. Synchronized flowering and seeding, in which coordinated reproduction across many tree species and even families occurs at irregular intervals across a large geographic scale, is a remarkable event in these humid tropical forests. The large numbers of seeds produced creates an abundance of food, affecting animal population dynamics and sustaining biodiversity.

5.2.1: Drivers and Mechanisms

Regeneration of the forest also depends on these synchronised events. The massed flowering is triggered by the combined condition of cool nights and drought (Numata *et al.*, 2022; Ushio *et al.*, 2020). Projections of future climate change found that relatively small increases in nighttime temperatures are predicted to result in approximately a 50% decrease in flowering for 57% of the major tree species; failure of dry conditions further inhibits flowering of some species (Numata *et al.*, 2022). Reproduction of many tropical trees globally is highly sensitive to changes in diel and seasonal temperature regimes. The loss and fragmentation of these forests has greatly increased fires, and in former forests on peatlands, this has particularly enhanced carbon emissions (Nikonovas *et al.*, 2020). Thus, subtle changes to climate drivers as a result of climate change may result in tipping to a collapse of this high diversity system to something much lower in biotic diversity.

However, the greatest and most immediate threat that can push these forests into a new stable state is clearcutting, particularly to establish oil palm plantations, which despite the global environmentalist outcries, continue to be profitable and continue to expand (Nikonovas *et al.*, 2020). Remaining forests following clearcutting may be too small and too fragmented for effective tree reproduction at larger scales (Numata *et al.*, 2022).

5.2.2: The impacts of SRM

SRM is predicted to reduce nighttime temperatures and create drier conditions (MacMartin *et al.*, 2016) that might counteract much of the impacts of climate change on these forests. Furthermore, Tan *et al.* (2023) explore the impact of SAI on precipitation in the Kelantan River Basin in Peninsular Malaysia, finding a reduction in precipitation when compared to RCP8.5, supporting the conjecture that SRM might sustain the massed flowering mechanism and reduce the chances of these Dipterocarp forests hitting tipping points. However, depending on the magnitude and nature of specific changes in precipitation and other hydrological variables, SRM may alter the overall water supply and demand relationships which determine the biogeography of tropical forests (Zarnetske *et al.*, 2021).

More research is needed to constrain uncertainties in model projected direction and magnitude of changes in the hydro-climate variables in Southeast Asia and to better understand the double-edged role of drought and nighttime temperatures in reproductive phenology (mass flowering) and how this is coordinated across many species. Ultimately these ecosystems are dependent on very particular regional climatic configurations which have not been adequately modelled nor understood. Moreover, understanding the climate sensitivity and resilience of these Dipterocarp forests across varying states of human disturbance is an important step before assessing the impact of SRM on tipping in these systems.

5.3: Amazon Basin

The Amazon basin is a region of many different tropical forest ecological systems and high biodiversity (although not considered a biodiversity hotspot, (Myers et al., 2000)). It is a key Earth system component (Armstrong McKay *et al.*, 2022), regulating regional and even global climates by cycling enormous amounts of water vapour and latent heat between land and atmosphere, by storing around 150–200 Pg carbon above and below ground, though this is in decline (Brienen *et al.*, 2015). As such, it is perhaps better to see the Amazon basin as a combined ecological-climatic system. It is predicted that 2-6 degrees Celsius of global warming (relative to preindustrial), interacting with other human activities such as clearcutting and fires, would likely force a tipping point for the Amazon basin to the replacement of tropical forest with tropical savanna or grassland. Indeed, whilst the Amazon has a series of local tipping elements within it, these can be considered to be connected by the atmospheric moisture recycling feedback, where intercepted precipitation and transpiration allows evapotranspiration from the forest to be recycled into precipitation elsewhere. This spatially connects the different local tipping points together, potentially allowing for tipping cascades through each of the local elements (Wunderling *et al.*, 2022).

5.3.1: Drivers and Feedbacks

The major driver behind this tipping point is drought caused by decreasing precipitation and increasing evaporation in this region under global warming, whilst annual precipitation changes seem of limited importance (Wunderling *et al.*, 2022). Secondary drivers related to warming include more widespread and frequent occurrence of extreme heatwaves (Jiménez-Muñoz *et al.*, 2016; Costa *et al.*, 2022) that cause tree and animal mortalities either directly or indirectly through increased wildfires and droughts. Feedbacks are likely to cause or accelerate such a tipping point because as global climate change induced drought kills areas of forest, the precipitation those trees had cycled back to the atmosphere disappears, furthering drought and killing more forest. Studies have found that vegetation-climate feedbacks in the Amazon could amplify the ongoing climate change induced warming and drought in this region (Zemp *et al.*, 2017; Wu *et al.*, 2021), potentially accelerating its tipping to alternative states. For example, Zemp *et al.* (2017) illustrated a feedback loop of reduced rainfall causing an increased risk of forest dieback causing forest loss induced intensification of regional droughts that self-amplifies forest loss in the Amazon basin.

Even if the conditions shift from those favouring savannah, it is possible that forest cover may remain for some time due to the micro-climatic conditions that forests support; however, if drying is so severe that wet season rains cannot replenish soil moisture, dieback is likely to occur. However, if micro-climatic inertia is significant, then the role of fire would be elevated in importance in tipping (Malhi *et al.*, 2009). Large parts of the Amazon have become increasingly flammable during drier months, although ignition sources are often scarce. The increase in human activity and forest fragmentation, however, increases the proximity of much of the forest to anthropogenic ignition points, further increasing the likelihood of hitting a tipping point (Malhi *et al.*, 2009). The impact of deforestation and degradation not only causes increased vulnerability to other tipping drivers (Wunderling *et al.*, 2022), as well as definitionally causing localised state changes, but via cascades may itself be a key driver of changes to the combined ecological-climatic system in the Amazon basin (Boers *et al.*, 2017).

Some researchers have suggested that ecosystems capable of developing Turing patterns might have multistability with many partly vegetated states, which may enhance resilience and lower irreversibility (Rietkerk *et al.*, 2021); it is unknown how SRM would enhance or detract from this resilience.

5.3.2: The impacts of SRM

The effect of SRM on Amazon tipping is deeply uncertain, given that it is highly dependent on a number of factors, some poorly understood, and a number of the impacts that SRM creates are novel. In addition, large areas of the Amazon are poorly studied, and the climatic drivers are consequently not understood (Carvalho *et al.*, 2023). Firstly, Amazon forests are highly dependent on regional precipitation, in particular drought. Tropical forests in general are commonly dependent not only on large-scale circulation patterns, which GCMs can be used to provide insight to understand the impact of SRM, but also may depend on monsoon dynamics and convection-forest interactions, which are not yet often accurately captured in models. Moreover, the effects may be highly dependent on the specifics of the particular SRM scenario, and different SRM approaches may have very different regional and local meteorological and ecological consequences even if they aim for similar global average temperatures (Fan *et al.*, 2021). Changes in relative humidity and vapour pressure deficit are also important for forest function (Grossiord *et al.*, 2020), with vapour pressure deficit generally decreasing under SRM and thus alleviating atmospheric aridity and stomatal stress even with reduced precipitation (Fan *et al.*, 2021). Whether global warming is increasing land aridity or not is a highly debated topic (Berg and McColl, 2021) and in light of this, whether SRM would alleviate or exacerbate aridity (including Amazon drying) is likewise highly uncertain. Because SRM would not reverse carbon based global climate change but would create novel environmental conditions, predicting the consequences beyond lowered temperatures in Amazon forests is extremely difficult. For example, in contrast to same-temperature conditions obtained by CO_2 reduction, SRM would result in lower temperature but elevated CO_2 levels, warmer nights relative to days and changes in direct/diffuse light ratio, with currently poorly understood vegetation responses. Thus, the utility of existing studies on these drivers is of limited utility.

Jones et al, (2018) used models of SAI deployment to keep temperature to 1.5^{O}C above preindustrial, and found that Amazon drying is very imperfectly compensated for by the deployment, although it is reduced relative to same-emission scenarios. The compensation is better in the East Amazon, where tipping concern under climate change is the greatest, than the West Amazon. They suggest that this is because much of the hydrology of the Amazon is controlled by changes to annual-mean photosynthetic activity and stomatal conductance, which are driven by elevated atmospheric CO_2 levels as well as temperature. These may also be impacted by the type of light, although this was not explored in the study. Simpson *et al.*, (2019) see precipitation reductions over the Amazon in GLENS that are equal to that of the comparative non-SAI scenario (RCP8.5), although soil moisture is greater under SRM than RCP8.5, as evapotranspiration is suppressed. This P-E reduction was also seen in Jones et al (2018). However, this analysis is limited as it looks at annual precipitation rather than looking at droughts, with the latter a much stronger driver of Amazon tipping. Touma *et al.*, (2023) uses an SAI scheme to keep temperature close to 1.5^{O}C above pre-industrial, and sees increases in drying and fires in the West Amazon when compared to SSP2-4.5, whilst a reduction in fires in Northeast Brazil, which includes part of the East Amazon. However, drought severity is found to increase slightly for both regions under SRM when compared to SSP2-4.5. In general, the East Amazon is the area of greatest concern for tipping behaviour under climate change (Malhi *et al.*, 2009), although the possibility of cascades through the atmospheric-moisture recycling feedback means that the drying in the West Amazon cannot be ruled out as precipitating regional tipping.

Whilst this may give some indication of possible regional climatic effects, the reliability of these results in such a complex system which GCMs struggle to represent is questionable. SRM cannot, however, affect deforestation, which is a key driver of tipping, both locally and regionally. Thus, the effect SRM has on Amazon tipping remains highly uncertain.

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5.3.3: Further Research

In light of the complexity of the ecological system and regional- to micro-climatology in the Amazon, more research is needed to better represent bioclimatological (vegetation-climate interaction) processes in GCMs and their land surface models in order to constrain future projects of the impact of SRM on Amazon forest tipping. At the same time, increasing the number of monitoring stations and continued archiving of satellite imagery of the Amazon microclimate and forest health status is critical for enriching empirical knowledge of this unique system to support model development (Carvalho *et al.*, 2023). The contrasting effects of SRM on hydrological aridity (precipitation and soil moisture) and atmospheric aridity (vapour pressure deficit), and their competing effects on forest health is also worth attention in assessing the overall effect of SRM on the Amazon system.

5.4: Shallow-Sea Tropical Coral Reefs

Coral reefs are most abundant in warm, shallow tropical waters, where the habitat they create sustains very high levels of diversity including about a quarter of the total fish species on Earth that spend at least some part of their lives on coral reefs. Coral reefs also provide major ecosystem services to humans. Corals are invertebrate animals belonging to thousands of species in the phylum Cnidaria, living in a range of marine environments. A single coral consists of a living polyp surrounded on 3 sides by a skeleton made of calcium carbonate. A reef is built up by the excretion of calcium carbonate from millions of coral polyps, which keep building up toward the light, leaving the coral reef structure underneath. The structure created by the corals creates a massive habitat for many other organisms. Tipping in shallow-water tropical coral reefs results in the establishment of an entirely different biotic and physical community space, often dominated by macroalgae without these hard skeletons (Holbrook *et al.*, 2016). More recent work has highlighted the presence of multiple stable states if fish are considered alongside benthic functional groups (Jouffray *et al.*, 2019).

5.4.1: Drivers and Mechanisms

Ocean warming is a primary driver of shallow-sea tropical coral reef tipping, normally via sustained high temperature events causing coral bleaching (Fox-Kemper *et al.*, 2021). During these events, corals will expel their symbiotic photosynthetic dinoflagellates; if they are bleached for extended periods of

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time, this can result in death (Wang *et al.*, 2023). If the corals are then replaced by other organisms, chiefly macroalgae, then a transition to an entirely new stable state can occur. It sometimes may be possible for the scleractinian coral to reestablish themselves after mass mortality events. However, warming is projected to outpace the adaptive capacity of corals with recurrent bleaching events making recovery very difficult, causing transitions to a second stable state to be more likely (Hughes *et al.*, 2017). Other interactions such as a drop in herbivory may make it easier for the macroalgae to become established, further promoting tipping (Holbrook *et al.*, 2016).

Acidification also is a secondary driver of tipping. As CO_2 levels increase and more CO2 dissolves in ocean water, the CO2 reacts with water to form a mild acid. As aragonite saturation levels drop, calcification by the polyps decreases, leading corals to either reduce their skeletal growth, keep the same rate of skeletal growth but reduce skeletal density increasing susceptibility to erosion, or to keep the same skeletal density and rate of growth whilst diverting resources away from other essential functions (Hoegh-Guldberg *et al.*, 2007). Dead coral structures are also dissolved or eroded at a faster rate in more acidic water, further reducing reef functioning. Nonetheless, the relationship between increased acidification and decreased calcification is complex with studies equivocal over how strong this relationship is, as well as how important non-pH factors are in changes to calcification rate (Mollica *et al.*, 2018).

Other factors may also contribute to coral tipping. Storm intensity is expected to increase under warming, causing physical damage to the reef which recovery may be difficult from (Gardner *et al.*, 2005). Sea Level Rise, if it outpaces the coral's ability to track, which may be the case due to the other factors mentioned, can promote increases in sedimentation. However, (Brown *et al.*, 2019) find Sea Level Rise promotes reef growth, likely by allowing space for the reef to grow, reducing aerial exposure and exposure to turbid waters. A variety of non-climatic or CO_2 related anthropogenic factors are also important. (Jouffray *et al.*, 2019) identified a number of different stressors on Hawaiian coral reefs, including fishing and pollution, and finds in certain regime shifts this has been a more important driver than climatic factors.

5.4.2: The impacts of SRM

SRM would likely help to reduce coral reefs tipping by reducing ocean temperatures (Couce *et al.*, 2013), thus reducing the frequency of bleaching events. SRM may increase acidification somewhat by decreasing pH and aragonite saturation relative to the same emissions pathway without SRM, due to cooler water having a higher CO_2 solubility (Couce *et al.*, 2013). However, (Jin, Cao and Zhang, 2022) argues that it is more complex; temperature decreases tend to increase pH and aragonite saturation for a given pCO_2 (Cao, Caldeira and Atul, 2009), whilst cooler temperatures generally reduce calcification and thus lead to lower pH and aragonite saturations. Their results suggest that whilst pH is slightly increased under SRM, aragonite saturation, the key variable of interest, is negligibly affected; thus we should expect SRM to have a close to negligible impact on the acidification driver of coral tipping.

SRM is likely to decrease the intensity of tropical storms, although with low confidence (Moore *et al.*, 2015). (Wang, Moore and Ji, 2018) find that SRM decreases the number of tropical cyclones relative to the same emissions pathway without SRM, although it does increase in the South Pacific, and so its overall impact on coral reef tipping is unclear. The impact is also heavily scenario dependent (Jones *et al.*, 2017; Wang, Moore and Ji, 2018).

The impact of SRM on the incoming radiation, both by reducing the amount and increasing the diffuse fraction, is also likely to impact photosynthesis but any effect is likely to be minor and have minimal impacts on tipping behaviour. Non-climatic or CO_2 related anthropogenic drivers will be unaffected by SRM.

(Couce *et al.*, 2013) finds that suitability for reef conditions are improved under SRM when compared to same emission pathway scenarios, although worse than same temperature scenarios generated through mitigation. However, conditions in much of the Pacific improved relative to present day. (Zhang, Jones and James C., 2017) specifically look at Caribbean coral reefs, and find that coral bleaching is significantly reduced by SRM due to its effect in allowing temperature to remain below the critical threshold for corals. Moreover, SRM is seen to reduce the frequency of Category 5 hurricanes, and whilst the recurrence time is increased, this is not enough to fully offset the impacts of climate change. Relative to the same emission pathway scenarios, both studies see SAI as reducing the likelihood of coral reef tipping, although they both undercompensate for the changes seen due to climate change.

There has also been interest in the use of MCB in combating bleaching, particularly short-term use around bleaching events (Tollefson 2021). Theoretically, such a programme ought to reduce bleaching on the corals, although full analysis of the limited field experiments carried out have not yet shown if the technology is capable of attaining the necessary cooling.

5.4.3 Further Research

Given the high level of temperature dependence of the climatic drivers, our understanding of the impact of SRM on coral reef tipping is quite strong, and so further research is here less of a priority. However, few studies have examined the frequency of extreme temperatures that may lead to bleaching under different types of SRM deployment, so such modelling may be useful. Moreover, given the interest in MCB with reference to coral tipping, more research into whether coral reefs could still tip given the other stressors they may be facing will help shed light on the overall importance of SRM in this context. Similarly, better research with how other reef restoration strategies may interact with SRM to reduce the probability of tipping, or may reduce its counterfactual impact, may also be important for the most realistic assessment.

5.5: Indian subcontinent biodiversity hotspots

Several biodiversity hotspots are found on the Indian subcontinent, including the eastern Himalaya/southwestern China (Sharma *et al.*, 2009), the Western Ghats, and the Sundarbans. All of these are vulnerable to tipping due to climate change. The region encompassed by the eastern Himalaya and southwestern China has over 10,000 plant species, thousands of which are endemic (i.e., with evolutionary origins there and found nowhere else). This exceptionally diverse region ranges from alpine to tropical systems. Warming temperatures, loss of the Himalayan glaciers, and greater evaporative demand threaten many species here with extinction. It is not known what an alternative state would be should this system be driven past a tipping point, but one speculation is low diversity grasslands, possibly dominated by invasive species. Whether SRM would cool sufficiently to prevent the loss of the Himalayan glaciers is discussed earlier here.

The Western Ghats stretch along the west coast of India, with high biodiversity of plants, mammals, birds, reptiles, invertebrates and others. The biodiversity in this region is highly dependent on the Indian monsoons. Higher temperatures and more intense rainfall would be likely to cause enough species loss to transform this system, but SRM might pull the monsoons back to drought conditions, tipping in a different direction.

The Sundarbans are the largest and most diverse mangrove wetlands in the world, formed in the delta of the confluence of the Ganges, Brahmaputra and Meghna Rivers in the Bay of Bengal in Bangladesh and into India, with very high and threatened biodiversity of many mammalian, bird and other species. Rising sea levels and failure of river water supply is pushing the system to a tipping point due to loss of land area and increasing salinity which is killing the dominant mangrove tree species (Raha *et al.*, 2012; Sievers *et al.*, 2020). Analogous to coral reefs, the mangroves form a living physical structure that creates habitat that supports many other species and complex species interactions. Therefore, their loss or replacement by other plant species would change the system to an alternative system, but the consequences of this change are poorly understood.

5.5.1: Drivers and Mechanisms

There are a number of potential climate change-induced drivers of tipping points in the Indian subcontinent, including melting montane glaciers, changes in the Hadley cells and the monsoon, sea level rise, droughts and heatwaves (Swapna *et al.*, 2017; Mishra, Aadhar and Mahto, 2021; Mall *et al.*, 2022). Global warming is melting high elevation glaciers rapidly worldwide (Sect. 2.3) (Hugonnet *et al.*, 2021). Glacial melting in the Himalaya (Potocki *et al.*, 2022) would result in climate change tipping points in the immediate area below the glaciers, and also for the vast areas of the Indian subcontinent below dependent on them as a source of water. Changes to the tropical monsoonal rains in the Indian subcontinent are also potential tipping points (Armstrong McKay *et al 2022)*, particularly in the Western Ghats. Climate change has been implicated in failure of the monsoon in parts of the subcontinent (Swapna *et al.*, 2017), and extreme rainfall events and severe flooding in other parts, with catastrophic change to some natural and agricultural systems.

5.5.2: The impacts of SRM

SRM’s cooling is expected to slow the melting of Himalayan glaciers (Sect. 2.3), which can potentially avoid tipping of some biodiversity hotspots in the Indian subcontinent that heavily depend on these glaciers as sustained water sources. While SRM might relieve the likelihood of hitting tipping points caused by extreme rainfall and flooding, changes to the movement of the Hadley cells predicted from some SAI scenarios might result in hitting drought-sensitive tipping points (Smyth, Russotto and Storelvmo, 2017; Cheng *et al.*, 2022). Even changes in the seasonality and predictability of the monsoons could force flash droughts (Mishra, Aadhar and Mahto, 2021) and related tipping in some ecological systems as well as crop failure. Moreover, the severe and extended heat in the Indian subcontinent in recent years (Mishra *et al.*, 2020) is likely to push some natural systems over tipping points. Reduction of the extent and severity of extreme heat from the implementation of SRM can therefore potentially prevent heat-related tipping points from occurring.

5.5.3: Further research

Research directions to better understand the potential impact of SRM on the Indian subcontinent biodiversity hotspots largely overlap with progress in research on mountain cryosphere, sea level rise and extreme events. But ecological tipping in these regions may happen before climate-driven tipping in Himalayan glaciers, sea level, and Indian monsoons because the functions of these biodiversity hotspots depend not only on external drivers in climate and hydrology but also on their internal feedbacks and human disturbance (such as damming) that could exacerbate the risks of collapsing or tipping. Therefore, the time and threshold of tipping in these biodiversity hotspots and how they will respond to climate change and SRM should deserve more collaborative research between climatologists, ecologists and biologists.

5.6: Northern Coniferous Forests

The taiga, or northern coniferous forest, is the largest of Earth's biomes, and although low in biodiversity with many circumboreal species and genera, also is a major reservoir for carbon. Anthropogenic warming is greatest in these northern regions due to Arctic amplification (Serreze and Barry, 2011), and warming nights and extended periods of extreme heat are directly and indirectly forcing major structural changes in some parts of this biome, potentially precipitating tipping points, perhaps from forests to shrublands or grassland due to biotic and abiotic disturbances (Seidl *et al.*, 2017) or from shrublands or grasslands to forests due to temperature-driven northern migration of boreal trees (Berner and Goetz, 2022). Studies have suggested that the extinction of large mammals (e.g. woolly mammoths) was a tipping point in the most recent glacial maxima in which their grazing maintained grasslands which had higher albedo than the coniferous forests, resulting in global cooling because the extent of these systems is so great; others have suggested that wildlife restoration can be a solution to reversing that tipping point (Zimov, 2005; Schmitz and Sylvén, 2023).

5.6.1: Drivers and Mechanisms

Warmer temperatures, increased evaporative demand, increased droughts, lower water availability and reduced snowpack and duration of snowpack under climate change both directly stress the coniferous forest (Ruiz-Pérez and Vico 2020) and in doing so makes them more vulnerable to other stressors such as insect attack. Northern expansion of bark beetles (McKay *et al*, 2022) and reduced generation times for these and other pests have killed large expanses of northern coniferous forests, and the dead and dying trees combined with warmer temperatures and drought have drastically reduced fire return intervals in many areas and greatly increased the scope and severity of fires (Bentz *et al.*, 2010). Reduced duration of snow cover also reduces albedo, potentially increasing surface absorption of direct radiant energy from sunlight by the dark canopies of these trees, leading to more likely positive feedbacks and runaway processes typical of tipping points. Fires and tree mortality could also contribute to positive feedbacks by returning long-stored carbon in living trees to the atmosphere. These impacts have a strong regional dependency (Ruiz-Pérez and Vico 2020).

5.6.2: Impact of SRM

By having SRM cooling average temperatures, it is possible that the driving forces that either promote (northern migration of trees) or suppress (fires and insect attacks) northern coniferous forests might all be lessened and the system pulled back from such tipping points in either direction. On the one hand, cooler temperatures will slow or stop the migration of trees into tundra and preserve the original biome configuration. On the other hand, extending periods below freezing by SRM might limit the northward spread of destructive insect outbreaks, extend snow cover, and possibly reduce drought and vapour pressure deficit, enhancing the resilience of these forests and pulling them back from a tipping point.

5.6.3: Further research

The migration of northern coniferous forests to higher mountains and higher latitudes is creating new ecological systems that demand more research to understand their tipping points. Further advancement in the monitoring and/or prediction of abiotic (fires, drought, wind, snow and ice) and biotic (insects, pathogens, invasive species) disturbance agents and their interactions (Seidl et al. 2017) under global warming are key to predict future disturbance and resilience of both existing and expanding northern coniferous forests under novel climates of SRM.

6: Discussion

Tipping elements are one of the most uncertain and potentially threatening hazards of climate change. These have been invoked as rationale for considering SRM (Heyward and Rayner, 2016; National Academies of Sciences and Medicine, 2021; United Nations Environment Programme, 2023), however, our review reveals that the impact of SRM on tipping elements is under-researched.

Where there existed direct evidence for the impact of SRM on tipping this was reviewed, as well as the evidence for the impact of SRM on associated non-tipping behaviour in the relevant systems that are believed to have similar drivers to tipping, such as AMOC weakening as a proxy for AMOC tipping. We then assessed the impact of SRM on tipping elements by identifying the key drivers of tipping for each of the relevant tipping elements and then assessing the evidence for the impact of SRM on these drivers. This approach is clearly limited. The evidence base we have drawn from is very limited and uncertain, both for the drivers and feedbacks involved in tipping and for many of the impacts of SRM. The use of such qualitative judgement also makes assessment when a variety of factors are involved significantly harder, and whilst judgements can sometimes be made as to whether SRM would help avoid or hasten tipping, judgements of efficacy are mostly beyond the scope of the study. In light of this, our conclusions ought to be mostly considered evidence-informed hypotheses in need of considerably more research, although the confidence in the conclusions does differ for different tipping elements. A summary of the identified impacts of SRM on the tipping elements is seen in the table below.

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Name of element	Key drivers	Effectiveness [1]	Can SAI reverse tipping once a) feedbacks processes have begun b) tipping is complete?[2]	Overall Confidence[3]
Greenland Ice Sheet	Temperature, Precipitation	Partial Compensation (possibly Insuffcent)	a. Uncertain (Yes or No dependent on the study) b. No	Medium
Antarctic Ice Sheets	Ocean Temperature, Circumpolar Deep Water driven melt, Atmospheric Temperature	Worsen to Partial Compensation	a. No b. No	Low
Mountain Glaciers	Temperature, Precipitation	Partial Compensation	a. Yes b. Likely	Medium
Summer sea ice decline	Temperature, radiative flux, atmospheric circulation	Partial Compensation	a. N/A b. Yes	High
Winter sea ice abrupt loss	Temperature	Partial Compensation	a. Yes b. Yes	Medium
Permafrost	Soil temperature, hydrology	Partial Compensation	a. Uncertain b. No	Medium
Methane hydrates	Deep ocean temperature	Uncertain	a. No b. Uncertain	Low
AMOC Collapse	Buoyancy gain in the North Atlantic through surface heating or freshening, driven by P-E, sea ice melt and greenland ice sheet melt	Partial to Over Compensation	a. Likely b. Yes, with hysteresis	Medium

SPG Collapse	Bouyancy gain in the North Atlantic through surface heating or freshening, driven by P-E, sea ice melt and greenland ice sheet melt	Partial Compensation	a. Plausibly b. Uncertain	Low
AABW Collapse	Freshening due to Antarctic Melt, Wind Changes	Uncertain	a. Uncertain b. Uncertain	Very Low
Marine Stratocumulus Clouds	Longwave forcing, Sea Surface Temperature	Partial Compensation	a. Uncertain b. Uncertain	Low
Dipterocarp Forests	Cool nights and drought changes, land use change	Partial Compensation	a. Likely b. Likely	Medium
Amazon Basin	Drought, fire, land use change	Uncertain with likely regional disparities	a. Uncertain b. Unlikely	Low
Coral Reefs	Sea Water Temperature, Acidity	Partial Compensation (for temperature driver), Worsens (for acidity driver)	a. Yes b. No	High
Indian Subcontinent Biodiversity Hotspots	Glacier Melt Water, sea level, monsoon, heatwaves	Partial Compensation	a. Likely b. Likely	Medium
Northern Coniferous Forests	Temperature, snowpack, fire, insects	Partial Compensation	Uncertain	Low

Table 1: A Table of the Earth System Tipping Elements and Threshold-Free Feedbacks assessed.
[1]Assessed on a scale of worsen, insufficient compensation, partial compensation, full compensation, over compensation

[2] *Yes/No=has significant supporting evidence, Likely/Unlikely=based mostly on conjecture from theory, Uncertain=no assessment could be reasonably made, N/A= Threshold Free Feedback*

[3] *Assessed on a scale of Very Low to Very High*

SRM was seen to partially compensate for the anthropogenic impacts of relative to same-emission pathways in 11 of the tipping elements, with another 4 of tipping elements being unclear as to the effect of SRM. However, our confidence in assessing the tipping elements was High for only 2 of them, highlighting the large uncertainties still remaining. In most cases, it was necessary for the reduced warming effect of SRM to continue indefinitely; thus peak-shaving scenarios are often necessary to avoid tipping, although merely slowing the ris in temperature may be useful in avoiding AMOC tipping and the tipping of a number of ecological systems.

It is plausible that many of the impacts identified are scenario dependent. Moreover, given a number of the tipping elements identified showed hysteresis, waiting until tipping has occurred before reversing it may not be plausible; thus 'emergency-use' may fail to avoid the negative impacts of many tipping elements. Moreover, the potential for SRM to halt the tipping process once positive feedbacks have been initiated has barely been studied, further adding to the uncertainty around 'emergency-use'.

For most tipping elements, a 'peak shaving' scenario was seen as necessary to avoid tipping, and the use of SRM to slow the rate of warming would merely postpone rather than avoid tipping. This also generally meant that termination shock would be unlikely to make tipping more likely than the same CO_2 concentrations without SRM. This however may not be the case for those tipping elements that are rate dependent, such as the AMOC in certain models and potentially some ecological tipping elements. The evidence for whether SRM could halt or reverse self-sustaining feedbacks once they had been initiated is scarce, with some suggestions that it may not be possible in certain cases, meaning significant worries remain over emergency deployment once indicators of tipping have begun. Nonetheless, there are indications that SRM could reverse tipping in some cases, although often this reversal does show hysteresis, making an 'emergency-use' scenario more dangerous than preemptive usage.

This study focused purely on the physical consequences of SRM, and not taken into account the social interactions. If mitigation deterrence is important (McLaren, 2016) resulting in total emissions being higher than in the absence of SRM, which is a controversial hypothesis (Cherry *et al.*, 2023), and peak-shaving proves implausible due to governance breakdown or an inability to carry out the necessary scale of CDR (Fuss *et al.*, 2018), then carrying out SRM may actually increase the chances of tipping for those elements identified here. Moreover we ignored the potential impacts of the land-use change required for the large scale CDR associated with 'peak-shaving' scenarios, which may significantly impact the biosphere in particular (Smith *et al.*, 2019).

6.1: Further Research

If we are to better understand SRM and its interactions with tipping, further research is necessary. These further research suggestions are contingent on this goal being one that the relevant communities ought to pursue, which may not be the case if we believe logics that involve risk assessment of SRM are unlikely to be important in guiding its development.

In some cases, the key uncertainty is the dependency of tipping on the value of a particular driver where the effect of SRM is well known, such as the dependency of abrupt permafrost thaw on particular values of Arctic temperature. In other cases, the impacts of SRM on the relevant variables may be the greater uncertainty, such as with the impacts of SRM on the Amazon Basin. Modelling involving SRM and tipping elements in global Earth System Models would be ideal. However, tipping is very difficult to simulate in these models, and the sorts of regional impacts of SRM are also rarely well captured. Therefore, other approaches ought to be the priority.

Firstly, better understanding of the effectiveness of various SRM deployment schemes, and the global and regional impacts of this deployment. Whilst this effort is ongoing, this study has highlighted a number of relevant uncertainties for assessing the impact of SRM on the drivers of tipping, some of which may be addressable by further research. A better understanding of the impacts of SRM in a wide variety of scenarios, especially non-ideal scenarios including termination, would allow for more realistic assessment of the impacts of SRM deployment on tipping elements.

Secondly, better understanding of tipping elements, their drivers and feedbacks involved, as well as the drivers of hysteresis, will also be key in improving an assessment of the impact of SRM on them. This effort is also ongoing.

The SRM research community and the tipping element research community should collaborate to better understand the interactions. Direct modelling may be feasible in certain cases, and whilst large uncertainties will likely remain, this will provide the most informative possible assessment. Simple

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scenarios that allow for high signal to noise ratio will be important initially, although this will compromise some of the realism of the scenarios, and thus in time ought to be replaced by more realistic scenarios. This compromise of the realism of the scenarios may also be needed to address a potential bias towards stability in the modelling of a number of tipping elements, such as the AMOC, but as modelling of tipping elements improve more realistic forcings can hopefully be used, allowing enhanced realism to all aspects of the scenarios. Direct modelling of ‘emergency-use’ after tipping feedbacks have begun, and modelling of the possibility of reversing tipping will also provide useful results; whilst we have suggested here that both seem mostly implausible at avoiding or reversing tipping in the short-term without considerable hysteresis, this has been based on extremely limited evidence.

This paper has focused on the effect of SRM on the earth system, but it is not guaranteed that this, rather than, for example, the assertion of power, is the underlying logic that may cause or stop SRM deployment in the future. Whether any research on SRM and tipping elements has the potential to inform and influence decisions around development and deployment under such logics is questionable, although any possible impacts must be considered when assessing the desirability of the research that we have proposed above. Only assessing the desirability of this research under the assumption that SRM will proceed under a logic of rationally reducing climate damages would be naive. Whilst we have presented the types of further research that would be useful under such a climate-damage orientated logic, there are further considerations to take into account to assess the overall desirability of such research, although what exactly these considerations are is beyond the scope of this study.

Finally, whilst we have tried to assess the impact of SRM deployment on tipping elements, we make no claim that this ought to be the most important consideration. SRM will have a variety of climatic, ecological, social and political consequences, and the diversity of such consequences ought to all be considered, with tipping elements as only one aspect of a comprehensive risk assessment.

Author Contributions

GF led in the conceptualisation, methodology and overall administration of the project, prepared the overall original draft by consolidating and editing sections, wrote the conclusion, contributed to the research and writing of the section on Amazon and Coral Reef tipping elements. MA researched and wrote the section on Greenland Ice Sheet, the Antarctic Ice Sheet and Mountain Glaciers. AD researched and wrote the section on Sea Ice, Permafrost and Methane Hydrates. YF and JG researched and wrote the biosphere system. PI researched and wrote the section on Marine Stratocumulus Clouds, and

provided supervision of the cryosphere section. CW assisted GF in the conceptualisation, wrote the introduction with assistance from GF and JG, and researched and wrote the Oceans section.

Competing Interests

The authors declare that they have no conflict of interest.

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